# Earth Remote Sensing

## March 14-18, 1994

## Engineering 867.115

## Coordinators:

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Short Course Program

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# lecture notes

# for

# David L. Glackin, MS

# EARTH REMOTE SENSING

## ELECTRO-OPTICAL REMOTE SENSING

**David L. Glackin**
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**Advanced Plans and Architecture**
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**UCLA Extension**
**Engineering Short Course**
**No. 867.115**
**Winter 1994**

# ELECTRO-OPTICAL REMOTE SENSING

D. L. GLACKIN

1994

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# PART 1

# INTRODUCTION

# REMOTE SENSING



- DEFINITION OF REMOTE SENSING
  - THE MEASUREMENT OF THE PHYSICAL PROPERTIES OF A BODY FROM A DISTANCE
- RANGE OF TECHNIQUES
  - GROUND-BASED, AIRBORNE & SPACEBORNE
  - PASSIVE & ACTIVE
  - ELECTRO-MAGNETIC, GRAVITATIONAL, MAGNETIC, ACOUSTIC, PARTICLE
- REPRESENTATIVE RANGE OF OBJECTS STUDIED
  - GALAXIES, STARS, QUASARS, PULSARS ➦ ASTROPHYSICS
  - PLANETS & SUN ➦ PLANETARY PHYSICS & SOLAR PHYSICS
  - EARTH ENVIRONMENT & RESOURCES ➦ EARTH REMOTE SENSING
  - POWER PLANT EMISSIONS ➦ REGULATORY MONITORING
- UTILITY
  - OBJECTS UNREACHABLE OR IMPRACTICAL TO STUDY *IN-SITU*
  - COVER LARGE AREAS EFFICIENTLY

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# SCOPE OF COURSE



- EARTH REMOTE SENSING & MONITORING
  - ATMOSPHERE, OCEANS, LAND SURFACE
    - — NO MAGNETOSPHERE/IONOSPHERE TOPICS
- SPACEBORNE & AIRBORNE
  - NO GROUND-BASED TECHNIQUES
- ELECTRO-OPTICAL TECHNIQUES
  - PASSIVE & ACTIVE VISIBLE, INFRARED, UV
- MICROWAVE TECHNIQUES
  - PASSIVE & ACTIVE MILLIMETER-WAVE & MICROWAVE
- NO GRAVITATIONAL, MAGNETIC, ACOUSTIC, OR PARTICLE TECHNIQUES
- USER ORIENTATION
- SYSTEMS APPROACH
- RETRIEVAL METHODS, ALGORITHMS, MODELING
- INTERNATIONAL PERSPECTIVE

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# SUGGESTED READING



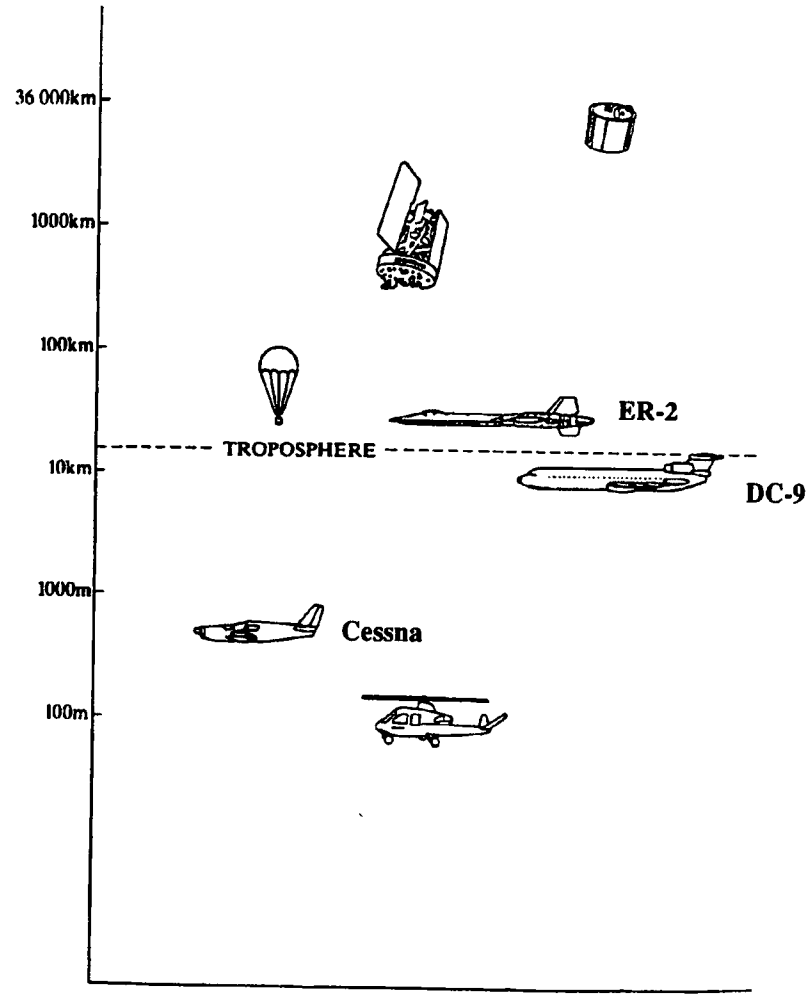
- **BACKGROUND**
  - SLATER, P. N., 1980, *REMOTE SENSING: OPTICS AND OPTICAL SYSTEMS*, ADDISON-WESLEY
  - CHEN, H. S., 1985, *SPACE REMOTE SENSING SYSTEMS: AN INTRODUCTION*, ACADEMIC PRESS
  - SCHNAPF, A., 1985, *MONITORING EARTH'S OCEAN, LAND, AND ATMOSPHERE FROM SPACE – SENSORS, SYSTEMS, AND APPLICATIONS*, AIAA, INC.
  - RAO, P. K., ET AL., 1990, *WEATHER SATELLITES: SYSTEMS, DATA, AND ENVIRONMENTAL APPLICATIONS*, AMERICAN METEOROLOGICAL SOCIETY
  - NASA, 1986-7, EOS INSTRUMENT PANEL REPORTS
- **POST-COURSE**
  - *SPACE NEWS* WEEKLY NEWSPAPER
  - *THE EARTH OBSERVER*, EOS PERIODICAL, EOS PROJECT SCIENCE OFFICE, NASA GSFC
  - 199*n* EOS REFERENCE HANDBOOK, EOS PROJECT SCIENCE OFFICE, NASA GSFC
  - *INTERNATIONAL JOURNAL OF REMOTE SENSING*
  - *JOURNAL OF APPLIED METEOROLOGY*
  - *IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING*

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# ADVANTAGES OF AIRBORNE SENSING



- PROOF-OF-CONCEPT SENSOR FLIGHTS
  - TESTBED FOR ADVANCED SENSOR DESIGNS
- EASE OF SERVICEABILITY
  - SENSOR PROBLEMS REMEDIED IN LAB
- EASE OF MODIFICATION
- HIGHER SPATIAL RESOLUTION
- MULTIPLE REVISIT OPPORTUNITIES
- SELECTABLE VIEWING ANGLE & ALTITUDE
- CALIBRATION UNDERFLIGHTS OF SPACE SENSORS
  - COLLECT HIGH-RESOLUTION GROUND TRUTH
- NO COMPLEX COMM NETWORK
- FASTER ACQUISITION PROCESS
- LOWER COST
- BALLOONS: RADIOSONDES, RAWINSONDES, PIBALS




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# ADVANTAGES OF SPACE VIEW



- GLOBAL COVERAGE WITH FEW SENSORS IN SHORT TIME
  - IMPRACTICAL FROM AIR OR GROUND PHYSICALLY & FINANCIALLY
    - — FEW GROUND-BASED OBSERVATIONS OF, E.G., SOUTH PACIFIC
      - -- CANNOT INSTRUMENT THE WHOLE GLOBE
    - — LIMITED # INSTRUMENTED AIRCRAFT
      - -- LIMITED RANGE & MANPOWER
      - -- RESTRICTED BY WEATHER
  - POSSIBLE TO COVER THE GLOBE WITH ONE SATELLITE IN 12 HOURS
  - VAST ARRAY OF IDENTICAL SENSORS UNNECESSARY
- POTENTIAL FOR GLOBAL MULTI-SENSOR VIEW SIMULTANEOUS IN SPACE & TIME
  - SENSOR FUSION
  - CAN BE SUN SYNCHRONOUS
- VIEW MAN'S IMPACT ON GLOBAL HABITABILITY
- LONG TERM MONITORING OF THE EARTH AS A SYSTEM

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# SATELLITE ORBIT EXAMPLES

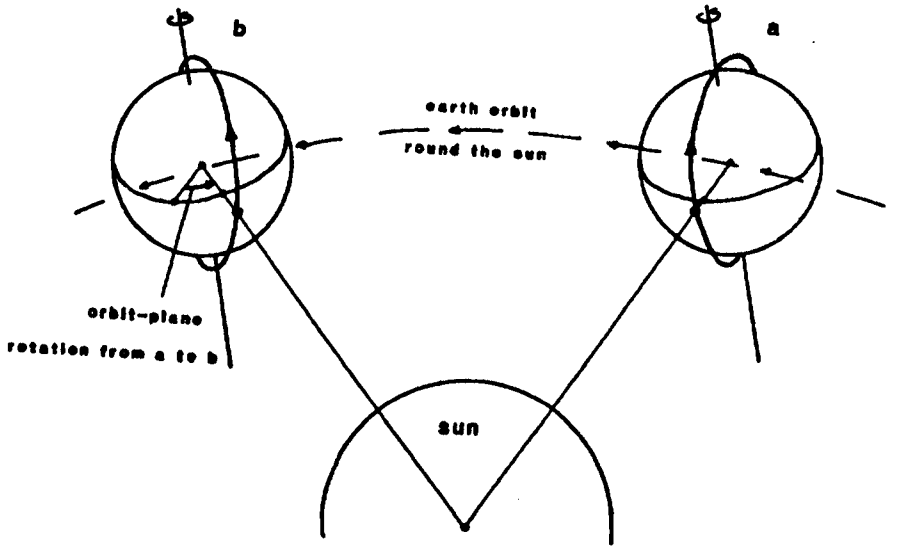


- LOW EARTH ORBIT (LEO) EXAMPLE
  - CIRCULAR POLAR SUN-SYNCHRONOUS
    - — VIEW SAME EARTH LOCATION AT SAME LOCAL TIME
    - — COMMON FOR ENVIRONMENTAL & EARTH RESOURCES SATELLITES
      - -- COMPROMISE ALTITUDE ≈ 700 - 850 KM; COVER GLOBE IN 12 HRS WITH 1 BIRD
    - — ≈ 98° INCLINATION ⇒ PRECESSION ≈ 1°/DAY
- GEOSTATIONARY & GEOSYNCHRONOUS (GEO)
  - ORBIT = 24 HR PERIOD @ 36000 KM ALTITUDE
  - COMMON FOR RAPID-REFRESH ENVIRONMENTAL SATELLITES
  - GLOBAL COVERAGE TO ≈ ± 60° LAT WITH 5 BIRDS
- MOLNIYA ORBIT
  - HIGHLY ELLIPTICAL, APOGEE NEAR ONE POLE AND > 36000 KM ALTITUDE
  - "HANGS" OVER THE CHOSEN POLAR REGIONS FOR ≈ 8 HOURS PER DAY
  - 24 HR POLAR REGION COVERAGE WITH 3 SATELLITES

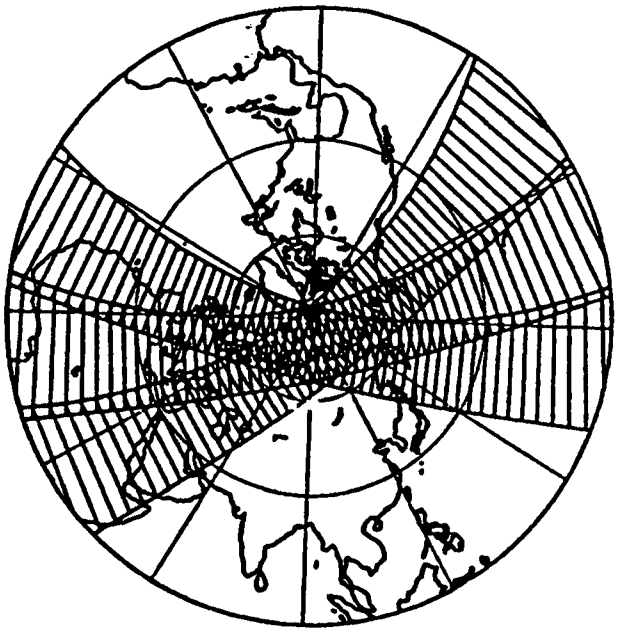
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# POLAR SUN-SYNCHRONOUS ORBITS

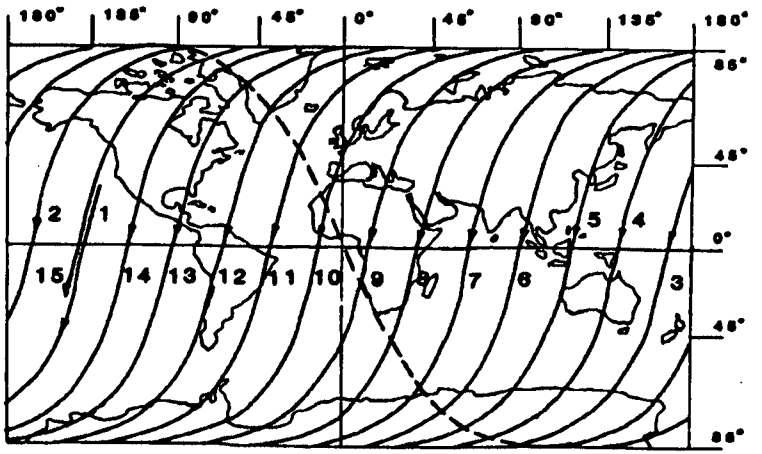





**Orbit Precession** (Reprinted with permission of the publisher from Ref 1, © 1985 Ellis Horwood Ltd.)

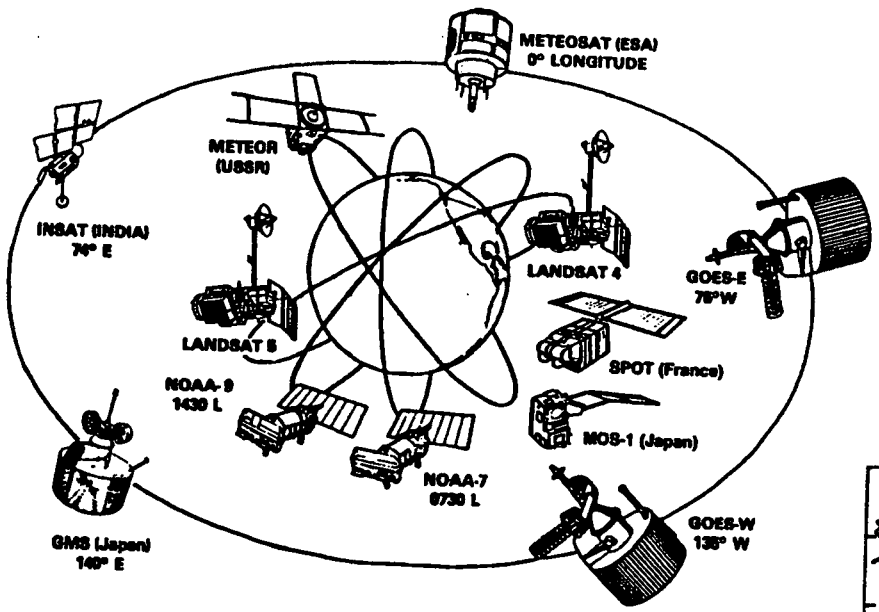


**Polar Swaths** (Reprinted with permission of the publisher from Ref 2, © 1990 AMS)




**1 Day of Landsat Descending Orbits** (Reprinted with permission of the publisher from Ref 1, © 1985 Ellis Horwood Ltd.)

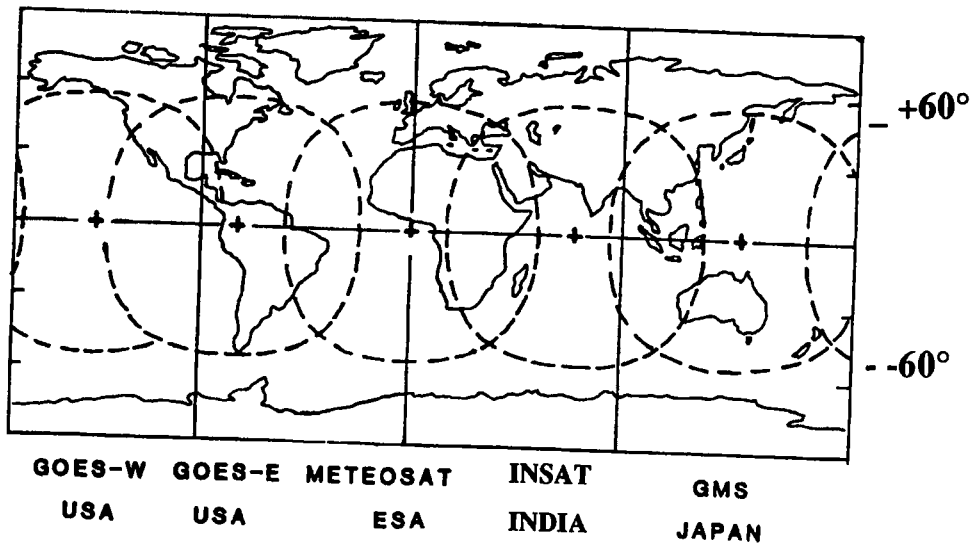
# GEOSYNCHRONOUS ORBITS




**Nominal Current Civil Environmental Birds (Ref 3)**

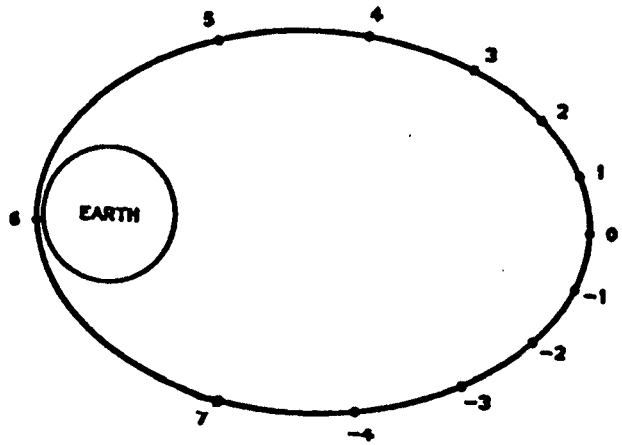
## Geosynchronous Satellite Useful Coverage

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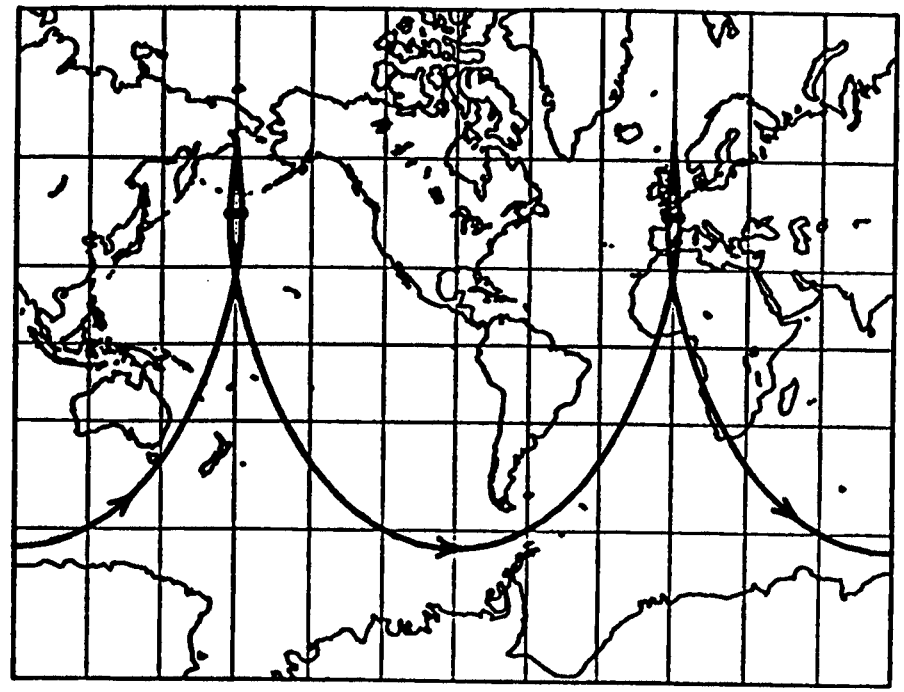
# MOLNIYA ORBITS






**Molniya Orbit Example**

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**Molniya ground track, apogee 0°, 180°; 63.4° N**

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**63.4° inclination prevents perihelion precession**

# SENSOR SCAN METHODS

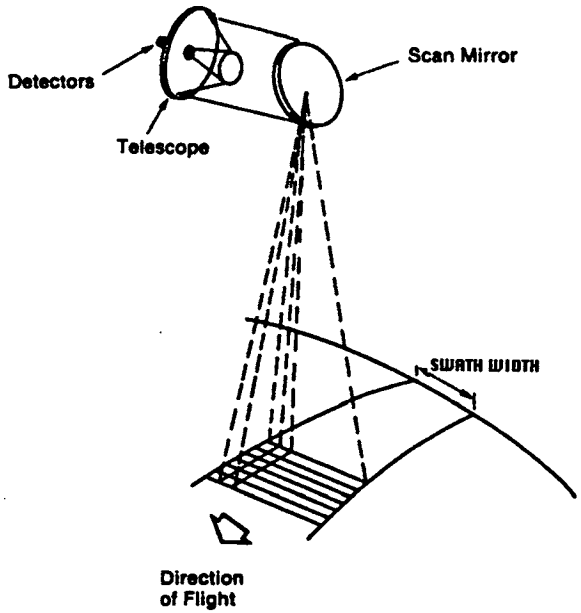


- SENSOR ON MOVING PLATFORM SCANS A SWATH
  - PLATFORM MOVES "ALONG-TRACK", $\perp$ DIRECTION $\equiv$ "CROSS-TRACK"
- WHISKBROOM
  - DETECTORS SCAN CROSS-TRACK WHILE PLATFORM MOVES ALONG-TRACK
  - SINUSOIDAL OR CONSTANT "BARREL ROLL" SCAN
- PUSHBROOM
  - LINEAR DETECTOR ARRAY ORIENTED CROSS-TRACK, PUSHED ALONG-TRACK
  - NO MOVING PARTS, EFFICIENT SIGNAL COLLECTION
- CONICAL
  - DETECTORS SCAN IN CIRCLE WHILE PLATFORM MOVES ALONG-TRACK
  - CONSTANT ANGLE REQUIREMENT, OR LARGE SCANNING MASS
- STEP-STARE
  - EX: STATIONARY PLATFORM WITH 2-D DETECTOR ARRAY
- LIMB SCANNING

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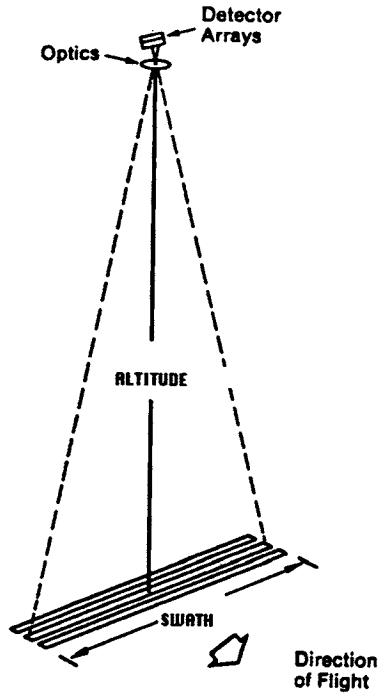
# SENSOR SCAN DIAGRAMS





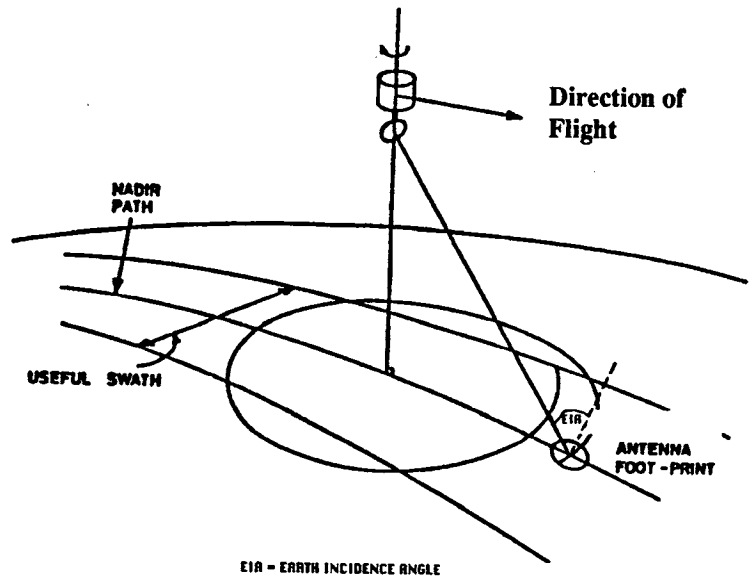

## Whiskbroom Scan

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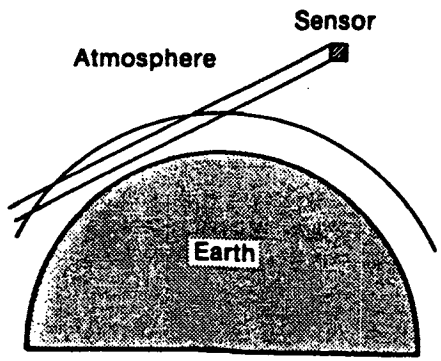

## Pushbroom Scan

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## Conical Scan

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## Limb Scan (Reprinted with permission of the publisher from Ref 4, © 1985 Academic Press)

# EARTH COVERAGE FROM SPACE

- OFTEN DESIRE FREQUENT GLOBAL COVERAGE
  - GEO ⇒ RAPID REFRESH BUT NO POLAR COVERAGE
  - LEO ⇒ 6 HR GLOBAL REFRESH WITH 2 POLAR BIRDS
    - — REQUIRES CONTIGUOUS EQUATORIAL SWATHS AND 90° ORBIT PLANE SEPARATION
    - — PROVIDES MORE FREQUENT POLAR COVERAGE
  - CAN COVER GLOBE FREQUENTLY WITH ≥ 2 LEO & 5 GEO BIRD CONSTELLATION
- COVERAGE FUNCTION OF
  - ORBIT: TYPE, GROUND SPEED, EXACT GROUND TRACK
  - NUMBER AND DISTRIBUTION OF SATELLITES
  - PHYSICS: CONSTRAINTS ON MAXIMUM VIEW ANGLE, ETC.
    - — EXTREME VIEW ANGLE ⇒ POOR DATA QUALITY
  - SENSOR: SCAN METHOD, FIELD OF REGARD, DETECTION SENSITIVITY, ETC.

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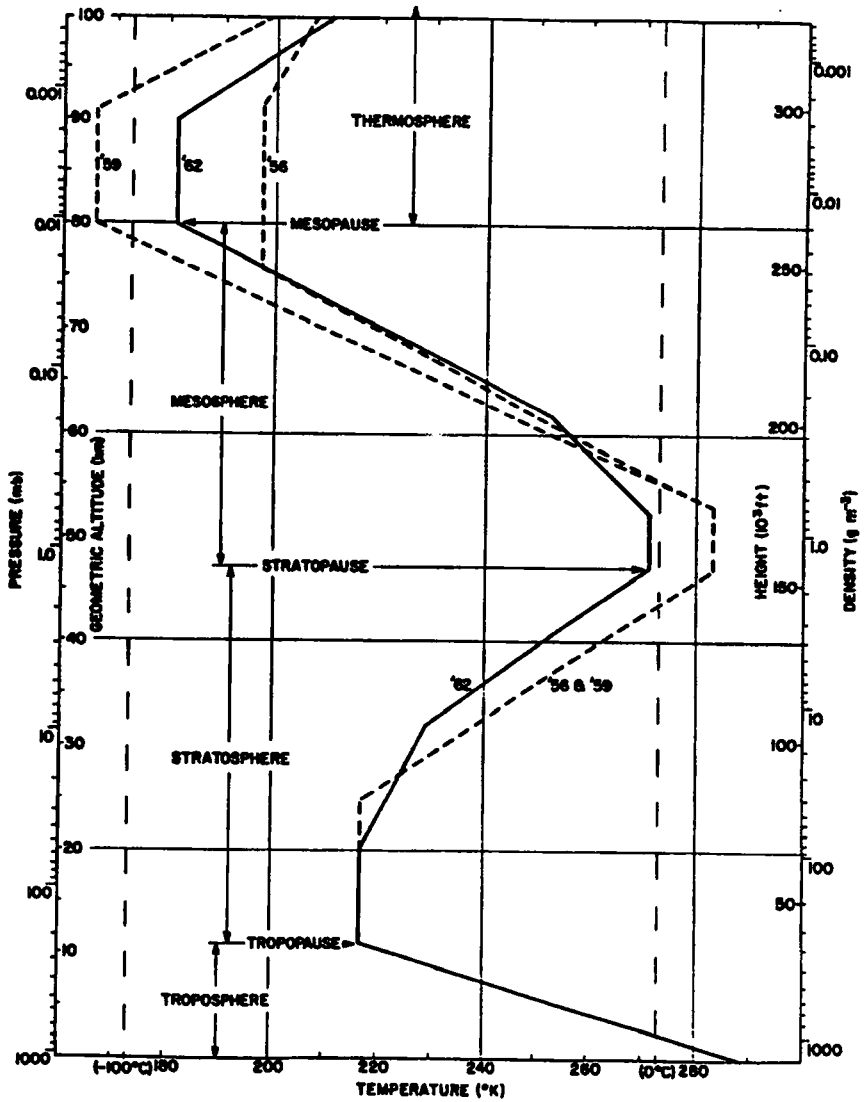
# ENVIRONMENTAL REGIMES



- ATMOSPHERE
  - TROPOSPHERE
    - — MOST CLOUDS, WATER VAPOR, AEROSOLS (DISPERSED SMALL PARTICLES)
    - — PLANETARY BOUNDARY LAYER = LOWEST 1-2 KM
  - STRATOSPHERE
    - — OZONE LAYER, VOLCANIC AEROSOLS
  - MESOSPHERE
    - — COLDEST REGION OF ATMOSPHERE AT TOP (MESOPAUSE)
  - THERMOSPHERE AND ABOVE: NOT DISCUSSED (TRANSITION TO SPACE)
- OCEANS
  - ≈ 70% OF EARTH'S SURFACE
  - "THERMAL FLYWHEEL" EFFECT ON WEATHER & CLIMATE CHANGE
- LAND SURFACE
  - SOIL, MINERALS, VEGETATION, FORESTS, SNOW, ICE, WETLANDS, URBAN AREAS, ...

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# U.S. STANDARD ATMOSPHERE




Ref 7

# DAY 1 & 2 (am) OUTLINE



- INTRODUCTION TO REMOTE SENSING
- PRINCIPLES OF PASSIVE ELECTRO-OPTICAL REMOTE SENSING
- SYSTEMS APPROACH TO ELECTRO-OPTICAL SENSOR SYSTEMS
- INTERNATIONAL PROGRAMS & ORGANIZATIONS
  - INCLUDES GLOBAL CHANGE REQUIREMENTS
- USER REQUIREMENTS ADDRESSABLE WITH PASSIVE E-O REMOTE SENSING
- SPACEBORNE PASSIVE E-O SENSING PROGRAMS
- SPACEBORNE PASSIVE E-O SENSORS & TRENDS
  - INCLUDES SPECIAL PASSIVE SENSORS
- ACTIVE E-O REMOTE SENSING
  - LIDAR

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# PART 2

# E-O PRINCIPLES:

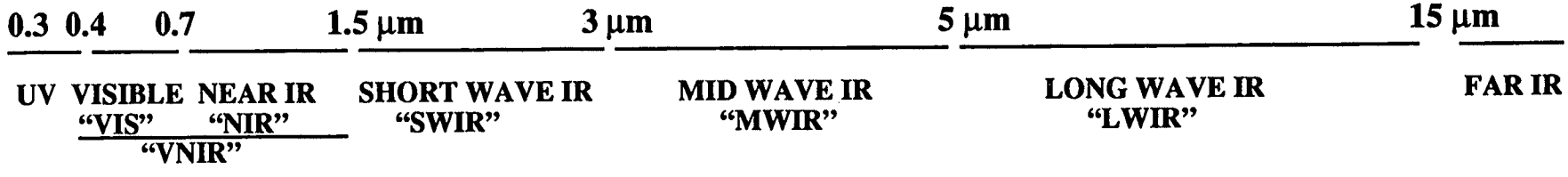
# PASSIVE SENSING

# ELECTRO-OPTICAL (E-O) SPECTRAL REGIMES



- WAVELENGTH MEASUREMENTS : MICRONS (μm) = $10^{-6}$ METERS

  NANOMETERS (nm) = $10^{-9}$ METERS



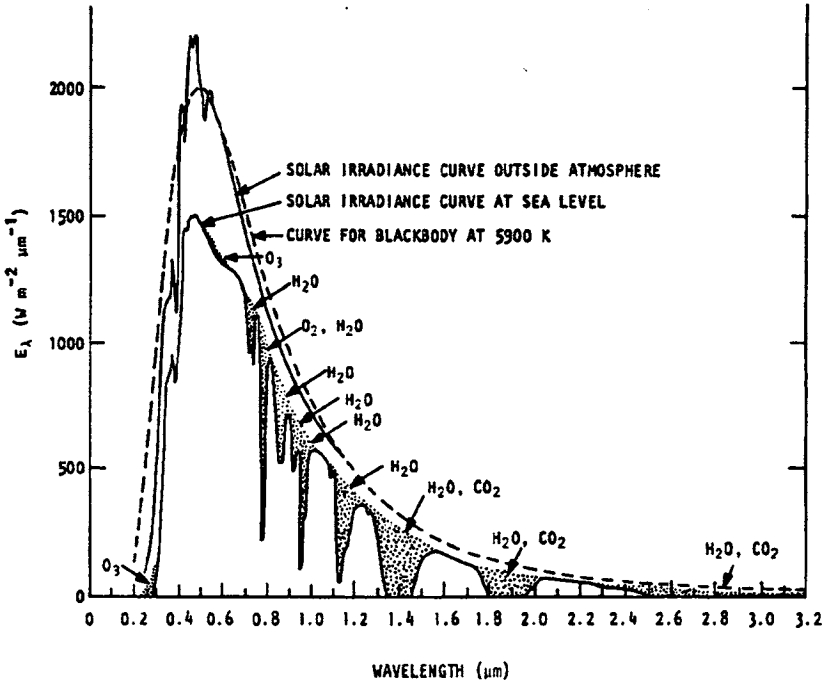

- BEYOND FAR IR: mm & cm λ's: MILLIMETER-WAVE & MICROWAVE REMOTE SENSING

- WINDOW BANDS
  - ATMOSPHERE TRANSPARENT, SEE TO SURFACE: IMAGING APPLICATIONS
- ABSORPTION BANDS
  - ATMOSPHERE OPAQUE BELOW CERTAIN ALTITUDE: SOUNDING APPLICATIONS
  - PRIMARY ABSORPTION SPECIES $H_2O$, $CO_2$ , $O_3$ & TRACE GASES
- LIMITED UTILITY OF UV SENSING DUE TO STRONG $O_3$ ABSORPTION BELOW 0.3 μm
  - $O_3$ SOUNDING, "POLAR MESOSPHERIC" CLOUDS

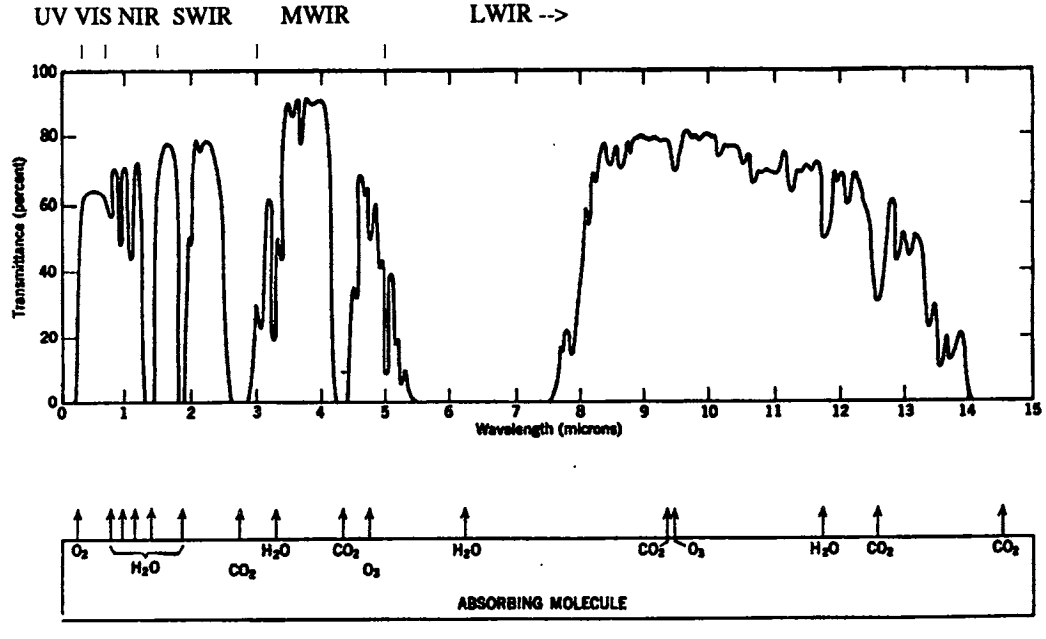
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# E-O SPECTRAL FEATURES






Solar Irradiance Curves (Ref 7)




Atmospheric Transmittance Along 6000' Horizontal Sea Level Path

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# REMOTE SENSING PHYSICS & PHENOMENOLOGY



- PHYSICS
  - SCIENCE OF MATTER & ENERGY AND RELATED PROPERTIES & PROCESSES
- PHENOMENOLOGY
  - SCIENCE OF UNDERSTANDING NATURAL PHENOMENA BASED ON OBSERVATION
- BOTH PLAY A ROLE IN REMOTE SENSING
  - EMPIRICAL KNOWLEDGE THRU PHENOMENOLOGY, UNDERSTANDING THRU PHYSICS
  - MEASURE RADIANT ENERGY FROM LAND/OCEAN/ATMOSPHERE SYSTEM WITH A SENSOR
  - CONVERT RAW DATA TO PHYSICAL UNITS
  - BUILD EMPIRICAL DATA BASE OF RELATIONSHIPS & EVOLUTION
  - APPLY BASIC LAWS OF PHYSICS TO MODEL & MEASURE PHYSICAL PROPERTIES
    - EM THEORY, ATOMIC/MOLECULAR PHYSICS, QUANTUM PHYSICS, THERMODYNAMICS, ...
  - PHYSICS PROVIDES BASIS FOR DETERMINING HOW TO MAKE MEASUREMENTS
    - SENSOR DESIGN
    - SIGNATURE & PROPAGATION EFFECTS

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# PHYSICAL QUANTITIES



- SOLID ANGLE
  - 3-D MEASURE OF ANGLE SUBTENDED BY AN AREA ON A SPHERE AS SEEN FROM ITS CENTER
  - $4\pi$ sr IN A SPHERE (sr = STERADIANS)
- RADIANCE: RATE OF RADIANT ENERGY FROM A SOURCE PER STERADIAN (BRIGHTNESS)
  - $W/cm^2$-sr "IN-BAND" or $W/cm^2$-sr-$\mu$m AT GIVEN WAVELENGTH
    - CONSTANT WITH DISTANCE IN A VACUUM
  - ALL PASSIVELY OBSERVED NATURAL PHENOMENA ARE RADIANCE SOURCES PRIMARILY VIA:
    - REFLECTION OR SCATTERING OF SUNLIGHT (PRIMARILY UV - SWIR)
    - NATURAL THERMAL EMISSION (PRIMARILY MWIR - LWIR)
  - "RADIOMETRY": THE MEASUREMENT OF RADIANT ENERGY
- IRRADIANCE: RATE OF RADIANT ENERGY ACROSS A UNIT AREA
  - $W/cm^2$
  - RADIANCE INTEGRATED OVER ANGLE
  - FALLS OFF AS $1/R^2$

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# PHYSICAL QUANTITIES (CONT'D)

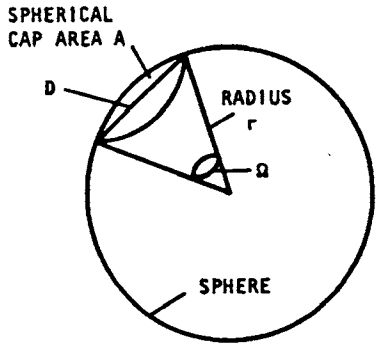


- REFLECTANCE (ρ): FRACTION OF RADIANCE INCIDENT ON A SURFACE THAT IS REFLECTED
  - FUNCTION OF ILLUMINATION & VIEWING GEOMETRY
    - — DIFFUSE: REFLECTANCE IN ALL DIRECTIONS
      - -- OCCURS FOR ROUGH SURFACES SUCH AS LAND
      - -- LAMBERTIAN: EQUAL REFLECTANCE IN ALL DIRECTIONS (OFTEN A POOR ASSUMPTION)
    - — SPECULAR: EQUAL ANGLES OF INCIDENCE & REFLECTION
      - -- OCCURS FOR SMOOTH SURFACES SUCH AS CALM OCEAN
  - STRONG DEPENDENCE ON MATERIAL TYPE
  - BIDIRECTIONAL REFLECTANCE DISTRIBUTION FUNCTION (BRDF)
    - — COMPLETE DESCRIPTION IN TERMS OF SUN ANGLE & LOOK ANGLE

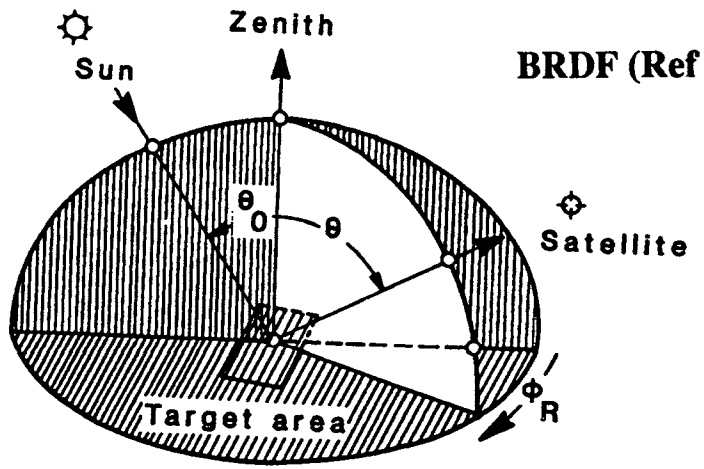
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# RADIANCE/REFLECTANCE DIAGRAMS

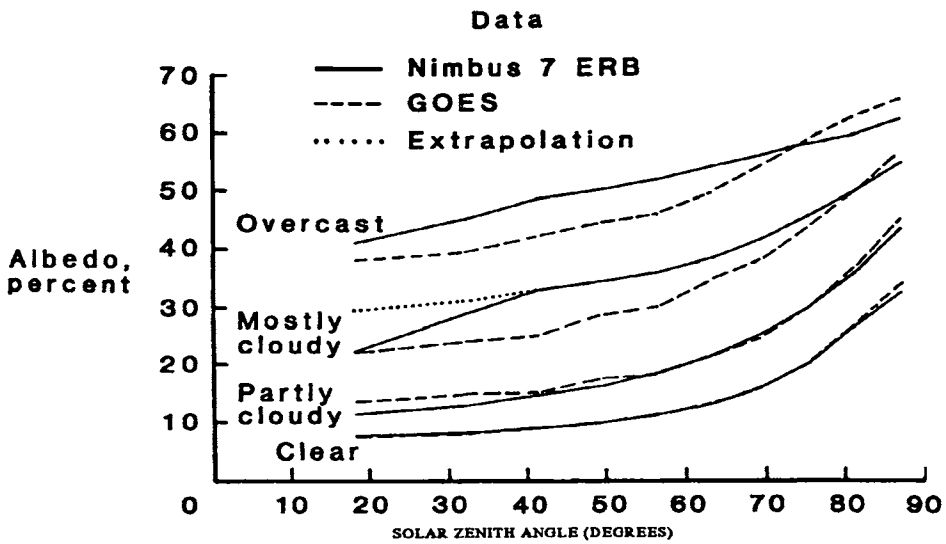




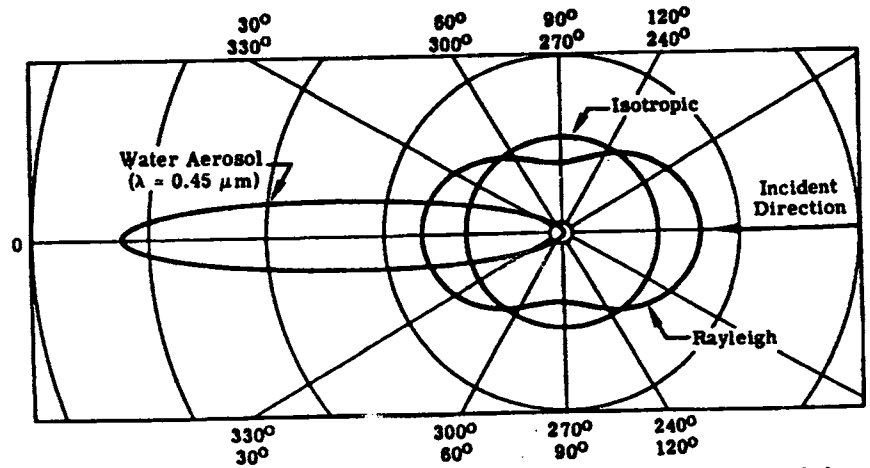

**Solid Angle**
(Reprinted from Ref 8 with permission, © 1980 P. Slater)




**BRDF (Ref 10)**




**Directional Reflectance Over Ocean (Ref 10)**




**Angular dependence of single-scattering phase functions in any azimuthal plane. The isotropic and Rayleigh functions have been multiplied by 10.**

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# PHYSICAL QUANTITIES (CONT'D)



- ABSORPTANCE ($\alpha$) : FRACTION OF INCIDENT RADIANCE CONVERTED TO KINETIC ENERGY
  - PRIMARILY ELECTRONIC OR VIBRATIONAL MOLECULAR BANDS IN ATMOSPHERE
    - — ENERGY ABSORPTION VIA QUANTIZED ELECTRONIC OR VIBRATIONAL STATES
    - — E.G., BY $H_2O$, $CO_2$ , $O_3$ , TRACE GASES
    - — PRODUCES PERIODIC "BAND STRUCTURE" IN THE SPECTRUM
  - STRONG VIS/NIR $\alpha$ FOR CLOUD & FOG, WEAK FOR AEROSOLS
- TRANSMITTANCE ($\tau$) : FRACTION OF INCIDENT RADIATION TRANSMITTED
  - HIGH TRANSMITTANCE = WINDOW BANDS IN ATMOSPHERE

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# PHYSICAL QUANTITIES (CONT'D)



- EMISSIVITY ($\varepsilon$) : FRACTION OF NATURAL THERMAL RADIANCE EMITTED BY A BODY WITH RESPECT TO THAT FROM A PERFECT EMITTER ("BLACK BODY"; $\varepsilon$=1)
  - BLACK BODY RADIATES ACCORDING TO PLANCK'S LAW
    - — RADIANCE UNIQUE SINGLE-PEAKED FUNCTION OF TEMPERATURE

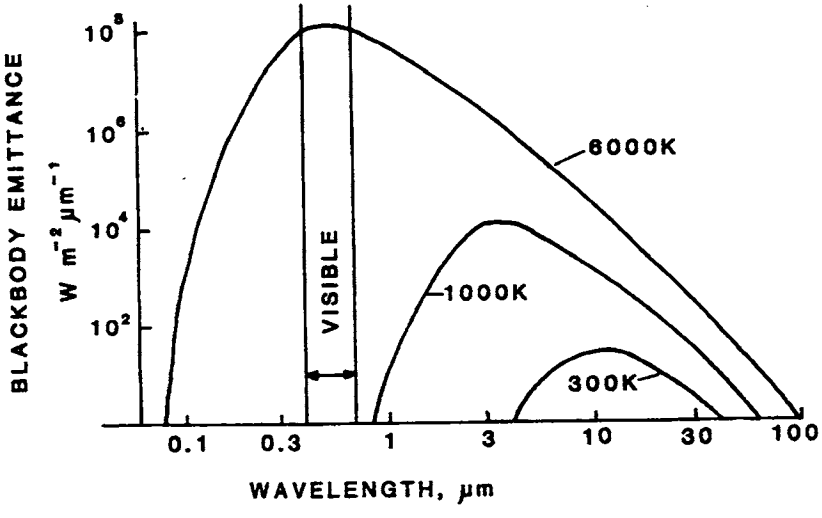
$$\text{Radiance} = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{ch/\lambda kT} - 1} \equiv B_\lambda(T)$$

    - -- HIGHER TEMP $\Rightarrow$ PEAK AT SHORTER $\lambda$
  - MOST REAL ENVIRONMENTAL BODIES ARE GREY BODIES ($\varepsilon < 1$) OR SELECTIVE RADIATORS
    - — GREY BODY RADIANCE < BLACK BODY; FUNCTION OF TEMP & COMPOSITION
    - — SELECTIVE RADIATOR MORE COMPLEX; RADIANCE FUNCTION OF $\lambda$

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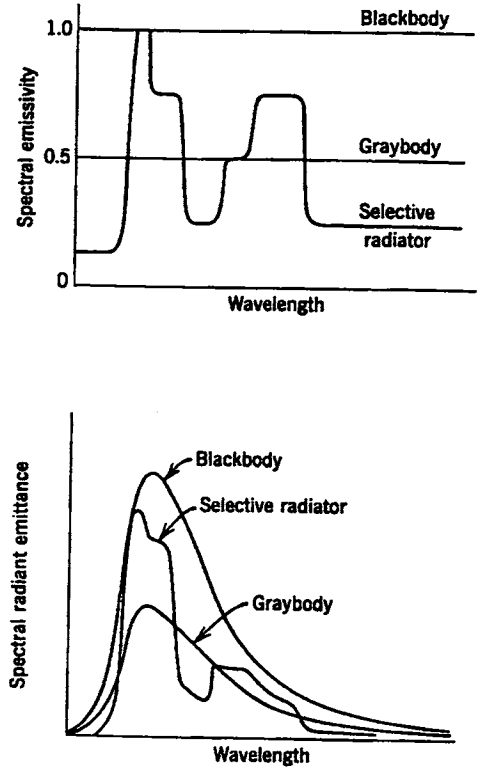
# THERMAL EMISSION






## Blackbody Curves

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## Emissivity Effects (Reprinted with permission from Ref 9
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# PHYSICAL QUANTITIES (CONT'D)

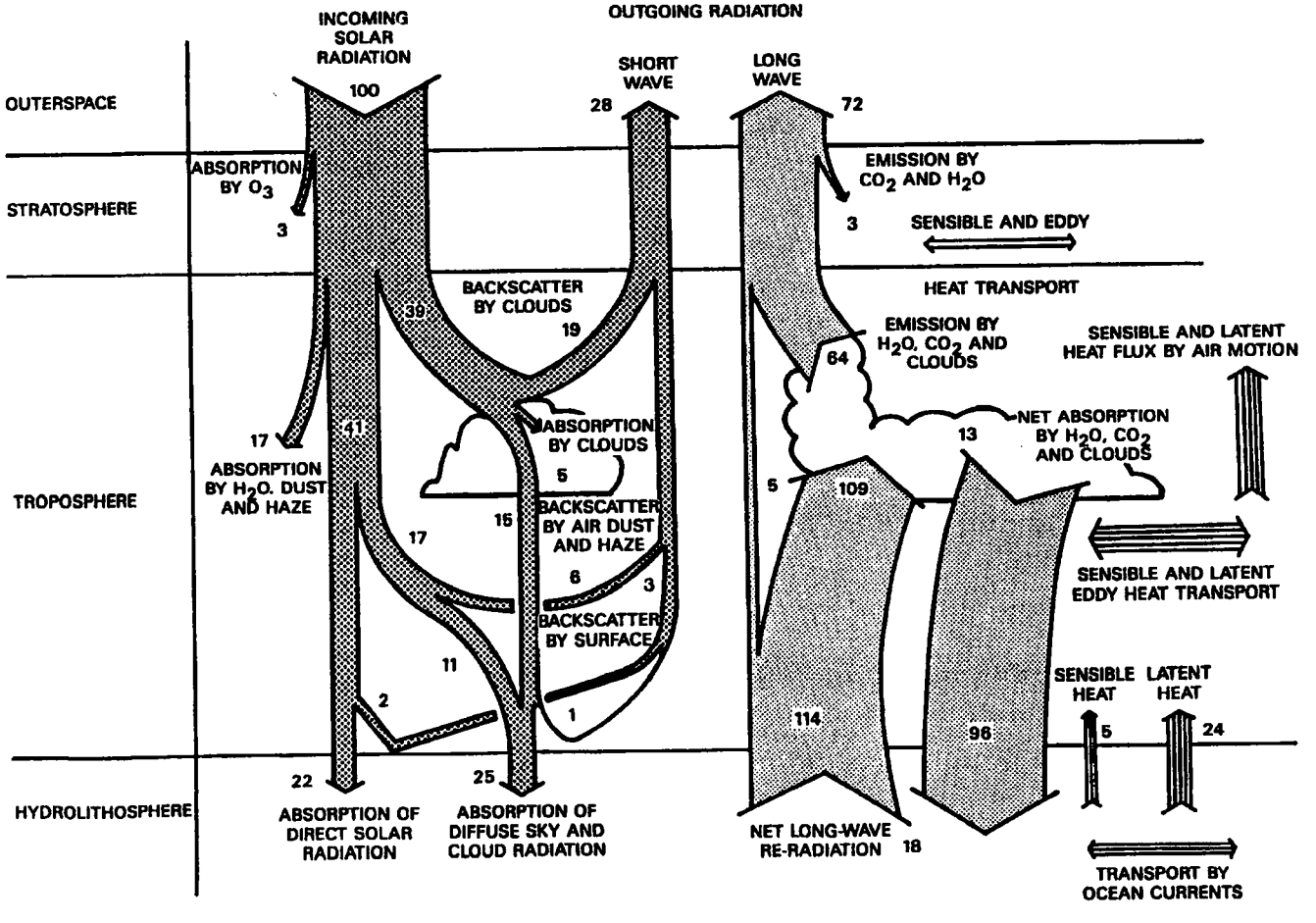


- SCATTERING ($\sigma$) : CHANGE IN DIRECTION OF RADIANCE DUE TO ATMOSPHERIC INTERACTION
  - RAYLEIGH SCATTERING FROM MOLECULES (diameter$<<\lambda$) $\sigma \propto \lambda^{-4}$ (GIVES BLUE SKY)
  - MIE SCATTERING FROM HAZE, DUST, FOG, CLOUD DROPLETS ($D \approx \lambda$) $\sigma \propto \lambda$ (approx; WHITE)
    - THEORY WELL DEVELOPED FOR SPHERES, WATER DROPS, HEXAGONAL ICE XTALS
  - SINGLE OR MULTIPLE SCATTERING DEPENDING ON MEDIUM
    - LATTER USUALLY NEGLECTED DUE TO COMPLEXITY
- EXTINCTION COEFFICIENT $k \equiv (\alpha + \sigma)$ = ABSORPTION + SCATTERING
- OPTICAL THICKNESS OR OPTICAL DEPTH $\equiv \int k$ along line-of-sight
- *RADIATIVE TRANSFER EQUATION* DESCRIBES TRANSPORT OF RADIANCE THROUGH THE ATMOSPHERE, SUBJECT TO THE ABOVE PROCESSES
  - SIMPLIFICATIONS REQUIRED FOR TRACTABLE SOLUTION
  - MATH DISCUSSED LATER UNDER "RETRIEVAL METHODS & ALGORITHMS"
  - TRANSMITTANCE $\tau = e^{-\int k}$ for a slab = 1/e for optical depth = 1

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# ATMOSPHERIC ENERGY BALANCE






Schematic diagram of the disposition of absorbed solar energy in the Earth system.

**(Ref 11)**

# ENVIRONMENTAL LIMITATIONS ON E-O SENSING



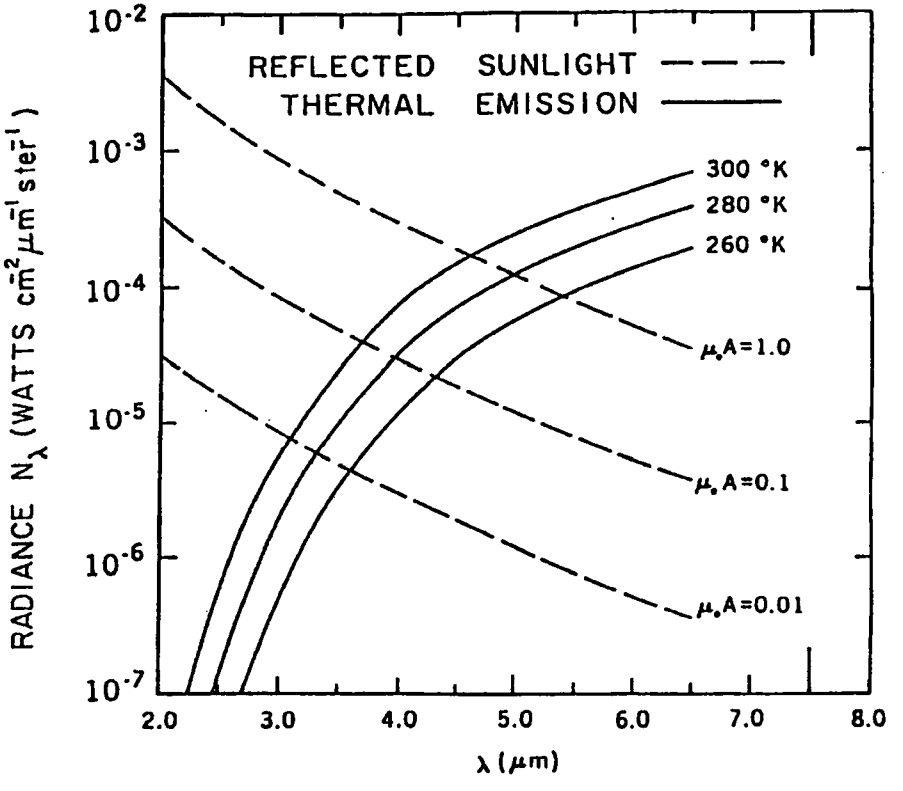
- CLOUDS
  - UV/VIS/IR CANNOT PENETRATE MOST CLOUDS, LIMITS VIEW
  - THIN CIRRUS UNCERTAINTIES
- ATMOSPHERIC EFFECTS ON SURFACE OBSERVATIONS
  - SCATTERING & ABSORPTION FROM MOLECULES & AEROSOLS
  - VERY DIFFICULT TO MODEL; CAN MASK WEAK SIGNALS
    - NOAA GOING TO VERY NARROW BANDS ON FUTURE VIS/IR POLAR ORBITING IMAGERS
- DIRECTIONAL REFLECTANCE
  - POOR KNOWLEDGE OF BIDIRECTIONAL REFLECTANCE PROPERTIES
  - SPECULAR REFLECTION, ESPECIALLY OVER THE OCEAN, CAN OVERWHELM IMAGE
- $O_3$ ABSORPTION LIMITS UTILITY OF UV
- POOR KNOWLEDGE OF EMISSIVITY/GREYBODY BEHAVIOR
  - ACCURATE TEMPERATURE MEASUREMENT DIFFICULT
  - HIGH-VARIABILITY SURFACES DIFFICULT TO CHARACTERIZE MEANINGFULLY

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# REFLECTANCE/THERMAL REGIMES



- UV → SWIR REFLECTANCE-DOMINATED
  - NOMINALLY DAY USE ONLY
  - SPECIAL CASES:
    - LUNAR ILLUMINATION @ NIGHT
    - UV FOR AURORA & AIRGLOW
- MWIR IS REFLECTANCE-THERMAL CROSSOVER REGION
  - CONFUSING COMBINATION IN DAYTIME
- LWIR IS THERMAL-DOMINATED
  - USEFUL DAY OR NIGHT




Computed nadir radiance of the ground as a function of wavelength.

A = albedo

μ = cos (Sun angle)

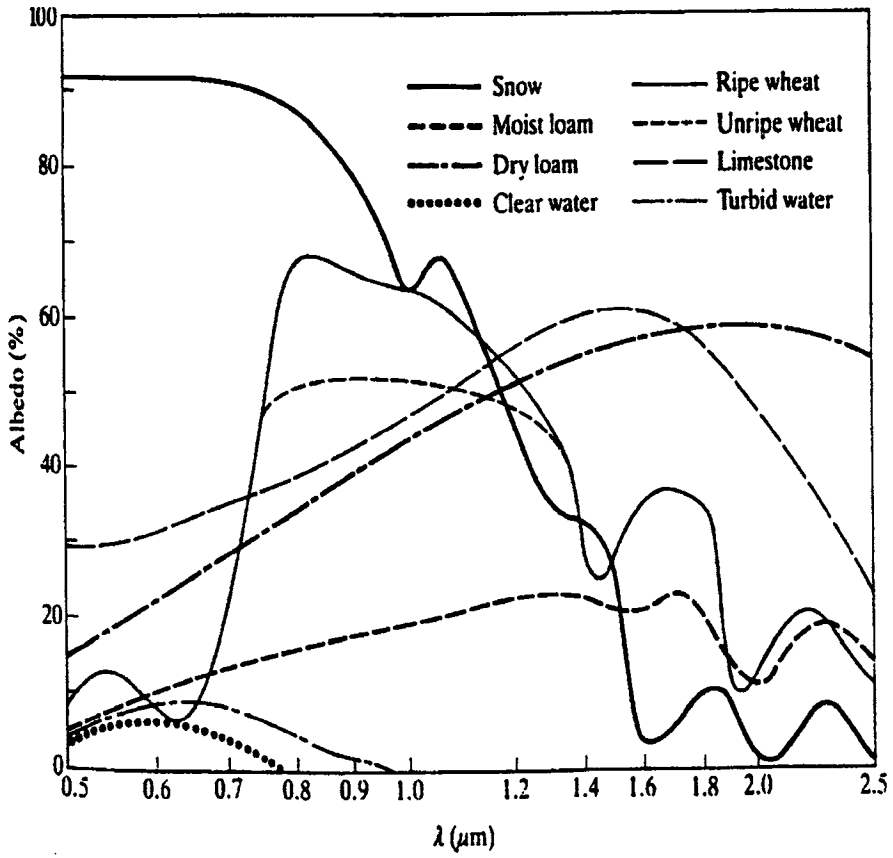
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# SAMPLE REFLECTANCE CURVES

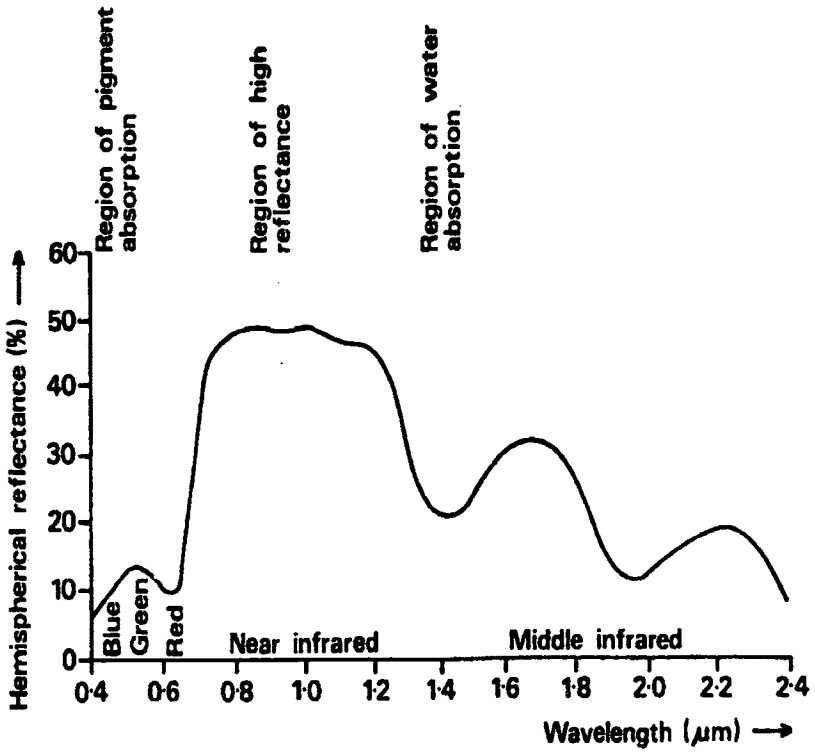


- **CLOUDS & SNOW**
  - **VIS/SWIR RATIO ⇒ DISCRIMINATION**




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- **VEGETATION**
  - **VIS/NIR RATIO ⇒ HEALTH INDEX**

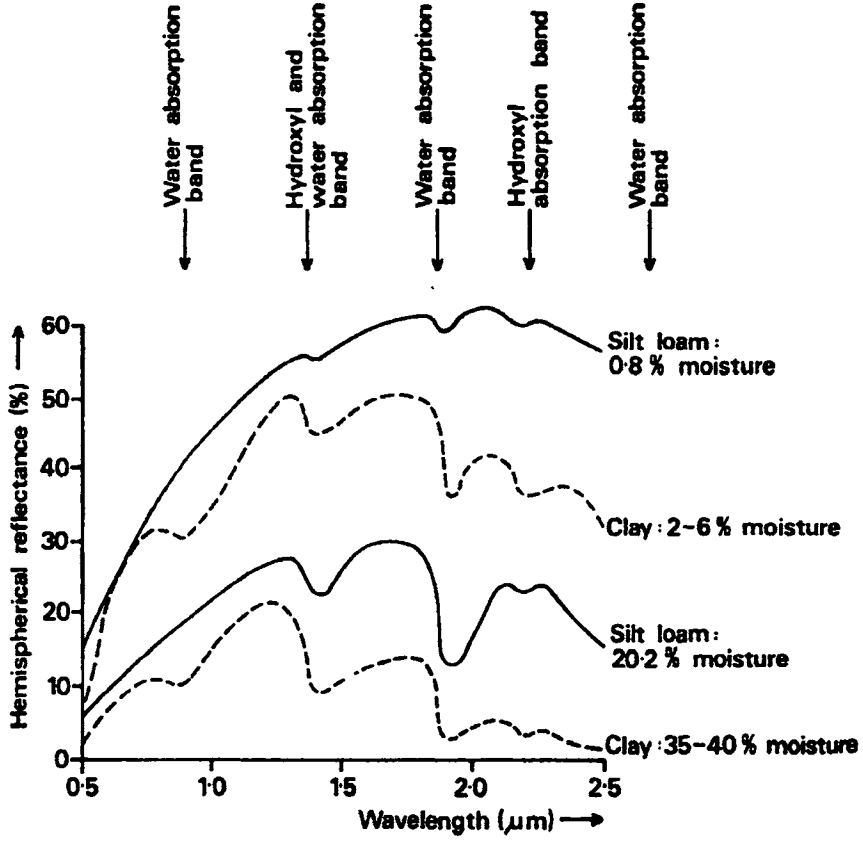



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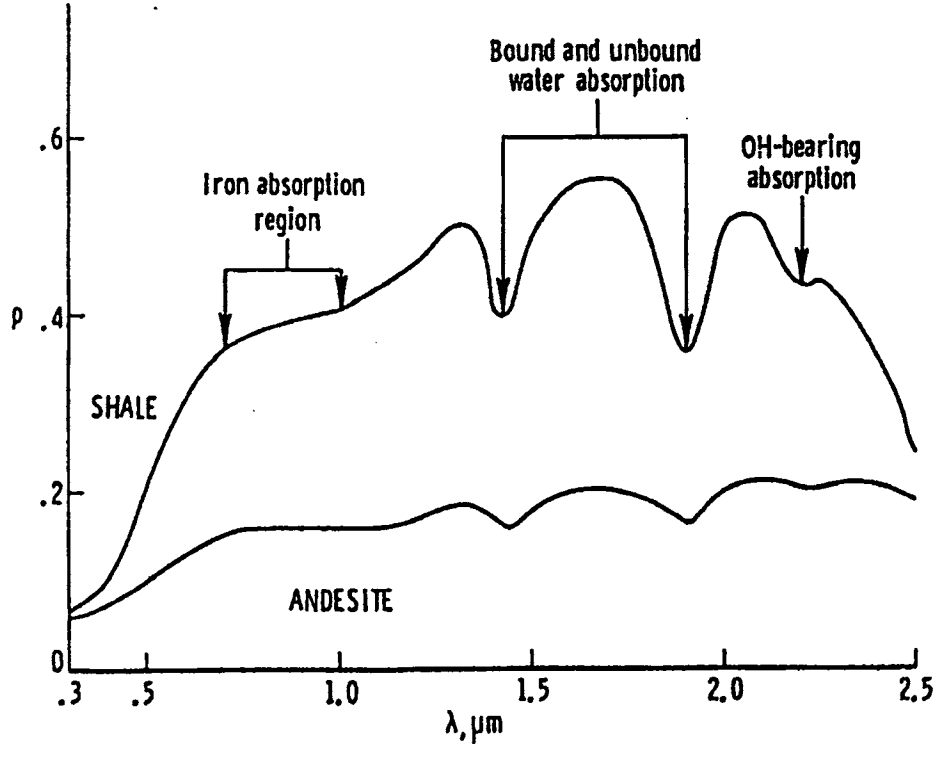
# SAMPLE REFLECTANCE CURVES (CONT'D)



- **SOIL TYPES**
  - **SPECTRAL FEATURES: TYPING**




- **MINERALS**
  - **SPECTRAL FEATURES: TYPING**



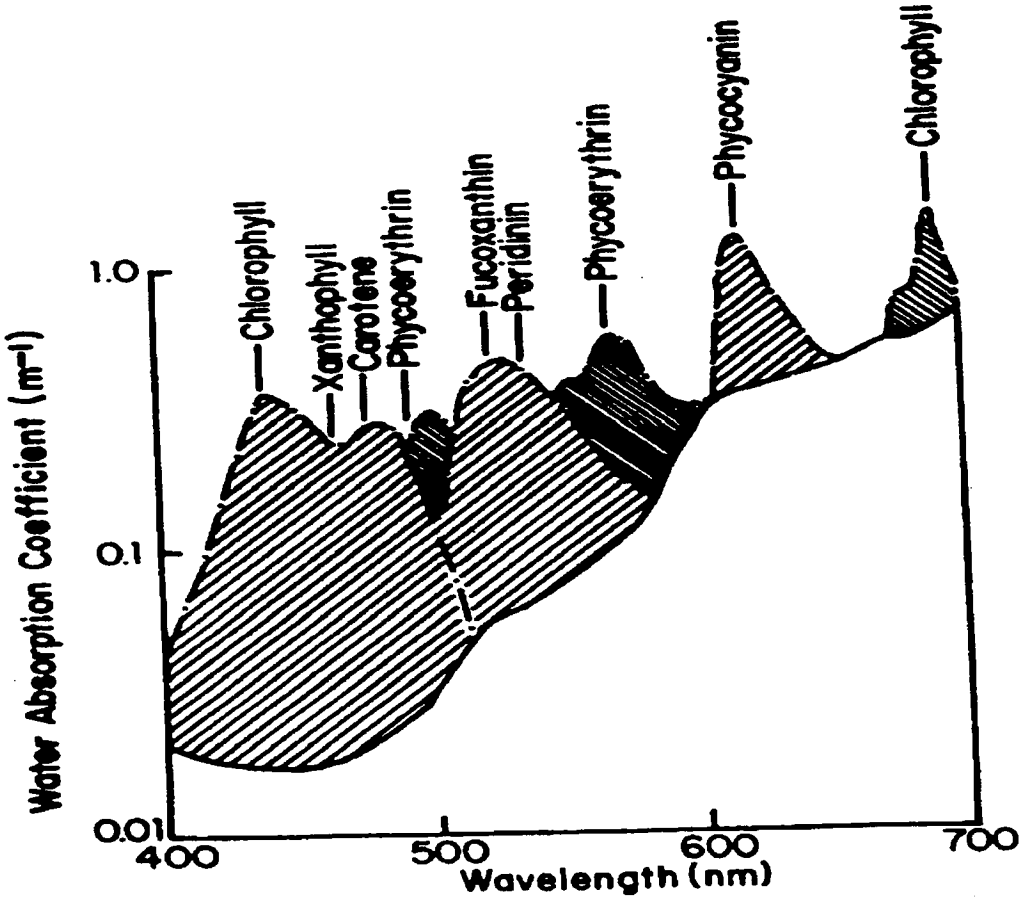

Typical reflectance curves for two rock formations.

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# SAMPLE ABSORPTION CURVE



- CLEAR WATER & PHOTOSYNTHETIC ALGAE ABSORPTION
  - PHYTOPLANKTON CURVE
  - OCEAN PRODUCTIVITY




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# BASIC TYPES OF PASSIVE E-O SENSING



- IMAGING / IMAGING RADIOMETRY
  - THE ACQUISITION OF 2-D SCENE BRIGHTNESS/RADIANCE IN (TYPICALLY) WINDOW BANDS
    - — USUALLY IN SEVERAL (< 10) VIS → LWIR BROAD BANDS
- SOUNDING
  - THE ACQUISITION OF RADIANCES AT VARIOUS FREQUENCIES IN ABSORPTION/EMISSION BAND
    - — MEASURE THE VERTICAL PROFILE OF TEMP, HUMIDITY, OR SPECIES CONCENTRATION
- SPECTROMETRY
  - THE ACQUISITION OF DETAILED SPECTRAL (e.g., $\rho$ or radiance) CURVES OF SELECTED OBJECTS
- IMAGING SPECTROMETRY
  - THE ACQUISITION OF 2-D IMAGERY IN NUMEROUS NARROW CONTIGUOUS SPECTRAL BANDS
- POLARIMETRY
  - THE ACQUISITION OF THE POLARIZATION PROPERTIES OF A SCENE
- RADIOMETRY
  - THE ACQUISITION OF (LOW SPATIAL RES) SCENE RADIANCE (e.g., FOR ENERGY BALANCE)

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# IMAGING / IMAGING RADIOMETRY



- BASIC PRODUCT: 2-D ARRAY OF PIXELS (PICTURE ELEMENTS), EACH REPRESENTING THE SCENE BRIGHTNESS OR RADIANCE WITHIN AN ELEMENTAL AREA
- A SPECTRAL BAND IS ASSOCIATED WITH EACH RAW IMAGE
  - MULTISPECTRAL IMAGING CONTAINS MORE INFORMATION
- "IMAGING"
  - NEED NOT PROVIDE CALIBRATION TO CONVERT BRIGHTNESS → RADIANCE
    - EX: 35 mm CAMERA
- "IMAGING RADIOMETRY"
  - PERFORMED WITH AN IMAGING RADIOMETER
    - SENSOR CHARACTERIZED SUCH THAT RADIANCE CAN BE CALCULATED
    - BUT OFTEN JUST CALLED "IMAGING"
- SENSORS TO BE DISCUSSED ARE IMAGING RADIOMETERS
- RADIANCE AT ANY POINT IN THE IMAGE MAY BE THE RESULT OF:
  - REFLECTANCE, EMISSION, ABSORPTION & SCATTERING

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# SOUNDING: NADIR SOUNDING



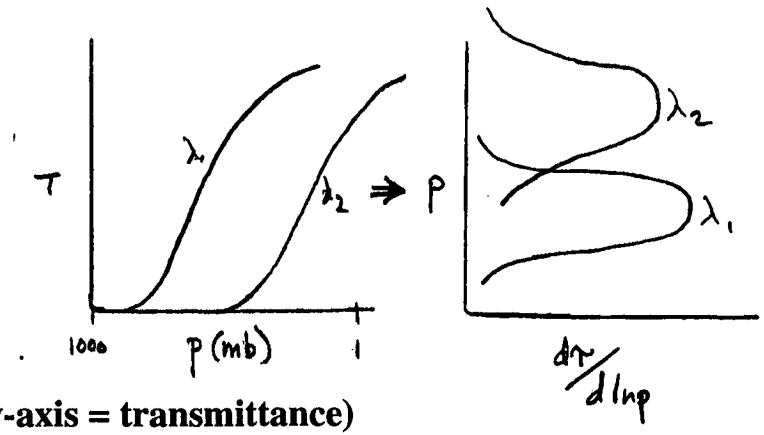
- E-O SOUNDING USUALLY IS DONE IN THE IR (STRONG VIB-ROT BANDS)
- TYPICALLY USES ABSORPTION BANDS, E.G.:
  - 4.3 μm or 15 μm $CO_2$ BAND FOR TEMPERATURE
  - 6.7 μm $H_2O$ BAND FOR WATER VAPOR
  - 9.6 μm $O_3$ BAND FOR OZONE
  - MANY OTHER SPECIES OF INTEREST FOUND IN 2 - 16 μm RANGE
  - MOST SENSORS CANNOT RESOLVE INDIVIDUAL SPECTRAL LINES
- BASIS OF METHOD (REF 68, 69, 70)
  - RADIANCE IN DIFFERENT PARTS OF BAND ARISES FROM DIFFERENT HEIGHTS IN ATMOSPHERE
    - — CAN SEE DEEPER INTO ATMOSPHERE AT λ's WHERE OPTICAL DEPTH LOWER
  - EACH ATMOSPHERIC HEIGHT CONTRIBUTES IN TERMS OF "WEIGHTING FUNCTION" AT EACH λ
    - — "PRESSURE HEIGHT" (p) IS USED IN PRACTICE
  - PHYSICS RELATES RADIANCE(λ) TO TEMP(p), MOISTURE(p) OR SPECIES CONCENTRATION(p)
    - — THE "INVERSION" PROBLEM IS CONVERSION OF OBSERVED RADIANCES TO PROFILES

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# PHYSICS OF SOUNDING

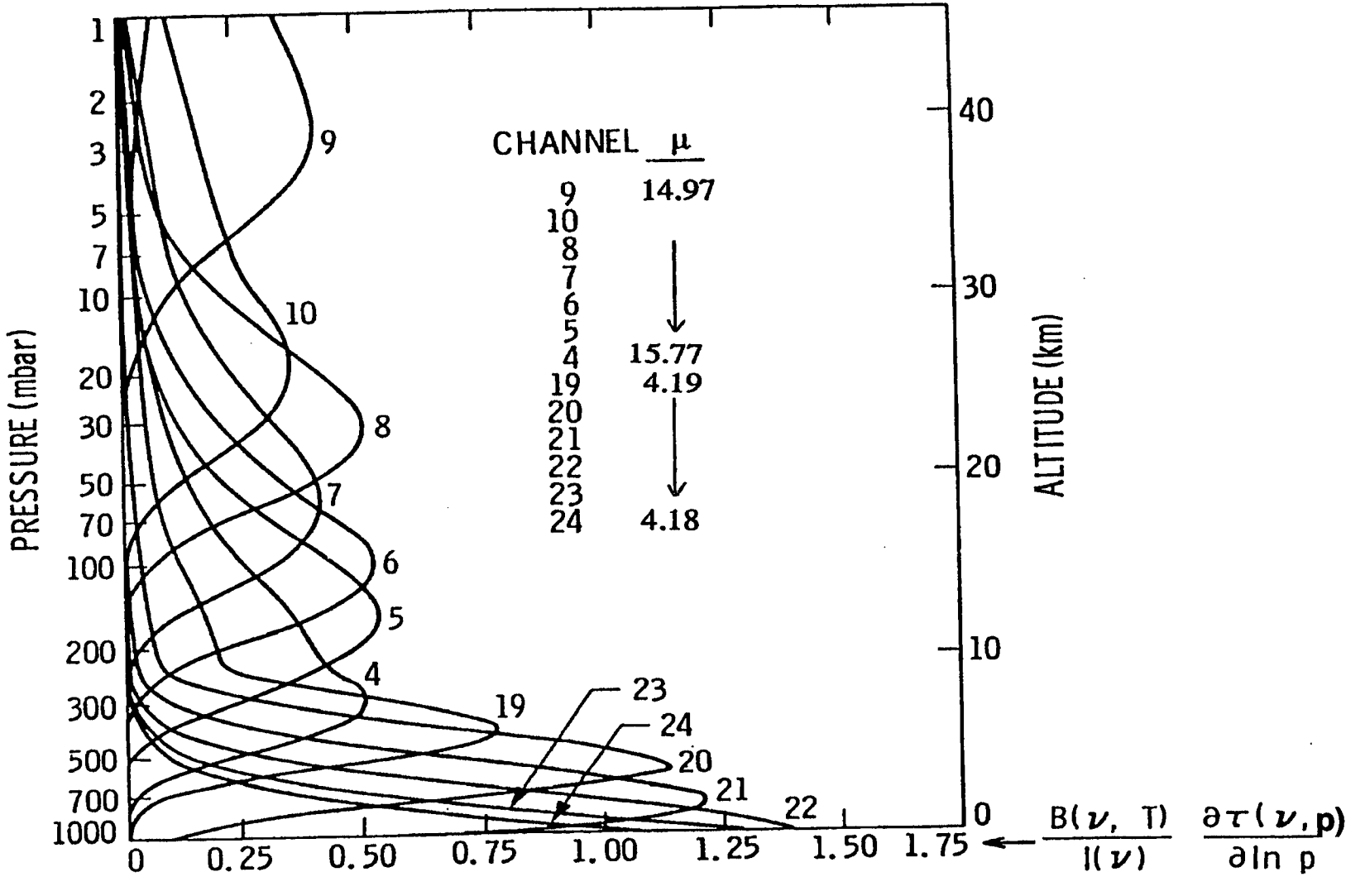


- FOR A GAS IN LOCAL THERMODYNAMIC EQUILIBRIUM (LTE), THE ATOMIC & MOLECULAR STATES ARE POPULATED ACCORDING TO THE BOLTZMANN DISTRIBUTION AT THE LOCAL KINETIC TEMPERATURE OF THE GAS
  - TRUE IF COLLISIONAL EXCITATION DOMINATES RADIATIVE DEEXCITATION
  - LTE HOLDS TO ≈ 80 km ALTITUDE FOR 15 μm $CO_2$ BAND; TO ≈ 35 km FOR 4.3 μm $CO_2$ BAND
- IN LTE, THE ATMOSPHERE RADIATES PROPORTIONALLY TO THE PLANCK FUNCTION
  - A THIN SLAB HAS RADIANCE $B_\lambda(T)\, k_\lambda\, dz$ BY KIRCHOFF'S LAW
  - A PROPORTION OF THIS RADIANCE $\tau_\lambda = \exp(-\int k_\lambda\, dz)$ REACHES TOP OF ATMOSPHERE
    - THIS PROPORTION IS 1/e FOR ATMOSPHERIC OPTICAL DEPTH 1
- TOTAL RADIANCE AT TOP OF ATMOSPHERE IS
  - $L_\lambda = \int B_\lambda(T)\, k_\lambda \exp(-\int k_\lambda\, dz)\, dz$
  - DEFINE $y = -\ln p$ AS NEW ALTITUDE VARIABLE
  - $L_\lambda = \int B_\lambda(T)\, (d\tau_\lambda/dy)\, dy$ = WEIGHTED AVG OF BLACKBODY RADIATION
    - $d\tau/d(\ln p)$ IS THE WEIGHTING FUNCTION (y-axis = transmittance)



# SAMPLE TEMPERATURE WEIGHTING FUNCTIONS






(Modified from Ref 32, JPL Advanced Moisture & Temp Sounder)

# TEMPERATURE & MOISTURE NADIR SOUNDING



*TEMPERATURE:*

- USE SPECTRAL BAND OF WELL-MIXED GAS (e.g., $CO_2$)
- ABSORPTION BAND SHAPE = FUNCTION OF AMBIENT TEMPERATURE
  - CAN PERFORM MATHEMATICAL INVERSION OF OBSERVED RADIANCE($\lambda$) $\rightarrow$ TEMPERATURE (p)
  - BASIC INVERSION METHODS (STATISTICAL & PHYSICAL) TO BE DISCUSSED
- BROAD WEIGHTING FUNCTIONS $\Rightarrow$ SHARP TEMPERATURE REVERSALS DIFFICULT TO DETECT

*MOISTURE:*

- USE SPECTRAL BAND OF WATER VAPOR
- INHERENTLY MORE DIFFICULT RETRIEVAL THAN TEMPERATURE
  - HIGH SPATIAL VARIABILITY OF WATER VAPOR
  - WEIGHTING FUNCTIONS SHIFT UP & DOWN AS FUNCTION OF TOTAL WATER CONTENT OF AIR
  - WEIGHTING FUNCTIONS ARE NONLINEAR FUNCTIONS OF TEMP PROFILE
  - PHYSICAL RETRIEVAL TECHNIQUE INDICATED

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# SOUNDING: LIMB SOUNDING

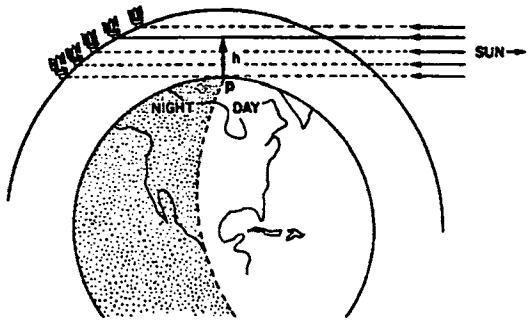


- OBSERVE ALONG LINE-OF-SIGHT ABOVE EARTH LIMB
- EMISSION METHOD
  - OBSERVE AGAINST BLACK SPACE BACKGROUND
  - MEASURE IR EMISSION IN BANDS AT SELECTED $\lambda$'s
  - USE OBSERVED RADIANCES AND DERIVED TEMP(p) TO COMPUTE OTHER PROFILES
  - VERTICAL RESOLUTION DETERMINED BY SENSOR FIELD OF VIEW
- SOLAR OCCULTATION
  - OBSERVE AGAINST SOLAR DISK
  - MEASURE ABSORPTION OF DIRECT SUN AT SELECTED $\lambda$'s
    - UV, VIS, NIR
    - E.G., OZONE UV BANDS @ 0.29 $\mu$m
  - METHOD GIVES VERY HIGH SIGNAL-TO-NOISE
  - VERTICAL RESOLUTION DETERMINED BY SENSOR-SUN GEOMETRY

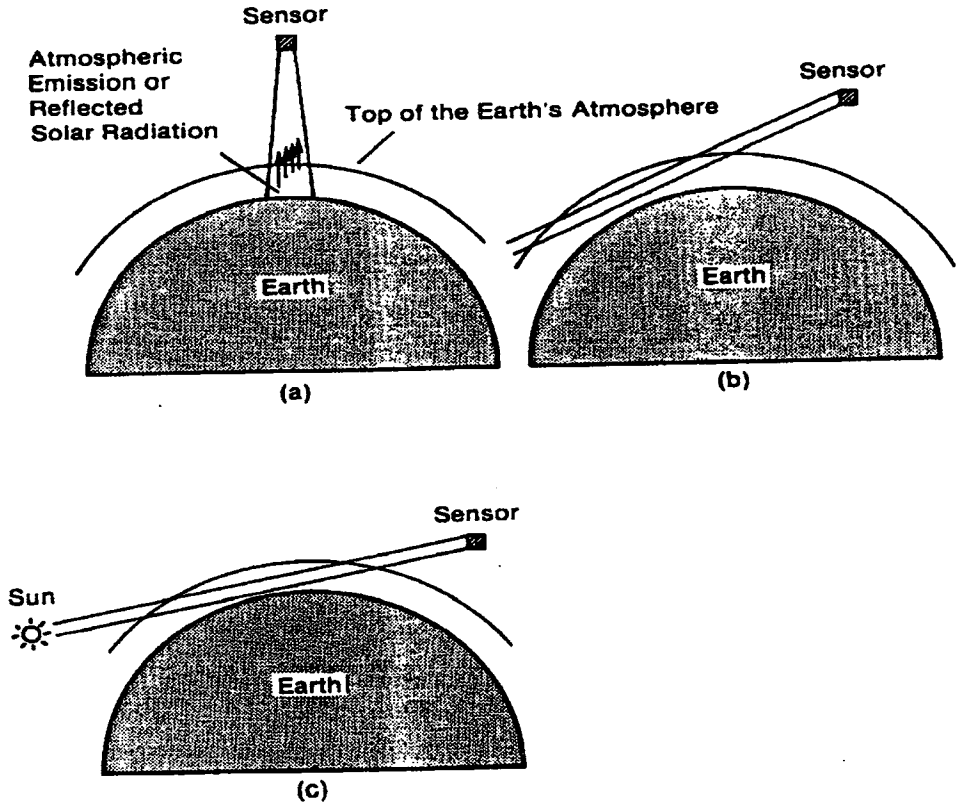
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# SOUNDING GEOMETRY






**Solar Occultation** (Ref 33)




**(a) nadir sounding**
**(b) limb sounding**
**(c) solar occultation**

(Modified from Ref 4, used with permission of the publisher, original © 1985 Academic Press)

# SPECTROMETRY



- THE ACQUISITION & EXPLOITATION OF SPECTRAL CURVES OF OBJECTS
  - REFLECTANCE, ABSORPTANCE, RADIANCE
- CONTINUA, LINES, & BANDS
- OBJECTS OFTEN HAVE UNIQUE *SPECTRAL SIGNATURES*
  - E.G., VEGETATION, SOIL, MINERALS, ALGAE $\rho$, $\alpha$ CURVES
- UTILITY
  - DISCRIMINATION
  - CLASSIFICATION / TYPING
  - ATMOSPHERIC COMPOSITION & CONDITIONS
- SPECTROMETERS ARE USUALLY NOT IMAGERS
  - HIGHER SPECTRAL RESOLUTION THAN MULTISPECTRAL IMAGERS
  - POINT MEASUREMENTS OF SPECTRA
- "IMAGING SPECTROMETRY" COMBINES IMAGING RADIOMETRY & SPECTROMETRY

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# POLARIMETRY



- FULL ELECTRO-MAGNETIC(EM) WAVE DESCRIPTION: RADIANCE AND *POLARIZATION*
  - E-VECTOR VARIES RANDOMLY WITH TIME: *UNPOLARIZED*
  - E-VECTOR HAS PREFERRED ORIENTATION WITH TIME: *POLARIZED*
    - LINEAR, CIRCULAR, ELLIPTICAL
  - ENVIRONMENTAL RADIANCE IS OFTEN *PARTIALLY POLARIZED*
    - STOKES PARAMETERS I (intensity), Q & U (ellipticity), V (circularity)
    - FUNCTION OF ILLUMINATION & VIEWING GEOMETRY
- SOURCES OF ENVIRONMENTAL POLARIZATION
  - SCATTERING & REFLECTION
- *POLARIMETRY* ≡ MEASUREMENT OF POLARIZATION
  - *POLARIMETER* : POINT MEASUREMENTS OR IMAGERY (PASSIVE & ACTIVE TECHNIQUES)
  - SOURCE OF ADDITIONAL INFORMATION IN REMOTE SENSING
  - LARGELY UNEXPLOITED IN E-O
    - SHUTTLE & ER-2 MISSIONS (REFs 76-78)

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# POLARIZATION DIAGRAM



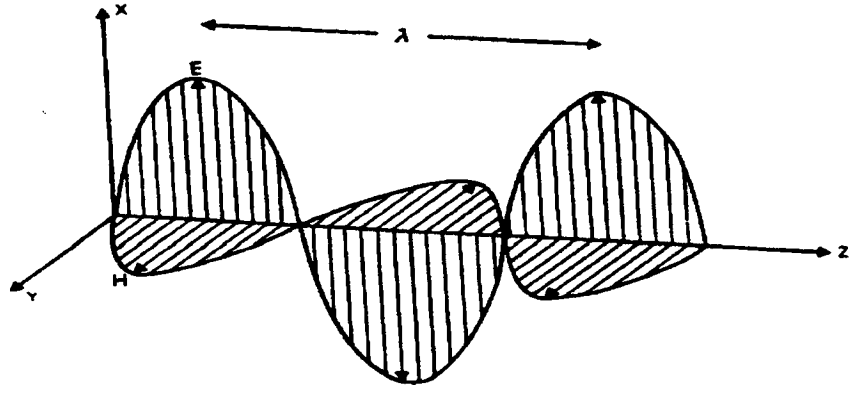
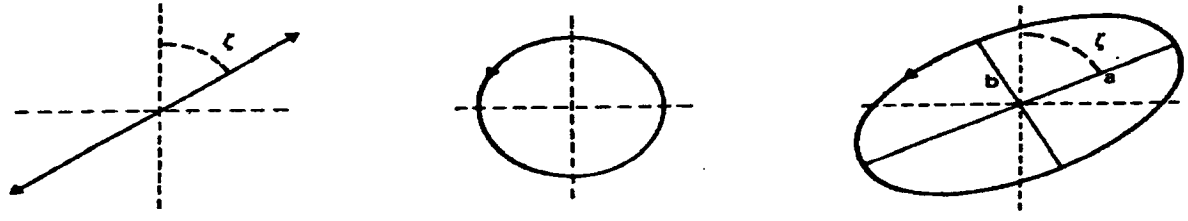



Figure 1. Electric and magnetic fields of an electromagnetic wave, vibrating at right angles and in phase to each other; for symbols refer to the Appendix.




(i) (ii) (iii)

Polarization states: orientation of the electric vector over time: (i) linear polarization, with polarization azimuth ($\zeta$), (ii) circular polarization and (iii) elliptical polarization, with ellipse azimuth ($\zeta$), semimajor ($a$) and semiminor ($b$) axes.

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# UTILITY OF POLARIMETRY

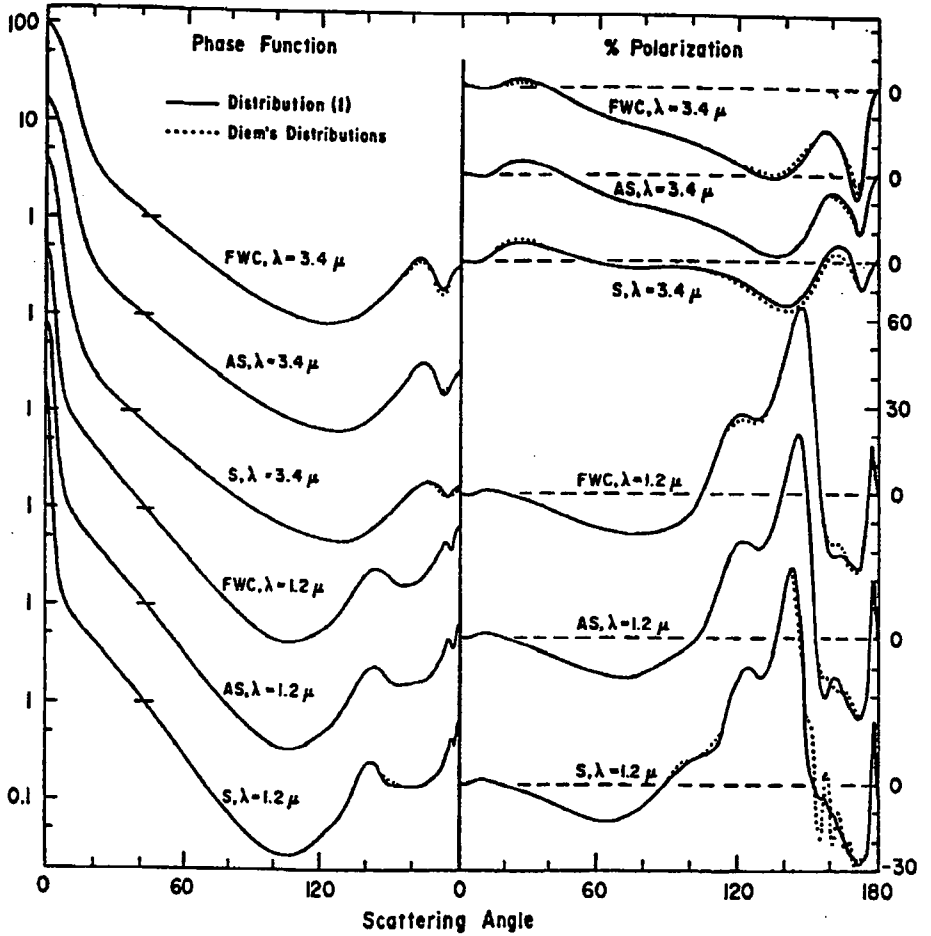


- POTENTIALLY IMPROVED MEASUREMENTS OF
  - CLOUD MICRO-PHYSICAL PROPERTIES
    - — DROP SIZE & SHAPE, OPTICAL THICKNESS, LIQUID/ICE PHASE
  - AEROSOL DISTRIBUTION & OPTICAL THICKNESS
    - — USEFUL FOR ACCURATE ATMOSPHERIC CORRECTIONS
  - SURFACE CHARACTERIZATION
    - — VEGETATION, LAND SURFACE
- REQUIRES
  - KNOWLEDGE OF SUN-SCENE-SENSOR GEOMETRY
  - CHARACTERIZATION/MINIMIZATION OF SENSOR-INDUCED POLARIZATION
  - IMPROVED SENSOR CALIBRATION
  - IMPROVED DATA ANALYSIS & MODELING TECHNIQUES

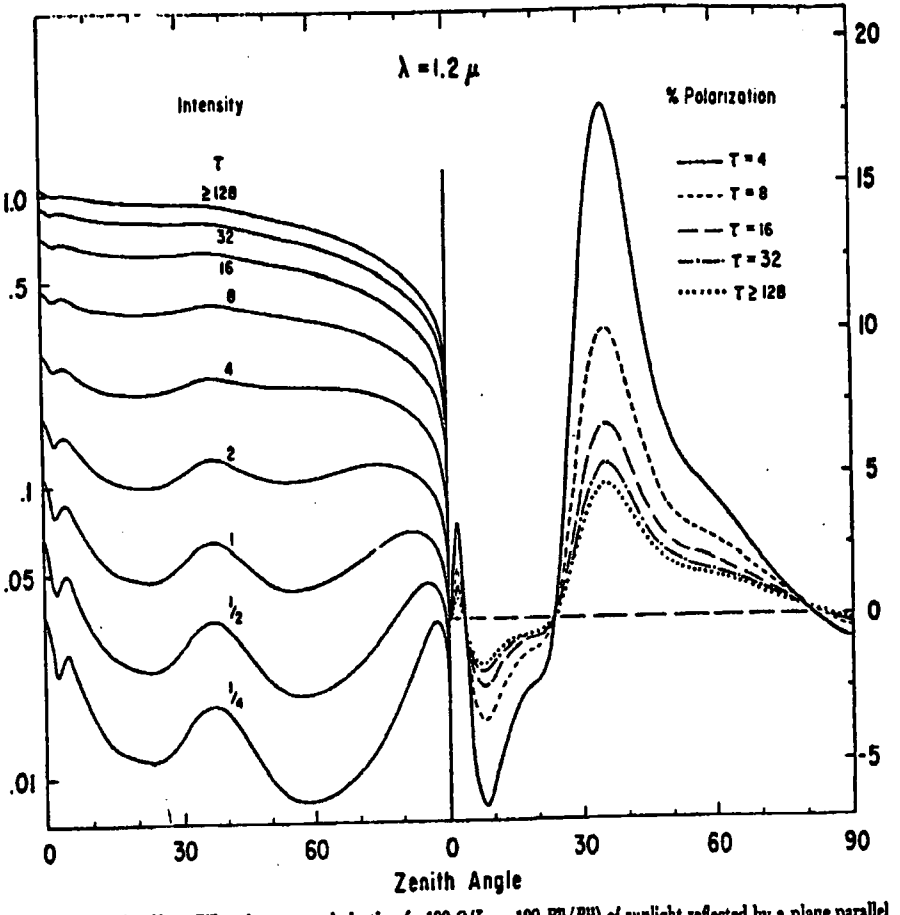
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# POLARIMETRY APPLICATION - CLOUDS






Phase function ($P^{11}$) and percent polarization ($-100P^{12}/P^{11}$) for single scattering by spherical particles for the size distributions in Fig. 1. FWC, AS and S represent fair weather cumulus, altostratus and stratus, respectively. The phase functions are successively displaced from one another by an order of magnitude with the horizontal bars occurring at the value unity. The polarizations are displaced from one another with the dashed lines indicating zero polarization.




Intensity ($I=\mu_0 R^{11}$) and percent polarization ($-100\,Q/I=-100\,R^{12}/R^{11}$) of sunlight reflected by a plane parallel cloud with the sun overhead ($\theta_0=0°$). The wavelength is 1.2 μ and results are shown for several optical thicknesses. On the horizontal axis is the zenith angle of the reflected light, $\theta=\cos^{-1}\mu$. The calculations are for the size distribution (1) with $a=6\,\mu$ and $b=\frac{1}{4}$.

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# PART 3

# SYSTEMS APPROACH TO

# E-O SENSOR SYSTEM DEFINITION

# USER REQUIREMENTS DEFINITION & FLOWDOWN



- REMOTE SENSING SYSTEM ≡ SENSOR, PLATFORM, DATA STORAGE/COMM, ANALYSIS
- NEW SYSTEM DRIVEN BY USER REQUIREMENTS
  - E.G., NEW/BETTER ENVIRONMENTAL DATA
  - MOTIVATION SHOULD BE A PROBLEM IN NEED OF A SENSOR SYSTEM, NOT *VICE VERSA*
- "TOP-DOWN" REQUIREMENTS FLOW
  - IDEALLY, DATA REQ'TS DRIVE BASIC SYSTEM ATTRIBUTES
  - START WITH TOP LEVEL SYSTEM AND WORK DOWN TO DETAILS
- CONSIDER DATA REDUCTION & ANALYSIS UP FRONT
  - TENDENCY TO IGNORE IN EARLY PROJECT PHASES
  - CAN HAVE MAJOR SYSTEMS IMPACT
  - DEFINE & BUDGET AT START

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# TYPICAL TEAM ORGANIZATION



- USER COMMUNITY
  - MULTI-FACETED
  - USER WORKING GROUP SETS REQUIREMENTS
- SYSTEMS ENGINEERS
  - SYSTEM-LEVEL SPECIFICATION IN RESPONSE TO REQ'TS
  - INTERACT WITH USERS, WRITE SPECS FOR INDUSTRY
- DESIGN ENGINEERS
  - PERFORM DETAILED DESIGN BASED ON SPECS, INTERACT W. SYSTEMS ENGINEERS
- IMPLEMENTORS
  - BUILD SYSTEM & LAUNCH/FLY IT
- OPERATORS
  - PERFORM ROUTINE OPS & ANOMALY INVESTIGATION
- USER COMMUNITY
  - ANALYZES DATA & REPORTS RESULTS

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# REQUIREMENTS INTERACTIONS



- USER MAY CHOOSE TO DEFINE
  - ENVIRONMENTAL DATA REQUIREMENTS ONLY
    - SYSTEMS & DESIGN ENGINEERS DO REST
  - SENSOR REQUIREMENTS ALSO
    - RISKY WITHOUT FULL ANALYSIS & UNDERSTANDING
- USER MAY NEED HELP
  - TO UNDERSTAND COST & RISK IMPLICATIONS OF REQ'TS
  - TO UNDERSTAND SENSOR & SYSTEM TRADEOFFS
  - TO DEVELOP A CONSISTENT SET OF REQUIREMENTS
- BEWARE OF "REQUIREMENTS CREEP"
  - NATURAL TENDENCY
  - CAN BE COSTLY
  - CAN KILL A PROGRAM
  - THINK THINGS THROUGH THOROUGHLY UP FRONT

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# SYSTEM COMPONENTS



- PLATFORM
  - SUPPORTS SENSORS
  - SPACECRAFT
    - 3-AXIS OR SPIN STABILIZED, OR SPUN/DESPUN
  - AIRCRAFT
    - POINTING STABILITY
    - TESTBED FIDELITY
  - BALLOON
    - RELATIVELY INEXPENSIVE
    - FLIGHT PATH & RECOVERY ISSUES
- SENSOR
- DATA HANDLING & COMMUNICATIONS
- DATA REDUCTION & ANALYSIS

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# SENSOR PLATFORM INTERFACE REQUIREMENTS



- WEIGHT
- POWER
- VOLUME
- ATTITUDE CONTROL (ACCURACY, KNOWLEDGE, STABILITY)
- THERMAL CONTROL
- CLEAR FIELD OF VIEW; GLINT CONTROL (PLATFORM & OTHER SENSORS)
- CONTAMINATION CONTROL
- OPERATIONAL COMMAND CAPABILITY
- DATA RATE FROM SENSOR TO PLATFORM
- SIGNIFICANT SHORTFALLS IN ANY OF ABOVE CAN LIMIT SENSOR CAPABILITY/UTILITY

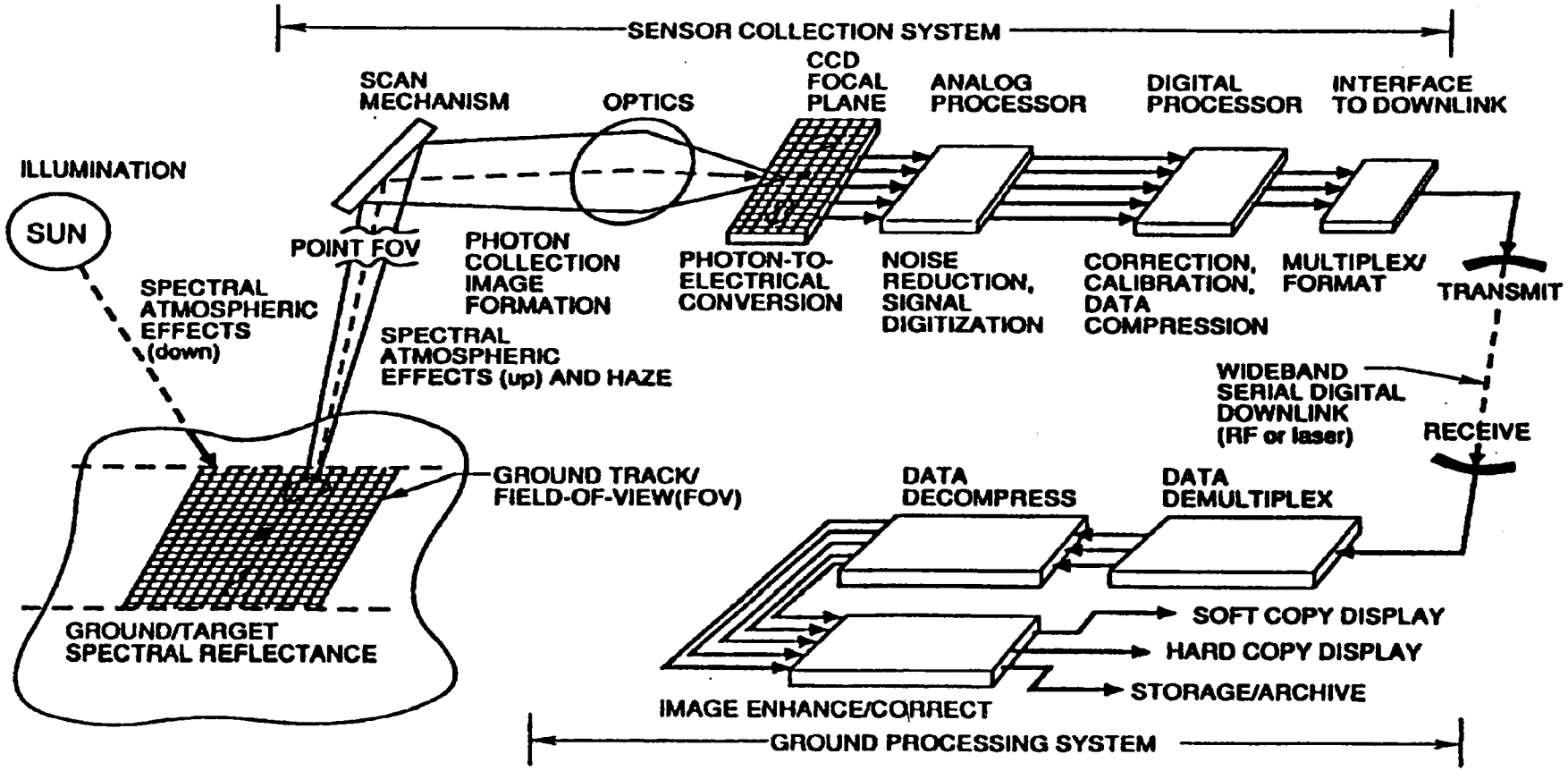
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- COST
  - ALWAYS A BASIC LIMITING FACTOR IN SENSOR CAPABILITY

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# SENSOR SYSTEM COMPONENTS DIAGRAM





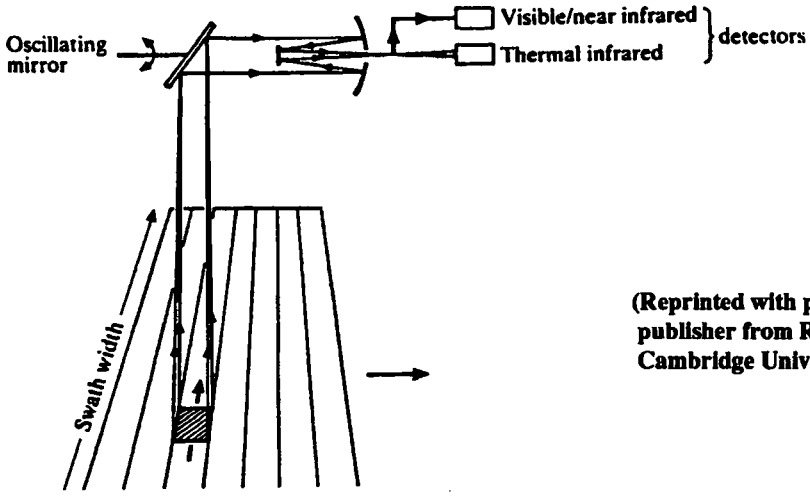

**Schematic showing the signal path through sensor collection system and ground processing system. The signal processing chain is similar for both pushbroom and whiskbroom sensor systems.**

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# SCAN MECHANISM



- SCANS SWATH OR SELECTED AREAS
- MIRROR(S)
  - E.G., WHISKBROOM CROSSTRACK

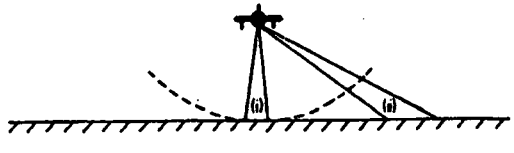



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- GIMBALS
  - E.G., AREA RASTER SCAN



- PLATFORM
  - E.G., TIP AIRCRAFT



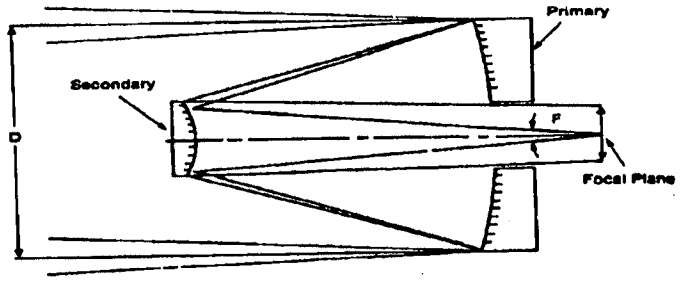

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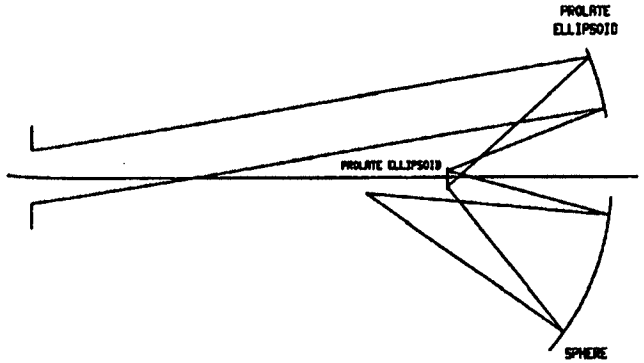
# OPTICS: REFLECTIVE



- REFLECTIVE (MIRRORS)
  - BROAD SPECTRAL RANGE
  - ON-AXIS (e.g., RITCHEY CHRETIEN)
    - EASY TO MANUFACTURE (CONICAL SURFACES)
    - COMPACT
    - NARROW FIELD OF VIEW (≤ 3 °) DUE TO ABERRATIONS
  - OFF-AXIS (e.g., 3-MIRROR UNOBSTRUCTED)
    - HARDER TO MANUFACTURE
    - LESS COMPACT
    - WIDER FIELD OF VIEW (UP TO ≈ 15°) SINCE ABERRATIONS BETTER CONTROLLED




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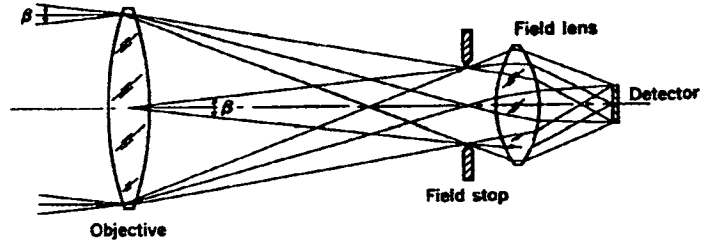
- APERTURE ≡ DIAMETER OF OPTICAL ELEMENT (e.g., PRIMARY MIRROR)
- FOCAL LENGTH ≡ DISTANCE AT WHICH OBJECT @ INFINITY IS BROUGHT TO A FOCUS
- f# ≡ FOCAL LENGTH/APERTURE
  - LOW f# ⇒ LARGE LIGHT-GATHERING POWER, AND "SPEED"

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# OPTICS: REFRACTIVE



- REFRACTIVE (LENSES)
  - RESTRICTED SPECTRAL RANGE BY PASSING THRU LENS
  - ALSO CHROMATIC ABERRATION
  - BUT EASY TO ACHIEVE VERY WIDE FIELD OF VIEW




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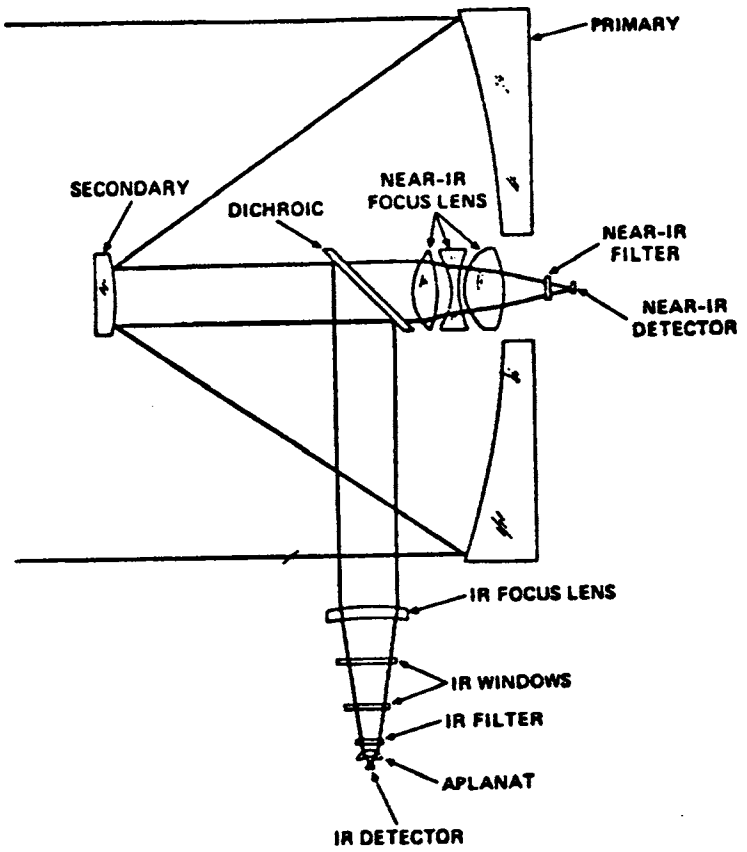
- FIELD STOP SERVES TO CONTROL STRAY LIGHT
  - LOWER STRAY LIGHT ⇒ HIGHER IMAGE CONTRAST
  - PLACED AT FOCAL PLANE, WHERE THE OBJECTIVE FOCUSES LIGHT FROM INFINITY
- FIELD LENS REFOCUSES IMAGE ONTO DETECTOR AND MAGNIFIES
  - ESSENTIALLY A TELESCOPE EYEPIECE
  - MAGNIFICATION = f# (field lens) / f# (objective)
    - — PRACTICAL LIMITS ON MAGNIFICATION SET BY LIGHT GATHERING POWER
- REPLACE "OBJECTIVE" WITH "PRIMARY", AND ABOVE HOLDS FOR REFLECTIVE OPTICS
- MULTIPLE FOREOPTICS SOLUTION
  - GOOD FOR WIDE SWATH IMAGING WITH LOW STRAY LIGHT

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# SAMPLE OPTICAL TRAIN



- FOREOPTICS (TELESCOPE) - COLLECT & FOCUS SCENE RADIANCE
- DEROTATION MIRROR ("K" MIRROR;p. G-17) HALF ANGULAR SPEED OF SCAN MIRROR
- RELAY OPTICS - RELAY THE BEAM TO THE DETECTORS
- BEAMSPLITTERS - SPLIT BEAM INTO 2 PATHS WITH DIFFERENT SPECTRAL RANGES
- BANDPASS FILTERS - DEFINE BANDPASS
- FIELD FLATTENER
- DETECTORS - CONVERT PHOTONS TO ELECTRICAL SIGNALS - FOCAL PLANE ARRAY (FPA)
- OPTICS DESIGN PROGRAMS
  - CODE V: POPULAR FOR BASIC DESIGN
  - GUERAP: STRAY LIGHT ANALYSIS
- ALTERNATIVE CONFIGURATIONS:
  - FILTER WHEEL, REDUCE # FPA's
  - INTERFEROMETER (LATER)



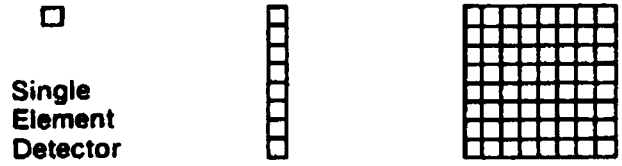

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# DETECTORS (FOCAL PLANE ARRAYS)



- CONVERT PHOTONS TO ELECTRICAL SIGNALS
- SINGLE DETECTOR, LINE ARRAY, AREA ARRAY
- COMMON MATERIALS
  - UV/VIS/NIR : Si CCD (CHARGE-COUPLED DEVICE)
  - SWIR/MWIR/LWIR : HgCdTe (all), InSb (MWIR), InGaAs (SWIR)
    - — PV (PHOTOVOLTAIC) *vs* PC (PHOTOCONDUCTIVE) OPERATION
      - -- PC: VARIATIONS IN e- CURRENT CHANGES VOLTAGE ACROSS RESISTANCE: BIAS REQ'D
        - --- GOOD: RESPONSIVE TO LWIR; SENSITIVITY MORE STABLE OVER LONG TERM; MORE MATURE TECHNOLOGY
        - --- BAD: LARGE HEAT LOAD TO DISSIPATE ⇒ LARGE COOLING SYSTEM
      - -- PV: p-n JUNCTION SEPARATES CHARGE CARRIERS: NO POWER SOURCE REQ'D
        - — PHOTON CREATES ELECTRON/HOLE PAIR: PHOTODIODE, e.g., InSb or InGaAs
        - --- GOOD: SMALL HEAT LOAD HENCE SMALLER COOLING SYSTEM, MORE LINEAR CONVERSION OF PHOTONS TO ELECTRONS, LESS 1/f NOISE
        - --- BAD: RESPONSIVITY LIMITATIONS IN LWIR BEYOND ≈ 11 μm; SENSITIVITY DEGRADES OVER LONG TERM




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# DETECTOR ATTRIBUTES



- SOME NOISE TYPES
  - THERMAL NOISE DUE TO RANDOM MOTION OF CHARGE CARRIERS ("DARK CURRENT")
    - ⇒ DETECTOR COOLING, ESPECIALLY LWIR (≈ 80° K)
      - - CAN BE A *MAJOR* SYSTEM DRIVER
      - - OPTICS JUST IN FRONT OF DETECTORS MAY REQUIRE COOLING ALSO
  - "1/f NOISE"
    - — RANDOM WALK OF SENSITIVITY (SNR), ESP. FOR PC LWIR



    - — ⇒ FREQUENT CALIBRATION FOR LWIR (seconds to minutes)
- D*
  - FIGURE-OF-MERIT FOR IR DETECTORS, INCLUDING ALL NOISE PARAMETERS
  - SEE REF. 62 FOR DETAILS
- FPAs SENSITIVE TO PARTICLE RADIATION
  - NOISE SPIKES OR PERMANENT LATTICE DISLOCATIONS
  - ALSO ELECTRONICS BIT FLIPS & LATCH-UP

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# DETECTOR COOLING



- FPA IN DEWAR IF AIRBORNE (e.g., $LN_2$)
- FPA TYPICALLY CONNECTED TO PASSIVE OR ACTIVE COOLER (e.g., BY COLD STRAP) IF SPACEBORNE
- PASSIVE COOLER
  - BLACKBODY RADIATES TO 3° K DEEP SPACE
  - AVOID SUN AND EARTHSHINE
    - REFLECTIVE SHIELD
    - ORBIT & SENSOR/COOLER POSITIONING CONSIDERATIONS
  - AVOID EXCESSIVE CONTAMINATION (COMMANDABLE COVER)
  - CAN ACHIEVE ≤ 80° K FOR SMALL HEAT LOADS (SMALL FPA's; PV FPA's)
- ACTIVE COOLER
  - STORED CRYOGENS, MECHANICAL REFRIGERATION, ETC.
  - GREATER COOLING, LIMITED LIFETIME, LESS RELIABLE, REQUIRE POWER
  - OXFORD STIRLING COOLER

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# CALIBRATION SUBSYSTEM



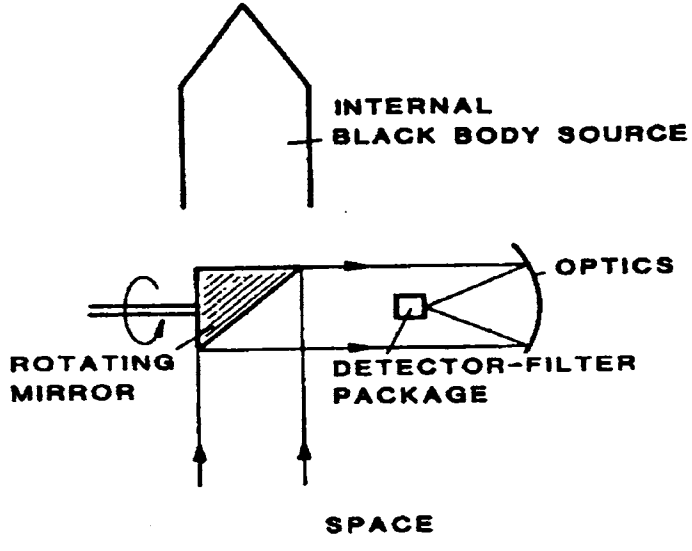
- AN IMAGING RADIOMETER'S OUTPUT MUST BE CALIBRATED
- RADIOMETRIC (GAIN & OFFSET) AND SPECTRAL CALIBRATION
- TWO TYPES OF RADIOMETRIC CALIBRATION
  - RELATIVE: BAND-TO-BAND
    - CRITICAL FOR ALL SPECTRAL BANDS
  - ABSOLUTE RADIANCE
    - CRITICAL FOR MWIR, LWIR FOR IMAGER TEMPERATURE MEASUREMENTS
- PRE-FLIGHT CALIBRATION CRUCIAL TO ESTABLISH BASELINE
  - WITH SOURCES DIRECTLY TRACEABLE TO NIST STANDARDS
    - NIST = NATIONAL INSTITUTE OF STANDARDS & TECHNOLOGY (FORMERLY NATIONAL BUREAU OF STANDARDS)
- IN-FLIGHT CALIBRATION NEEDED AT LEAST TO TRACK CHANGES

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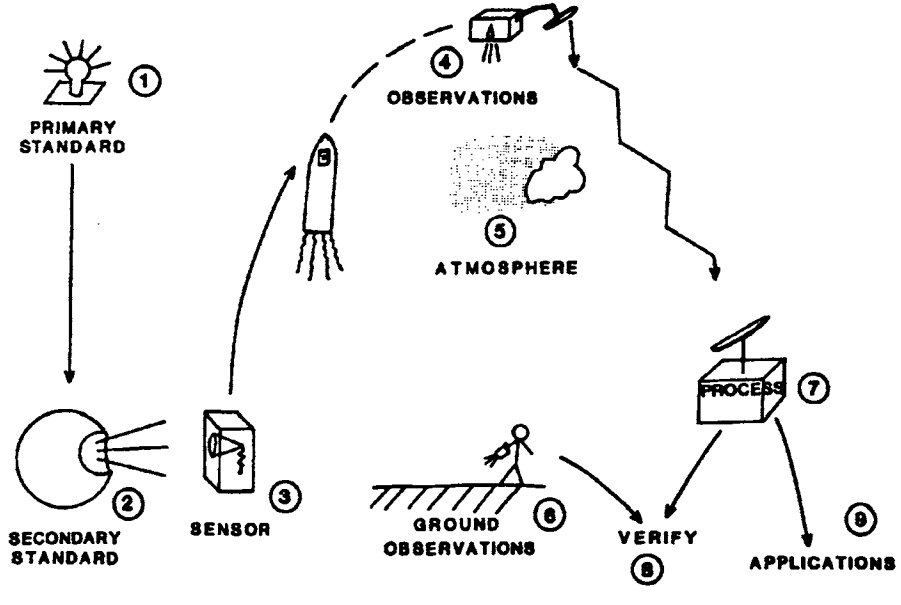
# IN-FLIGHT RADIOMETRIC CALIBRATION



- IN-FLIGHT RADIOMETRIC CALIBRATION
  - IR: ≥ 2 SOURCES: HOT & COLD PLATES OR HOT PLATE & SPACE
  - VIS
    - DARK SLIDE & LAMP OR SOLAR DIFFUSER
    - KNOWN TARGET E.G. WHITE SANDS
  - PROBLEM: AGING OF DETECTORS & SOURCES



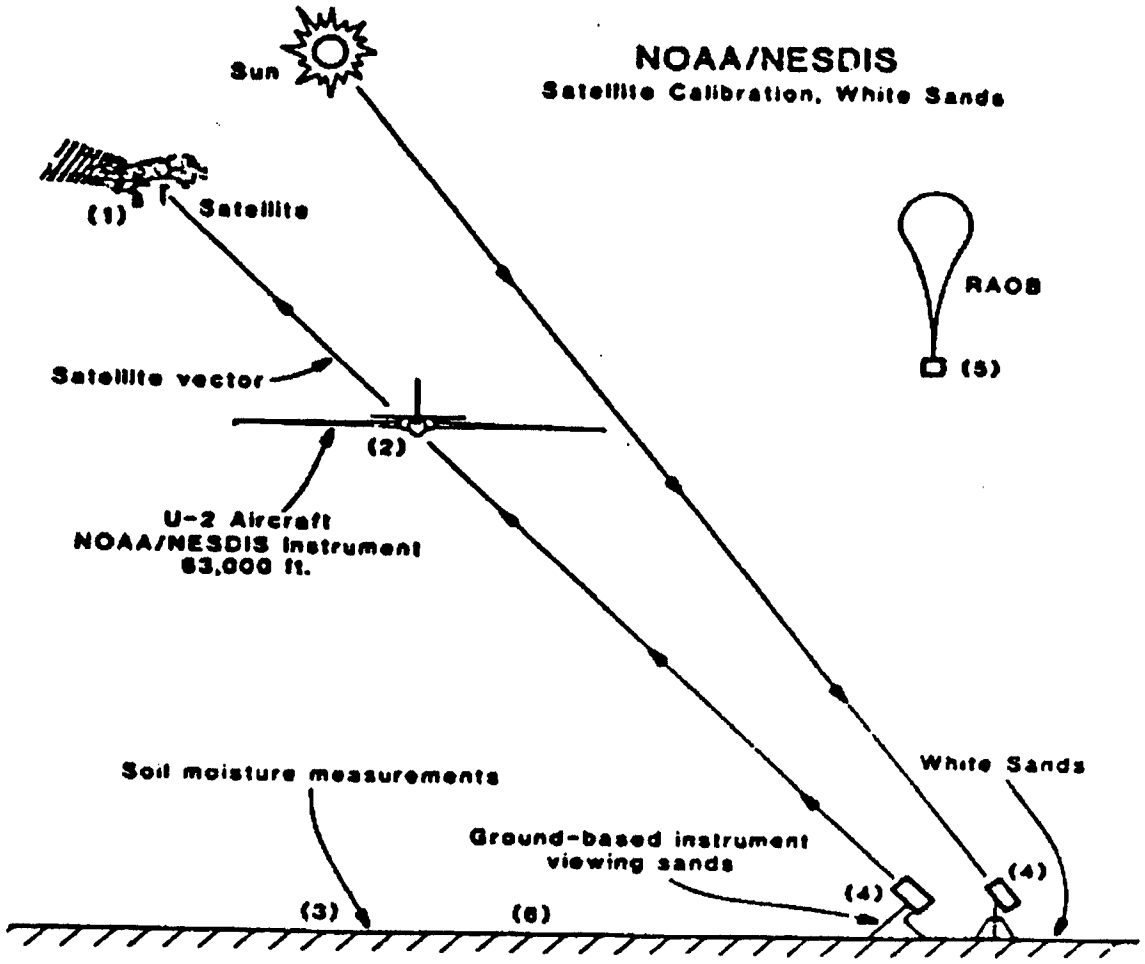

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# SOME CALIBRATION/VALIDATION METHODS






(Ref 41)

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# TYPICAL SIGNAL CHAIN ELECTRONICS



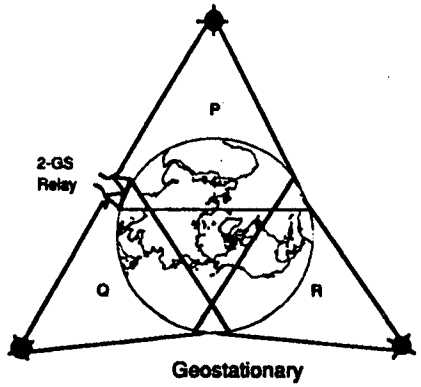
- DETECTOR PRE-AMPS
- ANALOG PROCESSING
  - ANALOG-TO-DIGITAL CONVERTER (ADC)
    - BITS PER PIXEL (BPP), DIGITAL COUNTS RANGE FROM 0 TO $(2^{BPP}-1)$
      - - BPP SET BY REQUIRED DYNAMIC RANGE, SENSITIVITY, & BY QUANTIZATION ERROR
- DIGITAL PROCESSING
  - ONBOARD CALIBRATION
  - DATA COMPRESSION : CODE DATA TO REDUCE REQUIRED BPP TO DOWNLINK (SPACEBORNE)
    - LOSSLESS = "ENTROPY PRESERVING" ≈ 3:1
    - LOSSY : EDGES & RADIOMETRIC ACCURACY DEGRADE > 3:1
    - CODE SPATIAL OR SPECTRAL INFORMATION, e.g., ΔRADIANCE ACROSS IMAGE
    - SOME METHODS: DISCRETE COSINE TRANSFORM (DCT), ADAPTIVE DIGITAL PULSE CODE MODULATION (ADPCM), VECTOR QUANTIZATION (VQ), FRACTALS
    - BEWARE OF "BIT HITS" IN DOWNLINK
- DATA MULTIPLEXER/FORMATTER

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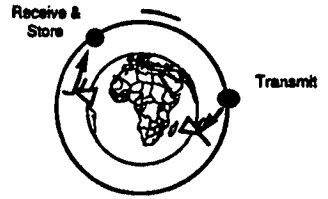
# DATA STORAGE, DOWNLINK, COMMUNICATION (SPACE)



- DATA TO USER
  - ONBOARD STORAGE, DELAYED PLAYBACK
    - TAPE RECORDERS, SOLID STATE MEMORY, OPTICAL DISK, ETC.
  - DIRECT DOWNLINK
    - REAL TIME READOUT TO USER SITE (e.g., LANDSAT)
  - SATELLITE LINK
    - e.g., NASA TDRSS (TRACKING & DATA RELAY SATELLITE SYSTEM)
  - STORE & FORWARD
    - e.g., GOES "STRETCHED VISSR"




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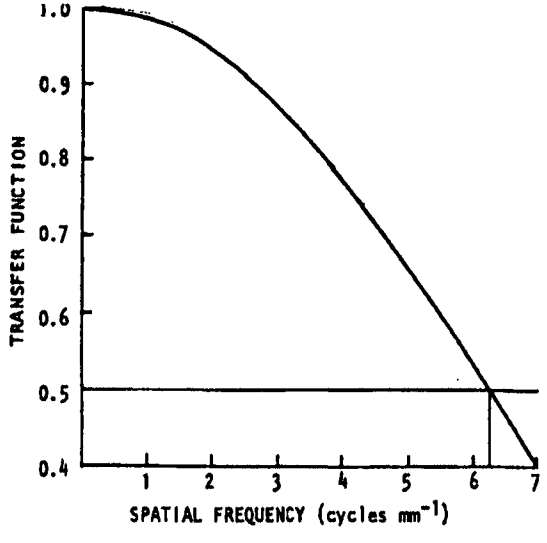

- ERROR DETECTION & CORRECTION
  - DOWNLINK IS ENCODED SUCH THAT BIT ERRORS CAN BE DETECTED AND CORRECTED
  - e.g., REED-SOLOMON, CONVOLUTIONAL CODING
  - BIT ERROR RATE (BER) LOWER LIMIT $\approx 10^{-5}$ to $10^{-6}$

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# SENSOR ATTRIBUTES/SYSTEM DRIVERS



- *SPATIAL RESOLUTION*
  - DISTINGUISHABILITY OF FEATURES IN SENSOR DATA
  - MODULATION TRANSFER FUNCTION (MTF)
  - DRIVES FOREOPTICS APERTURE (WEIGHT, POWER, $)
    - DIFFRACTION LIMITED $\Theta_{rad} = 2.44\,\lambda/D$
    - ALSO APPLIES TO μW, 3 dB SPOT MODIFIED FOR ANTENNA TAPER
  - DRIVES POINTING STABILITY (1/5 - 1/10 PIXEL RULE-OF-THUMB)
  - DATA RATE ∝ RESOLUTION $^{-2}$
  - CONSIDERATION IN ALTITUDE SELECTION (SPACE OR AIR)




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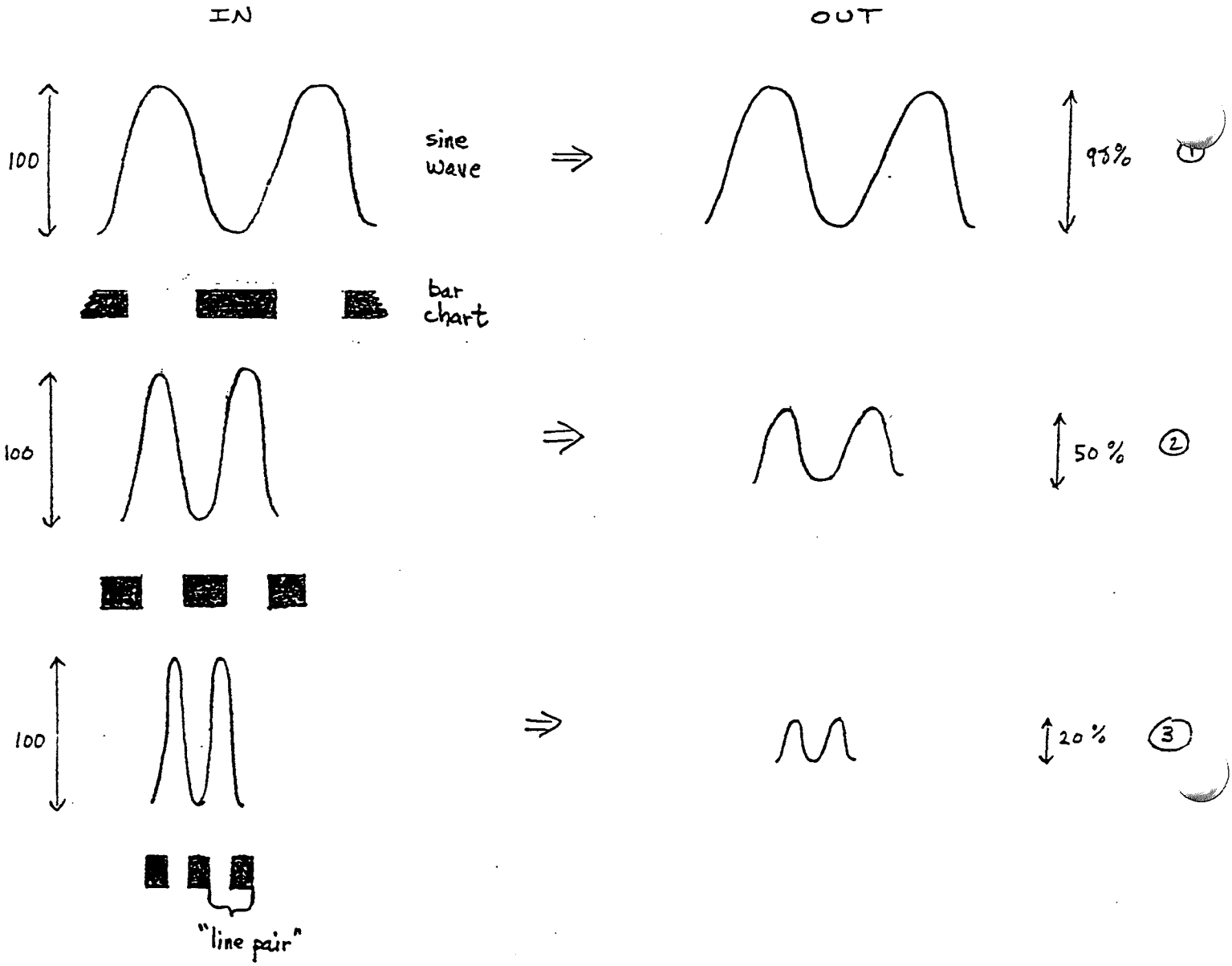
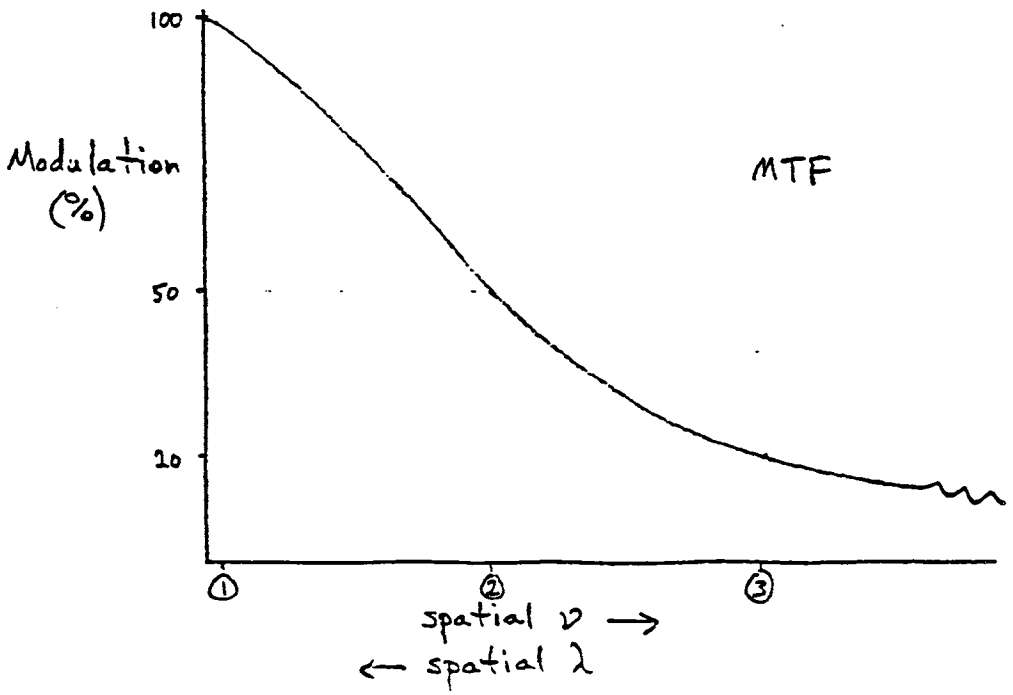



Figure 1b




D. Glackin
11/26/91

# SENSOR ATTRIBUTES/SYSTEM DRIVERS (CONT'D)



- *SENSITIVITY*
  - NOISE-EQUIVALENT-DELTA-RADIANCE (NE$\Delta\rho$) UV $\rightarrow$ SWIR
    - WHAT RADIANCE DIFFERENCE IN SCENE EQUALS NOISE IN IMAGE?
  - NOISE-EQUIVALENT-DELTA-TEMPERATURE (NE$\Delta$T) MWIR $\rightarrow$ LWIR
    - WHAT TEMERATURE DIFFERENCE IN SCENE EQUALS NOISE IN IMAGE?
  - CAN DRIVE FOREOPTICS APERTURE WELL BEYOND DIFFRACTION LIMIT ($$)
  - DRIVES FPA COOLING & MATERIAL QUALITY (WEIGHT, VOLUME, $)
  - DRIVES SIGNAL CHAIN ADC BPP, THUS DATA RATE

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# SENSOR ATTRIBUTES/SYSTEM DRIVERS (CONT'D)



- *RADIOMETRIC ACCURACY*
  - DIFFERENCE BETWEEN MEASURED AND TRUE RADIANCE
  - RELATIVE ACCURACY BAND-TO-BAND TYPICALLY REQUIRED
  - ABSOLUTE ACCURACY IN-BAND USUALLY REQUIRED IN IR (CLOUD, LAND, SEA SURFACE TEMP)
  - ADVANCES NEEDED FOR GLOBAL CHANGE MONITORING
  - DRIVES CALIBRATION SUBSYSTEM (WEIGHT, VOLUME, *$$*, CONTAMINATION CONTROL)
    - HALF OF MODIS-N COST IS FOR RADIOMETRIC CALIBRATION!
  - DRIVES STRAY LIGHT & INDUCED POLARIZATION REQ'TS
- *POINTING (ATTITUDE DETERMINATION & CONTROL)*
  - ACCURACY/CONTROL
  - KNOWLEDGE/MAPPING ACCURACY
  - STABILITY/JITTER ($1\sigma$ or $3\sigma$, OVER SCAN-RELATED PERIOD) : IMAGE SMEAR
  - DRIVES POINTING PLATFORM DESIGN (*$$* )
  - DRIVES EPHEMERIS/STAR TRACKER/EARTH SENSOR/GPS (SPACEBORNE)

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# SENSOR ATTRIBUTES/SYSTEM DRIVERS (CONT'D)



- *FIELD OF REGARD/SWATH WIDTH*
  - DRIVER FOR SCAN MECHANISM, FOREOPTICS, # FPA DETECTORS
  - DATA RATE DRIVER (LEO BIRD GROUND SPEED ≈ 7 KM/SEC)
  - CONSIDERATION FOR STRAY LIGHT/GLINT DESIGN
- *SPECTRAL BANDPASSES*
  - DATA RATE DRIVER
  - WEIGHT/VOLUME, $ DRIVER
  - LIMITER OF SENSITIVITY & RADIOMETRIC ACCURACY
- *COREGISTRATION*
  - SPATIAL REGISTRATION BETWEEN SPECTRAL BANDS
  - DRIVES MANUFACTURING MATERIALS & TOLERANCES, CAN BE BIG $ DRIVER
- *MEAN MISSION DURATION (MMD) (SPACEBORNE)*
  - CAN BE MAJOR $ DRIVER VIA PARTS QUALITY & SYSTEM REDUNDANCY
  - TENDENCY TOWARD LONGER MMD

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# SENSOR ATTRIBUTES/SYSTEM DRIVERS (CONT'D)



- *DYNAMIC RANGE*
  - RANGE FROM FAINTEST TO BRIGHTEST SIGNAL IN EACH BAND
  - DRIVES SIGNAL CHAIN (e.g., BPP)
  - CAN LEAD TO REQUIREMENT FOR COMPLEX GAIN SWITCHING & DRIVE FPA DESIGN
  - LOW END OF RANGE SETS SENSITIVITY REQUIREMENT
- *STRAY LIGHT*
  - UNWANTED EXTRANEOUS RADIANCE FROM DIRECTIONS AND/OR $\lambda$'s NOT OF INTEREST
  - CAN WREAK HAVOC WITH ACCURACY & SENSITIVITY
    - OFTEN IGNORED OR OVERSIMPLIFIED; REQUIRES PAINSTAKING ANALYSIS
    - DRIVER OF OPTICAL DESIGN & SENSOR PLACEMENT ON PLATFORM
- *POLARIZATION*
  - SENSOR CAN INDUCE ITS OWN (UNWANTED) POLARIZATION SIGNAL
    - COMMON FOR 45° MIRROR REFLECTIONS, FUNCTION OF SCAN $\angle$
  - CAN BE MAJOR COST DRIVER WHEN (SILVERED MIRRORS, ETC.)

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# SENSOR ATTRIBUTES/SYSTEM DRIVERS (CONCLUSION)



- *QUANTIZATION & ENCODING*
  - 8-BIT VIS, 10-BIT IR QUANTIZATION COMMON; 12-BIT SOMETIMES FOR DYNAMIC RANGE
  - DATA RATE DRIVER
  - CAN BE PRIMARY POWER DRIVER VIA ELECTRONICS BOARDS
  - ENCODING MAY BE LINEAR, PIECEWISE-LINEAR, LOGARITHMIC, ETC.
    - DYNAMIC RANGE & INFORMATION CONTENT AT DIFFERENT RADIANCE LEVELS

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# DATA TYPE DEFINITION



- NO STANDARD NOMENCLATURE - DEPENDS ON USER COMMUNITY
- EXAMPLES FROM OLD AND NEW NASA (EARTH OBSERVING SYSTEM) COMMUNITIES

- RAW DATA RECORD (RDR) = *EOS LEVEL 1A*
  - RAW SENSOR DATA, TIME REFERENCED & ANNOTATED WITH ANCILLARY INFO
- SENSOR DATA RECORD (SDR) = *EOS LEVEL 1B*
  - DATA PROCESSED TO SENSOR UNITS (e.g., EARTH-LOCATED RADIANCE)
- ENVIRONMENTAL DATA RECORD (EDR) = *EOS LEVEL 2*
  - DERIVED ENVIRONMENTAL PARAMETERS (e.g., CLOUD COVER) AT SAME RESOLUTION AND LOCATION AS SDR
- ASSIMILATED DATA = *EOS LEVEL 3*
  - ENVIRONMENTAL PARAMETERS MAPPED TO A UNIFORM SPACE-TIME GRID
- MODEL OUTPUT = *EOS LEVEL 4*
  - MATHEMATICAL REPRESENTATION OF PHYSICAL SYSTEM (FUTURE SECTION)

# DATA ATTRIBUTES/SYSTEM IMPACTS



- REQUIRED DATA (EDR) ATTRIBUTES DRIVE THE END-TO-END SYSTEM DESIGN
  - FROM SENSING OF EVENT TO DELIVERY TO USER
  - DESIGN OF PLATFORM, SENSOR, DATA SYSTEM, COMM, GROUND PROCESSING, DISPLAY AND RETRIEVAL ALGORITHM ALL IMPACT THE DATA PRODUCT QUALITY & UTILITY
- *SPATIAL RESOLUTION*
  - DISTINGUISHABILITY OF FEATURES IN EDR, AFFECTED IN PART BY
    - PLATFORM ALTITUDE & LOOK ANGLES TO SCAN SWATH
    - PLATFORM STABILITY
    - OPTICS APERTURE & IMAGE QUALITY (ABERRATIONS, ETC.)
    - FPA DETECTOR SIZE, MATCH TO OPTICS, READOUT CHARACTERISTICS (e.g., CTE)
    - FPA COREGISTRATION, FOR MULTISPECTRAL DATA
    - DATA COMPRESSION RATIO
    - FOR VERTICAL RESOLUTION OF SOUNDINGS: SENSITIVITY & BANDPASS PURITY

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# DATA ATTRIBUTES/SYSTEM IMPACTS (CONT'D)



- *MEASUREMENT RANGE*
  - RANGE FROM LOWEST TO GREATEST VALUE OF EDR, AFFECTED IN PART BY
    - SENSOR DYNAMIC RANGE (DETECTOR NOISE & FULL WELL)
    - SENSOR SENSITIVITY (OPTICS SIZE & DETECTOR NOISE)
    - QUANTIZATION & ENCODING
    - SPATIAL RESOLUTION (FOR STRUCTURED DATA FIELDS)
      - - SMALL-SCALE HIGH-EXCURSION FEATURES MAY BE MISSED
    - SPECTRAL BANDPASSES
- *MEASUREMENT ACCURACY*
  - RMS DIFFERENCE BETWEEN MEASURED AND TRUE EDR VALUE, AFFECTED IN PART BY
    - SENSOR RADIOMETRIC ACCURACY
      - - DESIGN OF CALIBRATION SUBSYSTEM & DATA COMPRESSION SCHEME
      - - SENSOR STRAY LIGHT, INDUCED POLARIZATION, SPECTRAL PURITY
    - PLATFORM POINTING KNOWLEDGE

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# DATA ATTRIBUTES/SYSTEM IMPACTS (CONT'D)



- *MEASUREMENT PRECISION*
  - RMS DEVIATION BETWEEN MEASURED MEAN VALUE AND INDIVIDUAL MEASUREMENTS, AFFECTED IN PART BY
    - SYSTEM SENSITIVITY
    - QUANTIZATION
    - PLATFORM POINTING STABILITY
- *MAPPING ACCURACY*
  - ERROR IN LOCATION OF EDR IN GEODETIC COORDINATES (USUALLY 3 $\sigma$), AFFECTED IN PART BY
    - SYSTEM SPATIAL RESOLUTION
    - PLATFORM POINTING KNOWLEDGE
      - ONBOARD EPHEMERIS, STAR TRACKER, EARTH SENSOR, GPS

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# *FUTURE TRENDS*



- INTEGRATED, COORDINATED, MULTI-NATIONAL SYSTEMS
- HIGHER SCAN EFFICIENCY (PUSHBROOM)
- FOCAL PLANE TECHNOLOGY (MORE DETECTORS, SENSITIVITY, IR AVAILABILITY & MATERIALS)
- IMPROVED CALIBRATION ACCURACY & STABILITY
- IMPROVED MULTISPECTRAL RADIOMETRY; IMAGING SPECTROMETRY; SPECTROMETRY
- EXPLOITATION OF POLARIMETRY
- IMPROVED ATMOSPHERIC CORRECTION METHODS
- ACTIVE COOLING (SPACEBORNE) & LONG LIFE COOLING (*MOST CRITICAL EOS NEED*)
- ACTIVE SENSING MOVING (SLOWLY) FROM AIRBORNE TO SPACEBORNE
- LARGER SATELLITES, HEAVIER PAYLOADS, MORE POWER, LONGER LIFE *AND* SMALLSATS
- USE OF GLOBAL POSITIONING SYSTEM
- BETTER DATA HANDLING & COMM (SPACE: ONBOARD PROCESSING & STORAGE, COMPRESSION)
- *MORE DATA*
  - EXPERT SYSTEMS, WORKSTATIONS, NETWORKS, SUPERCOMPUTERS, *QUALIFIED PEOPLE*

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# PART 4

# INTERNATIONAL PROGRAMS AND ORGANIZATIONS

# SELECTED NATIONAL SPACE AGENCIES



- USA - NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)
- EUROPE - EUROPEAN SPACE AGENCY (ESA)
  - FRANCE, GERMANY, ITALY, UK, BELGIUM, SPAIN, NETHERLANDS, SWEDEN, SWITZERLAND, DENMARK, AUSTRIA, NORWAY, IRELAND, PLUS CANADA (ASSOC. MEMBER)
- FRANCE - CENTRE NATIONAL d'ETUDES SPATIALE (CNES)
- GERMANY - GERMAN SPACE AGENCY (DARA)
- UK - BRITISH NATIONAL SPACE CENTER (BNSC)
- ITALY - AGENZIA SPAZIALE ITALIANA (ASI)
- CANADA - CANADIAN SPACE AGENCY (CSA)
- JAPAN - NATIONAL SPACE DEVELOPMENT AGENCY (NASDA)
  MINISTRY OF INTERNATIONAL TRADE & INDUSTRY (MITI)
- CIS - WAS GLAVKOSMOS (USSR), TO BE REPLACED BY INDUSTRIAL CONSORTIUM
- INDIA - INDIAN SPACE RESEARCH ORGANIZATION (ISRO)
- AUSTRALIA, INDONESIA, BRAZIL, CHINA, ...

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# OPERATIONAL ENVIRONMENTAL MONITORING AGENCIES



- SATELLITES MAY BE TRANSITIONED FROM NATIONAL SPACE AGENCIES TO OPERATIONAL MONITORING AGENCIES WHEN THEY ARE NO LONGER R&D PROGRAMS

- USA - NATIONAL ATMOSPHERIC AND OCEANOGRAPHIC ADMINISTRATION (NOAA)
- EUROPE - EUROPEAN ORGANIZATION FOR EXPLOITATION OF MET SATS (EUMETSAT) (DARMSTADT, GERMANY)
- CANADA - ATMOSPHERIC ENVIRONMENT SERVICE (AES)
- JAPAN - JAPAN METEOROLOGICAL AGENCY (JMA)
- CIS - WAS HYDROMETEOROLOGICAL SERVICE OF USSR, NOW ?

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# REMOTE SENSING RESEARCH ORGANIZATIONS



- NATIONAL SPACE AGENCIES & OPERATIONAL MONITORING AGENCIES OFTEN FUND/PERFORM BASIC & APPLIED RESEARCH IN REMOTE SENSING
- NATIONAL ENVIRONMENTAL AGENCIES OFTEN FUND/PERFORM APPLIED RESEARCH
  - e.g., USA ENVIRONMENTAL PROTECTION AGENCY (EPA)
- THESE *SELECTED* ORGANIZATIONS ALSO PERFORM RESEARCH:
  - USA - JET PROPULSION LABORATORY (JPL)

    ENVIRONMENTAL RESEARCH INSTITUTE OF MICHIGAN (ERIM)
  - UK - NATIONAL REMOTE SENSING CENTER Ltd. (NRSC)
  - FRANCE - CENTRE NATIONAL DE LA RECHERCE SCIENTIFIQUE (CNRS)
  - GERMANY - GERMAN AEROSPACE RESEARCH ESTABLISHMENT (DLR)
  - CANADA - CANADA CENTRE FOR REMOTE SENSING (CCRS)
  - JAPAN - REMOTE SENSING TECHNOLOGY CENTER (RESTEC)
  - INDIA - NATIONAL REMOTE SENSING AGENCY

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# COMMERCIAL AGENCIES



- COMMERCIAL AGENCIES EXIST FOR DISTRIBUTION OF SPECIFIC DATA
  - TYPICALLY EARTH RESOURCES SATELLITE DATA (LANDSAT, SPOT)
  - SOME ARE TIED TO GOVERNMENT AND "PSEUDO" COMMERCIAL
  - USA - EARTH OBSERVATION SATELLITE COMPANY (EOSAT) - LANDSAT DATA
  - FRANCE - SPOT IMAGE
  - UK - ENVIRONMENTAL REMOTE SENSING UNIT (ERSUN) OF NRSC
  - ITALY - EURIMAGE
  - CANADA - RADARSAT INTERNATIONAL
  - CIS - WAS SOYUZ KARTA (USSR), NOW ?
- OTHER *SELECTED* TYPES OF COMMERCIAL AGENCIES INVOLVED IN REMOTE SENSING
  - OIL, GAS & MINERAL EXPLORATION COMPANIES
    - THE GEOSAT COMMITTEE (INTERNATIONAL NON-PROFIT CONSORTIUM)
  - NEWS ORGANIZATIONS, e.g., SPACE MEDIA NETWORK (STOCKHOLM; NOW DEFUNCT)
  - FISHERIES

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# -- GLOBAL CHANGE PROGRAMS --

# INTERNATIONAL GEOSPHERE BIOSPHERE PROGRAM



- PURPOSE TO DESCRIBE & UNDERSTAND (REF 14)
  - "THE INTERACTIVE PHYSICAL, CHEMICAL & BIOLOGICAL PROCESSES THAT REGULATE THE TOTAL EARTH SYSTEM, THE UNIQUE ENVIRONMENT THAT IT PROVIDES FOR LIFE, AND CHANGES IN THE SYSTEM AND HOW THEY ARE INFLUENCED BY MAN"
- CURRENT KEY QUESTIONS
  - HOW IS ATMOSPHERIC CHEMISTRY REGULATED AND HOW DO BIOLOGICAL PROCESSES CONSUME & PRODUCE TRACE GASES?
  - HOW DO OCEAN BIOGEOCHEMICAL PROCESSES INFLUENCE & RESPOND TO CLIMATE CHANGE?
  - HOW DOES LAND USE AFFECT COASTAL ZONE, AND HOW DO SEA LEVEL CHANGES ALTER COASTAL ECOSYSTEMS?
  - HOW DOES VEGETATION INTERACT WITH THE PHYSICS OF THE HYDROLOGICAL CYCLE?
  - HOW WILL GLOBAL CHANGE AFFECT TERRESTRIAL ECOSYSTEMS?
  - WHAT SIGNIFICANT CLIMATE CHANGES HAVE OCCURRED IN THE PAST, AND WHY?
  - HOW CAN WE INTEGRATE & SYNTHESIZE A NUMERICAL PREDICTIVE CAPABILITY?
- SPONSOR - INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS (ICSU) (1986 -)

# IGBP CORE PROGRAMS



- ESTABLISHED (REF 14)
  - INTERNATIONAL GLOBAL ATMOSPHERIC CHEMISTRY PROJECT (IGAC)
  - JOINT GLOBAL OCEAN FLUX STUDY (JGOFS)
    - FLUXES OF CARBON & OTHER ELEMENTS; FIXATION OF $CO_2$
  - BIOSPHERIC ASPECTS OF THE HYDROLOGICAL CYCLE (BAHC)
    - SOIL-VEGETATION-ATMOSPHERE ENERGY & WATER FLUXES
  - GLOBAL CHANGE & TERRESTRIAL ECOSYSTEMS (GCTE)
    - EFFECT OF CHANGES & POSSIBLE FEEDBACK MECHANISMS
  - PAST GLOBAL CHANGES (PAGES)
- PROPOSED
  - STRATOSPHERE-TROPOSPHERE INTERACTIONS & THE BIOSPHERE
  - GLOBAL OCEAN EUPHOTIC ZONE STUDY
  - LAND-OCEAN INTERACTIONS IN THE COASTAL ZONE
  - GLOBAL ANALYSIS, INTERPRETATION & MODELING

# WORLD CLIMATE RESEARCH PROGRAM



- PHYSICAL ASPECTS OF CLIMATE SYSTEMS - REF 12
  - GLOBAL ATMOSPHERE (CLOUDS, RADIATION, ...)
  - WORLD OCEAN (CIRCULATION, AIR-SEA INTERACTION, ...)
  - CRYOSPHERE (ICE SHEETS, GLACIERS, SEA ICE)
  - LAND SURFACE (HYDROLOGY, ENERGY BUDGET, ...)
  - NATURAL & ANTHROPOGENIC VARIATIONS
    - DISCRIMINATE SPATIAL STRUCTURE & TIME SIGNATURE OF NATURAL VARIATIONS FROM MANMADE EFFECTS
  - TO WHAT EXTENT CAN CLIMATE BE PREDICTED?
- SPONSORS (1979 -)
  - INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS (ICSU)
  - WORLD METEOROLOGICAL ORGANIZATION

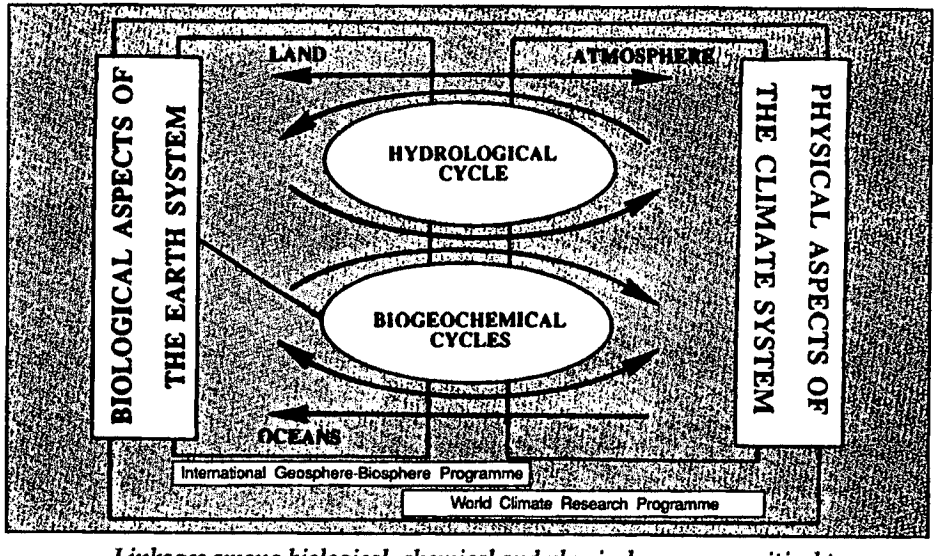
# WCRP PROGRAMS



- INTERNATIONALLY COORDINATED RESEARCH ACTIVITIES
- WORLD OCEAN CIRCULATION EXPERIMENT (WOCE)
  - "SLOW" CLIMATE SYSTEM - DELAYS CLIMATE RESPONSE TO FORCING
  - QUANTITATIVE UNDERSTANDING OF OCEAN CIRCULATION & HEAT XPORT
- TROPICAL OCEAN AND GLOBAL ATMOSPHERE (TOGA) PROGRAM - REF 13
  - TROPICAL OCEAN-ATMOSPHERE INTERACTIONS
  - EL NINO/SOUTHERN OSCILLATION (ENSO): PRINCIPAL YEAR-TO-YEAR CLIMATE SIGNAL
  - MONSOON REGIME
- GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (GEWEX)
  - STUDY, MODEL & PREDICT XPORT & EXCHANGE OF RADIATION, HEAT & WATER
  - "FAST" CLIMATE SYSTEM: ATMOSPHERE & UPPER OCEAN
  - INTERNATIONAL SATELLITE CLOUD CLIMATOLOGY PROJECT (ISCCP)
  - "GREENHOUSE" GASES, PRECIPITATION

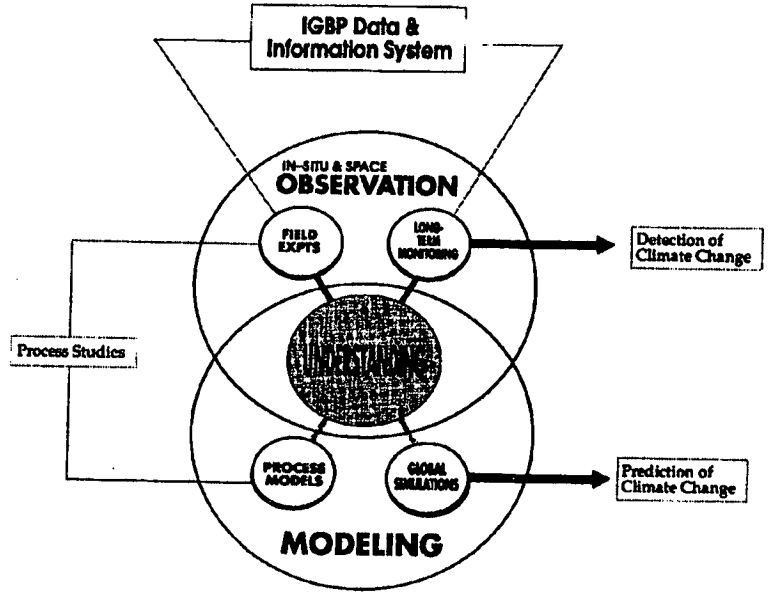
# IGBP/WCRP






*Linkages among biological, chemical and physical processes critical to our understanding of global change on a decade-to-century time scale. Arrows refer to the seven first research priority questions.*

(Ref 14)




(Ref 14)

- IGBP INFORMATION: ROYAL SWEDISH ACADEMY OF SCIENCES, STOCKHOLM
- ICSU INFORMATION: ICSU SECRETARIAT, PARIS

# U.S. GLOBAL CHANGE RESEARCH PROGRAM



- GOAL: ESTABLISH THE SCIENTIFIC BASIS FOR POLICYMAKING RELATING TO NATURAL & ANTHROPOGENIC CHANGES IN THE GLOBAL EARTH SYSTEM (REF 18)

- OBJECTIVES
  - ESTABLISH AN INTEGRATED, COMPREHENSIVE LONG-TERM PROGRAM OF DOCUMENTING THE EARTH SYSTEM ON A GLOBAL SCALE
  - CONDUCT A PROGRAM OF FOCUSED STUDIES TO IMPROVE UNDERSTANDING OF PHYSICAL, GEOLOGICAL, CHEMICAL, BIOLOGICAL, & SOCIAL PROCESSES THAT INFLUENCE EARTH
  - DEVELOP INTEGRATED CONCEPTUAL & PREDICTIVE EARTH SYSTEM MODELS

- THEMES FOR 1992
  - CLIMATE MODELING & PREDICTION
  - GLOBAL WATER & ENERGY CYCLES
  - GLOBAL CARBON CYCLE
  - ECOLOGICAL SYSTEMS & POPULATION DYNAMICS

- LINKED TO IGBP & WCRP VIA ICSU ("INTERNATIONAL GCRP")

- SPONSOR COMMITTEE ON EARTH & ENVIRONMENTAL SCIENCES (CEES) (1989 -)
  - UNDER US OFFICE OF SCIENCE & TECHNOLOGY POLICY

# MISSION TO PLANET EARTH



- NASA's RESPONSE TO US GCRP IS "MISSION TO PLANET EARTH"
  - INTEGRATED ATTACK ON GLOBAL CHANGE ISSUE
  - EARTH OBSERVING SYSTEM (EOS)
    - LEO ORBITING PLATFORMS, FIRST STUDIED 1983
    - EUROPEAN (e.g., COLUMBUS) & JAPANESE PLATFORMS IN EOS
    - SPACE STATION ATTACHED PAYLOADS
  - EARTH PROBES
    - E-O SENSORS: TOMS (OZONE), SeaWiFS (OCEAN COLOR)
  - GEOSYNCHRONOUS PLATFORMS
    - USA, EUROPEAN, JAPANESE PLATFORMS IN GEO ORBIT ENVISIONED
    - MULTITUDE OF SENSORS (REF 19), UNFUNDED
  - AIRBORNE SENSORS
  - GROUND-BASED SENSORS
  - INTEGRATED COMM & DATA HANDLING SYSTEMS

# EARTH OBSERVING SYSTEM

- USA, EUROPEAN, JAPANESE SPACE PLATFORMS & SENSORS, CANADIAN SENSORS (REF 15)
  - SPACE-BASED SENSOR SYSTEMS
    - INTEGRATED SCIENTIFIC OBSERVING SYSTEM OF EARTH'S CRITICAL PROCESSES
    - COORDINATED SIMULTANEOUS MEASUREMENTS OF INTERACTIONS OF ATMOSPHERE, OCEANS, LAND, AND HYDROLOGICAL & BIOGEOCHEMICAL CYCLES
  - DATA & INFORMATION SYSTEM (EOSDIS)
    - GLOBAL DATABASE OF REMOTE SENSING MEASUREMENTS FROM SPACE OVER A DECADE OR MORE TO ENABLE DEFINITIVE & CONCLUSIVE STUDIES
    - 60% OF EOS FUNDS PLANNED FOR DATA SYSTEM & ANALYSIS AS OF 1990
  - SCIENTIFIC RESEARCH PROGRAM
    - AMOUNTS, DISTRIBUTIONS, RATES, SOURCES, SINKS, ETC., OF ALL RELEVANT ITEMS

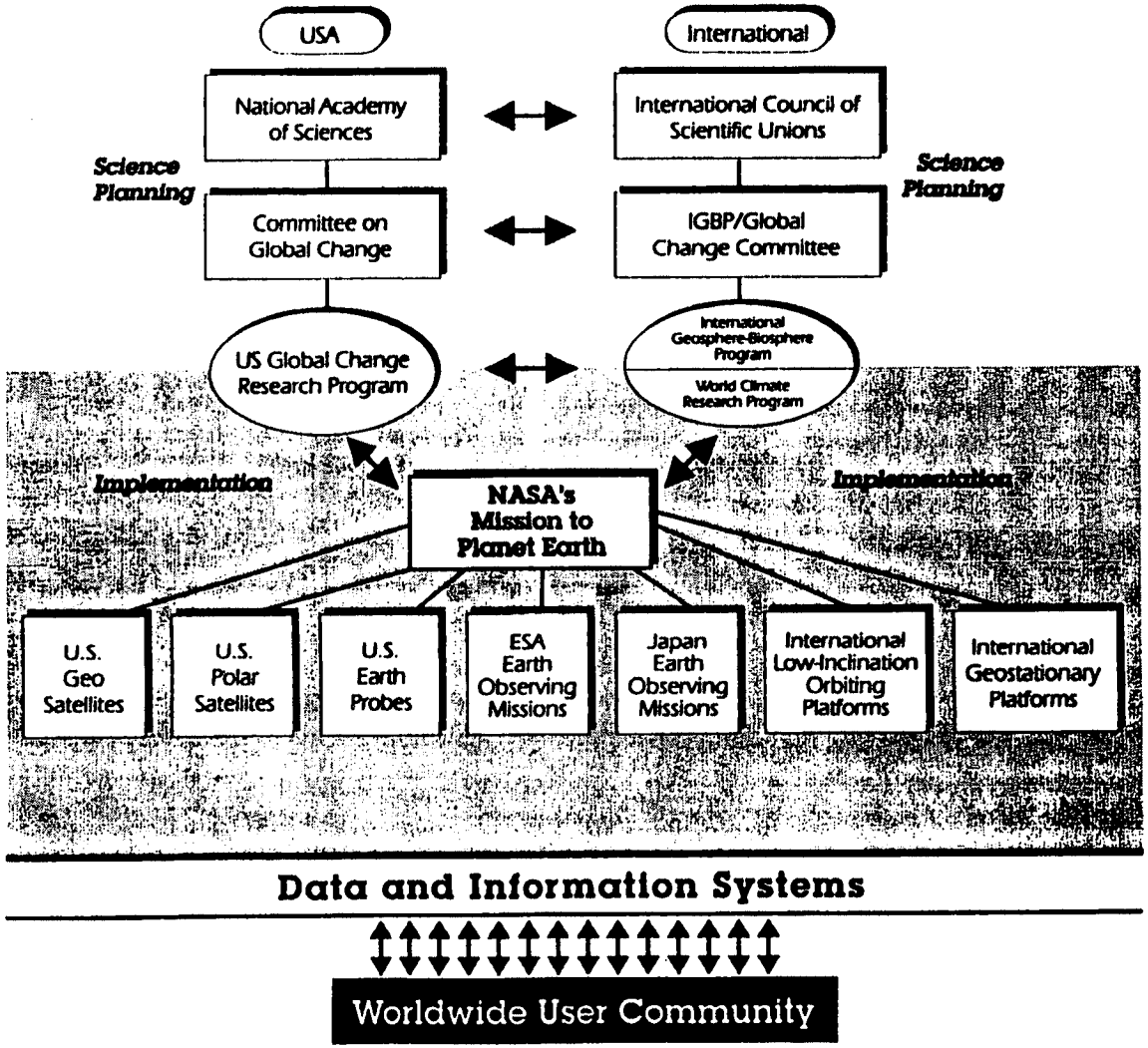
# EOS SPACE SEGMENT US STATUS



- OLD PLAN
  - US
    - 6 POLAR ORBITING 11,000 kg PLATFORMS (A-1 1998; B-1 2001)
      - - PAYLOAD 3500 kg, 3.2 kW, 30/300 Mbps, EACH 5-YR MMD, 15-YR TOTAL MISSION
      - - ≥ $ 30B OVER 15 YEARS
  - ESA: 2 POLAR ORBITING PLATFORMS (POEM-1 1997, EPOP-N1 1999)
  - JAPAN: POLAR ORBITING PLATFORM (JPOP, 1998), 55° INCLINATION PLATFORM (2000)
- NEW US PLAN (REF 16)
  - EOS ENGINEERING REVIEW ADVISORY COMMITTEE CITED BUDGETARY LIMITATIONS & LONG WAIT FOR DATA - REPORT SEPT 1991
  - FLY SMALLER SATELLITES, EARLIER, FOR LESS TOTAL COST ($ DECREASING FOR 1990's)
    - AM1 PLATFORM: 1120 kg P/L, 3 kW, 16/150 Mbps, 5-year MMD, 15-year MISSION
  - INVOLVE DOE, DOD & NOAA (CONVERGENCE STUDY)
  - GO SLOWER ON EOSDIS & STAY FLEXIBLE

# EOS INTERNATIONAL LINKS






(Ref 15)

# PART 5

# USER REQUIREMENTS ADDRESSABLE WITH PASSIVE E-O SENSING (AND APPROACH SUMMARY)

# REQUIREMENTS CLASSES



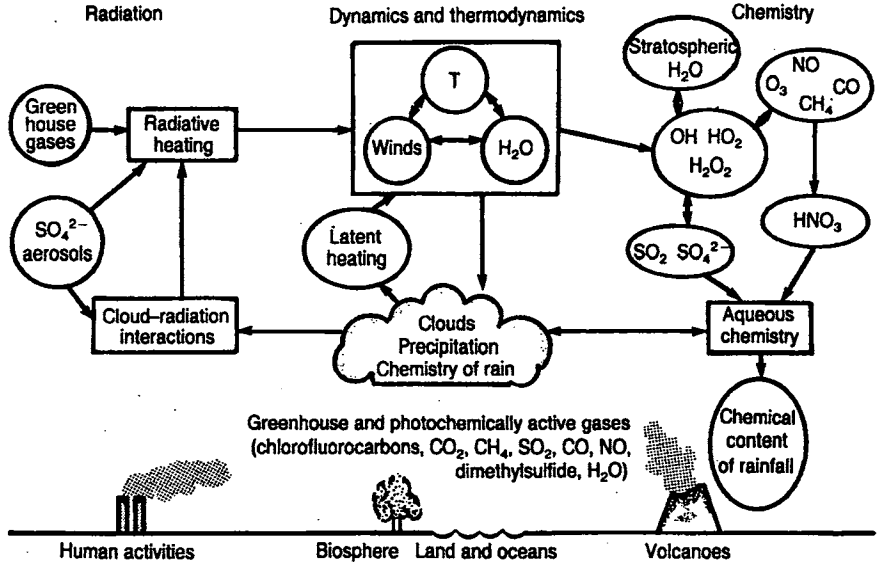
- ENVIRONMENTAL
  - ATMOSPHERE, OCEANS, LAND
- EARTH RESOURCES
  - GEOLOGY, AGRICULTURE, FORESTRY, HYDROLOGY, LAND USE, DISASTERS, ETC.
  - OVERLAPS WITH ENVIRONMENTAL, BUT NEEDS HIGHER RESOLUTION
- MAPPING
  - TOPOGRAPHY, DIGITAL ELEVATION (e.g., USGS)
- REGULATORY MONITORING
  - AIR & WATER POLLUTION, HAZARDOUS WASTE (e.g., EPA)
  - AIRBORNE TECHNIQUES REQUIRED FOR COMPREHENSIVE TREATMENT
- ECONOMIC / COMMERCIAL
  - OIL & GAS EXPLORATION, FISHERIES, NEWS REPORTING, ...
- ALL ARE ADDRESSABLE TO SOME EXTENT WITH E-O TECHNIQUES

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# SOME OUTSTANDING ENVIRONMENTAL PROBLEMS



- CLIMATE CHANGE
  - "GREENHOUSE" GASES
- OZONE DEPLETION*
  - CHLOROFLUOROCARBONS (CFCs), HALONS, ...
- AIR POLLUTION
  - CARS & INDUSTRY
- WATER POLLUTION
  - INDUSTRIAL PLANTS EFFLUENTS, RUNOFF
- ACID RAIN
  - SULFUROUS COMPOUND INJECTION & DEPOSITION
- HAZARDOUS WASTE
  - CHEMICALS, OILS, ...
- DESERTIFICATION, DEFORESTATION
- VOLCANOES




**Climate-Chemistry Coupling**

(Reprinted by permission, from Ref 17
© 1989 American Institute of Physics)

*Montreal Protocol (1987), revised (1990): Phaseout by ≈2000

# EOS ENVIRONMENTAL REQUIREMENTS -1991

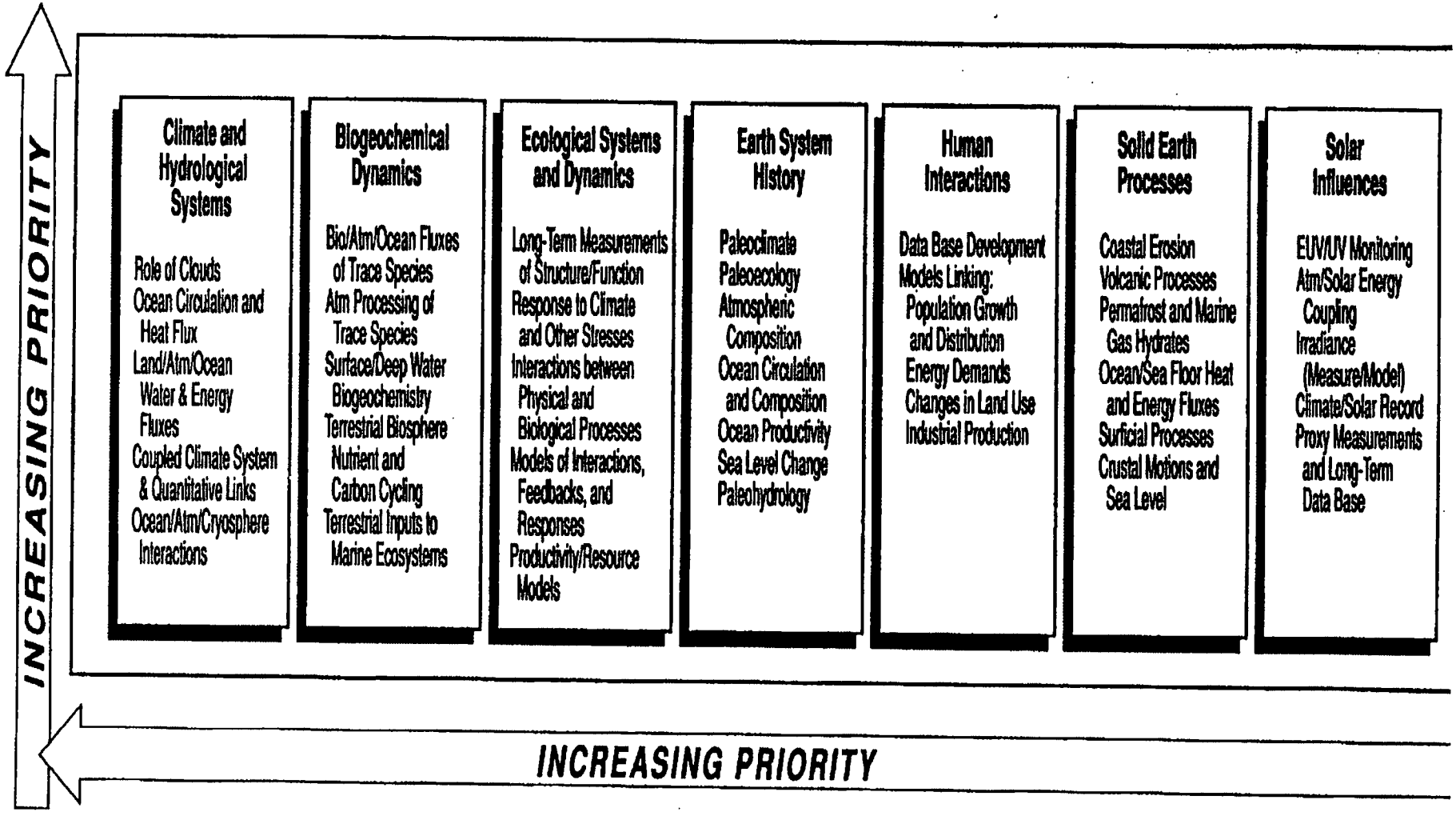


(Ref 15)

- Cloud properties
- Energy exchange between Earth and space
- Surface temperature
- Structure, composition, and dynamics of the atmosphere, winds, lightning, and precipitation
- Accumulation and ablation of snow
- Biological activity on land and in near-surface waters
- Circulation of the oceans
- Exchange of energy, momentum, and gases between the Earth's surface and atmosphere
- Structure and motion of sea ice; growth, melting, and flow rates of glaciers
- Mineral composition of exposed soils and rocks
- Changes in stress and surface elevation around geologic faults
- Input of solar radiation and energetic particles to the Earth.

# EOS SCIENCE PRIORITIES






(Ref 15)

# RESTRUCTURED EOS ENVIRONMENTAL REQ'TS - 1992



**Water and Energy Cycles:**

- cloud formation, dissipation, and radiative properties, which influence response of atmosphere to greenhouse forcing;
- large-scale hydrology and moist processes, including precipitation and evaporation.

**Oceans:**

- exchange of energy, water, and chemicals between ocean and atmosphere and between upper layers of ocean and deep ocean (includes sea ice and formation of bottom water).

**Chemistry of troposphere and lower stratosphere:**

- links to hydrologic cycle and ecosystems, transformations of greenhouse gases in atmosphere, and interactions with climatic change.

**Land surface hydrology and ecosystem processes:**

- improved estimates of runoff over surface and into oceans;
- sources and sinks of greenhouse gases;
- exchange of moisture and energy between land surface and atmosphere;
- changes in land cover.

**Glaciers and polar ice sheets:**

- predictions of sea level and global water balance.

**Chemistry of the middle and upper stratosphere:**

- chemical reactions, solar-atmosphere relations, and sources and sinks of radiatively important gases.

**Solid Earth:**

- volcanoes and their role in climatic change.

(Ref 20)

# SELECTED REQUIREMENTS *APPROX* ACCURACIES



| Parameter | Adequate accuracy | Desired accuracy | E-O |
|---|---|---|---|
| Climate: | | | |
| Surface albedo | 4% | 2% | |
| Surface radiation budget | 25 W/m² | 10 W/m² | |
| Solar flux, visible | 1% | 0.5% | |
| Solar flux, NUV | 3% | 1% | |
| Solar flux, MUV | 10% | 5% | |
| Solar flux, FUV | 10% | 5% | |
| Cloud cover | 20% | 5% | |
| Cloud-top temperature | 4 K | 2 K | |
| Cloud albedo | 4% | 2% | |
| Cloud total liquid water content | 50 mg/cm | 10 mg/cm | no |
| Environment: | | | |
| Temperature | 2 K | 1 K | |
| $CO_2$ | 10 ppm | 0.5 ppm | |
| $CH_4$ | 0.15 ppm | 0.05 ppm | |
| $N_2O$ | 0.03 ppm | 0.01 ppm | |
| $H_2O$ | 20% | 5% | |
| $O_3$ | 0.02 cm | 0.005 cm | |
| $NO_2$ | 10% | 2% | |
| CO | 10% | 2% | |
| $HNO_3$ | 20% | 5% | |
| Land: | | | |
| Surface albedo | 4% | 2% | |
| Precipitation | 25% | 10% | no |
| Vegetation cover | 10% | 5% | |
| Snow cover | 5% | 3% | partly |
| Soil moisture | 0.1 g/cm³ | 0.05 g/cm³ | no |
| Surface temperature | 2 K | 1 K | |
| Ocean: | | | |
| Sea surface temperature | 1 K | 0.2 K | |
| Evaporation | 25% | 10% | no |
| Sea surface elevation | 10 cm | 1 cm | no |
| Sea surface velocity | 10 cm/sec | 2 cm/sec | no |
| Sea ice cover | 5% | 3% | partly |
| Weather: | | | |
| Temperature profile | 2 K | 1 K | |
| Surface pressure | 3 mbar | 1 mbar | |
| Wind velocity | 3 m/sec | 1 m/sec | |
| Wind direction | 10° | 2° | |
| Humidity | 30% | 7% | |
| Cloud-top height | 1 km | 0.5 km | |
| Cloud amount | 20% | 5% | |

(Modified from Ref 4, used with permission of the publisher, original © 1985 Academic Press)

# ENVIRONMENTAL SENSING - CLOUDS



- CLOUDS
  - THE #1 UNKNOWN IN GLOBAL CHANGE
    - NET WARMING OR NET COOLING - *A BASIC UNANSWERED QUESTION*
      - HIGH CLOUDS TEND TO WARM, LOW CLOUDS TEND TO COOL
      - FEW % INCREASE IN GLOBAL LOW CLOUD COULD OFFSET WARMING DUE TO DOUBLING OF $CO_2$ (REF 21)
  - NASA # 1 PRIORITY
  - INTERNATIONAL SATELLITE CLOUD CLIMATOLOGY PROJECT (ISCCP) - WCRP
    - 30-DAY AND 250 X 250 KM BOX AVERAGED REQ'TS:
      - LOW, MIDDLE, & HIGH CLOUD AMOUNT TO $\pm$ 5 %
      - CLOUD TOP HEIGHT TO $\pm$ 1 KM, TEMP TO 1° K
      - OPTICAL DEPTH, SIZE DISTRIBUTION, VIS & IR RADIANCES
      - 3-HR SAMPLING
  - FIRE (FIRST ISCCP REGIONAL EXPERIMENT) - US, UK, FRANCE
    - CIRRUS & MARINE STRATOCUMULUS

# ENVIRONMENTAL SENSING - CLOUDS (CONT'D)



- GLOBAL COVER (%)
  - MULTISPECTRAL RADIOMETER & RETRIEVAL ALGORITHM (SENSOR P. G2)
    - VIS DAY, LWIR NIGHT, MWIR LOW CLOUD & FOG, SWIR SNOW/CLOUD, *THIN CIRRUS*
- CLOUD TYPE (CUMULUS, CIRRUS, STRATUS, ETC.)
  - MULTISPECTRAL RADIOMETER & RETRIEVAL ALGORITHM
- CLOUD HEIGHT (SURFACE - 20 KM, RARE TYPES HIGHER)
  - TOPS: MULTISPECTRAL RADIOMETER (LWIR/MWIR) & TEMPERATURE SOUNDER / LIDAR
  - ONLY KNOWN APPROACH TO LAYERS & BASES: MM-WAVE RADAR
- CLOUD PHASE (WATER, ICE)
  - MULTISPECTRAL RADIOMETER (SWIR) / LIDAR
- CLOUD DROP SIZE & OPTICAL DEPTH
  - POLARIMETER / LIDAR
- CLOUD BRDF
  - MULTI-ANGLE RADIOMETER (SENSOR P. G3)

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# ENVIRONMENTAL SENSING - ATMOSPHERE



- CLOUDS
- TEMPERATURE PROFILE
  - IR SOUNDER (SENSOR P. G5), PRESSURE MODULATED RADIOMETER (LIKE SENSOR P. G20), LIDAR
- MOISTURE PROFILE
  - IR SOUNDER, PRESSURE MODULATED RADIOMETER, LIDAR
- WIND PROFILE
  - GREATEST IMPACT ON NUMERICAL FORECAST MODELS OF ANY MISSING PARAMETER
  - TRANSPORT OF WATER VAPOR, GASES, AEROSOLS
  - OCEAN-ATMOSPHERE COUPLING (HEAT, MASS, MOMENTUM, ...)
  - SPECTROMETER (e.g., PRESSURE MODULATED RADIOMETER) UPPER ATMOSPHERE
  - LIDAR / CLOUD TRACKED WINDS, LOWER ATMOSPHERE
- AEROSOLS / VISIBILITY
  - POLARIMETER (SENSOR P. G19), MULTI-ANGLE IMAGING RADIOMETER, LIDAR

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# ENVIRONMENTAL SENSING - ATMOSPHERE (CONT'D)



- ENERGY BALANCE
  - BROAD-BAND UV/VIS/IR RADIOMETER (SENSOR P. G22)
- OZONE
  - LIMB SOUNDER (UV, VIS, IR), NADIR SOUNDER
- "GREENHOUSE" GASES
  - $H_2O$, $CO_2$ , $CH_4$ , $N_2O$, CFCs, ...
  - *WATER* IS THE MOST POWERFUL GREENHOUSE GAS
  - MUCH METHANE COMES FROM TERMITE WASTE ... THERE ARE 13 TONS OF SUCH WASTE FOR EVERY PERSON IN THE WORLD
  - SPECTROMETERS/SOUNDERS (SENSORS PP. G15, G17, G18)
- PRECIPITATION
  - NO GOOD E-O APPROACH, REQUIRES MICROWAVE SENSING

# ENVIRONMENTAL SENSING - OCEAN



- SEA SURFACE TEMPERATURE
  - MULTISPECTRAL RADIOMETER (LWIR, MWIR) (REF 71)
  - GOOD FISHING AT WARM/COLD INTERFACE
- OCEAN COLOR
  - PHYTOPLANKTON BIOMASS, PHOTOSYNTHETIC POTENTIAL, ...
  - COLD WATER NUTRIENT-RICH $\therefore$ HIGHEST PHYTOPLANKTON
  - OCEAN COLOR IMAGER (SPECIAL MULTISPECTRAL RADIOMETER) OR IMAGING SPECT.
    - CAREFUL ATMOSPHERIC CORRECTIONS MANDATORY
- SEA ICE
  - LIMITED INFORMATION FROM MULTISPECTRAL RADIOMETER
  - REQUIRES MICROWAVE TECHNIQUES (PASSIVE/ACTIVE)
- GLOBAL $CO_2$ OCEAN SINKS & AIR-SEA FLUXES
  - FLUXES MODELED USING TEMP, WIND, ETC., DATA

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# ENVIRONMENTAL SENSING - LAND



- LAND SURFACE TEMPERATURE
  - MULTISPECTRAL IMAGING RADIOMETER (LWIR/MWIR)
  - COMPLICATED BY VARIABLE AND UNKNOWN EMISSIVITY
- SURFACE ALBEDO (REFLECTIVITY)
  - BROADBAND IMAGING RADIOMETER
  - MODELING OF SOLAR INSOLATION REQUIRED FOR ACCURACY
- VEGETATION HEALTH INDEX
  - MULTISPECTRAL IMAGING RADIOMETER (VIS/NIR NORMALIZED RATIO), IMAGING SPECT.
- ENERGY BALANCE; BRDF
  - BROADBAND RADIOMETER; MULTI-ANGLE RADIOMETER
- SNOW & ICE, SURFACE MOISTURE
  - LIMITED INFORMATION FROM E-O; NEED PASSIVE/ACTIVE MICROWAVE
- FOREST FIRE & HOT SPOT MONITORING
  - IMAGING RADIOMETER, MWIR

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# EARTH RESOURCES SENSING



- OVERLAPS WITH ENVIRONMENTAL SENSING
  - BUT REQUIRES HIGHER SPATIAL (≈10 - 30 m) AND/OR SPECTRAL (≈0.01 - 0.02 μm) RESOLUTION
- GEOLOGY
  - MINERAL TYPE, SOIL TYPE & STATE, VOLCANIC PLUMES
- AGRICULTURE
  - CHLOROPHYLL CONCENTRATION, LEAF AREA INDEX, ...
- FORESTRY
  - GROWTH, DEFORESTATION, CANOPY CELLULOSE, LEAF WATER CONTENT, TRANSPIRATION,...
- HYDROLOGY
  - WETLANDS, INTERIOR WATER BODIES, SNOW
- LAND USE
  - URBANIZATION, DESERTIFICATION
- DISASTER ASSESSMENT, RANGE & RESOURCE MANAGEMENT
- SENSORS: IMAGING SPECTROMETER (SENSOR P. G13), IMAGING RADIOMETER

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# MAPPING & TOPOGRAPHIC SENSING



- TOPOGRAPHIC MAPPING (CARTOGRAPHY)
  - CONTENT, POSITION, ELEVATION
  - HIGH RESOLUTION MAPS HAVE 1:25,000 OR 1:50,000 SCALE WITH 5, 10, OR 20 m CONTOURS (REF 22)
- SENSOR: STEREO IMAGING RADIOMETER (SENSOR P. G4)
  - U. S. GEOLOGICAL SURVEY CONCEPT FOR LANDSAT 7 (REF 22, 23)
    - FORE/NADIR/AFT LOOKING PUSHBROOM RADIOMETER, 5 - 10 m RESOLUTION
    - STEREO PHOTOGRAMMETRY RECONSTRUCTS 3-D INFORMATION
    - HIGH POINTING ACCURACY/KNOWLEDGE REQUIRED
  - LANDSAT 7 MAY HAVE 5 m STEREO SENSOR WITH 60 km SWATH (HRMSI)
    - GEOPOSITIONING ACCURACY 23 m H, 17 m V
- SENSOR: EARTH RESOURCES IMAGER WITH POINTING AGILITY
  - IMAGE SAME AREA DURING DIFFERENT ORBITS FOR STEREO LOOK

# REGULATORY MONITORING



- AIR POLLUTION
  - TRACE GASES HAVE UNIQUE INFRARED SPECTRAL SIGNATURES
  - SPECTROMETER (e.g., FABRY-PEROT OR FOURIER TRANSFORM)
  - GAS CORRELATION SPECTRORADIOMETER (LIKE SENSOR P. G 20)
- WATER POLLUTION
  - OIL SPILLS, DUMPING FROM SHIPS, INDUSTRIAL EFFLUENTS
  - MULTISPECTRAL IMAGING RADIOMETER, IMAGING SPECTROMETER (REF 26)
  - AIRBORNE PLATFORM MOST APPROPRIATE FOR HIGH RESOLUTION
  - LASER FLUOROMETER USEFUL FOR OIL SPILLS
- HAZARDOUS WASTE ASSESSMENT
  - METALS, CHLORINATED ORGANICS, CFCs, ...
  - HIGH RESOLUTION SENSING OF LANDFILLS & PONDS REQUIRED: AIRBORNE SENSORS (REF 27)
  - IMAGING SPECTROMETER (SENSOR P. G13), MULTISPECTRAL IMAGING RADIOMETER

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# SELECTED ECONOMIC / COMMERCIAL SENSING



- OIL & GAS EXPLORATION
  - DETECT MINERALOGICAL VARIATIONS INDICATING POSSIBLE MICRO-SEEPAGE INDUCED PHENOMENA (BLEACHED AREAS DUE TO HYDROGEN-SULFIDE GAS), OR CERTAIN CLAY-RICH AREAS (ALSO REF 26)
- AGRICULTURE
  - WEATHER FORECASTS
  - CROP HEALTH & ASSESSMENT, e.g., AFRICA (REF 24, P. 233)
- OCEAN NAVIGATION & FUEL SAVINGS
  - MAP GULF STREAM, ETC., TO UTILIZE IN SHIP ROUTING (REF 24, P. 223)
- FISHERIES
  - MAP SEA SURFACE TEMPERATURE BECAUSE MANY FISH ARE TEMP-SENSITIVE
- MAP MAKING & UPDATING (REF 25)
- NATURAL DISASTER WARNING
  - HURRICANE TRACKING, SEVERE STORM FORECASTS, FLOOD WARNING (PRECIPITATION)
- NEWS REPORTING

# PART 6

# SELECTED

# SPACEBORNE PASSIVE E-O

# SENSING PROGRAMS

# SELECTED CURRENT PROGRAMS



*LEO:*
- NOAA TIROS (TELEVISION & IR OBSERVATION SATELLITE) - US - ENVIRONMENTAL
- DMSP (DEFENSE METEOROLOGICAL SATELLITE PROGRAM) - US - ENVIRONMENTAL
- LANDSAT - US - EARTH RESOURCES
- UARS (UPPER ATMOSPHERE RESEARCH SATELLITE) - US - ENVIRONMENTAL
- SPOT (SYSTEME PROBATOIRE D'OBSERVATION DE LA TERRE) - FRANCE
- ERS-1 (EARTH REMOTE SENSING SATELLITE)- ESA - OCEAN ENVIRONMENT
- IRS (INDIAN REMOTE SENSING SATELLITE) - INDIA - EARTH RESOURCES
- JERS-1 (JAPAN EARTH REMOTE SENSING SATELLITE) - JAPAN - OCEAN
- METEOR 3 - FORMER USSR - ENVIRONMENTAL (≈ 1200 km) / RESURS 01 - EARTH RESOURCES
- FY-1B - PEOPLE'S REPUBLIC OF CHINA - ENVIRONMENTAL (AVHRR, 901 km, NOAA-compatible)

*GEO:*
- GOES (GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITE) - US - ENV.
- METEOSAT - ESA - ENVIRONMENTAL
- GMS (GEOSTATIONARY METEOROLOGICAL SATELLITE) - JAPAN - ENVIRONMENTAL
- INSAT (INDIAN NATIONAL SATELLITE SYSTEM) - INDIA - ENVIRONMENTAL

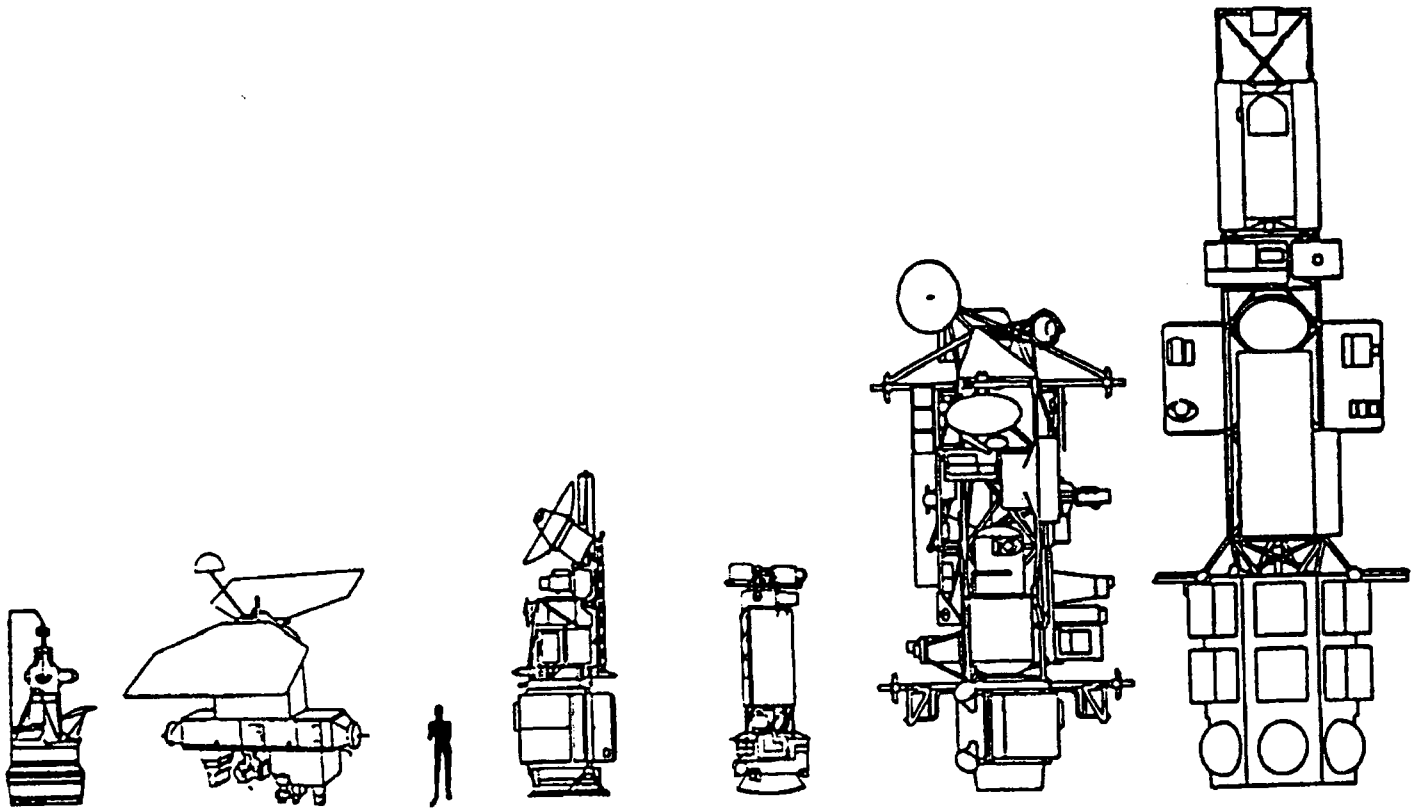
# SELECTED FUTURE PROGRAMS



- CONTINUING/EVOLVING PROGRAMS:
  - NOAA K-N, NOAA 2000 , DMSP BLOCKS 5D-3 & 6, LANDSAT 7, SPOT, ERS, IRS, METEOR
    - DMSP BLOCK 6 IN RISK REDUCTION PHASE
    - LANDSAT 7 JOINT NASA/DOD PROGRAM DISSOLVED
  - GOES-NEXT (I-M), METEOSAT, INSAT, GMS
    - RESOLVED DEVELOPMENTAL PROBLEMS WITH GOES-NEXT
- NEW PROGRAMS
  - EOS (EARTH OBSERVING SYSTEM)
    - US, EUROPEAN, JAPANESE PLATFORMS
  - ADEOS (ADVANCED EARTH OBSERVATION SATELLITE) - JAPAN
  - TRMM (TROPICAL RAINFALL MEASURING MISSION) - US/JAPAN
  - GOMS (GEOSYNCHRONOUS METEOROLOGICAL SATELLITE) - FORMER USSR (1993, 3-AXIS STAB.)
  - FY-2 (FENG YUN - 2) - PEOPLE'S REPUBLIC OF CHINA (VISSR, $\approx$ 106° E, GMS-COMPATIBLE)
  - SEA STAR, ORBITAL SCIENCES CORPORATION, SeaWiFS OCEAN COLOR SENSOR

# SATELLITE COMPARISON





**NIMBUS-7**
1,021 KG
1.6 M DIAMETER
3.6 M HIGH
303 KG PAYLOAD
(1978)

**ERBS**
2,225 KG
1.6 M DIAMETER
3.8 M HIGH
100 KG PAYLOAD
(1984)

**LANDSAT**
1,727 KG
2.2 M DIAMETER
5.6 M HIGH
318 KG PAYLOAD
(1984)

**ATN**
1,909 KG
1.9 M DIAMETER
4.2 M HIGH
361 KG PAYLOAD
(1990's)

**UARS**
6,736 KG
4.3 M DIAMETER
9.8 M HIGH
2,283 KG PAYLOAD
(1991)

**Eos-CONCEPT**
12,210 KG
4.3 M DIAMETER
12 M HIGH
3,500 KG PAYLOAD
(Old Concept)

**(Modified from Ref 11)**

# - SOME CURRENT PROGRAMS -

**(pp. F6 - F16 from Ref 3)**

## NOAA Advanced TIROS-N (ATN) Weather Satellites (E-J)
## 1983-94 Launches—U.S.A.

**Objectives of Mission:** Meteorological observations; measurements of sea surface temperature, sea ice, and snow cover; assessment of condition of vegetation

**Orbit Characteristics:** Polar, 833-870 km altitude, 7 a.m. and 2 p.m. equator crossing times

**Payload Characteristics:**

| Sensor | Applications | No. of Channels/ Frequencies | Spectral Range/ Frequency Range | Resolution | Swath Width |
|---|---|---|---|---|---|
| AVHRR/2 (Advanced Very High Resolution Radiometer) | Cloud Temp., Sea Surface Temp., Land Temp., Vegetation Index | 5 | 0.58–12.5 μm | 1.1 km at Nadir 4 km at Edge of Scan | 2,700 km |
| HIRS/2 (High Resolution Infrared Sounder) | Temp. and Moisture Profiles | 20 | 3.8–15.0 μm | 17.4 km | 2,240 km |
| SSU (Stratospheric Sounding Unit) | Atmospheric Sounding, Temp. Profiles | 3 | 14.7 μm (Centered) | 147 km | 736 km |
| MSU (Microwave Sounding Unit) | Atmospheric Sounding | 4 | 50.3–57.05 GHz | 109 km | 2,347 km |
| DCS (Argos) (Data Collection System) | Random Access from Buoys, Balloons, and Platforms | N/A | 136.77 MHz 137.77 MHz | N/A | N/A |
| SAR (Search and Rescue) | Search and Rescue Operations | N/A | 121.5 MHz 243.0 MHz 406.0 MHz | N/A | N/A |
| SBUV* (Solar Backscatter UV Experiment) | Solar Spectrum, Ozone Profiles, Earth Radiance Spectrum | 12 | 252.0–339.8 nm | 169.3 km | Nadir Viewing |
| ERBE (Earth Radiation Budget Experiment) | Determine Earth's Radiation Loss and Gain | 8 | 0.2–50.0 μm | 67.5 km | Horizon to Horizon |
| SEM (Space Environment Monitor) | Measurements of Solar Protons, Alpha Particles, "e" Flux Density | N/A | N/A | N/A | N/A |

Note: N/A means not applicable.
*P.M. satellite only

## Earth Radiation Budget Satellite (ERBS)
## Launched 1984—U.S.A.

**Objectives of Mission:** Provide observation of the Earth's radiation budget

**Orbit Characteristics:** 610 km, non-Sun-synchronous, circular orbit, inclined 56 degrees to the equator

**Payload Characteristics:**

| Sensor | Applications | No. of Channels/ Frequencies | Spectral Range/ Frequency Range | Resolution | Swath Width |
|---|---|---|---|---|---|
| ERBE Non-Scanner (Earth Radiation Budget Experiment) | Measurements Across the Shortwave Band, Total Radiation, Total Output of Radiant Heat and Light from the Sun | 1–4 | 0.2–3.5 μm<br>0.2–50.0 μm | 1,000 km along line of swath width | Limb to Limb—WFOV*<br>1,000 km—MFOV† |
| | | 5 | 0.2–50.0 μm | Full Solar Disc | N/A |
| ERBE Scanner | Reflected Solar Radiation, Earth Emitted Radiation | 3 | 0.2–50.0 μm | 40 km | 40 km Scans Limb to Limb |
| SAGE II (Stratospheric Aerosol and Gas Experiment) | Stratospheric Aerosols, $O_3$, $NO_2$, Water Vapor | 7 | 0.385–1.02 μm | 0.5 km | N/A |

Note: N/A means not applicable.
*WFOV is wide field of view.
†MFOV is medium field of view.

## Upper Atmosphere Research Satellite (UAR
## 1991 Launch—U.S.A.

**Objectives of Mission:** Coordinated measurement of major upper atmospheric parameters

**Orbit Characteristics:** 57 degree inclination, 600 km altitude

**Payload Characteristics:**

| Sensor | Applications | No. of Channels/ Frequencies | Spectral Range/ Frequency Range | Resolution | Coverage |
|---|---|---|---|---|---|
| CLAES (Cryogenic Limb Array Etalon Spectrometer) | Global Synoptic Measurement of Nitrogen and Chlorine Ozone Destructive Species, Minor Constituents Temperature | 8 Spectrally Scanned Channels | 3.5–12.7 μm | 2.8 km (Limb) 0.25 $cm^{-1}$ (Spectral) | 50.7 km (Vertical Limb Coverage) |
| HALOE (Halogen Occultation Experiment) | Stratospheric Gas Species Concentrations | 8 Fixed Channels | 2.4–10.3 μm | 2 km (Limb) (Gas filter-spectral) | 6–150 km (Vertical Limb Coverage) |
| HRDI (High Resolution Doppler Imager) | Middle Atmospheric Winds | 1 Spectrally Scanned Channel | 400–800 nm | 4 km (Limb) 0.001 nm (Spectral) | 5–100 km (Vertical Coverage) |
| ISAMS (Improved Stratospheric and Mesospheric Sounder) | Atmospheric Temp. and Species Concentration | 8 Spectrally Scanned Channels | 4.6–16.6 μm | 2.6 km (Limb) (Pressure Modulator-Spectral) | 65 km (Vertical Limb Coverage) |
| MLS (Microwave Limb Sounder) | Vertical Profiles of Ozone and Oxygen, Wind Measurements, Inferred Pressure | 3 Spectrally Scanned Channels | 63–206 GHz | 3 km (Limb) 50 mHz (Spectral) | 15–85 km (Vertical Limb Coverage) |
| PEM (Particle Environment Monitor) | Precipitating Charged Particle Entry Measurements for Atmosphere | 4 Measurements (Electrons, Protons, X-Rays, Magnetic Field) | 1 eV–5 MeV (Electrons) 1 eV–150 MeV (Protons) | N/A | In Situ |
| SOLSTICE (Solar/Stellar Irradiance Comparison Experiment) | Solar Spectral Irradiance | 3 Spectrally Scanned Channels | 115–430 nm | Solar—0.12 and 0.25 nm Stellar—0.5 and 0.10 nm | Solar/Stellar Pointing |
| SUSIM (Solar-UV Spectral Irradiance Monitor) | Solar Flux Changes | 7 Fixed and Spectrally Scanned Channels | 120–400 nm | 0.1 nm 1.0 nm 5.0 nm | Solar Pointing |
| WINDII (Wind Imaging Interferometer) | Doppler Shift of Energy, Upper Atmospheric Winds | 1 Spectrally Scanned Channel | 550–780 nm | 4 km (Limb) 1 nm (Spectral) | 70–310 km (Vertical Limb Coverage) |
| ACRIM II (Active Cavity Radiometer Irradiance Monitor) | Total Solar Irradiance | 3 Fixed Channels | 0.001–1,000 μm | Broadband | Solar Pointing |

## Landsat
## Launched 1972-85—U.S.A.

**Objectives of Mission:** Operational and commercial data, land use inventory, geological/mineralogical exploration, crop and forestry assessment, cartography

**Orbit Characteristics:** Sun-synchronous, 705 km altitude, 98.22 degree inclination, 9:30 a.m. equator crossing time, 16-day repeat cycle

**Payload Characteristics:**

| Sensor | Applications | No. of Channels/ Frequencies | Spectral Range/ Frequency Range | Resolution | Swath Width |
|---|---|---|---|---|---|
| MSS (Multi-Spectral Scanner) | Land Use, Urban Planning, Mapping, Agriculture, Forestry, Water Resources, Geology, Mineral Resources | 4 | 0.5–12.6 μm | 80 m | 185 km |
| RBV (Return Beam Vidicon) | Same as Above | 1 | 0.5–0.75 μm | 40 m | 185 km |
| TM (Thematic Mapper) | Same as Above | 7 | 0.45–12.5 μm | 30 m—Vis/IR<br>120 m—Thermal-IR | 185 km |

## Systeme Probatoire d'Observation de la Terre (SPOT)
## Launched 1986—France

**Objectives of Mission:** Operational land use and inventory monitoring system

**Orbit Characteristics:** Sun-synchronous, 832 km, 98.7 degree inclination, 10:30 a.m. equator crossing time, 26-day repeat cycle

**Payload Characteristics:**

| Sensor | Applications | No. of Channels/ Frequencies | Spectral Range/ Frequency Range | Resolution | Swath Width |
|---|---|---|---|---|---|
| HRV (High Resolution Visible Range Instruments) | Land Use, Urban Planning, Mapping, Agriculture, Forestry, Water Resources, Geology | 4 | 0.5–0.9 μm (Multispectral Mode) | 20 m | 60 km |
| | | | 0.5–0.73 μm nchromatic Mode) | 10 m | 60 km |

## ESA Earth Remote Sensing Satellite (ERS-1)
## 1991 Launch with Follow-ons—European Space Agency (ESA)

**Objectives of Mission:** Provide all-weather imagery of oceans, coastal water, ice fields, and land areas

**Orbit Characteristics:** Sun-synchronous, 777 km altitude, 10:30 a.m. equator crossing time, 3-day repeat cycle

**Payload Characteristics:**

| Sensor | Applications | No. of Channels/ Frequencies | Spectral Range/ Frequency Range | Resolution | Swath Width |
|---|---|---|---|---|---|
| AMI—SAR Mode (Active Microwave Instrument—Synthetic Aperture Radar) | Ice Topography, Geologic Structures, Wind Fields, Wave Spectra | 1 | 5.3 GHz | 30 m | 100 km |
| AMI—Wave Mode (Wave Spectrometer) | Wave Direction, Wave Length | 1 | 5.3 GHz | 25 m | 5 km × 5 km (Every 100 km) |
| AMI—Wind Mode (Active Microwave Instrument—Wind Scatterometer) | Surface Winds | 1 | 5.3 GHz | 50 km | 500 km |
| ATSR—M Radiometer (Along Track Scanning Radiometer) | Sea Surface Temperature, Atmospheric Water Vapor Content | 3 | 3.7–12.0 μm | 1 km | 500 km |
| ATSR—M Sounder (Along Track Scanning Radiometer with Microwave Sounder) | Atmospheric Profiles | 2 | 23.8 GHz<br>36.5 GHz | 22 km | 500 km |
| PRARE (Precise Range and Range Rate Equipment) | Precise Orbit Determination | 3 | 2.25 GHz<br>7.2 GHz<br>8.4 GHz | N/A | N/A |
| ALT (Radar Altimeter) | Sea Surface Topography | 1 | 13.5 GHz | 0.5 m (Wave Height) | Nadir Viewing |

Note: N/A means not applicable.

## Indian Remote Sensing Satellite (IRS)
## 1987 Launch with Follow-ons—India

**Objectives of Mission:** Provide agricultural, geological, and hydrological data for survey and management of natural resources

**Orbit Characteristics:** Sun-synchronous, 904 km altitude, 22-day repeat cycle

**Payload Characteristics:**

| Sensor | Applications | No. of Channels/ Frequencies | Spectral Range/ Frequency Range | Resolution | Swath Width |
|---|---|---|---|---|---|
| LISS-I (Linear Imaging Self-Scanner Sensor) | Land Use, Urban Planning, Mapping, Agriculture, Forestry, Water Resources, Geology, Mineral Resources | 4 | 0.45–0.86 μm | 73 m | 148 km |
| LISS-II | Same as Above | 4 | 0.45–0.86 μm | 36 m | 148 km |

## Marine Observation Satellite (MOS)
## Launched 1987 with Follow-ons—Japan*

**Objectives of Mission:** Observation of the state of sea surface and atmosphere

**Orbit Characteristics:** Sun-synchronous, 909 km altitude, between 10 a.m. and 11 a.m. equator crossing times, 99.1 degree inclination, 17-day repeat cycle

**Payload Characteristics:**

| Sensor | Applications | No. of Channels/ Frequencies | Spectral Range/ Frequency Range | Resolution | Swath Width |
|---|---|---|---|---|---|
| MESSR (Multispectral Electronic Self-Scanning Radiometer) | Sea Surface Color | 4 | 0.5–1.1 μm | 50 m | 100 km |
| VTIR (Visible and Thermal Infrared Radiometer) | Sea Surface Temperature | 4 | 0.5–0.7 μm<br>6.0–7.0 μm<br>10.5–12.5 μm | 0.9 km—Vis<br>2.7 km—IR | 1,500 km |
| MSR (Microwave Scanning Radiometer) | Water Content of Atmosphere | 2 | 23.8 GHz<br>31.4 GHz | 32 km<br>23 km | 317 km |

*MOS-1 Launched February 1987.

## Geostationary Operational Environmental Satellite (GOES)
## 1985-87 Launches—U.S.A.

**Objectives of Mission:** Operational weather data, cloud cover, temperature profiles, real-time storm monitoring, severe storm warning, sea surface temperature

**Orbit Characteristics:** Geostationary at east and west longitudes

**Payload Characteristics:**

| Sensor | Applications | No. of Channels/ Frequencies | Spectral Range/ Frequency Range | Resolution | Swath Width |
|---|---|---|---|---|---|
| VAS (Visible and Infrared Spin Scan Radiometer [VISSR] Atmospheric Sounder) | Imaging—Day/Night Cloud Cover | 5 | 0.55–0.7 μm<br>3.90–14.7 μm | 1 km—Vis<br>8 km—IR | Limb to Limb |
| | Sounding—Temp. and Water Content | 12 | 3.90–14.7 μm | 7–14 km | Limb to Limb |
| DCS (Data Collection System) | Random Access from Buoys, Balloons, and Platforms | N/A | 136.77 MHz<br>137.77 MHz | N/A | N/A |
| SEM (Space Environment Monitor) | Measurements of Solar Protons, Alpha Particles, "e" Flux Density | N/A | N/A | N/A | N/A |
| SAR (Search and Rescue) | Search and Rescue Operations | N/A | 406.0 MHz | N/A | N/A |

Note: N/A means not applicable.

# - SOME FUTURE PROGRAMS -

Table 1B. **NOAA Advanced TIROS-N (ATN) Weather Satellites (K-L-M) 1996-99 Launches—U.S.A.**

**Objectives of Mission:** Meteorological observations; measurements of sea surface temperature, sea ice, and snow cover; assessment of condition of vegetation

**Orbit Characteristics:** Polar, 833-870 km altitude, 7 a.m. and 2 p.m. equator crossing times

**Payload Characteristics:**

| Sensor | Applications | No. of Channels/ Frequencies | Spectral Range/ Frequency Range | Resolution | Swath Width |
|---|---|---|---|---|---|
| AVHRR/3* (Advanced Very High Resolution Radiometer) | Cloud Temp., Sea Surface Temp., Land Temp., Vegetation Index | 6 | 0.58–12.5 μm | 1.1 km at Nadir 4 km at Edge of Scan | Limb to Limb |
| HIRS/3 (High Resolution Infrared Sounder) | Temp. and Moisture Profiles, Radiation Budget | 20 | 0.2–15.0 μm | 17.4 km | 2,240 km |
| DCS (Argos) (Data Collection System) | Random Access from Buoys, Balloons, and Platforms | N/A | 136.77 MHz 137.77 MHz | N/A | N/A |
| SAR (Search and Rescue) | Search and Rescue Operations | N/A | 121.5 MHz 243.0 MHz 406.0 MHz | N/A | N/A |
| SBUV† (Solar Backscatter UV Experiment) | Solar Spectrum, Ozone Profiles, Earth Radiance Spectrum | 12 | 252.0–339.8 nm | 169.3 km | Nadir Viewing |
| SEM (Space Environment Monitor) | Measurements of Solar Protons, Alpha Particles, "e" Flux Density | N/A | N/A | N/A | N/A |
| AMSU-A (Advanced Microwave Sounding Unit-A) | All-weather Temp. Profiles | 15 | 23.0–90.0 GHz | 40 km | 2,240 km |
| AMSU-B (Advanced Microwave Sounding Unit-B) | All-weather Atmospheric Profiles (Water Vapor, Precipitation, and Ice) | 5 | 90.0–183.0 GHz | 15 km | 2,240 km |

Note: N/A means not applicable.
*Channels 3a and 3b are time shared during day and night.
†P.M. satellite only

Table 3B. **Landsat 6**
**Earth Observation Satellite Company (EOSAT)**
**1993 Launch —U.S.A.**

**Objectives of Mission:** Operational and commercial data, land use inventory, geological/mineralogical exploration, crop and forestry assessment, cartography

**Orbit Characteristics:** Sun-synchronous, 705 km altitude, 98.21 degree inclination, 9:45 a.m. equator crossing time, 16-day repeat cycle

**Payload Characteristics:**

| Sensor | Applications | No. of Channels/ Frequencies | Spectral Range/ Frequency Range | Resolution | Swath Width |
|---|---|---|---|---|---|
| ETM (Enhanced Thematic Mapper) | Land Use, Urban Planning, Mapping, Agriculture, Forestry, Water Resources, Geology | 8 | 0.45–12.5 μm | 15 m—Panchromatic<br>30 m—Vis/Near-IR<br>30 m—Shortwave-IR<br>120 m—Thermal-IR | 185 km |

## Geostationary Operational Environmental Satellite (GOES) 1994-2002 Launches—U.S.A.

**Objectives of Mission:** Operational weather data, cloud cover, temperature profiles, real-time storm monitoring, severe storm warning, sea surface temperature

**Orbit Characteristics:** Geostationary at east and west longitudes

**Payload Characteristics:**

| Sensor | Applications | No. of Channels/ Frequencies | Spectral Range/ Frequency Range | Resolution | Swath Width |
|---|---|---|---|---|---|
| Imager | Imaging | 5 | 0.55–12.5 μm | 1 km—Vis<br>4 or 8 km—IR | Selectable Areas |
| Sounder | Atmospheric Sounding Temp. and Moisture Profiles | 19 | 3.7–14.7 μm | 4–8 km | Selectable Areas |
| DCS (Data Collection System) | Random Access from Buoys, Balloons, and Platforms | N/A | 136.77 MHz<br>137.77 MHz | N/A | N/A |
| SEM (Space Environment Monitor) | Measurements of Solar Protons, Alpha Particles, "e" Flux Density | N/A | N/A | N/A | N/A |
| SAR (Search and Rescue) | Search and Rescue Operations | N/A | 406.0 MHz | N/A | N/A |

Note: N/A means not applicable.

**Recommended EOS Instruments**

| | Source | Instrument | Team Leader |
|---|---|---|---|
| ACRIM | U.S. | Active Cavity Radiometer Irradiance Monitor (no orbital requirement other than solar viewing) | R. Willson |
| AIRS | U.S. | Advanced Infrared Sounder (AIRS, AMSU-A, & MHS are a synergistic package that should fly on same platform) | M. T. Chahine |
| AMSU-A | U.S. | Advanced Microwave Sounding Unit-A | H. Tsu |
| ASTER | Japan | Advanced Spaceborne Thermal Emission and Reflection Radiometer | H. Tsu |
| CERES | U.S. | Cloud and Earth's Radiant Energy System (on multiple satellites in morning, afternoon, and inclined orbit) | B. R. Barkstrom |
| EOSP | U.S. | Earth Observing Scanning Polarimeter (subject to review by EOS Atmospheres Panel) | L. D. Travis |
| HIRDLS | U.S./U.K. | High-Resolution Dynamics Limb Sounder | J. Barnett & J. Gille |
| LIS | U.S. | Lightning Imaging Sensor (on TRMM) | H. J. Christian |
| MHS | Eumetsat | Microwave Humidity Sounder | |
| MIMR | ESA | Multifrequency Imaging Microwave Radiometer | TBD |
| MISR | U.S. | Multi-Angle Imaging Spectro-Radiometer | D. J. Diner |
| MODIS-N | U.S. | Moderate-Resolution Imaging Spectrometer - Nadir (in both morning and afternoon orbit) | V. V. Salomonson |
| MOPITT | Canada | Measurements of Pollution in the Troposphere | J. R. Drummond |
| NSCAT-2 | U.S. | Scatterometer (needed for continuity of NSCAT-1 data on ADEOS, which start in 1995) | M. H. Freilich |
| SAGE | U.S. | Stratospheric Aerosol and Gas Experiment (in both sun-synchronous and inclined orbit) | M. P. McCormick |
| SeaWiFS | U.S. | (Continuation of 1993 mission until launch of second MODIS-N) | |
| SOLSTICE | U.S. | Solar Stellar Irradiance Comparison Experiment (no orbital requirement other than solar viewing) | G. J. Rottman |
| TOPEX/ Poseidon-2 | France/U.S. | (Continuation of 1992 mission needed to avoid data gap) | |
| MLS | U.S. | Microwave Limb Sounder | J. W. Waters |
| TES | U.S. | Tropospheric Emission Sp[illegible]eter | R. Beer |

Ref 20

# REVISED EOS SENSOR COMPLEMENT



## EOS Era Remote-Sensing Satellites

| Satellites (Launch Status) | Mission Objectives |
|---|---|
| **EOS-AM Series** (1998)<br>Earth Observing System<br>Morning Crossing | Clouds, aerosols and radiation balance, characterization of the terrestrial ecosystem; land use, soils, terrestrial energy/moisture, tropospheric chemical composition; contribution of volcanoes to climate, and ocean primary productivity (includes Canadian and Japanese instruments) |
| **EOS-COLOR** (1998)<br>EOS Ocean Color Mission | Ocean primary productivity |
| **POEM-ENVISAT Series** (ESA—1998)<br>Polar-Orbit Earth Observation Mission<br>Environmental Satellite | Environmental studies in atmospheric chemistry and marine biology, and continuation of ERS mission objectives |
| **ADEOS IIa and IIb** (Japan—1999)<br>Advanced Earth Observing Satellite IIa and IIb | Visible and near-infrared microwave radiance/ reflectance, scatterometry, infrared and laser atmospheric sounding, tropospheric and stratospheric chemistry, and altimetry (may include French and U.S. instruments) |
| **EOS-PM Series** (2000)<br>Earth Observing System<br>Afternoon Crossing | Cloud formation, precipitation, and radiative properties; air-sea fluxes of energy and moisture; and sea-ice extent (includes European instruments) |
| **EOS-AERO Series** (2000)<br>EOS Aerosol Mission | Distribution of aerosols and greenhouse gases in the lower stratosphere (spacecraft to be provided through international cooperation) |
| **POEM-METOP Series** (ESA—2000)<br>Polar-Orbit Earth Observation Mission<br>Meteorological Operational Satellite | Operational meteorology and climate monitoring, with the future objective of operational climatology (joint with EUMETSAT and NOAA) |
| **TRMM-2** (Japan and NASA—Proposed for 2000)<br>Tropical Rainfall Measuring Mission | Precipitation and related variables and Earth radiation budget in tropics and higher latitudes |
| **EOS-ALT Series** (2002)<br>EOS Altimetry Mission | Ocean circulation and ice sheet mass balance (may include French instruments) |
| **EOS-CHEM Series** (2002)<br>EOS Chemistry Mission | Atmospheric chemical composition; chemistry-climate interactions; air-sea exchange of chemicals and energy (to include an as yet to be determined Japanese instrument) |

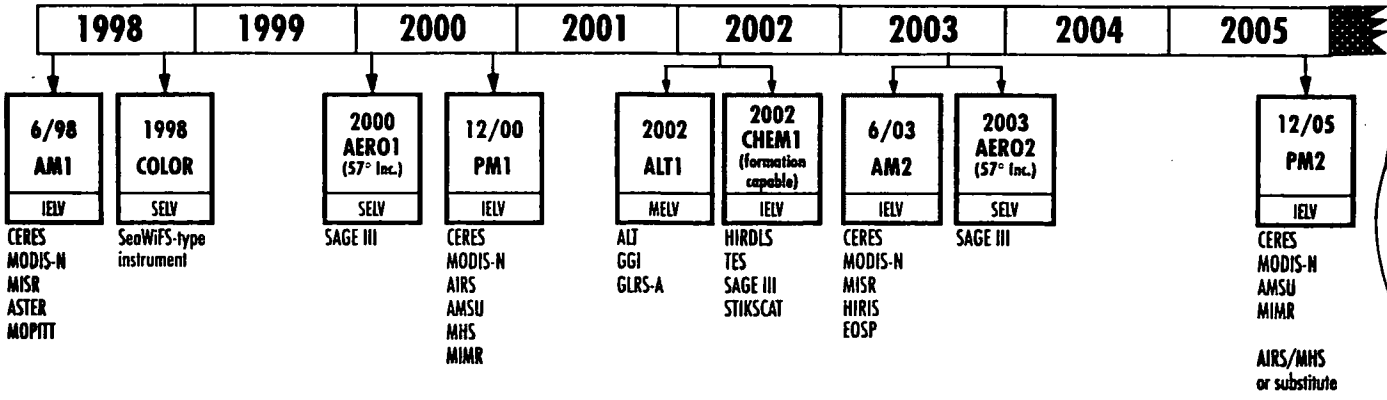
## Rescoped EOS Program

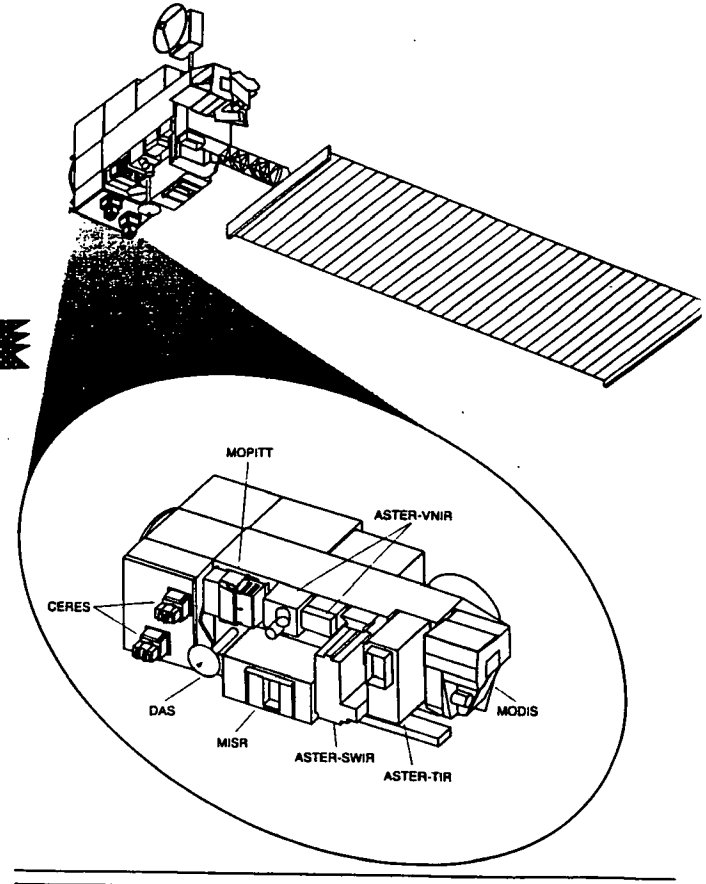
| Launch | Spacecraft | Lifetime | Instrument Complement | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1998 | AM1 | 5 | MODIS | MISR | CERES (2) | MOPITT | ASTER | |
| 2003 | AM2 | 5 | MODIS | MISR | CERES | EOSP | TES | MOPITT* |
| 2008 | AM3 | 5 | MODIS | MISR | CERES | EOSP | TES | |
| 1998 | COLOR | 3 | SeaWiFS-Type | | | | | |
| 2000 | AERO1 | 3 | SAGE III | | | | | |
| 2003 | AERO2 | 3 | SAGE III | | | | | |
| 2006 | AERO3 | 3 | SAGE III | | | | | |
| 2009 | AERO4 | 3 | SAGE III | | | | | |
| 2012 | AERO5 | 3 | SAGE III | | | | | |
| 2000 | PM1 | 5 | MODIS | AMSU | MIMR | AIRS | MHS | CERES (2) |
| 2005 | PM2 | 5 | MODIS | AMSU | MIMR | AIRS | MHS | CERES |
| 2010 | PM3 | 5 | MODIS | AMSU | MIMR | AIRS | MHS | CERES |
| 2002 | ALT1 | 5 | GLAS | TMR | SSALT | DORIS | | |
| 2007 | ALT2 | 5 | GLAS | TMR | SSALT | DORIS | | |
| 2012 | ALT3 | 5 | GLAS | TMR | SSALT | DORIS | | |
| 2002 | CHEM1 | 5 | HIRDLS | SOLSTICE II | ACRIM | MLS | SAGE III | TBD(J) |
| 2007 | CHEM2 | 5 | HIRDLS | SOLSTICE II | ACRIM | MLS | SAGE III | TBD(J) |
| 2012 | CHEM3 | 5 | HIRDLS | SOLSTICE II | ACRIM | MLS | SAGE III | TBD(J) |

(Ref 72)

# REVISED EOS SENSOR COMPLEMENT (CONT'D)





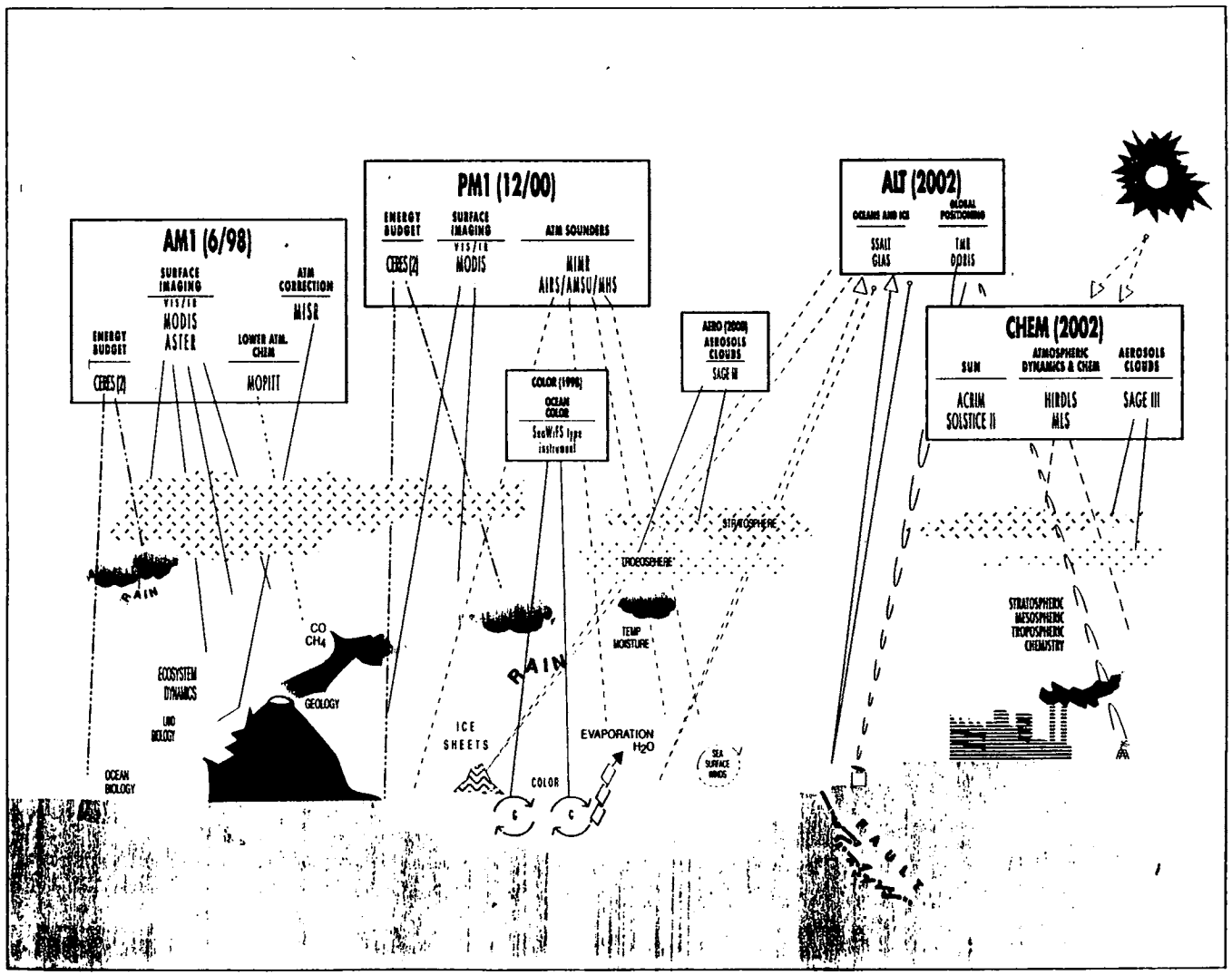

**The EOS-AM1 Satellite and Payload**

(Ref 72)

# REVISED EOS SENSOR COMPLEMENT (CONT'D)



**EOS Program Flight Elements (Post-Rescoping)**




(Ref 72)

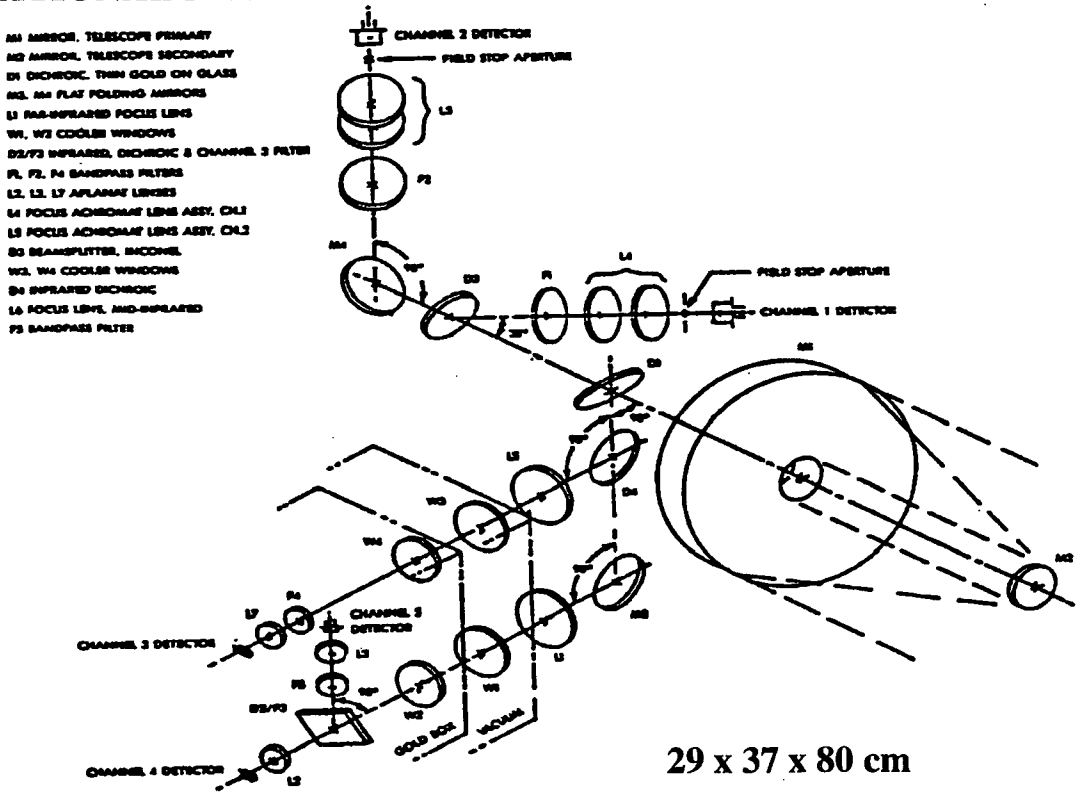
# PART 7

# SPACEBORNE PASSIVE E-O SENSORS & TRENDS

# MULTISPECTRAL IMAGING RADIOMETER - AVHRR



- ADVANCED VERY HIGH RESOLUTION RADIOMETER (REF 42) 29 X 37 X 80 cm
  - EXAMPLE OF CURRENT/FUTURE OPERATIONAL ENVIRONMENTAL SENSOR
  - AVHRR/2 ON NOAA/TIROS
  - VIS, NIR, MWIR, SPLIT LWIR BANDS
  - ≈ 1 km RESOLUTION AT NADIR
- AVHRR/3 ON NOAA K,L,M,N
  - ADD SWIR BAND, IMPROVE SNR
- APPLICATIONS
  - CLOUD COVER, TYPE, HEIGHT, ...
  - SURFACE TEMPERATURE
  - VEGETATION INDEX
  - ALBEDO
- TREND
  - ADDED BANDS, BETTER ACCURACY/SENSITIVITY




29 x 37 x 80 cm

arm transmittance ≈ 30 - 60%

AVHRR/2 OPTICAL CONFIGURATION

(Reprinted by permission of the author from Ref 42 )

# MULTISPECTRAL IMAGING RADIOMETER - MISR



- MULTIANGLE IMAGING SPECTRO-RADIOMETER (REF 43)
  - NEW TYPE OF ENVIRONMENTAL SENSOR FOR EOS
  - PI D. DINER (JPL)
  - 9 CCD PUSHBROOM SENSORS VIEW SCENE @ 9 ANGLES
    - NADIR, ± 25.8°, ± 45°, ± 60°, ± 72.5°
    - FOUR VNIR BANDS
    - CONTINUOUS GLOBAL COVERAGE @ 2 KM RES
- APPLICATIONS
  - BIDIRECTIONAL REFLECTANCE (BRDF) OF LAND
  - AEROSOL PROPERTIES
  - ATMOSPHERIC CORRECTION OF LAND SURFACE IMAGERY
  - CLOUD BRDF
- TREND
  - IMPROVED ATMOSPHERIC CORRECTION & REFLECTANCE CHARACTERIZATION

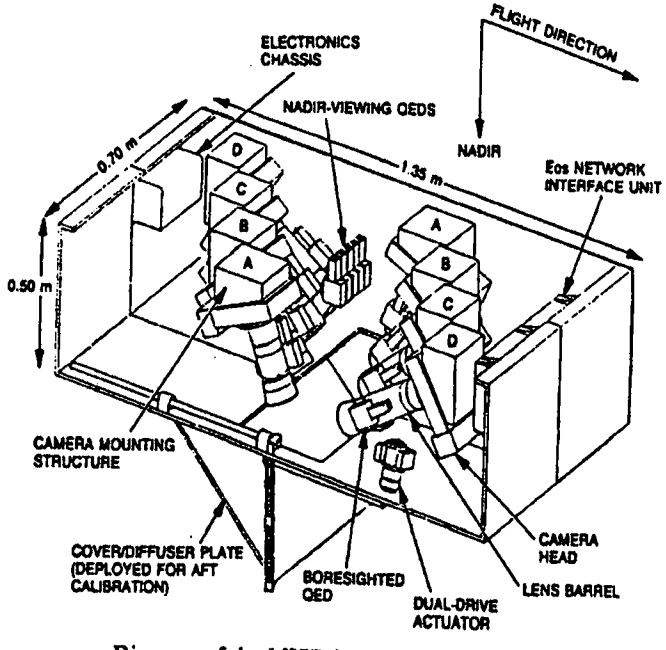



Diagram of the MISR instrument conceptual design.

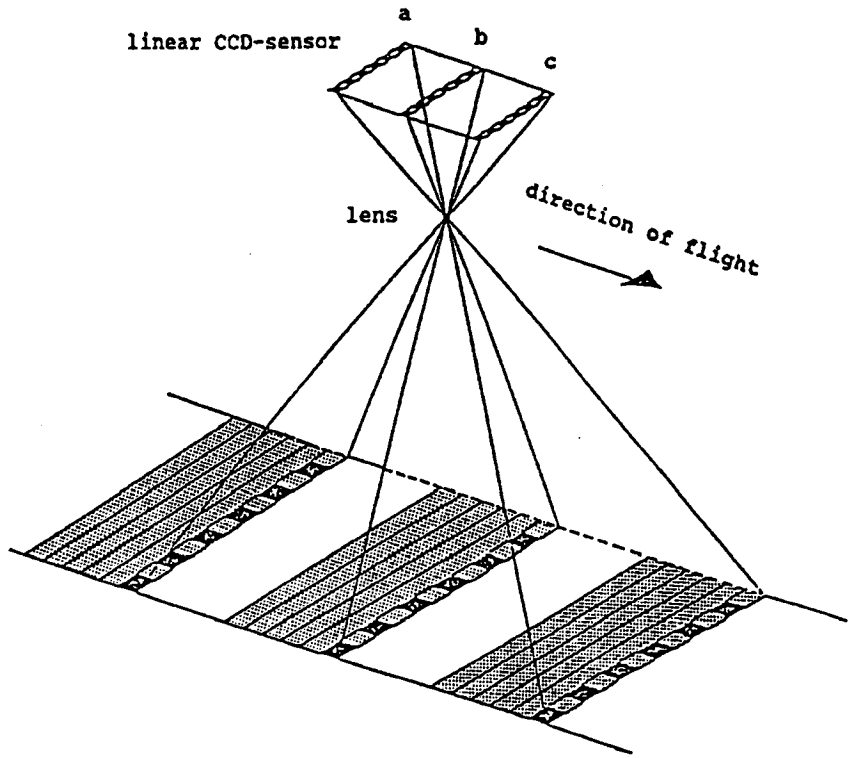
(Reprinted with permission of the publisher from Ref 43, © 1989 IEEE)

QEDs = self calibrating photo-diodes

# STEREO VISIBLE IMAGER - MEOSS



- MONOCULAR ELECTRO-OPTICAL STEREO SCANNER (REF 44) DLR (GERMANY)
  - WAS TO HAVE BEEN FIRST 3-LOOK ALONG-TRACK SPACE SENSOR
    - LAUNCH FAILURE INDIA'S SROSS 1988
  - FORE/NADIR/AFT LOOKS FOR RIGOROUS RECONSTRUCTION
  - 27° $\angle \approx$ OPTIMUM
  - ALSO DLR MOMS (MODULAR OPTOELECTRONIC MULTISPECTRAL SCANNER) FOR SHUTTLE
    - 13.5 m RES, 78 km SWATH, OTHER MODES
- APPLICATIONS
  - CARTOGRAPHY
  - TOPOGRAPHY (3-D PHOTOGRAMMETRY)
- TREND
  - IMPROVED MAPPING CAPABILITY
  - USE OF GPS FOR NAVIGATION




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# NADIR SOUNDER - HIRS



- HIGH-RESOLUTION INFRARED RADIATION SOUNDER
  - EXAMPLE OF CURRENT/FUTURE OPERATIONAL ENVIRONMENTAL SENSOR
  - HIRS/2 ON NOAA/TIROS
    - PART OF TOVS (TIROS OPERATIONAL VERTICAL SOUNDER)
    - 20 km RESOLUTION @ NADIR, 2250 km SWATH
  - 20-CHANNEL FILTER WHEEL RADIOMETER
    - 4.3, 15 μm $CO_2$ TEMP SOUNDING
    - 6.7 μm $H_2O$ WATER VAPOR SOUNDING
- HIRS/3 ON NOAA K,L,M,N
  - IMPROVED SENSITIVITY & COOLING
- TREND
  - AWAY FROM FILTER WHEELS
  - TOWARD GRATINGS (EOS AIRS) & INTERFEROMETERS (AIRBORNE HIS)
  - HIGHER SPECTRAL RESOLUTION FOR HIGHER VERTICAL RESOLUTION

**Spectral Channels, Detectors, and Purpose**

| Detector | Channel | Wavelength (μ m) | Sensitivity (NEΔ N)* | Purpose |
|---|---|---|---|---|
| | 1 | 14.95 | 3.00 | |
| | 2 | 14.71 | .67 | |
| | 3 | 14.49 | .50 | |
| | 4 | 14.22 | .31 | Temp |
| | 5 | 13.97 | .21 | Sounding |
| | 6 | 13.64 | .24 | |
| (HgCdTe) | 7 | 13.35 | .20 | |
| (Longwave) | 8 | 11.11 | .10 | Surface Temp |
| | 9 | 9.71 | .15 | |
| | 10 | 12.55 | .20 | Water Vapor |
| | 11 | 7.33 | .20 | Sounding |
| | 12 | 6.72 | .19 | |
| | 13 | 4.57 | .006 | |
| | 14 | 4.52 | .003 | Temp |
| | 15 | 4.46 | .004 | Sounding |
| InSb | 16 | 4.40 | .002 | |
| (Shortwave) | 17 | 4.13 | .002 | |
| | 18 | 4.00 | .002 | |
| | 19 | 3.76 | .001 | Surface Temp |
| Silicon (Visible) | 20 | 0.69 | .1%A | Cloud Detection |

*MW—M$^{-2}$—SR$^{-1}$—CM

(Ref 50)

*NEΔN=NEΔρ

# METHODS OF SPECTRAL DISCRIMINATION



*DISPERSERS* (Ref 8)

- PRISMS (refraction through "glass")
- GRATINGS (diffraction via parallel ruled grooves - reflective or transmissive)

*INTERFERENCE FILTERS (optical resonant cavities which selectively transmit)* (Ref 8)

- DICHROIC BEAMSPLITTERS (stack of variable refractive index dielectric layers; reflects/transmits below/above given $\lambda$)
- BANDPASS FILTERS (thin dielectric films deposited between two parallel silvered substrates)
- LINEAR & CIRCULAR VARIABLE FILTERS (bandpass varies along filter with wedge-shaped cross section)
- FABRY-PEROT ETALONS (two parallel flat silvered plates with air space; tunable; uses multiple reflections)
- MICHELSON INTERFEROMETERS (beam is split & recombined, interference gives Fourier xform of spectrum)

*GAS CORRELATION SPECTRORADIOMETER*

*ACOUSTO-OPTIC INTERACTION* (Refs 63, 64)

- ACOUSTO-OPTIC TUNABLE FILTERS (AOTFs) (electrically tunable bandpass filter: radio frequency signal applied to piezo-electric transducers generates sound waves in crystal through which beam passes; waves create optical diffraction grating by locally perturbing refractive index of material)

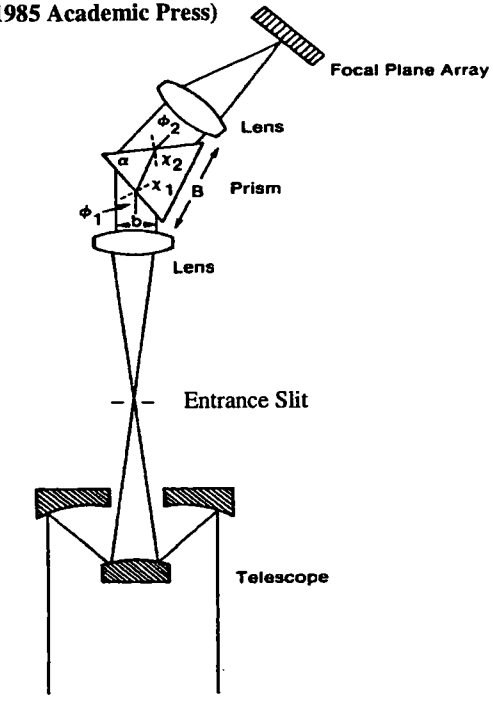
*IR LASER HETERODYNE SPECTROSCOPY*

# SOME TYPES OF SPECTROMETERS

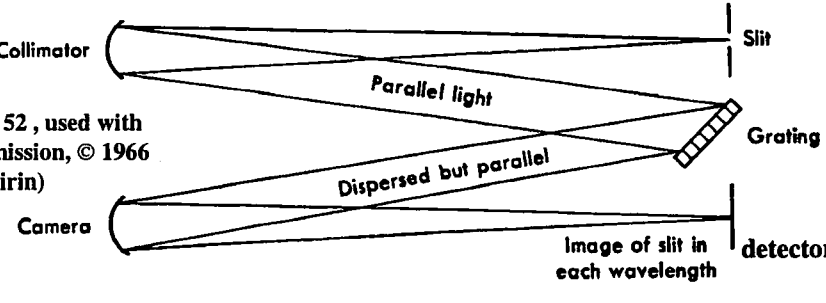


- DICHROIC BEAMSPLITTERS & FIXED-BANDPASS FILTERS
  - VARIATION ON MULTISPECTRAL IMAGING RADIOMETER
- FILTER WHEEL
  - DETECTOR SEQUENTIALLY SEES DIFFERENT BANDPASSES
- PRISM
  - REFRACTION PROVIDES DISPERSED SPECTRUM
  - NEEDS BULKY COLLIMATING & REIMAGING OPTICS
  - LOW SPECTRAL RESOLUTION BUT NO OVERLAPPING ORDERS
- GRATING
  - DIFFRACTION PROVIDES DISPERSED SPECTRUM
  - NEEDS COLLIMATING & REIMAGING OPTICS
  - HIGHER SPECTRAL RESOLUTION (SINCE MORE THRUPUT (BUT HAS OVERLAPPING ORDERS)
- ENTRANCE SLIT DEFINES SPATIAL EXTENT OF SPECTRAL DATA FOR PRISM & GRATING SENSORS

(Modified from Ref 4, used with permission of the publisher, original © 1985 Academic Press)



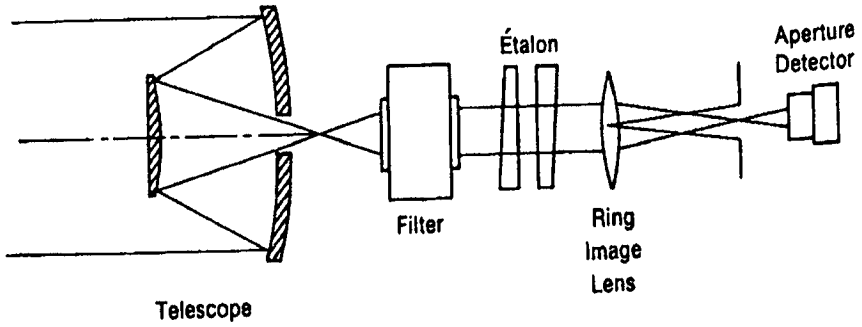

(Ref 52 , used with permission, © 1966 H. Zirin)



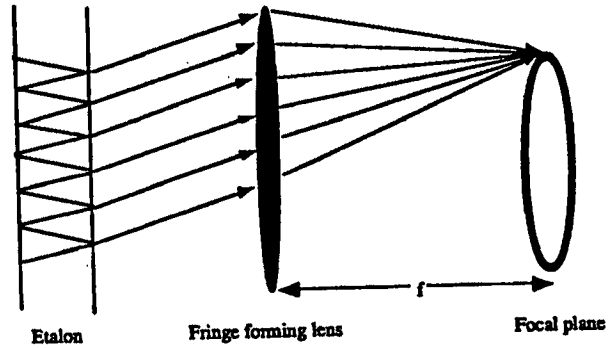
# TYPES OF SPECTROMETERS: FABRY-PEROT

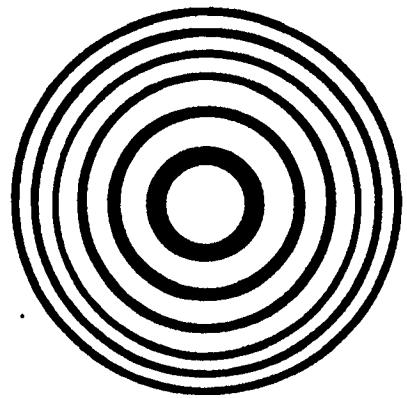


- **FABRY-PEROT ETALON**
  - **2 PARALLEL OPTICAL DISKS ⇒ SPECTRAL SYSTEM OF RINGS VIA INTERFERENCE**
  - **TUNED VIA PRESSURE CHANGE OR TILTING** $n\lambda = 2d\cos\theta$
  - **NO ENTRANCE SLIT, SO THROUGHPUT >> PRISM OR GRATING (≈100 X GRATING)**




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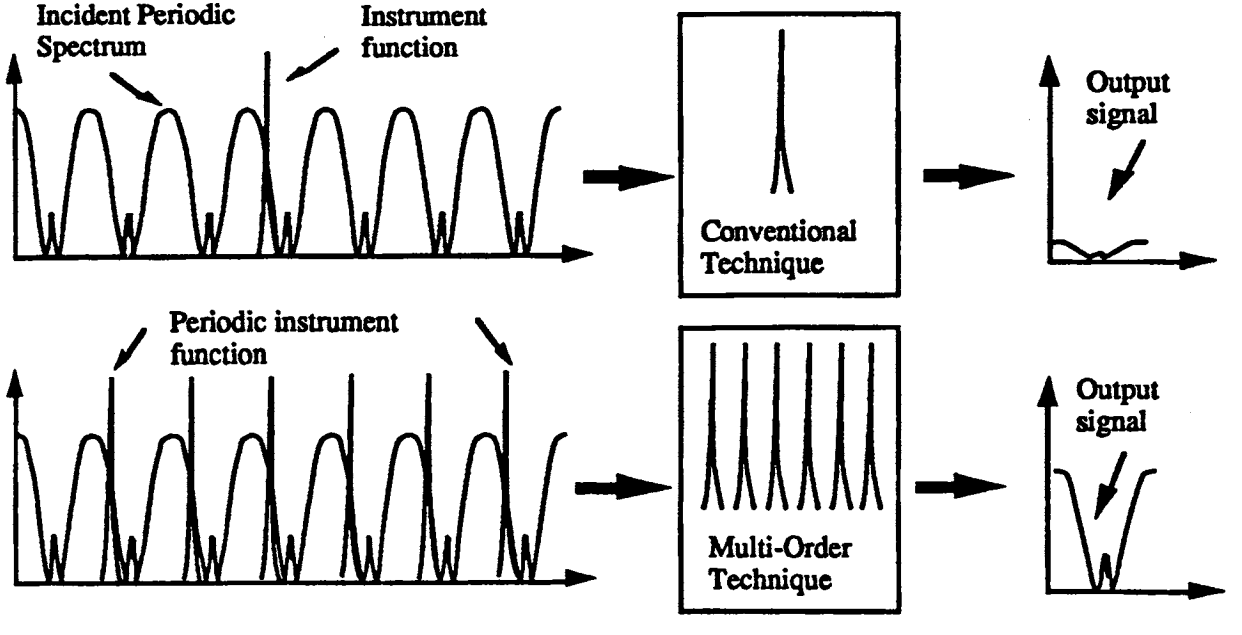
FPI Ring Pattern at Focal Plane

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# FABRY-PEROT MULTIPLEXING ADVANTAGE



- SPECTRALLY PERIODIC TRANSMISSION FUNCTION
  - CAN BE MATCHED TO UNIFORM SPACING OF $CO_2$ LINES WITHIN BAND
    - RESULTS IN HIGH SPECTRAL RESOLUTION AND GOOD SNR




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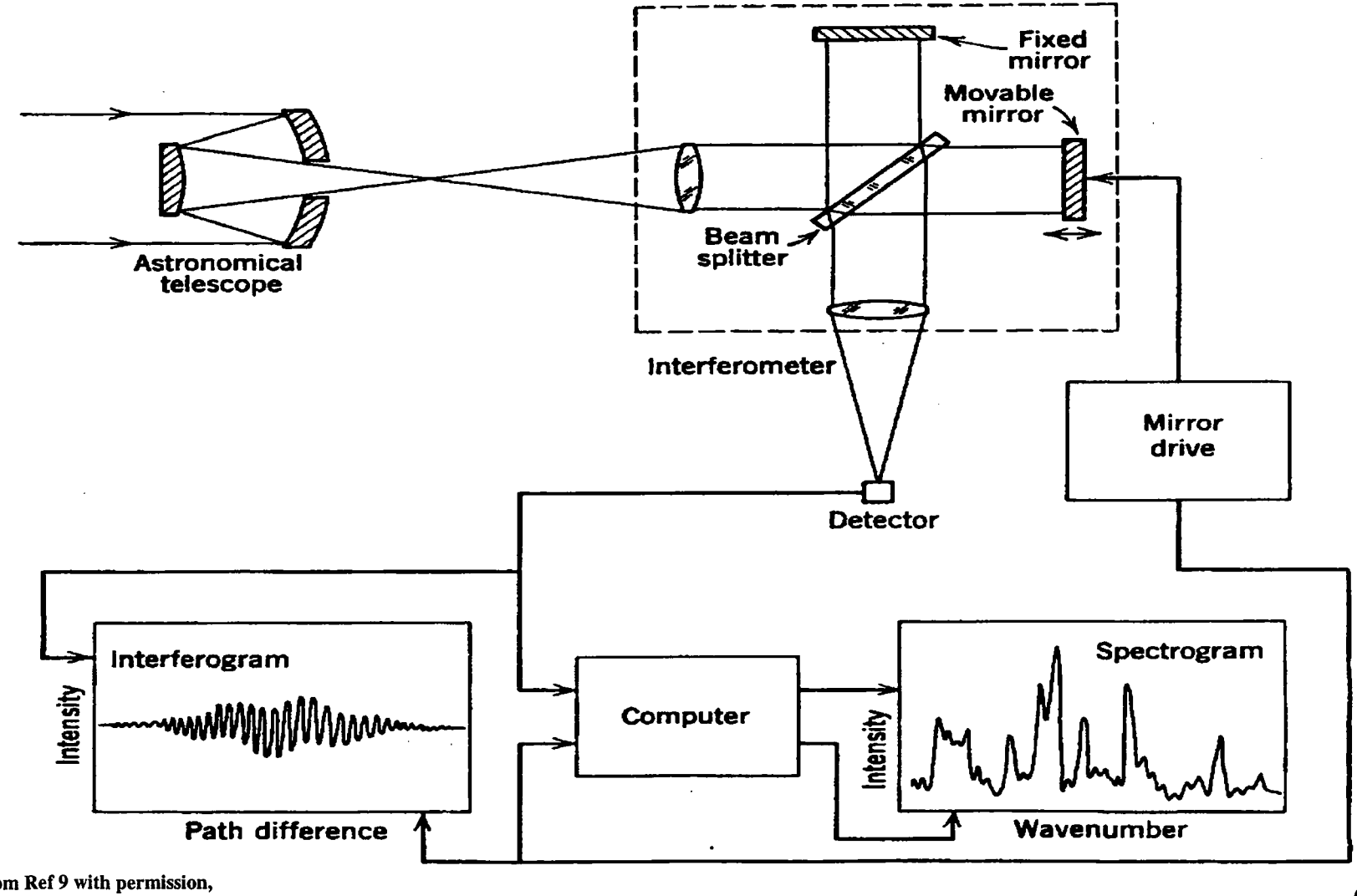
# TYPES OF SPECTROMETERS: FOURIER TRANSFORM



- FOURIER TRANSFORM SPECTROMETER (FTS) - REF 8
  - SOMETIMES BASED ON MICHELSON INTERFEROMETER
    - FLOWN ON NIMBUS 3 & 4 (1969/70) - IR INTERFEROMETER SPECTROMETER (IRIS)
    - BEAM IS SPLIT, TRAVELS OVER TWO PATHS OF DIFFERENT LENGTH, RECOMBINED
    - INTERFERENCE OF BEAMS GIVES THE FOURIER TRANSFORM OF THE SPECTRUM
    - ONE MIRROR MOVES TO SCAN THE INTERFEROGRAM OVER THE DETECTOR
      - TYPICAL SCAN SPEED ~0.5 cm/sec
  - SIMULTANEOUS DETECTION OF THE ENTIRE SPECTRUM
    - HIGH SIGNAL-TO-NOISE FROM ITS BIG "MULTIPLEXING" ADVANTAGE
    - NARROW SPECTRAL FEATURES ARE MEASURED AS EASILY AS BROAD ONES
  - HIGH SPECTRAL RESOLUTION OVER WIDE SPECTRAL RANGE
  - COMPLEX & DELICATE INSTRUMENT
  - DESIGNS WITH NO MOVING PARTS EXIST - REF 73
    - "HOLOGRAPHIC" SPECTROMETER W. LINEAR DETECTOR ARRAY

# FTS






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# IR HETERODYNE SPECTROMETER

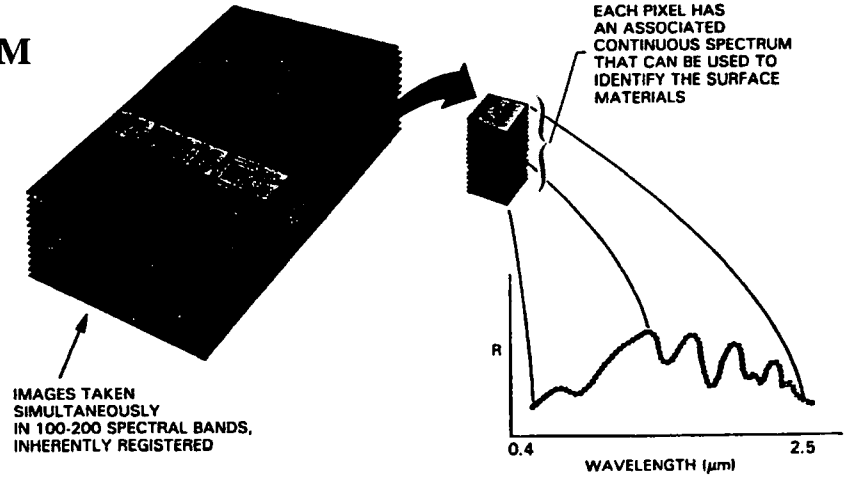


- ULTRA-HIGH SPECTRAL RESOLUTION TECHNIQUE (REF 75)
  - CAN MEASURE INDIVIDUAL LINE SHAPES
- HETERODYNE DETECTION
  - INCOMING RADIANCE MIXED WITH THAT FROM A LASER
    - STABLE COHERENT LOCAL OSCILLATOR
  - MIXING FREQUENCY CLOSE TO THAT OF INCOMING RADIANCE
    - MIXING GENERATES A BEAT FREQUENCY (INTERMEDIATE FREQ OR "IF") IN THE RF RANGE
  - RF SIGNAL DETECTED WITH NORMAL RADIO TECHNIQUES
- TUNABLE IN FREQUENCY WITH TUNABLE LASER
- NEVER USED FOR SPACE-BASED APPLICATIONS (USUALLY OVERKILL)

# TYPES OF SPECTROMETERS: IMAGING SPECTROMETER



- COMBINES MULTISPECTRAL RADIOMETRY WITH SPECTROSCOPY
- SIMULTANEOUS IMAGES IN HUNDREDS OF NARROW CONTIGUOUS SPECTRAL BANDS
  - ADD DISPERSING ELEMENT & OPTICS TO WHISKBROOM OR PUSHBROOM CONCEPT
    - GRATING, PRISM, AOTF, WEDGE FILTER, ...
  - INTEGRATION TIME FOR SNR CAN BE A PROBLEM
    - WHISKBROOM SUITED TO AIRBORNE USE
    - SPACEBORNE MUST BE PUSHBROOM
  - SPECTRAL RES ≈ 10-20 nm (0.01 - 0.02 μm)
  - SPECTRAL RANGE ≈ 0.4 - 2.5 μm
  - AVIRIS 20 m RES, 10.5 km SWATH
- EARTH RESOURCES APPLICATIONS
  - MINERALS, SOILS, VEGETATION, LAKES, SNOW, ...
- ENVIRONMENTAL APPLICATIONS
  - WATER VAPOR, $O_3$ , CLOUDS, AEROSOLS, OCEAN COLOR, ...




Schematic definition of imaging spectrometry

(Ref 67)

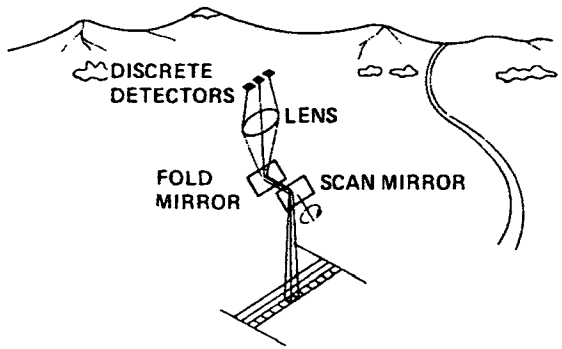
# IMAGING CONCEPTS



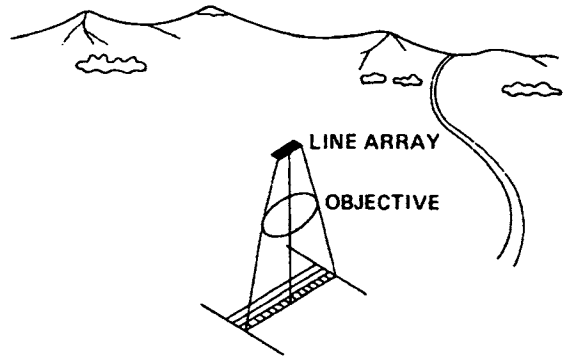
AREA ARRAY (D) :

- IMAGE IS SPATIAL IN ONE DIRECTION, SPECTRAL IN OTHER
- HIGH COOLING LOAD
- CALIBRATION: RADIOMETRIC *AND* SPECTRAL
  - NE$\Delta\rho \leq 1\%$ @ 20° sun angle
- DATA COMPACTION
  - SPATIAL AVERAGING
  - SPECTRAL AVERAGING
  - SPECTRAL SELECTION
  - ON-BOARD PROCESSOR
- HIGH-SPEED DIGITAL SIGNAL PROCESSORS
- POINTING AGILITY
  - RASTER SCANS, BRDF STUDIES

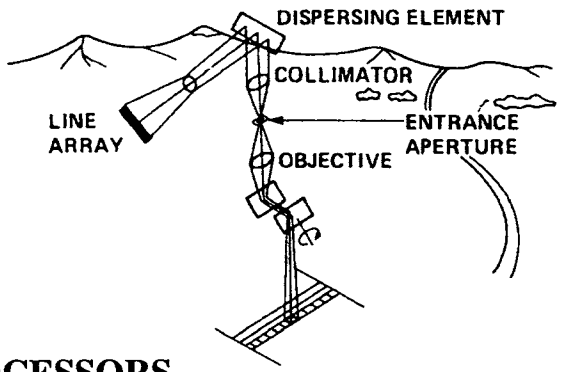
(a) Whiskbroom




(b) Pushbroom

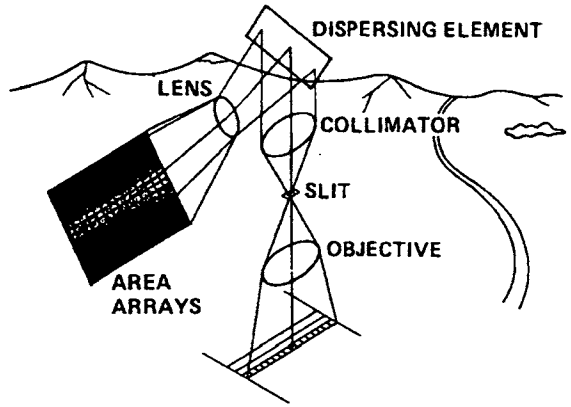



(c) Imaging Spectrometer w. line array




ex: JPL AVIRIS

(d) Imaging Spectrometer with area array




ex: EOS MODIS-T
EOS HIRIS

(Modified from Ref 67)

# PRISM SPECTROMETER/SOUNDER - SCIAMACHY



- UV - SWIR (0.2-2.4 μm) SENSOR FOR ESA POEM-1 (REF 15, 45)
  - SPECTRAL RES ≈ 0.1 - 0.2 nm = 0.0001 - 0.0002 μm
- ATMOSPHERIC TRACE GASES IN TROPOSPHERE & STRATOSPHERE
- NADIR OR LIMB VIEWING

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| Ch | Spectral Range | Detect. | Retrieved Molecules |
|---|---|---|---|
| Ia | 240 - 295 nm | Si | $NO^1$, $ClO^2$ |
| Ib | 290 - 365 nm | Si | $O_3$, $NO_2$, $SO_2{}^3$, $OClO^2$, |
| II | 360 - 700 nm | Si | $O_3$ (Chappius bands), $O_2$, $O_4$, $NO_2$, $OClO^2$ |
| III | 650 - 1060 nm | Si | $H_2O$, $O_2$ |
| IV | 940 - 1350 nm | InGaAs | $H_2O$, ($HO_2$) |
| Va | 1980 - 2020 nm | * | $CO_2$ |
| Vb | 2250 - 2390 nm | * | CO, $N_2O$, $CH_4$, $H_2O$ |

* In channel Va and Vb the detector material will be either "graded" InGaAs or HgCdTe with 2500 nm cutoff.

1 only above 60 Km height

2 only under "ozone hole" conditions

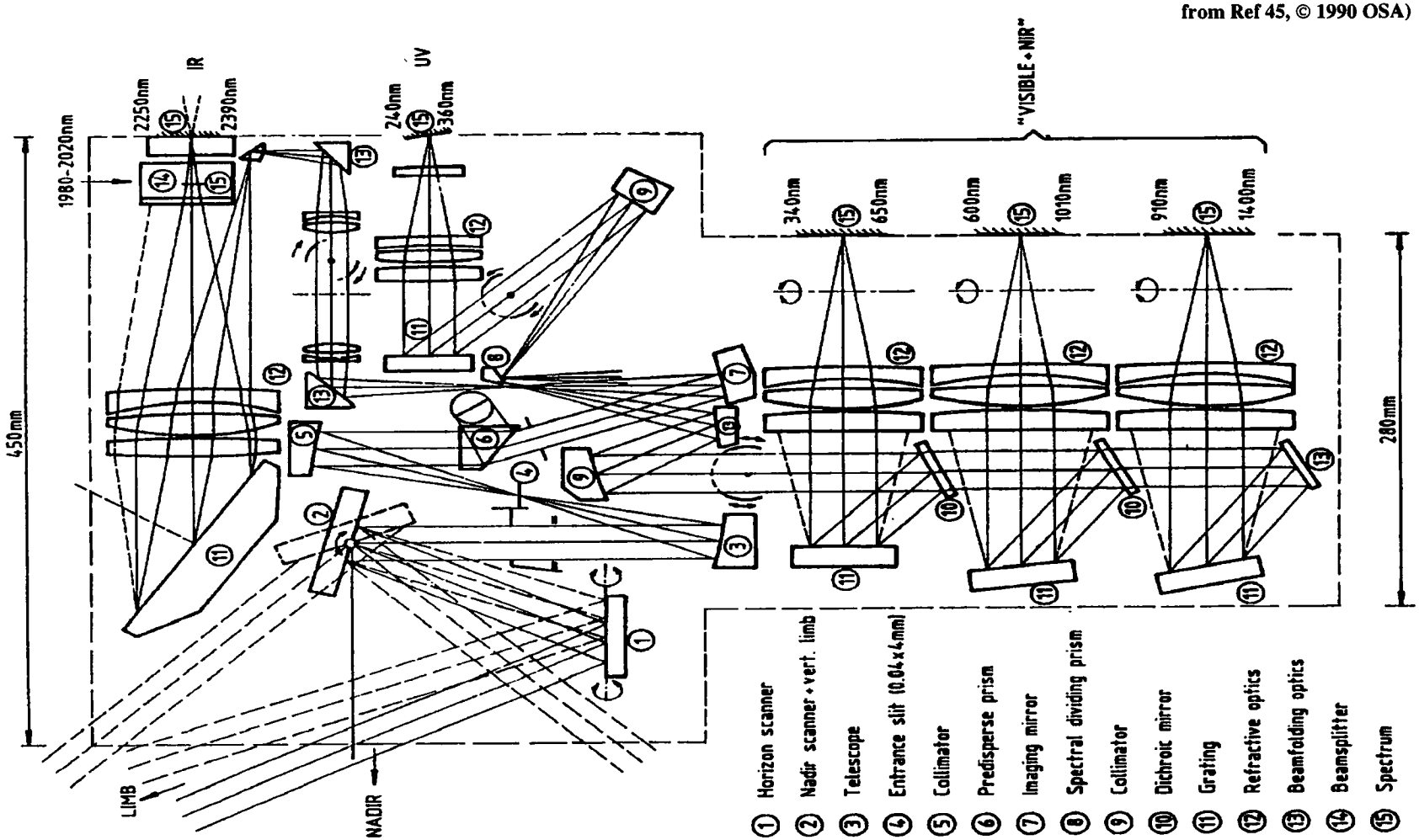
3 only in high pollutant situations

# SCIAMACHY



## Scanning Imaging Absorption Spectrometer for Atmospheric Chartography

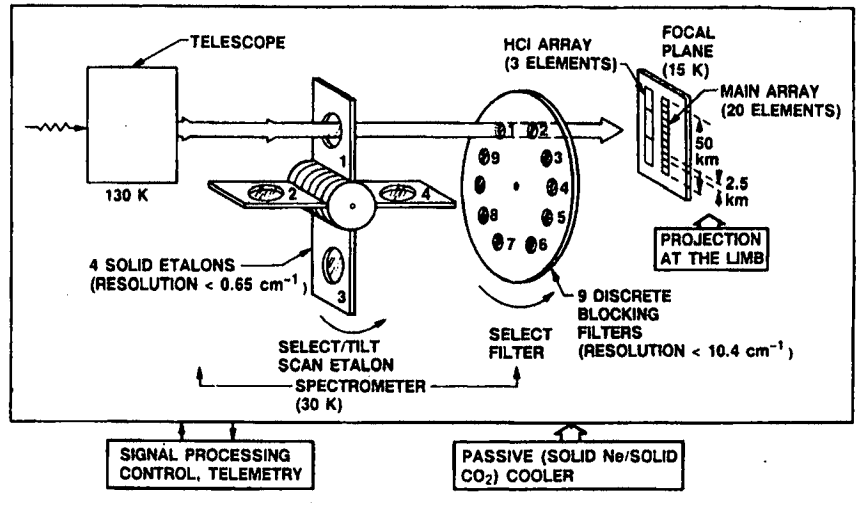
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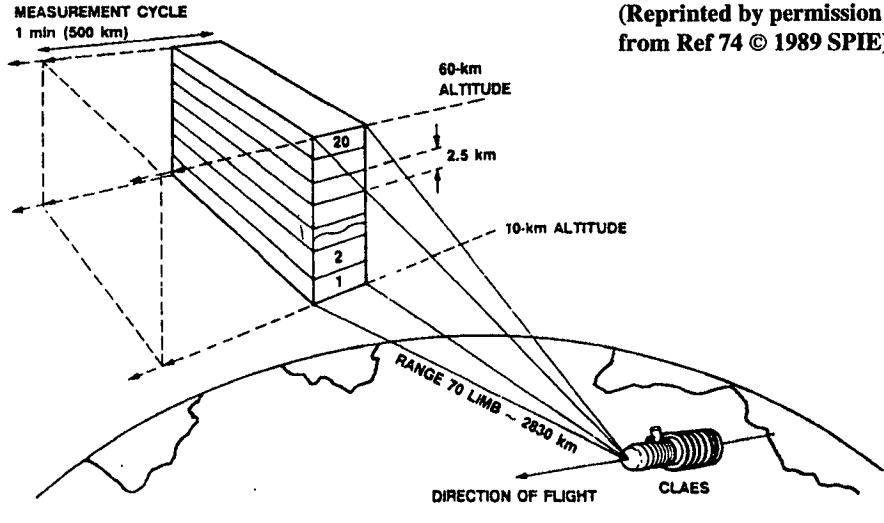
# FABRY-PEROT SPECTROMETER/LIMB SOUNDER - CLAES



- CRYOGENIC LIMB ARRAY ETALON SPECTROMETER (REF 46)
  - MWIR/LWIR (3.5 - 12.7 μm)
- ATMOSPHERIC SPECIES & TRACE GASES
  - 20 ALTITUDES FROM 20 - 60 km
- COOLING VIA SOLID NEON (-260° C) & SOLID $CO_2$ (-150° C)
  - 15 MONTH NOMINAL LIFETIME
- RADCAL ACCURACY 1 - 2%
- 4 FABRY-PEROT ETALONS, TUNED VIA TILTING
- SPECTRAL RESOLUTION ≈ 0.001 μm




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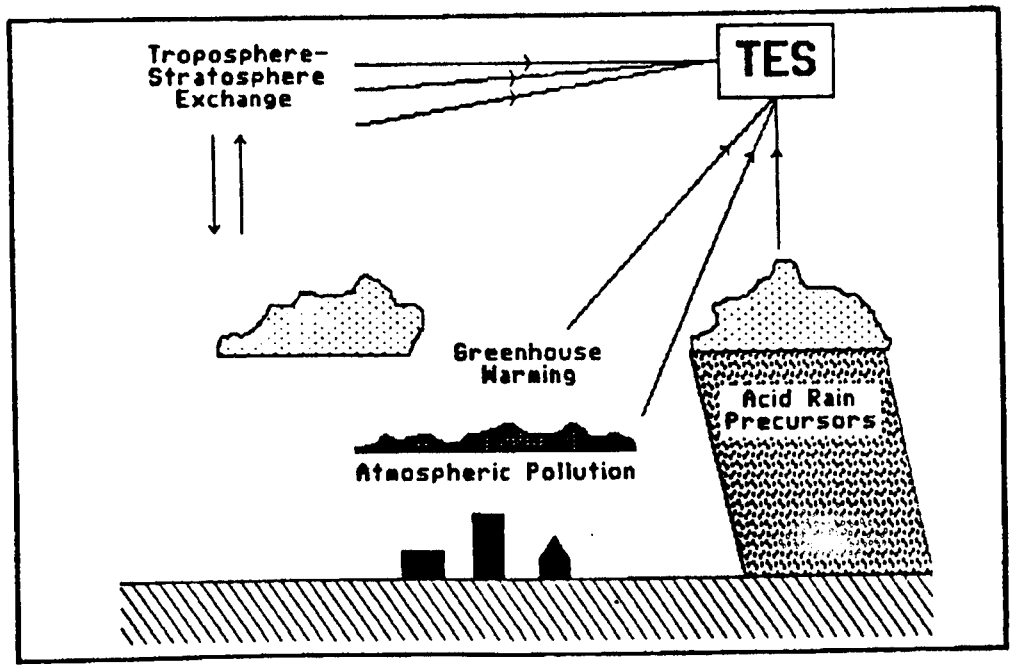



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# FOURIER TRANSFORM SPECTROMETER/SOUNDER - TES



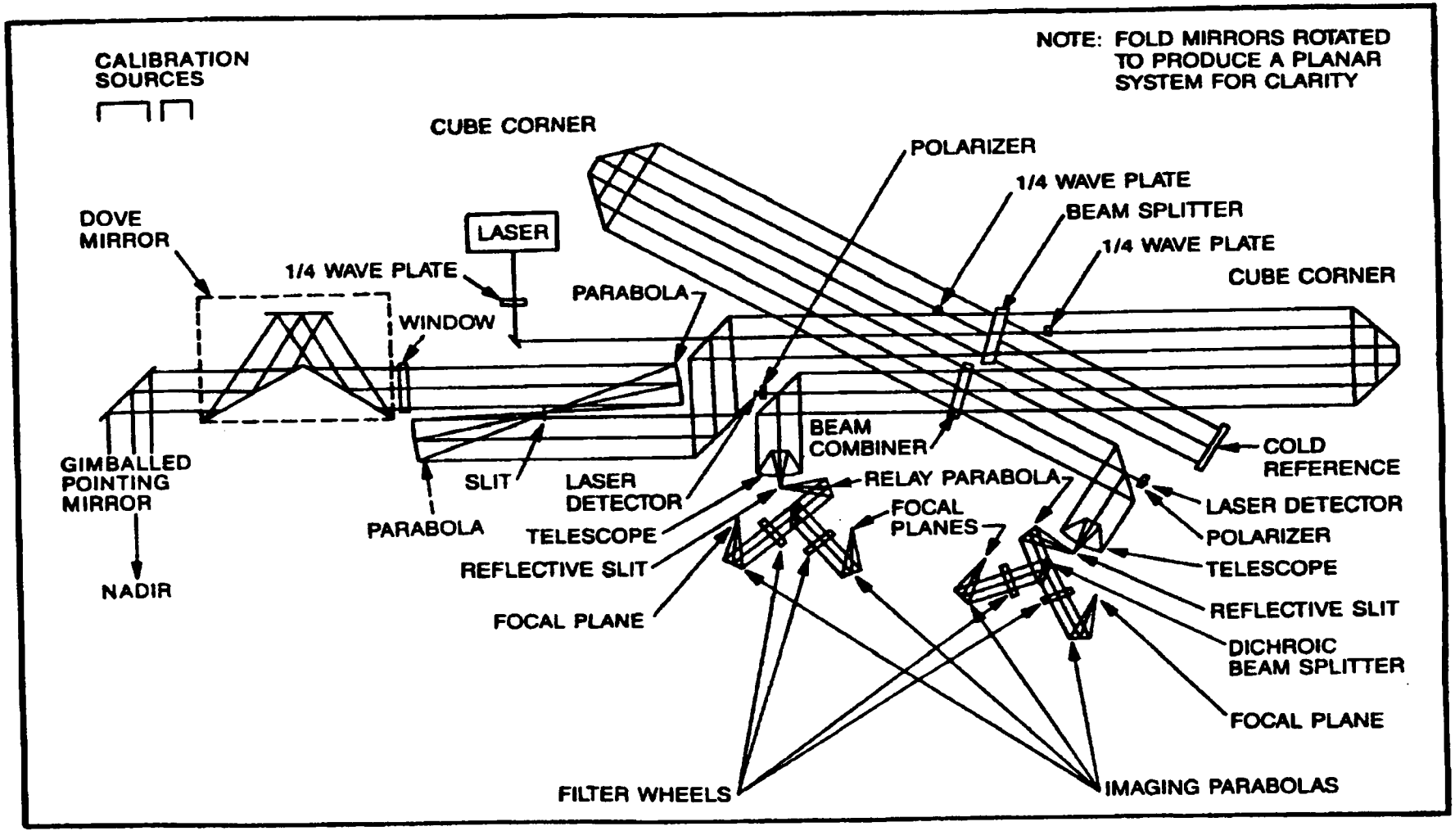
- TROPOSPHERIC EMISSION SPECTROMETER ON (LATE) EOS (REF 47)
  - SWIR - LWIR (2.3 - 16.7 μm)
- "GREENHOUSE" GASES, OZONE, ACID RAIN PRECURSORS, STRATOSPHERIC EXCHANGE
  - SURFACE - 30 km NADIR & LIMB SOUNDING (TROPOSPHERE, LOWER STRATOSPHERE
- TREND - VERY HIGH SPECTRAL RESOLUTION (≈0.0001 μm); "MULTIPLEXED" DATA




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# TES



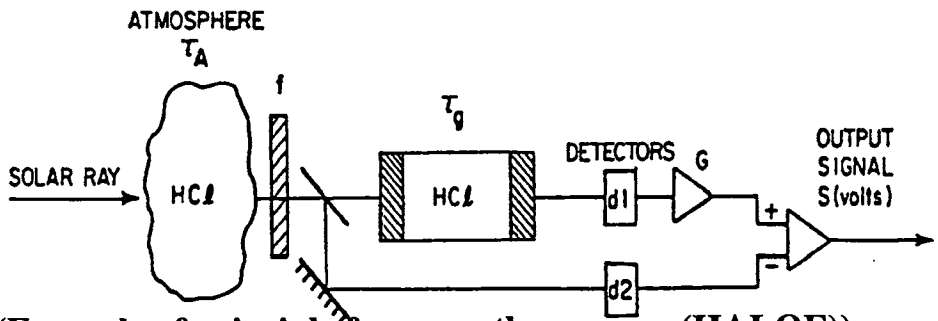



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# GAS CORRELATION SPECTRORADIOMETER

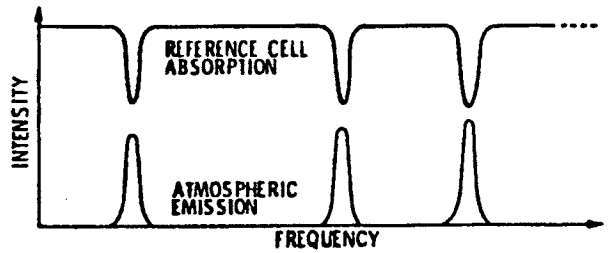


- SIMPLE, COMPACT, ROBUST METHOD OF SPECTRAL DETECTION
  - ISOLATE SPECTRAL LINES OF INTEREST WITH REFERENCE CELL
- EX: STRATOSPHERIC WIND INFRARED LIMB SOUNDER (REF 48)
- CORRELATES ABSORPTION SPECTRUM OF GAS IN REFERENCE CELL WITH THERMAL EMISSION SPECTRUM AT EARTH'S LIMB
  - LINE-OF-SIGHT DOPPLER SHIFT
  - 45° FORE-AFT VIEWS → 2 COMPONENTS ⇒ HORIZ WIND VECTOR
- 3 GAS CELLS $N_2O$, $CO_2$, $CO_2$ TO SPAN 20 -120 km
  - 1 - 5 m/s ACCURACY, 5 km VERTICAL RESOLUTION, ~200 km HORIZONTAL RESOLUTION

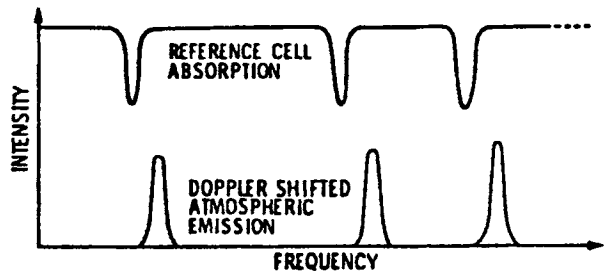



(Example of principle from another sensor (HALOE))

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Schematic representation of the correlation of atmospheric emission spectrum with reference cell absorption spectrum with no Doppler shift. Linewidths and spacing are not to scale.




Schematic representation of the correlation of atmospheric emission spectrum with reference cell absorption spectrum as in Fig. 1, except with a Doppler shift.

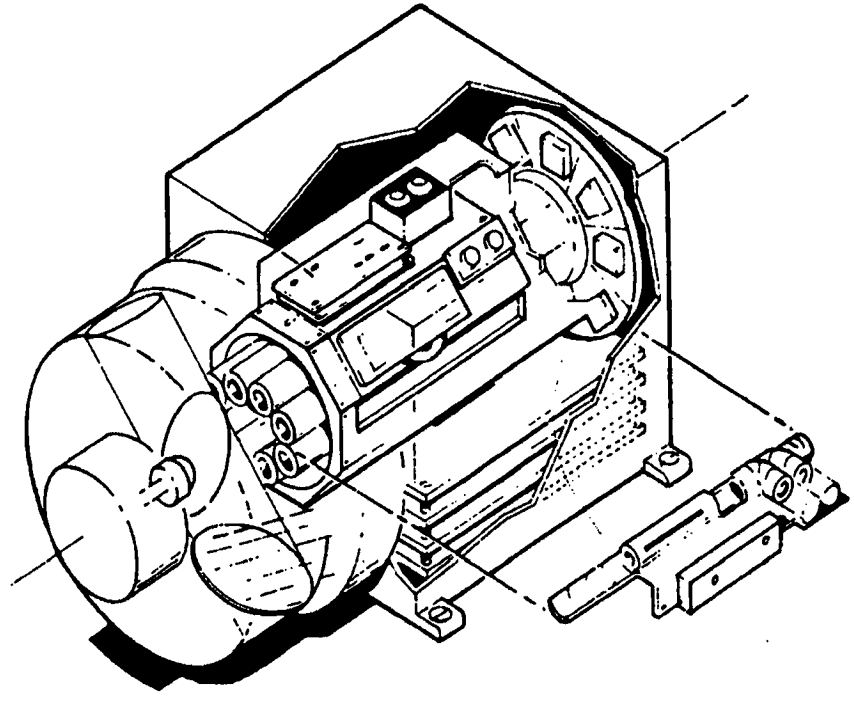
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# POLARIMETER - EOSP



- EARTH OBSERVING SCANNING POLARIMETER (REF 15)
  - TENTATIVE FOR EOS
- RADIANCE & LINEAR POLARIZATION IN 12 VIS - SWIR BANDS
  - BIREFRINGENT FILTERS TO CONVERT

    CIRCULAR TO LINEAR POL, THEN POLARIZERS
  - CROSS-TRACK LIMB-TO-LIMB SCANS
  - POLARIZATION TO 0.2%
- APPLICATIONS
  - CLOUD PROPERTIES
  - TROPO & STRATO AEROSOLS
  - BRDF
  - ATMOSPHERIC CORRECTIONS
- TREND
  - EXPLOITATION OF THE COMPLETE ENVIRONMENTAL SIGNATURE

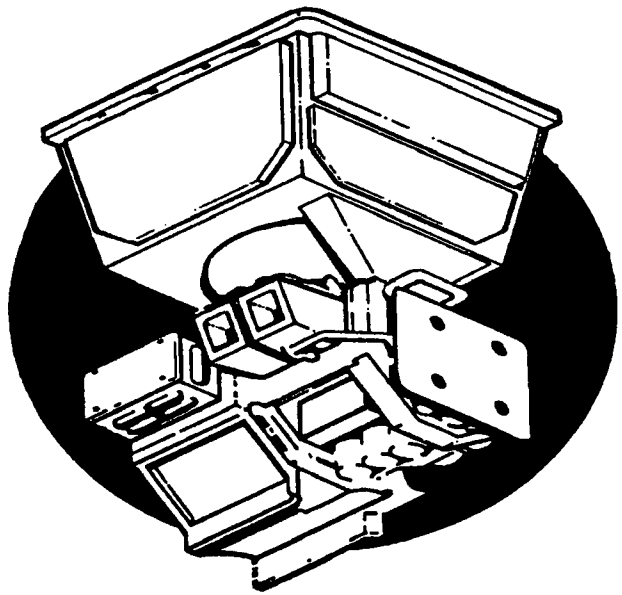


(Ref 15)

# RADIATION BUDGET RADIOMETER - CERES



- CLOUDS AND THE EARTH'S RADIANT ENERGY SYSTEM (REF 49)
  - EVOLUTIONARY DEVELOPMENT OF EARTH RADIATION BUDGET EXPERIMENT (ERBE)
    - CONTINUES CROSS-TRACK SCANNING GEOMETRY
    - ADDS AZIMUTHALLY-SCANNING SENSOR COMPONENT
  - PI B. BARKSTROM (NASA LaRC) - EOS SENSOR
  - MEASURES LONGWAVE & SHORTWAVE COMPONENTS OF RADIATIVE FLUXES
- TREND
  - MORE DETAILED & ACCURATE KNOWLEDGE OF EARTH'S RADIATION BUDGET



(Ref 15)

# SPECTRAL RESOLUTION SUMMARY

| SENSOR TYPE | SPECTRAL RESOLUTION* | |
|---|---|---|
| | μm | nm |
| FILTER WHEEL RADIOMETER | 0.01 - 0.5 | 10 - 500 |
| IMAGING SPECTROMETER | 0.01 - 0.02 | 10 - 20 |
| PRISM/GRATING SPECTROMETER | ~ 0.001 | ~ 1 |
| FABRY-PEROT INTERFEROMETER | ~ 0.001 | ~ 1 |
| FOURIER TRANSFORM SPECTROMETER | ~ 0.0001 | ~ 0.1 |
| IR HETERODYNE SPECTROMETER | ~ 0.000001 | ~ 0.001 |

* Spectral resolution is a function of wavelength.
It is often expressed in units of inverse centimeters ($cm^{-1}$), or unitless ($\lambda/\Delta\lambda$)

# SOME SENSOR & S/C CONTRACTORS



| PLATFORM | SENSOR | CONTRACTOR |
|---|---|---|
| TIROS | | MARTIN MARIETTA ASTRO-SPACE |
| | AVHRR | ITT (FT. WAYNE) |
| | HIRS-2 | ITT |
| LANDSAT | | MARTIN MARIETTA ASTRO-SPACE |
| | TM | SBRC (HUGHES SANTA BARBARA RES. CTR.) |
| GOES | | HUGHES AIRCRAFT CO. |
| | VISSR & VAS | SBRC |
| GOES-NEXT | | SPACE SYSTEMS LORAL |
| | IMAGER & SOUNDER | ITT |
| DMSP | | MARTIN MARIETTA ASTRO-SPACE |
| | OLS | WEC (WESTINGHOUSE ELECTRIC CO.) |
| | SSM/I | HUGHES AIRCRAFT COMPANY |
| | SSM/T, SSM/T-2 | AEROJET ELECTROSYSTEMS (AZUSA) |
| AIRCRAFT | AVIRIS | NASA JPL |
| UARS | | MARTIN MARIETTA ASTRO-SPACE |
| | CLAES | LOCKHEED RESEARCH & DEVELOPMENT DIV. |
| EOS | | AM: MARTIN MARIETTA ASTRO-SPACE |
| | MISR | JPL |
| | EOSP | SBRC |

# PART 8

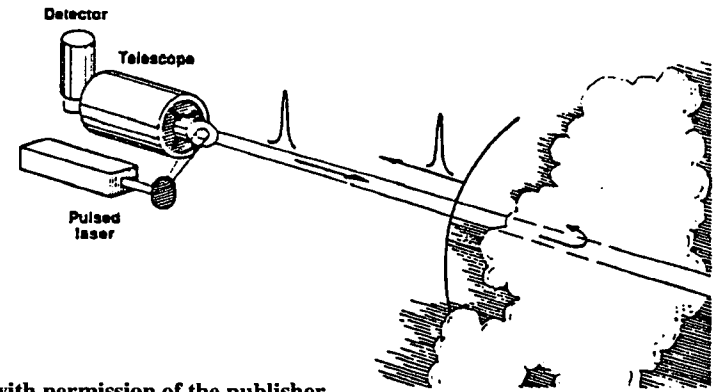


# ACTIVE E-O SENSING

# LIDAR



- LIDAR ≡ "LIGHT DETECTION AND RANGING"
  - EMITS LASER BEAM INTO ATMOSPHERE
  - BEAM BACKSCATTERS OFF CLOUDS, ATMOSPHERE, AEROSOLS & SURFACE
  - BACKSCATTERED RADIATION COLLECTED & DETECTED
- NEVER FLOWN IN SPACE FOR EARTH REMOTE SENSING (EXCEPT LASER ALTIMETER)
  - MARS WILL COME FIRST (MARS OBSERVER LASER ALTIMETER)
- GREAT POTENTIAL FOR
  - HIGH VERTICAL RESOLUTION TEMP & MOISTURE PROFILES
  - WIND PROFILES
  - CLOUD PHYSICS
  - TRACE SPECIES PROFILES
  - INDUSTRIAL PLANT EMISSIONS
  - OTHER APPLICATIONS




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# LIDAR OPERATION



- LASER MAY OPERATE CONTINUOUS WAVE (CW) OR PULSED
- LIDAR IS NORMALLY PULSED
  - PRF ≡ PULSE REPETITION FREQUENCY
  - PULSES "RANGE GATED"
    - UNAMBIGUOUS RANGE DETERMINATION SETS MAXIMUM PRF
- LIDAR EQUATION (SINGLE SCATTERING)

  P(R) = BACKSCATTERED SIGNAL

  $P_0$ = TRANSMITTED POWER

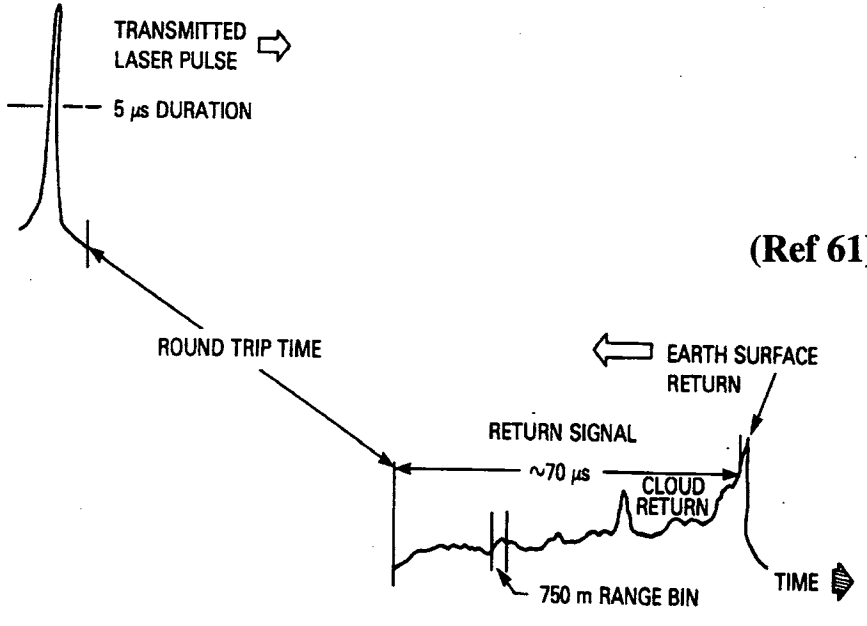
  F = OPTICAL EFFICIENCY

  $A/R^2$ = SOLID ANGLE OF RECEIVER AT RANGE R

  $c\tau/2$ = LENGTH OF ILLUMINATED PATH

  $\beta(R)$ = BACKSCATTER COEFFICIENT [per m-sr]

  $\sigma(r)$ = VOLUME EXTINCTION COEFFICIENT [per m]




Depiction of transmitted laser pulse and backscattered radiation.

(Ref 61)

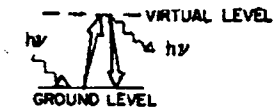
$$P(R) = P_0 F \frac{A}{R^2}\left(\frac{c\tau}{2}\right)\beta(R)\exp\left[-2\int_0^R \sigma(r)\,dr\right]$$

(Ref 54)

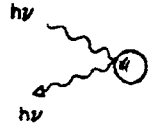
# BACKSCATTER MECHANISMS



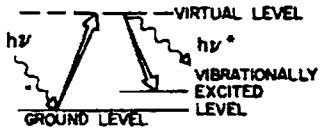
**Rayleigh scattering** — laser radiation **elastically** scattered from atoms or molecules is observed with no change of frequency



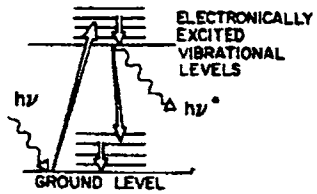

**Mie scattering** — laser radiation elastically scattered from small particulates or aerosols (of size comparable to wavelength of radiation) is observed with no change in frequency




**Raman scattering** — laser radiation inelastically scattered from molecules is observed with a frequency shift characteristic of the molecule ($h\nu - h\nu^* = E$)




**Fluorescence** — laser radiation matched to a specific electronic transition of atom or molecule suffers absorption and subsequent emission at lower frequency; collision quenching can reduce effective cross section of this process; broadband emission is observed with molecules




- *EYE SAFETY* IS AN ISSUE
  - $\lambda > 1.4\ \mu m$ "EYE SAFE"
- MULTIPLE SCATTERING IS AN ISSUE
  - IN CLOUDS & FOG
  - MORE COMPLEX LIDAR EQN
- POLARIZATION CAN BE AN ISSUE
  - e.g., FOR CLOUD MICROPHYSICS

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# LIDAR DETECTION MODES

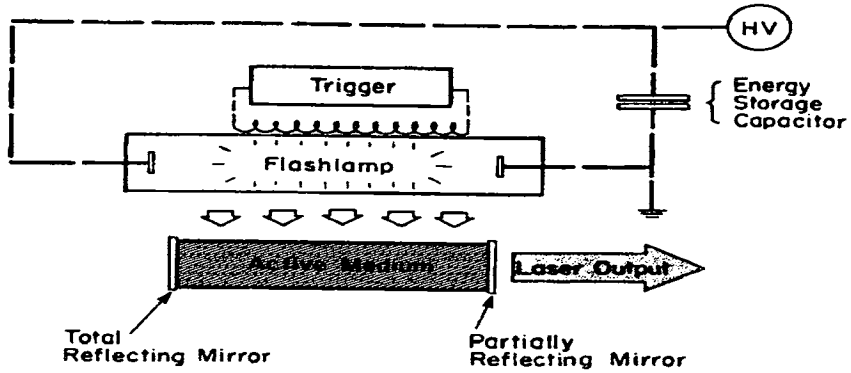


- DIRECT DETECTION (INCOHERENT)
  - RECEIVING TELESCOPE ACTS AS "LIGHT BUCKET"
  - OUTPUT SIGNAL ∝ LIGHT COLLECTED
  - FREQUENCY & PHASE INFORMATION LOST
- HETERODYNE DETECTION (COHERENT)
  - RECEIVING TELESCOPE DIFFRACTION LIMITED TO MAINTAIN WAVEFRONT
  - BACKSCATTERED SIGNAL IS PHOTO-MIXED ON THE DETECTOR WITH THE SIGNAL FROM A LOCAL OSCILLATOR LASER
    - GENERATES INTERMEDIATE FREQUENCY SIGNAL (IF)
  - HIGH SIGNAL-TO-NOISE RATIO (SNR) & SPECTRAL RESOLUTION
  - NARROW FIELD OF VIEW REQUIRED
  - LASER "SPECKLE" CAN REDUCE SNR
    - PULSE AVERAGING REQUIRED TO COUNTERACT THIS

# LASER SOURCE ATTRIBUTES



- POWER (JOULES/PULSE)
  - ~0.1 - SEVERAL J/PULSE REQUIRED FOR SPACE APPLICATIONS (LESS FOR HETERODYNE)
- SPECTRAL COVERAGE & TUNABILITY
- SPECTRAL STABILITY & PURITY
  - IMPORTANT FOR HETERODYNE DETECTION
- "WALL PLUG" EFFICIENCY (ε)
- LIFETIME
  - TOTAL SHOTS AVAILABLE; ≥ 3 YEARS DESIRABLE FOR SPACE
- COMPACTNESS & RUGGEDNESS; DESIRABLE FOR SPACE
- LASER SOURCE PUMPED TO CREATE POPULATION INVERSION
  - FLASHLAMPS
  - DIODE SEMICONDUCTOR LASER ARRAYS (AlGaAs)
  - ELECTRICAL DISCHARGE (GAS LASERS)
- "Q-SWITCHING" USED TO CREATE ONE LARGE PULSE




Schematic of a flashlamp-pumped laser.

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# TYPES OF LASER SOURCES



- GAS
  - $CO_2$ (9 - 12 μm)
    - HIGH PULSE ENERGY, ε (>5%), LIFETIME ($10^8$ - $10^9$ SHOTS IF CAREFUL)
  - EXIMER (XeCl, ArF, KrF)
    - ONLY UV SOURCES (~0.2 - 0.3 μm) WITH HIGH PULSE ENERGY
- LIQUID (DYE)
  - LIFETIME & SPECTRAL PURITY PROBLEMS
- SOLID STATE
  - Nd:YAG CRYSTAL (NEODYMIUM:YTTRIUM-ALUMINUM-GARNET)
    - CAN BE DIODE PUMPED; CAN PUMP OTHER LASERS; 1.064 μm
  - ALEXANDRITE
    - POOR ε, NOT DIODE PUMPABLE, 0.7 - 0.8 μm
  - TITANIUM:SAPPHIRE (Ti:$Al_2O_3$); TUNABLE 0.68 - 0.95 μm
  - THULIUM,HOLMIUM:YAG (Tm,Ho:YAG); PROMISING NEW 2.1 μm SOURCE

# LASER SOURCE TUNABILITY

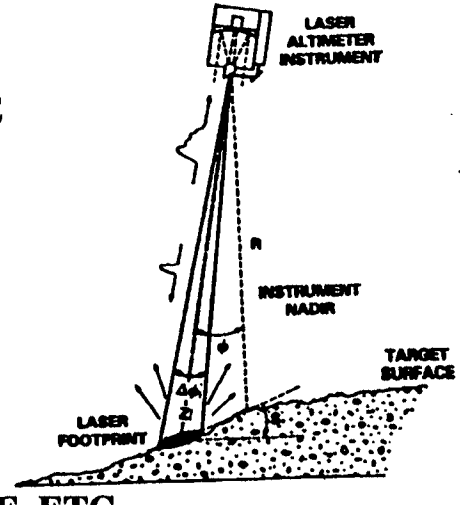


- INHERENTLY TUNABLE
  - ALEXANDRITE, Ti:SAPPHIRE
- WAVELENGTH SHIFTING
  - RAMAN SHIFTERS, e.g., $H_2$, $D_2$, $CH_4$
  - NONLINEAR CRYSTALS, e.g., KDP (Potassium Dihydrogen Phosphate)
    - FREQ. DOUBLING & TRIPLING
      - e.g., Nd:YAG 1.064, 0.53, 0.35 $\mu$m
- OPTICAL PARAMETRIC OSCILLATOR (R. BYER, STANFORD)
  - e.g., MgO:$LiNbO_3$ (Lithium Niobate)
  - $\nu$ (in) = $\nu$ (out1) + $\nu$ (out2)
  - HIGH $\varepsilon$, WIDE SPECTRAL RANGE, GOOD $\nu$ CONTROL

# TYPES OF LIDAR



- LIDAR SOUNDER (ATMOSPHERIC BACKSCATTER LIDAR)
  - NONTUNABLE, HIGH POWER
  - MEASURES CHANGES IN $\beta$ OR DENSITY OF AEROSOLS, CLOUDS, DUST, PLUMES
    - HIGHLY ACCURATE CLOUD TOPS (10's OF m)
  - DISCRIMINATE AEROSOL FROM MOLECULAR BACKSCATTER SPECTRALLY
- LASER ALTIMETER
  - SURFACE BACKSCATTER LASER - ONLY ONE THAT'S FLOWN IN SPACE
  - SURFACE TOPOGRAPHY, SEA ICE, LASER RANGING
- DIFFERENTIAL ABSORPTION LIDAR (DIAL)
  - TRANSMITS @ 2 $\lambda$'s, ONE IN ABSORPTION LINE, ONE NOT
  - DIFFERENCE IN RETURN $\Rightarrow$ PHYSICAL PARAMETERS AT EACH RANGE
    - CAN DERIVE SPECIES CONCENTRATION, TEMPERATURE, MOISTURE, ETC.
      - -- PARTS-PER-MILLION TO PARTS-PER-BILLION
    - RELIES ON PARAMETER DIFFERENTIALS RATHER THAN ABSOLUTE VALUES




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# TYPES OF LIDAR (CONT'D)



- DOPPLER LIDAR
  - USE DOPPLER SHIFT FOR WIND MEASUREMENT
    - BACKSCATTER FROM AEROSOLS CARRIED WITH WIND
  - SENSITIVE HETERODYNE DETECTION
  - FREQUENCY STABLE SOURCE
  - WIDE BANDWIDTH DETECTORS
- FLUORESCENCE LIDAR
  - TUNED TO SPECIES ABSORPTION LINE
  - RERADIATED FLUORESCENCE DETECTED BY SPECTRAL FILTERING
- RAMAN LIDAR
  - USE RAMAN SCATTERING TO DETECT SPECIES CONCENTRATION
  - LIMITED SPACE APPLICATIONS
    - USEFUL FOR CLOSE RANGE OR HIGH CONCENTRATION; LOW SENSITIVITY

# SELECTED APPLICATIONS



- BACKSCATTER LIDAR
  - INDUSTRIAL PLUMES, VOLCANIC ASH, AIR POLLUTION, THIN CIRRUS
- DIAL
  - HIGH-RESOLUTION TEMP & $H_2O$ PROFILES; $O_2$, $CO_2$, $SO_2$, ... CONCENTRATIONS
  - ~1 KM VERTICAL RESOLUTION, 1°K, 10%-20% HUMIDITY
- DOPPLER LIDAR
  - WIND PROFILES IN TROPOSPHERE & STRATOSPHERE
  - 1 - 2.5 m/s, 0.3 - 1 KM VERTICAL RESOLUTION, 100 - 300 KM HORIZONTAL RESOLUTION
- FLUORESCENCE LIDAR
  - OIL SPILLS

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| Constituent or parameter | Laser type | Accuracy | Lidar type | Range (km) |
|---|---|---|---|---|
| Dust, clouds, volcanic ash, smoke plumes | Ruby, Nd:YAG | 1 to 10% | Atmospheric backscatter | 10 to 50 |
| $H_2O$, $O_3$, $SO_2$, NO, $NO_2$, $N_2O$, $C_2H_4$, $CH_4$, HCl, CO, Hg, $SF_6$, $NH_3$, $CO_2$ | Dye, $CO_2$, OPO,* excimer, Co:$MgF_2$ | Variable, 1 ppb to 100 ppm | DIAL, Raman | 1 to 5 |
| OH, Na, K, Li, Ca, $Ca^+$ | Dye | $10^2$ to $10^7$ atoms per cubic centimeter | Fluorescence | 1 to 90 |
| Temperature, pressure | Dye, Nd:YAG | 1 K, 5 mbar | DIAL, Raman | 1 to 30 |
| Wind speed | $CO_2$ | 0.5 m/sec | Doppler | 15 |

*OPO, optical parametric oscillator.

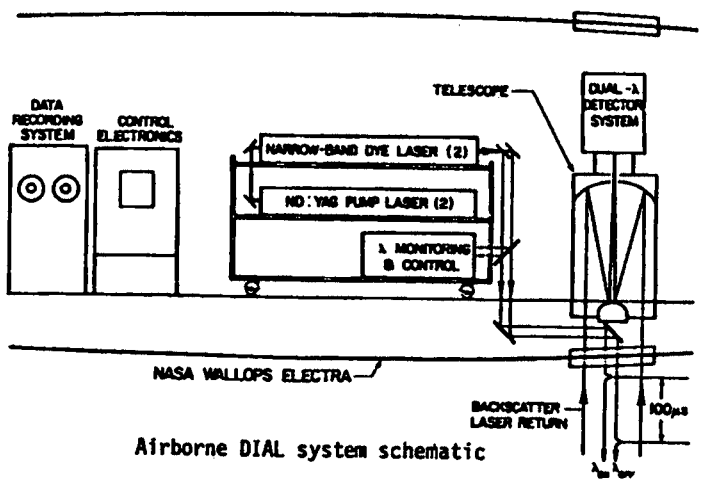
# SELECTED AIRBORNE PROGRAMS



- LIDAR NATURAL APPLICATION FOR AIRBORNE WORK
  - SPACE SYSTEMS REQUIRE HIGH POWER, WEIGHT, COST & COOLING
  - AIRBORNE IS PATHFINDER FOR SPACE
- NASA LANGLEY AIRBORNE DIAL
  - 2 DYE LASERS PUMPED BY 2 Nd:YAG LASERS
  - 0.72 μm $H_2O$; 0.3 μm $O_3$, $SO_2$ ; 0.6 μm AEROSOLS
- GERMAN FLUORESCENCE LIDAR
  - EXIMER 0.308 μm, DYE 0.450, 0.533 μm
- NASA GSFC AIRBORNE LASER POLARIMETER SYSTEM
  - STOKES PARAMETERS OF EARTH SURFACE
- NASA GLOBE, AF SABLE
  - GLOBAL BACKSCATTER EXPERIMENT (D. BOWDLE, NASA MSFC)
  - SOUTH ATLANTIC BACKSCATTER LIDAR EXP'T (S. ALEJANDRO, D. BEDO, PHILLIPS LAB)
  - *CLEAR AIR BACKSCATTER COEFFICIENTS MUCH LESS THAN PREVIOUSLY THOUGHT*

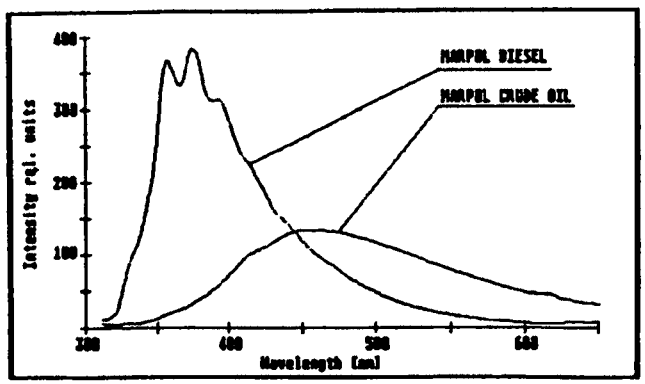
# NASA LaRC OZONE/OIL SIGNAL





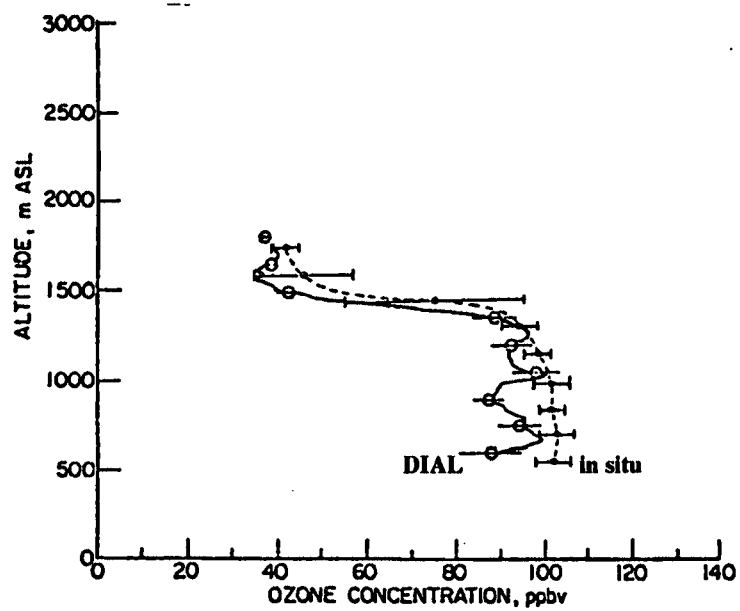

Airborne DIAL system schematic

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Emission spectra of the crude oil and the diesel oil used in the MARPOL exercise. Excitation wavelength is 308 nm.

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Comparison of DIAL and in situ $O_3$ measurements above and in the boundary layer

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# DIAL MOISTURE SOUNDER CONCEPT

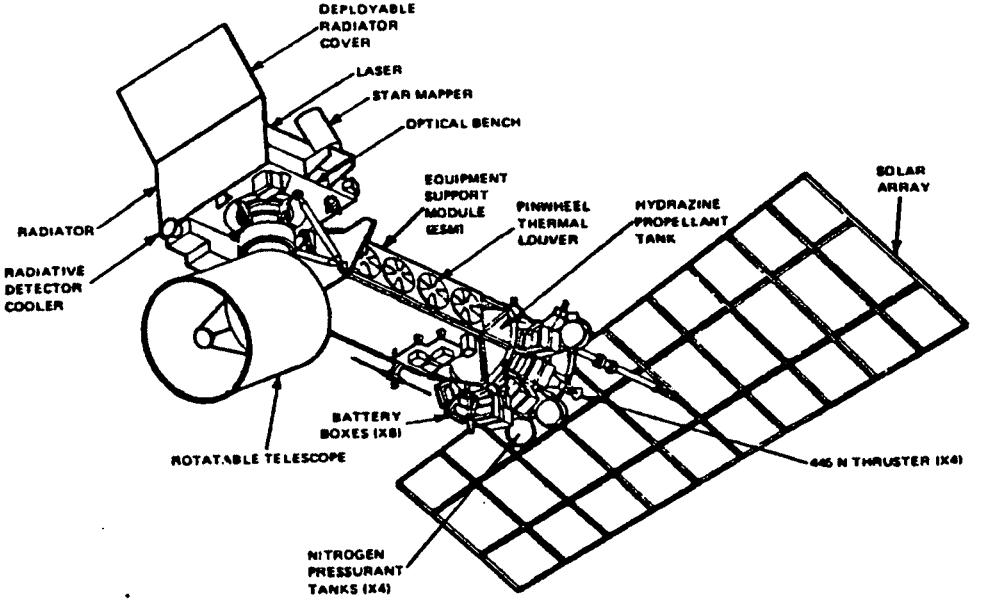


- USE WATER VAPOR LINES ~ 2 μm
  - WEAKER LINE FOR LOWER ATMOSPHERE, STRONGER FOR UPPER ATMOSPHERE
  - EYE SAFE
- SWIR SOLID-STATE DIODE-PUMPED COHERENT PULSED DIAL
  - Tm, Ho:YAG LASER 2.1 μm
    - DEVELOPMENT REQUIRED
  - HIGH-BANDWIDTH DETECTOR FOR HETERODYNE DETECTION
    - GaInAsSb PROMISING, BUT REQUIRES DEVELOPMENT
- CONICALLY SCANNING METER-CLASS RECEIVING TELESCOPE
- POTENTIAL ACCURACY UNKNOWN, REQUIRES SIMULATION STUDY

# WINDSAT/LAWS CONCEPT



- MEASURE DOPPLER SHIFT OF AEROSOLS CARRIED WITH WIND
- RADIAL WIND FROM TWO VIEWPOINTS GIVES HORIZONTAL WIND VECTOR
- >10 YR HERITAGE
  - WINDSAT - NOAA, DMSP  LAWS - NASA EOS
- CONICAL SCAN METER-CLASS RECEIVING TELESCOPE
- LASER SOURCE
  - BASELINE: $CO_2$ @ 9 μm
  - ALTERNATE: Tm,Ho:YAG @ 2.1 μm
- ≥ 1 KW PRIME POWER, HIGH WEIGHT & $
- SENSES WIND FROM 0 - ~20 KM ALTITUDE

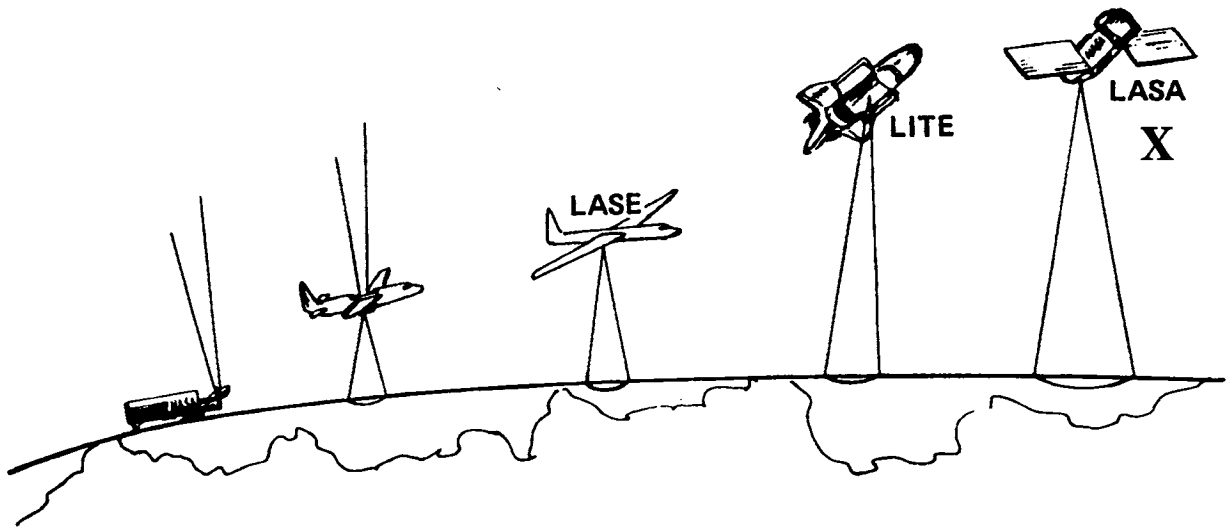


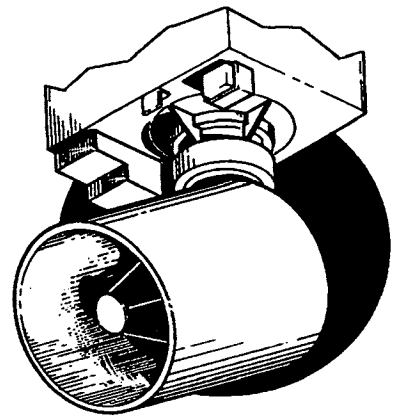

**WINDSAT Concept on Advanced TIROS-N**

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# THE FUTURE OF ACTIVE SENSING





**EOS LAWS (Ref 15)**

**?**

| | FIRST MEAS. | λ's | LASER (Tunable*) | MEAS. SPECIES | |
|---|---|---|---|---|---|
| GND Based 48 in. | 1970 | 2 | Ruby (694 nm, 347 nm) | Aerosols/Molecular Backscatter, Water Vapor | |
| Aircraft Electra/990 | 1978 | 3 | Ruby, YAG, YAG/Dye (1060, 720*, 694, 600*, 530, 347, 300* nm) | Aerosols/Water Vapor/ Ozone | |
| LASE/ER-2 | 1994 | 3 | Alexandrite (720*) | Water Vapor/Aerosols | **Lidar Atmospheric Sensing Exp't** |
| LITE/Shuttle | 1994 | 3 | YAG (1060, 530, 355 nm) | Aerosols/Density/T | **Lidar In-space Technology Exp't** |
| LASA/Eos | | $\geq 3$ | – | Aerosols/Clouds/Altimetry Density/Water Vapor/T | **Lidar Atmospheric Sounder & Altimeter** |

**(Ref 60)** **NASA lidar atmospheric measurements evolution.**

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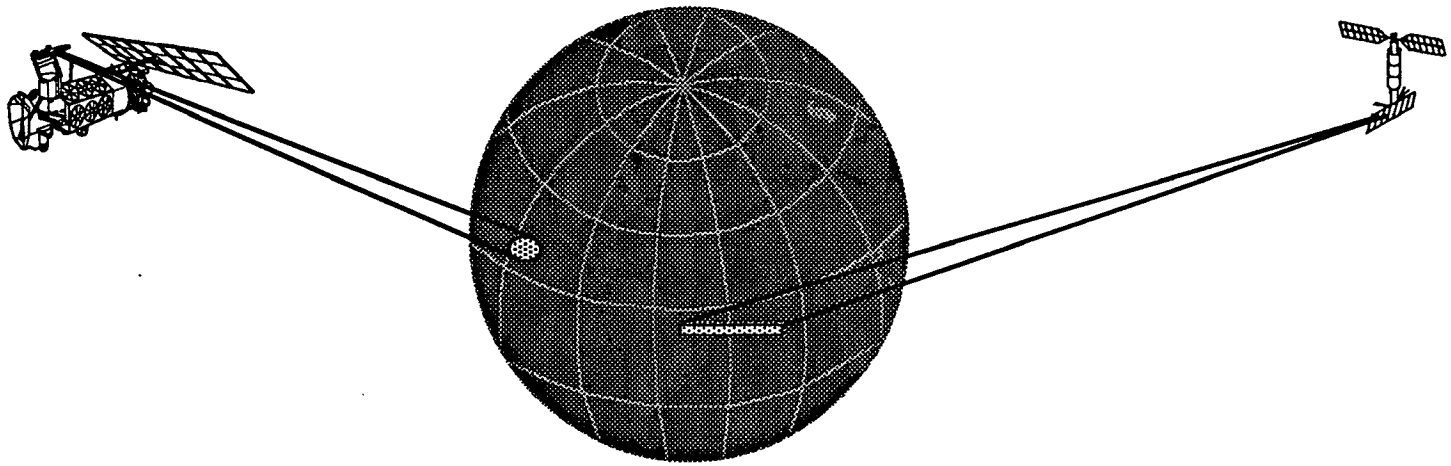
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# lecture notes

# for

# Samuel D. Gasster, PhD

# MICROWAVE REMOTE SENSING




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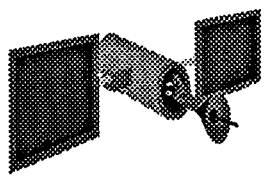

**MARCH 1994**

# MICROWAVE REMOTE SENSING
SAMUEL D. GASSTER
1993

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# PHYSICAL CONSTANTS AND CONVERSION FACTORS

| PARAMETER | SYMBOL | VALUE | UNITS |
|---|---|---|---|
| SPEED OF LIGHT | c | $2.99792458 \times 10^{8}$ | m/sec |
| PLANCK'S CONSTANT | h | $6.626176 \times 10^{-34}$ | Joule-sec |
| ELECTRON CHARGE | e | $1.6021892 \times 10^{-19}$ | Coulombs |
| BOLTZMANN CONSTANT | k | $1.380662 \times 10^{-23}$ | Joule/K |
| STEFAN-BOLTZMANN CONSTANT | $\sigma$ | $5.67032 \times 10^{-12}$ | $\text{Joule}/\text{sec} \cdot \text{cm}^2 \cdot \text{K}^4$ |
| PERMEABILITY OF VACUUM | $\mu$ | $4\pi \times 10^{-7}$ | Henry/m |
| PERMITTIVITY OF VACUUM | $\varepsilon$ | $8.85 \times 10^{-12}$ | Farad/m |
| IMPEDANCE OF FREE SPACE | $\eta$ | 376.7 | Ohms |
| PLANCK FUNCTION EXPONENT | $hc/k$ | 1.44 | cm-K |

# TOPICS

1.0 INTRODUCTION TO MICROWAVE REMOTE SENSING
- 1.1 MICROWAVE SPECTRAL REGION
- 1.2 REVIEW OF PHYSICAL PRINCIPLES
- 1.3 ANTENNAS

2.0 PASSIVE MICROWAVE REMOTE SENSING
- 2.1 PHENOMENOLOGY
- 2.2 MICROWAVE RADIOMETRY
- 2.3 RADIOMETER SYSTEMS
- 2.4 SENSOR SYSTEM CONCEPTS
- 2.5 SYNTHETIC APERTURE AND INTERFEROMETRIC SYSTEMS
- 2.6 APPLICATIONS
- 2.7 MICROWAVE RADIOMETRY EXAMPLE

3.0 ACTIVE MICROWAVE REMOTE SENSING
- 3.1 INTRODUCTION AND THE RADAR EQUATION
- 3.2 PHENOMENOLOGY - RADAR SCATTERING
- 3.3 ALTIMETRY
- 3.4 SCATTEROMETRY
- 3.5 REAL-APERTURE RADAR
- 3.6 SYNTHETIC APERTURE RADAR
- 3.7 POLARIMETRY
- 3.8 APPLICATIONS
- 3.9 RADAR INTERFEROMETRY

4.0 SPECIAL TOPICS
- 4.1 MICROWAVE REMOTE SENSING & GLOBAL CHANGE
- 4.2 REMOTE SENSING "QUESTIONS"
- 4.3 ARMY REMOTE SENSING

5.0 SYSTEMS ENGINEERING ISSUES

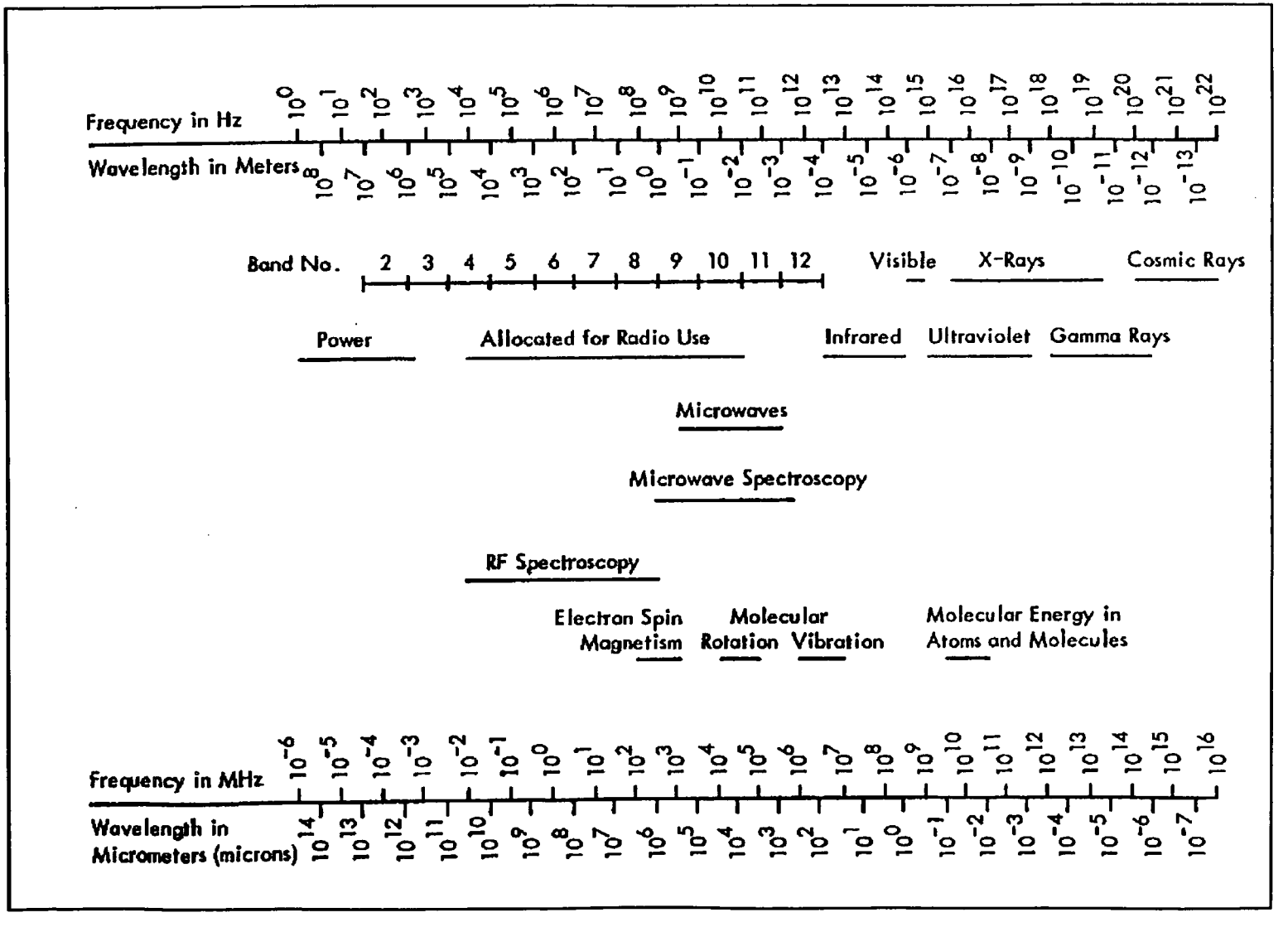
6.0 REFERENCES

# 1.0 INTRODUCTION TO MICROWAVE REMOTE SENSING

# 1.1 MICROWAVE SPECTRAL REGIMES

- ELECTROMAGNETIC SPECTRUM
- SPECTRUM ALLOCATION
- RADIO AND MICROWAVE SPECTRUM
- MILLIMETER AND SUBMILLIMETER WAVES

# ELECTROMAGNETIC SPECTRUM



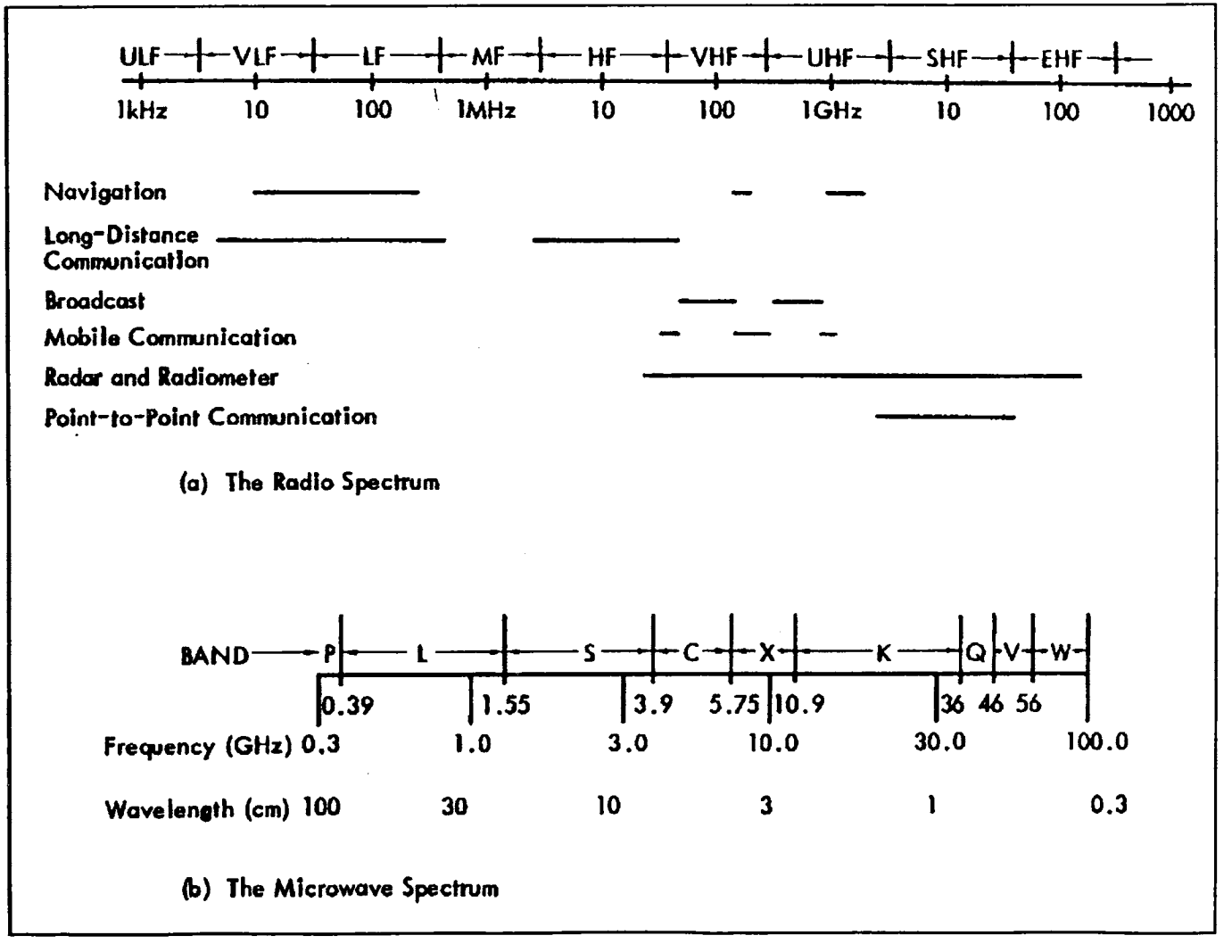

From: F. T. Ulaby, et al., Microwave Remote Sensing: Active and Passive, Vol. I, © 1981-1986, Artech House, Inc., Norwood, MA.

# USE AND ALLOCATION OF EM SPECTRUM

- **COMMUNICATIONS ACT OF 1934**
  - **FEDERAL COMMUNICATIONS COMMISION (FCC)**
    - » **REGULATES NON-FEDERAL GOVERNMENT USERS**
  - **NATIONAL TELECOMMUNICATIONS AND INFORMATION AGENCY (NTIA)**
    - » **REGULATES FEDERAL GOVERNMENT USERS**
- **USE OR ALLOCATION OF EACH SPECTRAL BAND IS DETERMINED BY INTERNATIONAL TREATY**
  - **WORLD ADMINISTRATIVE RADIO CONFERENCE (WARC) 1992**
    - » "... SET TREATY-LEVEL AGREEMENTS ON ISSUES AFFECTING THE INTERNATIONAL RADIO REGULATIONS, INCLUDING SPECTRUM ALLOCATIONS..."
    - » **ORGANIZED BY THE INTERNATIONAL TELECOMMUNICATIONS UNION (ITU)**
    - » **3 MHz to 300 GHz**
- **IMPACT ON REMOTE SENSING**
  - **DEFINES AND PROTECTS BANDS ALLOCATED FOR ACTIVE AND PASSIVE REMOTE SENSING**

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# RADIO & MICROWAVE SPECTRUM




From: F. T. Ulaby, et al., Microwave Remote Sensing: Active and Passive, Vol. I, © 1981-1986, Artech House, Inc., Norwood, MA.

# RADAR BANDS

| DESIGNATION | ASSIGNED FREQUENCIES |
|---|---|
| VHF | 138 – 144 MHz |
| | 216 – 225 MHz |
| UHF | 420 – 450 MHz |
| | 890 – 942 MHz |
| L | 1215 – 1400 MHZ |
| S | 2300 – 2500 MHz |
| | 2700 – 3700 MHz |
| C | 5250 – 5925 MHZ |
| X | 8500 – 10680 MHz |
| Ku | 13.4 – 14.0 GHz |
| | 15.7 – 17.7 GHz |
| K | 24.05 – 24.25 GHz |
| Ka | 33.4 – 36.0 GHz |

ASSIGNED SPECIFICALLY FOR RADAR BY THE INTERNATIONAL TELECOMMUNICATIONS UNION (ITU)

# MILLIMETER AND SUBMILLIMETER WAVES

- **MILLIMETER WAVES (MMW)**
  - 30 - 300 GHz ( 1 cm- 1 mm)
- **NEAR MMW**
  - 100 GHz - 1000 GHz ( 3 mm - 0.3 mm)
- **SUBMILLIMETER WAVES (SMMW)**
  - 150 - 3000 GHz ( 2 mm - 0.1 mm)

# 1.2 REVIEW OF PHYSICAL PRINCIPLES

- INTRODUCTION
- MAXWELL'S EQUATIONS
- WAVE PROPAGATION
- POLARIZATION OF ELECTROMAGNETIC WAVES

# INTRODUCTION

- IN THIS SECTION WE WILL REVIEW THE FUNDAMENTAL EQUATIONS WHICH DESCRIBE THE RELATIONSHIP BETWEEN THE ELECTRIC AND MAGNETIC FIELDS. THIS SET IS KNOWN AS MAXWELL'S EQUATIONS, ALTHOUGH SEVERAL OF THEM WERE OBTAINED BY PREVIOUS RESEARCHERS SUCH AS FARADAY.

- FROM MAXWELL'S EQUATIONS WE WILL OBTAIN THE WAVE EQUATIONS FOR BOTH FREE SPACE AND LOSSY MEDIA. THIS WILL PROVIDE A REVIEW FOR UNDERSTANDING MUCH OF THE PHENOMENOLOGY OF MICROWAVE REMOTE SENSING.

- FINALLY WE WILL REVIEW THE POLARIZATION OF ELECTROMAGNETIC (EM) RADIATION. THIS IS AN EXTREMELY IMPORTANT CONCEPT FOR MICROWAVE REMOTE SENSING, AND IS UTILIZED BY MANY TYPES OF MICROWAVE SENSORS BOTH PASSIVE AND ACTIVE. THE FACT THAT EM RADIATION CAN BE POLARIZED ALLOWS US ADDITIONAL DEGREES OF FREEDOM IN THE RETRIEVAL OF VARIOUS GEOPHYSICAL PHENOMENA.

# MAXWELL'S EQUATIONS

- **MAXWELL'S EQUATIONS**

$$\nabla \cdot \vec{D} = \rho \qquad \nabla \cdot \vec{B} = 0 \qquad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \nabla \times \vec{H} = -\frac{\partial \vec{D}}{\partial t} + \vec{J}$$

- **FIELD QUANTITIES AND CONSTITUTIVE RELATIONS**

$\vec{E}$ = Electric field intensity

$\vec{D}$ = Electric flux density

$\vec{H}$ = Magnetic field intensity

$\vec{B}$ = Magnetic flux density

$$\vec{D} = \varepsilon \vec{E}$$

$$\vec{B} = \mu \vec{H}$$

$$\vec{J} = \sigma \vec{E}$$

$\varepsilon$ = electric permittivity (dielectric constant)

$\mu$ = magnetic permeability

$\sigma$ = conductivity

# WAVE EQUATION

- **COMBINE MAXWELL'S EQUATIONS IN FREE SPACE TO OBTAIN THE HOMOGENEOUS WAVE EQUATION FOR LOSSLESS MEDIA**

$$\nabla^2\vec{E}(\vec{x},t) = \mu\varepsilon\frac{\partial^2\vec{E}(\vec{x},t)}{\partial t^2}$$

- **PLANE WAVE SOLUTIONS (TRAVELING WAVES)**

$$\vec{E}(\vec{x},t) = \vec{A}_0 \exp\left[j\left(\omega t \pm \vec{k}\cdot\vec{x}\right)\right]$$

$$k^2 = \mu\varepsilon\omega^2$$

$$\omega = 2\pi f \qquad k = \left|\vec{k}\right| = \frac{2\pi}{\lambda}$$

- **CONSTANT PHASE FRONTS DEFINE A PLANE SURFACE FOR A GIVEN TIME t:**

$$\omega t \pm \vec{k}\cdot\vec{x} = \text{constant}$$

# PLANE WAVES (contd)

- **PHASE VELOCITY - propagation speed of constant phase plane**

$$\vec{v}_p = \frac{d\vec{x}}{dt} = \pm\frac{\omega}{k}\hat{k}$$

$$v_p = \frac{\omega}{k} = \frac{1}{\sqrt{\mu\varepsilon}}$$

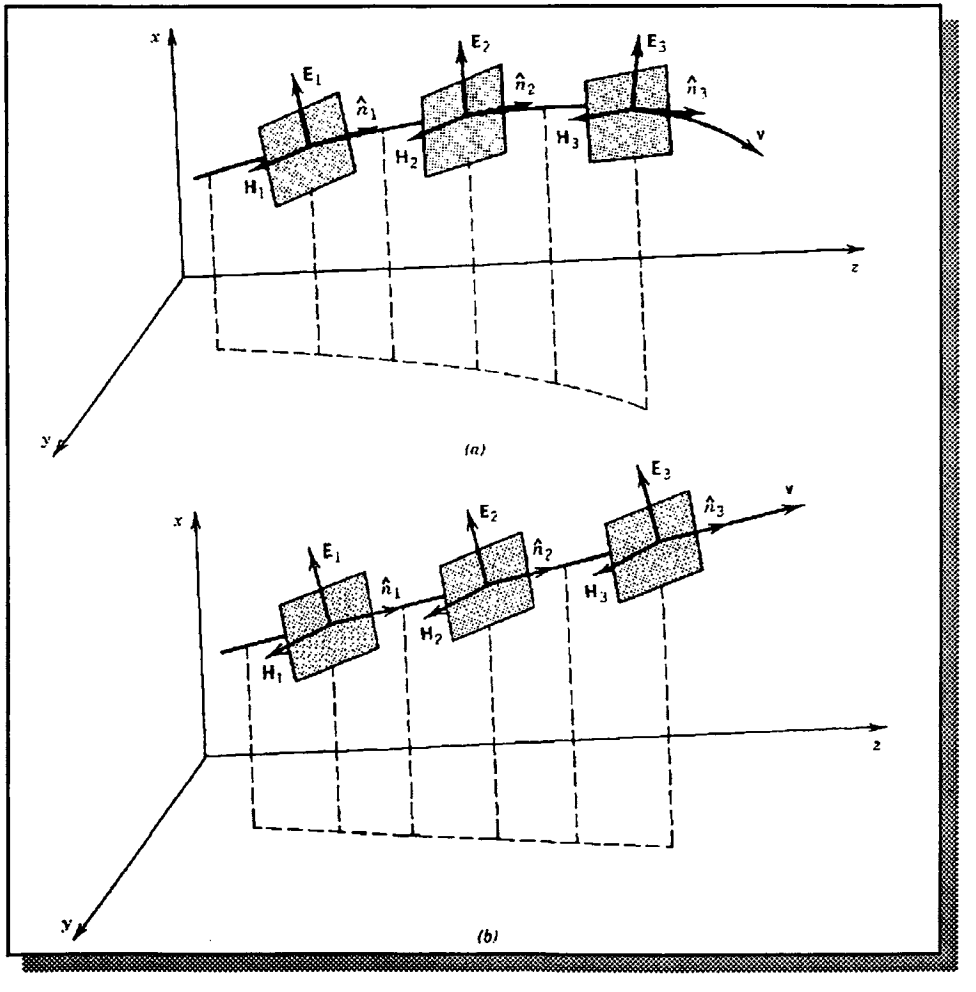
- **MAGNETIC FIELD IS ALSO TIME HARMONIC AND IS RELATED TO THE ELECTRIC FIELD BY MAXWELL'S EQUATIONS**

$$j\omega\vec{H}(\vec{x},t) = -\frac{1}{\mu}\nabla\times\vec{E}(\vec{x},t)$$

# TRANSVERSE ELECTROMAGNETIC WAVES

- **MODE**
  - particular field configuration, solution to Maxwell's equations, with given boundary values
- **TEM MODE**
  - both E and H fields, at each point in space are contained in a local plane (equi-phase plane), independent of time. Successive planes at different points in space are not necessarily parallel; if they are parallel the we have plane waves. If the wave amplitude is constant we have a uniform plane wave.

PHASE FRONTS FOR (a) TEM WAVES AND (b) PLANE WAVES




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# TEM WAVES (contd)

- **WAVE IMPEDANCE (Z) AND INTRINSIC IMPEDANCE ($\eta$)**
  - **-OBTAINED FROM THE RELATIONSHIP BETWEEN THE E AND H FIELDS GIVEN BY MAXWELL'S EQUATIONS**

$$Z_w = \sqrt{\frac{\mu}{\varepsilon}}$$

- **FOR UNIFORM PLANE WAVES AND TEM WAVES** $\eta = Z_w = \sqrt{\frac{\mu}{\varepsilon}}$

- **FREE SPACE** $\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377$ Ohms

- **GROUP VELOCITY: speed at which energy of the EM wave propagates**

$$v_g = \frac{1}{\sqrt{\mu\varepsilon}}$$

$$= \frac{1}{\sqrt{\mu_0\varepsilon_0}} = c \text{ (speed of light)}$$

- **ENERGY FLUX**
  - **POYNTING VECTOR** $\vec{S} = \vec{E} \times \vec{H} \left(\frac{\text{Watts}}{m^2}\right)$
  - **TIME AVERAGE POWER FOR A "+" TRAVELING WAVE:**

$$\vec{S}_{av} = \frac{1}{2}\text{Re}\left[\vec{E} \times \vec{H}\right] = \hat{e}_z \frac{|E_0^+|^2}{2\eta}$$

# WAVES IN LOSSY MEDIA

- **PLANE WAVES PROPAGATING IN A LOSSY, HOMOGENEOUS MEDIUM**
  - **MEDIUM IS CHARACTERIZED BY THE MACROSCOPIC PARAMETERS**

$\varepsilon$ = **electric permittivity (dielectric constant)**
$\mu$ = **magnetic permeability**
$\sigma$ = **conductivity**

- **FROM MAXWELL'S EQUATIONS**

$$\nabla^2\vec{\mathbf{E}}(\vec{\mathbf{x}},t) = \mu\left[\varepsilon\frac{\partial^2\vec{\mathbf{E}}(\vec{\mathbf{x}},t)}{\partial t^2} + \sigma\frac{\partial\vec{\mathbf{E}}(\vec{\mathbf{x}},t)}{\partial t}\right]$$

- **ASSUME TIME HARMONIC FIELDS**

$$\vec{\mathbf{E}}(\vec{\mathbf{x}},t) = \vec{\mathbf{E}}_0(\vec{\mathbf{x}})\,\exp\left(j\omega t\right)$$

$$\nabla^2\vec{\mathbf{E}}_0(\vec{\mathbf{x}}) + \omega^2\mu\varepsilon_c\vec{\mathbf{E}}_0(\vec{\mathbf{x}}) = 0$$

# WAVES IN LOSSY MEDIA (contd)

- **COMPLEX DIELECTRIC CONSTANT**

$$\varepsilon_c = \varepsilon - j\frac{\sigma}{\omega} = \varepsilon' - j\varepsilon''$$

- **WAVE EQUATION FOR A SOURCE FREE, LOSSY HOMOGENEOUS MEDIUM**

$$\nabla^2\vec{E}_0(\vec{x}) + \gamma^2\vec{E}_0(\vec{x}) = 0$$

$$\gamma^2 = \omega^2\mu\varepsilon_c$$

$$\gamma = \alpha + j\beta$$

$\gamma$ = propagation constant

$\alpha$ = attenuation constant

$\beta$ = phase constant (k)

# TEM WAVES IN LOSSY MEDIA

## PROPAGATION CONSTANT, WAVE IMPEDANCE, WAVELENGTH, VELOCITY AND SKIN DEPTH

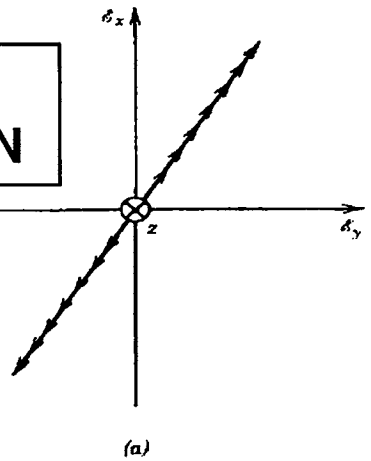
| FUNCTION | EXACT FORM | GOOD DIELECTRIC $\left(\frac{\sigma}{\omega\varepsilon}\right)^2 \ll 1$ | GOOD CONDUCTOR $\left(\frac{\sigma}{\omega\varepsilon}\right)^2 \gg 1$ |
|---|---|---|---|
| ATTENUATION CONSTANT $\alpha$ | $\omega\sqrt{\mu\varepsilon}\left\{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]\right\}^{1/2}$ | $\frac{\sigma}{2}\sqrt{\left(\frac{\mu}{\varepsilon}\right)}$ | $\sqrt{\left(\frac{\omega\mu\sigma}{2}\right)}$ |
| PHASE CONSTANT $\beta$ | $\omega\sqrt{\mu\varepsilon}\left\{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right]\right\}^{1/2}$ | $\omega\sqrt{\mu\varepsilon}$ | $\sqrt{\left(\frac{\omega\mu\sigma}{2}\right)}$ |
| IMPEDANCES WAVE/INTRINSIC $Z_w = \eta_c$ | $\sqrt{\frac{j\omega\mu}{\sigma+j\omega\varepsilon}}$ | $\sqrt{\frac{\mu}{\varepsilon}}$ | $(1+j)\sqrt{\frac{\omega\mu}{2\sigma}}$ |
| WAVELENGTH $\lambda$ | $\frac{2\pi}{\beta}$ | $\frac{2\pi}{\omega\sqrt{\mu\varepsilon}}$ | $2\pi\sqrt{\frac{2}{\omega\mu\sigma}}$ |
| VELOCITY $V$ | $\frac{\omega}{\beta}$ | $\frac{1}{\sqrt{\mu\varepsilon}}$ | $\sqrt{\frac{2\omega}{\mu\sigma}}$ |
| SKIN DEPTH $\delta$ | $\frac{1}{\alpha}$ | $\frac{2}{\sigma}\sqrt{\frac{\varepsilon}{\mu}}$ | $\sqrt{\frac{2}{\omega\mu\sigma}}$ |

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# WAVE POLARIZATION

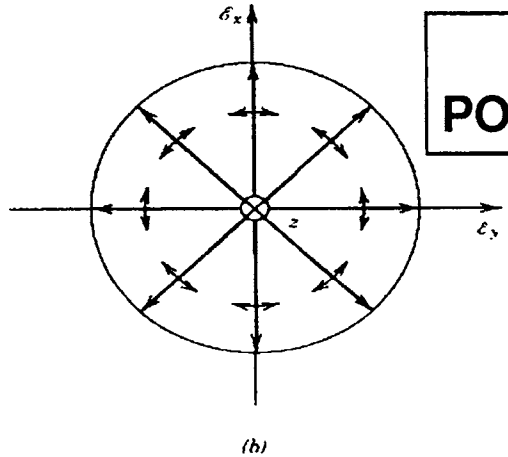
- **POLARIZATION**
  - **TIME VARYING DIRECTION AND RELATIVE MAGNITUDE OF THE ELECTRIC FIELD VECTOR OF AND EM WAVE - OBSERVED ALONG THE DIRECTION OF PROPAGATION**
  - **TYPES**

**LINEAR POLARIZATION**

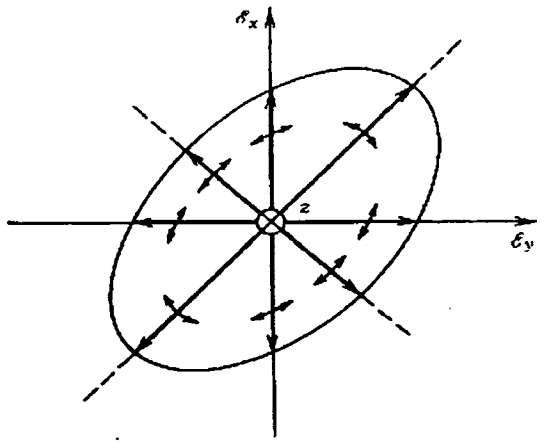



(a)

**CIRCULAR POLARIZATION**




(b)




**ELLIPTICAL POLARIZATION**

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# WAVE POLARIZATION (contd)

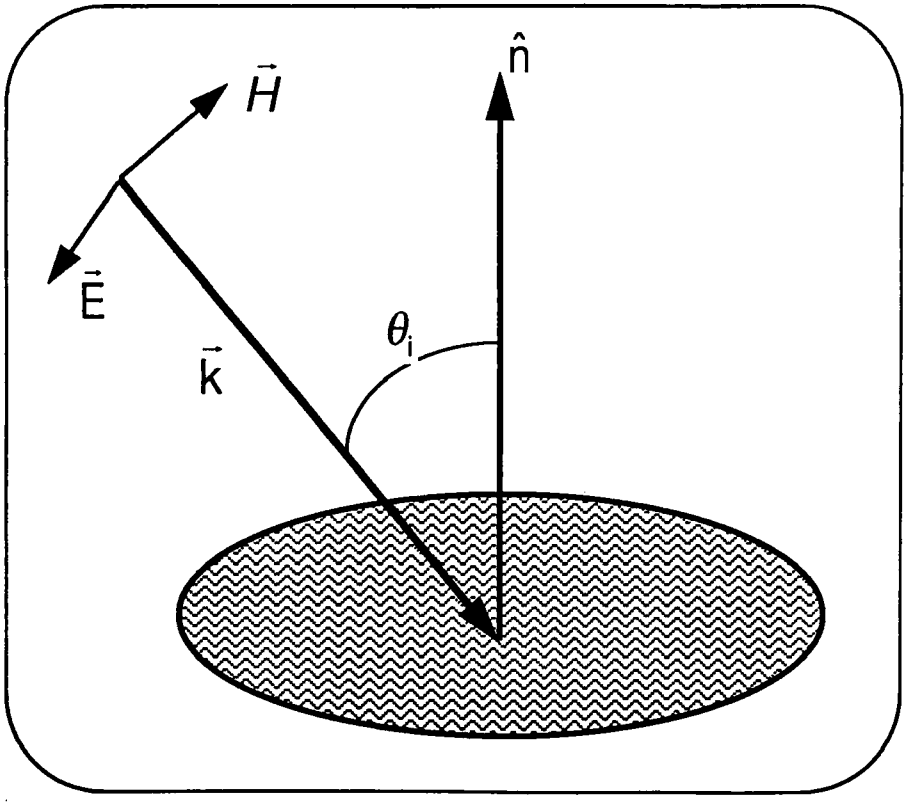
- **DEFINITION OF V AND H POLARIZATION**
  - PLANE OF INCIDENCE IS DEFINED BY $\hat{k}$ and $\hat{n}$

- **HORIZONTAL POLARIZATION**
  - E FIELD IS PERPENDICULAR TO PLANE OF INCIDENCE

$$\hat{h} = \frac{\hat{n} x \hat{k}}{|\hat{n} x \hat{k}|}$$

- **VERTICAL POLARIZATION**
  - E FIELD LIES IN THE PLANE OF INCIDENCE

$$\hat{v} = \frac{\hat{h} x \hat{k}}{|\hat{h} x \hat{k}|}$$



# POLARIZATION ELLIPSE

- **POLARIZATION OF AN EM WAVE CAN BE EXPRESSED IN TERMS OF TWO COMPONENTS (V AND H) WHICH ARE IN GENERAL RELATED TO TWO ANGLES OF THE POLARIZATION ELLIPSE**

**- EM WAVE** $\vec{E} = \left(\hat{v}E_v + \hat{h}E_h\right) \exp\left[-i\left(\omega t - \vec{k}\cdot\vec{r}\right)\right]$

**- NORMALIZED MATRIX FORM** $\vec{E} = E_0 A = E_0 \begin{bmatrix} a_v \\ a_h \end{bmatrix} = E_0 \begin{bmatrix} a_v \exp(-i\delta_v) \\ a_h \exp(-i\delta_h) \end{bmatrix}$

**- TOTAL POWER**

$$P_T = |E_0|^2 \text{ since}$$

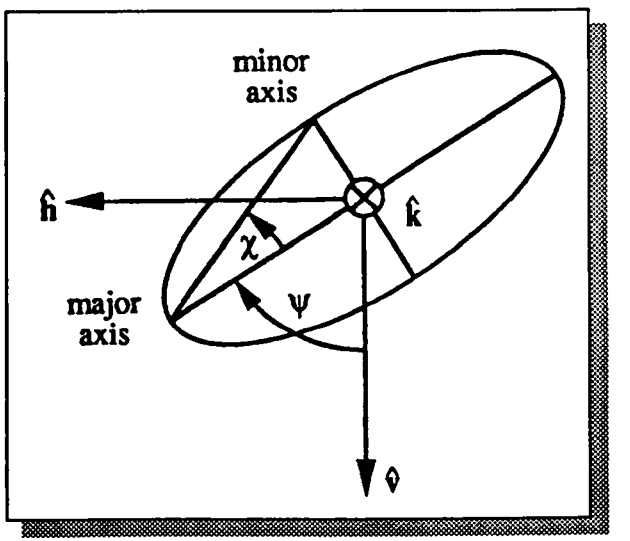
$$|a_v|^2 + |a_h|^2 = 1$$

$\psi$ = orientation $\chi$ = ellipticity

$$\tan(2\psi) = \tan(2\alpha)\cos(\delta_h - \delta_v)$$

$$\sin(2\chi) = \sin(2\alpha)\sin(\delta_h - \delta_v)$$

$$\tan(\alpha) = \frac{|a_h|}{|a_v|}$$




From: M. W. Whitt, *Microwave Scattering from Periodic Row-Structured Vegetation*, PhD Dissertation, Univ. of Michigan (1991).

# 1.3 INTRODUCTION TO ANTENNAS

- ANTENNA DEFINITION
- ANTENNA PARAMETERS AND TERMINOLOGY
- DIFFRACTION THEORY AND ANTENNA PATTERNS
- EXAMPLES

---

THE PURPOSE OF THIS SECTION IS TO ACQUAINT THE READER WITH ANTENNA SYSTEMS. ANTENNAS ARE AN IMPORTANT ELEMENT IN BOTH ACTIVE AND PASSIVE MICROWAVE REMOTE SENSING SYSTEMS, DIRECTLY AFFECTING SYSTEM PERFORMANCE. THE SCIENTIST OR ENGINEER INVOLVED IN MICROWAVE REMOTE SENSING NEEDS TO UNDERSTAND ANTENNA SYSTEMS PERFORMANCE, WHAT TYPES OF ANTENNAS ARE AVAILABLE AND HOW THE ANTENNA AFFECTS THE REMOTE SENSING MEASUREMENTS.

# ANTENNAS

- **DEFINE ANTENNA**
  - REGION OF TRANSITION BETWEEN AN ELECTROMAGNETIC WAVE PROPAGATING IN FREE SPACE (OR OTHER MEDIUM) AND A GUIDED WAVE PROPAGATING IN A TRANSMISSION LINE OR VICE VERSA

- **ANTENNAS CAN BE USED TO BOTH TRANSMIT AND RECEIVE MICROWAVE RADIATION**

- **ANTENNA RADIATION PATTERN**
  - FUNCTION DESCRIBING THE RELATIVE DIRECTIONAL DISTRIBUTION OF ENERGY TRANSMITTED BY AN ANTENNA [defined below]

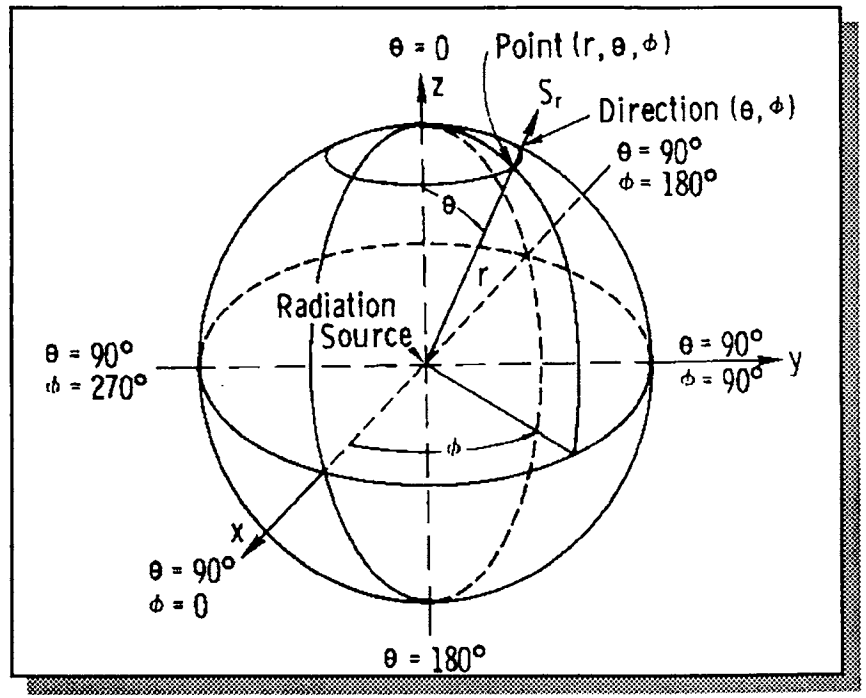
$$F(\theta,\varphi)$$

- **RECIPROCITY: MOST ANTENNAS HAVE THE SAME TRANSMIT AND RECEIVE RADIATION PATTERNS**

# ANTENNA RADIATION PATTERNS

- THE DESCRIPTION OF ANTENNA RADIATION PATTERNS REQUIRES THE USE OF SEVERAL DIFFERENT PARAMETERS WHICH WE SHALL NOW DEFINE.

- THE <u>DIRECTIONAL PATTERN</u> OF AN ANTENNA IS A PLOT OF $|S_r|$ AS A FUNCTION OF $\hat{r}$, AT A FIXED RANGE. GENERALLY FOR REMOTE SENSING APPLICATIONS WE ARE IN THE FAR-FIELD ZONE OF THE ANTENNA WHICH GIVES:




$$\vec{E} = \hat{\theta}\, E_\theta + \hat{\varphi}\, E_\varphi$$

$$\vec{H} = \frac{1}{\eta}\left[\hat{r} \times \vec{E}\right]$$

$$S_r = \frac{1}{2\eta}\left( |E_\theta|^2 + |E_\varphi|^2 \right)$$

$$S_r = \frac{1}{2}\mathrm{Re}\left(\vec{E} \times \vec{H}^*\right)$$

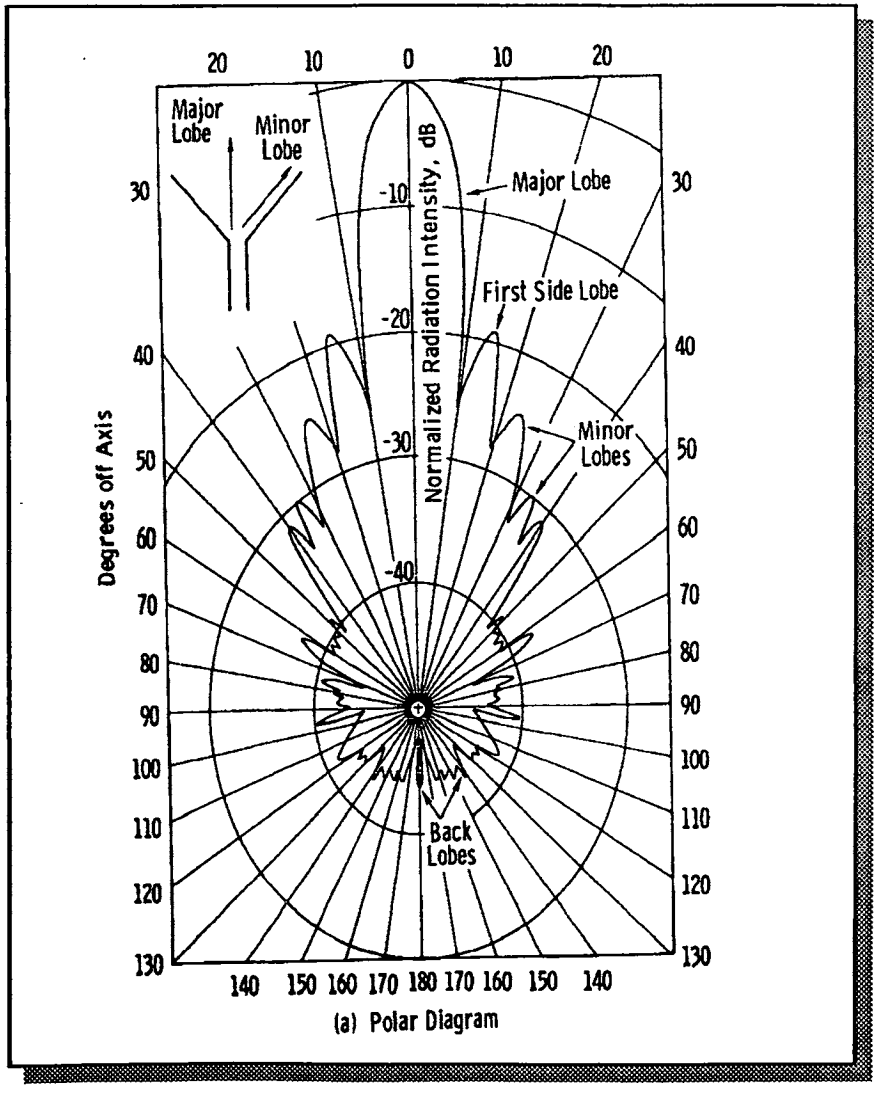
$r$ = range

$$E_\theta = \frac{\exp\{-jkr\}}{r} f_1(\theta,\varphi) \qquad E_\varphi = \frac{\exp\{-jkr\}}{r} f_2(\theta,\varphi)$$

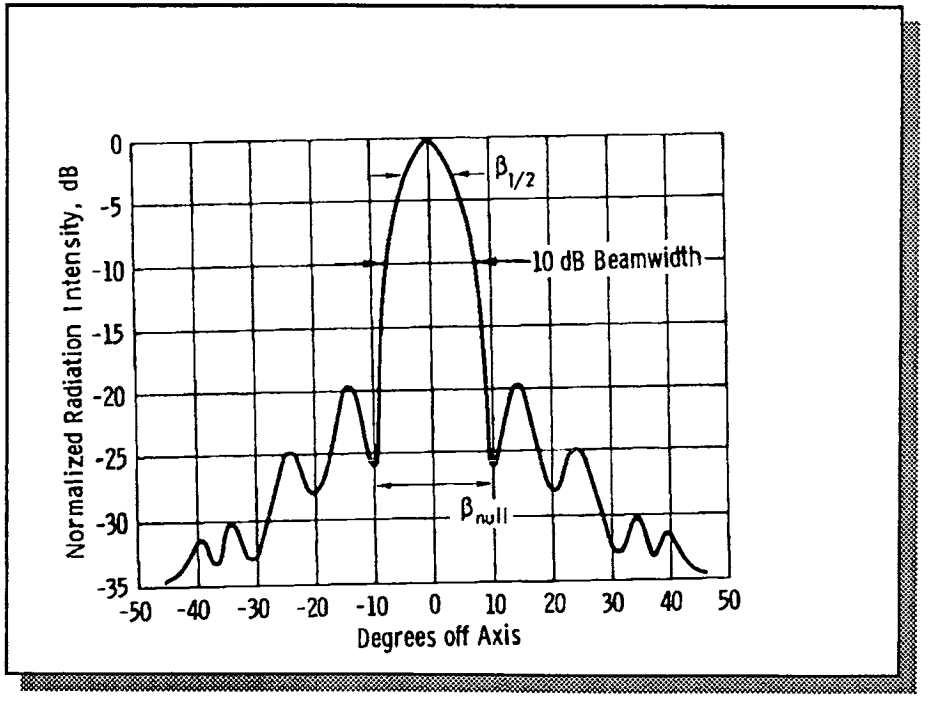
$$\hat{r} = (\theta,\varphi)$$

From: F. T. Ulaby, et al., Microwave Remote Sensing, Active and Passive, Vol. I, © 1981-1986 Artech House, Inc., Norwood, MA.

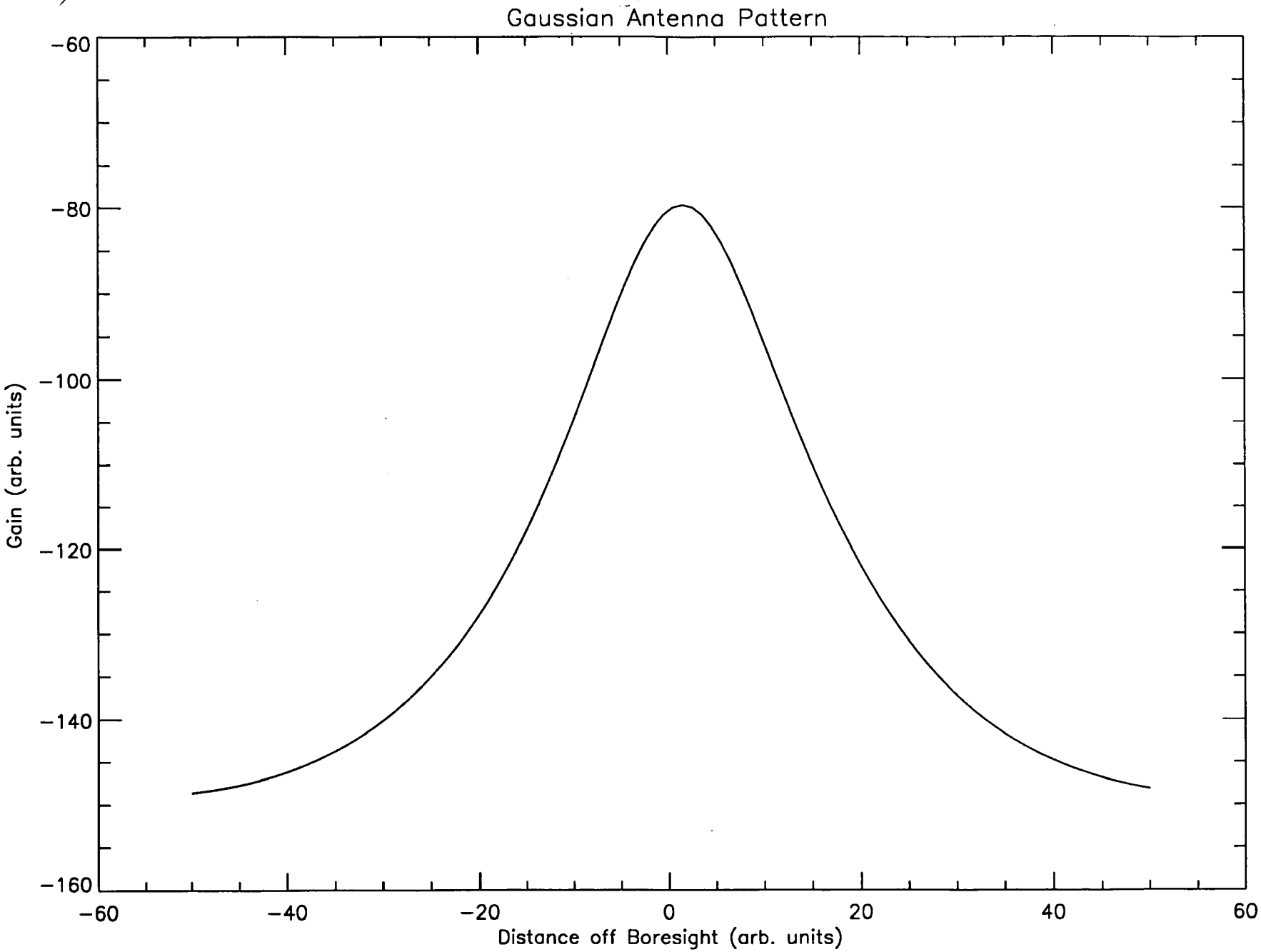
# POLAR AND RECTANGULAR PLOTS OF ANTENNA PATTERNS

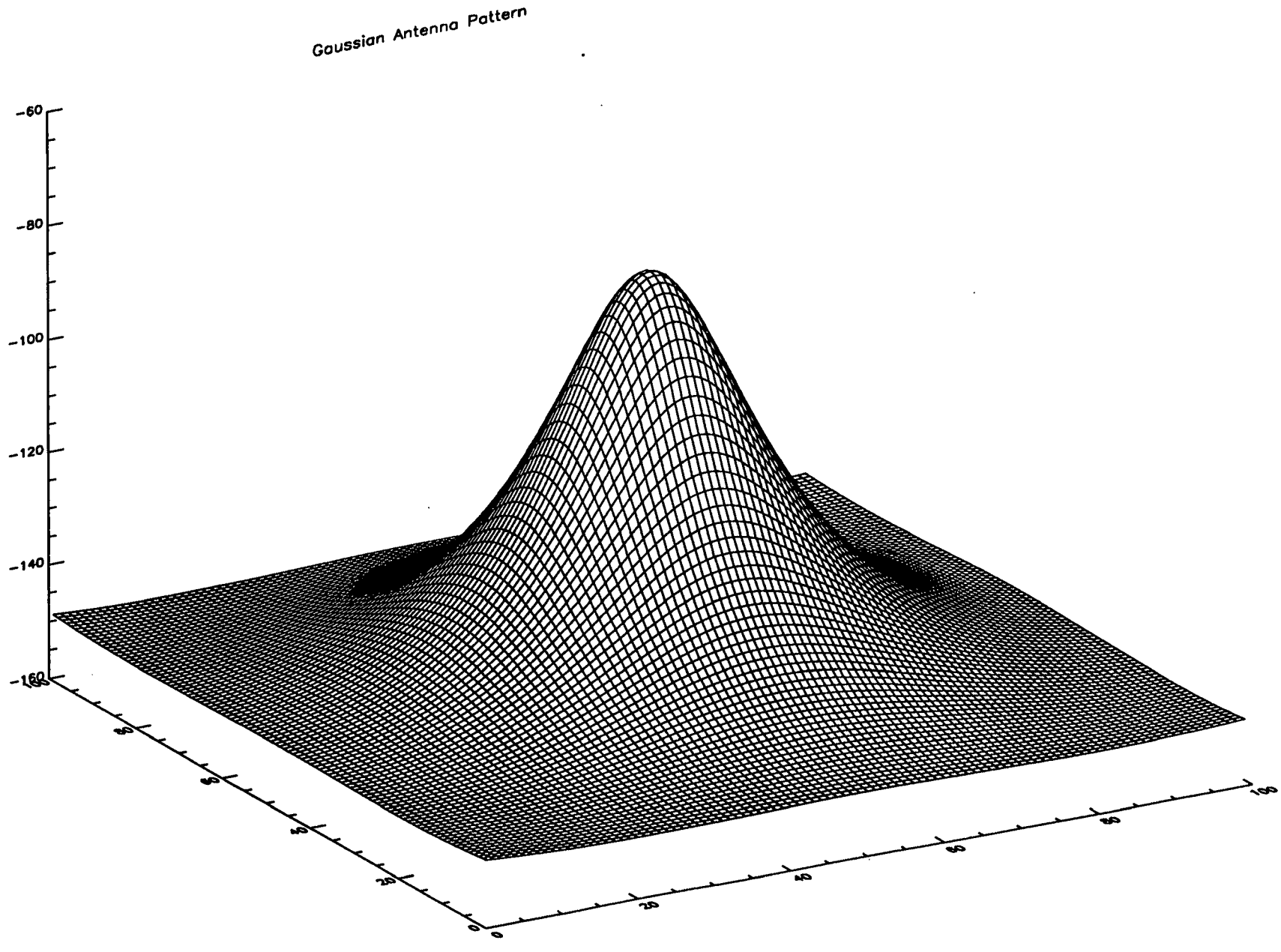


(a) Polar Diagram




From: F. T. Ulaby, et al., Microwave Remote Sensing, Active and Passive, Vol. I, © 1981-1986 Artech House, Inc., Norwood, MA.


Gaussian Antenna Pattern
-60
-80
-100
-120
-140
-160
Gain (arb. units)
-60
-40
-20
0
20
40
60
Distance off Boresight (arb. units)


Gaussian Antenna Pattern
-60
-80
-100
-120
-140
-160
0
20
40
60
80
100
0
20
40
60
80
100

# ANTENNA RADIATION PATTERNS (contd)

- FOR LARGE DISTANCES FROM THE ANTENNA, THE ELECTRIC FIELDS ARE APPROXIMATELY SPHERICAL IN CHARACTER MULTIPLIED BY A DIRECTIONAL FUNCTION

$$S_r = \frac{1}{2\eta r^2}\left( |f_1(\theta,\phi)|^2 + |f_2(\theta,\phi)|^2 \right)$$

- WE WOULD LIKE TO CHARACTERIZE ANTENNA PATTERNS BY A RANGE INDEPENDENT FUNCTION; THEREFORE DEFINE THE <u>RADIATION PATTERN F</u>:

$$F(\theta,\phi) = r^2 S_r = \frac{1}{2\eta}\left( |f_1(\theta,\phi)|^2 + |f_2(\theta,\phi)|^2 \right) \quad \left[\frac{\text{Watts}}{\text{sr}}\right]$$

- WE CAN NORMALIZE F TO ITS MAXIMUM VALUE TO GIVE A NORMALIZED ANTENNA RADIATION PATTERN:

$$F_N(\theta,\phi) = \frac{F(\theta,\phi)}{\{F(\theta,\phi)\}_{MAX}}$$

# ANTENNA RADIATION PATTERN
## *LEXICON*

- **SOLID ANGLES (steradians, sr)**

$$\Omega_P = \int_{4\pi} \int F_N(\theta,\phi)\, d\Omega \quad \text{pattern solid angle}$$

$$\Omega_M = \int_{\text{main lobe}} \int F_N(\theta,\phi)\, d\Omega \quad \text{main-beam (-lobe) solid angle to first minimum}$$

$$\Omega_m = \Omega_P - \Omega_M \quad \text{Minor-lobe solid angle}$$

- **MAIN-BEAM EFFICIENCY**

$$d\Omega = \sin(\theta)\, d\theta\, d\phi$$

$$\eta_M = \frac{\Omega_M}{\Omega_P} \text{ (fraction of power emitted in main-lobe)}$$

- **STRAY FACTOR**

$$\eta_m = \frac{\Omega_m}{\Omega_P} = 1 - \eta_M \text{ (fraction of power emitted in minor-lobes)}$$

# ANTENNA BEAM CHARACTERIZATION

- **HALF-POWER (3 dB) BEAMWIDTH** $\beta_{1/2}$
  - ANGULAR WIDTH OF THE MAIN LOBE BETWEEN THE TWO ANGLES AT WHICH: $|F_N| = \frac{1}{2}$
- **BEAMWIDTH BETWEEN FIRST NULLS** $\beta_{null}$
  - ANGULAR WIDTH OF THE MAIN LOBE BETWEEN THE FIRST NULLS ON EITHER SIDE OF THE PEAK IN $|F_N|$
- **ONE CAN ALSO SPECIFY THE BEAMWIDTH TO ANY LEVEL OF $|F_N|$ RELATIVE TO THE PEAK.**

- **DIRECTIVITY**
  - NORMALIZED VALUE OF $|F_N|$ WITH THE NORMALIZATION BEING WITH RESPECT TO THE AVERAGE OF $|F_N|$ OVER $4\pi$
  - THE MAXIMUM DIRECTIVITY $D_0$ IS DEFINED AS THE DIRECTIVITY IN THE DIRECTION WHERE $F_N(\theta,\phi) = 1$

$$D(\theta,\phi) = \frac{F_N(\theta,\phi)}{\frac{1}{4\pi}\int_{4\pi}\int F_N(\theta,\phi)\, d\Omega} = \frac{F_N(\theta,\phi)}{\frac{\Omega_P}{4\pi}}$$

$$D_0 = \frac{1}{\frac{\Omega_P}{4\pi}} = \frac{4\pi}{\Omega_P}$$

$$D(\theta,\phi) = D_0\, F_N(\theta,\phi)$$

# EFFECTIVE AREA

- THE EFFECTIVE AREA OF AN ANTENNA IS DEFINED IN TERMS OF THE ANTENNA DIRECTIVITY

$A_P$ = physical area or aperture of the antenna

$$D_0 = \left(\frac{4\pi}{\lambda^2}\right) A_{eff} = \left(\frac{4\pi}{\lambda^2}\right) \eta_a A_P$$

$$\eta_a = \frac{A_{eff}}{A_P} \quad \text{(aperture efficiency )}$$

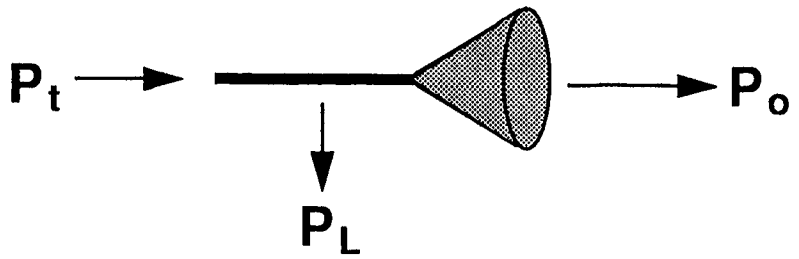
$$A_{eff} = \frac{\lambda^2 D_0}{4\pi} = \frac{\lambda^2}{\Omega_P}$$

$$\Omega_P A_{eff} = \lambda^2 \quad \text{(Antenna Theorem )}$$

# ANTENNA GAIN

- **RADIATION EFFICIENCY** $\eta_L$

$P_t$ = input power to antenna
$P_o$ = radiated power by antenna
$P_L$ = antenna losses




$$\eta_L = \frac{P_o}{P_t}$$

- **ANTENNA GAIN IN THE DIRECTION** $(\theta,\phi)$ $\qquad G(\theta,\phi) = \dfrac{S_r(\theta,\phi)}{S_{ri}}$

$S_r(\theta,\phi)$ = radiated power density in the direction $(\theta,\phi)$
$S_{ri}$ = power density radiated by a lossless, isotropic antenna

$$S_{ri} = \frac{1}{4\pi\eta_L}\int_{4\pi}\int S_r(\theta,\phi)\,d\Omega \qquad \left| \qquad G(\theta,\phi) = 4\pi\eta_L \frac{S_r(\theta,\phi)}{\displaystyle\int_{4\pi}\int S_r(\theta,\phi)\,d\Omega}\right.$$

# ANTENNA GAIN (contd)

- FROM THE DEFINITION OF DIRECTIVITY $G(\theta,\phi) = \eta_L D(\theta,\phi)$

- THE MAXIMUM GAIN IS GIVEN BY $G_0 = \eta_L D_0$

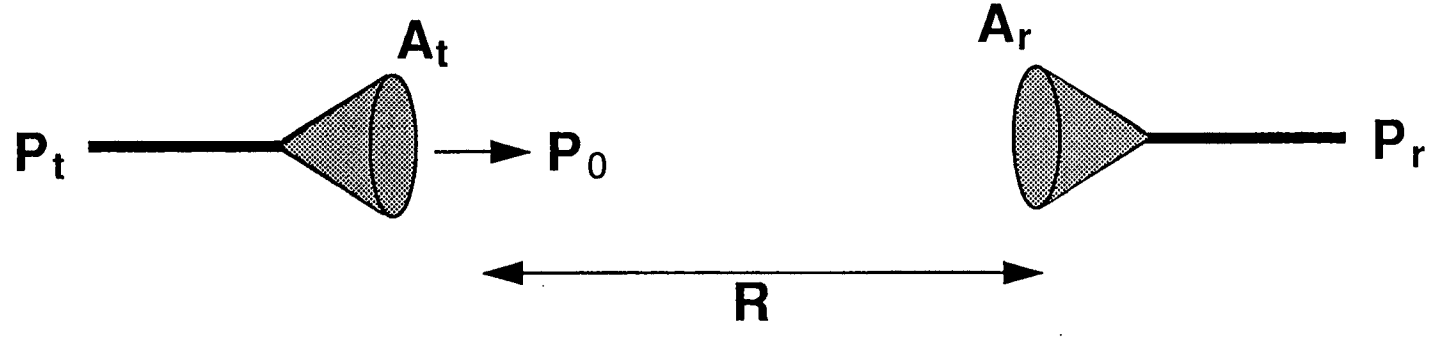
- THE ANTENNA GAIN INCLUDES OHMIC LOSSES DUE TO ANTENNA STRUCTURE, DESIGN, MATERIALS, ..., ETC., WHEREAS THE DIRECTIVITY DOES NOT.

- THE POWER DENSITY RADIATED BY AN ANTENNA IS GIVEN BY:

$$S_r(\theta,\phi) = \frac{P_t G(\theta,\phi)}{4\pi R^2}$$

# FRIIS TRANSMISSION FORMULA

- ASSUME : FREE SPACE, FAR-FIELD, ANTENNA GAIN PEAKS ALIGNED




$A_t$ $A_r$ ARE THE TRANSMITTING AND RECEIVING ANTENNA EFFECTIVE AREAS

- THE POWER INTERCEPTED BY THE RECEIVING ANTENNA AT A DISTANCE R FROM THE TRANSMITTER

$$P_i = S_R A_r = \left(\frac{P_t}{4\pi R^2}\right) G_t A_r$$

$G_t$ = maximum gain of transmitting antenna

# FRIIS TRANSMISSION FORMULA (contd)

$\eta_r = \eta_L$ for the receiving antenna

$P_r$ = power at the output terminal of the receiving antenna

$$P_r = \eta_L P_i = \eta_L G_t^0 A_r \left(\frac{P_t}{4\pi R^2}\right)$$

For the receiving antenna we have

$$G_r^0 = \eta_L D_r^0 = \eta_L \left(\frac{4\pi A_r}{\lambda^2}\right)$$

$$P_R = G_t^0 \left[G_R^0 \left(\frac{\lambda^2}{4\pi}\right)\right] \left(\frac{P_t}{4\pi R^2}\right)$$

$$= G_t^0 G_R^0 \left(\frac{\lambda}{4\pi R}\right)^2 P_t$$

**FRIIS TRANSMISSION FORMULA**

**POWER TRANSFER RATIO**

$$\boxed{\frac{P_R}{P_t} = G_t^0 G_R^0 \left(\frac{\lambda}{4\pi R}\right)^2}$$

# FRIIS TRANSMISSION FORMULA (contd)

- DEFINE THE FREE SPACE TRANSMISSION LOSS

$$L_{FS} = \left(\frac{4\pi R}{\lambda}\right)^2$$

$$\frac{P_R}{P_t} = \frac{G_t^0 G_R^0}{L_{FS}}$$

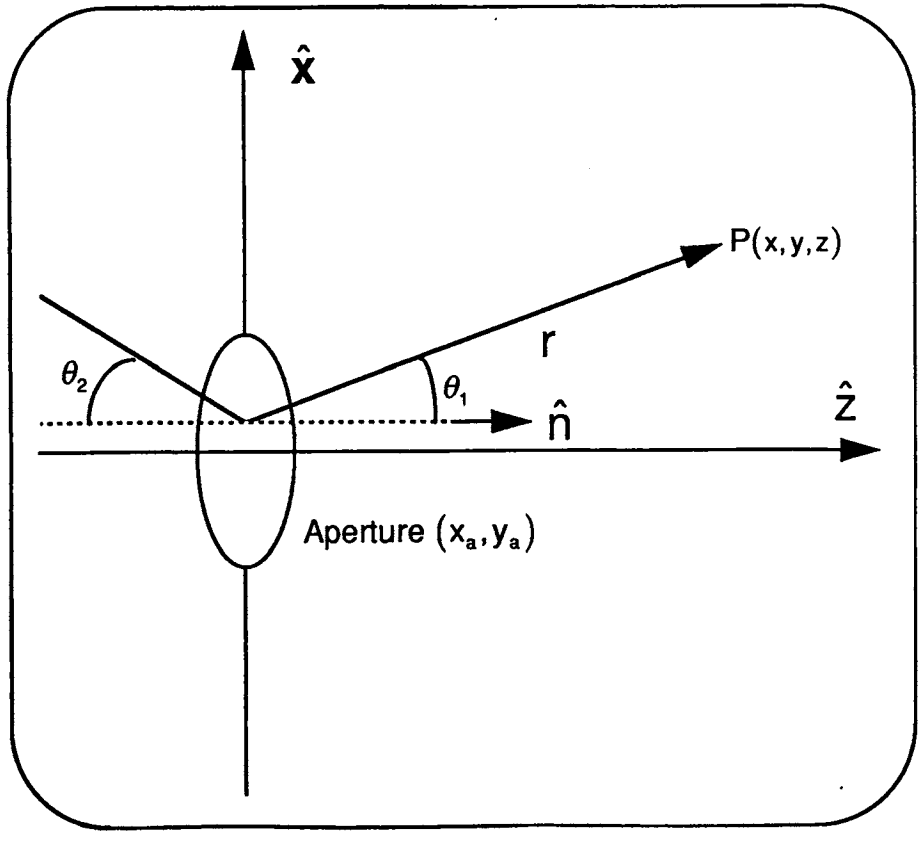
- FOR ANTENNA ORIENTATIONS OTHER THAN MAXIMUM:

$$\frac{P_R}{P_t} = \frac{G_t(\theta_t,\phi_t)\, G_R(\theta_R,\phi_R)}{L_{FS}}$$

# DIFFRACTION THEORY

- **RELATE APERTURE FIELD DISTRIBUTION TO FIELD VALUE AT POINT P**

$$E(x,y,z) = \frac{1}{4\pi}\int_{A_0} E_a(x_a,y_a)\frac{\exp\{-jkr\}}{r}\left[\left(\frac{1}{r}+jk\right)\cos\theta_1 + jk\cos\theta_2\right]dx_a dy_a$$




## FRESNEL APPROXIMATION

$$E(x,y,z) = \frac{j(1+\cos\theta)}{2\lambda}\frac{\exp\{-jkz\}}{r}\exp\left\{-\frac{jk\left(x^2+y^2\right)}{2z^2}\right\}h(x,y,z)$$

where the form factor h is given by

$$h(x,y,z) = \iint E_a(x_a,y_a)\exp\left\{-jk\frac{x_a^2+y_a^2}{2z}\right\}\exp\left\{jk\frac{xx_a+yy_a}{z}\right\}dx_a dy_a$$

# DIFFRACTION THEORY (contd)

- **TO COMPUTE THE ANTENNA PATTERN, DIRECTIVITY OR GAIN WE REQUIRE THE ELECTRIC FIELD COMPONENTS**
  - **CONVERT TO SPHERICAL POLAR COORDINATES CENTERED ON THE APERTURE**

$$x = R\cos\phi\sin\theta$$

$$y = R\sin\phi\sin\theta$$

$$z = R\cos\theta$$

$$E(R,\theta,\phi) = j\frac{1+\cos\theta}{2\lambda}\frac{\exp\{-jkR\}}{R}h(R,\theta,\phi)$$

$$G(\theta,\phi) \propto \left|\frac{1+\cos\theta}{2\lambda R}h(R,\theta,\phi)\right|^2$$

- **FRAUNHOFER REGION - FAR FIELD APPROXIMATIONS**
  - » **OBLIQUITY FACTOR APPROXIMATELY 1**
  - » **APERTURE IS SMALL SUCH THAT THE QUADRATIC PHASE OF THE FORM FACTOR h IS UNITY**

$$\text{OBLIQUITY FACTOR} \quad \frac{1+\cos\theta}{2} \approx 1$$

# DIFFRACTION THEORY (contd)

- **APPLY THE FRAUNHOFER REGION APPROXIMATIONS**

$$E(R,\theta,\phi) = j\frac{\exp\{-jkR\}}{\lambda R}h(\theta,\phi)$$

$$h(\theta,\phi) = \iint E_a(x_a,y_a)\exp\{jk\sin\theta[x_a\cos\phi + y_a\sin\phi]\}dx_a dy_a$$

$$\text{Define} \quad u = \frac{x}{\lambda R} = \frac{\cos\phi\sin\theta}{\lambda}$$

$$v = \frac{y}{\lambda R} = \frac{\sin\phi\sin\theta}{\lambda}$$

- **THE FORM FACTOR h IS NOW THE FOURIER TRANSFORM OF THE APERTURE ELECTRIC FIELD DISTRIBUTION**

$$h(u,v) = FT^{-1}\{E_a(x_a,y_a)\}$$

$$\text{Power Density} \quad S_r = \frac{1}{2\eta\lambda^2R^2}|h(\theta,\phi)|^2$$

# DIFFRACTION THEORY (contd)
# EXAMPLES

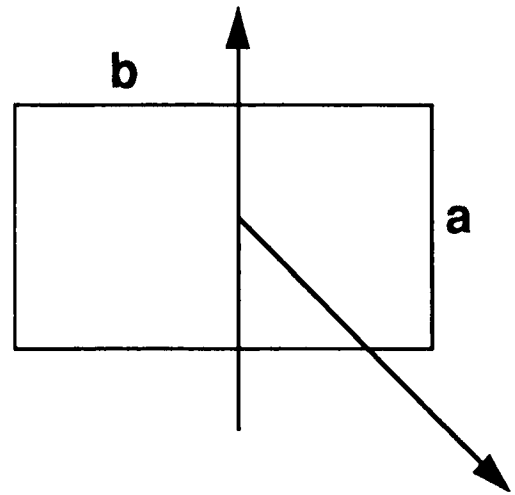
- **RECTANGULAR APERTURE**

$$h(u,v) = E_0 A_p \,\mathrm{sinc}(au)\,\mathrm{sinc}(bv)$$

$$E(u,v) = \frac{jE_0 A_p \exp\{-jkR\}}{\lambda R}\,\mathrm{sinc}(au)\,\mathrm{sinc}(bv)$$

$$\mathrm{sinc}(x) = \frac{\sin(\pi x)}{\pi x}$$

$$A_p = ab$$




- **ANTENNA PATTERN** $F_n(\theta,\phi) = \mathrm{sinc}^2\big(au(\theta,\phi)\big)\,\mathrm{sinc}^2\big(bv(\theta,\phi)\big)$

Half-Power Width (3 dB)

$$\beta_{½,x} = 2\sin^{-1}\left(\frac{1.39\lambda}{\pi a}\right) \approx \frac{0.88\lambda}{a}$$

$$\beta_{½,y} = 2\sin^{-1}\left(\frac{1.39\lambda}{\pi b}\right) \approx \frac{0.88\lambda}{b}$$

Null Width

$$\beta_{null,x} = 2\sin^{-1}\left(\frac{\lambda}{a}\right) \approx \frac{2\lambda}{a}$$

$$\beta_{null,y} = 2\sin^{-1}\left(\frac{\lambda}{b}\right) \approx \frac{2\lambda}{b}$$

# DIFFRACTION THEORY (contd)
# EXAMPLES

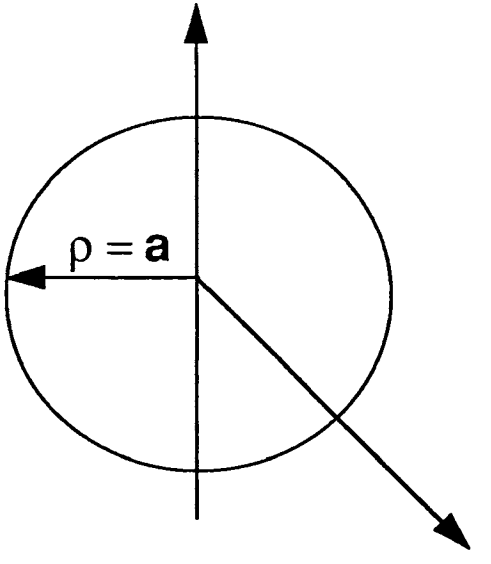
- **CIRCULAR APERTURE**

$$h(\theta,\phi) = h(\theta) = 2\pi\int_0^\infty E_a(\rho)J_0(k\rho\sin\theta)\rho d\rho$$

Uniform Illumination $E_a = E_0$

$$E(q) = j\frac{E_0 A_p}{\lambda R}\frac{2J_1(2\pi aq)}{2\pi aq}\exp\{-jkR\}$$

$$q = \frac{\sin\theta}{\lambda},\quad A_p = \pi a^2$$




- **ANTENNA PATTERN** $\quad F_n(\theta,\phi) = \left[\frac{J_1(2\pi aq)}{2\pi aq}\right]^2$

Half-Power Width (3 dB)

$$\beta_{½} = 2\sin^{-1}\left(\frac{0.25\lambda}{a}\right) \approx \frac{0.5\lambda}{a} \approx \frac{\lambda}{d}$$

Null Width (3 dB)

$$\beta_{null} = 2\sin^{-1}\left(\frac{0.61\lambda}{a}\right) \approx \frac{1.22\lambda}{a} \approx \frac{2.44\lambda}{d}$$

# RECTANGULAR APERTURE DISTRIBUTION FUNCTIONS

| APERTURE DISTRIBUTION | E(x) $\left(\lvert x\rvert < a/2\right)$ | F(u) $u = \left(\pi a/\lambda\right)\sin\theta$ | FIRST NULL (rad) | 3dB BEAMWIDTH (rad) | RELATIVE GAIN | SIDE LOBE LEVEL (dB) |
|---|---|---|---|---|---|---|
| RECTANGLE | 1 | $a\frac{\sin u}{u}$ | $\sin^{-1}\left(\frac{\lambda}{a}\right)$ | $0.886\frac{\lambda}{a}$ | 1 | -13.3 |
| VEE SHAPE | $\frac{2}{a}\lvert x\rvert$ | $a\left(\frac{\sin u}{u} - \frac{1-\cos u}{u^2}\right)$ | $\sin^{-1}\left(0.75\frac{\lambda}{a}\right)$ | $0.796\frac{\lambda}{a}$ | 0.742 | -4.6 |
| PARABOLA | $1-\left(\frac{2x}{a}\right)^2$ | $\frac{2a}{u^2}\left(\frac{\sin u}{u} - \cos u\right)$ | $\sin^{-1}\left(1.43\frac{\lambda}{a}\right)$ | $1.179\frac{\lambda}{a}$ | 0.833 | -21.3 |
| TRIANGLE | $1-\left(\frac{2\lvert X\rvert}{a}\right)$ | $\frac{a}{2}\frac{\sin^2 u}{\left(u/2\right)^2}$ | $\sin^{-1}\left(2\frac{\lambda}{a}\right)$ | $1.273\frac{\lambda}{a}$ | 0.742 | -26.5 |
| COSINE | $\cos\left(\frac{\pi x}{a}\right)$ | $2\pi a\frac{\cos u}{\pi^2-(2u)^2}$ | $4\pi a^2\frac{J_3(u)}{u^3}$ | $1.189\frac{\lambda}{a}$ | 0.81 | -23.1 |
| COSINE SQUARED | $\cos^2\left(\frac{\pi x}{a}\right)$ | $\frac{a}{2}\left(\frac{\sin u}{u}\right)\frac{\pi^2}{\pi^2-u^2}$ | $\sin^{-1}\left(2\frac{\lambda}{a}\right)$ | $1.441\frac{\lambda}{a}$ | 0.667 | -31.5 |

# CIRCULAR APERTURE DISTRIBUTION FUNCTIONS

| APERTURE DISTRIBUTION | E(r) $\rho < a/2$ | F(u) $u = \left(\pi a/\lambda\right)\sin\theta$ | FIRST NULL (rad) | 3dB BEAMWIDTH (rad) | RELATIVE GAIN | SIDE LOBE LEVEL (dB) |
|---|---|---|---|---|---|---|
| UNIFORM | 1 | $\frac{\pi a^2}{2}\frac{J_1(u)}{u}$ | $\sin^{-1}\left(1.22\frac{\lambda}{a}\right)$ | $1.016\frac{\lambda}{a}$ | 1 | -17.6 |
| PARABOLA | $1-\left(2\rho/a\right)^2$ | $\pi a^2\frac{J_2(u)}{u^2}$ | $\sin^{-1}\left(1.63\frac{\lambda}{a}\right)$ | $1.267\frac{\lambda}{a}$ | 0.75 | -24.6 |
| PARABOLA SQUARED | $\left(1-\left(2\rho/a\right)^2\right)^2$ | $4\pi a^2\frac{J_3(u)}{u^3}$ | $\sin^{-1}\left(2.03\frac{\lambda}{a}\right)$ | $1.47\frac{\lambda}{a}$ | 0.55 | -30.6 |

# 2.0 PASSIVE MICROWAVE REMOTE SENSING

# PASSIVE MICROWAVE REMOTE SENSING

## TOPICS

- 2.1 PHENOMENOLOGY
- 2.2 MICROWAVE RADIOMETRY
- 2.3 RADIOMETER SYSTEMS
- 2.4 SENSOR SYSTEM CONCEPTS
- 2.5 SYNTHETIC APERTURE AND INTERFEROMETRIC SYSTEMS
- 2. 6 APPLICATIONS

# 2.1 PHENOMENOLOGY OF PASSIVE MICROWAVE REMOTE SENSING

- THERMAL RADIATION
  - BLACKBODY RADIATION; PLANCK'S LAW
  - NON-BLACKBODY RADIATION; EMISSIVITY
- SURFACE PROPERTIES
- ATMOSPHERIC PROPAGATION

# BLACKBODY RADIATION

- THERMAL RADIATION EMITTED BY ALL OBJECTS

- PLANCK'S LAW: SPECTRAL RADIANCE OR RADIANT EMITTANCE

$$B_f(T) = \frac{2hf^3}{c^2}\left(\frac{1}{\exp(hf/kT) - 1}\right)\left(\frac{W}{m^2\text{-}sr\text{-}Hz}\right)$$

- EMISSIVITY: $\varepsilon = \frac{B_{obs,f}(T)}{B_f(T)} \leq 1$

- STEFAN-BOLTZMANN LAW: $B_{total}(T) = \frac{\sigma T^4}{\pi}$, $\sigma = 5.67 \times 10^{-8}\left(\frac{W}{m^2\text{-}K^4\text{-}sr}\right)$

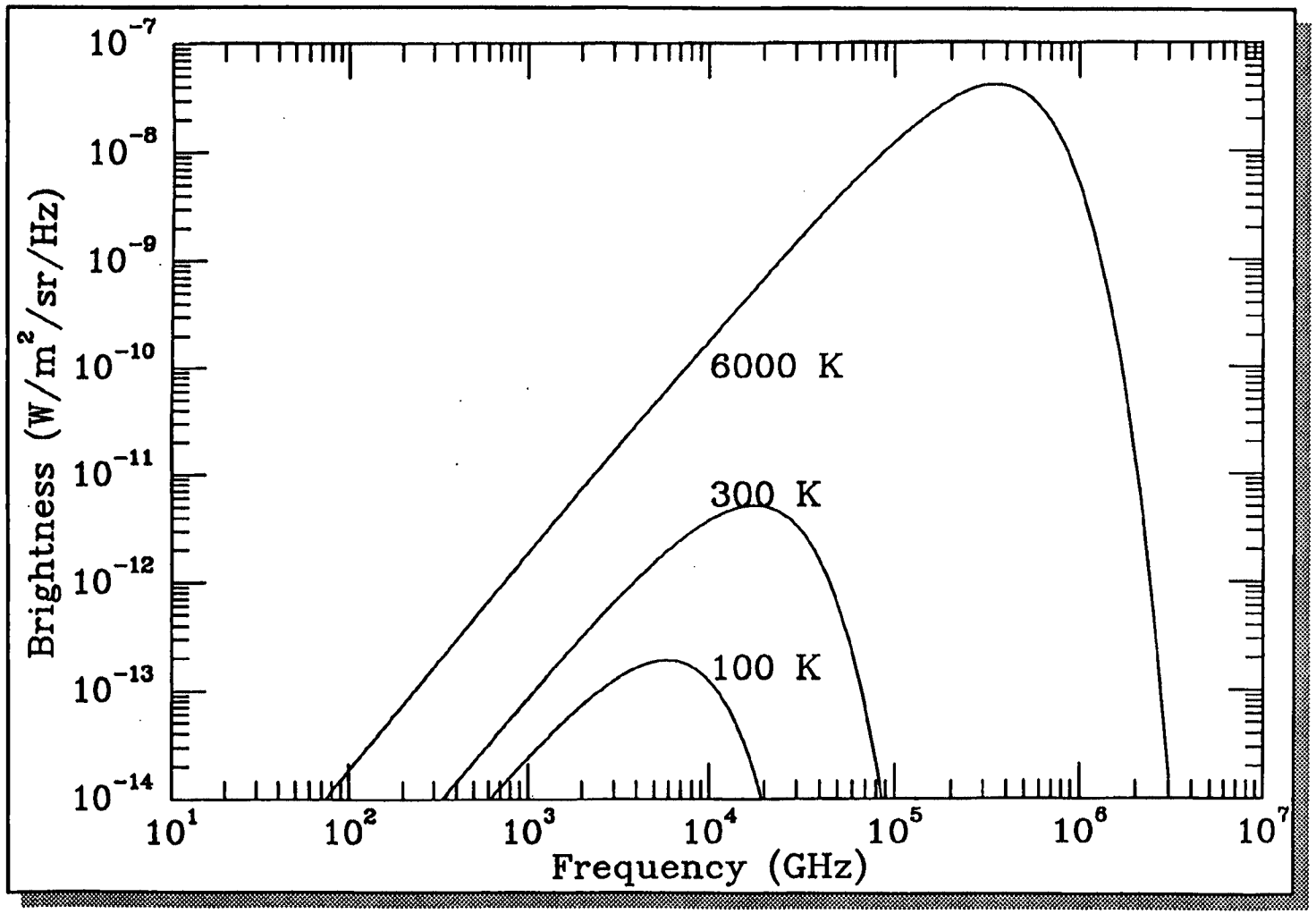
- WIEN'S DISPLACEMENT LAW: $\frac{f_{max}}{T} = 58.7\,\frac{GHz}{K}$

- KIRCHHOFF'S LAW: Good emitters are good absorbers, that's why its called a blackbody

$$\varepsilon(f) = \alpha(f)$$

# BLACKBODY RADIATION SPECTRUM

## PLANCK FUNCTION

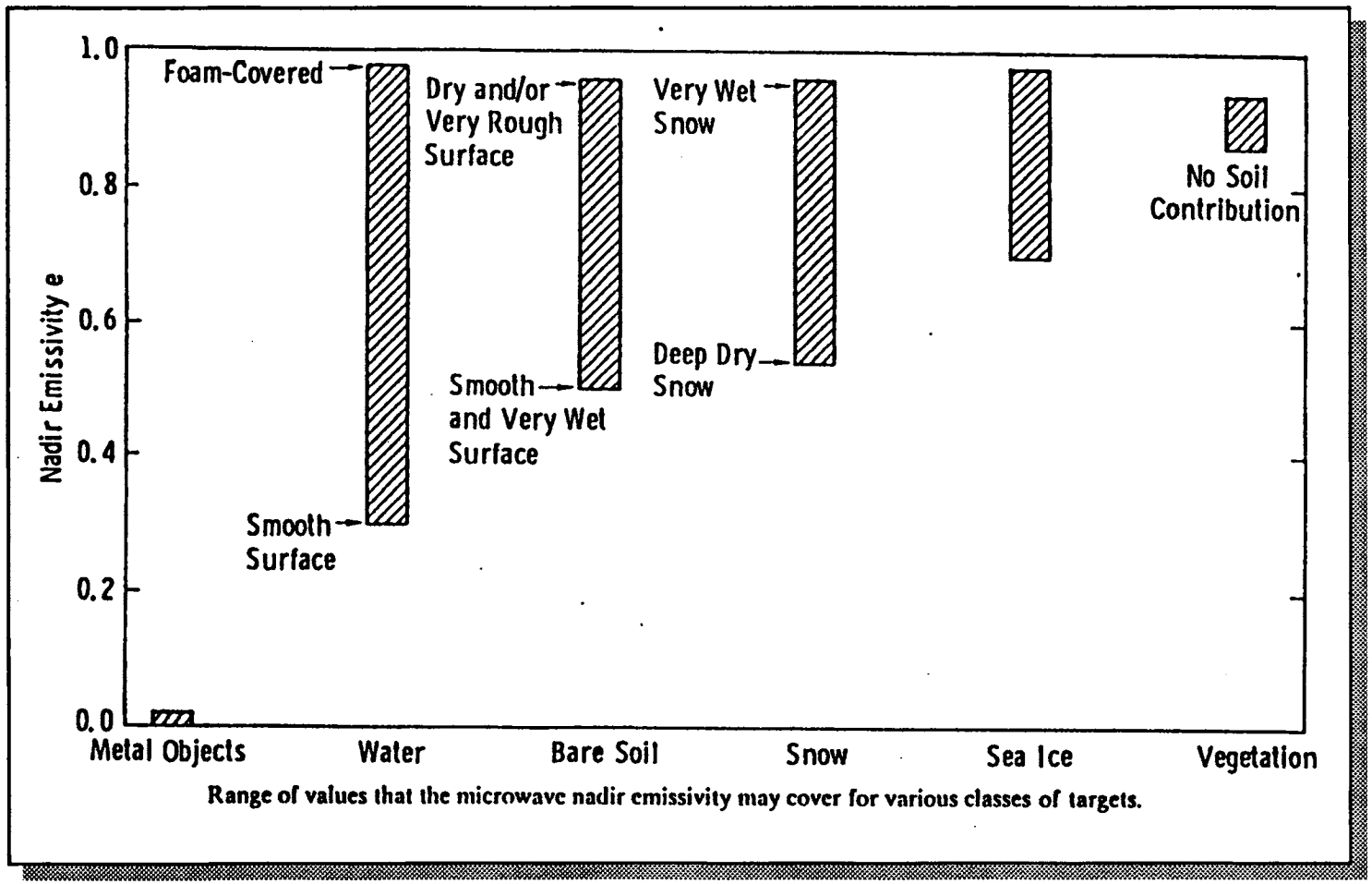


# MICROWAVE PROPERTIES OF THE LAND SURFACE AND OCEANS

- **LAND SURFACE EMISSION AND SCATTERING**
  - FREQUENCY, POLARIZATION AND INCIDENCE ANGLE DEPENDENT
  - REQUIRES MODELS WHICH INCLUDE BOTH SURFACE AND VOLUME EFFECTS
  - DEPENDS ON: DIELECTRIC CONSTANT, SOIL MOISTURE, GROUND COVER (VEGETATION, SNOW, ICE) AND SURFACE ROUGHNESS

- **OCEAN SURFACE EMISSION AND SCATTERING**
  - FREQUENCY, POLARIZATION AND INCIDENCE ANGLE DEPENDENT
  - SKIN DEPTH VERY SMALL - SURFACE SCATTERING/EMISSION ONLY
  - BRAGG SCATTERING OR RESONANCE EFFECT IMPORTANT
  - DEPENDENCE ON OCEAN SURFACE WAVE SPECTRUM, FOAM AND WHITECAPS

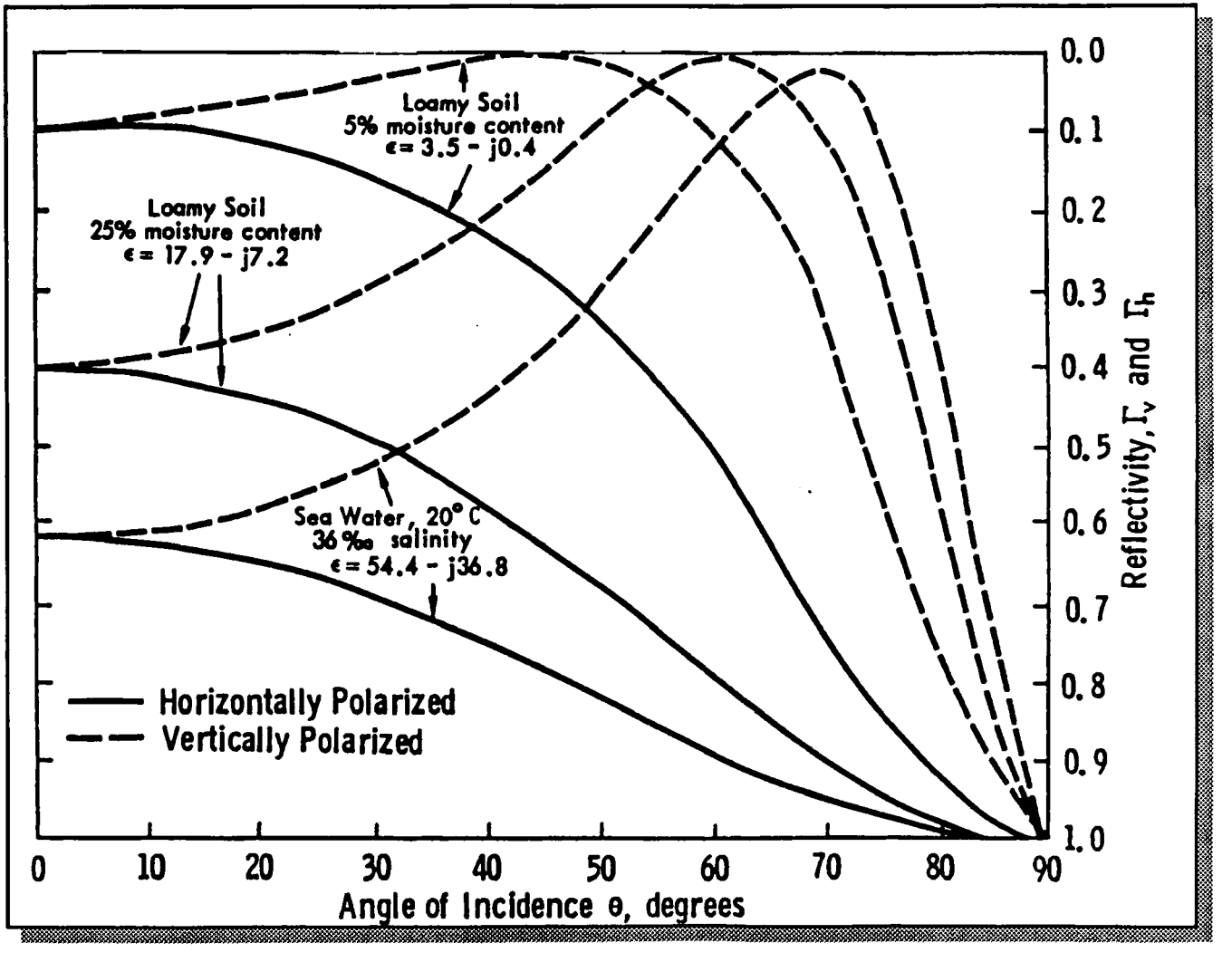
# MICROWAVE EMISSIVITY FOR A VARIETY OF MATERIALS




Range of values that the microwave nadir emissivity may cover for various classes of targets.

From: F. T. Ulaby, Microwave Remote Sensing: Active and Passive, Vol. I, © 1981-1986 Artech House, Inc., Norwood, MA.

# REFLECTIVITY OF VARIOUS SURFACES
## NOTE BREWSTER ANGLE FOR EACH MATERIAL IN THE VERTICALLY POLARIZED SIGNAL




From: F laby, *Notes for Engineering Summer Conferences, Course 8722, Radar S ttering & Image Interpretation*, Univ. of Michigan (1987).

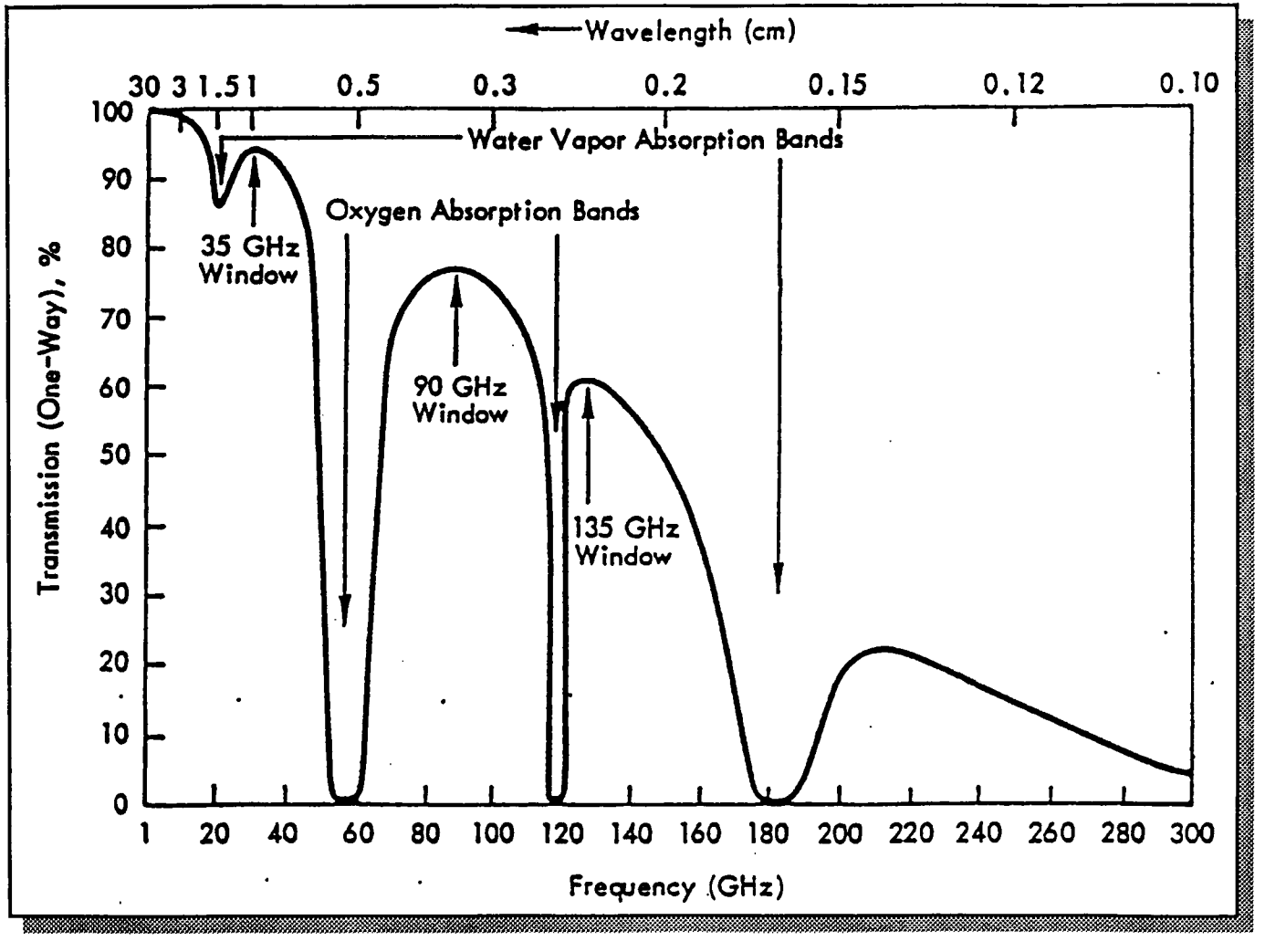
# MICROWAVE PROPERTIES OF THE ATMOSPHERE

- **ABSORPTION**
  - DOMINATED BY GASEOUS WATER AND OXYGEN, SOME TRACE GASES ALSO CONTRIBUTE
  - LIQUID DROPLETS IN CLOUDS, FOG AND RAIN (MIE THEORY FOR $\sigma_A$)

- **SCATTERING**
  - MIE SCATTERING FROM LIQUID WATER DROPLETS, SNOW AND ICE PARTICLES
  - $\sigma_S$ DEPENDS ON PARTICLE DENSITY, SHAPE, SIZE DISTRIBUTION AND COMPLEX DIELECTRIC CONSTANT

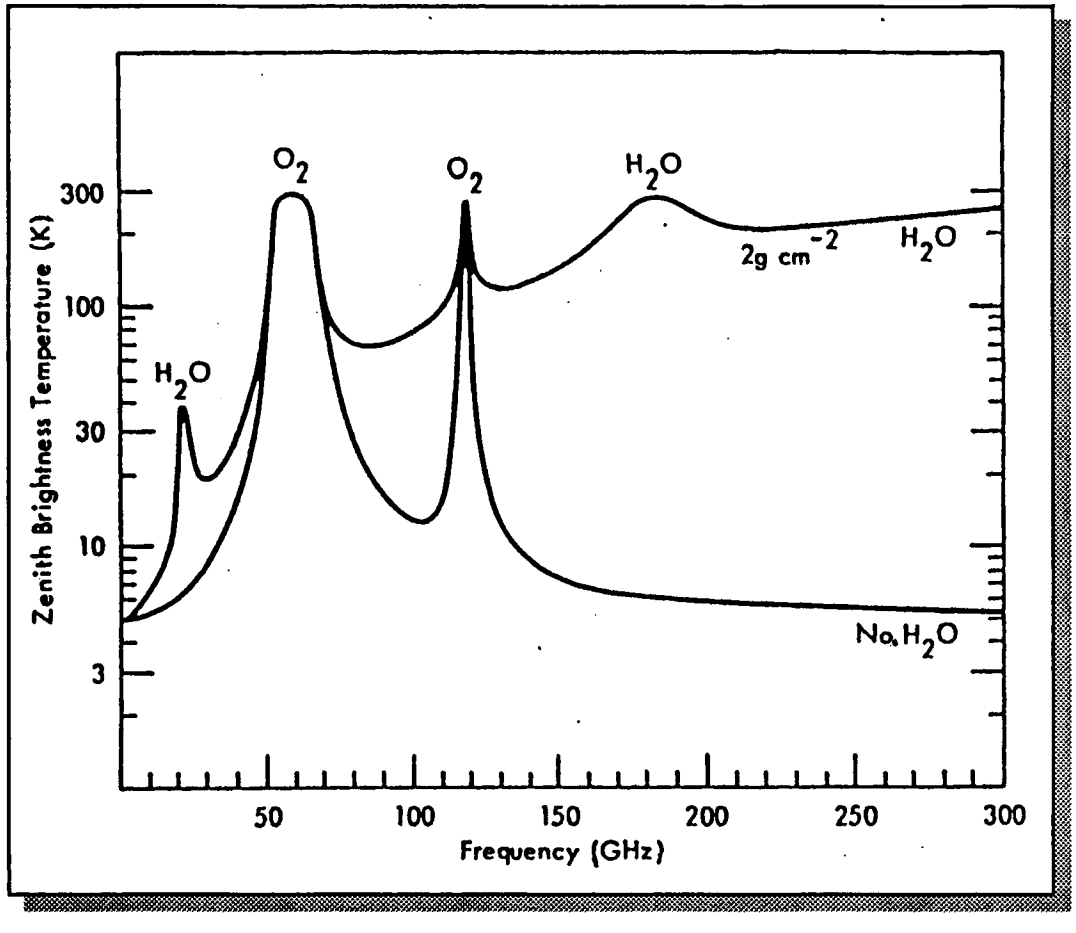
- **EMISSION**
  - THERMAL EMISSION FROM ATMOSPHERIC GASES AND CLOUDS
  - EMISSIVITY
    - * STRONG FUNCTION OF FREQUENCY ABOVE 10 GHz
    - * INCREASES WITH RAIN RATE

# ATMOSPHERIC TRANSMISSION



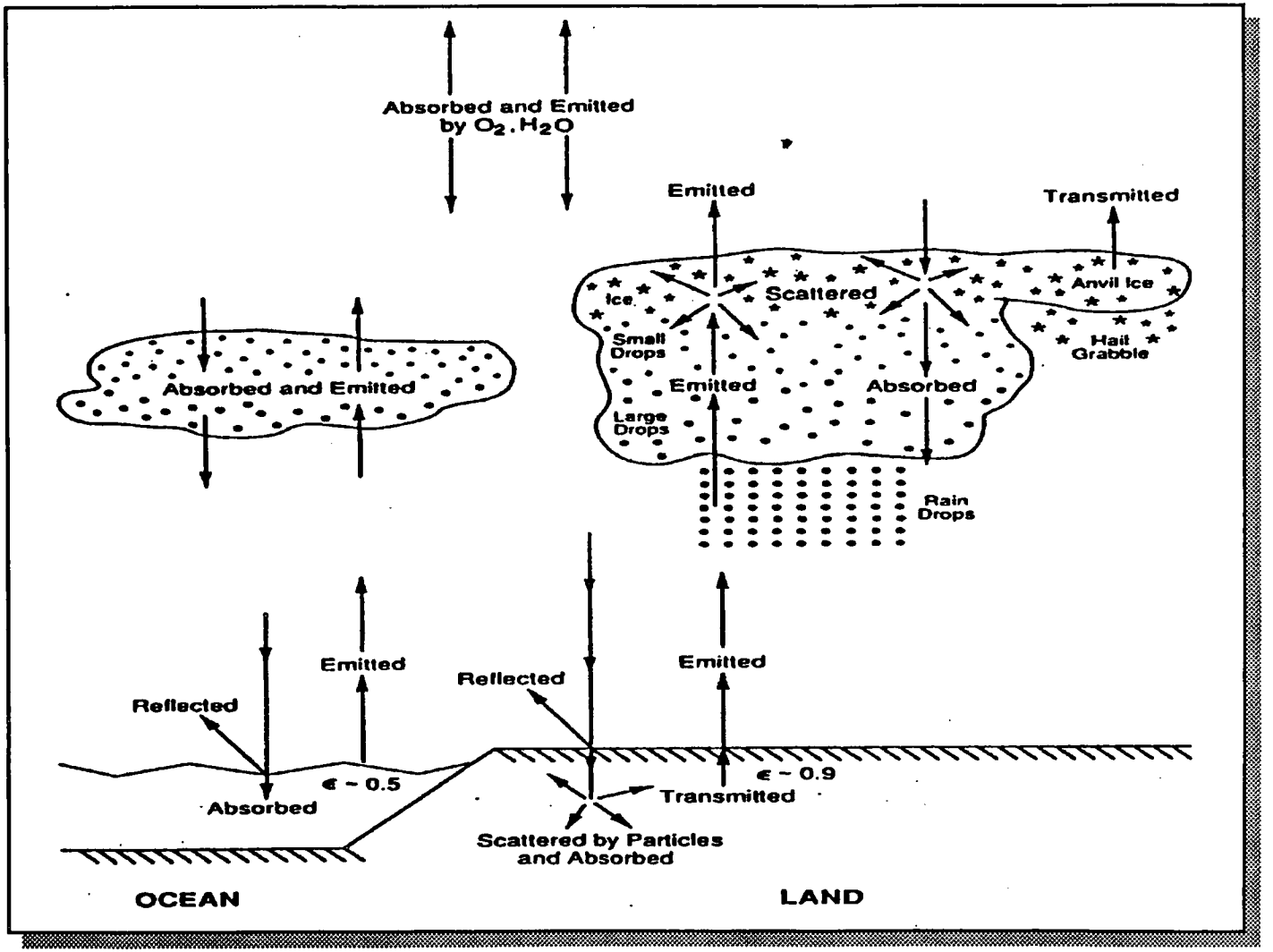

From: F. )by, Microwave Remote Sensing: Active and Passive, Vol. I, © 1981-19 rtech House, Inc., Norwood, MA.

# ATMOSPHERIC EMISSION




From: F. T. Ulaby, Microwave Remote Sensing: Active and Passive, Vol. I, © 1981-1986 Artech House, Inc., Norwood, MA.

# MICROWAVE INTERACTIONS




From: W Satellites: Systems, Data, and Environmental Applications, P. K. Rao, ed., American Meteorological Society, Boston (© 1990).

# 2.2 MICROWAVE RADIOMETRY

- DEFINITION OF RADIOMETRY
  - TERMS, SYMBOLS AND UNITS
- POWER-TEMPERATURE RELATIONSHIP
  - BRIGHTNESS TEMPERATURE
  - APPARENT TEMPERATURE
  - ANTENNA TEMPERATURE
- ANTENNA CONSIDERATIONS
- RADIATIVE TRANSFER THEORY

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## • DEFINITION OF RADIOMETRY

- SCIENTIFIC DISCIPLINE RELATING TO THE MEASUREMENT OF ELECTROMAGNETIC RADIATION; USUALLY IMPLIES AN ABSOLUTE MEASUREMENT (I.E., CALIBRATION)
- TABLE ON FOLLOWING CHART PROVIDES THE DEFINITIONS OF VARIOUS QUANTITIES USED IN MICROWAVE RADIOMETRY
- ALL QUANTITIES DEPEND ON FREQUENCY (WAVELENGTH) AND MAY DEPEND ON TIME (t) AND POSITION ($\vec{r}$).

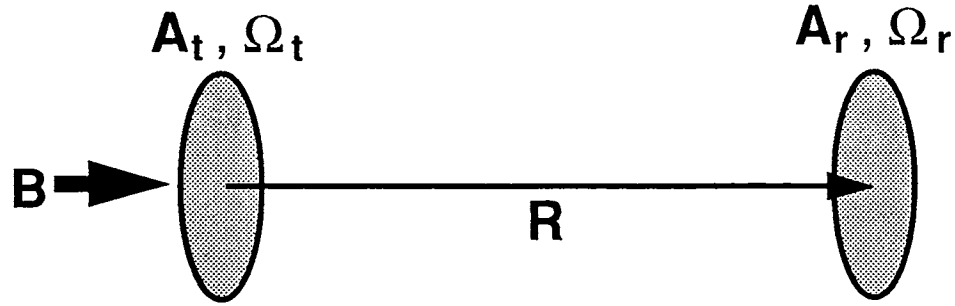
# RADIOMETRIC QUANTITIES

| QUANITY | SYMBOL | DEFINITION | UNITS |
|---|---|---|---|
| ENERGY | E | - | J |
| ENERGY DENSITY | $E_v$ | $E_v = \frac{\partial E}{\partial V}$ | $J/m^3$ |
| POWER | P | $P = \frac{\partial E}{\partial t}$ | W |
| POWER DENSITY | S | $S = \frac{\partial P}{\partial A}$ | $W/m^2$ |
| INTENSITY | F or I | $F = \frac{\partial P}{\partial \Omega}$ | $W/sr$ |
| BRIGHTNESS/RADIANCE | B or L | $B = \frac{\partial^2 P}{\partial \Omega \partial A}$ | $W/sr \cdot m^2$ |
| EMISSIVITY | $\varepsilon$ | $\varepsilon = B_{obs}(f,T)/B_{BB}(f,T)$ | none |
| REFLECTIVITY | $\Gamma$ | $\Gamma = \frac{P_r}{P_i}$ | none |
| ABSORPTIVITY | $\alpha$ | $\alpha = \frac{P_a}{P_i}$ | none |
| TRANSMISSIVITY | $\tau$ | $\tau = \frac{P_t}{P_i}$ | none |

After: Ulaby, et al., Microwave Remote Sensing: Active and Passive, Vol. I, © 1981-1986 Artech House, Inc., Norwood, MA.

# BRIGHTNESS

$\Omega_i$ = solid angle subtended by aperture i as viewed from the opposite aperture (area A )




ANTENNA APERTURES ALIGNED ALONG MAXIMUM DIRECTIVITY

$S_t$ = transmitted power density $\left[\frac{W}{m^2}\right]$ assumed constant over $A_r$

$P_r = S_t A_r$ = received power [W]

$F_t = S_t R^2$ (Intensity) $\left[\frac{W}{sr}\right]$

$P_r = \frac{F_t}{R^2} A_r$ (received power-point sources)

## FOR EXTENDED SOURCES DEFINE

$$B = \frac{F_t}{A_t} \left[\frac{W}{m^2\ sr}\right]$$

$$P_r = \frac{B\ A_r\ A_t}{R^2}$$

$$\Omega_t = \frac{A_t}{R^2} \Rightarrow P_r = B\ A_r\ \Omega_t$$

# BRIGHTNESS (contd)

- FOR AN EXTENDED SOURCE AND RECEIVING ANTENNA WITH DIRECTIONAL DISTRIBUTIONS:

$$P_r = \frac{A_r}{2}\int_{\Delta f} df \int_{4\pi} B_f(\theta,\phi)\, F_N(\theta,\phi)\, d\Omega \qquad [\text{WATTS}]$$

WHERE WE HAVE INCLUDED THE FREQUENCY DEPENDENCE (f) AND THE FACT THAT MOST MICROWAVE ANTENNAS ARE DESIGNED TO MEASURE ONLY A SINGLE POLARIZATION, AND THE BRIGHTNESS IS ASSUMED UNPOLARIZED. THE SPECTRAL POWER (FLUX) DENSITY IS GIVEN BY:

$$S_f = \int_{4\pi} B_f(\theta,\phi)\, F_N(\theta,\phi)\, d\Omega \qquad \left[\frac{\text{WATTS}}{m^2\ \text{Hz}}\right]$$

$$P_r = \frac{A_r}{2}\int_{\Delta f} df\ S_f$$

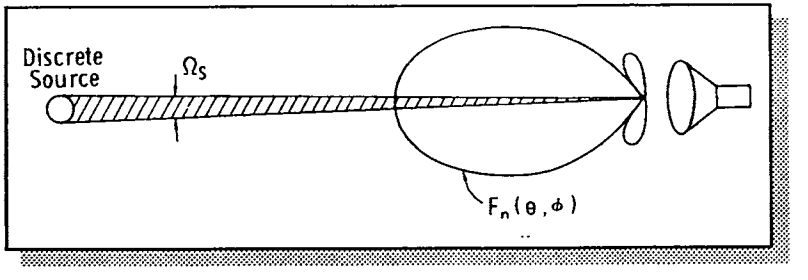
# BRIGHTNESS (contd)

## DISCRETE SOURCES

- FOR SOURCES NOT SMALL ENOUGH TO BE A POINT SOURCE AND NOT LARGE ENOUGH TO COMPLETELY FILL THE MAIN BEAM WE HAVE:

$\Omega_S$ = solid angle subtended by source with brightness $B_f^0$

$$S_f^0 = \int_{\text{main beam}} B_f^0(\theta,\phi)\, F_N(\theta,\phi)\, d\Omega$$




IF $F_N \approx 1$ OVER $\Omega_S$ THEN

$$S_f^0 \approx B_f^0\, \Omega_S$$

From: F. T. Ulaby, et al., Microwave Remote Sensing: Active and Passive, Vol. I, © 1981-1986 Artech House, Inc., Norwood, MA.

# POWER - TEMPERATURE CORRESPONDENCE

- **RECALL THE RAYLEIGH-JEANS APPROXIMATION FOR BLACKBODY RADIATION (T = physical temperature)**

$$B_{f,BB} = \frac{2kT}{\lambda^2}\left[\frac{\text{Watts}}{m^2\ \text{sr Hz}}\right] \qquad \frac{hc}{\lambda kT} << 1$$

**CONSIDER AN ANTENNA SURROUNDED BY A BB (SEE FIGURE ON NEXT CHART). THE RECEIVED POWER DUE TO THE BB RADIATION IS:**

$$P_{BB} = \frac{A_r}{2}\int_{\Delta f} df \int_{4\pi} B_{f,BB}(\theta,\phi)\, F_N(\theta,\phi)\, d\Omega$$

$$= \frac{A_r}{2}\int_{\Delta f} df \int_{4\pi} \frac{2kT}{\lambda^2} F_N(\theta,\phi)\, d\Omega$$

**Assume** $\left(\frac{\Delta f}{f}\right) << 1$ **then**

$$P_{BB} \approx \frac{A_r \Delta f}{2}\left(\frac{2kT}{\lambda^2}\right)\int_{4\pi} F_N(\theta,\phi)\, d\Omega$$

$$\approx \left(\frac{kT\,\Delta f A_r}{\lambda^2}\right)\Omega_P$$

$\Omega_P A_r = \lambda^2$ **(Antenna Theorem)**

$$\boxed{P_{BB} \approx kT\Delta f}$$

**FUNDAMENTAL POWER-TEMPERATURE RELATIONSHIP FOR A LOSSLESS ANTENNA AND NOISE FREE RECEIVER**

# POWER - TEMPERATURE CORRESPONDENCE (contd)

- **NON-BLACKBODIES**
  - **IN ANALOGY TO THE CASE FOR A PERFECT BLACKBODY, DEFINE SIMILAR EXPRESSION BUT INCLUDE EMISSIVITY**

$$B_f(\theta,\phi) = \frac{2kT_B(\theta,\phi)}{\lambda^2}$$

$T_B(\theta,\phi) =$ Brightness Temperature

$$\varepsilon_f(\theta,\phi) = \frac{B_f(\theta,\phi)}{B_{f,BB}(\theta,\phi)} = \frac{T_B(\theta,\phi)}{T} \leq 1$$

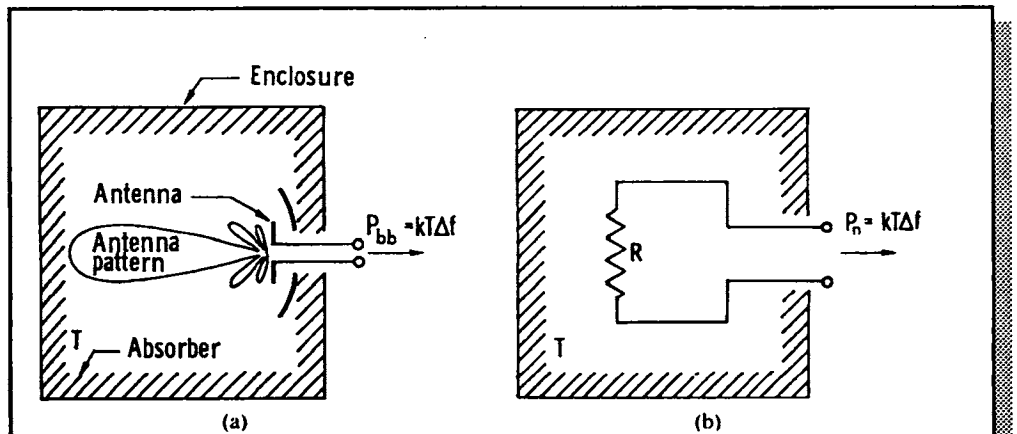



**Fig. 4.6** The power delivered by (a) an antenna placed inside a blackbody enclosure of temperature $T$ is equal to the power delivered by (b) a resistor maintained at the same temperature $T$ (assuming each is connected to a matched receiver of bandwidth $\Delta f$).

# APPARENT TEMPERATURE

- **NOTE THE FIGURE ON THE FOLLOWING CHART**
  - **CONTRIBUTIONS TO TOTAL RADIATION INCIDENT ON THE ANTENNA**
  - **POWER OUTPUT OF ANTENNA IS RELATED TO THE VARIOUS SOURCES IN THE *SCENE***
  - **TO AVOID CONFUSION, FOLLOWING ULABY, ET AL., WE USE**

**BRIGHTNESS TEMPERATURE** $T_B \Leftrightarrow$ **SELF-EMITTED RADIATION FROM A SURFACE OR VOLUME**

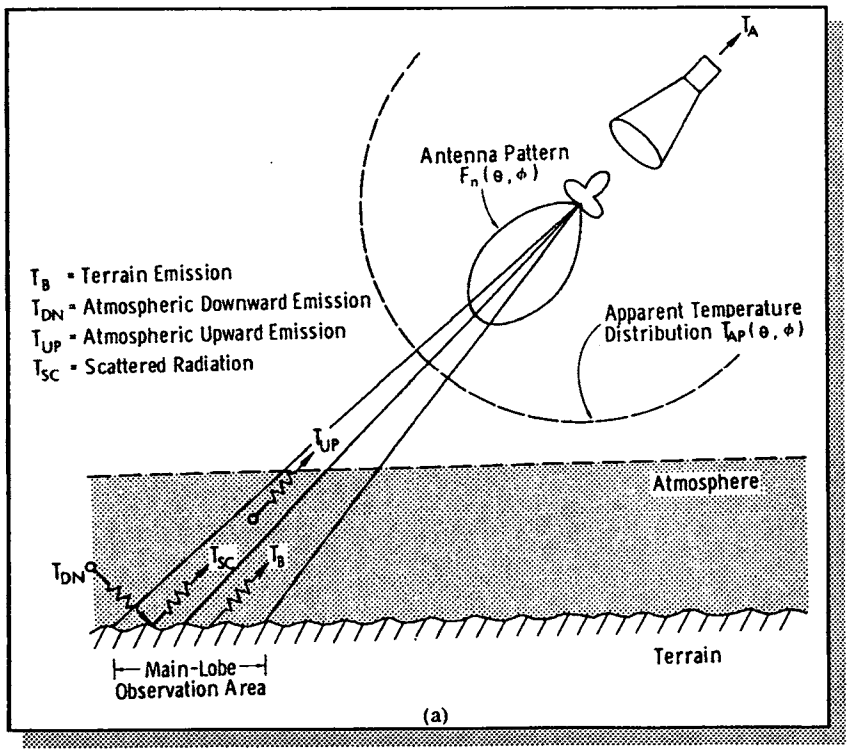
**APPARENT TEMPERATURE** $T_{AP} \Leftrightarrow$ **ENERGY OR RADIATION INCIDENT UPON AN ANTENNA**

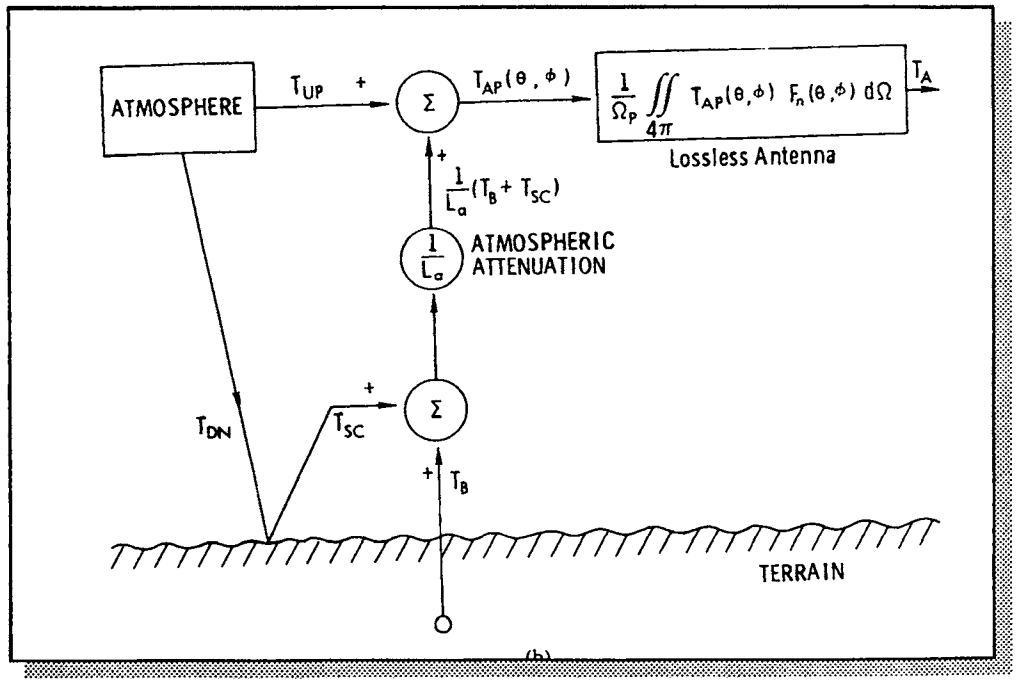
DEFINE $T_{AP}$ IN TERMS OF AN INCIDENT

BRIGHTNESS DISTRIBUTION $B_{inc}$

$$B_{inc}(\theta,\phi) = \left(\frac{2k}{\lambda^2}\right) T_{AP}(\theta,\phi)$$

# RELATIONSHIP BETWEEN ANTENNA, APPARENT, AND BRIGHTNESS TEMPERATURES

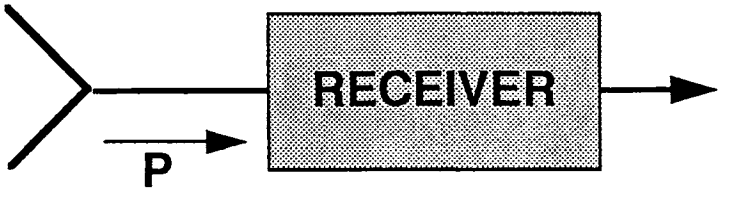



**$T_{AP}$ is a sum of terms due to $T_{up}$ and $\frac{1}{L_a}(T_B + T_{SC})$**

# ANTENNA TEMPERATURE

RESISTOR EQUIVALENT TEMPERATURE IS DEFINED SUCH THAT THE NOISE POWER DELIVERED BY THE RESISTOR IS EQUAL TO THE ACTUAL POWER P




$$P = P_{noise} = kT_A\Delta f$$

$$P = \frac{A_r\Delta f}{2}\int_{4\pi} B_i(\theta,\phi)\, F_N(\theta,\phi)\, d\Omega$$

$$T_A = \frac{A_r}{\lambda^2}\int_{4\pi} T_{AP}(\theta,\phi)\, F_N(\theta,\phi)\, d\Omega$$

$T_A$ = ANTENNA RADIOMETRIC TEMPERATURE

# ANTENNA TEMPERATURE (contd)

- RECALL THAT:

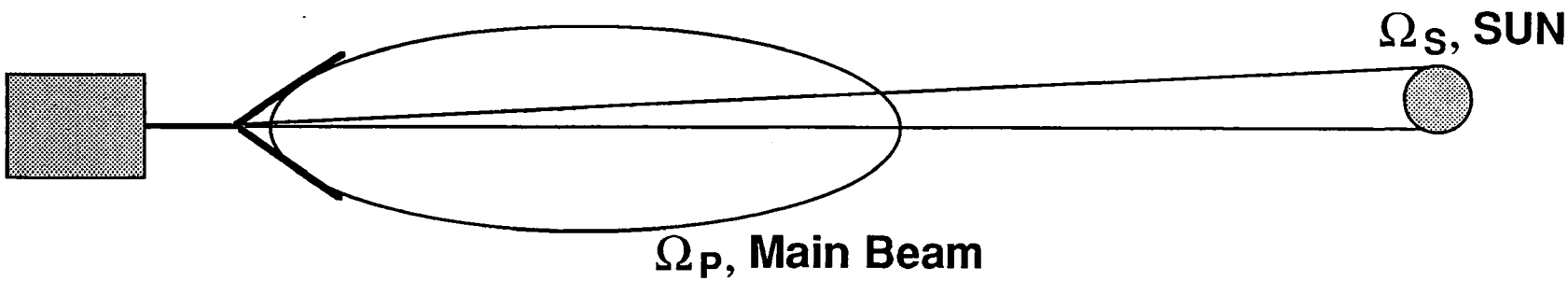
$$A_r \, \Omega_P = \lambda^2$$

$$\Omega_P = \int_{4\pi} F_N(\theta,\phi)\, d\Omega$$

- THIS IMPLIES THAT THE ANTENNA TEMPERATURE IS A WEIGHTED AVERAGE OF THE APPARENT TEMPERATURE DISTRIBUTION:

$$T_A = \frac{\int_{4\pi} T_{AP}(\theta,\phi)\, F_N(\theta,\phi)\, d\Omega}{\int_{4\pi} F_N(\theta,\phi)\, d\Omega}$$

- RADIO TELESCOPE OBSERVING THE SUN

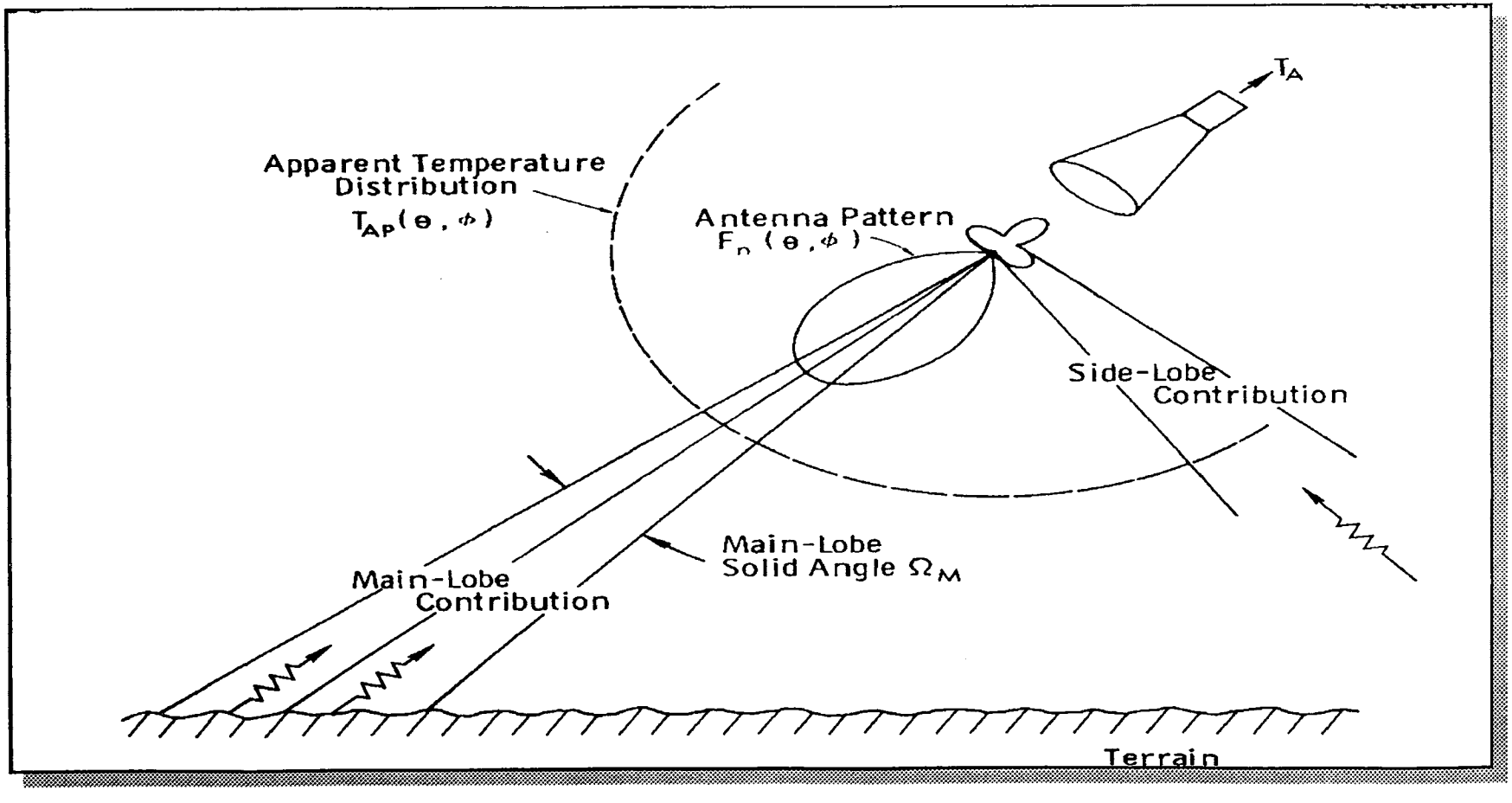



$T_S$ = apparent temperature of the sun, neglecting atmospheric losses and other sources

$$T_A = \left[\frac{\Omega_S}{\Omega_P}\right] T_S$$

# ANTENNA EFFICIENCY

- A MICROWAVE RADIOMETER IS A PASSIVE DEVICE AND MUST RELY PRIMARILY ON THE ANTENNA PATTERN TO ACHIEVE SPATIAL RESOLUTION. THE ANTENNA SIDE LOBES WILL RECEIVE SOME THERMAL EMISSION FROM VARIOUS SOURCES. WHAT IS THE EFFECT OF THE ENERGY RECEIVED BY THE SIDE LOBES?




From: F ...aby, et al., Microwave Remote Sensing: Active and Passive, Vol. I, © 19... 1986 Artech House, Inc., Norwood, MA.

# ANTENNA EFFICIENCY (contd)

$$T_A = [\text{MAIN LOBE} \quad (\text{ML})] \; + \; [\text{SIDE LOBES} \quad (\text{SL})]$$

$$\tilde{F}_N = \frac{F_N(\theta,\phi)}{\Omega_P} \qquad \text{SL} = 4\pi - \text{ML}$$

$$T_A = \int_{ML} T_{AP}(\theta,\phi)\, \tilde{F}_N(\theta,\phi)\, d\Omega \; + \int_{SL} T_{AP}(\theta,\phi)\, \tilde{F}_N(\theta,\phi)\, d\Omega$$

- DEFINE THE EFFECTIVE APPARENT TEMPERATURE MAIN LOBE (ML) CONTRIBUTION:

$$\overline{T}_{ML} = \frac{\int_{ML} T_{AP}(\theta,\phi)\, F_N(\theta,\phi)\, d\Omega}{\int_{ML} F_N(\theta,\phi)\, d\Omega}$$

# ANTENNA EFFICIENCY (contd)

- RECALL THE MAIN-BEAM EFFICIENCY DEFINITION AND GENERATE A SIMILAR TERM FOR THE SIDE LOBE CONTRIBUTION

$$\eta_M = \frac{\int_{ML} F_N(\theta,\phi)\, d\Omega}{\Omega_P}$$

$$\eta_{SL} = \frac{\int_{SL} F_N(\theta,\phi)\, d\Omega}{\Omega_P} = 1 - \eta_M$$

$$[ML] = \eta_M \overline{T}_{ML}$$

$$\overline{T}_{SL} = \frac{\int_{SL} T_{AP}(\theta,\phi)\, F_N(\theta,\phi)\, d\Omega}{\int_{SL} F_N(\theta,\phi)\, d\Omega}$$

$$[SL] = \eta_{SL} \overline{T}_{SL}$$

$$T_A = \eta_M \overline{T}_{ML} + (1 - \eta_M) \overline{T}_{SL}$$

- CLEARLY, IF ONE WANTS TO MINIMIZE THE SL CONTRIBUTION TO $T_A$ ONE SHOULD MAXIMIZE $\eta_M$

# RADIATION EFFICIENCY

- PREVIOUS ANALYSIS ASSUMED LOSSLESS ANTENNAS, WHICH IS NOT TRUE IN GENERAL. THE ANTENNA CONVERTS SOME OF THE RECEIVED ENERGY INTO HEAT.

$\eta_L$ = Antenna Radiation Efficiency

$T_A'$ = Antenna temperature for a lossy antenna

$$T_A' = \eta_L T_A$$

- LOSSY DEVICES ALSO EMIT (KIRCHHOFF'S LAW) AND WE MUST THEREFORE INCLUDE SELF-EMISSION IN THE EXPRESSION FOR $T_A'$

$$T_N = (1 - \eta_L) T_0$$

$T_0$ = Physical Antenna Temperature

$$T_A' = \eta_L T_A + (1 - \eta_L) T_0$$

$$T_A' = \eta_L \eta_M \overline{T}_{ML} + \eta_L (1 - \eta_M) \overline{T}_{SL} + (1 - \eta_L) T_0$$

$$\text{for } \eta_M \to 1 \quad T_A' \to \eta_L \overline{T}_{ML} + (1 - \eta_L) T_0$$

# RADIOMETRY AND SIGNAL DETECTION

- $T_A'$ IS THE SIGNAL OR MEASURED QUANTITY WHICH CARRIES INFORMATION ABOUT THE VARIOUS SOURCES OF EMISSION OBSERVED BY THE RADIOMETER. THE GOAL IS TO RELATE THE MEASURED RADIOMETER OUTPUT VOLTAGE $V_0$ TO $\overline{T}_{ML}$. SINCE $V_0$ IS LINEARLY RELATED TO THE POWER DELIVERED TO A MATCHED LOAD, ONE CAN CALIBRATE THE RADIOMETER TO *READ* OR OUTPUT TEMPERATURE UNITS.

- $T_A'$ IS MEASURED AND WE WOULD LIKE TO ESTIMATE $\overline{T}_{ML}$, USING THE PREVIOUS EQUATIONS:

$$\overline{T}_{ML} = \left(\frac{1}{\eta_L \eta_M}\right) T_A' - \left(\frac{1-\eta_M}{\eta_M}\right) \overline{T}_{SL} - \left(\frac{1-\eta_L}{\eta_L \eta_M}\right) T_0$$

SCALE FACTOR

BIAS FACTORS

# RADIOMETRY AND SIGNAL DETECTION (contd)

$\eta_L$ AND $\eta_M$ CAN BE MEASURED, $T_0$ CAN ALSO BE MEASURED (USING THERMISTORS MOUNTED DIRECTLY ON ANTENNA STRUCTURE).

$\eta_L$ AND $\eta_M$ MUST BE ACCURATELY MEASURED SINCE THEY CONTRIBUTE TO BOTH THE ABSOLUTE AND RELATIVE ESTIMATES OF $\overline{T}_{ML}$ . BOTH OF THESE FACTORS WILL AFFECT THE RADIOMETER ACCURACY AND PRECISION.

$\overline{T}_{SL}$ DEPENDS ON THE ANTENNA SIDE LOBE LEVELS AND THE SCENE BEING OBSERVED. FOR A SPACEBORNE RADIOMETER THIS TERM CAN VARY WITH TIME. MAXIMIZING $\eta_M$ WILL HELP TO REDUCE THIS TERM.

FROM $\overline{T}_{ML}$ IT IS POSSIBLE TO DETERMINE $T_{AP}$ USING ANTENNA PATTERN CORRECTIONS

# INTRODUCTION TO MICROWAVE RADIATIVE TRANSFER

- SIMPLE RADIATIVE TRANSFER MODEL USED TO ILLUSTRATE THE BASIC CONCEPTS
- MORE DETAILED MODELS MAY BE REQUIRED DEPENDING ON THE APPLICATION AND ACCURACY REQUIREMENTS (SEE REFERENCES)
- REFER TO FIGURE ON FOLLOWING CHART

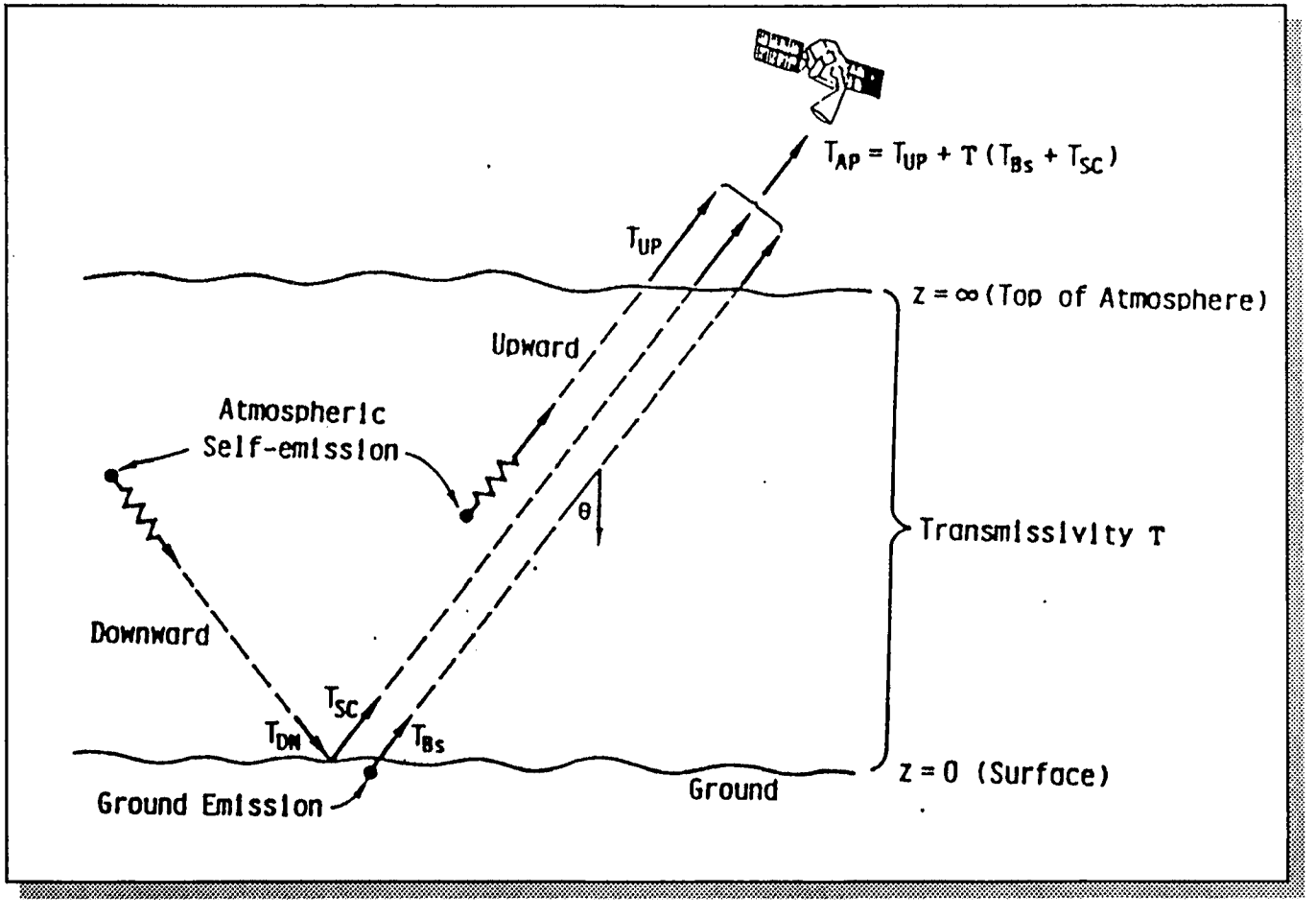
$$T_{AP}(f,q,\hat{n}) = T_{UP}(f,q,\hat{n}) + \{T_{BS}(f,q,\hat{n}) + T_{SC}(f,q,\hat{n})\} \exp\left[-\tau(0,\infty)\sec(\theta)\right]$$

$T_{AP}(f, q, \hat{n})$ = apparent brightness temperature observed by the satellite radiometer

$$\tau(z_1,z_2) = \text{optical depth} = \int_{z_1}^{z_2} \kappa(f,z')\,dz'$$

$\kappa(f,z)$ = atmospheric extinction coefficient

# SIMPLE RADIATIVE TRANSFER MODEL




From: F. T. Ulaby, et al., Microwave Remote Sensing: Active and Passive, Vol. III, © 1981-1986 Artech House, Inc., Norwood, MA.

# MICROWAVE RADIATIVE TRANSFER (contd)

f = frequency

WHERE: q = linear polarization (H or V)

$\hat{n} = (\theta, \varphi)$ = direction

$T_{UP}(f, q, \hat{n})$ = brightness temperature corresponding to the upward atmospheric emission

$$T_{UP}(f,q,\hat{n}) = \sec(\theta) \int_0^\infty \kappa(f,z)\, T_{atm}(z)\, \exp\left[-\tau(z,\infty)\sec(\theta)\right] dz$$

$T_{BS}(f, q, \hat{n})$ = brightness temperature corresponding to the emission from the earth's surface

$$T_{BS}(f, q, \hat{n}) = \varepsilon_s(f,q,\hat{n})\, T_s$$

$\varepsilon_s(f,q,\hat{n})$ = emissivity of the earth's surface

$T_s$ = surface temperature

# MICROWAVE RADIATIVE TRANSFER (contd)

$T_{SC}(f, q, \hat{n})$ = brightness temperature corresponding to the surface scattered component - fraction of the downwelling atmospheric emission which is scattered from the surface and into the radiometer FOV.

$$T_{SC}(f,q, \hat{n}) = [1 - \varepsilon_s(f,q, \hat{n})]\, T_{DN}(f,q, \hat{n})$$

$T_{DN}(f, q, \hat{n})$ = brightness temperature corresponding to the downward atmospheric emission

$$T_{DN}(f,q, \hat{n}) = \sec(\theta) \int_0^\infty \kappa(f,z)\, T_{atm}(z)\, \exp[-\tau(0,Z)\, \sec(\theta)]\, dz$$

$T_{atm}(z)$ = atmospheric temperature profile

- THE RADIATIVE TRANSFER EQUATION (RTE) IS USED TO MODEL VARIOUS RADIATIVE PROCESSES AND ASSIST IN
  - DESIGN OF NEW SENSORS
  - PHYSICAL INTERPRETATION OF RADIOMETER DATA
  - RETRIEVAL OF GEOPHYSICAL PARAMETERS FROM RADIOMETER MEASUREMENTS

# 2.3 RADIOMETER SYSTEMS

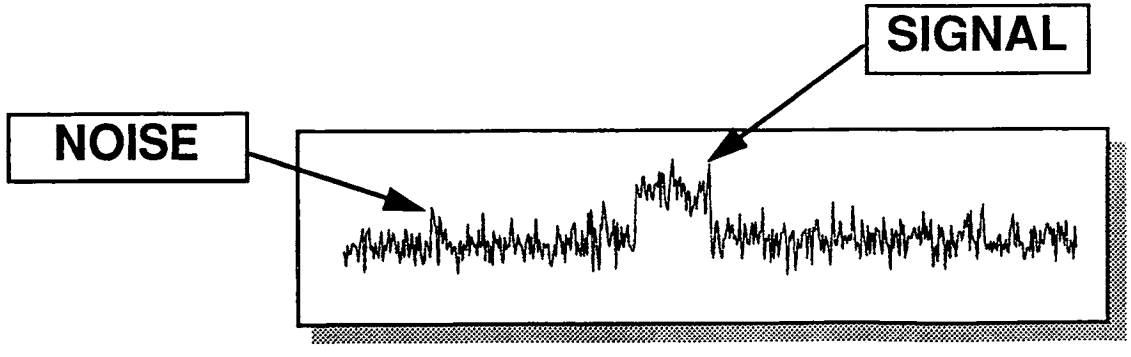
- NOISE AND NOISE TEMPERATURE
  - RECEIVER NOISE TEMPERATURE
  - SYSTEM NOISE POWER
- RADIOMETER SYSTEM PERFORMANCE
  - MEASUREMENT ACCURACY & PRECISION
- IMAGING SYSTEMS
- RADIOMETER CALIBRATION

# NOISE AND NOISE TEMPERATURE

- **RADIOMETER**
  - SENSITIVE RECEIVER DESIGNED TO MEASURE (ESTIMATE) THERMAL EMISSION OVER A WELL DEFINED SPECTRAL BAND IN THE MICROWAVE REGION
  - POWER RECEIVED BY THE RADIOMETER IS RELATED TO THE ANTENNA TEMPERATURE

$$P' = kT'_A B$$

- $T'_A$ ACTUALLY REPRESENTS THE AVERAGE VALUE OF A FLUCTUATING NOISE LIKE SIGNAL. THE RADIOMETER MUST MEASURE THE NOISE LIKE THERMAL EMISSION OF THE OBJECT OR SCENE OF INTEREST, WHILE CONTENDING WITH VARIOUS SOURCES OF NOISE. THESE NOISE SOURCES WILL LIMIT THE SENSITIVITY OF THE RADIOMETER, WHICH IN TURN WILL LIMIT THE PRECISION OF THE RADIOMETRIC MEASUREMENTS.



# NOISE TEMPERATURE (contd)

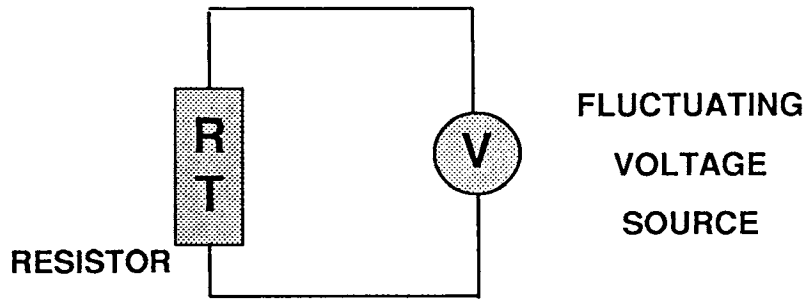
- **THERMAL NOISE**
  - THERMAL FLUCTUATIONS ARE PRESENT IN ALL MATERIALS
  - CONSIDER THE FOLLOWING CIRCUIT MODEL

$$\langle V_N \rangle = 0 \quad \text{(ZERO MEAN)}$$

$$\langle V_N^2 \rangle = 4RkTB \quad \text{(Nyquist or Johnson Noise)}$$

$$B = \text{noise bandwidth}$$

$$V_{rms} = \sqrt{\langle V_N^2 \rangle} = [4RkTB]^{1/2}$$

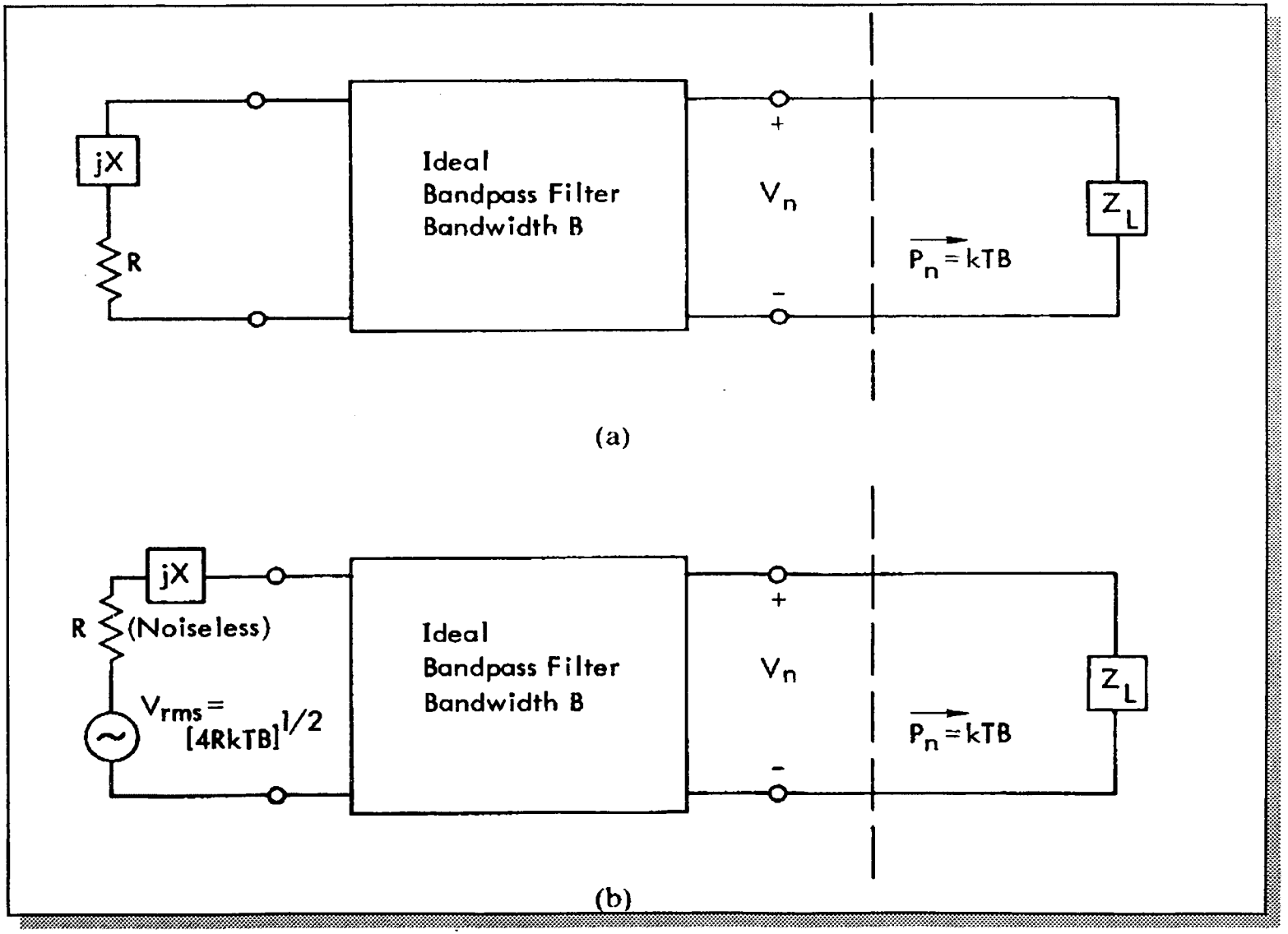



- **EQUIVALENT CIRCUIT:** REPLACE NOISY RESISTOR AT TEMPERATURE T BY AN IDEAL NOISE FREE RESISTANCE, REACTANCE jX, AND NOISE GENERATOR. THE POWER TRANSFER TO THE LOAD IS MAXIMUM FOR A MATCHED LOAD CONDITION.

$$Z_L = Z^* = R - jX$$

$$P_N = \frac{V_{rms}^2}{4R} = kTB$$

# NOISE TEMPERATURE (contd)



# NOISE TEMPERATURE (contd)

- **EXTEND THIS CONCEPT TO ANY OTHER NOISE SOURCE, THERMAL OR OTHERWISE, TO OBTAIN THE EQUIVALENT OUTPUT NOISE TEMPERATURE**

$$T_{E0} = \lim_{\Delta f \to 0} \frac{P_{n0}(f)}{k\,\Delta f}$$

$P_{N0}(f)$ = output noise power from noise source over a narrow band centered at frequency f

$\Delta f$ = bandwidth

- **IF $P_{N0}$ DOES NOT VARY WITH FREQUENCY OVER THE BAND $\Delta f$, THEN**

$$P_{N0} = k\,T_{E0}B$$

**RELATIONSHIP TO ANTENNA TEMPERATURE**

**THE AVERAGE POWER DELIVERED BY AN ANTENNA TO A MATCHED LOAD EQUALS THE AVERAGE POWER DELIVERED BY A RESISTOR TO A MATCHED LOAD IF THE TEMPERATURE OF THE RESISTOR, T, IS THE SAME AS THE ANTENNA RADIOMETRIC TEMPERATURE**

$$T_A'$$

# NOISE FIGURE

- **NOISE FIGURE IS A MEASURE OF THE NOISE OUTPUT FROM A MICROWAVE DEVICE**

$$F = \frac{(P_{SI}/P_{NI})}{(P_{SO}/P_{NO})}$$

$P_{SI}$ = available input signal power (W)

$P_{NI} = kT_0B$ = available input noise power (W)

$P_{SO}$ = available output signal power (W)

$P_{NO}$ = available output noise power (W)

**F IS DEFINED FOR A SPECIFIC REFERENCE INPUT NOISE POWER, CORRESPONDING TO A MATCHED RESISTOR AT THE INPUT PORT, AT TEMPERATURE $T_0$= 290 K ONE CAN SHOW THAT**

$$P_{N0} = FGkTB$$

G = device gain

**THIS INCLUDES BOTH THE DEVICE AND INPUT NOISE. THE NOISE PERFORMANCE OF THE DEVICE IS EQUIVALENT TO A NOISE FREE DEVICE WITH AN INPUT NOISE TEMPERATURE OF $FT_0$**

- **NOISE FACTOR**
  - **NOISE FIGURE IN dB** $F(dB) = 10\log_{10}(F)$

# EQUIVALENT NOISE TEMPERATURE

**$\Delta P_{NO}$ = device contribution to ouptut noise power**

**DEFINE EQUIVALENT INPUT NOISE TEMPERATURE $T_E$ $\Delta P_{NO} = G \cdot kT_E B$**

**Referred to the device input, the noise power is $P_E = kT_E B$**

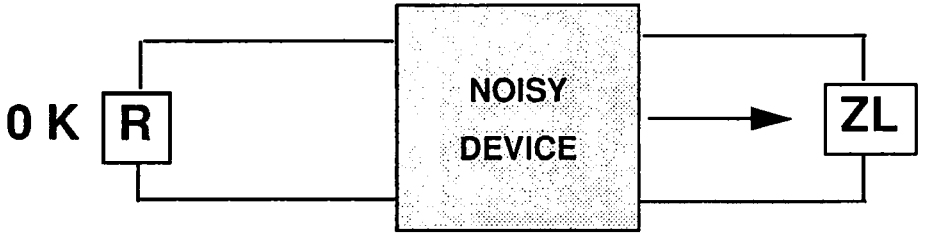
$$\Delta P_{NO} = P_{NO} - GkT_0B = FGkT_0B - GkT_0B$$

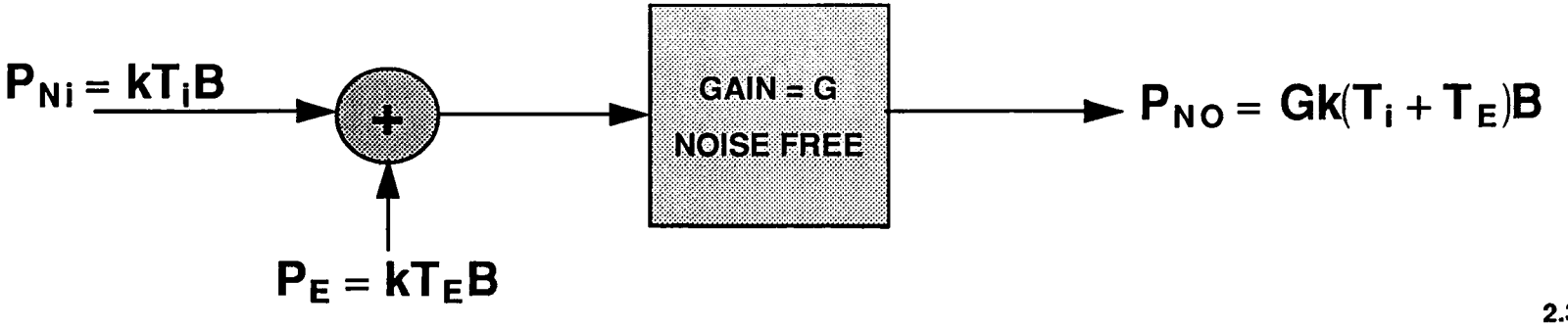
$$\Delta P_{NO} = G(F-1)kT_0B$$

$$\Rightarrow \quad T_E = (F-1)T_0$$

$$F = 1 + \frac{T_E}{T_0}$$

**THEREFORE, THE NOISE CHARACTERISTICS OF A DEVICE MAY BE SPECIFIED BY EITHER $T_E$ or F &$T_0$**



# NOISE OF CASCADED SYSTEMS

- **N DEVICES IN CASCADE**

$$T_E = T_{E1} + \frac{T_{E2}}{G_1} + \frac{T_{E3}}{G_1 G_2} + \cdots + \frac{T_{EN}}{G_1 G_2 \cdots G_{N-1}}$$

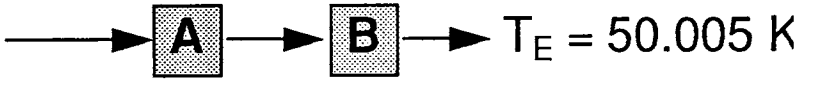
$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_N - 1}{G_1 G_2 \cdots G_{N-1}}$$

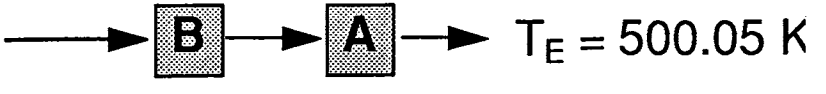
- **LOW NOISE DEVICES ARE USUALLY MORE COMPLICATED AND EXPENSIVE. IF THE FIRST DEVICE IS LOW NOISE AND HIGH GAIN, THE IMPACT OF NOISE FOR THE TOTAL CASCADE IS MINIMIZED.**

- **EXAMPLE**

A $T_{EA} = 50$ K $G_A = 10^5$

B $T_{EB} = 500$ K $G_B = 10^4$



# ATTENUATOR

- **ATTENUATOR - LOSSY MICROWAVE COMPONENT WITH GAIN GIVEN BY**

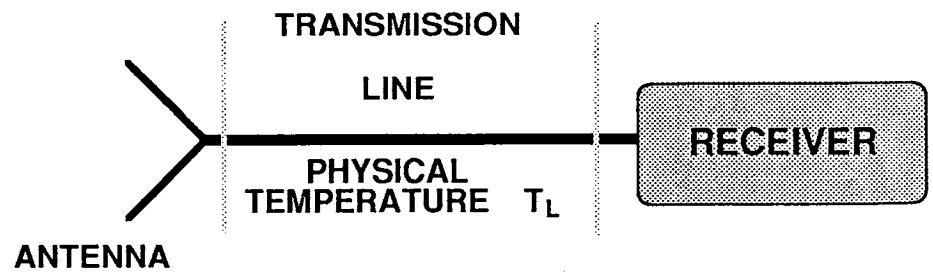
$$G_L = \frac{1}{L} \qquad T_E = (L-1)\,T_L \text{ (Effective Noise Temperature)}$$

$$P_o = \frac{P_i}{L} \qquad F = 1 + (L-1)\frac{T_L}{T_0} \text{ (Noise Figure)}$$

Temperature $T_L$

- **EXAMPLE - EFFECT OF TRANSMISSION LINE LOSS - FIND EQUIVALENT NOISE TEMPERATURE OF THE TRANSMISSION LINE-RECEIVER CASCADE**

$\tilde{T}_{rec}$ = **equivalent input noise temperature of receiver**




$$\tilde{T}_{rec} = T_{E,line} + \frac{T_{rec}}{G_{line}}$$

$$= (L-1)T_L + \frac{T_{rec}}{1/L}$$

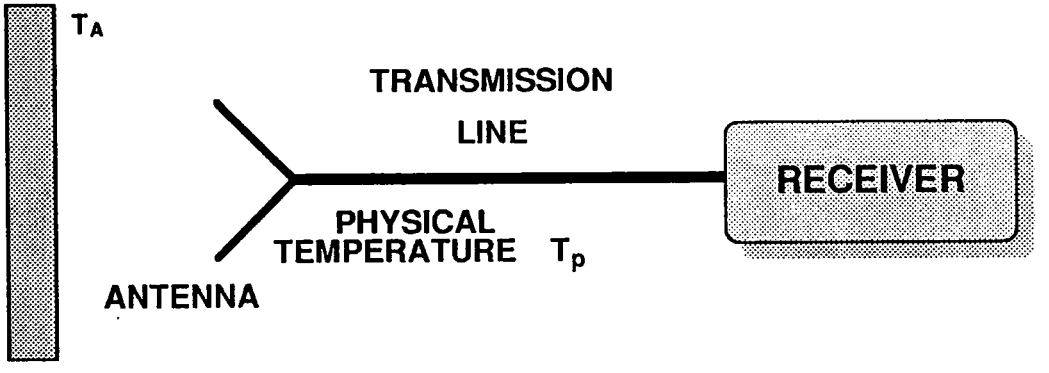
$$= (L-1)T_L + LT_{rec}$$

**Let $T_{rec}$ = 50K, $L = 0.5$ dB, $T_L = 290$K**

**then**

$\tilde{T}_{rec} = 91.5$K (an 83% increase in noise )

# EQUIVALENT SYSTEM NOISE POWER AT THE ANTENNA TERMINALS




SYSTEM NOISE POWER CONSISTS OF CONTRIBUTIONS FROM THE ANTENNA, TRANSMISSION LINE AND THE RECEIVER.

$T'_A$ = ANTENNA NOISE TEMPERATURE

$\eta_L$ = ANTENNA RADIATION EFFICIENCY

$T_A$ = ANTENNA RADIATION TEMPERATURE OF SCENE

$$T'_A = \eta_L T_A + (1 - \eta_L) T_p$$

$$P'_A = k\, T'_A\, B \text{ (noise power )}$$

RECALL FROM PREVIOUS CHART THAT: $P'_{rec} = kT'_{rec}\, B = k[(L - 1) T_p + L\, T_{rec}]\, B$

$$P_{sys} = P'_A + P'_{rec} = k\, T_{sys}\, B$$

$$T_{sys} = \eta_L T_A + (1 - \eta_L) T_p + [(L - 1) T_p + L\, T_{rec}]$$

**Psys represents the input power to an equivalent noise free receiver or radiometer. The radiometer output voltage is proportional to Psys and therefore to Tsys.**

# RADIOMETER OPERATION AND PERFORMANCE

- PURPOSE OF A RADIOMETER IS TO MEASURE THE ANTENNA RADIOMETRIC TEMPERATURE WITH A SPECIFIED ACCURACY AND PRECISION.

- ACCURACY
  - HOW CLOSE TO THE TRUE VALUE IS THE MEASUREMENT?
  - FUNCTION OF:
    - (1) RADIOMETER CALIBRATION
    - (2) SYSTEMATIC OR BIAS EFFECTS

- PRECISION
  - SMALLEST MEASURABLE CHANGE IN THE SIGNAL
  - FUNCTION OF:
    - (1) NOISE SOURCE
    - (2) QUANTIZATION LEVELS (DIGITAL SYSTEMS)
  - RADIOMETER FIGURE OF MERIT FOR SENSOR PRECISION IS THE RADIOMETRIC SENSITIVITY

$\Delta T$ = SMALLEST CHANGE IN $T'_A$ THAT CAN BE DETECTED

# RADIOMETER SENSITIVITY

- **SENSITIVITY FOR A TOTAL POWER RADIOMETER**

$$\left.\begin{aligned} P_{sys} = kT_{sys}B &= P'_A + P'_{rec} \\ T_{sys} &= T'_A + T'_{rec} \end{aligned}\right\} \text{EQUIVALENT SYSTEM MODEL}$$

$$P_{IF} = G\,k\,T_{sys}B = \text{output power from IF amplifier}$$

- **RESULT** (see Ulaby, et al., Chapter 6, for a complete derivation)

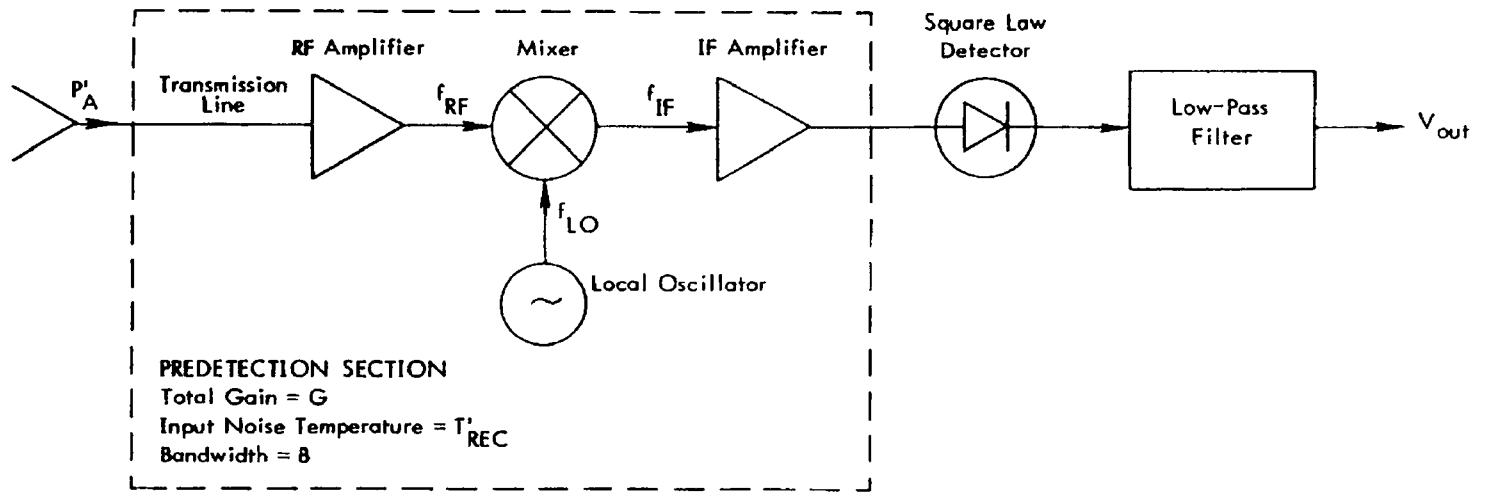
$$\Delta T_{sys} = T_{sys}\frac{1}{\sqrt{B\tau}}$$

$\Delta T_{sys}$ = **standard deviation associated with the estimated value of** $T_{sys}$

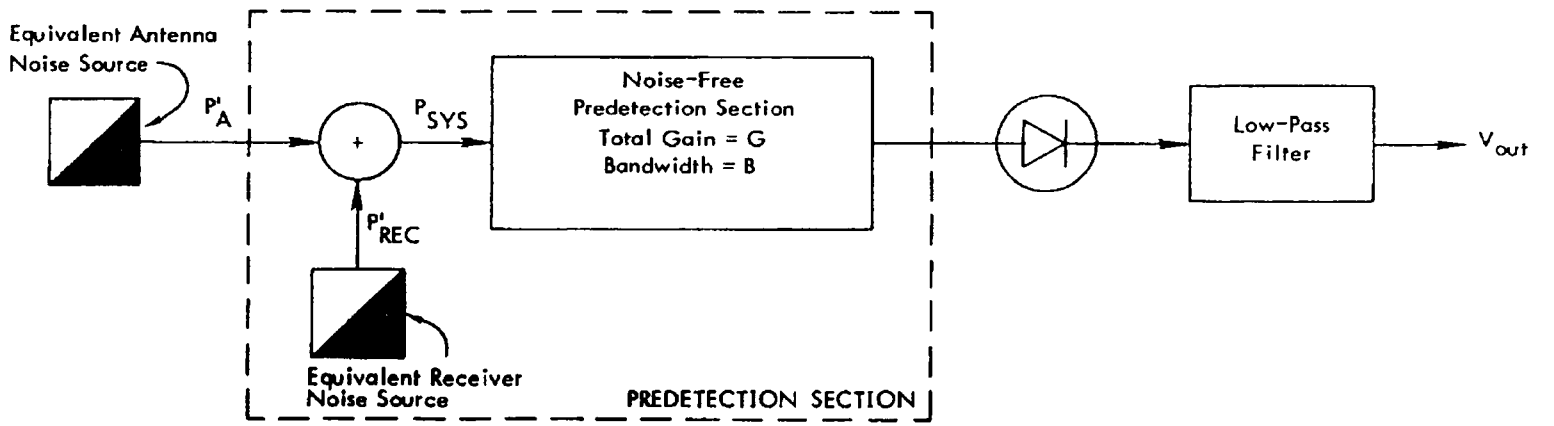
**B = bandwidth (Hz)**

$\tau$ = **integration time (sec)**

# RADIOMETER SENSITIVITY (CONTD)




(a) Block Diagram of Total-Power Radiometer

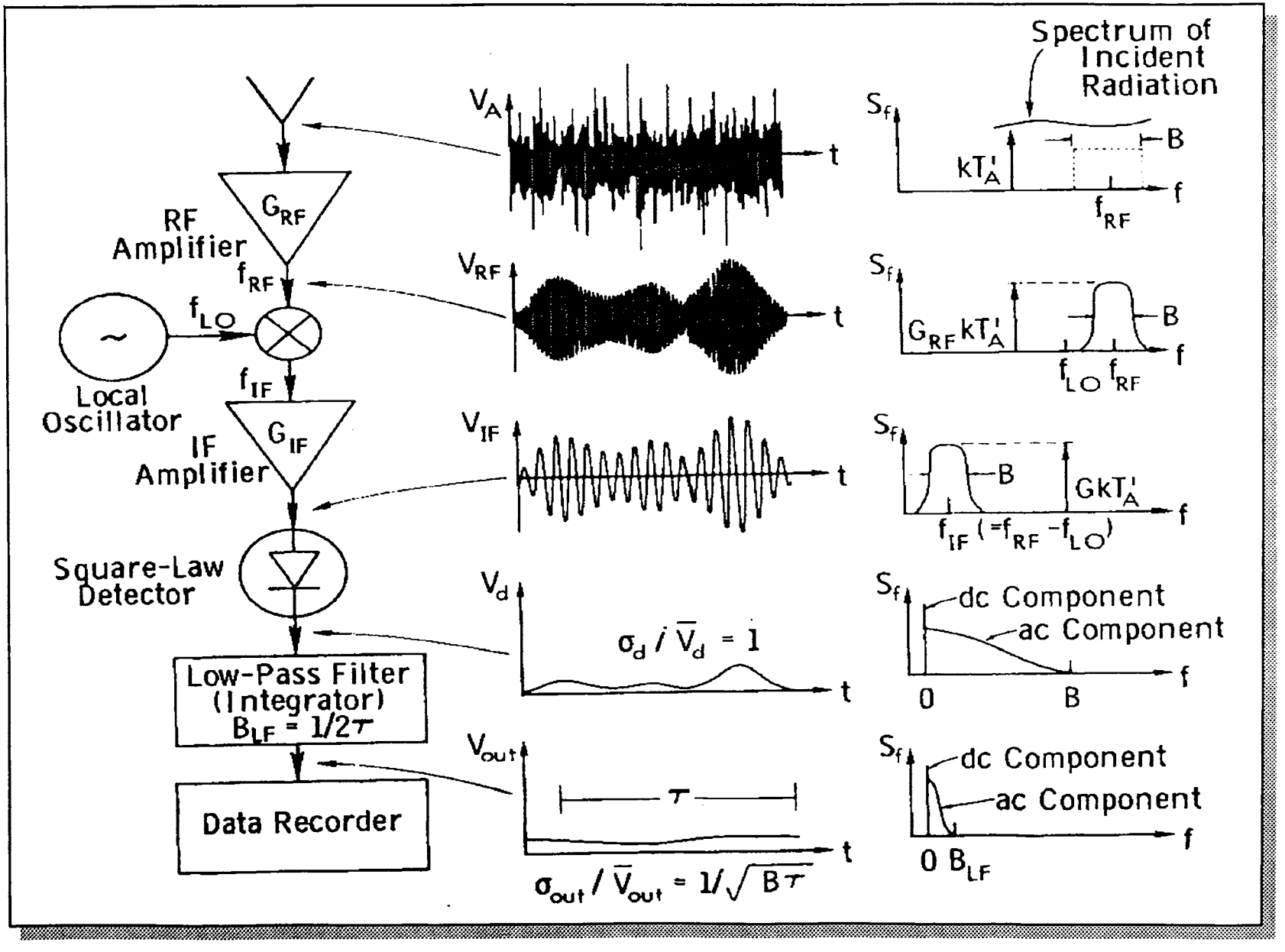



(b) Equivalent Representation of (a) in Terms of a Noise-Free Receiver and Equivalent Noise Sources at the Receiver Input

**Fig. 6.13** Total-power radiometer block diagram (a) and its equivalent (b).

From: F. T. Ulaby, et al., Microwave Remote Sensing: Active and Passive, Vol. I, © 1981-1986 Artech House, Inc., Norwood, MA.

# RADIOMETER SENSITIVITY (CONTD)




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# RADIOMETER SENSITIVITY (contd)

- DEFINE $\Delta T_N$ = MINIMUM DETECTABLE CHANGE IN THE RADIOMETRIC ANTENNA TEMPERATURE

$$\Delta T_N = \Delta T_{sys} = \frac{T'_A + T'_{rec}}{\sqrt{B\tau}}$$

THIS GIVES THE SENSITIVITY OF AN IDEAL TOTAL POWER RADIOMETER WITH NO GAIN FLUCTUATIONS

- EFFECT OF RECEIVER GAIN FLUCTUATIONS
  - -OUTPUT VOLTAGE FROM A TOTAL POWER RADIOMETER

$$V_{out} = G_s \cdot T_{sys}$$

$$G_s = g_{LF} \times R_d \times G \times k \times B$$

$g_{LF}$ = voltage gain of low pass filter

$R_d$ = responsivity of square law detector $\left(\frac{\text{volts}}{\text{watt}}\right)$

$G$ = RF & IF gain , pre -detection power gain

$k$ = Boltzmann constant

$B$ = RF bandwidth

# RADIOMETER SENSITIVITY (contd)
## GAIN FLUCTUATIONS

- LONG TERM DRIFTS IN G CAN BE REMOVED BY FREQUENT CALIBRATION
- SHORT TERM VARIATIONS IN G CAN BE INTERPRETED AS SIGNAL, I.E., CHANGES IN $T_{SYS}$

Let $\Delta T_G = T_{SYS}\left(\frac{\Delta G_s}{G_s}\right)$

where $\Delta T_G$ = rms error in T measurement due to fluctuations in system gain

$\Delta G_s$ = rms system power gain fluctuations

$G_s$ = average system power gain

- ASSUMING $\Delta T_N$ AND $\Delta T_G$ ARE STATISTICALLY INDEPENDENT

$$\Delta T = \left[(\Delta T_N)^2 + (\Delta T_G)^2\right]^{1/2}$$

$$= T_{SYS}\left[\frac{1}{B\tau} + \left(\frac{\Delta G_s}{G_s}\right)^2\right]^{1/2}$$

# RADIOMETER SENSITIVITY (contd)
## GAIN FLUCTUATIONS

- **EXAMPLE: TOTAL POWER RADIOMETER**
  - **WE WOULD LIKE TO HAVE** $\Delta T \leq 1$ **K**

$$f = 1.4 \text{ GHz} \qquad \lambda = 21.4 \text{ cm (L-band)}$$

$$T'_{rec} = 600 \text{ K} \qquad \tau = 10 \text{ msec}$$

$$B = 100 \text{ MHz} \qquad \left(\frac{\Delta G_s}{G_s}\right) = 10^{-2}$$

$$\text{assume } T'_A = 300 \text{ K} \Rightarrow \qquad T_{sys} = 900 \text{ K}$$

$$\Delta T_N = 0.9 \text{ K} \qquad \Delta T_G = 9 \text{ K}$$

- **THEREFORE** $\Delta T \approx 9.1$ **K WHICH IMPLIES THAT THE RELATIVE GAIN VARIANCE IS TOO LARGE TO MEET OUR REQUIREMENT. FOR REMOTE SENSING APPLICATIONS WE TYPICALLY REQUIRE**

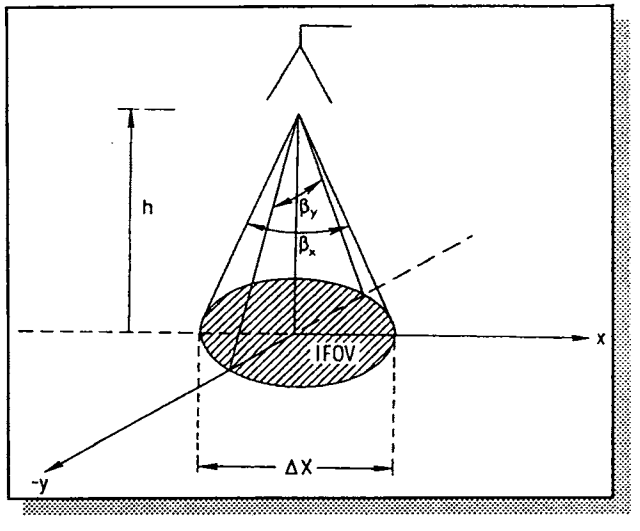
$$\left(\frac{\Delta G_s}{G_s}\right) \leq 10^{-4}$$

# IMAGING SYSTEMS

- **SPATIAL RESOLUTION**
  - INSTANTANEOUS FIELD OF VIEW (IFOV) IS DEFINED BY THE -3dB OR 1/2 POWER BEAMWIDTHS OF THE ANTENNA PATTERN
  - RELATED TO GROUND FOOTPRINTS $\Delta X$ AND $\Delta Y$
  - FOR A DIFFRACTION LIMITED CIRCULAR APERTURE (DIAMETER D) WITH COSINE TAPERING

$$\left.\begin{aligned}\Delta X &= \beta_X H \\ \Delta Y &= \beta_Y H\end{aligned}\right\} \text{NADIR VIEW}$$

$$\beta = 1.2\frac{\lambda}{D}$$

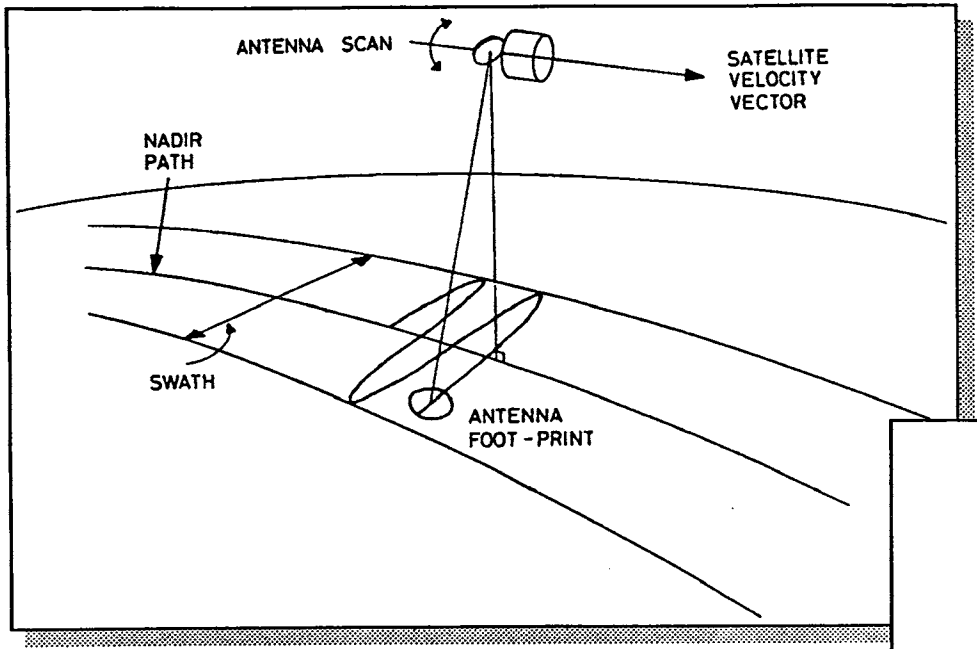



- **IMAGING MAY BE ACCOMPLISHED BY TWO TECHNIQUES**
  - (1) SCANNING MAIN BEAM OF ANTENNA
  - (2) USE OF MULTIPLE BEAMS SIMULTANEOUSLY

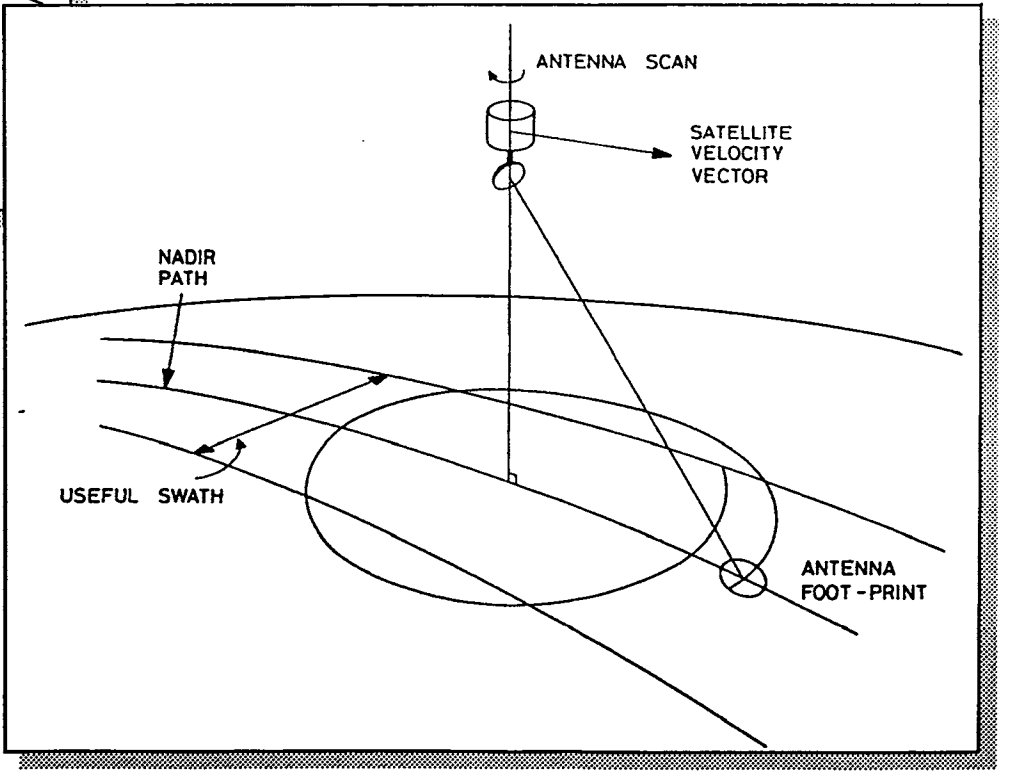
# IMAGING SYSTEMS (contd)

- CASE 1
  - SCAN MAIN BEAM OF ANTENNA
    - * SCAN COMPLETE UNIT
    - * CAN JUST SCAN ANTENNA REFLECTOR
    - * SCAN ANTENNA FEEDHORNS
  - CROSS TRACK SCAN (LINE SCAN OR WISKBROOM): MAIN BEAM IS SCANNED PERPENDICULAR TO SPACECRAFT VELOCITY VECTOR
    - * INCIDENCE ANGLE VARIES WITH SCAN ANGLE
    - * RELATIVE POLARIZATION NOT CONSTANT
    - * GROUND FOOTPRINT SIZE VARIES WITH SCAN ANGLE
  - CONICAL SCAN: ANTENNA MAIN BEAM IS POINTED OFF-NADIR AT A FIXED ANGLE AND SCANS CONTINUOUSLY OR BACK AND FORTH
    - * MAINTAINS FIXED INCIDENCE ANGLE AND POLARIZATION RELATIVE TO EARTH'S SURFACE
    - * CONSTANT GROUND FOOTPRINT SIZE
  - ELECTRONIC SCAN: PHASED ARRAY ANTENNA IS USED TO ELECTRONICALLY ADJUST PHASES OF RECEIVING ELEMENTS TO POINT ANTENNA MAIN BEAM

# IMAGING SYSTEMS (contd)




**LINE SCANNING RADIOMETER**

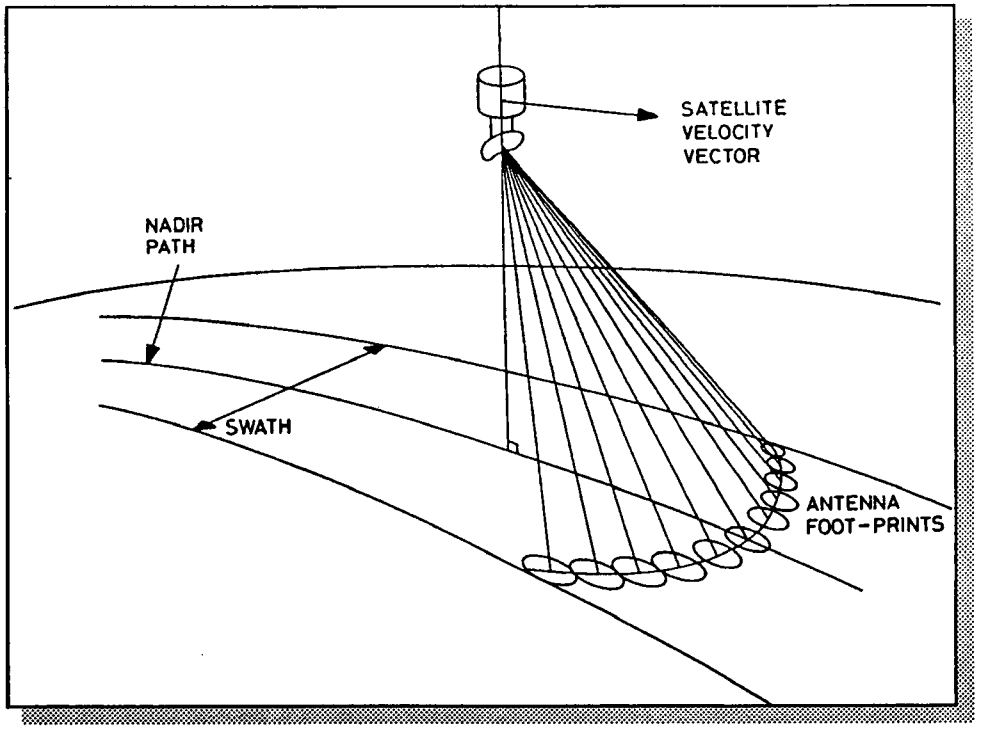



**CONICAL SCANNING RADIOMETER**

From: N[illegible]pu, Microwave Radiometer Systems: Design and Analysis, © 1989 Arte[illegible] House, Inc., Norwood, MA.

# IMAGING SYSTEMS (contd)

- **CASE 2**
  - PUSHBROOM TYPE OF SCAN: MULTIPLE ANTENNA BEAMS ALIGNED CROSS TRACK AT A FIXED NADIR ANGLE
  - TYPICALLY NOT USED DUE TO INCREASED WEIGHT AND COMPLEXITY
  - AS MICROWAVE COMPONENTS BECOME LIGHTER WEIGHT AND INTEGRATED CIRCUIT CONCEPTS ARE DEVELOPED THIS MAY BECOME A POSSIBILITY FOR SPACEBORNE SYSTEMS




**PUSHBROOM IMAGING RADIOMETER**

From: Neils Skou, Microwave Radiometer Systems: Design and Analysis, © 1989 Artech House, Inc., Norwood, MA.

# IMAGING SYSTEMS (contd)

- **CONSTRAINTS ON INTEGRATION AND DWELL TIME**
  - RECALL RADIOMETER SENSITIVITY EQUATION

$$\Delta T = \frac{\zeta}{\sqrt{B\tau}}$$

  - PLATFORM MOTION AND SCAN COMBINE TO LIMIT $\tau$

$\zeta$ = constant

  - DWELL TIME $\tau_d = \left(\frac{\Delta Y}{2\pi V_s}\right)\left(\frac{\Delta X}{R_s}\right)$

  - EFFECT OF RELATIVE MAGNITUDE OF INTEGRATION TIME AND DWELL TIME

**CONSIDER** $\tau = \tau_d \Longrightarrow$

$$(\Delta T)^2 B (\Delta X \Delta Y) = \zeta^2 (2\pi V_s R_s)$$

NOTE THAT THE RIGHT HAND SIDE IS A CONSTANT FOR A GIVEN GEOMETRY, ORBIT AND RADIOMETER TYPE. THUS THE LEFT HAND SIDE IS CONSTRAINED AND ONE MUST TRADE-OFF THE TEMPERATURE RESOLUTION, BANDWIDTH AND SPATIAL RESOLUTION WHEN DESIGNING THE RADIOMETER.

# RADIOMETER CALIBRATION

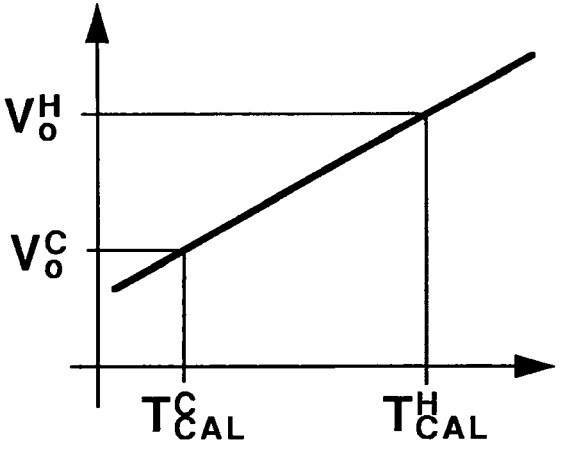
- **TWO STEP PROCESS**
  - (1) RECEIVER CALIBRATION: RELATE RADIOMETER OUTPUT TO ANTENNA TEMPERATURE
  - (2) ANTENNA CALIBRATION/CHARACTERIZATION
  - ON-ORBIT ONE CAN
    - * PERFORM RECEIVER CALIBRATION BY INJECTING NOISE SIGNAL INTO THE RADIOMETER FRONT-END (AFTER THE ANTENNA).
    - * ANTENNA IS MONITORED FOR ITS PHYSICAL TEMPERATURE AND MAY BE INCLUDED IN AN END-TO-END CALIBRATION BY VIEWING DEEP SPACE (T = 3 K).

- **RECEIVER CALIBRATION**
  - LINEAR TRANSFER FUNCTION
  - HOT AND COLD LOADS ALLOW ONE TO DETERMINE $\alpha$ AND $\beta$

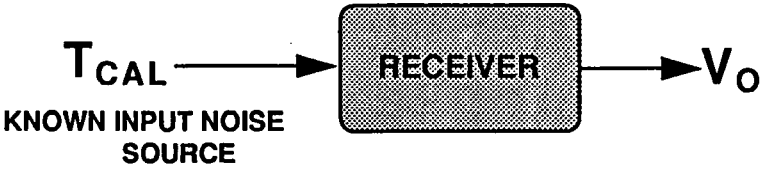
$$V_o = \alpha\left(T'_A + \beta\right)$$

SCALE FACTOR

OFFSET




$$\alpha = \frac{V_o^H - V_o^C}{T_{cal}^H - T_{cal}^C} \qquad \beta = \frac{V_o^C T_{cal}^H - V_o^H T_{cal}^C}{V_o^H - V_o^C}$$



# RADIOMETER CALIBRATION (contd)

- TYPES OF CALIBRATION SOURCES
  - MATCHED LOADS AT KNOWN CONSTANT TEMPERATURE (E.G., RESISTORS)
  - MATERIAL OF WELL KNOWN EMISSIVITY, USUALLY $\varepsilon \approx 1$, AT A CONTROLLED TEMPERATURE
  - VIEWING DEEP SPACE ( T = Tcos = 3 K) FOR A SPACEBORNE RADIOMETER
  - LOW TEMPERATURE DURING PRE-FLIGHT CAL CAN BE OBTAINED USING LN2 WHICH BOILS AT 77 K
- ISSUES
  - ONE MUST MAKE CAREFUL TEMPERATURE MEASUREMENTS OF CALIBRATION LOADS
  - CALIBRATION NOISE SOURCES MUST BE BROADBAND AND RELATIVELY FLAT ACROSS THE RADIOMETER BANDWIDTH
  - CAREFUL MEASUREMENTS AND MODELING OF ALL RADIOMETER IMPEDANCE MISMATCHES

# RADIOMETER CALIBRATION (contd)

- **ANTENNA CALIBRATION**
  - DETERMINE ENERGY RECEIVED BY ANTENNA MAIN-LOBE, SIDE-LOBE AND ANTENNA SELF EMISSION
  - RECALL EXPRESSION FOR ANTENNA TEMPERATURE

$$T_A' = \eta_L \eta_M \overline{T}_{ML} + \eta_L (1 - \eta_M) \overline{T}_{SL} + (1 - \eta_L) T_0$$

$\eta_L$ = antenna radiation efficiency
$\eta_M$ = antenna mainbeam efficiency
$T_0$ = antenna physical temperature
$T_A'$ = antenna temperature measured by radiometer

THE GOAL IS TO ESTIMATE $\overline{T}_{ML}$, WHICH IMPLIES THAT $\overline{T}_{SL}$, $\eta_L$, $\eta_M$ AND $T_0$ MUST BE KNOWN. $\eta_L$, $\eta_M$ AND $T_0$ CAN BE MEASURED, HOWEVER $\overline{T}_{SL}$ CANNOT BE MEASURED AND ALSO DEPENDS ON THE INCIDENT ENERGY DISTRIBUTION FROM THE SCENE. THE SCALE FACTOR FOR THIS TERM DEPENDS ONLY ON $\eta_M$. THUS IF WE MAKE $\eta_M$ AS CLOSE TO 1 AS POSSIBLE WE MINIMIZE THE IMPACT OF $\overline{T}_{SL}$.

$$\text{for } \eta_M \to 1 \quad T_A' \to \eta_L \overline{T}_{ML} + (1 - \eta_L) T_0$$

# 2.4 SENSOR SYSTEM CONCEPTS

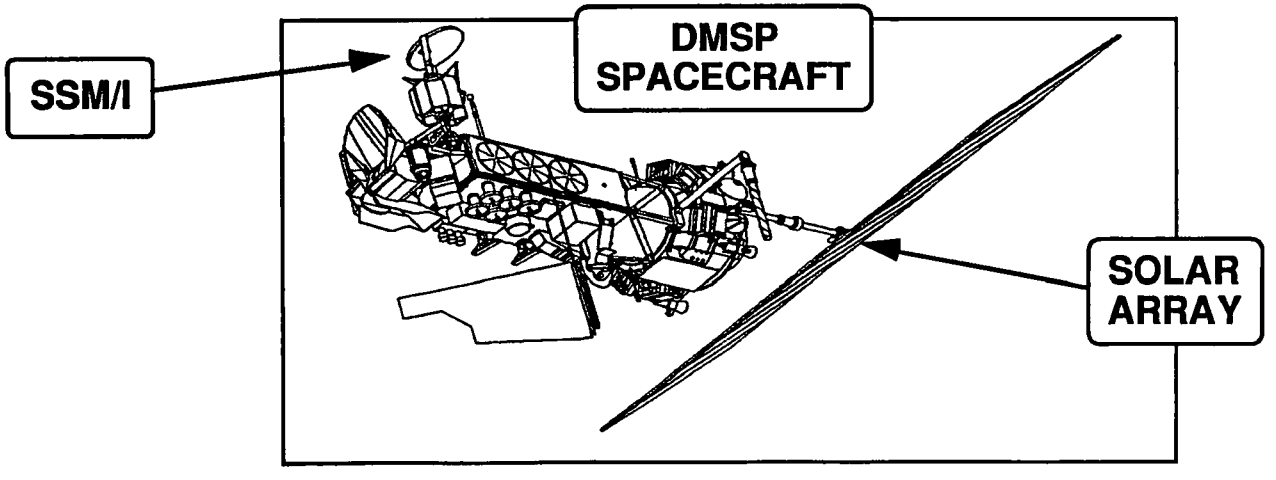
- MICROWAVE IMAGING RADIOMETERS
  - DMSP SSM/I
  - SMMR
  - EOS: AMSR
  - MOS-1

- MICROWAVE SOUNDERS
  - THEORY OF ATMOSPHERIC SOUNDING
  - AMSU
  - ERS-1 MWS
  - LIMB SOUNDING
  - RETRIEVAL

# INTRODUCTION TO DMSP

**The Defense Meteorological Satellite Program provides environmental data to both DoD and civilian groups world wide. The next few charts provide a brief introduction to DMSP in order to provide a context for understanding the role played by the SSM/I. The DMSP satellites are launched into near polar, sun synchronous orbits and phased so that they pass over a given point on the earth at the same local time each day. The primary sensor is the Operational Line Scanner, a visible-infrared imager. The SSM/I on F8, F10 and F11 are still operational, while F9 does not carry an SSM/I. The 85 GHz channel on the F8 SSM/I is not functioning. Note that the spacecraft flies in a *sideways* orientation, with its long axis perpendicular to the velocity vector. Also, since it is required to always have the *bottom* of the spacecraft facing the earth (nadir view) the spacecraft must maintain a constant pitch rate during its orbit.**

**The complete DMSP System consists of not only 2 orbiting spacecraft, but an extensive network of ground receiving and relay stations, coupled with relay satellites. The system is capable of providing real time data to tactical sites or carrier-based receivers in addition to the ability to store data over one orbit and down load this to a ground station for processing at one of the central sites (AFGWC or FNOC).**




DMSP - DEFENSE METEOROLOGICAL SATELLITE PROGRAM

SSM/I - SPECIAL SENSOR MICROWAVE/IMAGER

AFGWC - AIR FORCE GLOBAL WEATHER CENTRAL

FNOC - FLEET NUMERICAL OCEANOGRAPHIC CENTER

# INTRODUCTION TO DMSP (contd)

- **MISSION**
  - COLLECT AND DISSEMINATE ON A GLOBAL BASIS VIS-IR CLOUD DATA, OTHER METEOROLOGICAL, OCEANOGRAPHIC AND SOLAR -GEOPHYSICAL DATA
  - PROVIDE SUPPORT TO DoD OPERATIONS WORLD WIDE
  - -DELIVER DATA
    - * AIR FORCE GLOBAL WEATHER CENTRAL (AFGWC)
    - * FLEET NUMERICAL OCEANOGRAPHY CENTER (FNOC)
    - * REAL-TIME TRANSMISSION TO WORLDWIDE TACTICAL RECEIVING TERMINALS
- **MICROWAVE RADIOMETER PROVIDES METEOROLOGICAL AND OCEANOGRAPHIC DATA**
- **CURRENT SYSTEM: BLOCK 5D-2**
  - 2 SATELLITE CONSTELLATION
  - 833 KM., NEAR POLAR, SUN SYNCHRONOUS ORBIT, 98.8 deg. INCLINATION
  - PERIOD 102 MIN., 14.1 REV/DAY
  - 24 HR GLOBAL COVERAGE, POLAR CAPS MISSED DUE TO INCLINATION
  - REQUIREMENTS FOR 2 SSM/I ON-ORBIT

| SATELLITE NO. | STATUS | PHASING |
|---|---|---|
| F8 | SSM/I OPERATIONAL | 06:15 LTAN |
| F9 | NO SSM/I | 09:29 LTAN |
| F10 | SSM/I OPERATIONAL | 19:34 LTDN |
| F11 | SSM/I OPERATIONAL | 17:17 LTAN |

(LTAN: local time of the ascending node, LTDN: local time of the descending node)

# SSM/I CHARACTERISTICS

## • CONICAL SCANNING MICROWAVE RADIOMETER

- TOTAL POWER RADIOMETER DESIGN
- 7 CHANNELS: (frequency and polarization)

| FREQUENCY (GHz) | POLARIZATION | BANDWIDTH (MHZ) |
|---|---|---|
| 19.35 | V & H | 240 |
| 22.235 | V | 240 |
| 37.0 | V & H | 900 |
| 85.5 | V & H | 1400 |

- ANTENNA:
  - * Offset parabolic reflector, corrugated, broad-band, 7-port horn antenna
  - * 61 x 66 cm reflector
- CONTINUOUS ROTATION: axis parallel to local spacecraft vertical
  - * $45^{o}$ nadir angle
  - * $\pm 51.2^{o}$ cross track scan
  - * 31.6 rev/min, 1.9 sec. period
- RESOLUTION: 12.5 KM (85 GHz), 50 KM (19 GHz)
- SWATH WIDTH: 1395 KM
- DATA RATE: 3276 BITS/SEC

# SSM/I CHARACTERISTICS (contd)

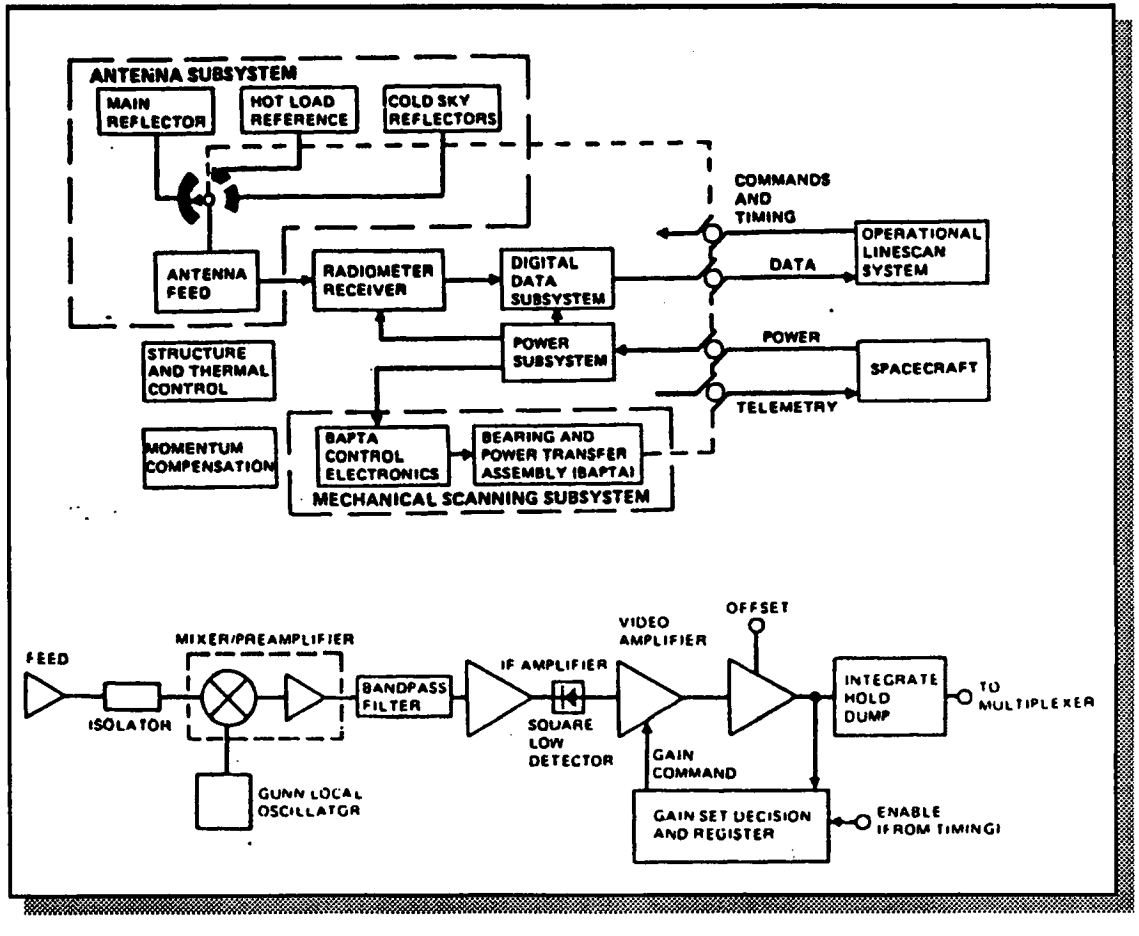
- SAMPLING:
  - * 4.2 msec
  - * 128 samples/scan at 85 GHz
  - * 64 samples every other scan at 19, 22, 37 GHz
- WEIGHT:
  - * 85 lbs (spinning portion)
  - * 20 lbs (momentum wheel and electronics)
- POWER: 45 Watts
- CALIBRATION
  - * Hot/Cold Loads
  - * Performed once each 1.9 sec scan
- SENSITIVITY (F8 PRELAUNCH)

| CHANNEL | $\delta T$(K) |
|---|---|
| 19V | 0.45 |
| 19H | 0.42 |
| 22V | 0.73 |
| 37V | 0.37 |
| 37H | 0.38 |
| 85V | 0.69 |
| 85H | 0.73 |

# SSM/I MAJOR SUBSYSTEMS

- **ANTENNA SUBSYSTEM**
  - This consists of the main reflector which sends energy from either an earth view or one of the calibration loads. The calibration system consists of a hot load and a cold space view.
- **RECEIVER SUBSYSTEM**
  - The receiver system down converts, amplifies and detects the RF energy output by the feed horns in the antenna subsystem. Signals are then integrated, digitized and formatted for transfer to the ground via the OLS data stream.
- **SCANNER SUBSYSTEM**
  - This system rotates the main reflector, feed horns and receiver subsystem. The complete system is part of the bearing and power transfer assembly (BAPTA).
- **MECHANICAL SUBSYSTEM**
  - Provides structure for integration of the electronic boxes into the sensor as well as an electrical contact ring assembly to transmit electrical signals across the spinning interface.
- **MOMENTUM WHEEL SUBSYSTEM**
  - The momentum wheel assembly contains a high speed spinning wheel used to cancel the momentum produced by the spinning SSM/I sensor.

# SSM/I SENSOR OVERVIEW AND BLOCK DIAGRAM

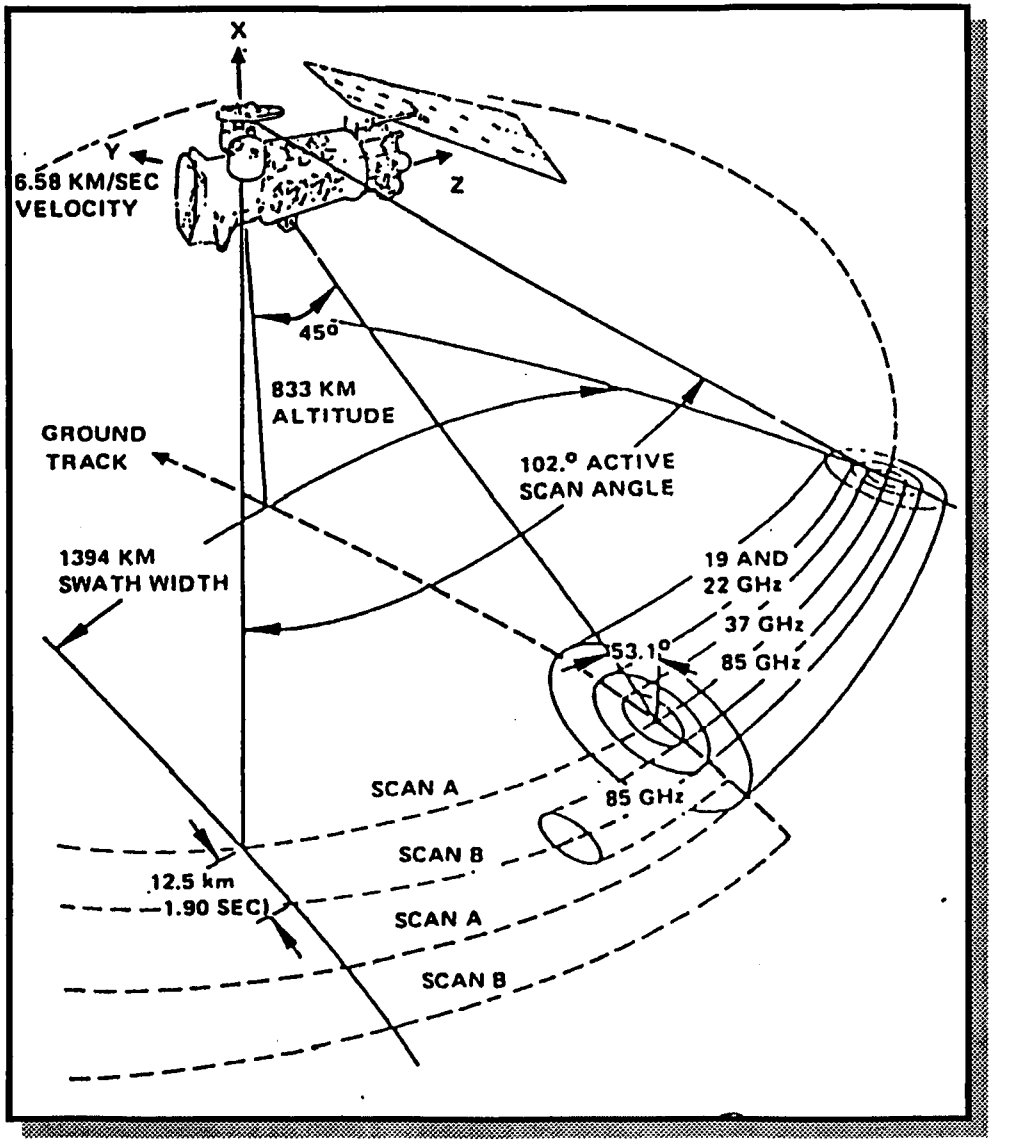



**The upper figure is a block diagram illustrating the major SSM/I subsystems and their interconnection to both the other SSM/I subsystems and other spacecraft subsystems. The bottom figure illustrates the schematic of the radiometer receiver typical of each SSM/I channel.**

From: DMSP Special Sensor Microwave/Imager Calibration/Validation, DMSP SSM/I CAL/VAL TEAM, Coord. by Jim Hollinger, NRL, Wash. DC (1989).

# SSM/I SCAN GEOMETRY

This figure illustrates the scan pattern of the SSM/I as a function of frequency (channel); shown are the ground projections of the antenna 3 dB beam patterns. The SSM/I is a conical scanning radiometer with a constant nadir angle. All of the channels share a common boresight and the scan is from left to right when looking in the aft direction. Also shown is the scan and earth viewing geometry and swath width or coverage. The fact that the spot size of the 85 GHz channel is much smaller than the other channels, combined with the spatial resolution requirements for the geophysical parameters, requires a specialized sampling scheme. The 85 GHz channel is sampled on both the A and B scans whereas the 19, 22 and 37 GHz channels are only sampled on the A scans.




From: DI ...pecial Sensor Microwave/Imager Calibration/Validation, DMSP SSM/I C... ...AL TEAM, Coord. by Jim Hollinger, NRL, Wash. DC (1989).

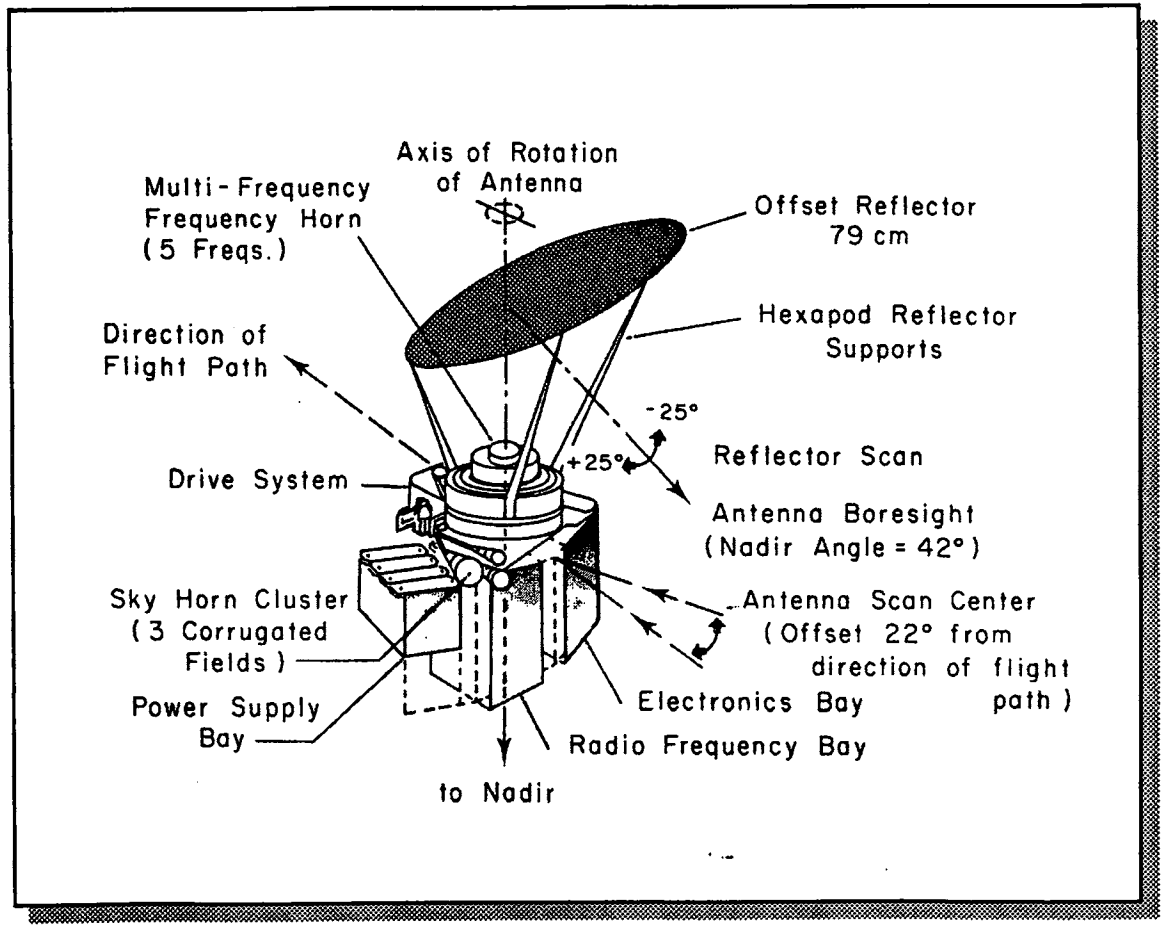
# SSM/I ENVIRONMENTAL DATA PRODUCTS

| PARAMETER | GEOMETRIC RESOLUTION (km) | RANGE OF VALUES | QUANTIZATION LEVELS | ABSOLUTE ACCURACY |
|---|---|---|---|---|
| Ocean Surface Wind Speed | 25 | 3-25 | 1 | ± 2m/s |
| Ice | | | | |
| • Area Coverage | 25 | 0-100 | 5 | ± 12% |
| • Age | 50 | 1st Year. Multiyear | 1yr. >2yr | None |
| • Edge Location | 25 | N/A | N/A | ± 12.5 km |
| Precipitation Over Land Areas | 25 | 0-25 | 0,5,10,15, 20, ≥25 | ± 5mm/hr |
| Cloud Water | 25 | 0-1 | 0.05 | ± 0.1 $kg/m^2$ |
| Integrated Water Vapor | 25 | 0-80 | 0.10 | ± 2.0 $kg/m^2$ |
| Precipitation Over Water | 25 | 0-25 | 0,5,10,15, 20, ≥25 | ± 5mm/hr |
| Soil Moisture | 50 | 0-60% | 1 | None |
| Land Surface Temperature | 25 | 180-340K | 1 | None |
| Snow Water Content | 25 | 0-50 cm | 1 | ± 3cm |
| Surface Type | 25 | 12 Types | N/A | N/A |
| Cloud Amount | 25 | 0-100% | 1 | ± 20% |

**Based on requirements defined by the Air Force and Navy, the SSM/I must provide the environmental data products listed in the following chart. For each parameter, the requirements specify the geometric horizontal resolution, a dynamic range over which each parameter is to be measured, the quantization levels for the measurement and the absolute accuracy of the measurement. The ability of the SSM/I system to meet these requirements depends not only on the SSM/I sensor specifications and performance, but also on the spacecraft and ground processing performance. This is Systems Engineering! The range of values and quantization levels are given in the same units as the absolute accuracy. The geometric resolution is not the same as spatial resolution, but is related to how the scene is sampled.**

# SCANNING MULTICHANNEL MICROWAVE RADIOMETER (SMMR)

- 10 CHANNEL RADIOMETER FLOWN ON NIMBUS-7 AND SEASAT




From: R. Stewart, Methods of Satellite Oceanography, Copyright © 1985 The Regents of the University of California.

# SMMR CHARACTERISTICS

- DICKE SUPERHETERODYNE RADIOMETER
- WEIGHT: 52.3 KG, POWER: 60 W
- CONICAL SCANNER SIMILAR TO SSM/I (42 DEG NADIR ANGLE)

| PARAMETER | CHANNEL | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| WAVELENGTH (CM) | 4.54 | 2.8 | 1.66 | 1.36 | 0.81 |
| FREQUENCY (GHz) | 6.6 | 10.69 | 18.00 | 21.00 | 37.00 |
| POLARIZATION | H & V | H & V | H & V | H & V | H & V |
| RF BANDWIDTH(MHz) | 250 | 250 | 250 | 250 | 250 |
| INTEGRATION TIME (msec) | 126 | 62 | 62 | 62 | 30 |
| DYNAMIC RANGE (K) | 10-330 | 10-330 | 10-330 | 10-330 | 10-330 |
| $\Delta T_{rms}$ (K) | 0.9 | 0.9 | 1.2 | 1.5 | 1.5 |
| ANTENNA BEAMWIDTH (deg) | 4.2 | 2.6 | 1.6 | 1.4 | 0.8 |
| ANTENNA BEAM EFFICIENCY (%) | 87.0 | 87.0 | 87.0 | 87.0 | 87.0 |

# EOS MICROWAVE RADIOMETERS

- EARTH OBSERVING SYSTEM MICROWAVE RADIOMETERS
  - MANY DIFFERENT CONCEPTS HAVE BEEN CONSIDERED
  - RECENTLY NASA HAS REORGANIZED THE EOS SPACE SEGMENT CONFIGURATION
  - EXAMPLE OF ONE CONCEPT PRESENTED - STAY TUNED!
- ADVANCED MICROWAVE SCANNING RADIOMETER (AMSR)
  - PRELIMINARY DESIGN STUDIES CONDUCTED BY JAPAN (NASDA)
  - CONICAL SCANNING TO MAINTAIN CONSTANT EARTH INCIDENCE ANGLE
  - ELECTRICAL SCANNING WITH SWITCHING ARRAY ANTENNA: LONGER INTEGRATION TIME AND NO MOMENTUM COMPENSATION REQUIRED
  - MULTIBEAM SCANNING: EACH CHANNEL HAS 2 - 4 SCANNING BEAMS FOR LONG INTEGRATION TIME AND HIGHER SENSITIVITY
  - LOW NOISE HEMT AMPLIFIERS WITH MULTIPLE DICKE RECEIVERS
  - 1200 KM SWATH WIDTH
  - HIGH SPATIAL RESOLUTION
  - GEOPHYSICAL MEASUREMENTS
    - * SEA SURFACE WIND SPEED
    - * ATMOSPHERIC WATER VAPOR
    - * CLOUD AND PRECIPITATING LIQUID WATER
    - * SEA ICE CONCENTRATION AND TERRAIN SNOW COVERAGE

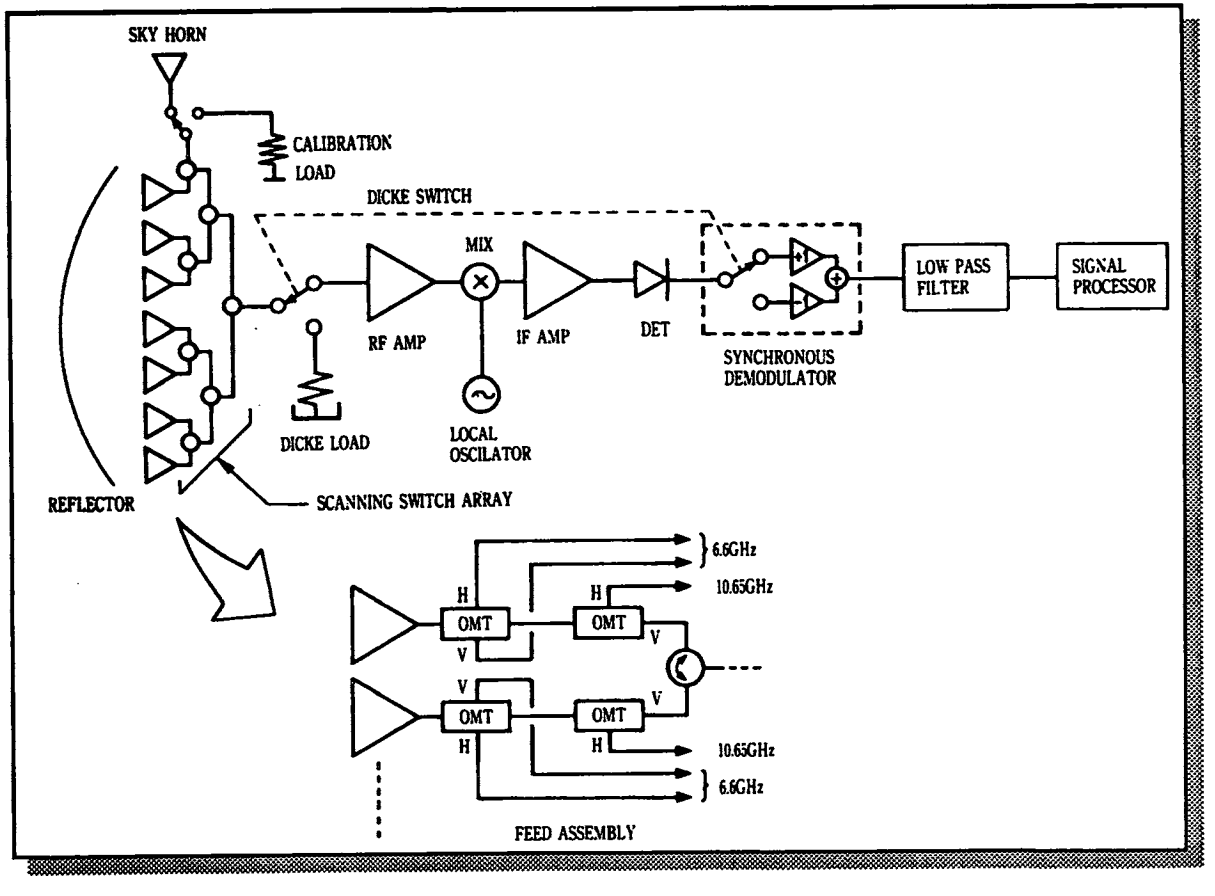
# AMSR PRELIMINARY PERFORMANCE

| PARAMETERS | SPECIFIED PERFORMANCE | | | | |
|---|---|---|---|---|---|
| FREQUENCIES (GHz) | 6.6 | 10.65 | 18.7 | 23.8 | 36.5 |
| BANDWIDTH (MHz) | 400 | 100 | 200 | 400 | 1000 |
| POLARIZATION | VERTICAL AND HORIZONTAL | | | | |
| SENSITIVITY, $\Delta$Trms (K) (300 K Target) | 0.3 | 0.5 | 0.6 | 0.5 | 0.6 |
| ABSOLUTE ACCURACY (K) | < 1.5 | | | | |
| DYNAMIC RANGE (K) | 30 – 350 | | | | |
| INTEGRATION TIME (ms) | 125 | | 62 | | |
| INCIDENCE ANGLE (deg) | 55 , 58.4 | | 52.7 , 51.2 | | |
| IFOV ON THE EARTH SURFACE (km) (Average) | 26 × 50 (at 6.6 GHz)<br>20 × 47 (at 10.65 GHz)<br>11 × 18 (at 18.7 GHz)<br>10 × 16 (at 23.8 GHz)<br>8 × 13 (at 36.5 GHz) | | | | |
| SWATH WIDTH (km) | 1,200 | | | | |

(PLATFORM ALTITUDE : 824km)

FROM: NASDA PAMPHLET

# AMSR SYSTEM BLOCK DIAGRAM




FROM: A PAMPHLET

# JAPAN'S MARINE OBSERVATION SATELLITE (MOS-1)

- JAPANESE EARTH REMOTE SENSING SATELLITE
  - MOS-1 LAUNCHED FEB. 19, 1987
  - MOS-1b LAUNCHED FEB. 7, 1990
  - SENSOR PAYLOADS
    - * MULTISPECTRAL ELECTRONIC SELF-SCANNING RADIOMETER (MESSR)
    - * VISIBLE AND THERMAL IR RADIOMETER (VTIR)
    - * MICROWAVE SCANNING RADIOMETER (MSR)
- ORBIT
  - SUN SYNCHRONOUS, NEAR RECURRING ORBIT
  - H = 909 km, i = 99 deg., T = 103 min, approx. recurrent period 17 days
- MEASUREMENT OBJECTIVES
  - SNOW PACK MAPPING
  - SEA ICE CONCENTRATION MAPPING
  - OIL CONTAMINATION MEASUREMENTS
  - ATMOSPHERIC WATER (VAPOR & LIQUID) MEASUREMENTS
  - PRECIPITATION MEASUREMENTS
  - CLOUD MOISTURE CONTENT

# MOS-1 SATELLITE (contd)

- **MSR INSTRUMENT**
  - DUAL FREQUENCY DICKE TYPE MICROWAVE RADIOMETER
  - CONICAL SCAN: 18.75 rpm, 3.2 sec period
  - SWATH WIDTH: 317 km
  - ANTENNA: OFFSET CASSEGRAIN, DIAMETER = 50 cm
  - 10 BIT QUANTIZATION
  - WEIGHT: 54 kg
  - POWER: 60 W
  - DATA RATE: 2 kbits/sec

| PARAMETER | CHANNEL 1 | CHANNEL 2 |
|---|---|---|
| WAVELENGTH (cm) | 1.26 | 0.96 |
| FREQUENCY (GHz) | 23.8 | 31.4 |
| POLARIZATION | H | V |
| BEAMWIDTH (deg) | 1.89 | 1.31 |
| INTEGRATION TIME (msec) | 10/47 | 10/47 |
| $\Delta T$ (@ 300 K) | 1 K | 1 K |
| RANGE (K) | 30 - 300 | 30 - 300 |
| IFOV (km) | 32 | 23 |

# MICROWAVE ATMOSPHERIC SOUNDING THEORETICAL CONSIDERATIONS

- ATMOSPHERIC GASES WILL BOTH ABSORB AND EMIT RADIATION (KIRCHHOFF'S LAW)
  - EMITTED RADIATION DEPENDS ON PHYSICAL STATE OF THE ATMOSPHERE AT EACH ALTITUDE
  - MEASUREMENT OF THE EMITTED RADIATION PLUS MODELING ALLOWS FOR THE RETRIEVAL OF ATMOSPHERIC PARAMETERS, E. G., TEMPERATURE PROFILE T(z)
  - EMISSION CAN BE CORRELATED WITH ALTITUDE BY SPECIFIC CHOICE OF THE SPECTRAL LINE FOR NADIR VIEWING CASE
- SOUNDING GEOMETRIES
  - NEAR-NADIR VIEWING
  - LIMB VIEWING
- DETERMINE ATMOSPHERIC TEMPERATURE PROFILE T(z)

-CONDITIONS WHICH MUST BE SATISFIED BY A CANDIDATE ABSORPTION BAND

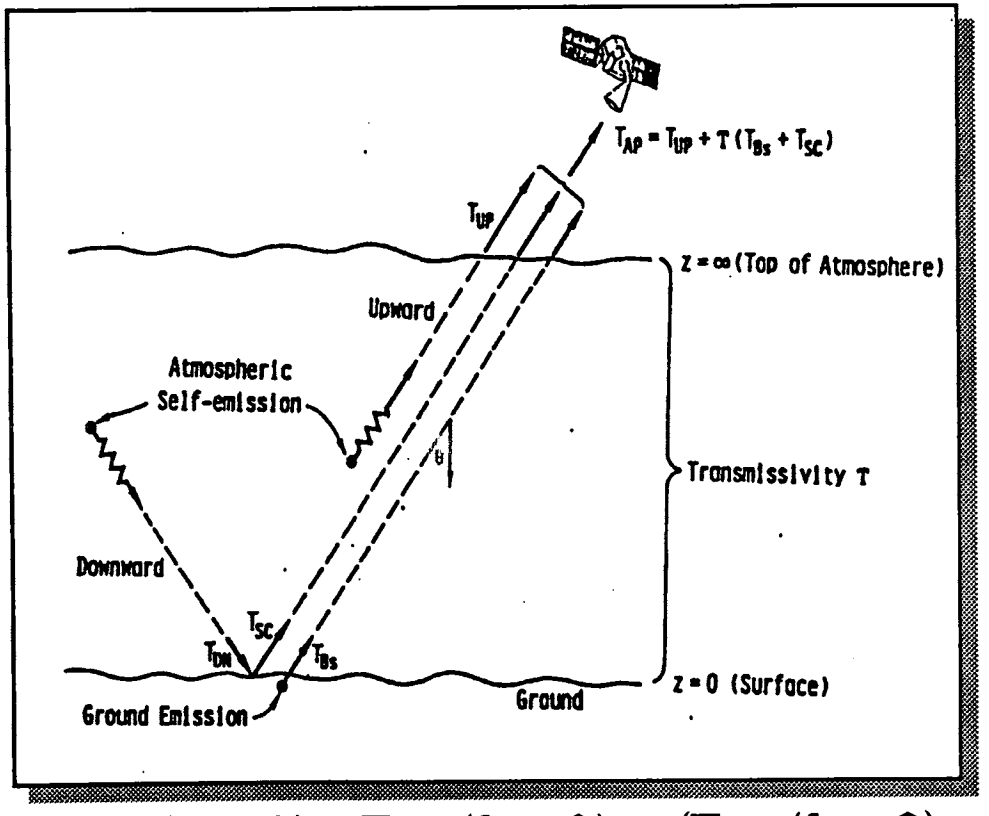
(1) CONSTITUENT SHOULD BE UNIFORMLY MIXED

(2) BAND SHOULD NOT BE OVERLAPPED BY BANDS OF OTHER SPECIES

(3) LOCAL THERMODYNAMIC EQUILIBRIUM (LTE) SHOULD HOLD, THIS IMPLIES THAT THE EMISSION IS PROPORTIONAL TO THE LOCAL ATMOSPHERIC TEMPERATURE

(4) WAVELENGTH SHOULD BE LONG ENOUGH SO THAT SCATTERED SOLAR RADIATION CAN BE NEGLECTED; THIS IS CLEARLY THE CASE IN THE MW AND MMW REGIONS

# TEMPERATURE SOUNDING




- GEOMETRY FOR ATMOSPHERIC SOUNDING
- NADIR SOUNDING
  - RECALL RADIATIVE TRANSFER EQUATION

$$T_{AP}(f,q,\hat{n}) = T_{UP}(f,q,\hat{n}) + \{T_{BS}(f,q,\hat{n}) + T_{SC}(f,q,\hat{n})\} \exp\left[-\tau(0,\infty)\sec(\theta)\right]$$

$$T_{UP}(f,q,\hat{n}) = \int_0^\infty W_T(f,q,\hat{n})\, T_{atm}(z)\, dz$$

$$W_T(f,q,\hat{n}) = \sec(\theta)\, \kappa(f,z) \exp\left[-\tau(z,\infty)\sec(\theta)\right]$$

From: F aby, et al., Microwave Remote Sensing, Active and Passive, Vol. III, © 1 -1986, Artech House, Inc., Norwood, MA.

# TEMPERATURE SOUNDING (contd)

- **W IS THE TEMPERATURE WEIGHTING FUNCTION**
  - NOTE THAT THE UPWELLING BRIGHTNESS TEMPERATURE IS A WEIGHTED AVERAGE OF THE WEIGHTING FUNCTION AND THE ATMOSPHERIC TEMPERATURE PROFILE
  - USING THE EQUATIONS OF HYDROSTATIC EQUILIBRIUM AND STATE FOR THE ATMOSPHERE ONE CAN EXPRESS W IN TERMS OF A NEW VARIABLE: -ln(P), WHERE P IS THE ATMOSPHERIC PRESSURE. THE RESULTING FUNCTION W(-ln(P)) APPROXIMATELY INDEPENDENT OF TEMPERATURE

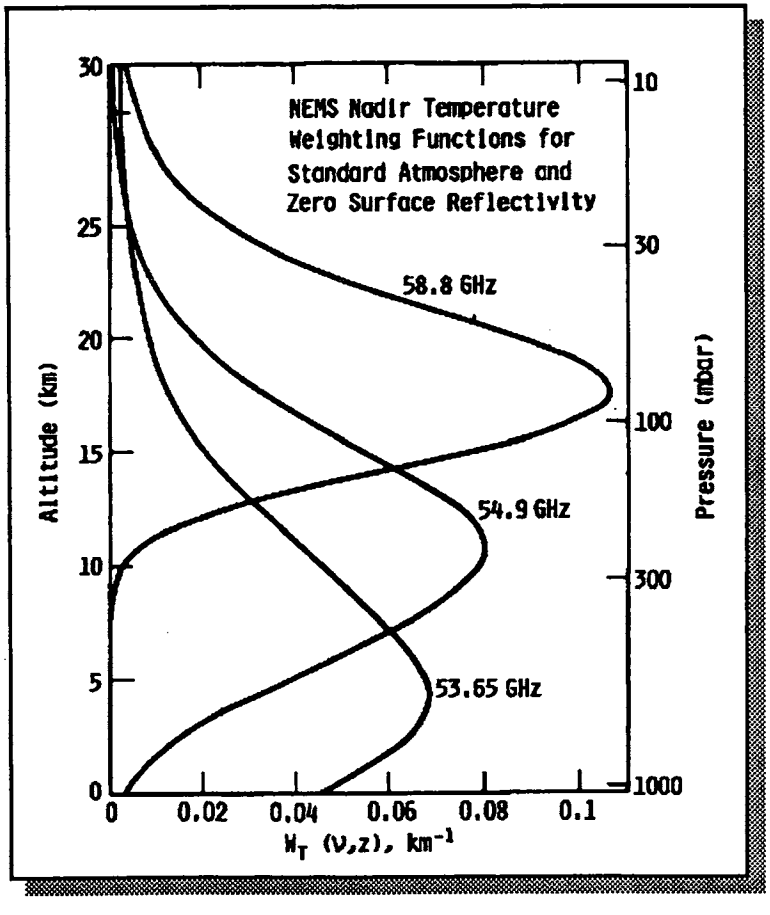
$$W_T(f,q,\hat{n},z) = \frac{\partial \exp\left[-\tau\left(z,\infty\right)\sec(\theta)\right]}{\partial z}$$

$$z \rightarrow -\ln(P)$$

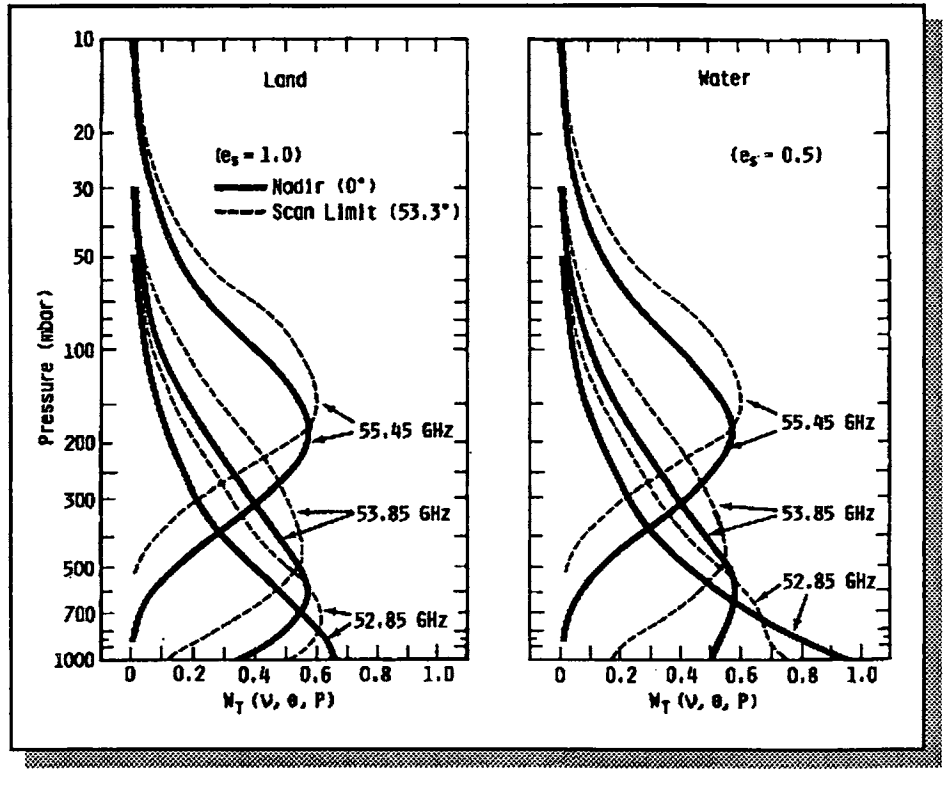
$$W_T(f,q,\hat{n},-\ln(P)) = -\frac{\partial \exp\left[-\tau\left(-\ln(P),\infty\right)\sec(\theta)\right]}{\partial \ln(P)}$$

# EXAMPLES OF TEMPERATURE WEIGHTING FUNCTIONS

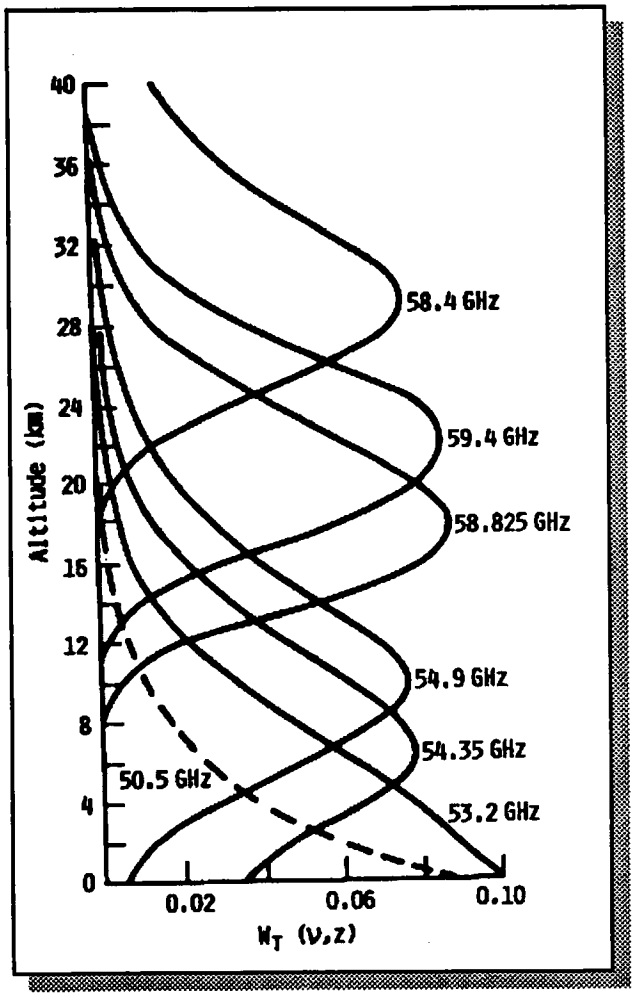
## NIMBUS-E MICROWAVE SPECTROMETER WEIGHTING FUNCTIONS




## SCANNING MICROWAVE SPECTROMETER WEIGHTING FUNCTIONS



# TEMPERATURE WEIGHTING FUNCTIONS FOR THE DMSP SSM/T




From: F. T. Ulaby, et al., Microwave Remote Sensing, Active and Passive, Vol. III, © 1981-1986, Artech House, Inc., Norwood, MA.

# ADVANCED MICROWAVE SOUNDING UNIT

- ADVANCED MICROWAVE SOUNDING UNIT-A (AMSU-A)
  - TEMPERATURE SOUNDING
  - CONCEPT DEVELOPED BY JPL
  - TO FLY ON NOAA-NEXT AND EOS(?)
  - CROSS-TRACK SCANNING RADIOMETER
  - MULTIPLE CHANNELS
    - *60 GHz MOLECULAR OXYGEN BAND
    - * 22 GHz WATER VAPOR LINE - ATMOSPHERIC CORRECTIONS
    - * 31, 89 GHz WINDOWS - SENSE PRECIPITATION - USE AS DATA QUALITY FLAG
  - -PERFORMANCE
    - * SOUNDS UP TO 40 KM
    - *± 1-1.5 K ACCURACY, EXCEPT NEAR SURFACE
    - * RESOLUTION: VERT - 5-10 KM, HOR. 40 KM
- ADVANCED MICROWAVE SOUNDING UNIT-B (AMSU-B)
  - MOISTURE SOUNDING
    - * 3 CHANNELS CENTERED ON THE 183 GHz WATER LINE
    - * 166 GHz CHANNEL FOR LOWER ATMOSPHERE SOUNDING
    - * 89 GHz WINDOW CHANNEL FOR SURFACE EMISSIVITY CORRECTIONS
  - -PERFORMANCE
    - * ± 10-20%
    - * RESOLUTION: VERT. 2.5 KM, HOR. 15 KM

# AMSU CHANNELS

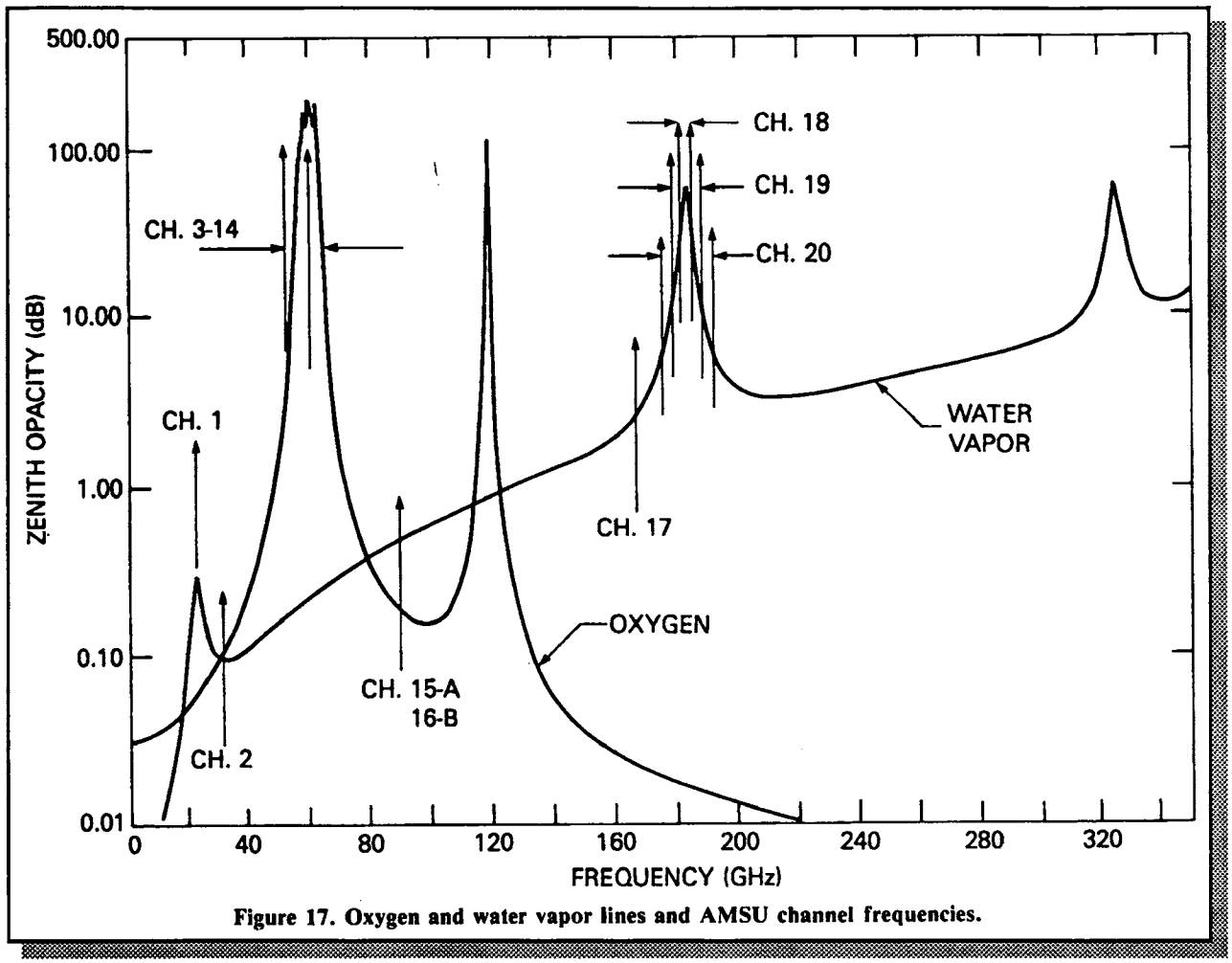



**Figure 17. Oxygen and water vapor lines and AMSU channel frequencies.**

From: High-Resolution Multifrequency Microwave Radiometer Instrument Panel Report, Earth Observing System Vol. IIe, NASA (1987).

## Table 21. AMSU-A

| Channel Number | Center Frequency (GHz) | Number of Pass Bands | Maximum Bandwidth (MHz) | Center Frequency Stability (MHz) | Temperature Sensitivity (K) | Absolute Calibration Accuracy (K) |
|---|---|---|---|---|---|---|
| 1 | 23.9 | 1 | 270 | 10.0 | 0.30 | 2.0 |
| 2 | 31.4 | 1 | 180 | 10.0 | 0.30 | 2.0 |
| 3 | 50.3 | 1 | 180 | 10.0 | 0.40 | 1.5 |
| 4 | 52.8 | 1 | 400 | 5.0 | 0.25 | 1.5 |
| 5 | 53.596 ± 0.115 | 2 | 170 | 5.0 | 0.25 | 1.5 |
| 6 | 54.4 | 1 | 400 | 5.0 | 0.25 | 1.5 |
| 7 | 54.94 | 1 | 400 | 5.0 | 0.25 | 1.5 |
| 8 | 55.5 | 1 | 330 | 10.0 | 0.25 | 1.5 |
| 9 | 57.29 | 1 | 330 | 0.5 | 0.25 | 1.5 |
| 10 | 57.29 ± 0.217 | 2 | 78 | 0.5 | 0.40 | 1.5 |
| 11 | 57.29 ± 0.322<br>57.29 ± 0.048 | 4 | 36 | 0.5 | 0.40 | 1.5 |
| 12 | 57.29 ± 0.322<br>57.29 ± 0.022 | 4 | 16 | 0.5 | 0.60 | 1.5 |
| 13 | 57.29 ± 0.322<br>57.29 ± 0.010 | 4 | 8 | 0.5 | 0.80 | 1.5 |
| 14 | 57.29 ± 0.322<br>57.29 ± 0.004 | 4 | 3 | 0.5 | 1.20 | 1.5 |
| 15 | 89.0 | 1 | 6,000 | 50.0 | 0.50 | 2.0 |

**AMSU-A CHANNELS**

## Table 22. AMSU-B Channel Characteristics

| Channel Number | Center Frequency (GHz) | Number of Pass Bands | Maximum Bandwidth (MHz) | Center Frequency Stability (MHz) | Temperature Sensitivity (K) | Absolute Calibration Accuracy (K) |
|---|---|---|---|---|---|---|
| 16 | 89.0 | 1 | 6,000 | 50 | 0.60 | 2.0 |
| 17 | 166 | 1 | 4,000 | 50 | 0.60 | 2.0 |
| 18 | 183.31 ± 1.00 | 2 | 1,000 | 30 | 0.80 | 2.0 |
| 19 | 183.31 ± 3.00 | 2 | 2,000 | 30 | 0.80 | 2.0 |
| 20 | 183.31 ± 7.00 | 2 | 4,000 | 30 | 0.80 | 2.0 |

**AMSU-B CHANNELS**

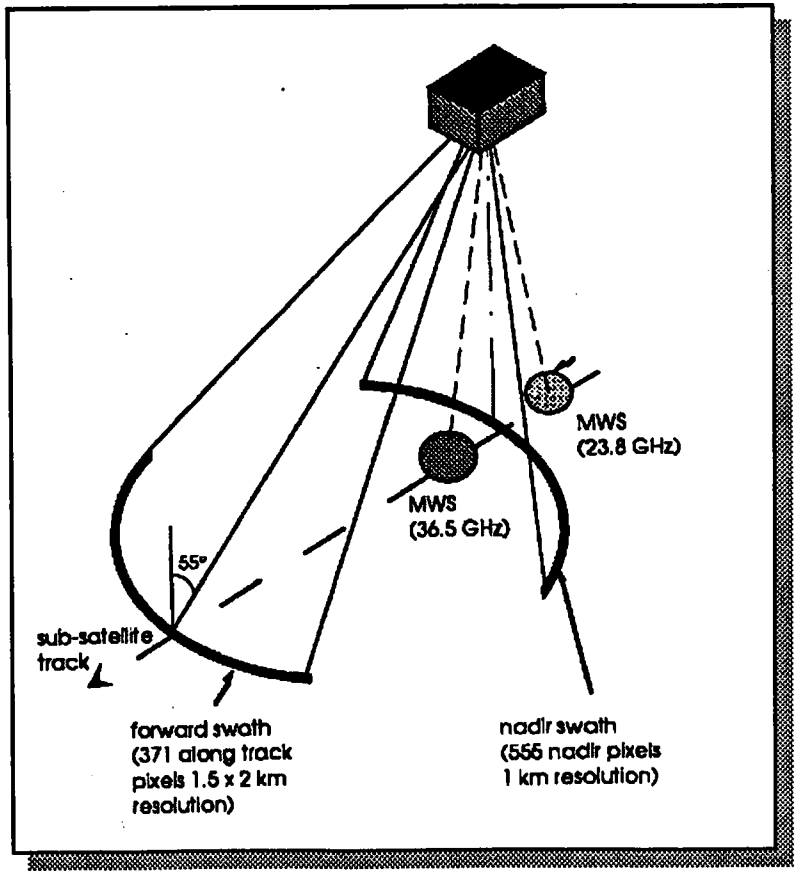
From: High-Resolution Multifrequency Microwave Radiometer Instrument Panel Report, Earth Observing System Vol. IIe, NASA (1987).

# ERS-1 MICROWAVE SOUNDER (MWS)

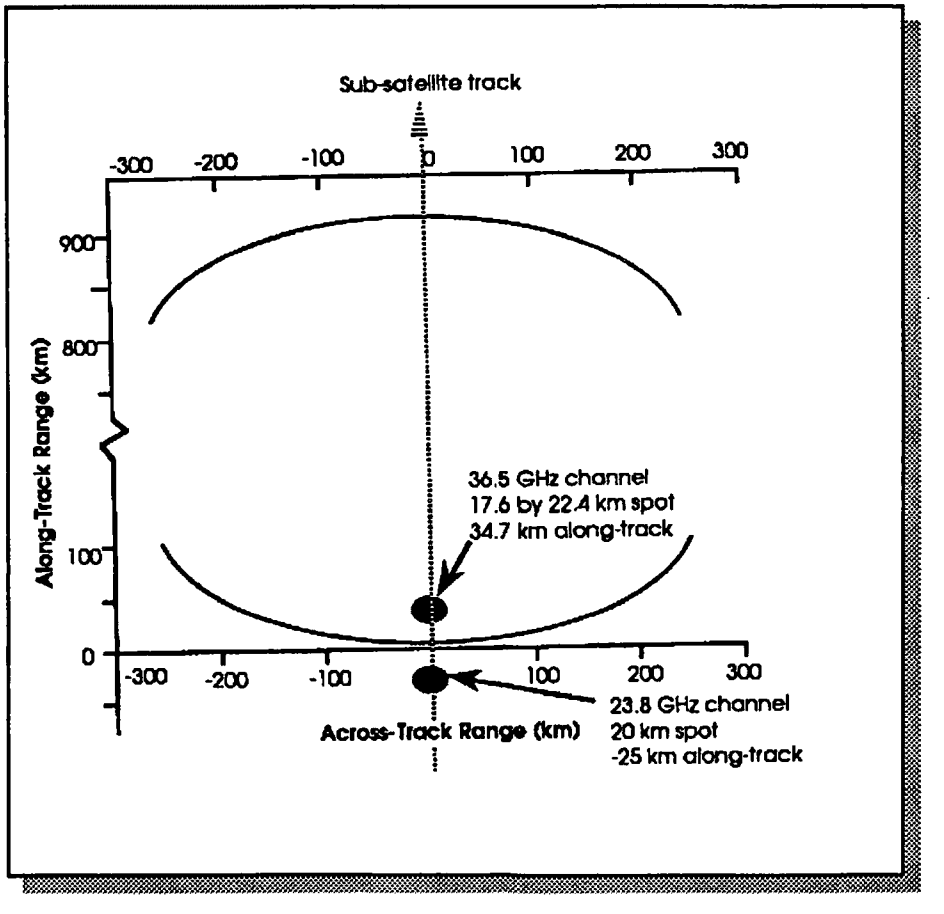
- MAIN PURPOSE OF THE MWS
  - MEASUREMENT OF THE TROPOSPHERIC PATH DELAY FOR THE PRECISE ALTIMETER RANGE CORRECTION, THROUGH THE MEASUREMENT OF THE ATMOSPHERIC INTEGRATED WATER VAPOR CONTENT
  - ATTENUATION OF THE ALTIMETER SIGNAL BY LIQUID WATER THROUGH THE MEASUREMENT OF THE TOTAL LIQUID WATER CONTENT
  - CONTINUOUS MEASUREMENT OF LIQUID WATER AND WATER VAPOR CONTENT OF THE ATMOSPHERE OVER THE OCEANS
- MWS CHARACTERISTICS
  - 2 CHANNEL DICKE RECEIVER, V-POLARIZATION IN ORBIT PLANE
  - REFLECTOR
    - * 60 cm OFF-AXIS PARABOLOID CASSEGRAIN
    - * 35 cm FOCAL LENGTH
  - CALIBRATION
    - * AMBIENT TERMINATED WAVEGUIDES
    - * SKY HORNS VIEWING DEEP SPACE

# ERS-1 MWS (contd)

## MWS VIEWING GEOMETRY



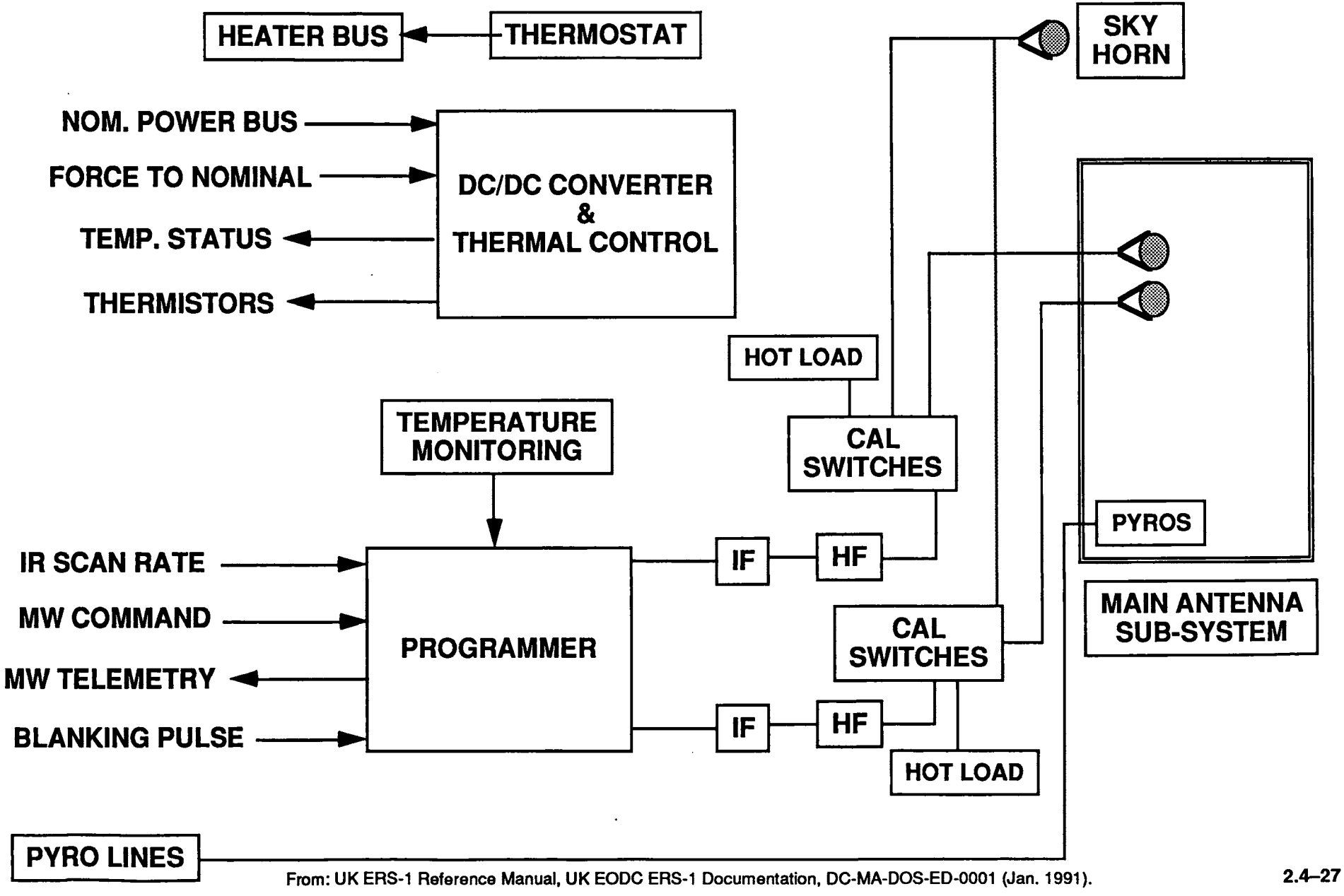

## PROJECTION OF THE ATSR AND MWS SCANS




ATSR: ALONG-TRACK SCANNING RADIOMETER

From: E[illegible]S-1 Reference Manual, UK EODC ERS-1 Documentation, DC-MA-DOS [illegible]001 (Jan. 1991).

# ERS-1 MWS SCHEMATIC DIAGRAM

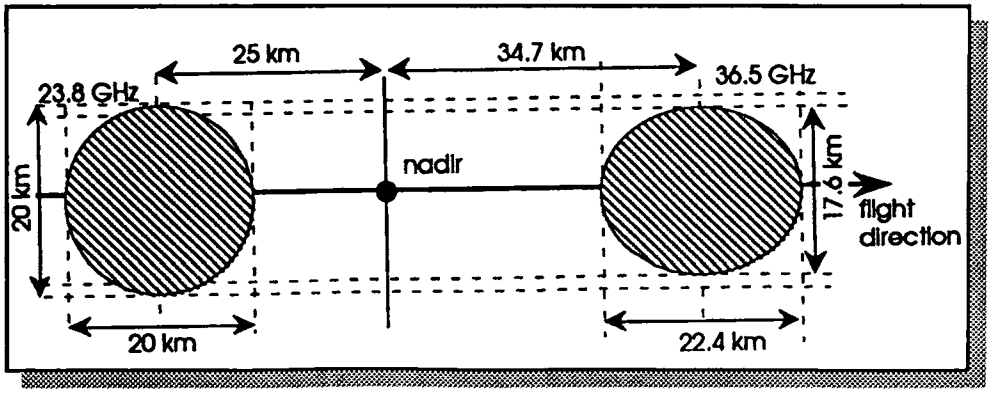



From: UK ERS-1 Reference Manual, UK EODC ERS-1 Documentation, DC-MA-DOS-ED-0001 (Jan. 1991).

# ERS-1 MWS (contd)

| PARAMETER | CHANNEL 1 | CHANNEL 2 |
|---|---|---|
| FREQUENCY (GHz) | 23.8 | 36.5 |
| NADIR POINTING ANGLE (deg.) | -1.93 | 2.50 |
| ANTENNA GAIN (dB) | 40.62 | 42.0 |
| 3 dB BEAMWIDTH (deg.) | | |
| ALONG TRACK | 1.52 | 1.61 |
| CROSS TRACK | 1.51 | 1.37 |
| 3 dB FOOTPRINT (km) | | |
| ALONG TRACK | 21.2 | 22.5 |
| CROSS TRACK | 21.2 | 19.1 |
| 20 dB APERTURE (MAX, deg.) | 4.2 | 4.1 |
| MAIN LOBE EFFICIENCY | 0.91 | 0.91 |
| FIRST SECONDARY LOBE (dB) | -24 | -35 |

**ERS-1 MWS FOOTPRINTS**




From: UK ERS-1 Reference Manual, UK EODC ERS-1 Documentation, DC-MA-DOS-ED 0001 (Jan. 1991).

# LIMB SOUNDING

- SUITABLE FOR REMOTE SENSING OF THE UPPER ATMOSPHERE (15-150 km)
- ASSUMPTIONS
  - (1) ATMOSPHERE IS SPHERICALLY STRATIFIED AND SYMMETRIC
  - (2) ATMOSPHERIC REFRACTION CAN BE NEGLECTED
  - (3) EMITTING ATMOSPHERIC SPECIES ARE IN LOCAL THERMODYNAMIC EQUILIBRIUM (LTE)
- TEMPERATURE SOUNDING

$$T_{AP}(f,h_T) = T_{cos}\exp[-2\tau_f(h_T,\infty)] + \int_{h_T}^{\infty} T_{atm}(z)\, W_T(f,q,z)\, dz$$

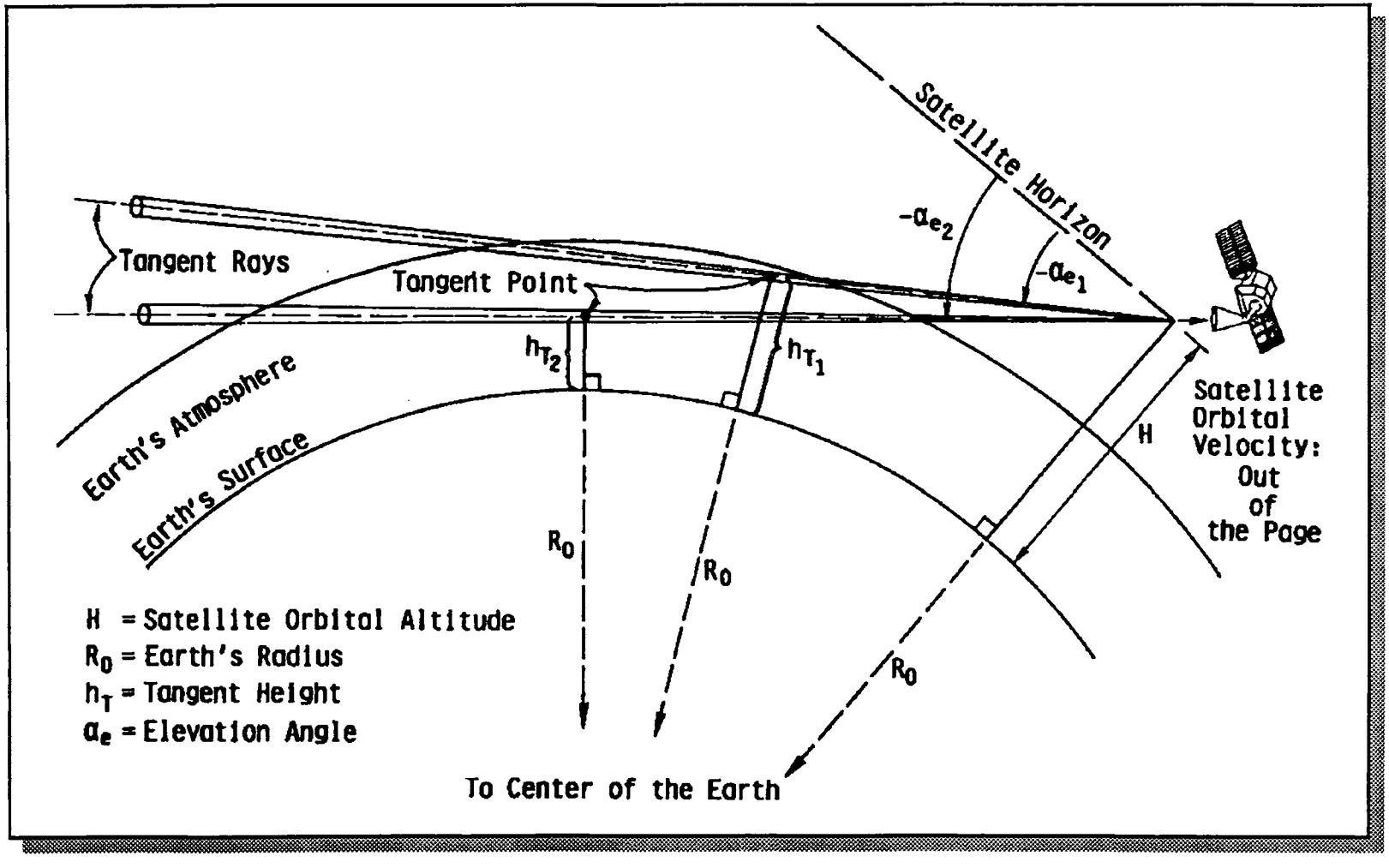
$$W_T(f,q,z) = \kappa_f(z)\exp[-\tau_f(z,\infty)]\{1 + \exp[-2\tau_f(h_T,z)]\}\, g(z)$$

$$\tau_f(z_1,z_2) = \int_{z_1}^{z_2} \kappa_f(z)\, g(z)\, dz$$

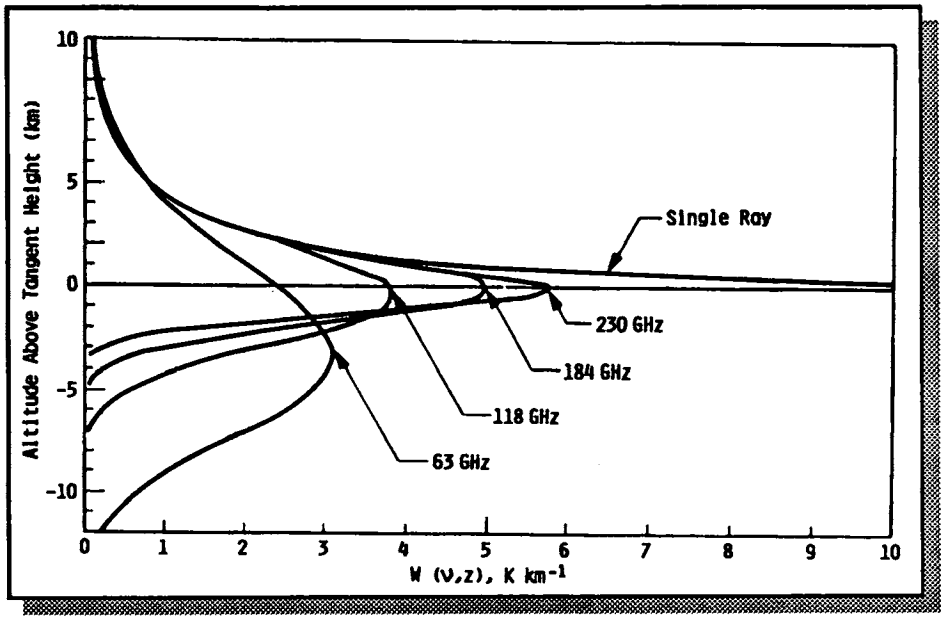
$$g(z) = \frac{R_0 + z}{\left[(R_0 + z)^2 - (R_0 + h_T)^2\right]^{1/2}}$$

g(z) is a geometry factor

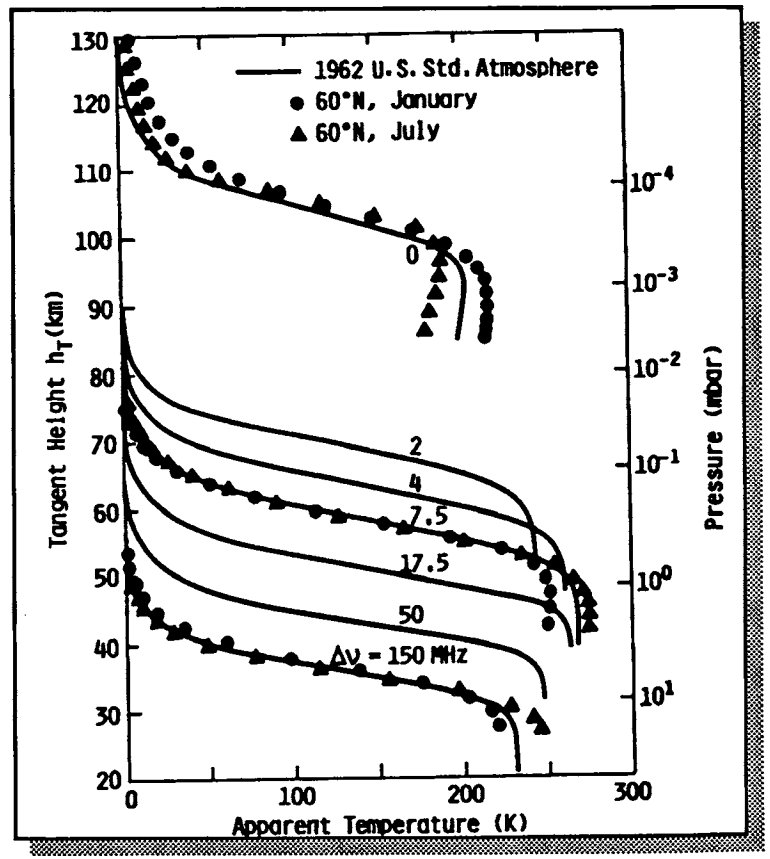
# GEOMETRY FOR LIMB SOUNDING



# LIMB SOUNDING (contd)



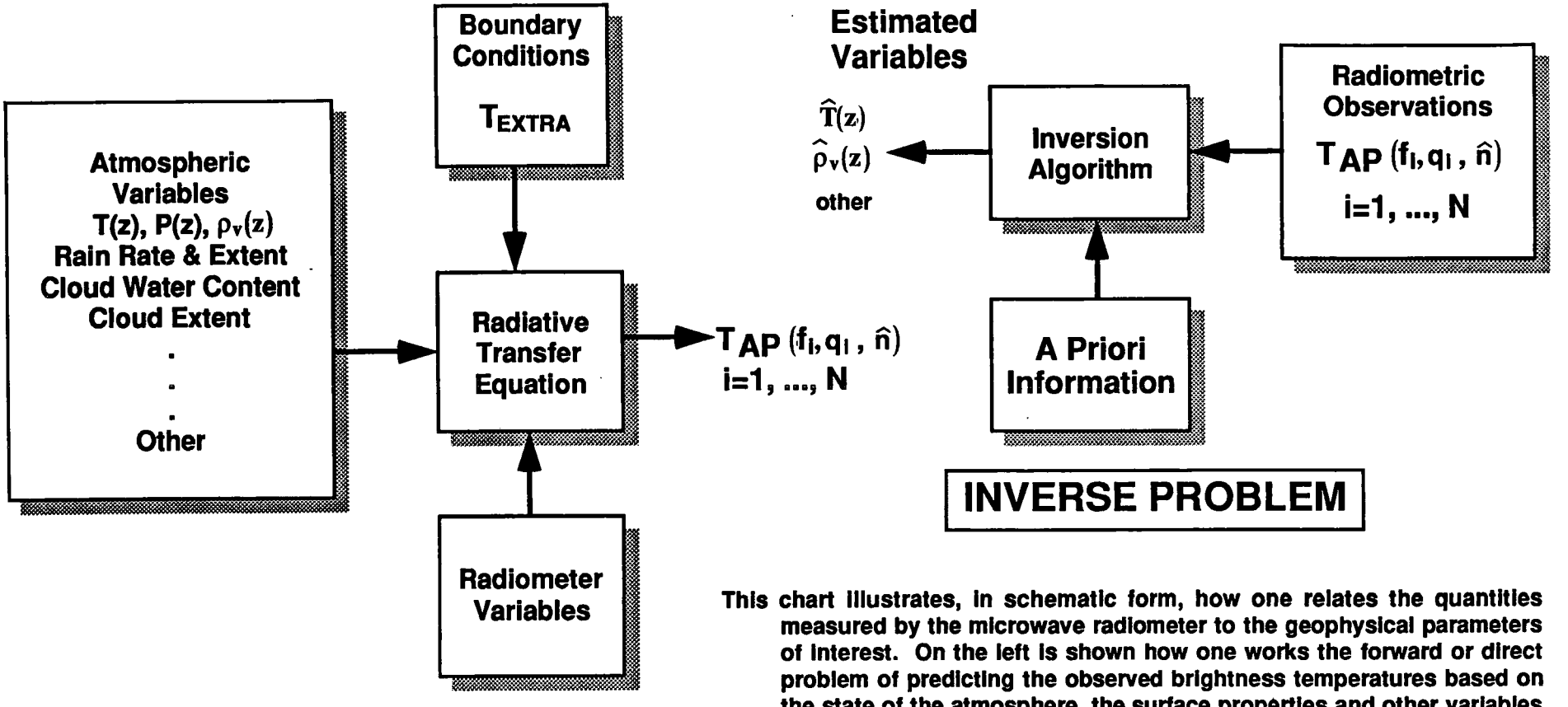

LIMB-WEIGHTING FUNCTIONS FOR A 1-M ANTENNA IN A 250KM ATMOSPHERE AT A TANGENT HEIGHT OF 50 KM. THE MIXING RATIO OF THE EMITTING GAS IS ASSUMED CONSTANT.




LIMB EMISSION FROM THE 118.75 GHz OXYGEN LINE, CALCULATED FOR A 1-M ANTENNA AT AN ORBITAL ALTITUDE OF 250 KM. Δν DENOTES THE FREQUENCY DEVIATION FROM THE LINE CENTER.

From: F. T. Ulaby, et al., Microwave Remote Sensing, Active and Passive, Vol. III, © 1981-1986, Artech House, Inc., Norwood, MA.

# RETRIEVAL OF ENVIRONMENTAL DATA PRODUCTS FROM MICROWAVE MEASUREMENTS




T(z) = atmospheric vertical temperature profile
P(z) = atmospheric vertical pressure profile
$\rho_v(z)$ = atmospheric water vapor vertical profile

This chart illustrates, in schematic form, how one relates the quantities measured by the microwave radiometer to the geophysical parameters of interest. On the left is shown how one works the forward or direct problem of predicting the observed brightness temperatures based on the state of the atmosphere, the surface properties and other variables describing the radiative transfer problem. On the other hand, the radiometer measures a set of brightness temperatures which need to be combined in some manner in order to estimate the geophysical parameters. This is the inverse or estimation problem. Many retrieval or inversion algorithms are based on relating linear combinations (regression) of brightness temperatures, measured by each radiometer channel (frequency and polarization), to the geophysical quantity to be estimated (e.g., rain rate). The algorithms are then "tuned" or "calibrated" using ground truth measurements in conjunction with satellite observations of the same area (see DMSP CAL/VAL report).

After: F aby, et al., Microwave Remote Sensing, Active and Passive, Vol. III, © 1986, Artech House, Inc., Norwood, MA.

# 2.5 SYNTHETIC APERTURE AND INTERFEROMETRIC SYSTEMS

- BASIC PRINCIPLES AND CONCEPT
- PROPOSED SYSTEM CONCEPT

---

## • BASIC CONCEPT

"THE TECHNIQUE INVOLVES COHERENTLY MEASURING THE PRODUCT OF THE SIGNAL FROM PAIRS OF ANTENNA WITH MANY DIFFERENT ANTENNA SPACINGS. EACH ANTENNA PAIR MEASURES THE CORRELATION FUNCTION OF THE ANTENNA VOLTAGE, R(X), AT AN ARGUMENT, X, DETERMINED BY THE DISTANCE BETWEEN THE ANTENNAS. FOR DISTANT SOURCES, IT CAN BE SHOWN THAT THE CORRELATION FUNCTION IS PROPORTIONAL TO THE FOURIER TRANSFORM OF THE INTENSITY OF THE SOURCE AT A FREQUENCY WHICH DEPENDS ON THE SPACING, X. THUS, BY MAKING MEASUREMENTS AT MANY DIFFERENT SPACINGS ONE, IN EFFECT, DETERMINES THE SPECTRUM OF THE INTENSITY OF THE SOURCE. THE INTENSITY CAN BE OBTAINED AFTER ALL MEASUREMENTS ARE COMPLETER BY INVERTING THE TRANSFORM. THE RESOLUTION OBTAINED IN THIS MANNER IS DETERMINED BY HOW WELL THE CORRELATION FUNCTION HAS BEEN MEASURED, NOT BY THE SIZE OF THE ANTENNAS USED. THUS, IN PRINCIPLE, ONE CAN OBTAIN VERY HIGH RESOLUTION MAPS OF THE SOURCE BY MEASURING AT MANY DIFFERENT BASELINES USING RELATIVELY SMALL ANTENNAS."

From: D. M. LE VINE AND J. C. GOOD, *APERTURE SYNTHESIS FOR MICROWAVE RADIOMETERS IN SPACE*, NASA TECH. MEMO. 85033 (1983).

# BASIC CONCEPT (contd)

- **SPATIAL RESOLUTION**
  - DETERMINED BY HOW WELL THE CORRELATION FUNCTION (I.E., THE FOURIER TRANSFORM OF THE SCENE BRIGHTNESS DISTRIBUTION) IS SAMPLED AND NOT BY THE ANTENNA SIZE
  - USING MANY SMALL ANTENNAS AND FINELY SPACED MEASUREMENTS ONE OBTAINS, IN PRINCIPLE, A LARGE FOV AND HIGH SPATIAL RESOLUTION

- **EXAMPLE: ANTENNAS ON A UNIFORMLY SPACED CARTESIAN GRID**

$2N_X + 1$, $2N_Y + 1$ } NUMBER OF ANTENNAS IN EACH DIRECTION

$f_0$ = CENTER FREQUENCY

$$\rho_X = \frac{1}{N_X K_X} \qquad K_X = \frac{d_X}{cR_0} f_0 = \frac{d_X}{\lambda R_0} \qquad \Rightarrow \rho_X = \frac{\lambda}{L_X} R_0$$

$$\rho_Y = \frac{1}{N_Y K_Y} \qquad K_Y = \frac{d_Y}{cR_0} f_0 = \frac{d_Y}{\lambda R_0} \qquad \rho_Y = \frac{\lambda}{L_Y} R_0$$

$R_0$ = Range from antenna to scene $L_{X,Y} = N_{X,Y} d_{X,Y}$ Array size

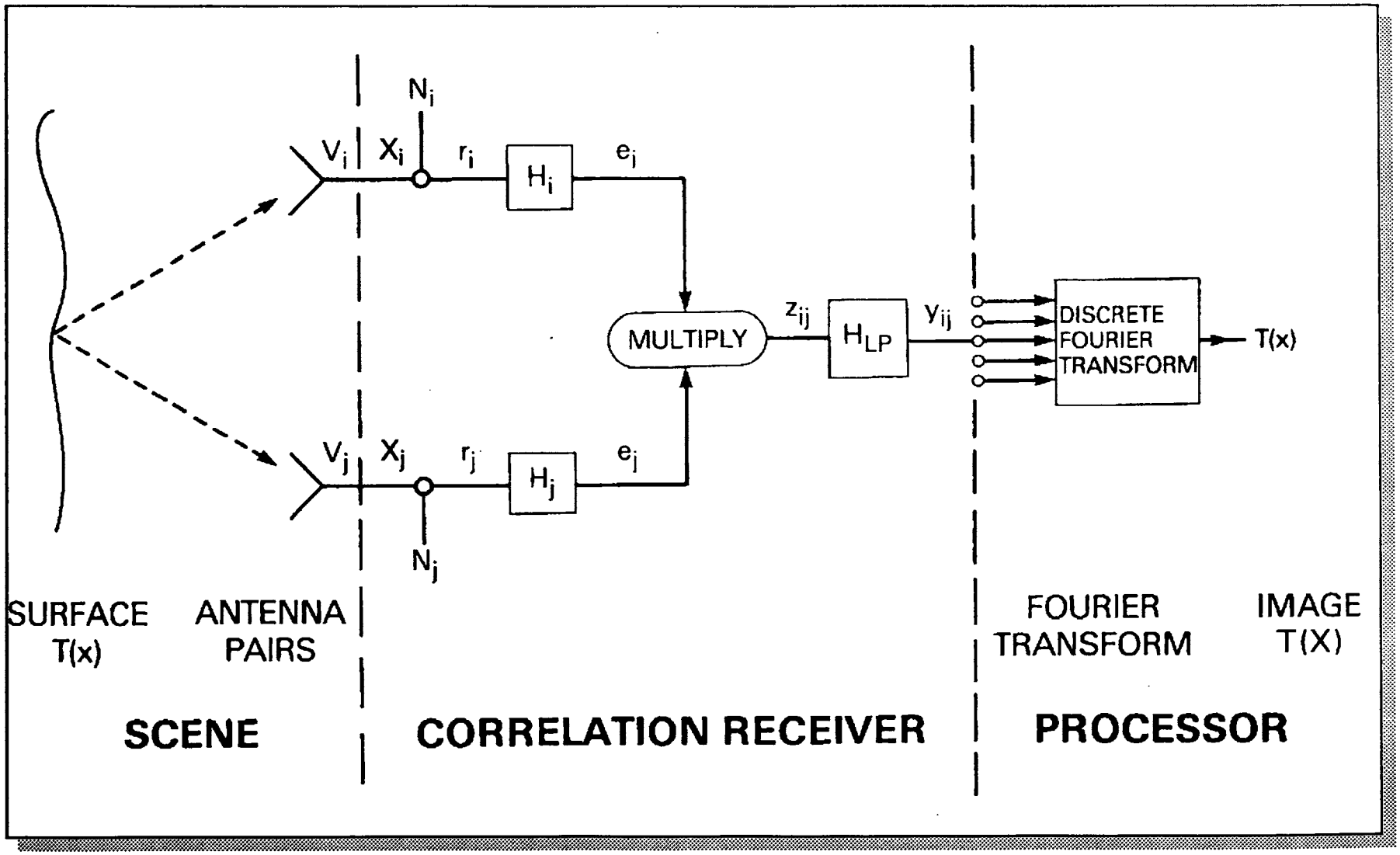
- **FIELD OF VIEW (FOV)**

$$FOV_X = \frac{\lambda}{D_X} R_0$$

$$FOV_Y = \frac{\lambda}{D_Y} R_0$$

$D_{X,Y}$ = ANTENNA APERTURE SIZES

# SCHEMATIC OF A CORRELATION RECEIVER




From: D. M. Le Vine, *The Sensitivity of Synthetic Aperture Radiometers for Remote Sensing Applications From Space*, NASA Tech. Memo. 100741 (1989).

# COMPARISON OF THE SENSITIVITY OBTAINED WITH A TOTAL POWER RADIOMETER AND VARIOUS APERTURE SYNTHESIS TECHNIQUES

| | | Total power | Synthesis T | Synthesis <T> | Synthesis ESTAR | Synthesis Cross | Synthesis <Cross> |
|---|---|---|---|---|---|---|---|
| SENSITIVITY (ΔT) | General | $\frac{T_{sys}}{\sqrt{B\tau}}$ | ← $\frac{T_{sys}}{\sqrt{2B\tau}} \cdot \frac{1}{\sqrt{NM}} \cdot \frac{A_{syn}}{A_e}$ → | | | | |
| | Example | $\frac{T_{sys}}{\sqrt{B\tau}}$ | $\frac{T_{sys}}{\sqrt{B\tau}} \frac{L}{\sqrt{2W}}$ | $\frac{T_{sys}}{\sqrt{B\tau}} \sqrt{\frac{L}{2W}}$ | $\frac{T_{sys}}{\sqrt{B\tau}} \frac{L}{NW}$ | $\frac{T_{sys}}{\sqrt{B\tau}} \frac{L}{W}$ | $\frac{T_{sys}}{\sqrt{B\tau}} \sqrt{\frac{L}{W}}$ |
| | Value (K) | 0.8 | 18.7 | 1.3 | 1.8 | 26.4 | 1.9 |
| PARAMETERS | $T_{sys}$ (K) | 500 | 500 | 500 | 500 | 500 | 500 |
| | B (MHz) | 30 | 10 | 10 | 10 | 10 | 10 |
| | τ (sec) | .0143 | 1.43 | 1.43 | 1.43 | 1.43 | 1.43 |
| | L (M) | 20 | 20 | 20 | 20 | 20 | 20 |
| | W (M) | 20 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | N | (100) | 100 | 100 | 15 | 100 | 100 |

From M. Le Vine, *The Sensitivity of Synthetic Aperture Radiometers for Remote Sensing Applications From Space*, NASA Tech. Memo. 100741 (1989).

# SYSTEM CONCEPT

- RECOMMENDED MEASUREMENT REQUIREMENT FOR SOIL MOISTURE

| | IDEAL | ADEQUATE |
|---|---|---|
| FREQUENCY (GHz) | 1.4, 6 | 1.4 |
| SPATIAL RESOLUTION (km) | 10 | 25 |
| RADIOMETRY | | |
| ACCURACY (K) | 1.5 | 1.5 |
| SENSITIVITY (K) | 1.0 | 1.0 |
| REVISIT TIME (DAYS) | 1 - 3 | 3 |

- ELECTRONICALLY SCANNED THINNED ARRAY (ESTAR)
  - PROPOSED SENSOR FOR HIGH RESOLUTION SOIL MOISTURE MEASUREMENTS AT 1.4 GHz (L-band)
  - HYBRID REAL-AND-SYNTHETIC APERTURE SYSTEM
    - * STICK ANTENNAS GIVE FAN BEAMS ORIENTED TO PROVIDE ALONG TRACK RESOLUTION AND WIDE CROSS TRACK SWATH
    - * CROSS TRACK RESOLUTION IS OBTAINED FROM APERTURE SYNTHESIS
    - * ZERO REDUNDANCY ARRAY

# ESTAR CONCEPT

## • ESTAR CHARACTERISTICS

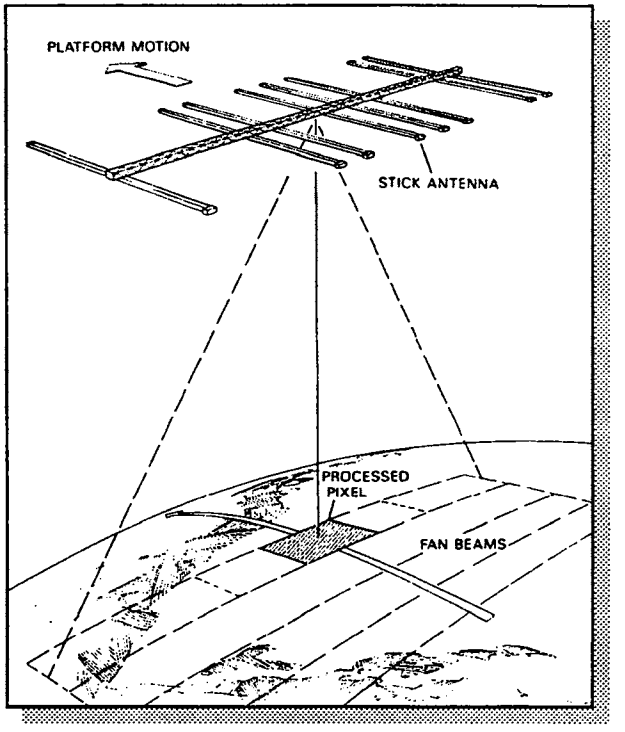
- SPECIFICATIONS

| | |
|---|---|
| WAVELENGTH ($\lambda$) | 21.23 cm |
| ANTENNA LENGTH (D) | 20 m |
| ANTENNA WIDTH (d) | 11 cm |
| NUMBER OF ANTENNAS | 25 |
| INTEGRATION TIME | 0.6 sec |
| ORBIT ALTITUDE (H) | 824 km |
| SATELLITE SPEED (V) | 7.5 km/sec |
| RECEIVER BANDWIDTH (B) | 25 MHz |
| SYSTEM NOISE TEMPERATURE | 300 K |
| TYPICAL SCENE TEMPERATURE | 280 K |

- PERFORMANCE REQUIREMENTS

| | |
|---|---|
| RESOLUTION (NADIR) | 10 km |
| SWATH WIDTH | 1400 km |
| SENSITIVITY ($\Delta$T) | 1.0 K |

SCHEMATIC ILLUSTRATION OF THE ESTAR CONCEPT




From: D. M. Le Vine, et al., *Initial Results in the Development of a Synthetic Aperture Microwave Radiometer*, IEEE GSRS, **28(4)**, (1990). ©1990 IEEE.

From: D. M. Le Vine, et al., *A Multifrequency Microwave Radiometer of the Future*, IEEE GSRS, **27(2)**, (1989). ©1990 IEEE.

# 2.6 APPLICATIONS OF PASSIVE MICROWAVE REMOTE SENSING

- FOCUS ON APPLICATIONS RELEVANT TO EARTH REMOTE SENSING AND ENVIRONMENTAL CHANGE
- POLAR ORBITING INSTRUMENTATION (LEO)
  - HIGH SPATIAL RESOLUTION WITH MODERATE SIZED ANTENNAS
  - GLOBAL COVERAGE
    - * 1500 KM SWATH WIDTH
    - * 2 DAYS FOR GLOBAL COVERAGE
  - REASONABLE REVISIT TIME FOR MANY PROCESSES OF INTEREST
- GEOSTATIONARY INSTRUMENTATION (GEO)
  - REQUIRE MUCH LARGER ANTENNAS TO ACHIEVE ADEQUATE SPATIAL RESOLUTION
  - AREA COVERAGE
    - * VIEW APPROXIMATELY 1/3 GLOBE
    - * NO POLAR COVERAGE
  - POTENTIAL TO PROVIDE HIGH TEMPORAL RESOLUTION OR REVISIT
    - * APPROXIMATELY EVERY 30 MINUTES
- "ALL WEATHER"/ DAY-NIGHT CAPABILITY

# APPLICATIONS (contd)

- PASSIVE MW IS SENSITIVE TO SURFACE TEMPERATURE AND EMISSIVITY
  - OBTAIN INFORMATION ABOUT THE SURFACE BY RELATING MEASUREMENTS OF T AND $\varepsilon$ TO PHYSICAL CHARACTERISTICS OF THE SURFACE
- PROVIDES INFORMATION FOR UNDERSTANDING THE FUNDAMENTAL GEOPHYSICAL PROCESSES CONTROLLING THE ENVIRONMENT
- HYDROLOGIC CYCLE
  - IDENTIFIED BY NASA EOS PROGRAM AS HIGH PRIORITY FOR MW SENSOR MEASUREMENTS
  - GEOPHYSICAL MEASUREMENTS
    - SOIL MOISTURE
    - PRECIPITATION
    - SNOW (COVERAGE/MOISTURE CONTENT)
    - ATMOSPHERIC WATER VAPOR
    - EVAPORATION (OCEANS)
    - EVAPOTRANSPIRATION (LAND)

# APPLICATIONS (contd)

- OCEANS / AIR-SEA INTERACTION
  - SEA SURFACE TEMPERATURE (SST)
  - SURFACE WIND SPEED
  - SEA ICE (CONCENTRATION AND PROPERTIES)
- ATMOSPHERIC SOUNDING
  - ATMOSPHERIC TEMPERATURE AND WATER VAPOR PROFILES
  - TOTAL LIQUID WATER CONTENT
- REVIEW OF RECOMMENDATIONS BY NASA EOS HIGH RESOLUTION MULTIFREQUENCY MICROWAVE RADIOMETER (HMMR) SCIENCE PANEL

# MICROWAVE PARAMETERS

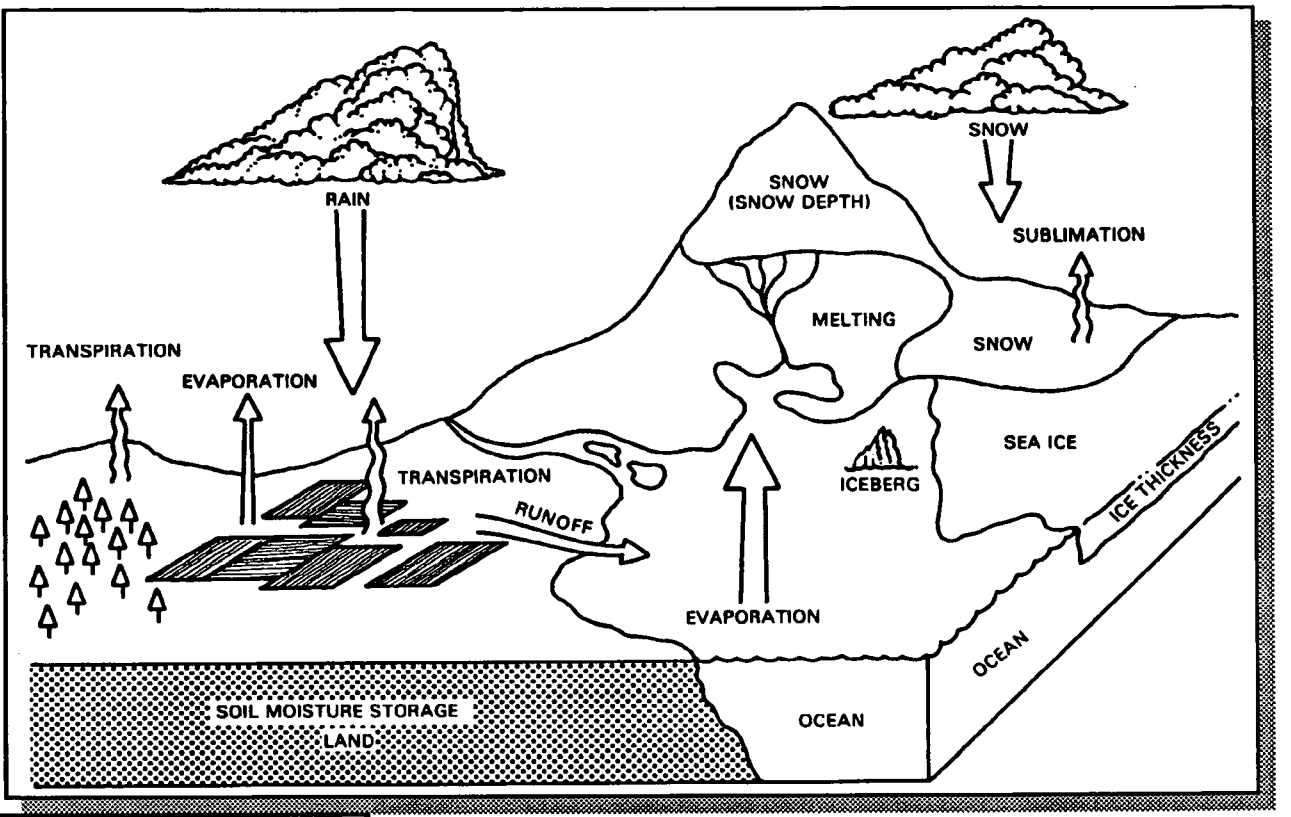
**Table 1. Parameters Which are Measured with Microwave Sensors and the Frequencies at Which the Measurements are Made**

| Physical Observable | Frequency of Observation (GHz) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1.4 | 6 | 10 | 18 | 21 | 37 | 50-60 | 90 | 160 | 183 |
| Soil moisture | ● | O | | | | | | | | |
| Snow | | O | O | ● | | ● | | ◒ | | |
| Precipitation | | | | | | | | | | |
| Ocean | | | ◒ | ● | O | ◒ | | | | |
| Land | | | | ◒ | | ● | | ● | | ◒ |
| Sea surface temperature | | ● | ◒ | ◒ | ◒ | O | | | | |
| Sea ice | | | | | | | | | | |
| Extent | | | | ● | | ● | | O | | |
| Type | | O | ◒ | ● | | ● | | ◒ | | |
| Wind speed (sea surface) | | | ● | ◒ | O | O | | | | |
| Water vapor | | | | | | | | | | |
| Total (over ocean) | | | | ● | ● | ◒ | | | | |
| Profile | | | | | ◒ | O | ◒ | O | ◒ | ● |
| Cloud water (over ocean) | | | | | ◒ | ● | | ◒ | | |
| Temperature profile | | | | | O | O | ● | O | | |

Key: ● Necessary ◒ Important O Helpful

From: *...R Instrument Panel Report, Earth Observing System, Vol. IIe*, NASA (19...)

# HYDROLOGIC CYCLE




**Summary of Measurement Requirements (Soil Moisture)**

| | Ideal | Adequate |
|---|---|---|
| Frequency | 1.4, 6 GHz | 1.4 GHz |
| Spatial resolution | 10 km | 25 km |
| Radiometric accuracy | 1.5 K | 1.5 K |
| Radiometric sensitivity | 1.0 K | 1.0 K |
| Revisit time | 1-3 days | 3 days |

**Summary of Measurement Requirements (Precipitation)**

| | Ideal | Adequate |
|---|---|---|
| Frequency | 18, 21, 37, 90 GHz | 18, 21, 37, 90 GHz |
| Spatial resolution | 1 km | 10 km |
| Radiometric accuracy | 2.0 K | 2.0 K |
| Radiometric sensitivity | 2.0 K | 2.0 K |
| Sampling interval | 1 day | 3 days |

From: *HMMR Instrument Panel Report, Earth Observing System, Vol. IIe*, NASA (1987).

# HYDROLOGIC CYCLE (contd)

**Summary of Snow Parameters and Measurements**

| Parameters | Instrumentation | Technological Development State |
|---|---|---|
| Snow cover extent | Microwave at 18 or 37 GHz | Demonstrated feasibility |
| Snow water equivalent | Microwave at 1.4, 6, 10, 18, and 37 GHz dual polarization | Demonstrated feasibility to obtain relative values for shallow, dry snow; research needed for deeper snowpacks and to assess influence of snow properties |
| Snow wetness | 18 or 37 GHz | Feasible up to ~5% water content |
| Albedo | Optical 0.6, 0.9, and 1.6 $\mu$m | Demonstrated feasibility |
| Temperature | 3.7 and 11 $\mu$m | Demonstrated feasibility |

**Summary of Measurement Requirements (Snow)**

| | Ideal | Adequate |
|---|---|---|
| Frequency | 1.4, 6, 10, 18, 37, 91 GHz | 10, 18, 37, 91 GHz |
| Spatial resolution | 1 km | 10 km |
| Radiometric accuracy | 2.0 K | 2.0 K |
| Radiometric sensitivity | 2.0 K | 2.0 K |
| Revisit time | 0.5 days | 3 days |

From: *I* *Instrument Panel Report, Earth Observing System, Vol. IIe*, NASA (198[illegible]

# OCEANS

**Summary of Measurement Requirements (Oceans)**

| | Ideal | Adequate |
|---|---|---|
| Frequency | 6, 10, 18 GHz | 6, 10 GHz |
| Spatial resolution | 1-5 km | 10-25 km |
| Radiometric accuracy | 1.0 K | 1.0 K |
| Radiometric sensitivity | 0.1 K | 0.5 K |
| Revisit time | 1 day | 3 days |

**Summary of Measurement Requirements (Sheet Ice)**

| | Ideal | Adequate |
|---|---|---|
| Frequency | 10, 18, 37, 90 GHz | 18, 37 GHz |
| Spatial resolution (spot size: one spot every 10 km) | 1 km | 1 km |
| Accuracy | 2 K | 2 K |
| Revisit time | | |
| Surface melt | 1 day | 3 days |
| Accumulation rate | 1 day | 3 days |

**Summary of Measurement Requirements (Sea Ice)**

| | Ideal | Adequate |
|---|---|---|
| Frequency | 10, 18, 37, 90 GHz | 18, 37, 90 GHz |
| Spatial resolution | | |
| Ice boundary | 5-25 km | 25 km |
| Concentration | 1-10 km | 25 km |
| Type | 1-10 km | 25 km |
| Albedo | 1-10 km | 10 km |
| Surface melt | 1-10 km | 10 km |
| Radiometric accuracy | 2.0 K | 2.0 K |
| Radiometric sensitivity | 2.0 K | 2.0 K |
| Revisit time | 1 day | 3 days |

From: *HMMR Instrument Panel Report, Earth Observing System, Vol. IIe*, NASA (1987).

# ATMOSPHERE

**Summary of Measurement Requirements (Atmosphere)**

| | Ideal | Adequate |
|---|---|---|
| **Temperature Profiles** | | |
| Frequency | 50-60* GHz | 50-60 GHz |
| Resolution (horizontal) | 10 km | 100 km |
| Resolution (vertical) | 500 m | 2 km |
| Accuracy | ±1 K | ±1 K |
| Radiometric sensitivity | 0.3 K | 0.3 K |
| Radiometric accuracy | 1.0 K | 1.0 K |
| Temporal resolution | 1 per hour | 2 per day |
| **Humidity Profiles** | | |
| Frequency | 183** GHz | 183 GHz |
| Resolution (horizontal) | 10 km | 100 km |
| Resolution (vertical) | 500 m | 2 km |
| Accuracy | ±10% (±1 g/kg) | ±10% (±1 g/kg) |
| Radiometric sensitivity | 0.8 K | 0.8 K |
| Radiometric accuracy | 2.0 K | 2.0 K |
| Temporal resolution | 1 per hour | 2 per day |

*Plus ancillary channels at 21, 37, and 90 GHz for atmospheric corrections
**Plus ancillary channels at 90 and 160 GHz for atmospheric corrections

From: *Instrument Panel Report, Earth Observing System, Vol. IIe*, NASA (19[illegible]

# EOS HMMR MEASUREMENT CHARACTERISTICS

| HMMR Measurement Characteristics | | | | |
|---|---|---|---|---|
| **Parameter** | **ESTAR** | **AMSR** | **AMSU-A** | **AMSU-B** |
| Frequencies (GHz) | 1.4 | 6, 10, 18, 21, 37, 90 | 23.8, 31.4 50-60 (12 Ch), 89 | 89, 157, 183 (3 Ch) |
| Wavelengths (mm) | 212 | 50, 28, 16, 14, 8.2, 3.3 | 12.6, 9.6 5.5 (12 Ch), 3.4 | 3.4, 1.8, 1.6 (3 Ch) |
| Antenna size (m) | 18×18 | 4×7 | 0.15, 0.28 | 0.28 |
| IFOV (km) | 10 | 25 to 2 | 50 | 15 |
| Swath (km) | 1,400 | 1,400 | 1,500 | 1,500 |
| ΔT (K) | 1.0 | 0.4–1.7 | 0.25–1.3 | 1.0–1.2 |
| Data rate (kbps) | 5 | 50 | 5 | 5 |
| Instrument size (m) | 18×18×0.5 | 6×8×4 | 1.5×1×1 | 0.7×0.7×0.5 |
| Power (W) | 200 | 250 | 115 | 60 |
| Weight (Kg) | 350 | 350 | 64 | 30 |

From: *HMMR Instrument Panel Report, Earth Observing System, Vol. IIe*, NASA (1987).

# EOS HMMR MEASUREMENT CAPABILITY

**HMMR Measurement Capability**

| Parameter | ESTAR | AMSR | AMSU-A | AMSU-B |
|---|---|---|---|---|
| **Hydrologic Cycle** | | | | |
| Evaporation (land)* | B | B | | B |
| Evaporation (ocean)* | | A | | B |
| Soil moisture | A | | | |
| Sea surface temperature | | B | | |
| Snow | | A | | B |
| Precipitation (ocean) | | A | | |
| Precipitation (land) | | A | | B |
| **Oceanic Science** | | | | |
| Ocean dynamics | | C | | |
| Sea ice | | A | | |
| **Tropospheric Science** | | | | |
| Temperature profile | | | A | |
| Water vapor (total) | | A | A | A |
| Water vapor (profile) | | | | A |
| Cloud water | | B | B | |

Code: A = Definitive Measurement
B = Significant Measurement
C = Contributing Measurement

*Evaporation is an inferred quantity. It requires measurement of supporting geophysical parameters by HMMR and other Eos instruments.

From: *H' Instrument Panel Report, Earth Observing System, Vol. IIe*, NASA (1987)

# 2.7 MICROWAVE RADIOMETRY EXAMPLES

# PASSIVE MICROWAVE REMOTE SENSING EXAMPLE

- MW RADIATIVE TRANSFER CODE: RADTRAN
  - RT COMPUTER MODEL DEVELOPED BY THE AF GEOPHYSICS LABORATORY
  - COMPUTES APPARENT TEMPERATURES AND ATMOSPHERIC TRANSMISSION FROM 1-1000 GHz
- EXAMPLE CASE
  - SIMULATION OF THE 19.35 V & H CHANNELS OF THE SSM/I
  - FOV INCLUDES 4 DIFFERENT PIXEL TYPES
    - * CALM OCEAN
    - * WINDY OR ROUGH OCEAN
    - * CLOUD OVER CALM OCEAN
    - * VEGETATION (LAND)

# RADTRAN SIMULATION PARAMETERS

FREQUENCY = 19.35 GHZ, 1962 US STANDARD ATMOSPHERE

TOTAL WATER VAPOR CONTENT = 1.612 PRECIPITABLE CM

TOTAL CLOUD WATER CONTENT = 0.000 GRAMS PER SQ CM

PIXEL TYPE 1 – CALM OCEAN – GROUND = 0 , TEMP1 = 300.00

| NADIR ANGLE | ATTENUATION | TRANSMISSION | BRIGHTNESS TEMPERATURE (DEGREES K) | | | EMISSIVITY | |
|---|---|---|---|---|---|---|---|
| (DEG) | (NEPERS) | FACTOR | DOWN | UP HORIZ | UP VERT | HORIZONTAL | VERTICAL |
| 54.0 | 0.8682E-01 | 0.91684 | 22.79731 | 106.13596 | 184.06224 | 0.25691 | 0.57728 |

PIXEL TYPE 2 - WINDY OCEAN - U.S. STANDARD

GROUND = 1 TEMP1 = 290.00 TEMP2 = 290.00 A1 = 0.03000 FS1 = 0.01000 A2 = 1.00000 FS2 = 0.00000

E2WET = ( 0.00000, 0.00000) DEPWET = 5.000

| NADIR ANGLE | ATTENUATION | TRANSMISSION | BRIGHTNESS TEMPERATURE (DEGREES K) | | | EMISSIVITY | |
|---|---|---|---|---|---|---|---|
| (DEG) | (NEPERS) | FACTOR | DOWN | UP HORIZ | UP VERT | HORIZONTAL | VERTICAL |
| 54.0 | 0.8682E-01 | 0.91684 | 22.79731 | 125.41737 | 194.36609 | 0.33618 | 0.61964 |

PIXEL TYPE 3 - CLOUDY OCEAN, GROUND = 0 TEMP1 = 300.00

TOTAL CLOUD WATER CONTENT = 0.428 GRAMS PER SQ CM

| NADIR ANGLE | ATTENUATION | TRANSMISSION | BRIGHTNESS TEMPERATURE (DEGREES K) | | | EMISSIVITY | |
|---|---|---|---|---|---|---|---|
| (DEG) | (NEPERS) | FACTOR | DOWN | UP HORIZ | UP VERT | HORIZONTAL | VERTICAL |
| 54.0 | 0.8169E+00 | 0.44180 | 148.40839 | 226.71223 | 246.48387 | 0.25691 | 0.57728 |

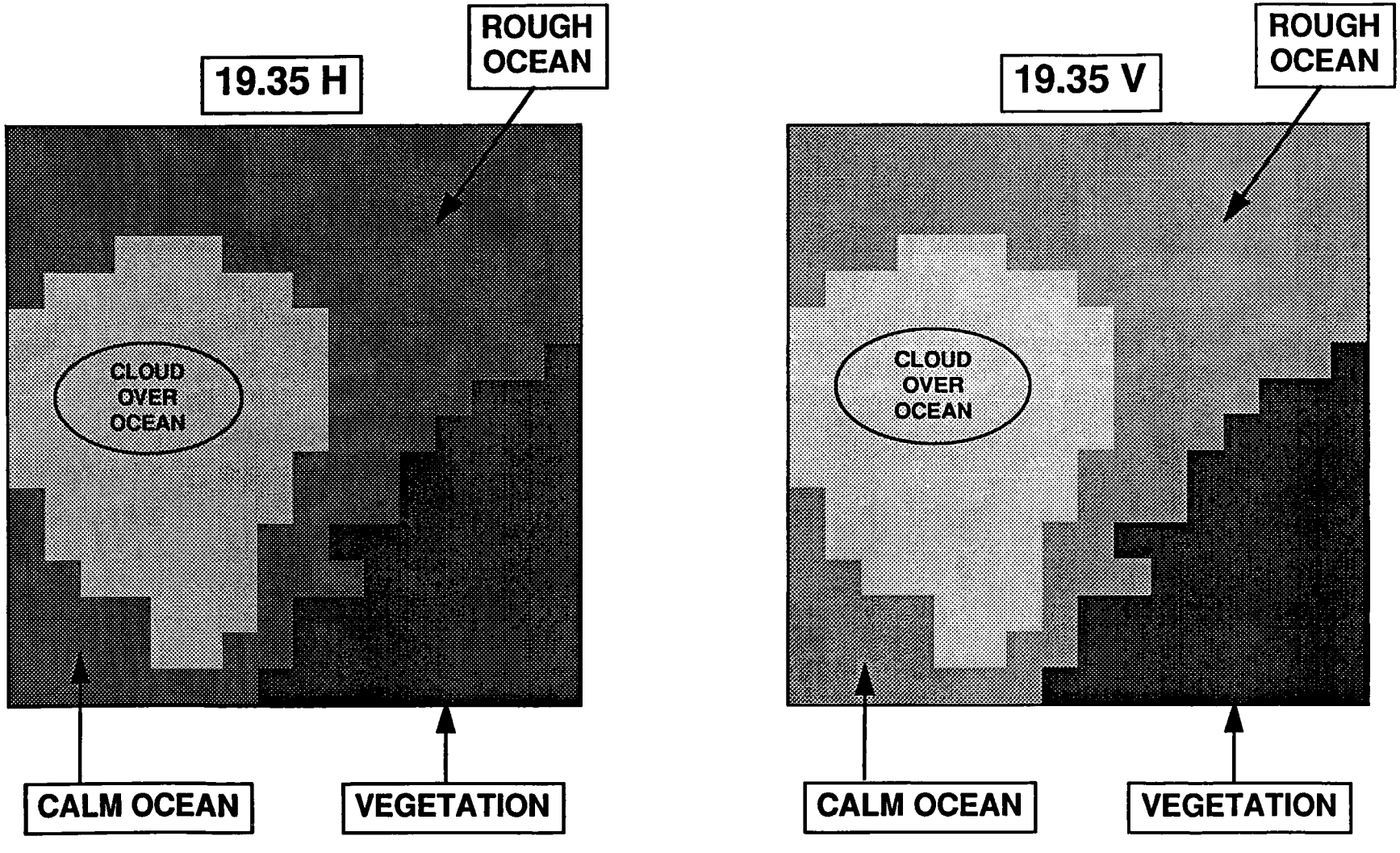
PIXEL TYPE 4 - VEGETATION (MV=0.1) - U.S. STANDARD

GROUND = 5 TEMP1 = 288.00 TEMP2 = 286.00 LP = 0.10000 LZ = 1.00000 MV = 0.10000 E2RAN = ( 0.00000, 0.00000)

DEPRAN = 200.000 H = 0.10000 DMV = 0.20000 VV = 0.00330 VB = 0.10000 VBW = 0.05000 BULK = ( 3.000000, 0.000000)

| NADIR ANGLE | ATTENUATION | TRANSMISSION | BRIGHTNESS TEMPERATURE (DEGREES K) | | | EMISSIVITY | |
|---|---|---|---|---|---|---|---|
| (DEG) | (NEPERS) | FACTOR | DOWN | UP HORIZ | UP VERT | HORIZONTAL | VERTICAL |
| 54.0 | 0.8682E-01 | 0.91684 | 22.79731 | 283.32715 | 285.05423 | 0.98538 | 0.99248 |

# SIMULATION RESULTS



# 3.0 ACTIVE MICROWAVE REMOTE SENSING

# ACTIVE MICROWAVE REMOTE SENSING

# TOPICS

- 3.1 INTRODUCTION
- 3.2 PHENOMENOLOGY - RADAR SCATTERING
- 3.3 ALTIMETRY
- 3.4 SCATTEROMETRY
- 3.5 REAL-APERTURE RADAR
- 3.6 SYNTHETIC APERTURE RADAR (SAR)
- 3.7 POLARIMETRY
- 3.8 APPLICATIONS

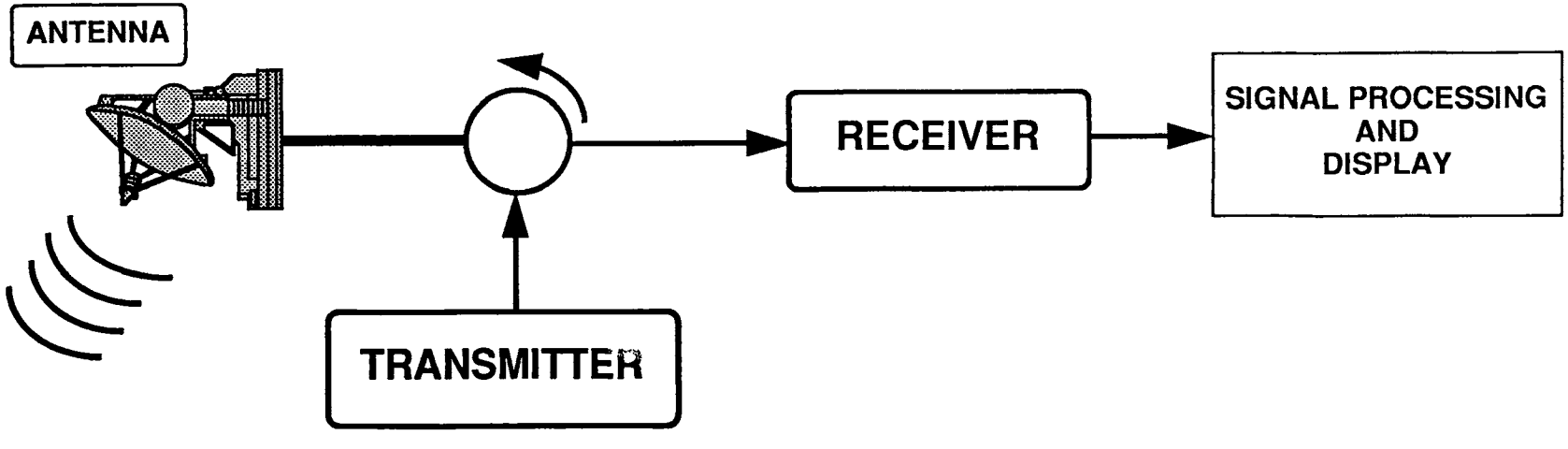
# 3.1 INTRODUCTION TO RADAR

- RADAR FUNDAMENTALS
- RADAR EQUATION
- DEFINITIONS
  - RADAR CROSS SECTION (RCS) $\sigma$
  - SCATTERING COEFFICIET $\sigma^0$

- RADAR
  - RADIO DETECTION AND RANGING

# RADAR FUNDAMENTALS

- **RADAR SYSTEM**
  - TRANSMITTER
  - RECEIVER
  - ANTENNA
- **RADARS MEASURE**
  - RANGE TO TARGET
  - CROSS RANGE POSITION OF TARGET IN SOME CASES
  - TARGET RANGE RATE OR DOPPLER
  - SCATTERING STRENGTH OF TARGET



# RADAR FUNDAMENTALS (contd)

- **RADARS MEASURE THESE QUANTITIES BY TRANSMITTING A MODULATED CARRIER WAVE. MOST COMMON TYPE OF MODULATIONS ARE**
  - **CW**
  - **RECTANGULAR PULSE OF FIXED DURATION**
  - **LINEAR FREQUENCY MODULATION (FM) OR CHIRP**
- **RANGE**
  - **MEASURE ROUND TRIP TRAVEL TIME OF PULSE**

$$R = \frac{c\tau_R}{2}$$

$$\left[R(\text{km}) = 0.15\,\tau_R(\mu\,\text{sec})\right]$$

  - **PULSE REPETITION FREQUENCY IS CONSTRAINED BY MAXIMUM RANGE TO TARGET, OR UNAMBIGOUS RANGE**

$$R_u = \frac{c}{2PRF}$$

$$PRF = 1500\ \text{Hz}\ ,\ R_u = 100\ \text{km}$$

# RADAR FUNDAMENTALS (contd)

- **RANGE RATE OR DOPPLER**
  - DOPPLER SHIFT RESULTS WHEN THERE IS A RELATIVE VELOCITY BETWEEN THE RADAR AND THE TARGET. THIS RESULTS IN A CHANGE OF PHASE IN THE RADAR SIGNAL
  - COMPARISON OF THE TRANSMITTED AND RECEIVED SIGNAL PHASES GIVES A MEASURE OF THE DOPPLER SHIFT
  - REQUIRES A PHASE COHERENT RADAR

$$f_D = \frac{d}{dt}\left(\frac{2R}{\lambda}\right) = \frac{2\dot{R}}{\lambda} = \frac{2U_R}{\lambda}$$

R = range from radar to target

$\lambda$ = carrier wavelength

$U_R$ = component of the relative target-radar velocity along the line of sight

- **RELATIVE TARGET POSITION**
  - SCANNING OR TRACKING RADAR (ANTENNA)
  - SYNTHETIC APERTURE RADAR
- **SCATTERING STRENGTH**
  - CALIBRATED RADAR
  - ABSOLUTE MEASUREMENT OF RECEIVED POWER

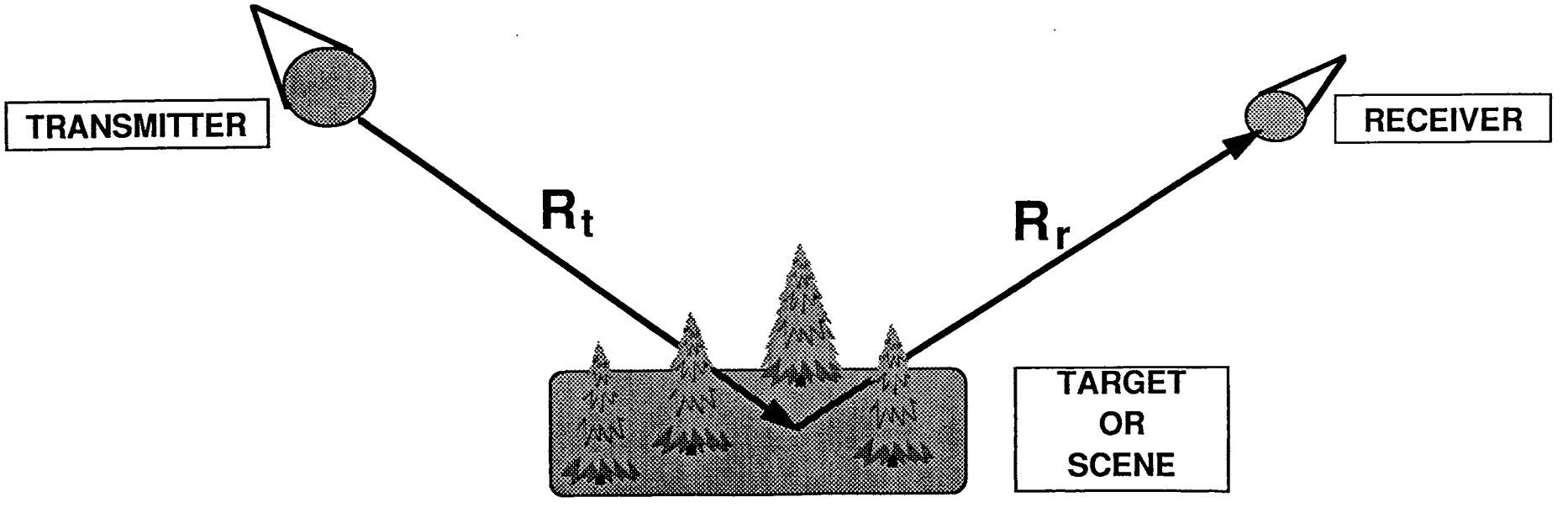
# THE RADAR EQUATION

- WHAT IS THE RELATIONSHIP BETWEEN:
  - RADAR TRANSMITTER PARAMETERS
  - TARGET SCATTERING CHARACTERISTICS
  - RADAR RECEIVER PARAMETERS
- THE RADAR EQUATION, IN ITS VARIOUS FORMS, EXPRESSES THIS RELATIONSHIP
- SCENARIO
  - RADAR TRANSMITS POWER WHICH PROPAGATES TO THE TARGET, IS SCATTERED, AND THE SCATTERED RADIATION PROPAGATES TO THE RECEIVER.

# THE RADAR EQUATION (contd)

- **MONOSTATIC**
  - TRANSMITTER AND RECEIVER ARE CO-LOCATED AND MAY USE THE SAME ANTENNA
- **BISTATIC**
  - TRANSMITTER AND RECEIVER ARE LOCATED AT DIFFERENT POINTS IN SPACE AND USE DIFFERENT ANTENNAS

## GENERAL GEOMETRY FOR RADAR SCATTERING




$R_t$ = RANGE FROM TRANSMITTER TO TARGET

$R_r$ = RANGE FROM RECEIVER TO TARGET

# THE RADAR EQUATION (contd)

- THE POWER PER UNIT AREA INCIDENT ON THE TARGET IS GIVEN BY THE POYNTING VECTOR (MAGNITUDE) AT THE SCATTERER:

$$S_s = P_t G_t \cdot \left(\frac{1}{4\pi R_t^2}\right)$$

SPREADING LOSS DUE TO SPHERICAL WAVE EXPANDING IN SPACE

$P_t$ = TRANSMITTED POWER
$G_t$ = ANTENNA GAIN IN THE DIRECTION OF THE TARGET

- THE SCATTERER WILL INTERCEPT A FRACTION OF THE INCIDENT POWER DENSITY, WHICH WILL DEPEND ON ITS EFFECTIVE AREA $A_{rs}$

$$P_{rs} = S_s A_{rs}$$

$A_{rs}$ IS NOT NECESSARILY THE GEOMETRICAL AREA OF THE TARGET, RATHER IT A MEASURE OF THE EFFECTIVENESS OF THE TARGET AS A RECEIVING ANTENNA. THE SCATTERER WILL ABSORB SOME FRACTION $f_a$ OF THE INCIDENT ENERGY AND RERADIATE A FRACTION $1 - f_a$

$$P_{ts} = P_{rs}\left(1 - f_a\right)$$

# THE RADAR EQUATION (contd)

- THE INCIDENT EM FIELDS INDUCE CURRENTS IN THE SCATTERER WHICH RESULT IN A DISTRIBUTION IN THE RADIATION PATTERN FROM THE SCATTERER. THIS CAN BE DESCRIBED BY ASSIGNING A GAIN TO THE SCATTERER. THE GAIN FACTOR $G_{ts}$ DEPENDS ON THE RELATIVE SCATTERING GEOMETRY (DIRECTION) BETWEEN THE INCIDENT AND SCATTERED FIELDS (I. E. THE DIRECTION OF THE TRANSMITTER AND RECEIVER), AND THE SCATTERER ORIENTATION. THUS THE RADIATED POWER DENSITY AT THE RECEIVER IS:

$$S_r = P_{ts}\, G_{ts} \cdot \left(\frac{1}{4\pi R_r^2}\right)$$

SPREADING LOSS DUE TO SPHERICAL WAVE EXPANDING IN SPACE

- THE RECEIVED POWER WILL DEPEND ON THE EFFECTIVE AREA OF THE RECEIVER:

$A_r$ = EFFECTIVE AREA OF THE RECEIVER

$$P_r = S_r\, A_r$$

# THE RADAR EQUATION (contd)

$$P_r = P_t G_t \cdot \left(\frac{1}{4\pi R_t^2}\right) A_{rs}(1-f_a) G_{ts} \cdot \left(\frac{1}{4\pi R_r^2}\right) A_r$$

$$P_r = \frac{P_t G_t A_r}{(4\pi)^2 R_t^2 R_r^2} \cdot [A_{rs}(1-f_a) G_{ts}]$$

THE FACTORS RELATING TO THE SCATTERER OR TARGET ARE INCLUDED IN THE EXPRESSION IN [ ], WHEREAS THE FACTORS PERTAINING TO THE TRANSMITTER, RECEIVER AND RELATIVE GEOMETRY ARE GIVEN FIRST. IT IS GENERALLY NOT POSSIBLE, NOR OF INTEREST, TO SEPARATELY MEASURE THE FACTORS IN [ ]. THESE FACTORS ARE USUALLY COMBINED INTO A SINGLE FACTOR DEFINED AS THE SCATTERING CROSS SECTION:

$$\sigma = [A_{rs}(1-f_a) G_{ts}]$$

$\sigma$ DEPENDS ON:

- RELATIVE GEOMETRY BETWEEN RECEIVER AND TRANSMITTER (I. E. DIRECTION OF INCIDENT AND SCATTERED WAVES)
- SHAPE OF SCATTERER
- DIELECTRIC PROPERTIES OF SCATTERER, I.E., ITS MATERIAL COMPOSITION

THE UNITS OF $\sigma$ ARE $m^2$ (AREA)

# THE RADAR EQUATION (contd)

## RADAR EQUATION

$$P_r = \frac{P_t G_t A_r}{(4\pi R_t R_r)^2} \sigma$$

**MONOSTATIC CASE: BACKSCATTERING**

$$R_t = R_r = R$$

$$\left.\begin{array}{l} G_t = G_r = G \\ A_t = A_r = A \end{array}\right\} A = \frac{\lambda^2 G}{4\pi}$$

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4} \sigma = \frac{P_t A^2}{4\pi \lambda^2 R^4} \sigma$$

THESE EQUATIONS APPLY TO TARGETS OF LIMITED SPATIAL EXTENT, TYPICALLY MUCH SMALLER THAN THE ANTENNA BEAM AT THE TARGET. FOR EARTH REMOTE SENSING APPLICATIONS WE ARE PRIMARILY INTERESTED IN EXTENDED TARGETS SUCH AS THE EARTH'S LAND AND OCEAN SURFACE. WE MUST THEREFORE DEVELOP EXPRESSIONS FOR AREA (AND IN SOME CASES VOLUME) SCATTERING.

# THE RADAR EQUATION (contd)

- ONE CAN TREAT THE SCATTERING FROM THE AREA ILLUMINATED BY THE RADAR AS COMPOSED OF MANY INDIVIDUAL POINT SCATTERERS. BY AVERAGING OVER THIS AREA ONE CAN DEFINE A DIFFERENTIAL SCATTERING COEFFICIENT (SOMETIMES JUST CALLED THE SCATTERING COEFFICIENT):

$$\sigma^0 = \left\langle \frac{\sigma_i}{a_i} \right\rangle$$

THIS LEADS TO THE EXTENDED AREA VERSION OF THE RADAR EQUATION

$$P_r = \frac{\lambda^2}{(4\pi)^3} \int_{\Delta A} \frac{P_t G^2}{R^4} \sigma^0 \, dA$$

$\Delta A$ = ILLUMINATED AREA

- THIS FORM OF THE RADAR EQUATION ASSUMES:
  1. MANY INDIVIDUAL POINT SCATTERERS MUST BE PRESENT OVER THE ELEMENTAL AREA WHERE G, P AND R ARE ASSUMED CONSTANT
  2. MANY MORE SCATTERERS MUST EXIST IN THE TOTAL ILLUMINATED AREA AT ANY GIVEN TIME

THIS MODEL REQUIRES THAT WITHIN THE ILLUMINATED AREA NO SINGLE SCATTERING CENTER OR ELEMENTS DOMINATES.

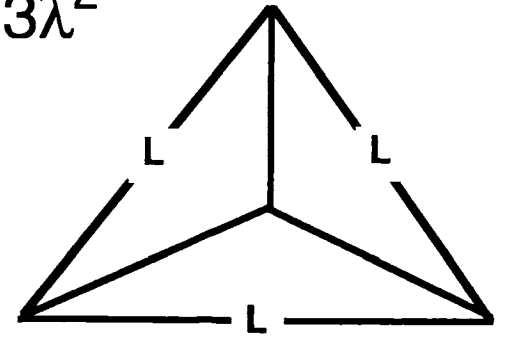
# 3.2 PHENOMENOLOGY - RADAR SCATTERING

- SCATTERING FROM TERRESTRIAL SURFACES
- RADAR PARAMETERS AND PHENOMENA AFFECTING RADAR SCATTERING

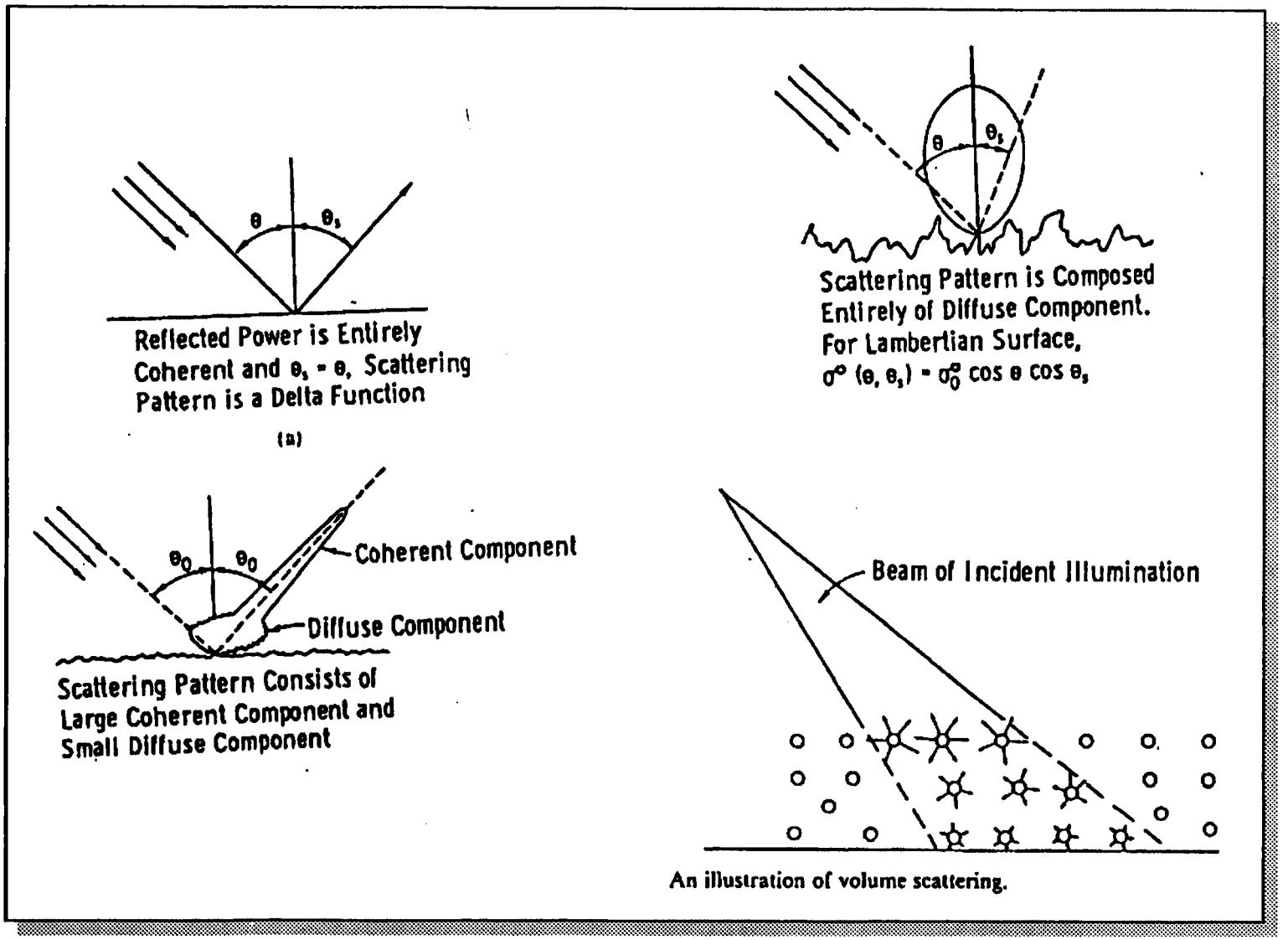
# RADAR SCATTERING

- TYPES OF TARGETS: NATURAL & MAN-MADE
- POINT & EXTENDED TARGETS
- DEPENDENCE ON PHYSICAL PROPERTIES OF MATERIAL
  - DIELECTRIC CONSTANT
  - SIZE AND SHAPE
  - SURFACE ROUGHNESS
  - VOLUME EFFECTS
- POINT TARGET EXAMPLE
  - TRIHEDRAL CORNER REFLECTOR
  - $\lambda$ SENSITIVE
  - HALF-POWER BEAMWIDTH $\approx 30^{o} - 40^{o}$
  - RCS MUCH LARGER THAN PHYSICAL AREA

$$\sigma_{max} = \frac{\pi L^4}{3\lambda^2}$$



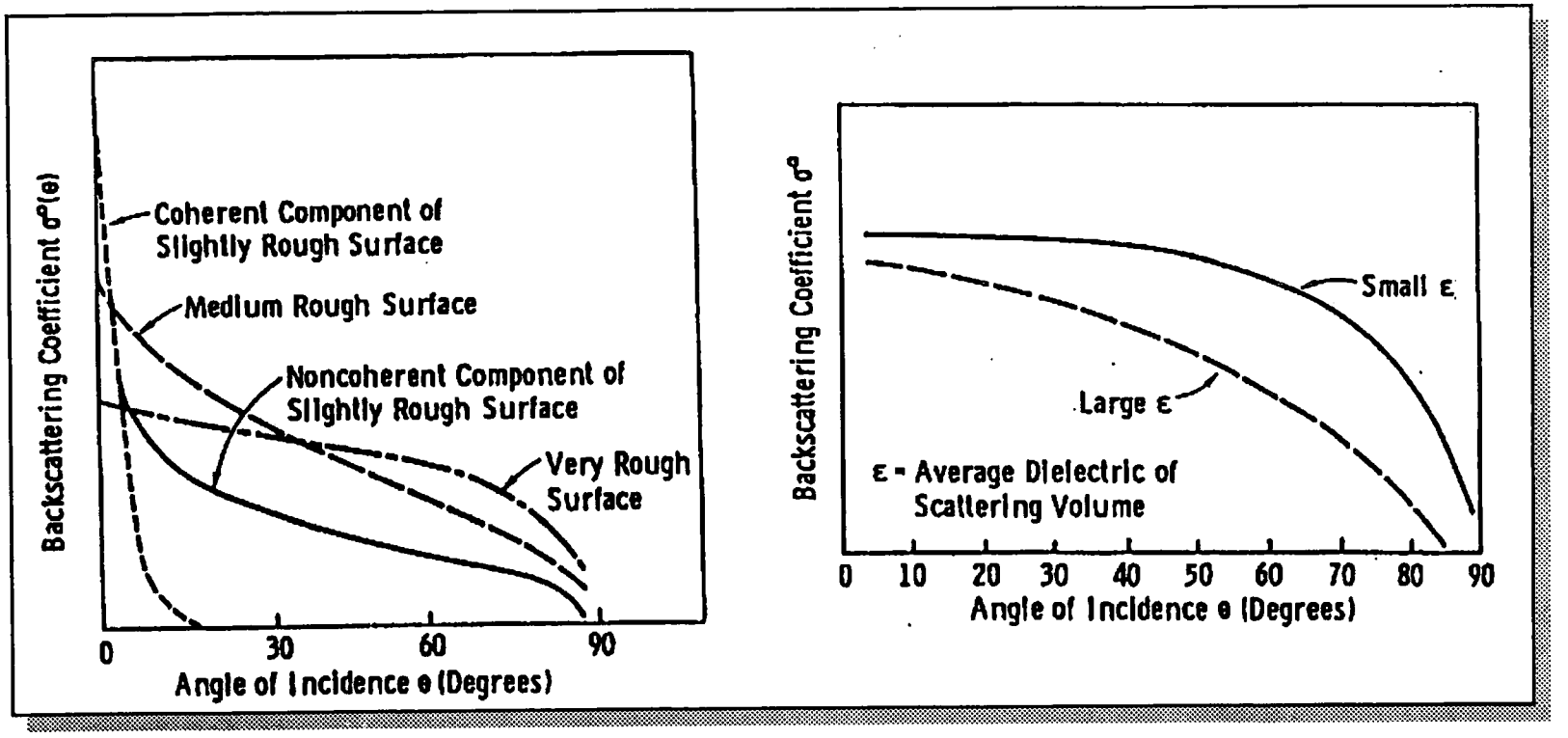
# SURFACE ROUGHNESS AND VOLUME EFFECTS




An illustration of volume scattering.

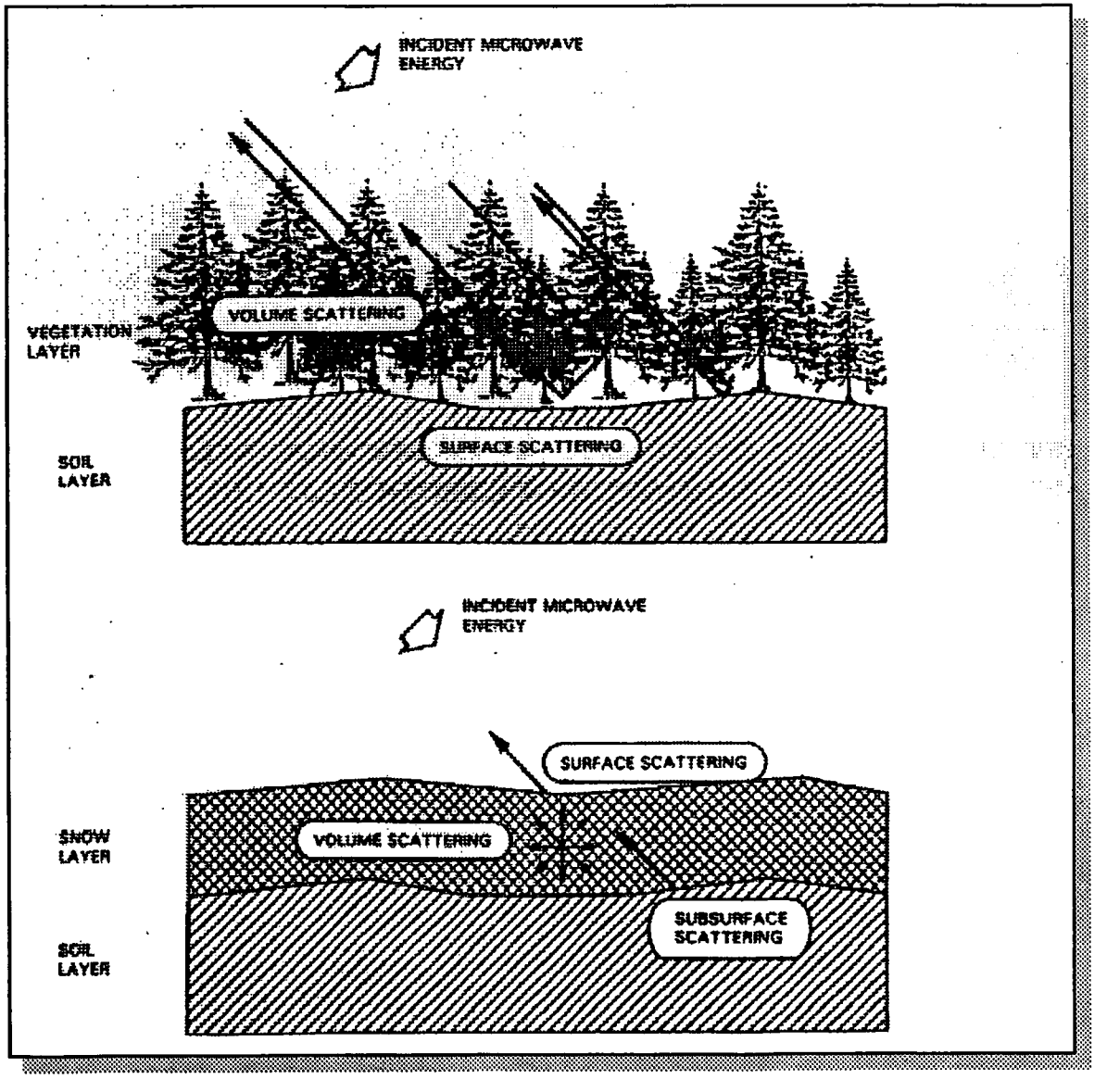
From: F. T. Ulaby, et al., Microwave Remote Sensing: Active and Passive, Vol. II, © 1981-1986, Artech House Inc., Norwood, MA.

# Dependence of Backscatter on Surface Roughness and Dielectric Constant



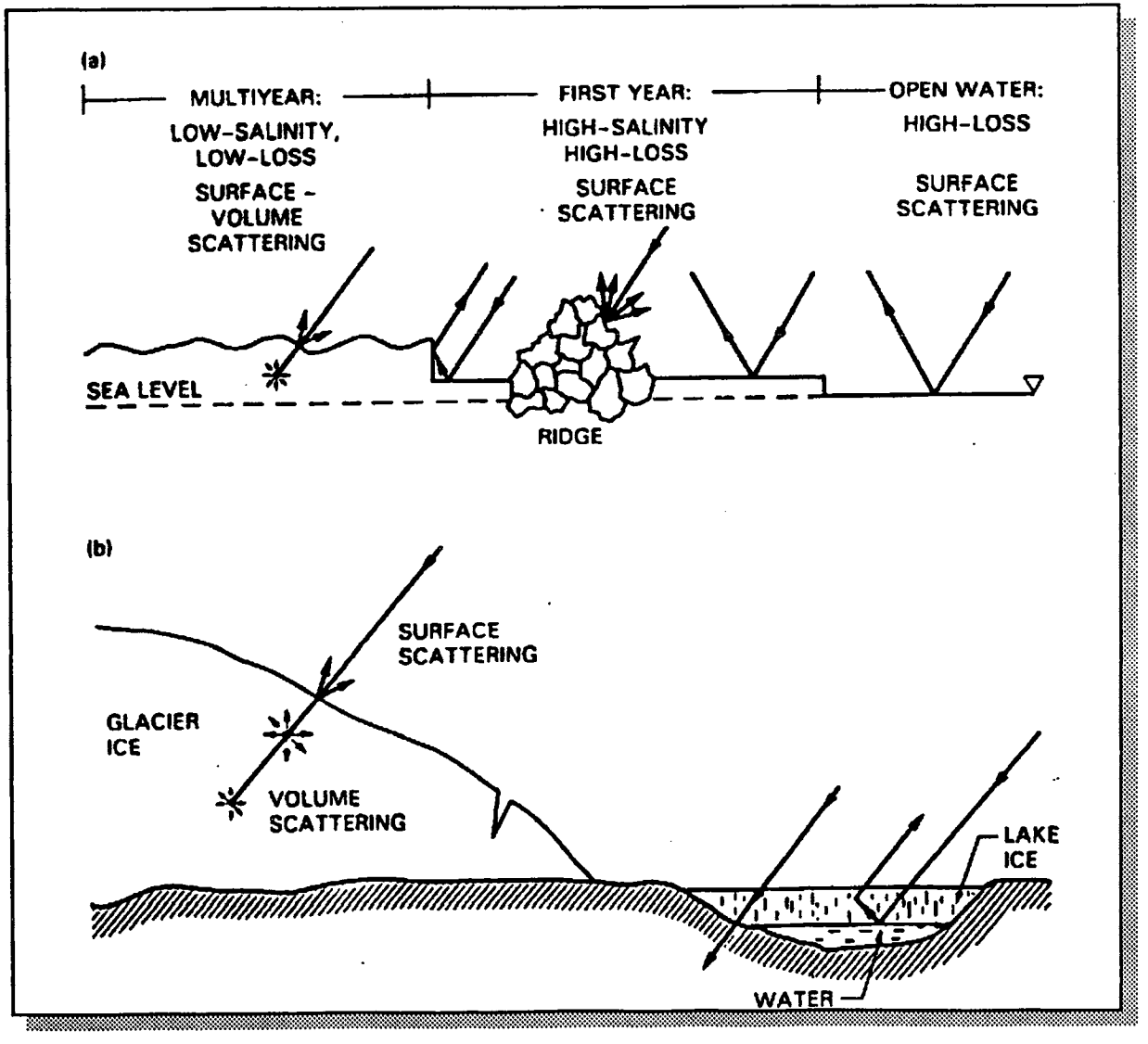

From Ulaby, et al., Microwave Remote Sensing: Active and Passive, Vol. II, © 1981-1986, Artech House Inc., Norwood, MA.

# Scattering from Two-layer Systems: Soil-Vegetation and Soil-Snow Systems



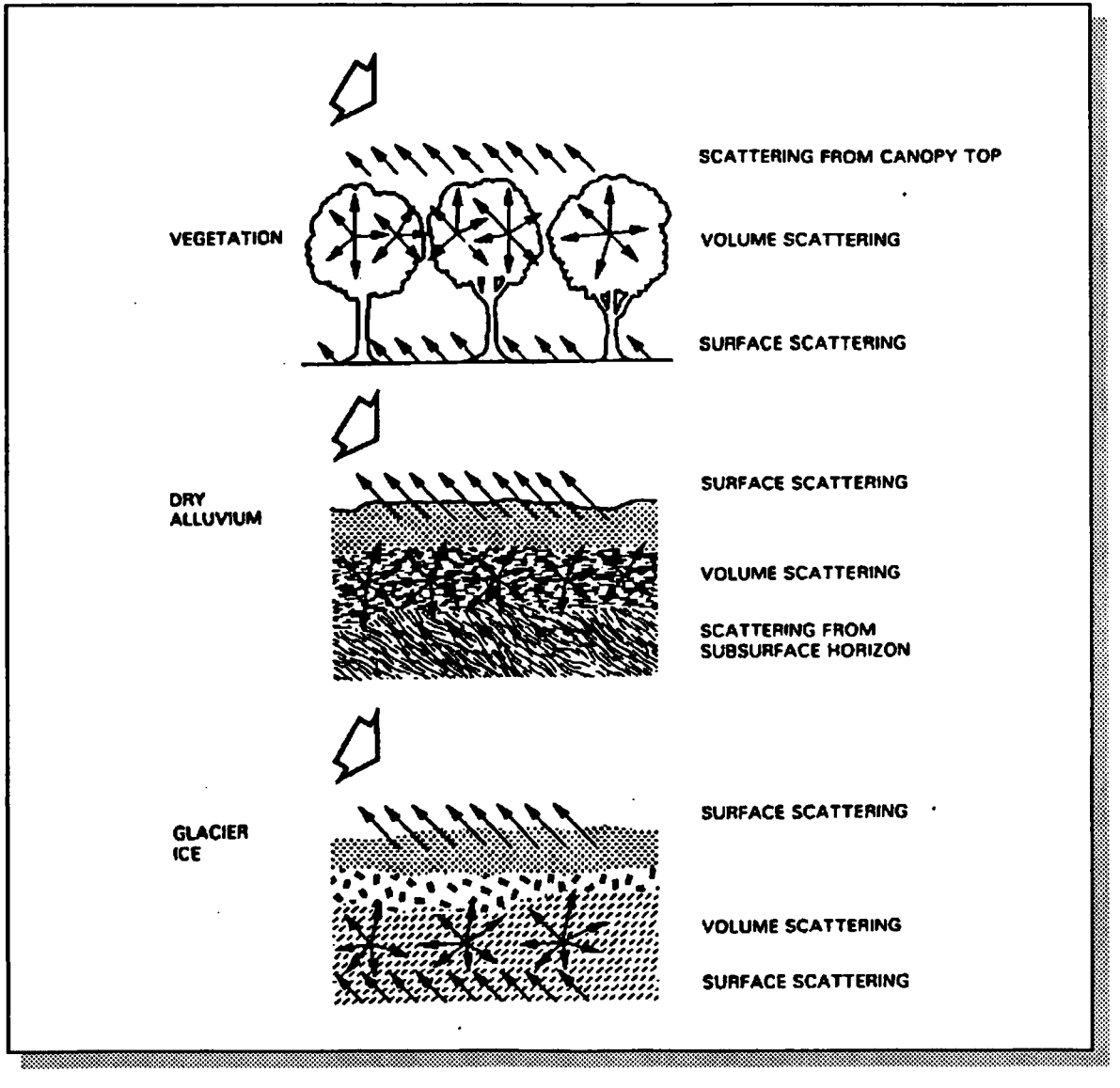

From: SAR INSTRUMENT PANEL REPORT, EARTH OBSERVING SYSTEM, VOL. IIf, NASA (no date given).

# Interactions Between Radar and Different Ice Types: Sea Ice, Glaciers, Ice Sheets and Lake Ice




From: INSTRUMENT PANEL REPORT, EARTH OBSERVING SYSTEM, VOL. [illegible] NASA (no date given).

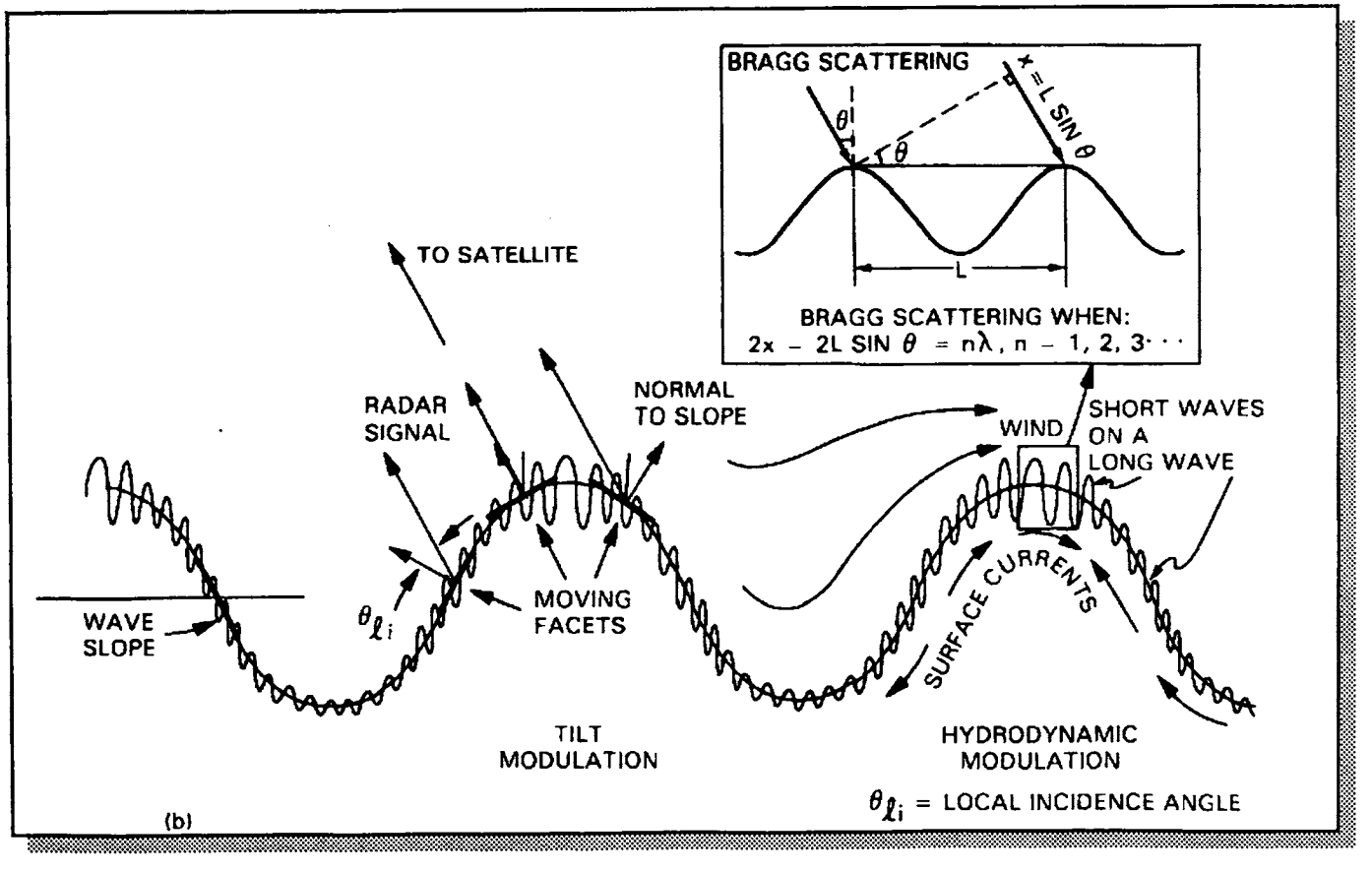
# Like- and Cross-Polarized Surface and Volume Scattering




From: SAR INSTRUMENT PANEL REPORT, EARTH OBSERVING SYSTEM, VOL. IIf, NASA (no date given).

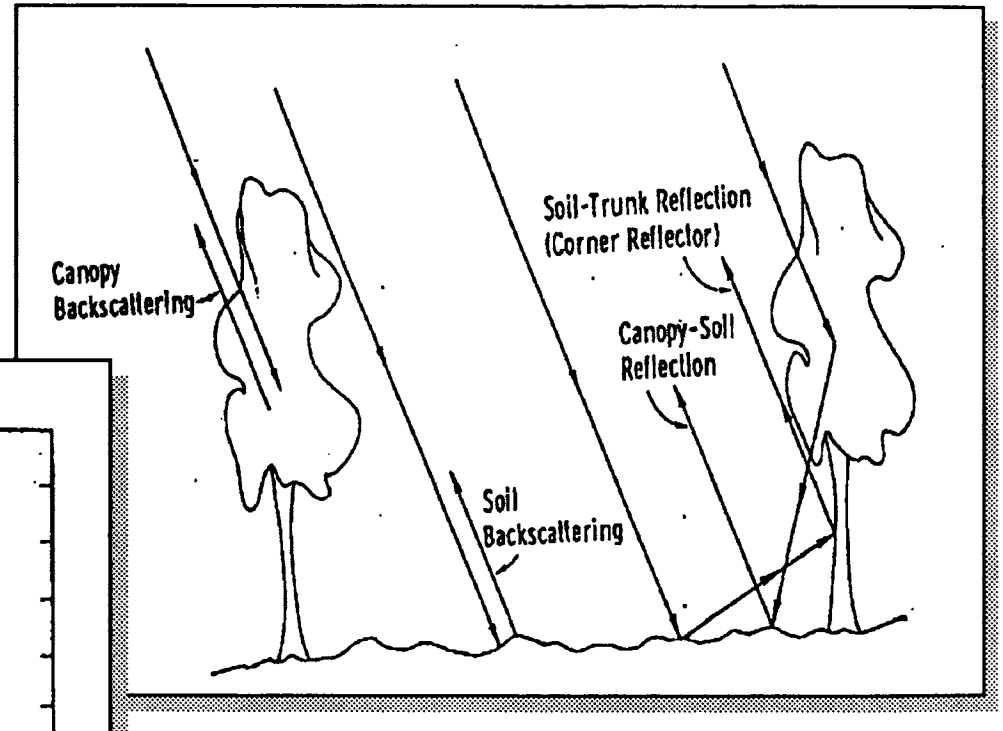
# OCEAN RADAR SCATTERING

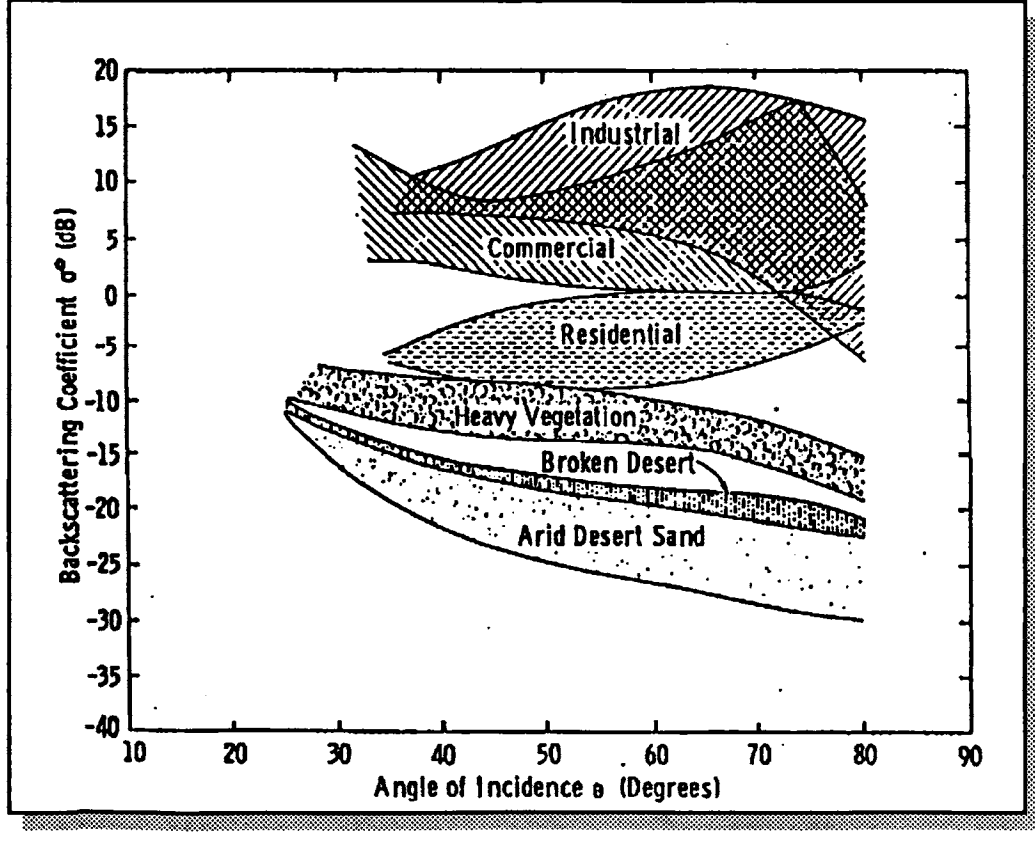
- ILLUSTRATION OF THE SURFACE TILT AND HYDRODYNAMIC INTERACTIONS WHICH AFFECT THE BACKSCATTERING OF RADAR SIGNALS FROM THE OCEAN SURFACE. THE TILT AND HYDRODYNAMIC EFFECTS MODULATE THE AMBIENT SURFACE BRAGG WAVES (WIND GENERATED CAPILLARY WAVES).




From: INSTRUMENT PANEL REPORT, EARTH OBSERVING SYSTEM, VOL ··· NASA (no date given).

# Terrain Backscattering Coefficient and Vegetation Backscattering




From: F. T. Ulaby, et al., Microwave Remote Sensing: Active and Passive, Vol. II, © 1981-1986, Artech House Inc., Norwood, MA.

# RADAR PARAMETERS AND PHENOMENA AFFECTING RADAR BACKSCATTERING

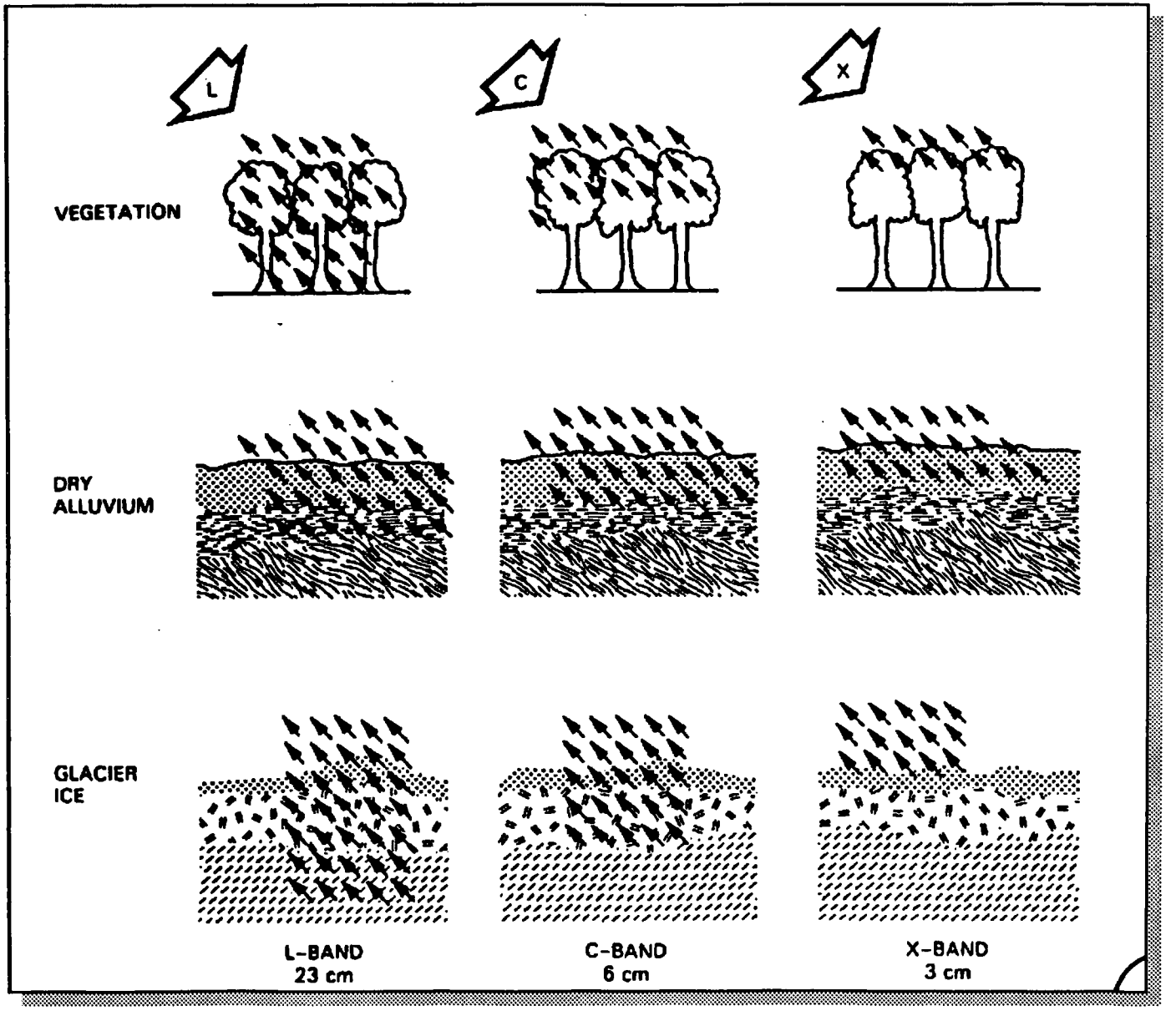
- RADAR AND RETURN PARAMETERS
  - WAVELENGTH
  - INCIDENCE ANGLE
  - POLARIZATION
  - ANTENNA PARAMETERS
  - BANDWIDTH AND DWELL TIME (SPATIAL RESOLUTION)
  - SURFACE ROUGHNESS AND DIELECTRIC CONSTANT
- PENETRATION
- GEOMETRY AND MOTION EFFECTS
  - VERY IMPORTANT FOR SYNTHETIC APERTURE RADAR

# PENETRATION

- Penetration increases with longer $\lambda$
- Penetration increase with smaller loss tangent tan ($\delta$)
  - CAN BE SUBSTANTIAL FOR SNOW AND ICE
- Layers: surfaces can cause internal reflections (e.g. , ice)
- Amount of penetration into a medium will be a function of
  - INCIDENCE ANGLE
  - SURFACE ROUGHNESS
  - DIELECTRIC CONSTANT OF MEDIA
- Skin Depth = $1/\alpha$
- Small tan ($\delta$) implies significant penetration
- Volumetric properties (density, voids, subsurface layers, gradients, . . ., etc.)

$$\alpha = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon'}{2}}\left[\sqrt{1+\tan^2(\delta)} - 1\right]^{1/2} \qquad \tan(\delta) = \frac{\sigma}{\omega\varepsilon'}$$

# Penetration Capability of Multifrequency Radar




From: INSTRUMENT PANEL REPORT, EARTH OBSERVING SYSTEM, VOL. [illegible] NASA (no date given).

# Examples of Penetration Depth

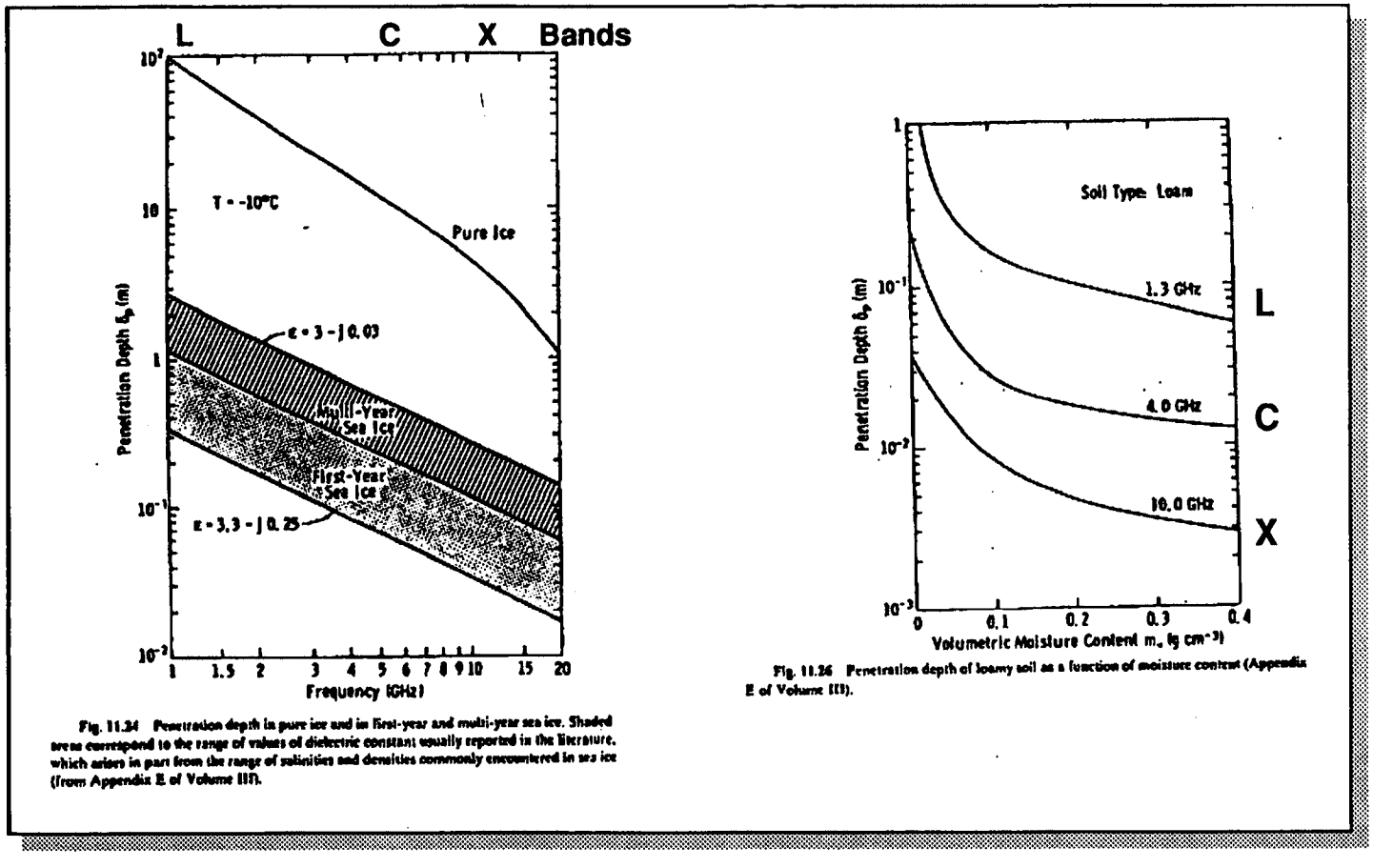



Fig. 11.24 Penetration depth in pure ice and in first-year and multi-year sea ice. Shaded areas correspond to the range of values of dielectric constant usually reported in the literature, which arises in part from the range of salinities and densities commonly encountered in sea ice (from Appendix E of Volume III).

Fig. 11.26 Penetration depth of loamy soil as a function of moisture content (Appendix E of Volume III).

# 3.3 SATELLITE ALTIMETRY

- PRINCIPLES OF SATELLITE RADAR ALTIMETRY
- ALTIMETRY ERROR SOURCES
- ALTIMETER SYSTEM EXAMPLE
  - TOPEX/POSEIDON RADAR ALTIMETER

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## SPACEBORNE SATELLITE ALTIMETERS

| SATELLITE (YEAR) | F (GHz) | BANDWIDTH (MHz) | RANGE RES AVER. TIME | PULSE COMPRES. | WAVE HEIGHT ACCURACY/RANGE |
|---|---|---|---|---|---|
| Skylab/1973 | 13.9 | 100 | 1.0m/0.3s | 13 | 1-3 m |
| Geos-3/1975 | 13.9 | 80 | 0.5m/0.2s | 30 | ±25%(4-10m) |
| Seasat/1978 | 13.5 | 320 | 0.1m/1.0s | 1000 | ±10%(1-20m) |
| Geosat/1985 | 13.5 | 320 | 0.1m/1.0s | 30k | ±10%(1-20m) |
| ERS-1/1991 | 13.8 | 330/82.5 | 0.1m/1.0s | 8000 | ±10%(1-20m) |
| Topex/1992 | 13.6 | 320 | 0.03m/3.0s | 58k | ±10%(1-20m) |

# PRINCIPLES OF SATELLITE RADAR ALTIMETRY

- TRANSMIT A SHORT RADAR PULSE (OR WIDEBAND PULSE) AND ACCURATELY MEASURE THE ROUND TRIP TRAVEL TIME TO THE PULSE ECHO
- ACCURATE RANGE MEASUREMENT REQUIRES THE MEASUREMENT AND MODELING OF MANY DIFFERENT EFFECTS AND ERROR SOURCES
- INFORMATION ABOUT THE NATURE OF THE SCATTERING SURFACE MAY BE OBTAINED FROM MEASUREMENTS OF:
  - SHAPE OF RADAR ECHO WAVEFORM
  - ABSOLUTE ECHO POWER
- ALTIMETER PULSE SHOULD BE REFLECTED FROM AS SMALL AN AREA ON THE SURFACE AS POSSIBLE
  - BEAM LIMITED GEOMETRY - USE A LARGE ANTENNA TO CREATE A NARROW BEAM
  - PULSE LIMITED GEOMETRY - USE A MODEST SIZE ANTENNA, WHICH GIVES A WIDE BEAM, BUT TRANSMIT A VERY NARROW PULSE (WIDE BANDWIDTH)

# ALTIMETRY PRINCIPLES (contd)

- CONSIDER SIMPLE CASE OF ZERO WIDTH PULSE

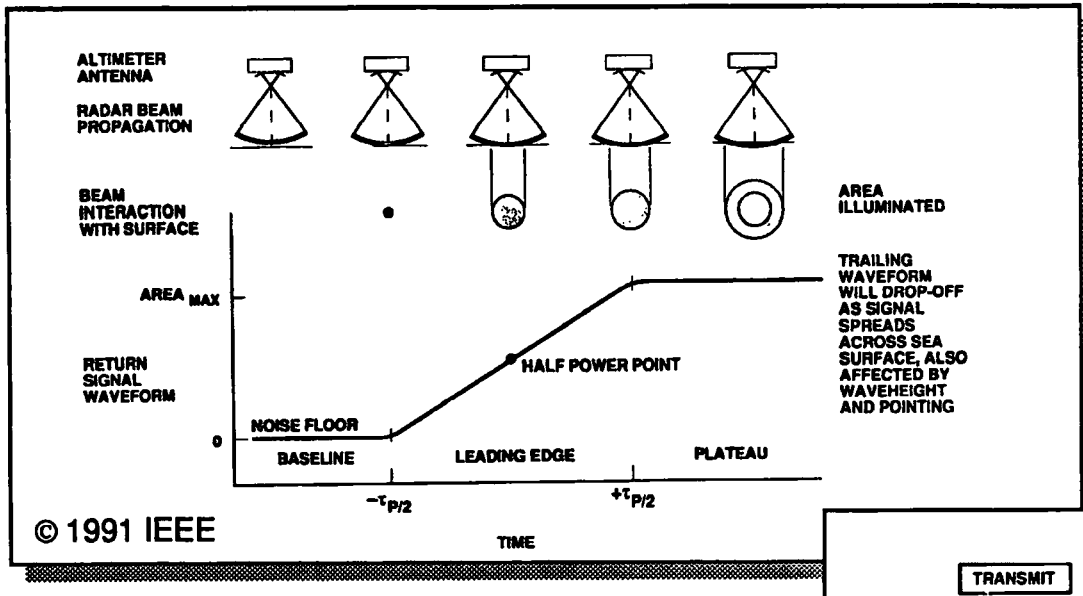
  $T = 0$ transmit pulse

  $T = \frac{2H}{c}$ 1st echo received from nadir point

  $T > \frac{2H}{c}$ echos received from off nadir point

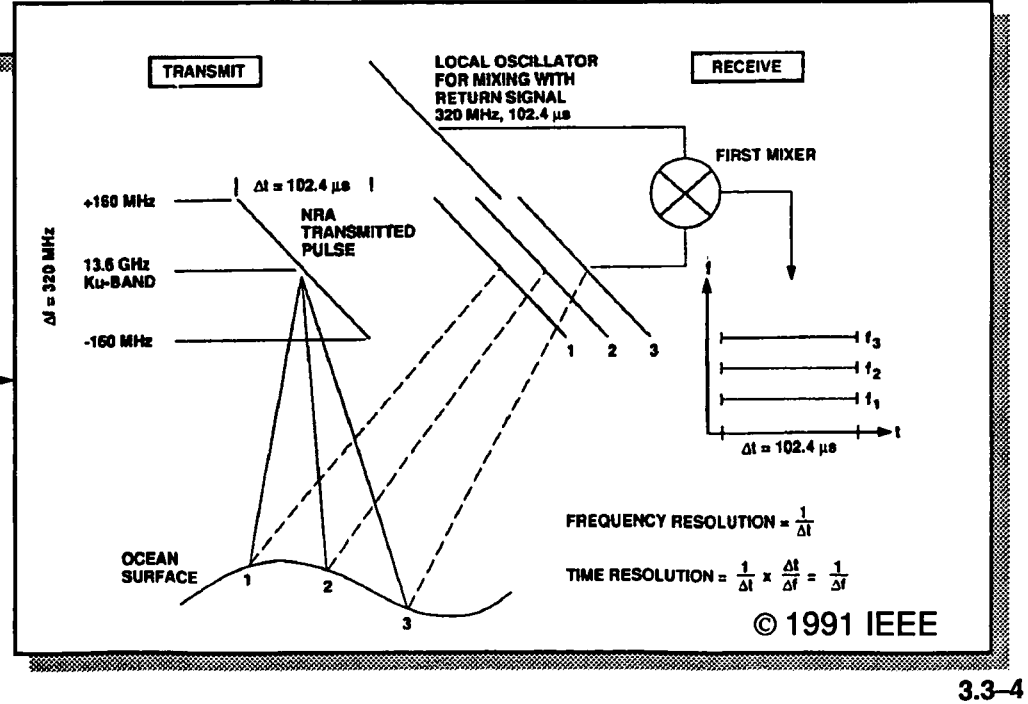
- PULSE LIMITED ALTIMETER
  - MAXIMUM FOOTPRINT RADIUS $r_\tau = \sqrt{Hc\tau_p}$
  - COMPARE TO BEAM LIMITED ALTIMETER
- RADAR RETURN POWER HAS 3 SEPARATE REGIONS
  - (1) BASELINE $T < -\frac{\tau_p}{2}$, NO SURFACE ILLUMINATION
  - (2) LEADING-EDGE; LINEAR INCREASE WITH TIME, ILLUMINATED SPOT $0 \rightarrow r_\tau$
  - (3) PLATEAU; SURFACE ILLUMINATION IS ANNULAR
- SCATTERING OF A CHIRPED PULSE (LINEAR-FM) FROM THE OCEAN SURFACE
- RECEIVED ECHO IS COMPRESSED TO ACHIEVE HIGH RANGE RESOLUTION

# ALTIMETRY PRINCIPLES (contd)




**ALTIMETER PULSE INTERACTION WITH THE SEA SURFACE AND THE CHARACTERISTIC RETURN WAVEFORM**

**SCATTERING OF A LINEAR FM PULSE FROM THE OCEAN SURFACE**




From: A. R. Zieger, et al., *NASA Radar Altimeter for the TOPEX/POSEIDON Project*, Proc. IEEE, **79(6)**, 810-826 (1991).

# ALTIMETRY PRINCIPLES (contd)

- **ALTIMETER AVERAGE RETURN WAVEFORM**

$$W(t) = P_{FS}(t) * q_s(t) * p_t(t)$$

- **FLAT OCEAN IMPULSE RESPONSE FUNCTION**

$$P_{FS}(t) = A_0 \exp(-\delta t)\, I_0(\beta t^{1/2})\, U(t)$$

$$\delta = \left(\frac{4}{\gamma}\right)\left(\frac{c}{H}\right)\frac{\cos(2\xi)}{\left(1+\frac{H}{R_e}\right)}$$

$$\beta = \left(\frac{4}{\gamma}\right)\sqrt{\left(\frac{c}{H}\right)}\,\frac{\sin(2\xi)}{\sqrt{\left(1+\frac{H}{R_e}\right)}}$$

$U(t)$ = unit step function $\begin{cases} 1 & t \geq 0 \\ 0 & t < 0 \end{cases}$

$I_0$ = modified Bessel function

$H$ = spacecraft altitude

$R_e$ = earth's radius

$c$ = speed of light

$\xi$ = off-nadir pointing angle

# ALTIMETRY PRINCIPLES (contd)

- **ANTENNA PATTERN ASSUMED TO BE GAUSSIAN**

$$G(\theta) = G_0 \exp\left[-\frac{2\sin^2(\theta)}{\gamma}\right]$$

$$\frac{4}{\gamma} = \frac{\ln(4)}{\sin^2\left(\frac{\theta_w}{2}\right)}$$

$\gamma$ = antenna beamwidth

$\theta_w$ = full width at half maximum

- **SIGNAL AMPLITUDE**

$$A_0 = \frac{G_0 \lambda_r^2 c \sigma^0(0)}{4(4\pi)^2 L_p H^3 \left(1+\frac{H}{R_e}\right)^3} \exp\left[-\frac{4}{\gamma}\sin^2(\xi)\right]$$

$\lambda_r$ = radar wavelength

$\sigma^0(0)$ = ocean backscattering coefficient at normal incidence

$G_0$ = antenna boresight gain

$L_p$ = 2-way propagation loss

# ALTIMETRY PRINCIPLES (contd)

- **OCEAN SURFACE ELEVATION PROBABILITY DENSITY FUNCTION (PDF)**

$$q_s(t) = \frac{1}{\sigma_s\sqrt{2\pi}}\left\{1 + \frac{\lambda_s}{6}\left[\left(\frac{t}{\sigma_s}\right)^3 - 3\left(\frac{t}{\sigma_s}\right)\right]\right\} \exp\left[-\frac{1}{2}\left(\frac{t}{\sigma_s}\right)^2\right]$$

$\sigma_s$ = rms surface elevation in ranging-time units

$\lambda_s$ = surface skewness parameter

- **RADAR ALTIMETER IPR** $p_t(t)$
  - EFFECTIVE TRANSMITTED PULSE SHAPE
  - THEORETICAL FORM: $\text{sinc}^2(x)$
  - IN PRACTICE IPR IS MEASURED DURING CALIBRATION
- **THE ALTIMETER WAVEFORM IS FITTED TO THE MODEL FUNCTION W(t) TO ALLOW DETERMINATION OF OCEAN PARAMETERS**

# SATELLITE ALTIMETRY

- SEA SURFACE ADJUSTS TO AN EQUIPOTENTIAL (GRAVITATIONAL) SURFACE IN THE ROTATING EARTH REFERENCE FRAME

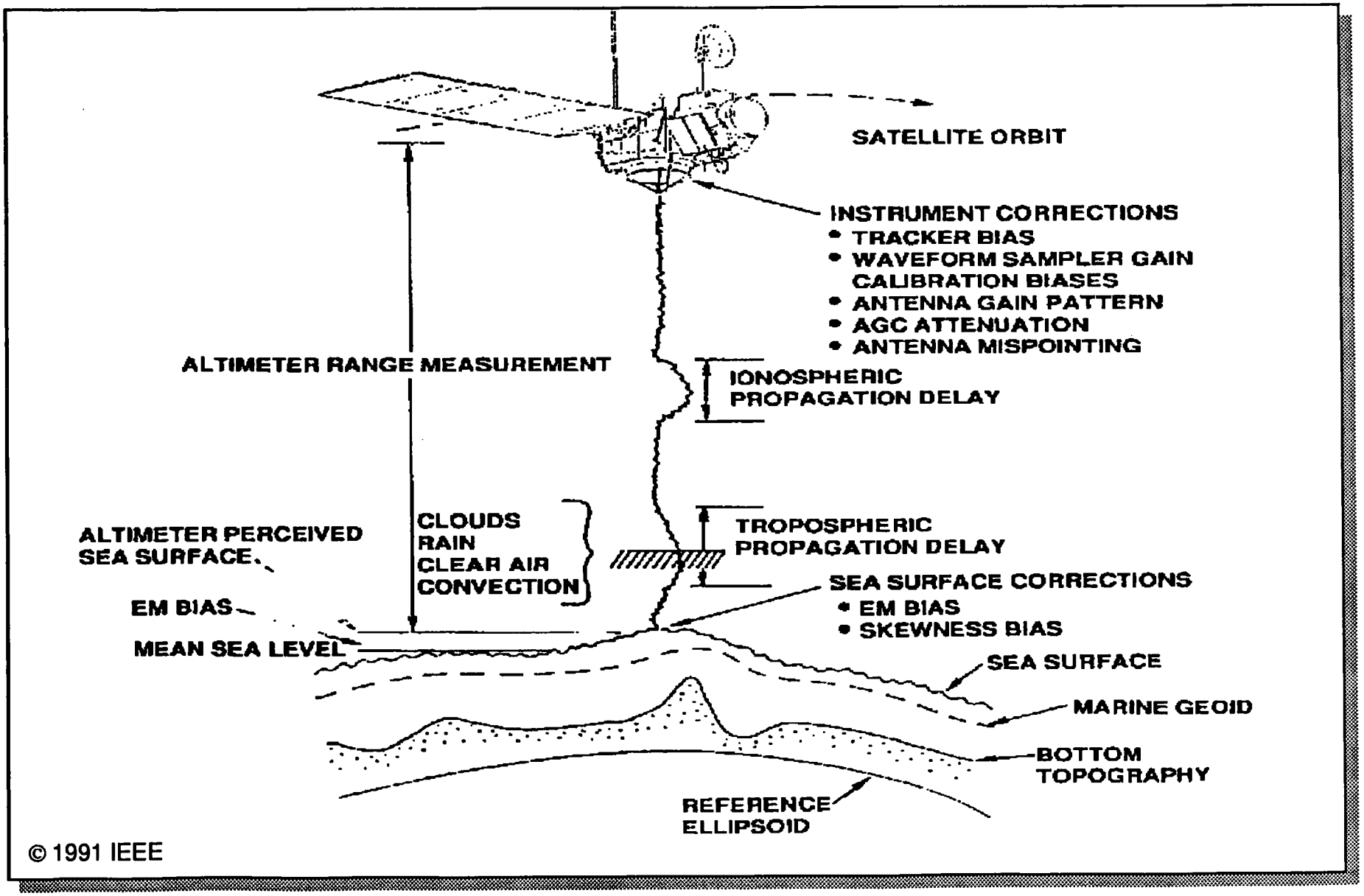
$$\Phi = \Phi_G + \Phi_{ATM}$$

$\Phi_G$ = Gravitational potential due to solid earth and water plus centrifugal acceleration

$\Phi_{ATM}$ = Gravitational potential due earth's atmosphere

- GEOP: SURFACE ON WHICH $\Phi$ IS CONSTANT
- GEOID: GEOP CORRESPONDING TO THE MEAN SEA LEVEL
- REFERENCE ELLIPSOID: BEST SMOOTH APPROXIMATION TO THE GEOID
  - DETERMINED PRIMARILY BY THE MEAN MASS OF THE EARTH AND ROTATIONAL EFFECTS
- SEA SURFACE TOPOGRAPHY: DISPLACEMENT OF THE SEA SURFACE RELATIVE TO THE GEOID

# ALTIMETER RANGE MEASUREMENT AND CORRECTIONS




© 1991 IEEE

From: A. R. Zieger, et al., *NASA Radar Altimeter for the TOPEX/POSEIDON Project*, Proc. IEEE, **79(6)**, 810-826 (1991).

# ALTIMETRY ERROR SOURCES

| ERROR SOURCE | σ (CM) | L (KM) |
|---|---|---|
| **ALTIMETER** | | |
| INSTRUMENT NOISE | 2.0 | 20 |
| BIAS DRIFT | 2.0 | (MANY DAYS) |
| **MEDIA** | | |
| EM BIAS | 2.0 | 20-1000 |
| SKEWNESS | 1.0 | 20-1000 |
| TROPOSPHERE,DRY | 0.7 | 1000 |
| TROPOSPHERE,WET | 1.2 | 50 |
| IONOSPHERE | 1.3(2.0*) | 20 |
| **ORBIT** | | |
| ATMOSPHERIC DRAG | 1.0 | >10000 |
| SOLAR RADIATION | 1.0 | 10000 |
| EARTH RADIATION | <1.0 | 10000 |
| GM | 2.0 | 10000 |
| GRAVITY | 10.0 | 10000 |
| EARTH/OCEAN TIDES | 1.0 | 10000 |
| STATION AND SATELLITE CLOCK | 1.0 | 10000 |
| TROPOSPHERE | 1.0 | 10000 |
| STATION LOCATION | 5.0 | 10000 |
| HIGHER ORDER IONOSPHERE | 5.0(1.0♣) | 10000 |
| **RSS ABSOLUTE ERROR** | 13.3 | |

# ALTIMETRY ERROR SOURCES
# NOTES

σ – standard deviation of uncertainty

L – correlation length

* For the 1-frequency Poseidon altimeter;inferred from models using data from Doris

♣ From Doris tracking data

• Major assumptions:

1. Dual-frequency altimeter
2. Dual-frequency radiometer
3. Upgraded Tranet tracking system; 40 stations
4. Altimeter data averaged over 3 sec
5. H1/3 = 2 m; wave skewness = 0.1
6. Tabular corrections based on limited waveform-tracker comparisons
7. 1300 km orbit altitude
8. No anomalous data; no rain
9. Improved gravity model (X2 over existing models)
10. ±3 mbar surface pressure from weather charts
11. 100-μsec spacecraft clock

From: R. Stewart, et al., *Science Opportunities From the Topex/Poseidon Mission*, JPL Publication 86-18, NASA JPL (July 15, 1986).

# ALTIMETRY ERROR SOURCES

- **ORBIT**
  - RADIAL SATELLITE POSITION ERROR
  - ALONG-TRACK ERROR CONTRIBUTION = ALONG-TRACK POSITION × RELATIVE SLOPE OF SURFACE
- **IONOSPHERE**
  - IONOSPHERIC INDEX OF REFRACTION DEPENDS ON THE NUMBER OF FREE ELECTRONS
  - HEIGHT ERROR IS PROPORTIONAL TO THE COLUMNAR CONTENT OF FREE ELECTRONS
- **TROPOSPHERIC**
  - ATMOSPHERIC INDEX OF REFRACTION DEPENDS ON TEMPERATURE & PRESSURE OF THE ATMOSPHERE AT ALTITUDE Z, AND THE PARTIAL PRESSURE OF WATER VAPOR AT ALTITUDE Z
  - THE HEIGHT ERROR DEPENDS ON THE SURFACE PRESSURE AND THE TOTAL PRECIPITABLE WATER VAPOR (KG/SQ M)
- **ELECTROMAGNETIC BIAS**
  - EM BIAS DUE TO OCEAN SURFACE WAVES
  - SHAPE OF WAVES IS SUCH THAT THE WAVE TROUGH REFLECTS PULSES BETTER THAN THE WAVE CREST - THIS SHIFTS THE CENTROID OF THE RETURN PULSE AWAY FROM THE MEAN TOWARDS THE TROUGHS, RESULTING IN AN UNDER ESTIMATE IN THE SEA SURFACE HEIGHT
- **RAIN**
  - SCATTERING ATTENUATES THE ALTIMETER PULSE ENERGY, REDUCING THE RETURN POWER; PERFORMANCE DEGRADATION BECOMES SIGNIFICANT FOR RAIN RATES GREATER THAN ABOUT 5 MM/HR

# ALTIMETRY ERROR SOURCES (contd)

- **INSTRUMENT ERRORS**
  - FINITE PULSE BANDWIDTH RESULTS IN JITTER IN THE DETERMINATION OF THE PULSE LEADING EDGE
  - AMPLITUDE OF RETURN SIGNAL FLUCTUATIONS - SOME COMPENSATION IS ACHIEVED USING AN AGC - TRACK THE POSITION OF THE PULSE LEADING EDGE
  - ATTITUDE CONTROL OF THE SATELLITE RESULTS IN POINTING ERRORS WHICH DISPLACE THE SUB-SATELLITE POINT TOWARDS THE BEAM EDGE

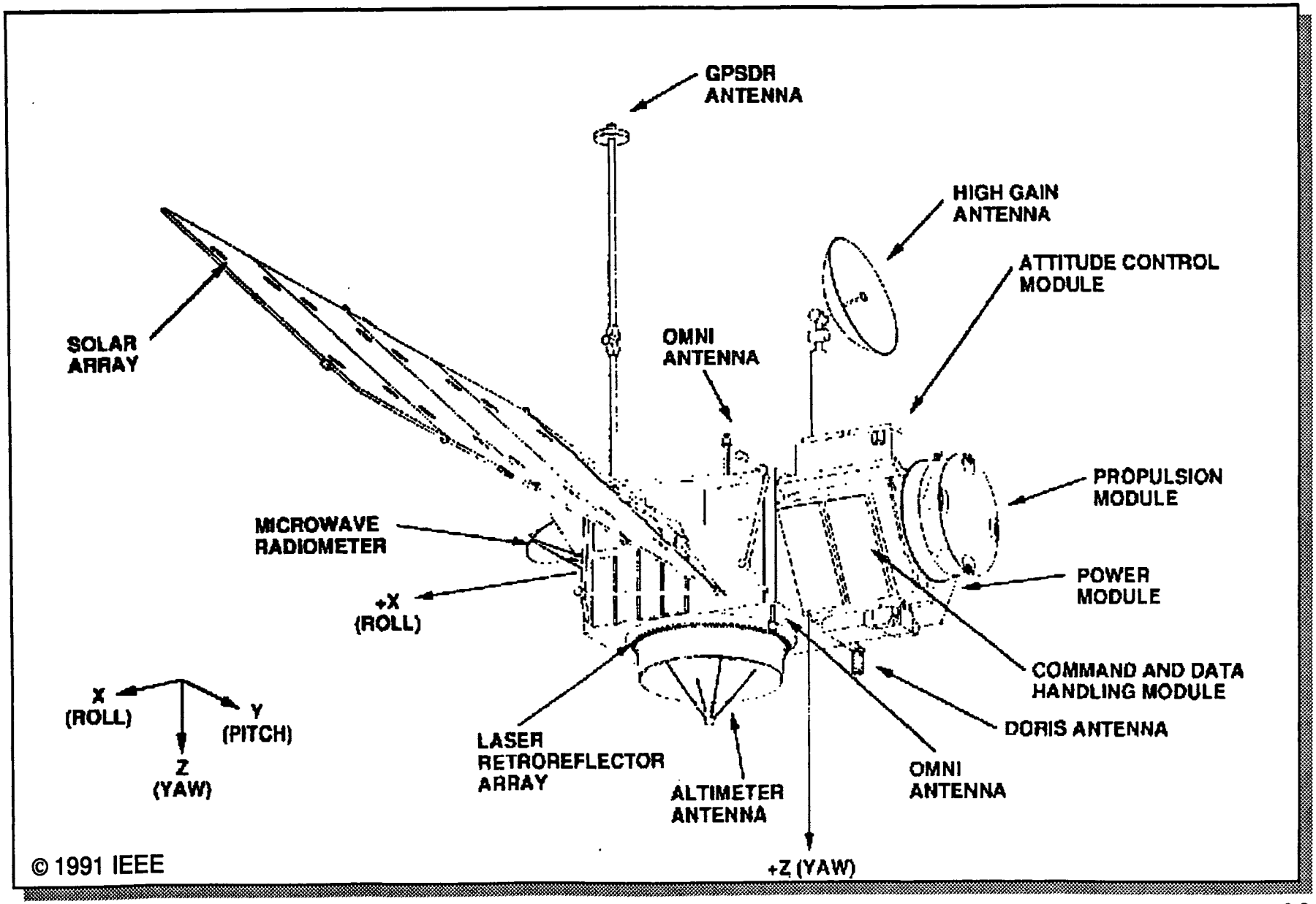
# ALTIMETER SYSTEMS
# TOPEX/POSEIDON

- **TOPEX/POSEIDON PROJECT**
  - JOINT US/FRANCE MISSION
  - GOAL: DEVELOP & ORBIT SATELLITE CAPABLE OF MAKING PRECISE MEASUREMENTS OF SEA LEVEL
  - HERITAGE IN SEASAT AND GEOSAT
  - MAIN SENSOR: NASA RADAR ALTIMETER (NRA)
- **NRA CHARACTERISTICS** (see table)
- **IMPROVEMENTS OVER PREVIOUS MISSIONS**
  - DUAL FREQUENCY; PROVIDE PATH DELAY CORRECTIONS FOR IONOSPHERIC PROPAGATION
  - LARGER ANTENNA; IMPROVED SNR
  - HIGHER ORBIT ALTITUDE; EASIER TO MAINTAIN PRECISION ORBIT DUE TO REDUCED DRAG
  - HIGHER KU-BAND PRF; IMPROVED PRECISION AT HIGHER OCEAN WAVE HEIGHTS
  - NADIR LOOKING MICROWAVE RADIOMETER PROVIDES COLLOCATED TROPOSPHERIC PATH DELAY CORRECTIONS (18, 21 & 37 GHz CHANNELS)

# TOPEX/POSEIDON
## STATUS

- **LAUNCHED AUGUST 10, 1992**
  - ARIANE 42P FROM KOUROU, FRENCH GUIANA
  - ENTERED OPERATIONAL ORBIT SEPT. 21, 1992
  - ORBIT
    - * NEAR CIRCULAR, 1336 KM EQUATORIAL ALTITUDE
    - * 12.8 REV/DAY
    - * 10 DAY REPEAT
    - *GROUND TRACK SPACING AT THE EQUATOR = 315 KM
  - CURRENTLY IN 5 MONTH VERIFICATION PHASE

# SATELLITE CONFIGURATION FOR THE TOPEX MISSION




From: A. [illegible]eger, et al., *NASA Radar Altimeter for the TOPEX/POSEIDON Project*, [illegible] IEEE, **79(6)**, 810-826 (1991).

# NASA RADAR ALTIMETER CHARACTERISTICS

| ITEM | PARAMETER | DESCRIPTION |
|---|---|---|
| TRANSMITTED WAVEFORM | CHIRP MODULATION | LINEAR FM SWEEP |
| | CENTER FREQUENCY | 13.6 GHZ/5.30 GHz |
| | PULSE WIDTH | 102.4μsec |
| | BANDWIDTH | 320 MHz |
| | C SELECTABLE PW/BW | 32μsec/100MHz |
| | PULSE PERIOD | 204.8msec |
| | BURST PERIOD (1334 km) | 8893 msec |
| | PRF | 4200 HZ (Ku-Band)/ 1220 Hz (C-Band) |
| ANTENNA | TYPE | 1.5 M PARABOLA |
| | GAIN | 43.9 dB (Ku); 35.7 dB (C) |
| | BEAMWIDTH | 1.1 deg (Ku); 2.7 deg (C) |
| TRANSMITTER | PEAK POWER | 20 W (Ku & C) |
| | DUTY FACTOR | 46% (KU); 12% max. (C) |
| | POWER CONSUMPTION | 70 W (Ku); 28 W (C) |
| SIGNAL PROCESSOR | WAVEFORM SAMPLES | 128 PER CHANNEL |
| | RANGE RESOLUTION | 0.5 M |
| | TRACKER TYPE | ALPHA-BETA |

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From: A. R. Zieger, et al., *NASA Radar Altimeter for the TOPEX/POSEIDON Project*, Proc. IEEE, **79(6)**, 810-826 (1991).

# NASA RADAR ALTIMETER CHARACTERISTICS (contd)

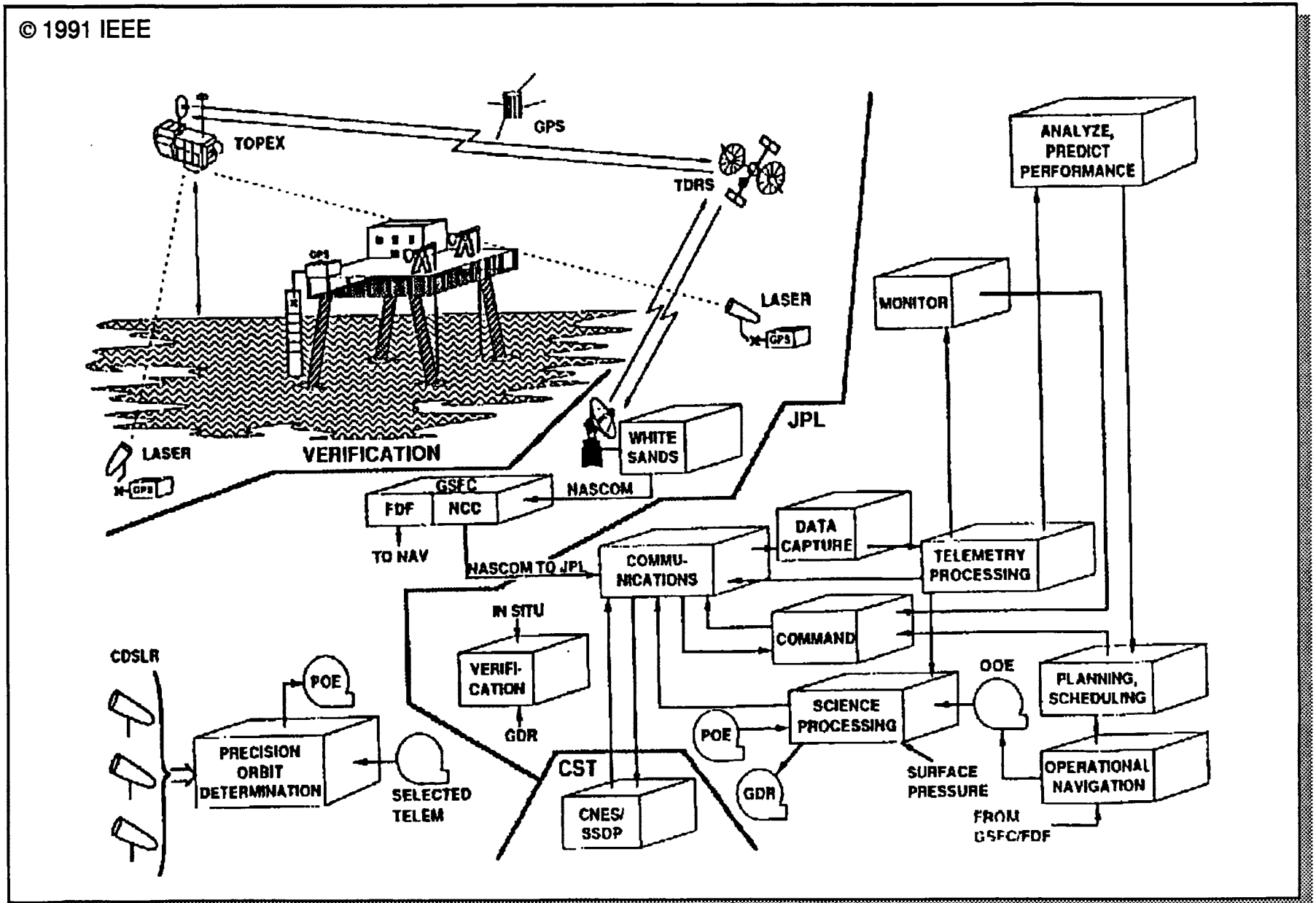
| ITEM | PARAMETER | DESCRIPTION |
|---|---|---|
| OPERATION MODES | IDLE | WHILE CNES ALT. ON |
| | STANDBY | NOT TRANSMITTING |
| | TRACK | 4 TRACK MODES |
| | CALIBRATE | 4 CALIBRATE MODES |
| | TEST | 4 TEST MODES |
| INPUTS | POWER BUS | 23-35 V DC |
| | TIMING SIGNAL | 5 MHz (0.89 V P-P) |
| | COMMANDS | RELAY (20, 1/S) |
| | | DATA (16b, 1 kb/s) |
| OUTPUTS | TELEMETRY | 1228 BYTE FRAME |
| | RATE | ABOUT 9.8 kb/s |
| POWER DEMAND | IDLE | 141 W |
| | STANDBY | 226 W |
| | CALIBRATE, TEST | 226 W |
| | TRACK | 232 W |
| WEIGHT | COMPLETE UNIT | 219 KG |

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From: A. F ger, et al., *NASA Radar Altimeter for the TOPEX/POSEIDON Project*, P EEE, **79(6)**, 810-826 (1991).

# TOPEX GROUND SYSTEM FUNCTIONAL DIAGRAM

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From: A. R. Zieger, et al., *NASA Radar Altimeter for the TOPEX/POSEIDON Project*, Proc. IEEE, **79(6)**, 810-826 (1991).

# 3.4 SCATTEROMETRY

- INTRODUCTION TO SCATTEROMETRY
- RADAR CALIBRATION
- SCATTEROMETER SYSTEMS
  - WIND SCATTEROMETRY
  - MULTIPLE FREQUENCY SYSTEMS

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## INTRODUCTION TO SCATTEROMETRY

- A SCATTEROMETER IS A RADAR CALIBRATED TO ALLOW MEASUREMENT OF
  - SCATTERING CROSS SECTION OR COEFFICIENT
  - IN SOME CASES PHASE
  - POLARIZATION (SEE SECTION 3.7)
- EXAMPLES
  - ALTIMETERS
  - WIND SCATTEROMETERS
  - POLARIMETERS
  - SAR

# INTRODUCTION TO SCATTEROMETRY (contd)

- ISSUES
  - CALIBRATION (ACCURACY)
  - DETERMINATION OF ILLUMINATED AREA
  - MEASUREMENT SAMPLING AND PRECISION
- IMPORTANT CHARACTERISTICS OF RADAR SYSTEM
  - OUTPUT AS A FUNCTION OF $\left(\frac{P_r}{P_t}\right)$
  - ANTENNA: PEAK GAIN, PATTERN
  - PULSE SHAPE, OUTPUT-FILTER WIDTH/SHAPE (FM RADAR)
  - RF SYSTEM LOSSES
  - NOISE FIGURE
  - IF FILTER SHAPE/WIDTH
  - PRF OR FM SWEEP RATE
  - FM SWEEP WIDTH AND LINEARITY
  - DELAY TIME THROUGH SYSTEM

# RADAR CALIBRATION

- **CALIBRATION**
  - PRECISION: RELATIVE CALIBRATION OF THE MEASUREMENT, DEPENDS ON MEASUREMENT RANDOM NOISE AND NUMBER OF INDEPENDENT SAMPLES AVERAGED.
  - ACCURACY: ABSOLUTE CALIBRATION - HOW CLOSE TO THE "TRUE" VALUE IS THE MEASUREMENT? DEPENDS ON SYSTEMATIC EFFECTS AND BIAS.
- **ABSOLUTE CALIBRATION AND BEAM ILLUMINATION EFFECTS**
  - RECALL RADAR EQUATION
  - OBJECT OF SCATTEROMETRY IS TO INVERT THIS EQUATION AND DETERMINE SCATTERING COEFFICIENT
  - TWO CASES OF INTEREST
    - (1) BEAMWIDTH-LIMITED CASE
    - (2) RANGE-RESOLUTION LIMITED CASE

$$P_r = \frac{\lambda^2}{(4\pi)^3} \int_{\Delta A} \frac{P_t G^2}{R^4} \sigma^0_{rt} \, dA$$

$\Delta A$ = illuminated area

# RADAR CALIBRATION (contd)

- **BEAMWIDTH LIMITED CASE**
  - RADAR DESIGNED SUCH THAT SCATTERING COEFFICIENT AND TRANSMITTED POWER ARE CONSTANT OVER AREA $\Delta A$

$$P_r = \frac{P_t \lambda^2}{(4\pi)^3 R^4} \sigma^0_{rt} \int_{\Delta A} G^2 dA \quad \Longrightarrow \sigma^0_{rt} = \left(\frac{P_r}{P_t}\right) \frac{(4\pi)^3 R^4}{\lambda^2 \int_{\Delta A} G^2 dA}$$

- **REQUIRE ACCURATE KNOWLEDGE OF**
  - $\left(\frac{P_r}{P_t}\right)$
  - WAVELENGTH - $\lambda$
  - RANGE - R
  - ANTENNA GAIN PATTERN - G
  - PROBLEM IS REDUCED TO DETERMINING Aw WHICH REQUIRES CAREFUL CHARACTERIZATION OF THE ANTENNA PATTERN AND POLARIZATION

$$G = G_0 \, g(\theta,\phi)$$

$$A_w = \int_{\Delta A} g^2(\theta,\phi) \, dA$$

$$\Longrightarrow \sigma^0_{rt} = \left(\frac{P_r}{P_t}\right) \frac{(4\pi)^3 R^4}{\lambda^2 G_0^2 A_w}$$

# RADAR CALIBRATION (contd)

- **RANGE-RESOLUTION LIMITED CASE**
  - ILLUMINATION ON SURFACE REQUIRES KNOWLEDGE OF PULSE SHAPE
  - RADAR DESIGNED WITH SUFFICIENTLY NARROW BEAMWIDTH AND RANGE RESOLUTION SUCH THAT THE SCATTERING COEFFICIENT AND R ARE CONSTANT OVER AREA $\Delta A$

$$P_r = \frac{P_{t0}\lambda^2}{(4\pi)^3}\int_{\Delta A} \frac{G^2 p\left(t - \frac{2R}{c}\right)}{R^4}\,\sigma^0_{rt}\,dA \qquad A_{wp} = \int_{\Delta A} g^2(\theta,\phi)\, p\left(t-\frac{2R}{c}\right) dA$$

$$\Longrightarrow \sigma^0_{rt} = \left(\frac{P_r}{P_{t0}}\right)\frac{(4\pi)^3 R^4}{\lambda^2 G_0^2 A_{wp}}$$

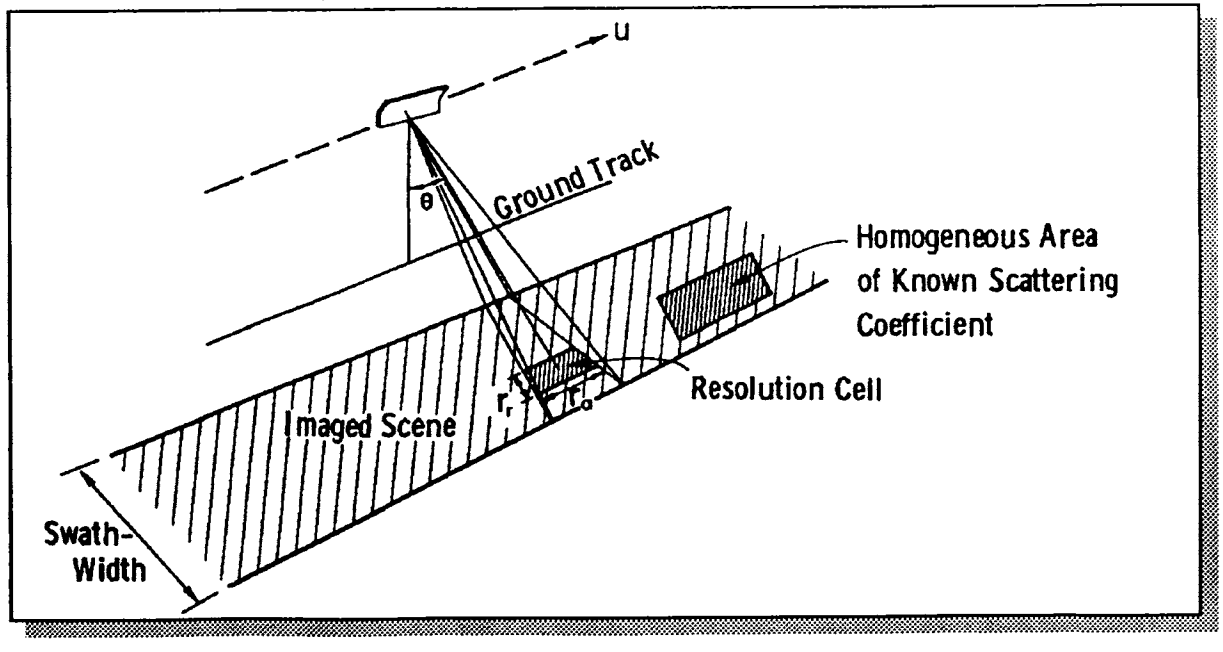
$P_t = P_{t0}p(t)$ = transmitted power

- **INTERNAL CALIBRATION**
  - ALLOWS DETERMINATION OF RELATIVE SCATTERING COEFFICIENTS
    - * PRECISION DETERMINED BY THE NUMBER OF INDEPENDENT SAMPLES
  - TWO TECHNIQUES
    - (1) SEPARATE CALIBRATION OF SYSTEM COMPONENTS OR ELEMENTS
    - (2) RATIO METHOD - SAMPLE OF TRANSMITTED SIGNAL IS INJECTED THROUGH SYSTEM FRONT END
  - METHOD (1) REQUIRES MANY MEASUREMENTS TO BE MADE AND KNOWLEDGE OF HOW COMPONENTS ARE MATCHED (VSWR)

# RADAR CALIBRATION (contd)

- **INTERNAL CALIBRATION (contd)**
  - METHOD (2) SUPERIOR - CHARACTERIZATION OF COMPLETE SYSTEM, NEED ONLY KNOW ANTENNA GAIN, MAY BE DESIGNED INTO SYSTEM AND USED FOR ON-ORBIT CALIBRATION

- **EXTERNAL CALIBRATION**
  - MEASURE RETURN POWER FROM A TARGET OF KNOWN CROSS SECTION OR SCATTERING COEFFICIENT
  - EXAMPLES
    - * CORNER REFLECTORS
    - * TERRAIN OF KNOWN, HOMOGENEOUS, AND STABLE $\sigma^0$




From: F. [illegible]by, et al., Microwave Remote Sensing: Active and Passive, Vol. II, © 19[illegible]986, Artech House, Inc., Norwood, MA.

# WIND SCATTEROMETRY

## • WIND SCATTEROMETRY PRINCIPLES

- SCATTERING OF RADAR SIGNALS FROM THE OCEAN SURFACE DEPENDS ON SURFACE ROUGHNESS ON A SCALE ON THE ORDER OF THE RADAR WAVELENGTH (RECALL BRAGG SCATTERING)
- SMALL SCALE SURFACE ROUGHNESS IS IN TURN DETERMINED BY LOCAL WIND SPEED AND DIRECTION
- OBSERVATION OF SURFACE SCATTERING COEFFICIENT CAN IN PRINCIPLE BE USED TO INFER LOCAL WIND SPEED AND DIRECTION
- REQUIRES THAT ONE KNOW THE RELATIONSHIP BETWEEN THE SURFACE SCATTERING COEFFICIENT, RADAR PARAMETERS AND WIND SPEED AND DIRECTION (VECTOR WIND)

## • GEOPHYSICAL MODEL FUNCTION

- RELATIONSHIP BETWEEN $\sigma^0$ AND NEAR SURFACE WINDS

$$\sigma^0 = \sigma^0\left(|\vec{u}_w|, \chi, \theta, f, q, \cdots, T\right)$$

$|\vec{u}_w|$ = wind speed

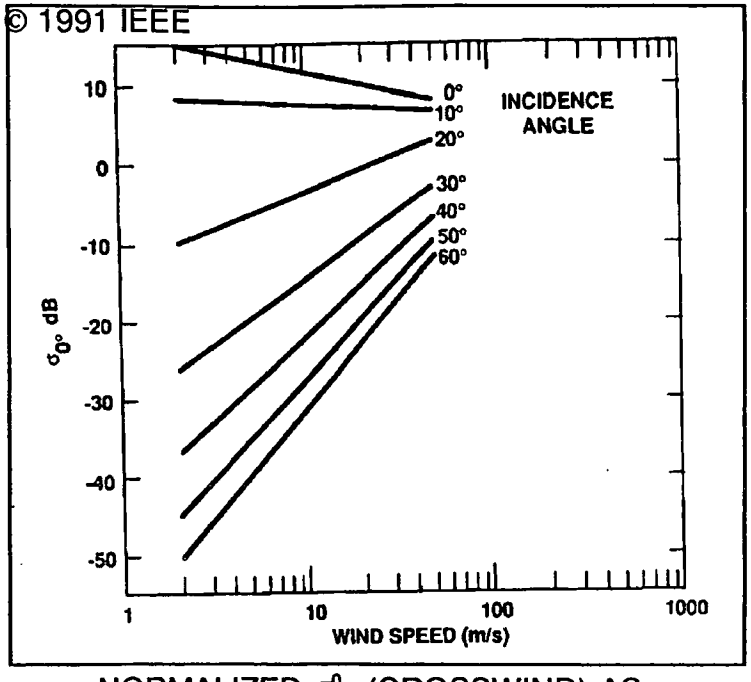
$\chi$ = relative azimuth angle between radar and wind

$\theta$ = incidence angle  $q$ = polarization

$f$ = radar frequency  $T$ = temperature

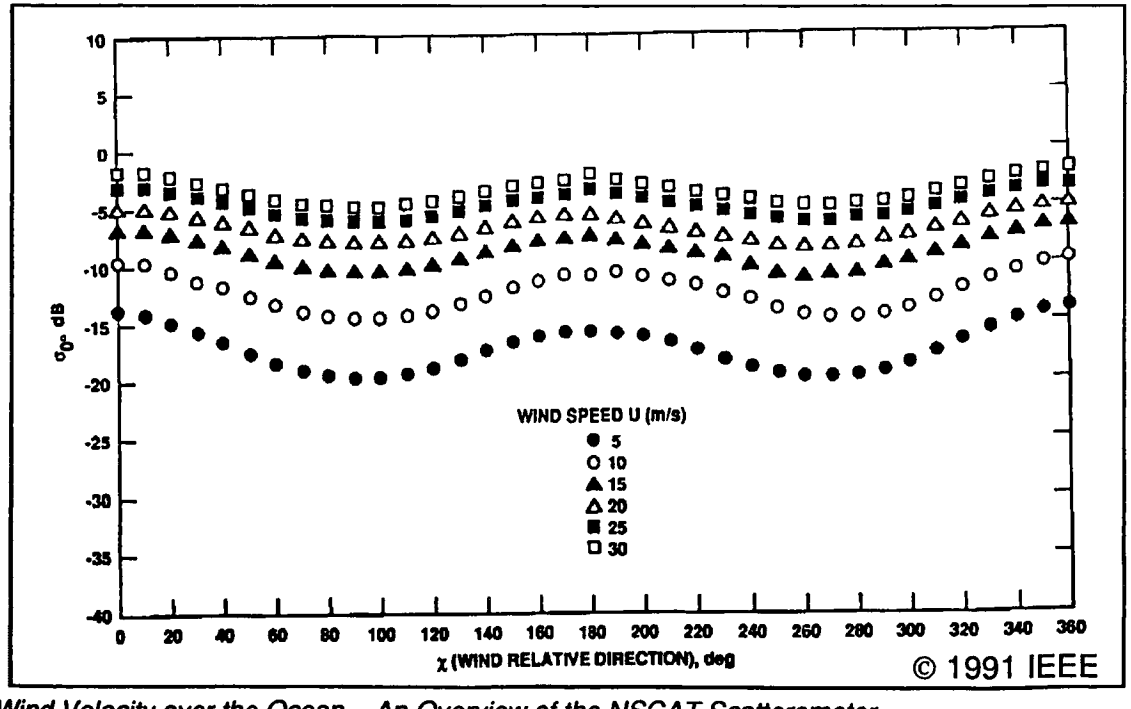
$\ldots$ = other geophysical variables

# WIND SCATTEROMETRY (contd)




NORMALIZED $\sigma^0_{VV}$ (CROSSWIND) AS A FUNCTION OF $|\vec{U}_W|$ AND $\theta$.

NORMALIZED $\sigma^0_{HH}$ AS A FUNCTION OF $\chi$ AND $|\vec{U}_W|$ ($\theta = 30^\circ$).

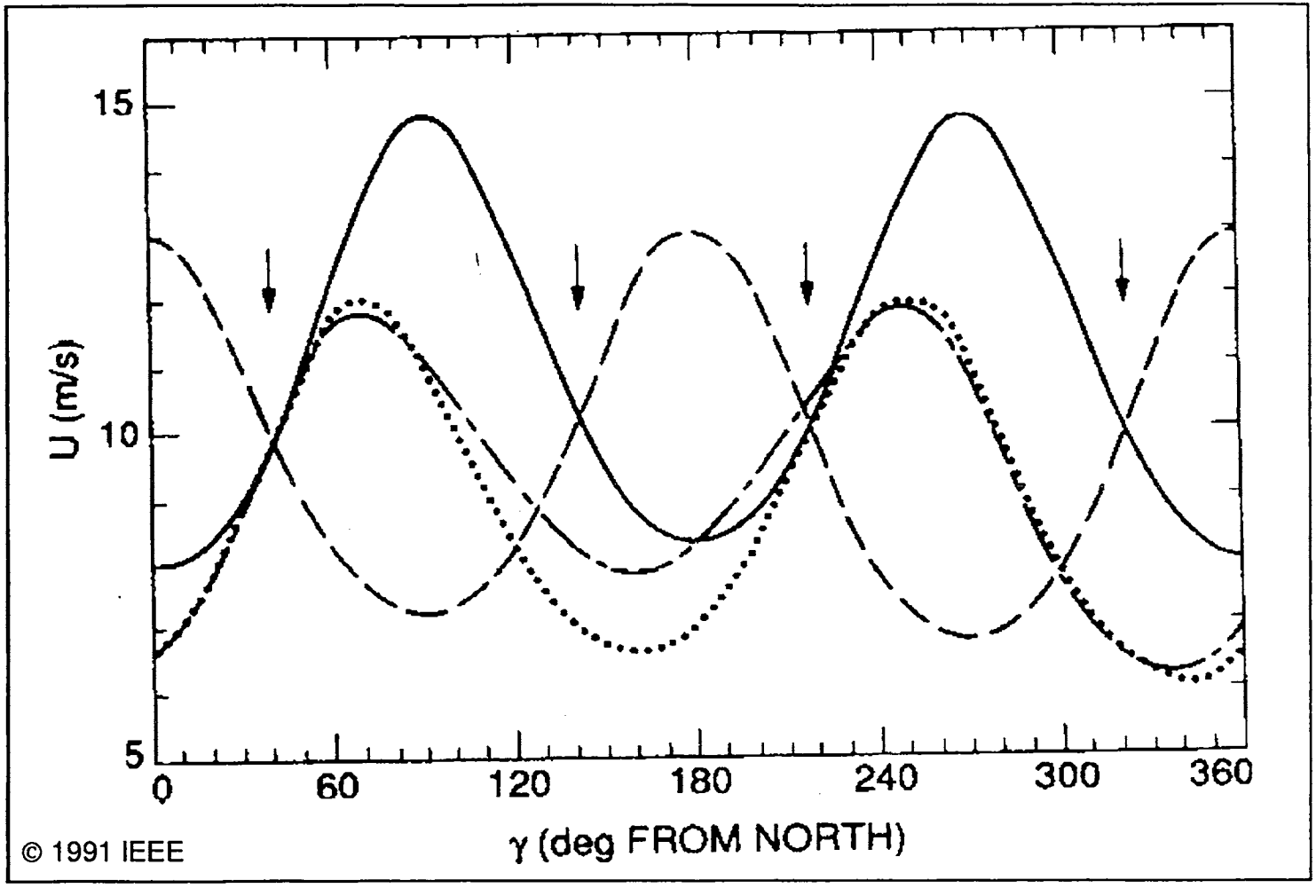



From: F. M. Naderi, et al., *Spaceborne Radar Measurement of Wind Velocity over the Ocean - An Overview of the NSCAT Scatterometer Sy* Proc. IEEE, **79(6)**, 850-866 (1991).

# WIND SCATTEROMETRY (contd)

- WIND SCATTEROMETRY PRINCIPLES: ISSUE OF WIND DIRECTION AND RADAR SCATTERING
  - UP-WIND AND DOWNWIND ASYMMETRY $\sigma^0_{UW} > \sigma^0_{DW}$
    - * ASYMMETRY INCREASES WITH INCREASING INCIDENCE ANGLE
    - * LARGER FOR HH THAN VV POLARIZATION
    - * LARGER AT SMALLER WIND SPEEDS
  - ASYMMETRY ALLOWS RESOLUTION OF AMBIGUITY IN WIND SPEED DIRECTION
    - * SINGLE MEASUREMENT OF $\sigma^0$ DOES NOT YIELD A UNIQUE WIND DIRECTION
    - * 2 MEASUREMENTS SEPARATED BY 90 DEG STILL RESULTS IN A 4 -FOLD AMBIGUITY
    - * INCREASING THE NUMBER OF MEASUREMENTS FURTHER (DIRECTIONS AND/OR POLARIZATIONS) RESULTS IN AMBIGUITY BEING REDUCED TO ESSENTIALLY ONE OF TWO POSSIBLE DIRECTIONS (180 DEG AMBIGUITY)
    - * REQUIRES FURTHER SIGNAL PROCESSING TO CHOSE CORRECT DIRECTION

# WIND SCATTEROMETRY (contd)



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**LOCI OF POSSIBLE VECTOR WINDS ASSOCIATED WITH COLLOCATED NOISE-FREE MEASUREMENTS OBTAINED FROM ANTENNAS AT VARIOUS AZIMUTH ANGLES.**

**HEAVY SOLID LINE: 0 deg. (V-pol); DASHED LINE: 90 deg. (V-pol); LIGHT SOLID LINE: 25 deg. (V-pol); DASHED LINE: 25 deg. (H-pol).**

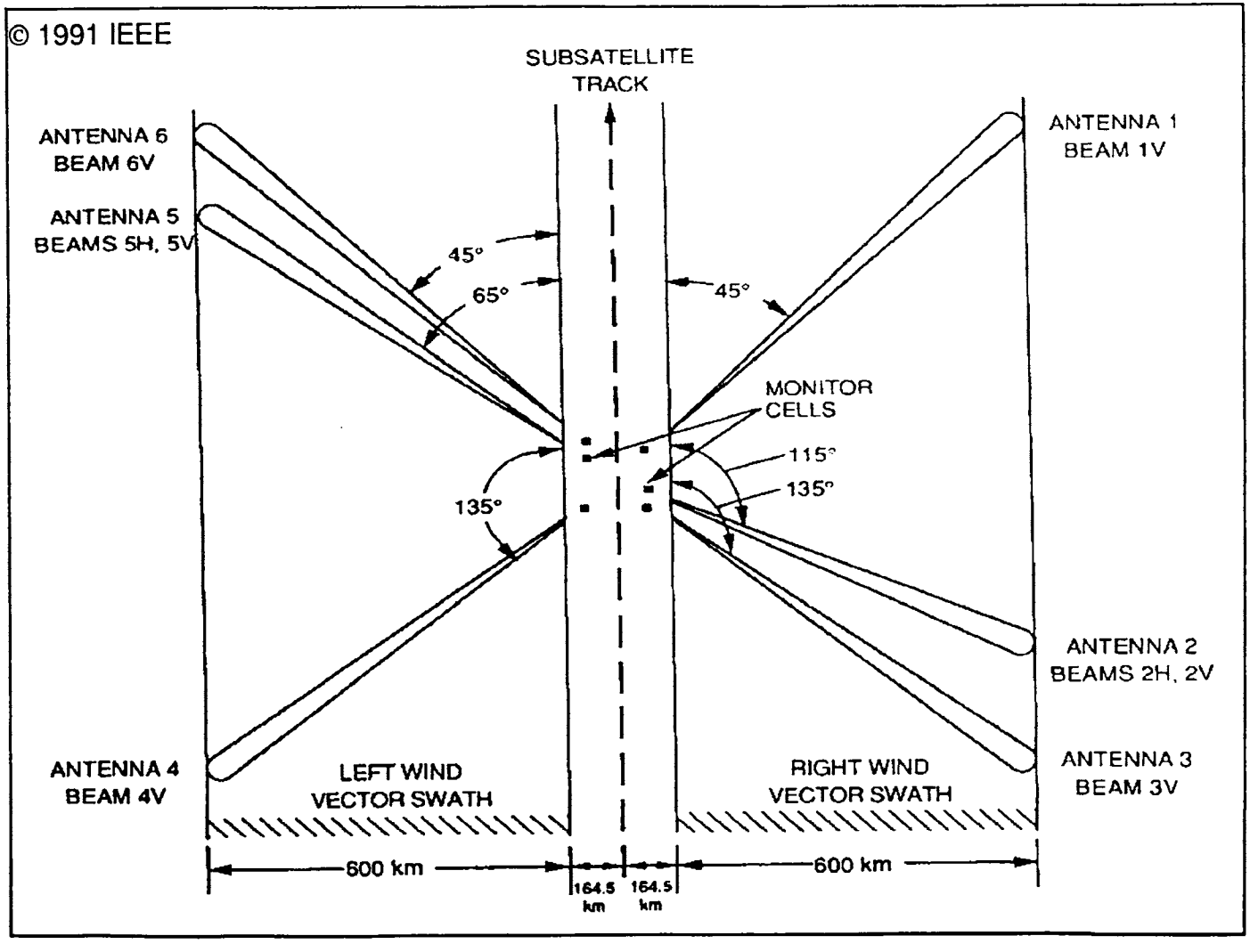
**ARROWS INDICATE SOLUTIONS OBTAINED USING ONLY THE ANTENNAS AT 0 AND 90 DEG.**

From: F. M. Naderi, et al., *Spaceborne Radar Measurement of Wind Velocity over the Ocean - An Overview of the NSCAT Scatterometer Sy[illegible]*, Proc. IEEE, **79(6)**, 850-866 (1991).

# WIND SCATTEROMETRY (contd)

- SCATTEROMETER DESIGN
  - FAN BEAM DESIGNS CHOSEN USING STICK ANTENNAS
    - * OBSERVE THE OCEAN AT SEVERAL AZIMUTH DIRECTIONS WITH NARROW BEAMWIDTH FOR GOOD DIRECTIONALITY
    - * GIVES WIDE SWATH COVERAGE
    - * MULTIPLE BEAMS (STICKS) USED TO RESOLVE DIRECTIONAL AMBIGUITY
  - PROBLEMS WITH FAN BEAMS
    - * VARIATION OF INCIDENCE ANGLE CROSS SWATH (ALONG BEAM)
    - * NADIR (SUBSATELLITE) HOLE
    - * RECEIVED POWER DECREASES ACROSS SWATH (IMPACTS ACCURACY AT SWATH EDGE)
  - REQUIRES WELL CALIBRATED SYSTEM WITH STABLE TRANSMITTERS AND RECEIVERS

# WIND SCATTEROMETRY (contd)




From: F. M. Naderi, et al., *Spaceborne Radar Measurement of Wind Velocity over the Ocean - An Overview of the NSCAT Scatterometer Sy* , Proc. IEEE, **79(6)**, 850-866 (1991).

# WIND SCATTEROMETRY (contd)

- **EXAMPLE: NASA SCATTEROMETER (NSCAT)**
  - SCHEDULED FOR LAUNCH ON ADEOS (ADVANCED EARTH OBSERVING SATELLITE, JAPAN) IN 1995
  - DEVELOPED BY NASA/JPL
  - HERITAGE: SEASAT SCATTEROMETER (SASS)
  - 6 STICK ANTENNAS PROVIDE FAN BEAMS
    - * WIDE SWATH (600 KM ON EACH SIDE)
    - * SUB-SWATH RESOLUTION OBTAINED BY TIMING AND DOPPLER FILTERING (ALONG-BEAM AND ALONG-TRACK RESOLUTION)

- **PERFORMANCE**
  - SCATTEROMETER PERFORMANCE FIGURE OF MERIT (FOM) $K_p = \frac{\delta\sigma^0}{\sigma^0}$
  - MINIMIZE $K_p$ - DESIGN DRIVER
  - VECTOR WIND MEASUREMENT PERFORMANCE VARIES ACROSS THE SWATH DUE TO
    - * $K_p$ VARIATION
      - • INCREASE IN SLANT RANGE
      - • INCREASE IN MEASUREMENT CELL SIZE
      - • $\sigma^0$ DECREASING WITH INCREASING INCIDENCE ANGLE
      - • ANTENNA GAIN PATTERN EFFECTS
    - * DEPENDENCE OF GEOPHYSICAL MODEL FUNCTION ON INCIDENCE ANGLE

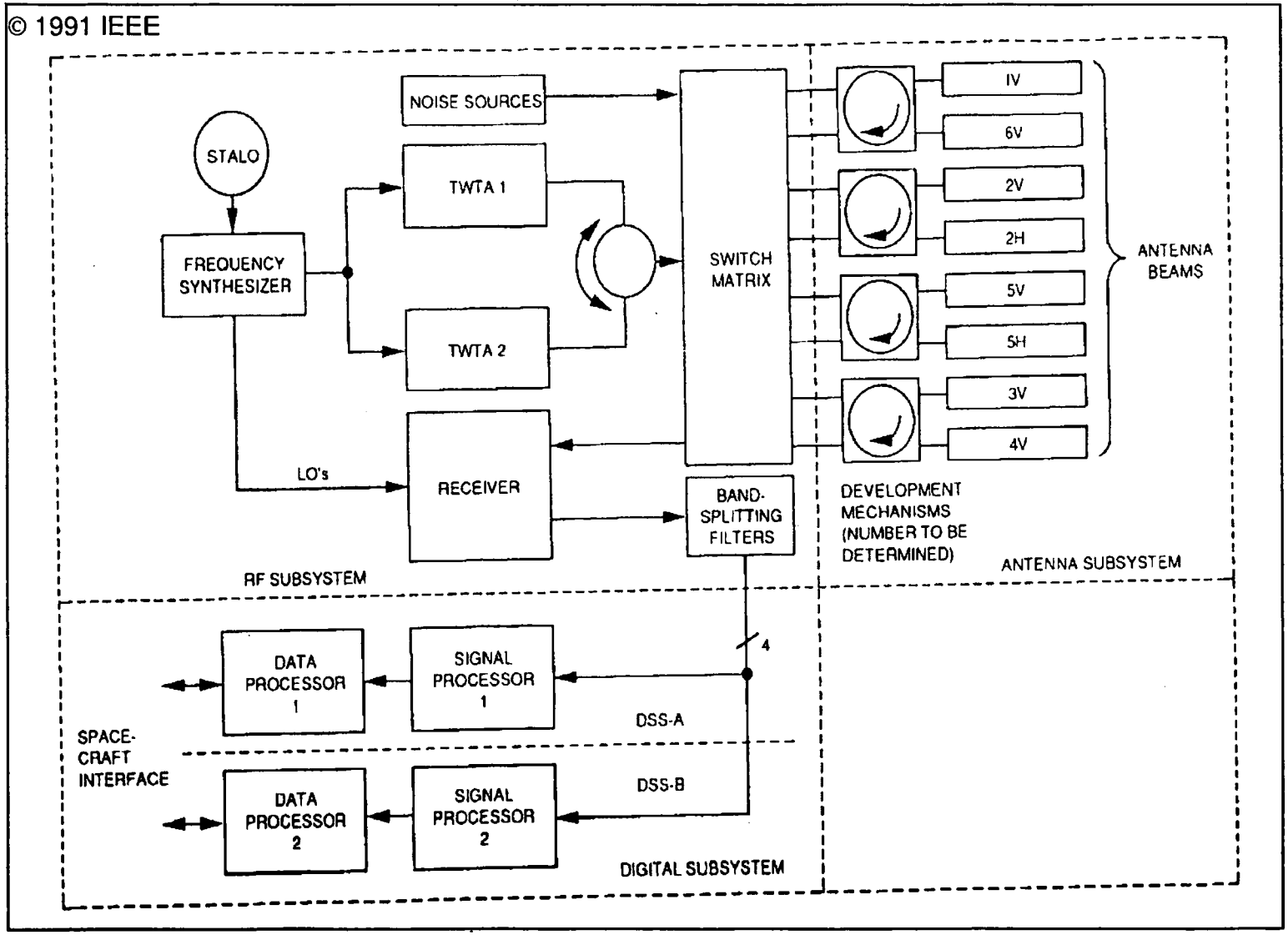
# NASA SCATTEROMETER (NSCAT)
## MISSION REQUIREMENTS

| | ACCURACY/RESOLUTION | RANGE |
|---|---|---|
| WIND SPEED | 2 m/sec rms | 3 - 20 m/sec |
| | 10% | 20 - 30 m/sec |
| WIND DIRECTION | 20 deg. rms | 3 - 30 m/sec |
| | (closest ambiguity) | |
| SPATIAL RESOLUTION | 25 km | $\sigma^0$cells |
| | 50 km | Wind cells |
| LOCATION ACCURACY | 25 km rms | Absolute |
| | 10 km rms | Relative |
| COVERAGE | 90 % ice free ocean | |
| | every 2 days | |
| MISSION DURATION | 36 months | |

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From: F. M. Naderi, et al., *Spaceborne Radar Measurement of Wind Velocity over the Ocean - An Overview of the NSCAT Scatterometer Sy[illegible]*, Proc. IEEE, **79(6)**, 850-866 (1991).

# WIND SCATTEROMETRY (contd)
## NSCAT BLOCK DIAGRAM




From: F. M. Naderi, et al., *Spaceborne Radar Measurement of Wind Velocity over the Ocean - An Overview of the NSCAT Scatterometer System*, Proc. IEEE, **79(6)**, 850-866 (1991).

# 3.5 REAL-APERTURE RADAR

- A REAL APERTURE RADAR (RAR) IS A RADAR SYSTEM IN WHICH
  - RANGE RESOLUTION IS DETERMINED BY TRANSMIT PULSE WAVEFORM CHARACTERISTICS (PULSE WIDTH OR BANDWIDTH)
  - CROSS-RANGE RESOLUTION IS DETERMINED BY THE ANTENNA PATTERN - TYPICALLY DETERMINED BY THE ANTENNA SIZE
  - PULSED SYSTEMS PROPOSED FOR SPACE APPLICATIONS
  - COHERENT AND INCOHERENT SYSTEMS
- EXAMPLES
  - ALTIMETERS (SEE SECTION 3.3)
  - SCATTEROMETERS (SEE SECTION 3.4)
  - DOPPLER RADARS
  - POLARIMETERS (SEE SECTION 3.7)
- LIMIT DISCUSSION TO SPACEBORNE WEATHER RADAR
  - NO SYSTEMS HAVE BEEN BUILT OR FLOWN TO DATE
  - TECHNOLOGY LIMITATIONS AND COST
  - SIGNIFICANT ADVANCES IN TECHNOLOGY MAKE SYSTEM CONCEPTS FEASIBLE WITHIN THE NEXT DECADE

# SPACEBORNE WEATHER RADAR

- PROPOSED SYSTEMS
  - TROPICAL RAIN MEASURING MISSION (TRMM)
  - TROPICAL RAIN MAPPING RADAR (TRAMAR)
  - BILAN ENERGETIQUE DU SYSTEME TROPICAL (BEST)
- APPLICATIONS
  - PRECIPITATION MONITORING AND MEASUREMENT
  - CLOUD AND WIND MEASUREMENTS
- GLOBAL MONITORING
  - GLOBAL MONITORING OF PROCESSES WHICH IMPACT AND REGULATE CLIMATE
  - GLOBAL PRECIPITATION MONITORING (LONG TERM SCIENCE)
    - * HYDROLOGICAL CYCLE
    - * COUPLING BETWEEN ATMOSPHERE AND OCEAN
    - * ROLE OF LATENT HEAT IN LARGE SCALE CIRCULATION
    - * MORPHOLOGY AND DYNAMICS OF TROPICAL STORM SYSTEMS
- NEAR-TERM BENEFITS
  - AGRICULTURE, WATER RESOURCE MONITORING, FLOOD WARNING
  - SEASONAL, ANNUAL, LONG TERM VARIATIONS IN AMOUNT AND DISTRIBUTION OF RAINFALL
- EXAMPLE SYSTEM: TROPICAL RAINFALL MEASURING MISSION (TRMM)

# TROPICAL RAINFALL MEASURING MISSION (TRMM)

- **PROPOSED RESEARCH SYSTEM**

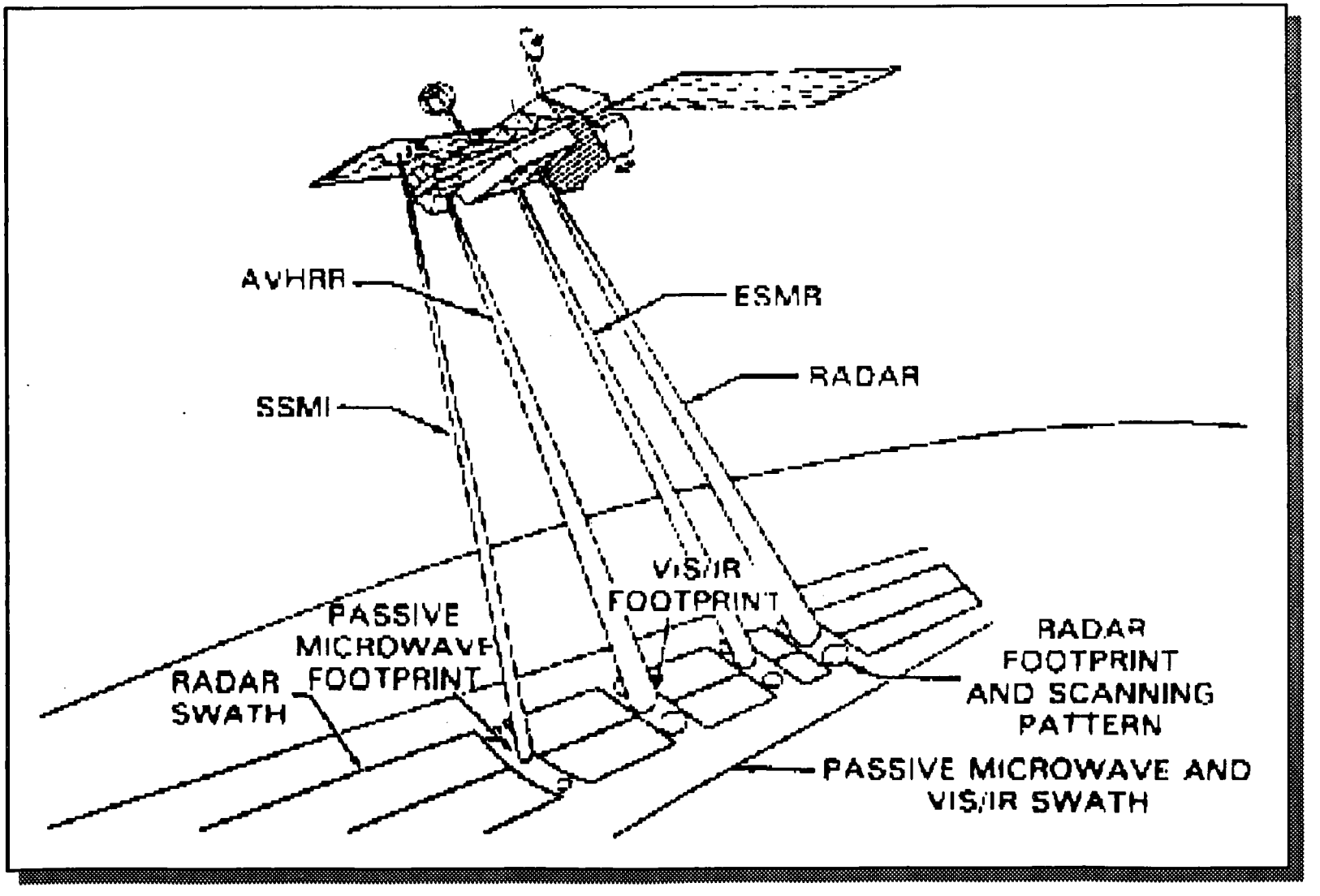
- **MISSION GOALS AND OBJECTIVES**

  - ADVANCE THE EARTH SYSTEM SCIENCE OBJECTIVE OF UNDERSTANDING THE GLOBAL ENERGY AND WATER CYCLES BY MEANS OF PROVIDING DISTRIBUTIONS OF RAINFALL AND ASSOCIATED INFERRED HEATING OVER THE GLOBE;
  - UNDERSTAND THE MECHANISMS THROUGH WHICH TROPICAL RAINFALL AND ITS VARIABILITY INFLUENCE GLOBAL CIRCULATION AND IMPROVE THE ABILITY TO MODEL THESE PROCESSES IN ORDER TO PREDICT GLOBAL CIRCULATION AND RAINFALL VARIABILITY AT MONTH AND LONGER TIME SCALE
  - IMPROVE THE MODELING AND UNDERSTANDING CONVECTIVELY DRIVEN PRECIPITATION CLOUD SYSTEMS IN THE TROPICS, THEIR ORGANIZATION ON THE MESOSCALE, AND THEIR INTERACTIONS WITH THE OCEAN AND THE AMBIENT ATMOSPHERE
  - EVALUATE SPACE-BASED SYSTEM FOR RAINFALL MEASUREMENTS
  - DEVELOP TECHNIQUES FOR STUDYING AND REMOVING THE DIURNAL CYCLE FROM TEMPORALLY AND SPATIALLY SMOOTHED TROPICAL RAINFALL DATA BY USING A NON-SUN SYNCHRONOUS ORBIT
  - OBTAIN A MINIMUM 3 YEAR DATA SET OF MONTHLY AVERAGED ESTIMATED TROPICAL RAINFALL RATE PROBABILITIES AVERAGED OVER GRID BOXES OF THE ORDER OF 500 KM ON A SIDE WITH SAMPLING ERRORS OF A FEW PERCENT
  - DEVELOP NEW TECHNIQUES FOR MEASURING TROPICAL RAINFALL BY COMBINING THE MEASUREMENTS FROM SEVERAL INSTRUMENTS TO REDUCE STATISTICAL BIASES AND TO LEARN HOW TO COMBINE MEASUREMENTS FROM OTHER COINCIDENT SATELLITE AND GROUND INSTRUMENTS TO FURTHER IMPROVE THE ACCURACY OF MEASUREMENT AND ESTIMATION OF RAINFALL
  - DEVELOP RESEARCH DATA SETS FOR STUDIES OF DIABATIC INITIALIZATION OF WEATHER FORECAST MODELS
  - DEVELOP A COMPREHENSIVE TROPICAL RAINFALL VALIDATION PROGRAM, BOTH BEFORE AND AFTER LAUNCH, THROUGH INTERNATIONAL COLLABORATION

FROM: TROPICAL RAINFALL MEASURING MISSION (TRMM) SCIENCE: RESEARCH OPPORTUNITIES, NASA RESEARCH ANNOUNCEMENT, NRA-90-OSSA-15 (JULY 10, 1990).

# TRMM (contd)

## SCHEMATIC ILLUSTRATION OF THE PROPOSED TRMM SATELLITE, SENSORS AND FOOTPRINTS




From: R. ' ghini and T. Kozu, *Spaceborne Weather Radar*, © 1990, Artech House Norwood, MA.

# TRMM CONFIGURATION

1993

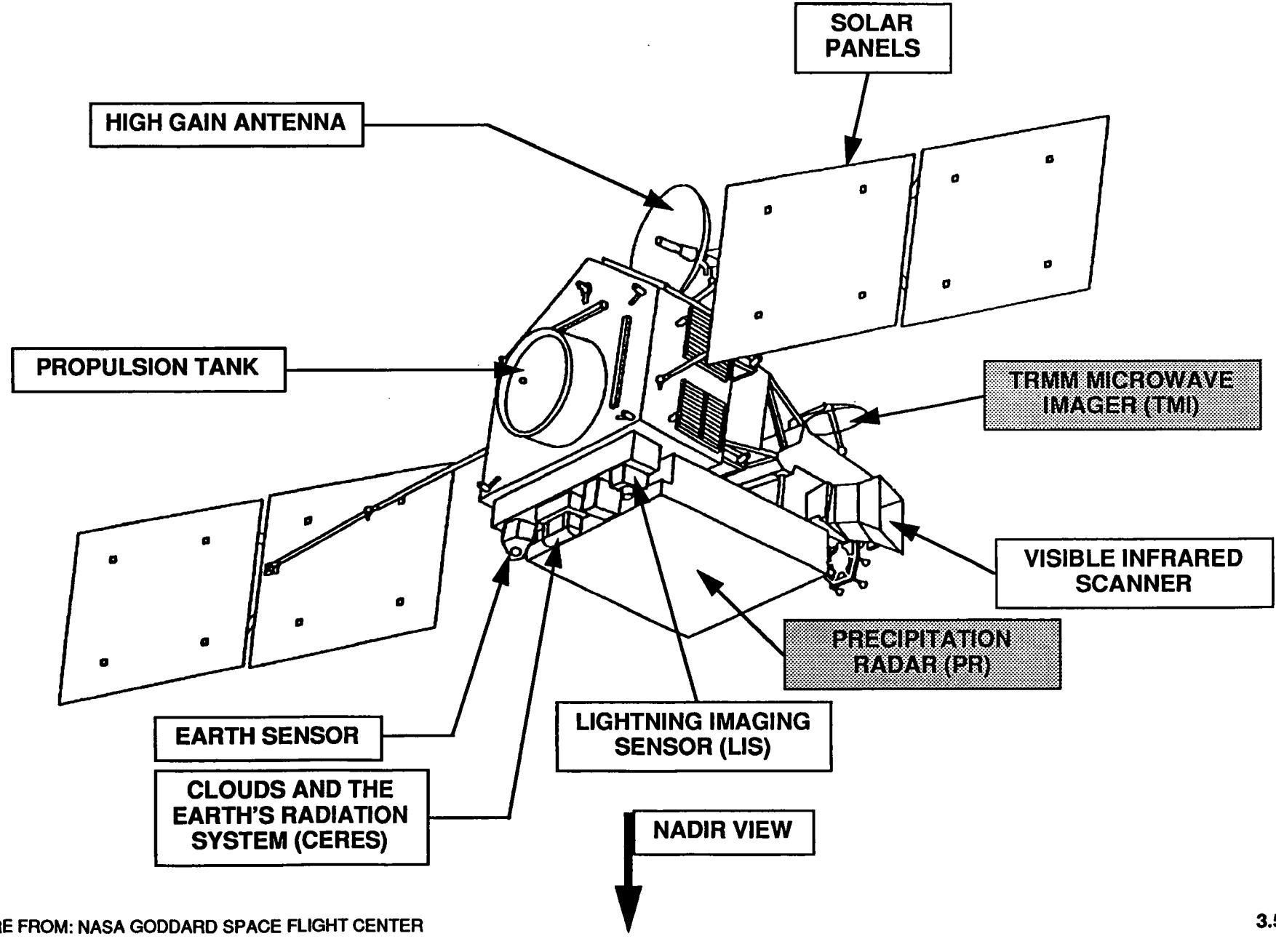



FIGURE FROM: NASA GODDARD SPACE FLIGHT CENTER

# TRMM CHARACTERISTICS
# RADAR AND MW RADIOMETER

- **PRECIPITATION RADAR (PR)**

| PARAMETER | RANGE |
|---|---|
| OBSERVABLE RANGE | Surface to 15 KM |
| RAIN RATE (mm/hr) | ≥ 0.5 |
| FREQUENCY (GHZ) | 13.8 |
| IFOV (DIA., KM) | 4.3 |
| SWATH WIDTH (KM) | 220 |
| SPATIAL RESOLUTION | |
| HORIZONTAL (m) | 4300 |
| VERTICAL (m) | 250 |
| MASS (KG) | 376 |
| POWER (W) | 223 |
| DATA RATE (KBPS) | 92.5 |

- **TRMM MICROWAVE RADIOMETER (TMI)**

| CHANNEL NUMBER | CENTRAL FREQUENCY (GHz) | BANDWIDTH (GHz) | POLARIZATION | PRIMARY PURPOSE | PRIMARY DATA AREA |
|---|---|---|---|---|---|
| 1 | 10.65 | 100 | V | VERY HEAVY RAIN | OCEAN |
| 2 | 10.65 | 100 | H | VERY HEAVY RAIN | OCEAN |
| 3 | 19.35 | 500 | V | HEAVY RAIN | OCEAN |
| 4 | 19.35 | 500 | H | HEAVY RAIN | OCEAN |
| 5 | 21.3 | 500 | H | TOTAL WATER VAPOR | LAND/OCEAN |
| 6 | 37 | 2000 | V | LIGHT RAIN | LAND/OCEAN |
| 7 | 37 | 2000 | H | LIGHT RAIN | LAND/OCEAN |
| 8 | 85.5 | 3000 | V | VERY LIGHT RAIN | LAND/OCEAN |
| 9 | 85.5 | 3000 | H | VERY LIGHT RAIN | LAND/OCEAN |

# TRMM (contd)

## • SUMMARY OF PROPOSED SENSORS

- 600 KM SWATH DESIRED
- MICROWAVE RADIOMETER: CROSS TRACK SCANNING
  * ESMR HERITAGE
  * 19 GHz, DUAL POL. CHANNEL, 10 KM NADIR RESOLUTION
- MICROWAVE RADIOMETER: CONICAL SCANNING
  * SSM/I HERITAGE
  * 19, 22, 37, 85 GHz, DUAL POL., CHANNELS
- VISIBLE/INFRARED IMAGER (AVHRR)
  * VISIBLE (MOONLIGHT) AND 10 MICRON CHANNELS
  * 1 KM RESOLUTION AT NADIR
- PRECIPITATION RADAR
  * MANY DIFFERENT CANDIDATE OPTIONS CONSIDERED

## • SPACECRAFT/PAYLOAD CHARACTERISTICS

- MASS: 2195 KM (AT LAUNCH)
- POWER: 1 KW (MIN., EOL)
- DATA RATE: 1 Mbps
- ORBIT: 320 KM ALTITUDE, 30-35 DEGREE INCLINATION ANGLE

# TRMM PRECIPITATION RADAR

## • OPTIONS CONSIDERED FOR THE PRECIPITATION RADAR

| SUBSYSTEM | DESIGN 1 | DESIGN 2 | DESIGN 3 | DESIGN 4 | DESIGN 5 | DESIGN 6 |
|---|---|---|---|---|---|---|
| ANTENNA | PLANAR | PLANAR | PLANAR | PLANAR | CYLINDRICAL | CYLINDRICAL |
| TRANSMITTER | TWTA | TWTA | SSPA | SSPA | TWTA | TWTA |
| PC/NPC | PC | NPC | PC | NPC | PC | NPC |
| POWER (W) | | | | | | |
| PRIME | 339 | 315 | 396 | 324 | 339 | 315 |
| | | (378)1 | | (355)1 | | (378)1 |
| MARGIN | 61 | 85 | 4 | 76 | 61 | 85 |
| | | (22)1 | | (45)1 | | (22)1 |
| WEIGHT (kg) | 310 | 310 | 468 | 560 | 300)2 | 300)2 |
| SIZE (m) | | | | | | |
| 13.8 GHz | 2.1x2.1x.46 | 2.1x2.1x.46 | 2.3x2.3x.65 | 2.3x2.3x.65 | 3.0x2.52x1.55 | 3.0x2.52x1.55 |
| 24.15 GHz | 1.25x1.25x.3 | 1.25x1.25x.38 | 1.3x1.3x.65 | 1.3x1.3x.65 | 3.0x2.52x1.55 | 3.0x2.52x1.55 |
| SNR (dB) | | | | | | |
| 13.8 GHz | -1.0 | 0.6 | -1.5 | 2.1 | -1.0 | 0.6 |
| 24.15 GHz | -0.9 | 0.8 | -1.4 | -0.7 | -0.9 | 0.8 |

**1: WHEN VARIABLE PRF AND NON-LINEAR SCAN ARE USED.**

**2: SIZE OF OCCUPIED VOLUME BY A CYLINDRICAL PARABOLIC ANTENNA SYSTEM (REFLECTOR + FEED). THIS SIZE ASSUMES THAT ONLY THE FEED OF 13.8 GHz IS CONSIDERED AND INCREASES IF BOTH THE 13.8 AND 24.15 GHz FEEDS ARE CONSIDERED.**

**PC = PULSE COMPRESSION, NPC = NO PULSE COMPRESSION**

From: R. ghini and T. Kozu, *Spaceborne Weather Radar*, © 1990, Artech House Norwood, MA.

# TRMM (contd)

- TRMM LEVEL 2 GEOPHYSICAL PARAMETERS/DATA PRODUCTS
  - AVHRR
    - * CLOUD COVER AND RAIN ESTIMATION
  - ESMR
    - * RAIN RATE
  - SSM/I
    - * RAIN RATES (MULTICHANNEL AND COMPOSITE)
  - PRECIPITATION RADAR
    - * PROFILED RAIN RATE
    - * PATH AVERAGED RAIN RATE
    - * LIQUID WATER CONTENT
    - * STORM HEIGHT

# 3.6 SYNTHETIC APERTURE RADAR (SAR)

- OVERVIEW OF BASIC PRINCIPLES OF SAR
- SAR PROCESSING OVERVIEW
- SPACEBORNE AND AIRBORNE SAR SYSTEMS
- CHARACTERIZATION AND EXPLOITATION OF RADAR IMAGERY
- INTERFEROMETRIC SAR

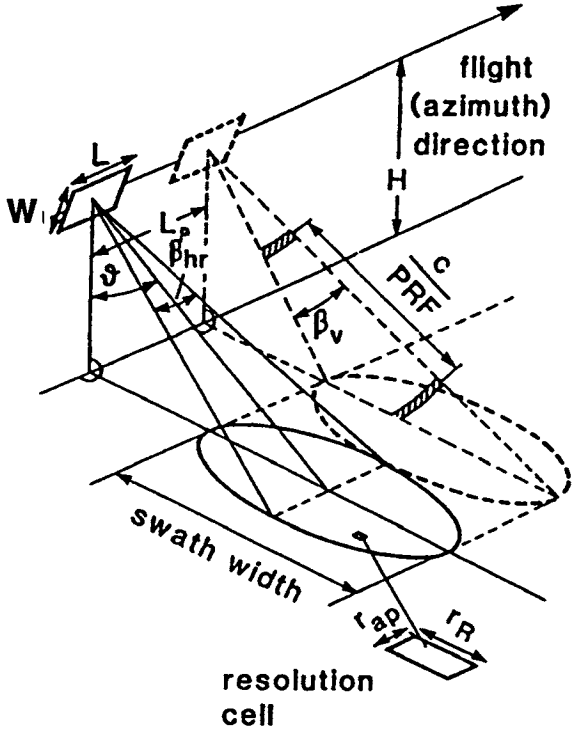
# OVERVIEW OF SAR CONCEPT

- ORIGINALLY DEVELOPED IN THE 1950's BY C. WILEY AT GOODYEAR, AEROSPACE USING DOPPLER BEAM-SHARPENING APPROACH
  - -UNIQUE INTERPRETATION
  - - ACTIVE SYSTEM - CREATES MAP OF SCENE BY SIGNAL PROCESSING TECHNIQUES
  - - DAY AND NIGHT CAPABILITY
  - - ABILITY TO IMAGE THROUGH CLOUDS AND MOST WEATHER CONDITIONS
- MANY DIFFERENT VIEWPOINTS FROM WHICH TO UNDERSTAND SAR PRINCIPLE
  - (1) SYNTHETIC ANTENNA APERTURE
  - (2) DOPPLER BEAM-SHARPENING (RANGE-DOPPLER APPROACH)
  - (3) CORRELATION WITH REFERENCE POINT TARGET RESPONSE
  - (4) MATCHED FILTER FOR RECEIVED POINT TARGET SIGNAL
  - (5) DE-CHIRPING OF DOPPLER FREQUENCY SHIFT
  - (6) OPTICAL-FOCUSING ANALOGY

# INTRODUCTION TO SAR

- **REAL APERTURE ANTENNA**
  - **DIFFRACTION LIMITED RESOLUTION**
    - » **RANGE** $\beta_r = K_r \frac{\lambda}{W}$
    - » **AZIMUTH** $\beta_{az} = K_{az} \frac{\lambda}{L}$

  $K_r$ and $K_{az}$ depend on antenna weighting functions, ≈1




- **EXAMPLE: SEASAT ANTENNA SIZE 10 m X 2 m**
  - **PARAMETER VALUES**

    $\lambda = 23.5$ cm (L – Band)

    $K_r = K_{az} \approx 1.76$

    $\Rightarrow \beta_r \approx 0.21$ rad

    $\beta_{az} \approx 0.04$ rad

  **at a range of ≈ 1000 km, the footprint size is roughly**

    $\delta_r \approx 207$ km

    $\delta_{az} \approx 41$ km

# INTRODUCTION TO SAR

- **RANGE RESOLUTION**
  - **DEPENDS ON BANDWIDTH OF TRANSMITTED PULSE**
    - » **RECTANGULAR PULSES**
    - » **MODULATED PULSES: LINEAR FREQUENCY MODULATED (FM) OR CHIRP MOST COMMON**

$$\text{PULSE WIDTH} = \Delta\tau_p$$

$$\text{BANDWIDTH} = \Delta f = \frac{1}{\Delta\tau_p}$$

$$\text{RANGE RESOLUTION } \Delta\rho_r = \frac{c}{2\Delta f}$$

  - **SIGNAL PROCESSING (PULSE COMPRESSION) USED TO GIVE INCREASED RANGE RESOLUTION**

- **EXAMPLE**

$$\Delta f = 100 \text{ MHz}$$

$$c = 300 \text{ MHz-m}$$

$$\Delta\rho_r = \frac{300}{2\times 100} \text{ m} = 1.5 \text{ m}$$

# INTRODUCTION TO SAR

- AZIMUTH OR CROSS RANGE RESOLUTION
  - HOW TO IMPROVE AZIMUTH RESOLUTION OVER THAT OBTAINED FROM A DIFFRACTION LIMITED ANTENNA?
  - SYNTHESIZE A LARGER EFFECTIVE APERTURE

- APERTURE SYNTHESIS FROM DOPPLER BEAM SHARPENING PERSPECTIVE
  - DURING THE TIME THE TARGET IS IN THE MAIN BEAM FOOTPRINT, EACH PULSE COLLECTS AMPLITUDE, PHASE AND FREQUENCY INFORMATION ON TARGET BACKSCATTERING
  - SEPARATE TARGETS IN AZIMUTH USING DOPPLER FREQUENCY SHIFTS FOR EACH TARGET
    - » GENERATE TARGET PHASE HISTORY
    - » DOPPLER SHIFT

$$f_D(t) \approx \frac{2V_p}{\lambda}\theta(t)$$

$\theta$ is the target azimuth angular offset from broadside as a function of time

# INTRODUCTION TO SAR

- **AZIMUTH RESOLUTION**
  - **DETERMINED BY THE ABILITY TO RESOLVE TARGET DOPPLER SHIFTS**

R = TARGET SLANT RANGE

$$\Delta f_D \approx \frac{2V_p}{\lambda}\Delta\theta$$

$$\Delta\theta = \frac{\Delta\rho_{az}}{R}$$

  - **AZIMUTH RESOLUTION**

$$\Delta\rho_{az} = \frac{\lambda R}{2V_p}\Delta f_D$$

- **EFFECTIVE SYNTHETIC APERTURE LENGTH**

$$\Delta\rho_{az} = \frac{\lambda R}{L_p}$$

$$\Rightarrow L_P = \frac{2V_P}{\Delta f_D}$$

# INTRODUCTION TO SAR

- **HIGH AZIMUTH RESOLUTION DEPENDS ON ABILITY TO RESOLVE DOPPLER SHIFTS**
  - **DOPPLER RESOLUTION REQUIRES LONG MEASUREMENT TIME**

$$\Delta f_D\big|_{MIN} \geq \frac{1}{T_M}$$

  - **ASSUME A TRACKING FILTER WHICH GIVES A DWELL TIME (TIME ON TARGET)**

$$\Delta f_D = \frac{1}{T_D}$$

$$T_D = T_M \qquad L_P = 2V_P T_D$$

$$\Delta\rho_{az} = R\frac{\lambda}{L_P} = \frac{R\lambda}{2V_P T_D}$$

  - **$T_D$ DEPENDS ON THE REAL ANTENNA AZIMUTH BEAMWIDTH**

$$T_D = \beta_{az}\frac{R}{V_P}$$

$$\beta_{az} = K_{az}\frac{\lambda}{L}$$

$$\Delta\rho_{az} = \frac{\lambda}{2\beta_{az}}$$

$$\boxed{\Delta\rho_{az} = \frac{L}{2K_{az}}}$$

EXAMPLE FOR SEASAT

$$\Delta\rho_{az} \approx 5 \text{ m}$$

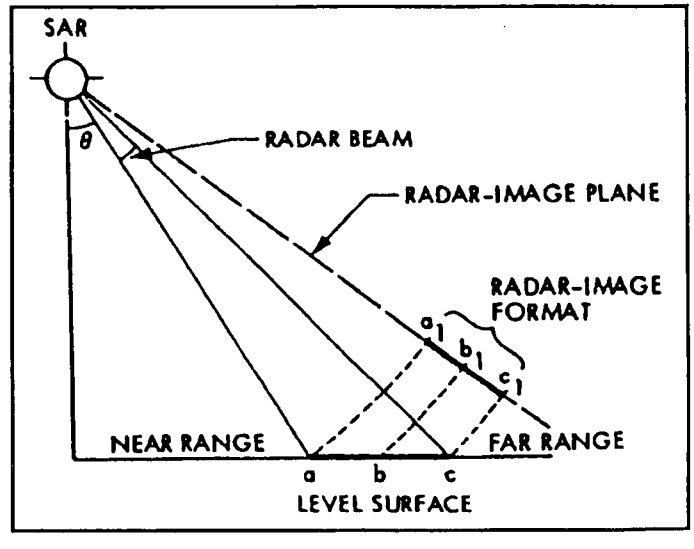
# SAR IMAGE GEOMETRY

- SLANT-TO-GROUND RANGE CONVERSION
- FORESHORTENING
- LAYOVER
- SHADOWING
- MULTIPLE BOUNCE

# SLANT-TO-GROUND RANGE CONVERSION

- **EXPLOITATION OF SAR IMAGERY OFTEN REQUIRES CONVERSION FROM SLANT TO GROUND PLANE**
- **SLANT AND GROUND RANGE RESOLUTION**

$$\Delta\rho_r = \frac{c}{2\Delta f} \qquad \Delta\rho_g = \frac{\Delta\rho_r}{\sin\theta}$$

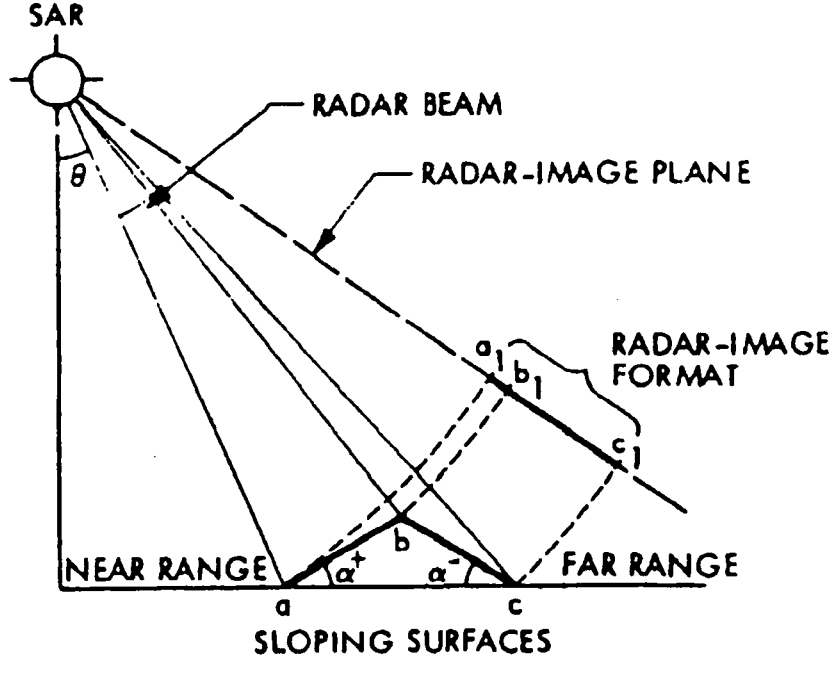



θ is the look angle

- **MAPPING FROM SLANT TO GROUND PLANE**
  - **PRODUCES NON-UNIFORM SAMPLE SPACING, VARYING WITH LOCAL INCIDENCE ANGLE**
  - **RESAMPLE TO UNIFORM GRID IN GROUND PLANE**
  - **SLANT RANGE POINTS a1, b1 AND c1**
  - **CORRESPONDING GROUND RANGE POINTS a, b AND c, ASSUMING A LEVEL SURFACE**

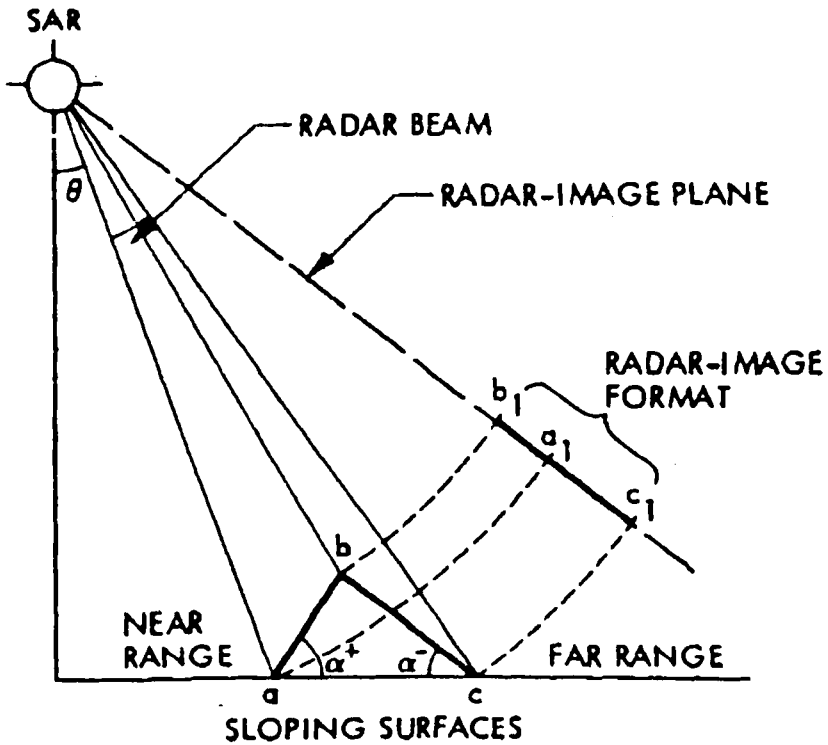
# FORESHORTENING

- SLOPES TOWARD THE RADAR APPEAR COMPRESSED RELATIVE TO SLOPES INCLINED AWAY FROM THE RADAR
  - SLOPE ab IS PROJECTED AS SLOPE a1b1 IN THE RADAR SLANT PLANE
  - SIMILARLY FOR SLOPE bc



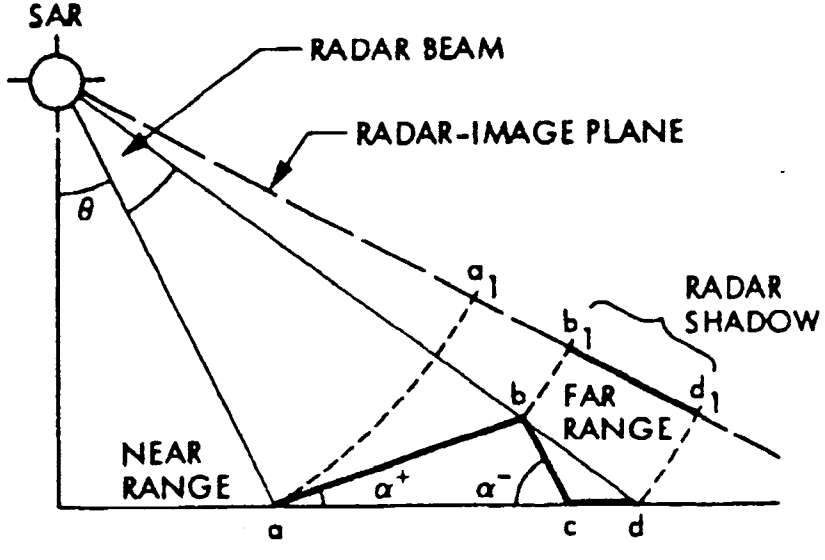
# LAYOVER

- **LAYOVER IS AN EXTREME CASE OF FORESHORTENING**
  - **OCCURS WHEN THE LOOK ANGLE $\theta$ IS SMALLER THAN THE FORESLOPE $\alpha^+$**
  - **SLOPE ab IS PROJECTED AS b1a1 ON RADAR IMAGE SLANT PLANE**



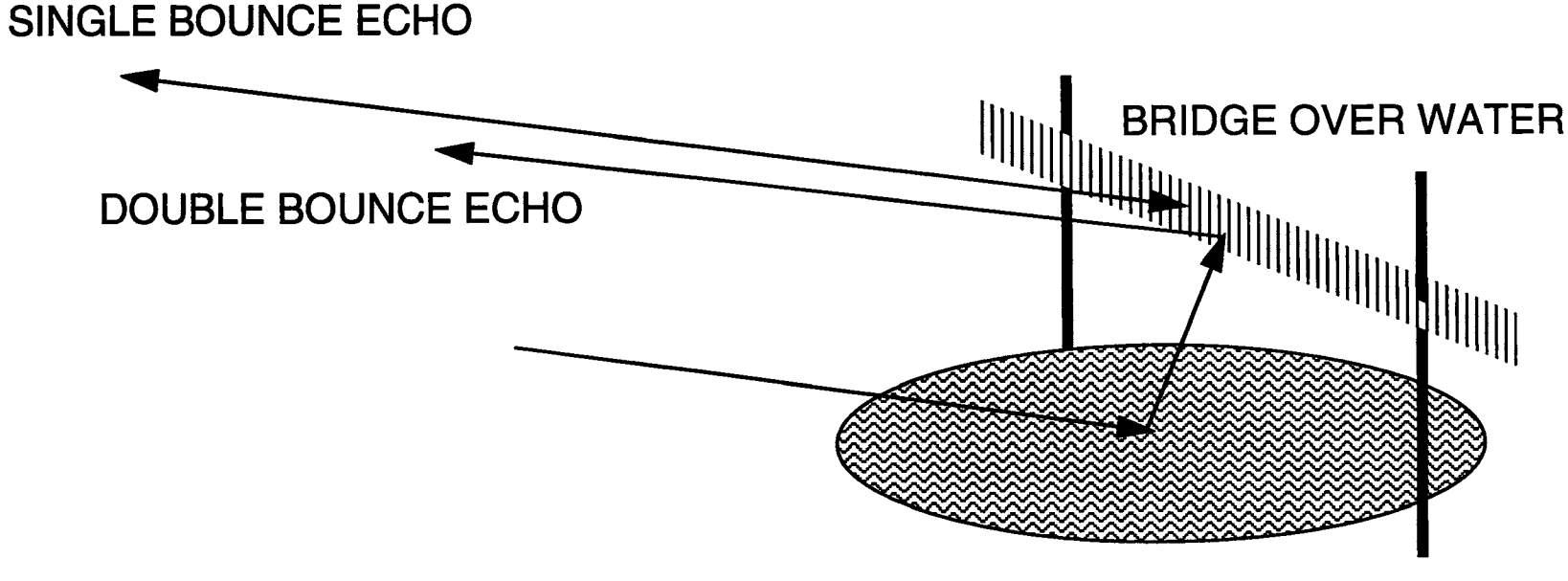
# SHADOWING

- SHADOWING OCCURS WHEN RADAR ENERGY IS BLOCKED FROM ILLUMINATING A REGION IN THE SCENE RESULTING IN NO RADAR RETURN FROM THAT REGION
- SLOPES INCLINED AWAY FROM THE RADAR WILL BE IN SHADOW WHEN THE THE LOOK ANGLE, $\theta$, PLUS THE BACKSLOPE, $\alpha^-$, EXCEEDS 90°
- CAN PROVIDED ADDITIONAL INFORMATION ON TARGET GEOMETRY AND SHAPE



# MULTIPLE BOUNCE

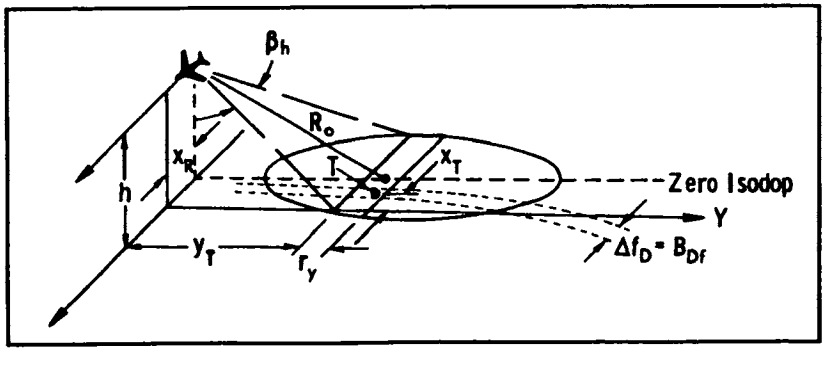
- **RANGE POSITION OF TARGET IS DETERMINED BY DELAY TIME OF RADAR ECHO**
- **MULTIPLE BOUNCES CAN RESULT IN DISPLACED "GHOSTS"**

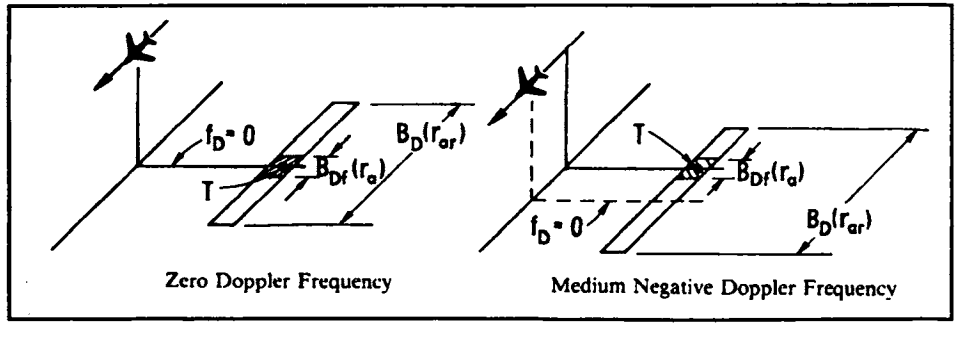


# DOPPLER BEAM-SHARPENING

- **DOPPLER BEAM-SHARPENING (RANGE-DOPPLER) APPROACH**
  - **SIGNAL RESPONSE FROM A PARTICULAR SCATTERER IS DISCRIMINATED BY IDENTIFYING ITS LOCATION IN RANGE-DOPPLER SPACE**
  - **RANGE: SLANT DISTANCE FORM SAR TO SCATTERER**
  - **DOPPLER: PHASE SHIFT ON SCATTERER'S RETURN SIGNAL DUE TO PLATFORM MOTION**

$$f_D(t) = \frac{-2u\,[x_R(t) - x_T]}{\lambda R}$$




From: F. T. Ulaby, et al., Microwave Remote Sensing: Active and Passive, Vol. II, © 1981-1986 Artech House, Inc., Norwood, MA.

# DOPPLER BEAM-SHARPENING (contd)

- **DOPPLER BANDWIDTH** $B_D = \frac{2V_p\beta_{az}}{\lambda} = \frac{2V_pK_{az}}{L}$

$\beta_{az}$ = along track or azimuth antenna beamwidth

- **USE NARROW BAND FILTERS TO TRACK DOPPLER SHIFT FROM TARGET**

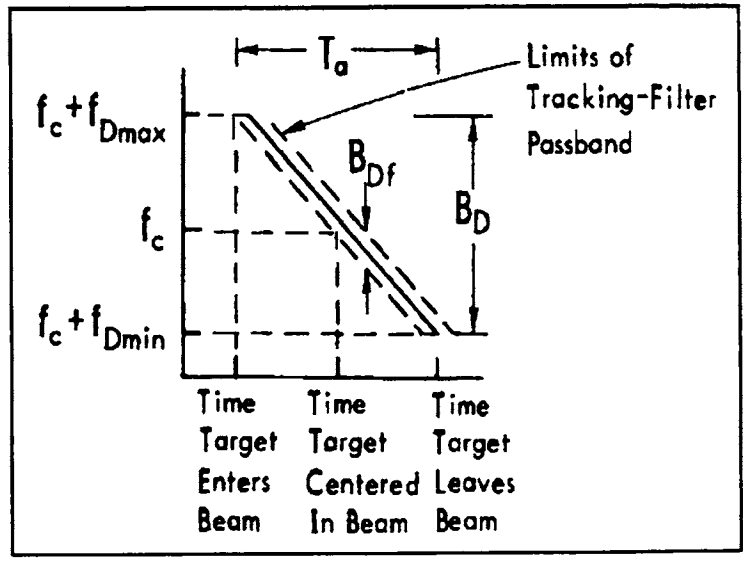
- **FILTER LIMITS RELATED TO ALONG - TRACK (AZIMUTH) RESOLUTION**

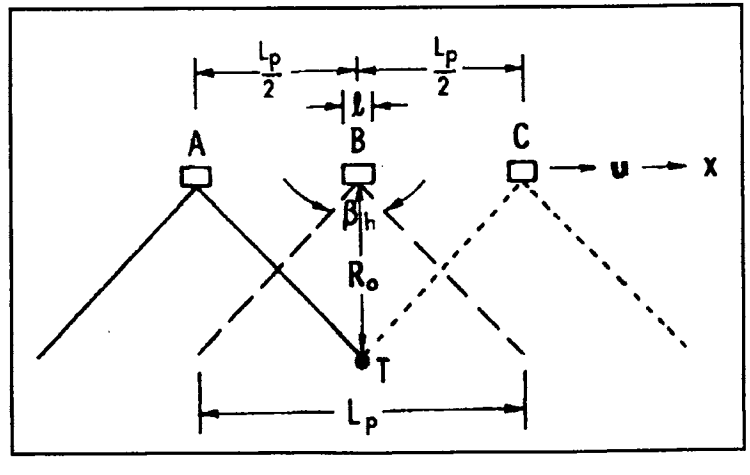
$$\Delta f_D = B_{Df} \Leftrightarrow \Delta\rho_{az}$$

$$\Delta f_D = \frac{2V_p}{\lambda R}\Delta\rho_{az}$$

$$\Delta\rho_{az} = \frac{\lambda R}{2V_p}\Delta f_D$$

- **DISCRIMINATION OF OTHER TARGETS IS ACCOMPLISHED USING FILTER BANDWIDTH AND CENTER FREQUENCY, WHICH TRACK A GIVEN POINT TARGET**




From: F. T. Ulaby, et al., Microwave Remote Sensing: Active and Passive, Vol. II, © 1981-1986 Artech House, Inc., Norwood, MA.

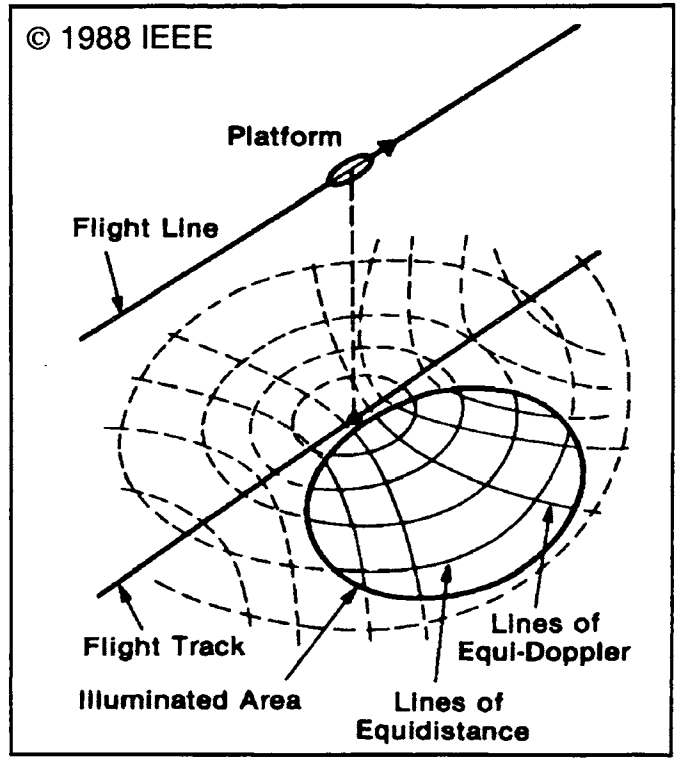
# SAR
## SPATIAL RESOLUTION

- **ISO-RANGE RETURNS**
  - ISOLATED BY ANALYSIS OF ECHOS FROM A SINGLE PULSE , WITH RESOLUTION DETERMINED BY THE TRANSMIT SIGNAL BANDWIDTH (CHIRP OR LINEAR FM TYPICAL)
  - LARGE BANDWIDTH
  - FAST ADC
  - PULSE MODULATION

$$\Delta\rho_r = \frac{c}{2B}$$

- **ISO-DOPPLER RETURNS**
  - ISOLATED BY ANALYSIS OF DOPPLER PHASE SHIFT OVER TIME DURING WHICH TARGET IS IN THE BEAM, I. E., OVER MANY PRF CYCLES
  - RESOLUTION DETERMINED BY SAMPLING AND DWELL TIME
  - LONG COHERENT DWELL
  - PRECISE MOTION KNOWLEDGE AND MODEL
  - COMPARE STRIP AND SPOT MODES

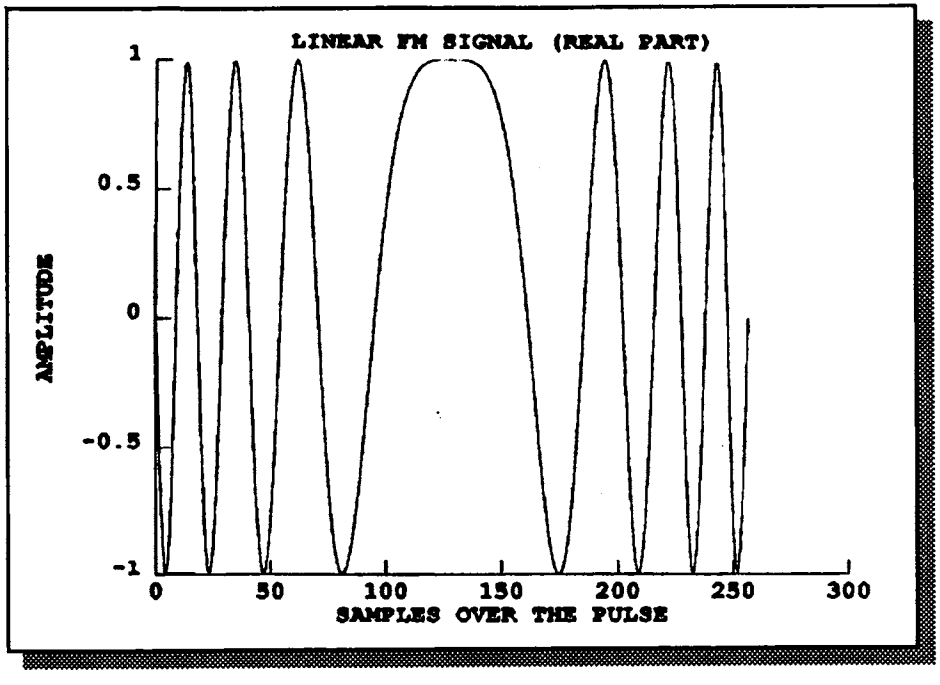
$$\Delta\rho_{az} = \frac{\lambda}{2\left(V_p/R\right)T_D}$$



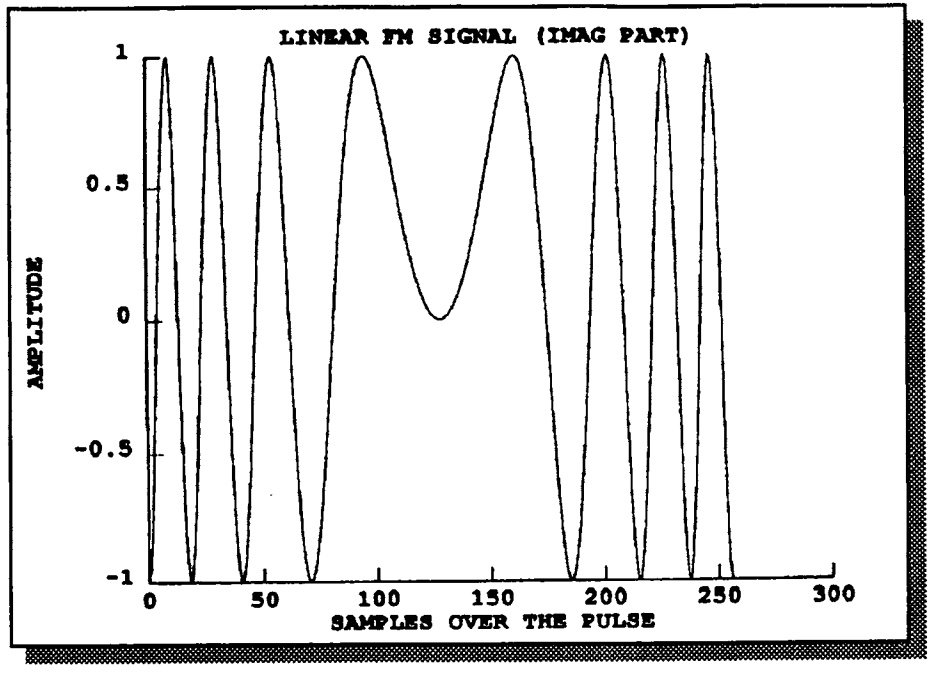

From: C. Elachi, Spaceborne Radar Remote Sensing: Applicatins and Techniques, IEEE, NY (1988).

# LINEAR FM SIGNAL

## REAL PART




## IMAGINARY PART




- **LINEAR FREQUENCY MODULATION (FM) OR "CHIRP"**
  - **TRANSMITTED SIGNAL**

$$V(t) = \begin{cases} \exp\left[j\left(\omega_0 t + \frac{\alpha t^2}{2}\right)\right], & 0 \le t \le \tau_p \\ 0, & \text{otherwise} \end{cases}$$

$\tau_p$ = pusle duration

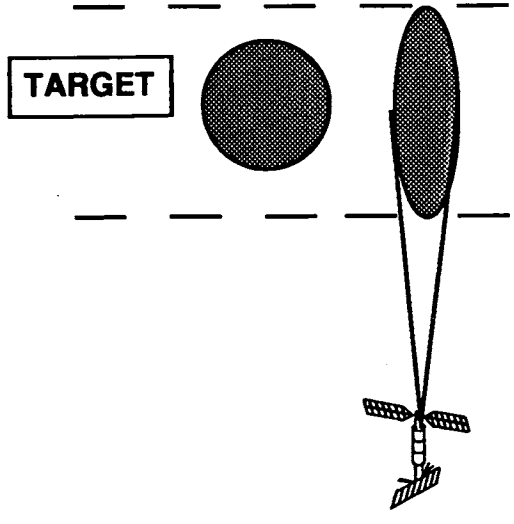
  - **FREQUENCY**

$$\omega(t) = \frac{\partial \phi}{\partial t} = \omega_0 + \alpha t$$

$\alpha$ = chirp rate

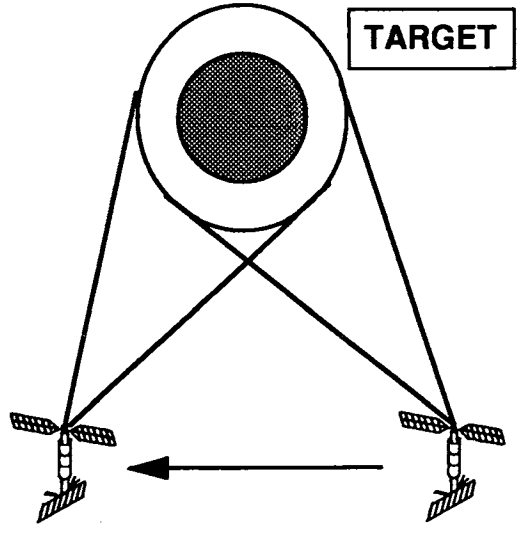
Figures courtesy of Dr. N. Marechal, The Aerospace Corp.

# COMPARISON OF SAR MODES




## STRIPMAP SAR

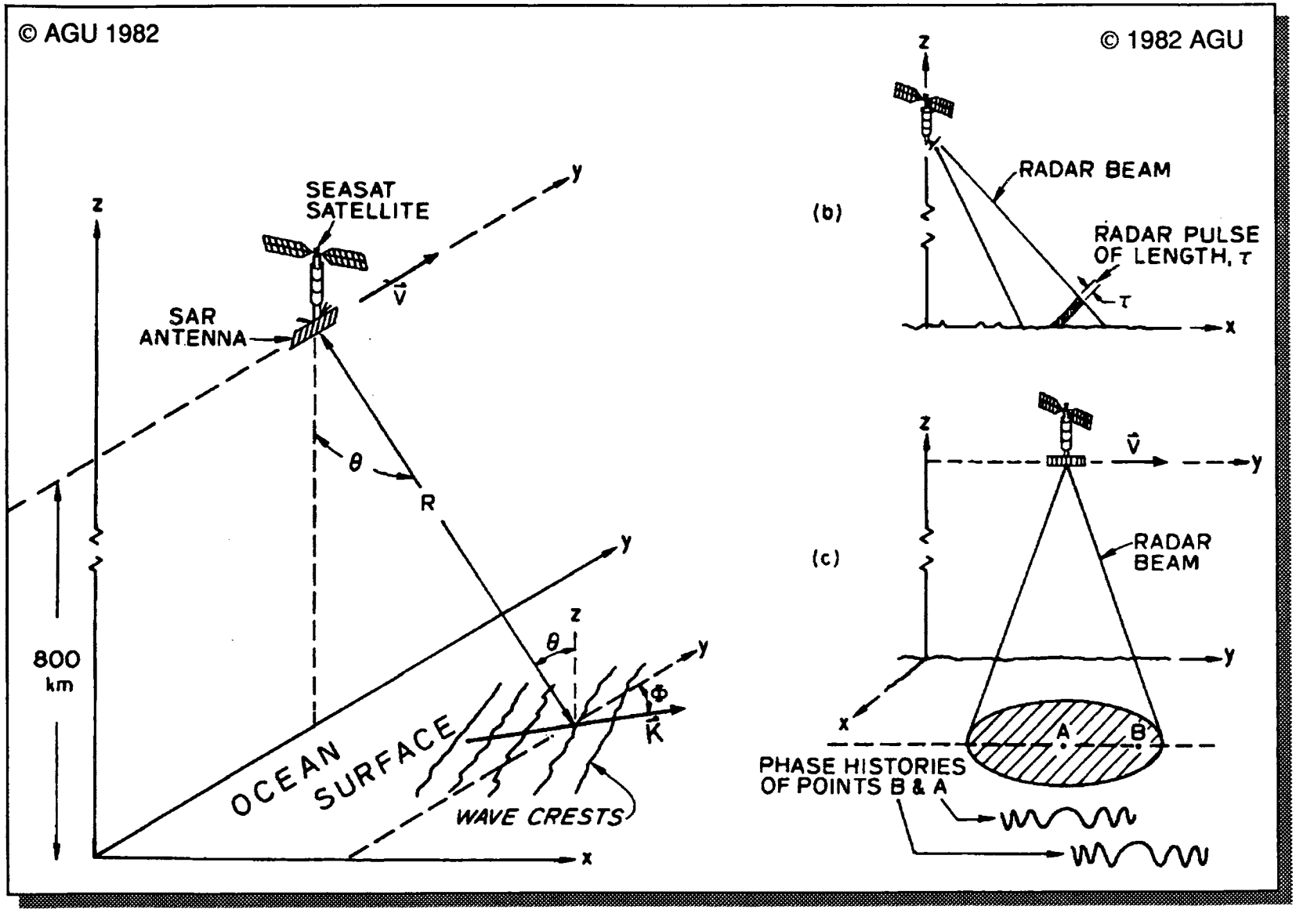
- FIXED BEAM (LOOK DIRECTION)
- SIDE LOOKING OR SQUINT
- MECHANICALLY SIMPLER
- LIMITED DOPPLER RESOLUTION
- WIDE SWATH COVERAGE POSSIBLE




## SPOTLIGHT SAR

- BEAM FOOTPRINT IS HELD FIXED ON TARGET
- BEAM STEERING REQUIREMENTS
- "UNLIMITED" DOPPLER RESOLUTION
- INCREASED DWELL TIME
- LIMITED AREA OR SWATH COVERAGE

# SPACEBORNE SAR
## TYPICAL VIEWING GEOMETRY




From: J. F. Vesecky and R. H. Stewart, JGR, **87(C5)**, 3397-3430 (1982).

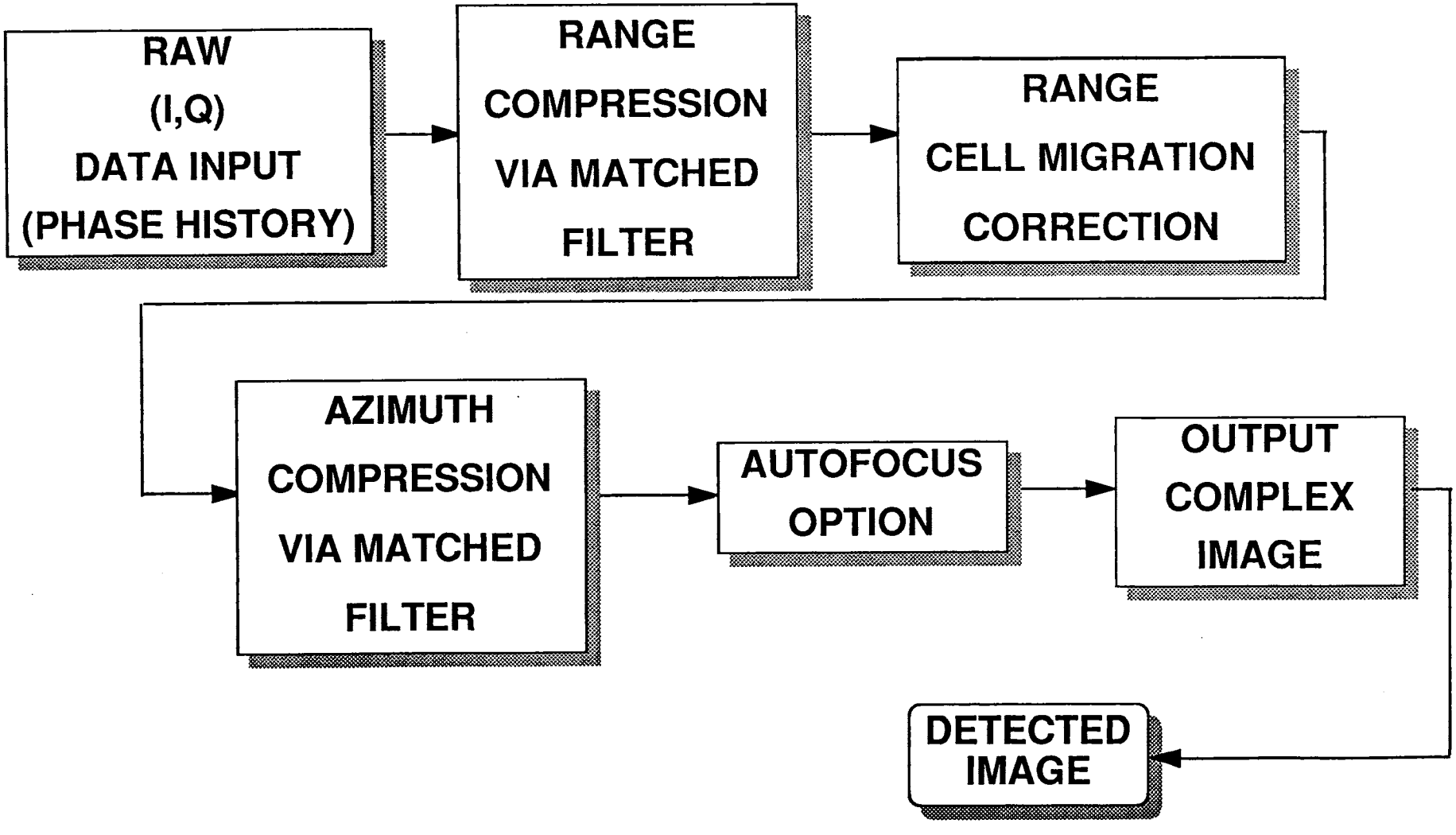
# GEOMETRY AND MOTION EFFECTS

- SLANT TO GROUND RANGE CONVERSION
- RELIEF DISPLACEMENT
  - FORESHORTENING
  - LAYOVER
- SHADOWING
- EARTH CURVATURE AND ROTATION
- MULTIPLE REFLECTIONS
- TARGET MOTION

# STRIPMAP SAR PROCESSING FUNDAMENTALS

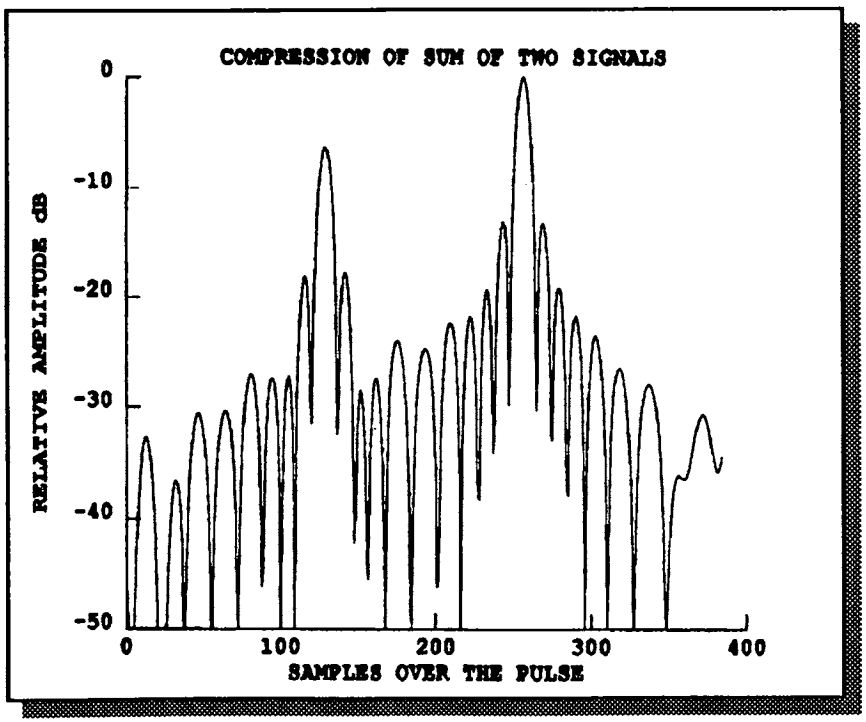
- RECEIVED SIGNAL INTERPRETATION
  - RANGE-DOPPLER MODEL
- MATCHED FILTER PROCESSING
  - RANGE AND AZIMUTH COMPRESSION
- RANGE CELL MIGRATION AND RANGE WALK

# GENERIC STRIPMAP PROCESSOR

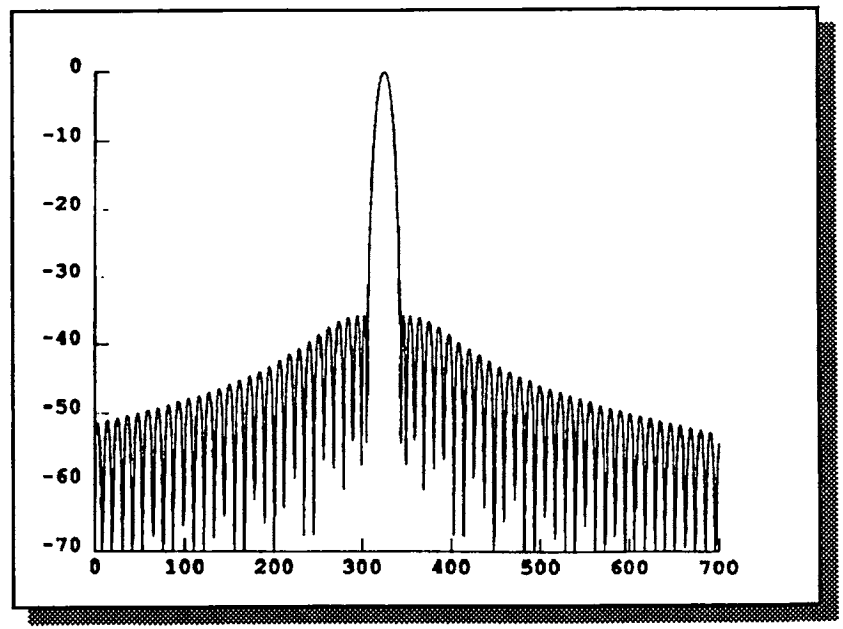


# COMPRESSED SIGNALS

## EXAMPLE OF COMPRESSED PULSES FROM TWO POINT TARGETS




## 35dB TAYLOR WEIGHTED IPR




Figures courtesy of Dr. N. Marechal, The Aerospace Corp.

# RANGE CELL MIGRATION

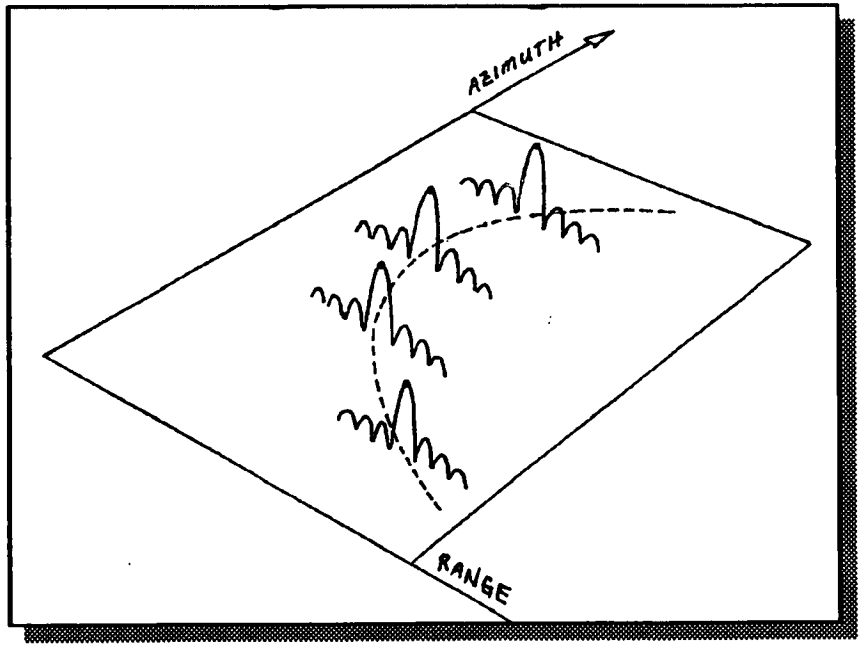
- Range compressed peak location varies with slow time t
  - RANGE WALK - LINEAR TERM
  - RANGE CURVATURE - QUADRATIC TERM

$$X(t) = C_0 + C_1 t + C_2 t^2$$

- RANGE CELL MIGRATION CORRECTION
  - USUALLY REQUIRED FOR SPACEBORNE SAR
  - STRAIGHTENS OUT CURVE
  - NOT DONE IF MIGRATION IS LESS THAN HALF OF A RESOLUTION CELL
- RANGE WALK CORRECTION
  - TRANSLATION AND INTERPOLATION OFTEN SUFFICIENT
  - FAST, ACCURATE METHOD AVAILABLE IN THE FOURIER DOMAIN

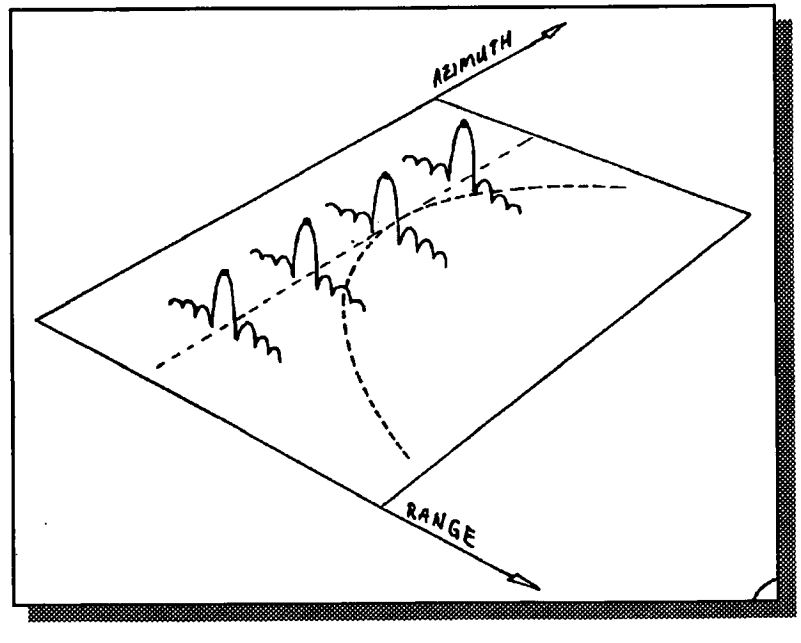
# RANGE CELL MIGRATION (contd)

## ILLUSTRATION OF RANGE CELL MIGRATION CORRECTION




**BEFORE**

**AFTER**




Figures courtesy of Dr. N. Marechal, The Aerospace Corp.

# SAR MISSIONS
# EXAMPLES

- **SPACEBORNE**
- **INTERNATION SPACEBORNE**
- **AIRCRAFT**

THE FOLLOWING TABLES ARE ADAPTED FROM: JoBea Way and E. A. Smith, The Evolution of Synthetic Aperture Radar Systems and their Progression to the EOS SAR, IEEE Trans. GSRS, **29(6)**, 962–985 (1991).

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# Spaceborne Missions

| | Seasat SAR | SIR-A | SIR-B | SIR-C/X-SAR | EOS SAR |
|---|---|---|---|---|---|
| *Imaging Characteristics* | | | | | |
| Band (wavelength, cm; frequency, GHz) | L (23.5, 1.275) | L (23.5, 1.278) | L (23.4, 1.282) | L (23.9, 1.25)<br>C (5.7, 5.3)<br>X (3.1, 9.6) | L (23.9, 1.25)<br>C (5.7, 5.3)<br>X (3.1, 9.6) |
| Polarization | HH | HH | HH | quad (L, C)<br>VV (X) | quad (L), HH,<br>VV (C, X) |
| Look (Incidence) Angle | 20° (23°) | 47° (50°) | 15° –60° (15°-64°) | (15° –55°) | (15° –45°) |
| Azimuth Resolution (m) | 25 | 40 | 25 | 25 | 20–250 |
| Range resolution (m) | 25 | 40 | 58-17 | 60-10 | 8–250 |
| Looks | 4 | 6 | 4 | 4 | 4 |
| Swath width (km) | 100 | 50 | 10-60 | 15-60 | 30-360 |
| Special Modes | | | squint,<br>spotlight | squint, spotlight,<br>SCANSAR | SCANSAR |
| *Instrument Characteristics* | | | | | |
| Antenna Type | corporate feed | corporate feed | corporate feed | phased array | phased array |
| Antenna Size (m x m) | 2.16 X 10.7 | 2.16 X 9.4 | 2.16 X 10.7 | (2.95 + 0.75 + 0.40)***<br>×12 | (1.9 + .49 + 26)***<br>×10.8 |
| DC Power (kW) | 1.2 | 1.0 | 1.2 | 3.9 (L-band)<br>2.4 (C-band) | 5.8 (peak)<br>1.5 (avg) |
| Bandwidth(s) (MHz) | 19 | 6 | 12 | 40, 20, 10 | 20, 10, 5 |
| Noise equivalent $\sigma^0$ *** | –24 | –32 | –28 | –48/ –36/ –28 | –36/ –27/ –22 |

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# Spaceborne Missions (contd )

| | Seasat SAR | SIR-A | SIR-B | SIR-C/X-SAR | EOS SAR |
|---|---|---|---|---|---|
| *Orbit Characteristics* | | | | | |
| Altitude (km) | 800 | 259 | 224*† | ~225 | 620 |
| Inclination | 108° | 38° | 57° | 57° | 98° |
| Sun Synchronous | no | no | no | no | yes |
| Equator Crossing Time | --- | --- | --- | --- | 1:30-4:00 p.m. |
| Daytime Node | variable | descending | descending | descending | ascending |
| Exact Repeat (days) | 17 (June 27-Aug 25)<br>3 (Aug 25-Oct 10) | --- | --- | --- | 16 |
| Approx. Repeat (days) | 3 (June 27-Aug 25) | 1 | 1 | 1 | 5 |
| *Mission Characteristics* | | | | | |
| Spacecraft | Seasat | Shuttle (Columbia, STS–2) | Shuttle (Challenger, 41-G) | Shuttle | Dedicated Satellite |
| Launch Date | June 27, 1978†** | November 12, 1981 | October 5, 1984 | 1993, 1994, 1996 | 1999 |
| Mission End | October 10, 1978 | November 14, 1981 | October 13, 1984 | --- | 2014 |
| Mission Duration | 100 days | 2.4 days | 8.3 days | 8.3 days each | 15 years |
| *Data Characteristics* | | | | | |
| Data Rate (Mbps) | 110 | --- | 30† | 240/recorder<br>45 through TDRS | 180 (peak)<br>15 (average) |
| Recording Options | digital | optical | optical, digital/TDRS | digital/TDRS | digital/TDRS |
| Onboard Recorder Capacity | --- | | 8 h 20 min/tapes, 7 tapes | 30 min/cassette<br>~ 100 cassettes | TBD |

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# Spaceborne Missions (contd )

| | Seasat SAR | SIR-A | SIR-B | SIR-C/X-SAR | EOS SAR |
|---|---|---|---|---|---|
| Operation Time | 42 h | 8 h | 7 h (digital)<br>8 h (optical) | 60 h | 25% duty cycle |
| Coverage (million sq. mi.) | 100 | 10 | 15 | TBD | global/5 days |
| *Processing* | optical/digital | optical | optical/digital | digital | digital |
| Type | JPL | JPL | JPL | JPL,DLR | EOS DAACs |
| Location | | | | | |
| *Other Sensors* | Microwave Radiometer, Scatterometer, Radar Altimeter, V/IR Radiometer | MAPS, FILE, SMIRR, others | ERBE satellite, MAPS, FILE | MAPS | EOS |

***L-, C- and X-bands at 50° for SIR-C/X-SAR and 40° for EOS SAR.

*†initially at 354 km for first 22 orbits, 257 km for next 11 orbits and finally 224 km for remainder of mission

†45 Mbps direct downlink through TDRS also possible but TDRS link failed

†**at 01:12:44 GMT, Day 178

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# International Spaceborne Missions

| | Almaz-1 | ERS-1 | JERS-1 | RADARSAT |
|---|---|---|---|---|
| *Imaging Characteristics* | | | | |
| Band (wavelength (cm), frequency (GHz)) | S (10, 3.0) | C (5.7, 5.25) | L (23.5, 1.275) | C (5.7, 5.3) |
| Polarization | HH | VV | HH | HH |
| Look (Incidence) Angle | 30°-60° | 20° (23°) | 35° (38°) | (20°-59°) |
| Swath (km) | 20-45 | 100 | 75 | 45-500 |
| Range Resolution (m) | 15-30 | 20 | 18 | 10-100 |
| Azimuth Resolution (m) | 15 | 30 | 18 | 10-100 |
| Looks | | 4 | 3 | 1-16 |
| Right/Left Looking | both | right | right** | right*** |
| *Instrument Characteristics* | | | | |
| Antenna Type | waveguide | corporate feed | corporate feed | phased array |
| Antenna Size (mxm) | 15 × 1.5 (two) | 10 × 1 | 11.9 × 2.4 | 15 × 1.5 |
| DC Power (W) | | 1245 | 675 (1100 peak) | 300 (5000 peak) |
| Bandwidth (MHz) | | 15.5 | 15 | 30, 17.3, 11.6 |
| Noise Equivalent $\sigma^0$ | | −18 | −20.5 | −23 |
| *Orbit Characteristics* | | | | |
| Altitude (km) | 300 | 785, 782 | 568 | 793 – 821 |
| Inclination | 73° | 98.5° | 97.7° | 98.6° |
| Sun Synchronous | no | yes | yes | yes |
| Equator Crossing Time | --- | 10:30 a.m. | 10:30-11:00 a.m. | 6:00 p.m. |
| Daytime Node | --- | descending | descending | terminator |
| Exact Repeat Cycle (days) | | 3, 35, 176 | 44 | 24 |
| Approximate Repeat Cycle | | | | |

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# International Spaceborne Missions (contd)

| | Almaz-1 | ERS-1 | JERS-1 | RADARSAT |
|---|---|---|---|---|
| *Mission* | | | | |
| Spacecraft | Almaz-1 | ERS-1 | JERS-1 | RADARSAT |
| Launch Date | March 31, 1991 | July 16, 1991 | February, 1992 | December, 1994 |
| Mission Duration | 2 years | 2-3 years | 2 years | 5 years |
| *Data Characteristics* | | | | |
| Downlink Data Rate (Mbps) | | 105 | 30 (2 channels) | 74-105 |
| Downlink | recorder/ ground station | ground station | recorder/ ground station | two recorders/ ground station |
| Recorder Rate (Mbps) | | --- | 32 × 2 channels | 85 |
| Recorder Capacity (min) | 2 | --- | 20 | 10 |
| Operation Time/Orbit | | 10 min | 20 min | 28 min |
| *Processing* | | | | |
| Type | digital | digital | digital | digital |
| Location | USSR | ASF, Canada, Europe, etc. | ASF, Canada, Europe, Japan, etc. | ASF, Canada, Europe, etc. |
| *Other Sensors* | Radiometric Scanner (RMS) | Radar Altimeter, Wind/Wave Scatterometer, Along Track Scanning Radiometer | Optical Sensor (OPS) | None |

** yaw 180° to map Antarctica

*** two 2-week periods with SAR left looking are planned

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# Aircraft SARs

| | NASA/JPL | P-3 SAR | CCRS C/X-SAR | DLR SAR |
|---|---|---|---|---|
| *Imaging Characteristics* | | | | |
| Band (wavelength, cm; frequency, GHz) | L (23.9, 1.25)<br>C (5.6, 5.3)<br>P (67, 0.438) | L (23.9, 1.25)<br>C (5.7, 5.3)<br>X (3.2, 9.34) | C (5.66, 5.30)<br>X (3.24, 9.25) | L,C,X |
| Polarization | quad | quad | quad | HH,VV |
| Look Angle (deg) | 20 – 60° | 11 – 79° | 0 – 74°, 45 – 76°, 45 – 85°* | |
| Azimuth Resolution (m) | 2 | 2.2 | 6, 6, 10* | 3 |
| Range Resolution (m) | 7.5 (slant range) | 8.4 | 6, 6, 20* | 3 |
| Looks | 4 | 4 | 7 | 8 |
| Swath (km) | 7 – 13 | 6 – 48 | 22, 18, 63* | 3 |
| *Instrument Characteristics* | | | | |
| Peak Power (kW) | 1 | | 3.4 (C), 3.8 (X) | |
| Bandwidths (MHz) | 20,40 | | 25, 8 (C); 31, 7.5 (X) | |
| Antenna Width x Length (cm) | 91.4 x 182.9 (P)<br>45.7 x 161.3 (L)<br>16.5 x 135.9 (C) | | | |
| *Aircraft Characteristics* | | | | |
| Altitude (km) | 8 | 3 – 8 | 5 – 6 | |
| Flight Duration | 8 – 11 h | 8 – 12 h | 5 h | |
| Aircraft | NASA DC-8 | NADC P-3 | Convair-580 | DO 228 |
| Operational Date | 1988 | 1988 | 1978 | 1989 |

# Aircraft SARs (contd)

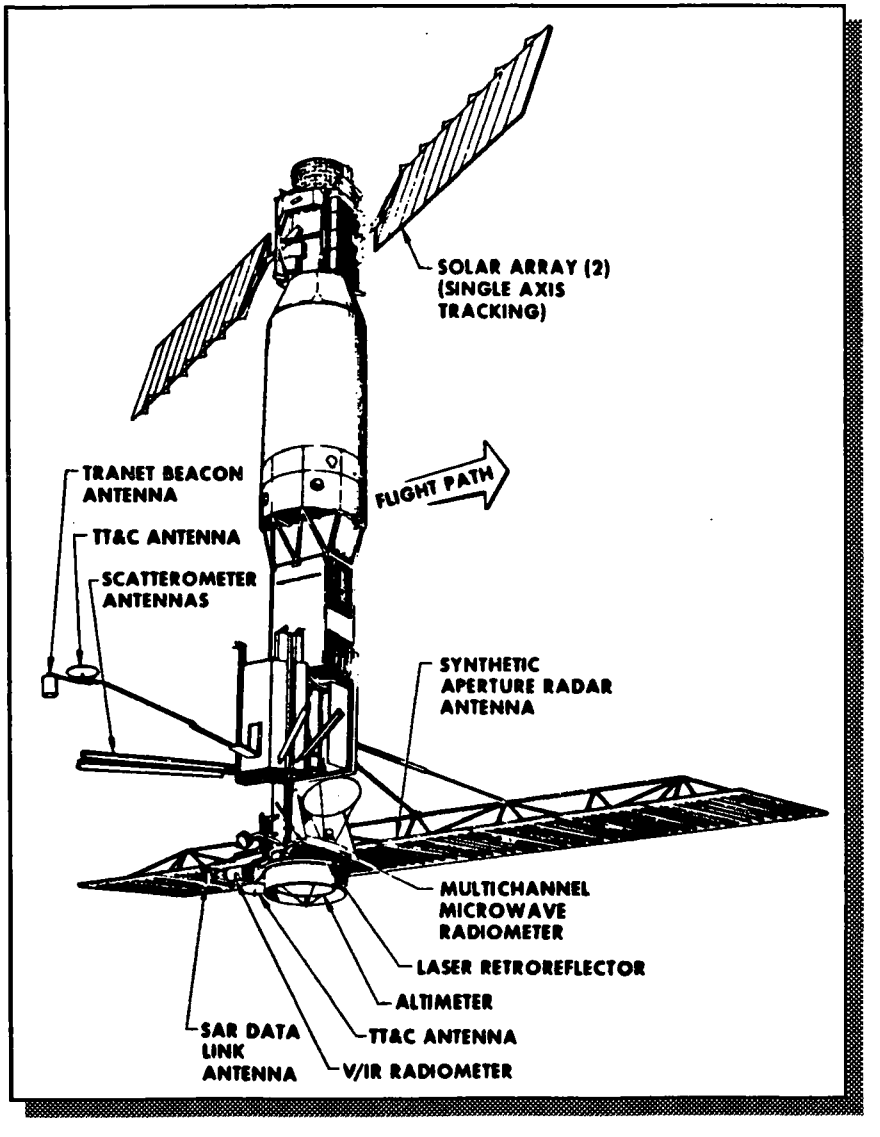
| | NASA/JPL | P-3 SAR | CCRS C/X-SAR | DLR SAR |
|---|---|---|---|---|
| *Data Characteristics* | | | | |
| Simultaneous Channels** | 12 | 4 | 1 (2 if half swath) | 1 |
| Recorder Capacity/HDDT (min) | 15 | 20 | | |
| *Processing* | | | | |
| Type | digital | digital | digital | digital |
| Location | JPL | ERIM | CCRS | DLR |
| Real Time | yes (image, strip) | yes (strip) | yes (2 strip/X and C) | yes |

*nadir mode, narrow swath mode, wide swath mode.

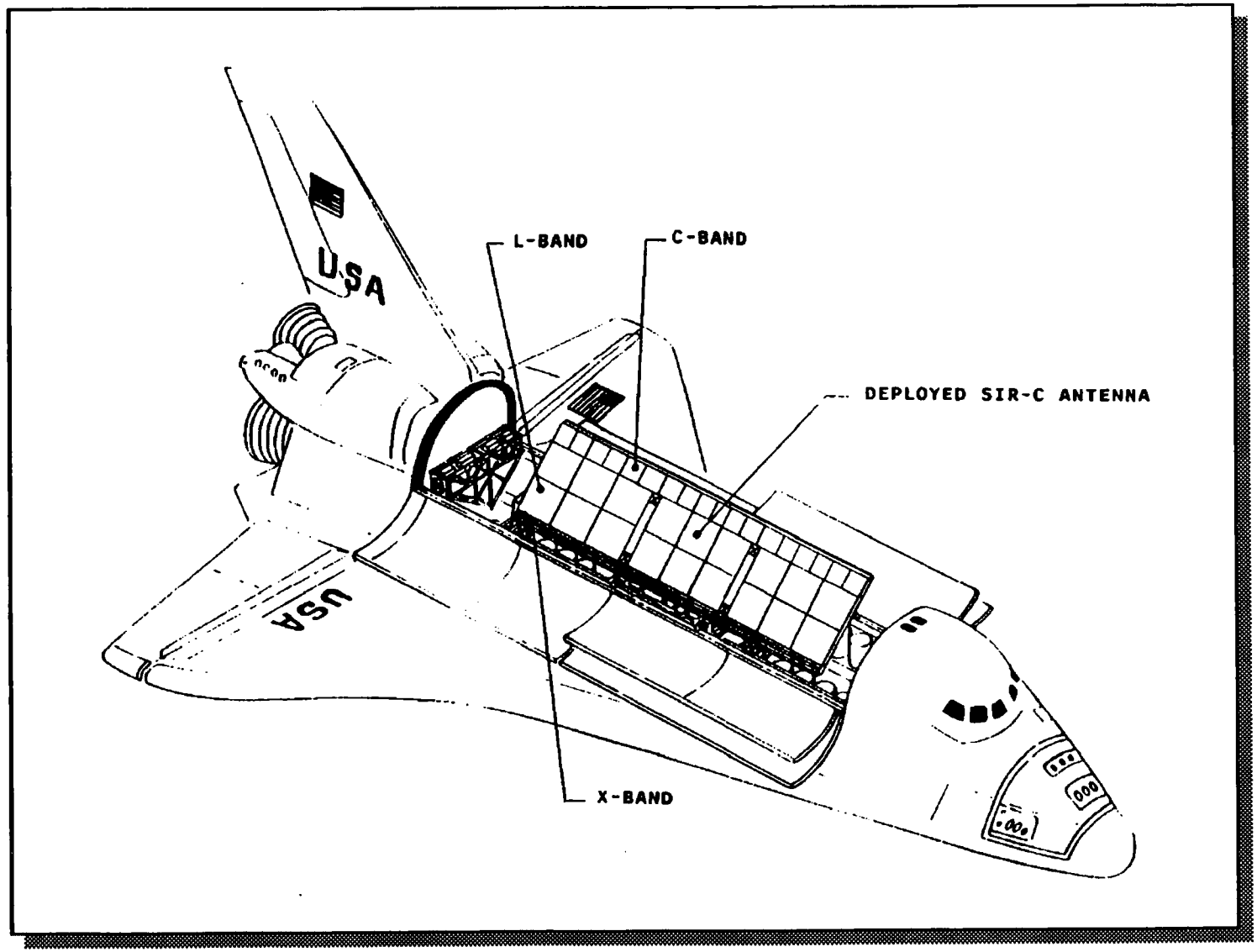
**one channel = single frequency, single polarization.

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# SEASAT


SOLAR ARRAY (2)
(SINGLE AXIS
TRACKING)
FLIGHT PATH
TRANET BEACON
ANTENNA
TT&C ANTENNA
SCATTEROMETER
ANTENNAS
SYNTHETIC
APERTURE RADAR
ANTENNA
MULTICHANNEL
MICROWAVE
RADIOMETER
LASER RETROREFLECTOR
ALTIMETER
TT&C ANTENNA
V/IR RADIOMETER
SAR DATA
LINK
ANTENNA

# SHUTTLE IMAGING RADAR-C
## SIR-C



# CHARACTERIZATION AND EXPLOITATION OF RADAR IMAGERY

- IMAGE CHARACTERIZATION
  - WHY
    - * DETECT PRESENCE OF FEATURES OR OBJECTS IN THE IMAGE WITH THE GOAL OF CLASSIFYING OR IDENTIFYING OBJECTS
    - * INTERPRET THE PHYSICAL PROPERTIES OF OBJECTS OR TERRAIN
  - HOW
    - * CHARACTERIZATION INVOLVES THE DESCRIPTION OF HOW VARIOUS OBJECTS WILL APPEAR IN THE RADAR IMAGE, E. G., POINT TARGETS, DISTRIBUTED TARGETS AND CLUTTER
    - * USE AN END-TO-END MODEL FOR AN IMAGING RADAR SYSTEM TO RELATE THE TARGET/SCENE SPACE TO THE IMAGE SPACE
- DATA COLLECTION ISSUES
- IMAGE CHARACTERIZATION
- IMAGE EXPLOITATION AND INTERPRETATION

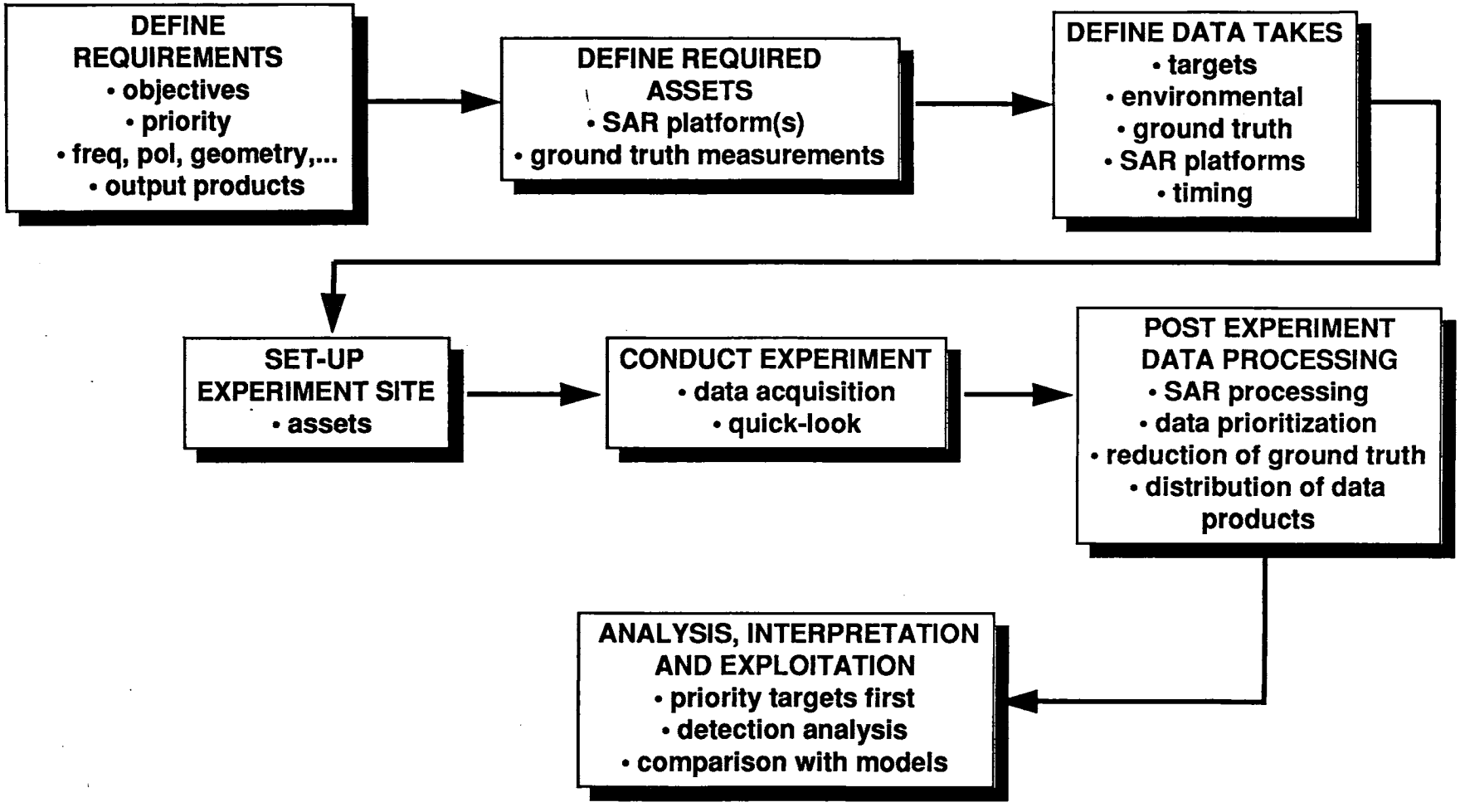
# DATA COLLECTION ISSUES

- **DATA RATE ISSUES**
  - DATA RATE

$$DR = 2BN \times PRF \times \left[\tau + \frac{2S_w}{c}\sin(\theta)\right]$$

    - B = BANDWIDTH
    - N = NO. BITS/SAMPLE
    - PRF = PULSE REPETITION RATE
    - Sw = SWATH WIDTH
    - $\tau$ = PULSE WIDTH
    - $\theta$ = INCIDENCE ANGLE
  - DATA STORAGE
  - DATA DISSEMINATION
- **FLOW DIAGRAM FOR SAR EXPERIMENT PLANNING AND ANALYSIS**

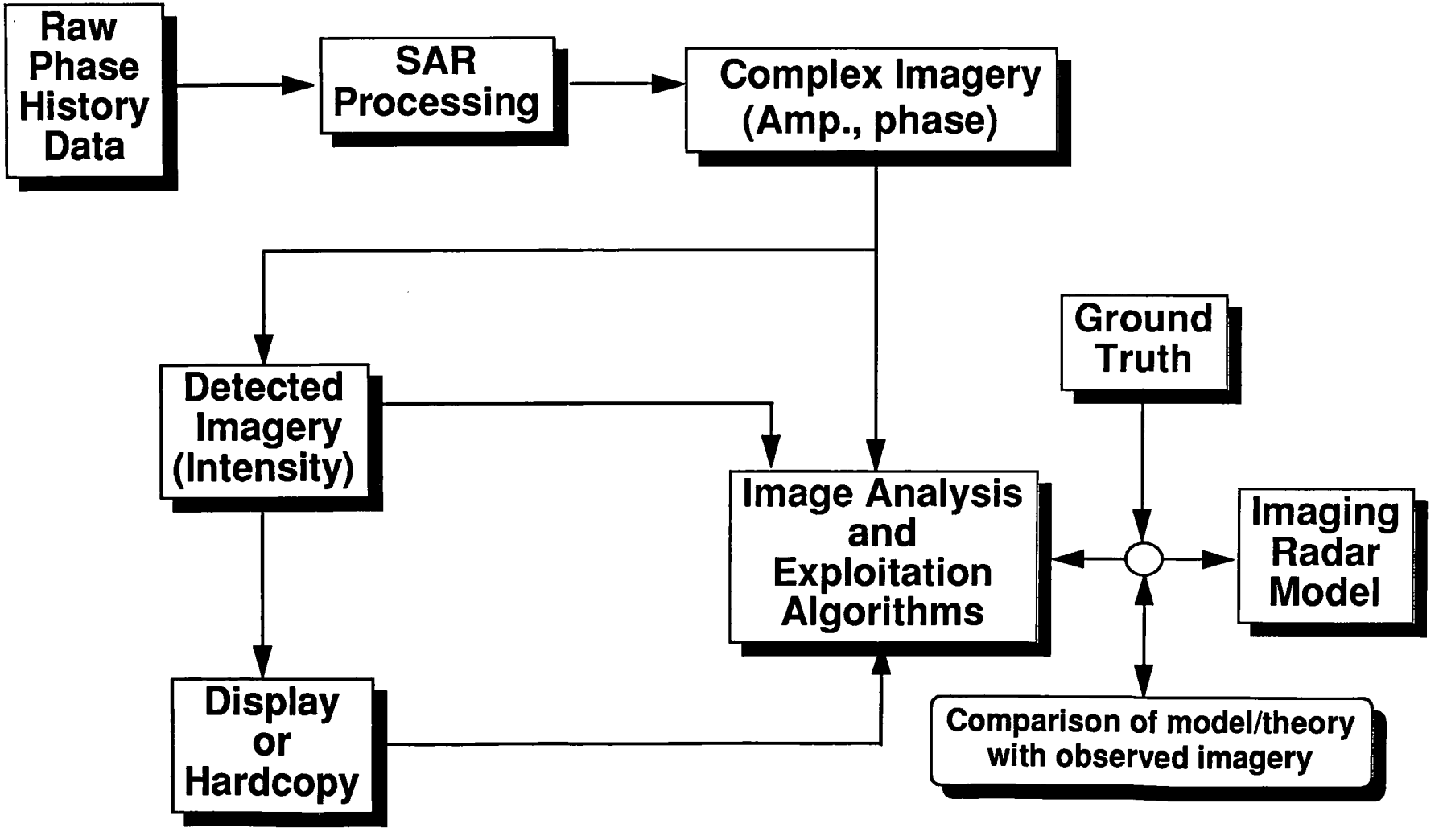
# SAR DATA COLLECTION AND EXPLOITATION



# IMAGE CHARACTERIZATION

- UNIQUE PROPERTIES OF SAR IMAGERY
  - COMPARISON WITH EO AND IR IMAGERY
  - SENSITIVITY TO SURFACE ROUGHNESS
  - COHERENCE PROPERTIES
  - DYNAMIC RANGE
  - VOLUME SCATTERING EFFECTS
- USE OF END-TO-END RADAR IMAGING MODEL

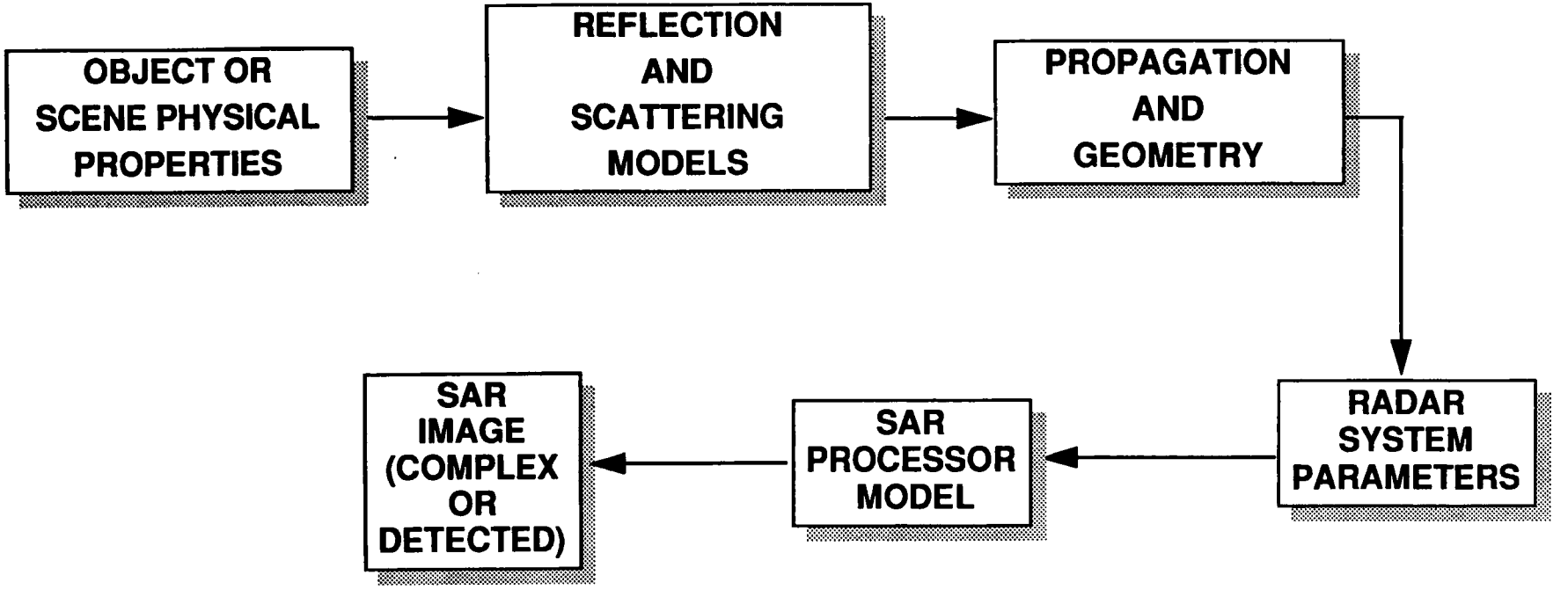
# SAR IMAGE CHARACTERIZATION



# IMAGING RADAR MODEL

- LINEAR MODEL WHICH RELATES OBJECT/SCENE PROPERTIES TO IMAGE PROPERTIES
- INCLUDES
  - RCS OF TARGETS AND CLUTTER
  - SCATTERING COEFFICIENTS OF EXTENDED TARGETS AND CLUTTER
  - VIEWING GEOMETRY
  - PLATFORM MOTION EFFECTS (EARTH ROTATION)
  - PROPAGATION EFFECTS
  - RADAR SYSTEM PARAMETERS
  - IMAGE GENERATION PROCESS
- APPLICATIONS
  - UNDERSTANDING OF THE RELATIONSHIP OF VARIOUS PARAMETERS TO IMAGE CHARACTERISTICS OF TARGETS AND BACKGROUND
  - TRADE STUDIES AND SYSTEM DESIGN
  - AID IN THE INTERPRETATION OF RADAR IMAGERY
  - RELATE PHYSICAL PROPERTIES OF SCATTERERS TO OBSERVED RADAR IMAGERY

# IMAGING RADAR SYSTEM MODEL



# IDEALIZED IMAGING RADAR SYSTEM MODEL

$$S(x_i, y_j) = \left| \int dy \int g(x_i - x, y_j - y)\, r(x,y)\, dx \right|^2$$

$g(x,y)$ = complex, 2D radar impulse response function

$r(x,y) = \sqrt{\sigma(x,y)}\exp(i\phi)$ = complex terrain/object reflectivity

$$g(\vec{x}) = \int_{-\frac{\vec{k}_B}{2}}^{\frac{\vec{k}_B}{2}} W(\vec{k}) \exp[i\phi_\varepsilon(\vec{k})] \exp(i2\pi\vec{k}\cdot\vec{x})\, d\vec{k}$$

$g(\vec{x})$ = complex impulse response

$\vec{x}$ = image spatial coordinates

$\vec{k}$ = spatial frequency

$\vec{k}_B$ = signal bandwidth

$W(\vec{k})$ = aperture weighting function

$\phi_\varepsilon(\vec{k})$ = residual phase error

**35dB TAYLOR WEIGHTED IPR**

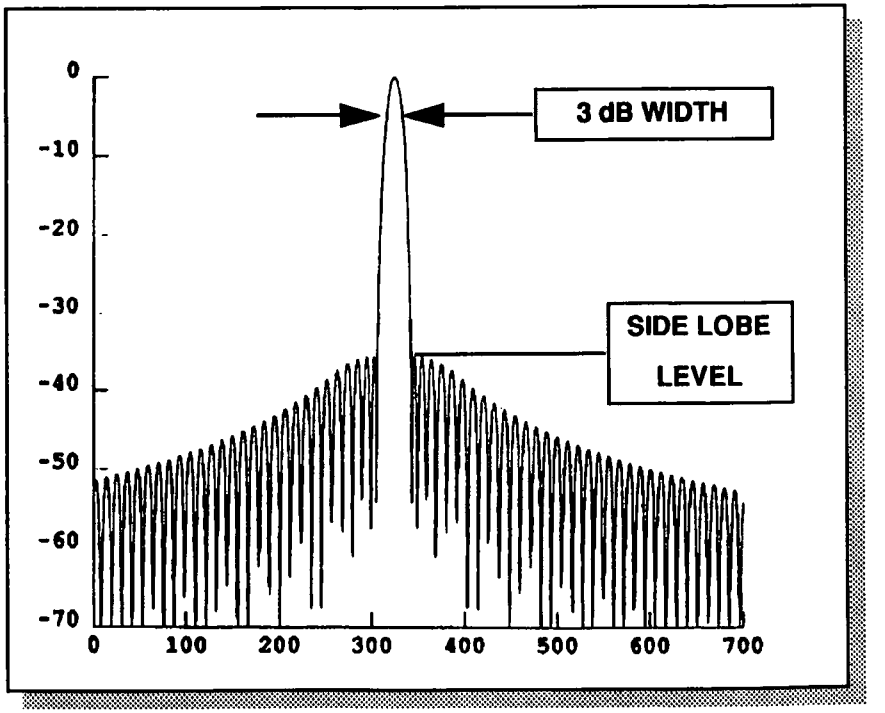



Figure courtesy of Dr. N. Marechal, The Aerospace Corp.

# IMAGE QUALITY PARAMETERS

- IMPULSE RESPONSE FUNCTION (IPR)
  - MAIN LOBE WIDTH AND SIDE LOBE LEVELS (NEAR AND FAR)
  - PEAK INTENSITY RELATIVE TO NEAR SIDE LOBE LEVEL
- SYSTEM AND ADDITIVE NOISE RATIO
- MULTIPLICATIVE NOISE RATIO (MNR)
  - SIGNAL DEPENDENT ENERGY WHICH ADDS TO THE RETURN FROM A RESOLUTION CELL DUE TO SCATTERING FROM OTHER RESOLUTION CELLS
- SIGNAL - TO - NOISE RATIO (SNR)
  - $\text{SNR} = \dfrac{\text{PEAK IMAGE INTENSITY FROM } 1\text{M}^2 \text{ POINT SCATTERER}}{\text{EQUIVALENT NOISE BACKSCATTER COEFFICIENT (IPR AREA)}}$
- SIGNAL - TO - BACKGROUND RATIO (SBR)
  - $\text{SBR} = \dfrac{\text{PEAK IMAGE INTENSITY FROM } 1\text{M}^2 \text{ POINT SCATTERER}}{\text{TOTAL SYSTEM BACKGROUND}}$

TOTAL SYSTEM BACKGROUND IS THE SUM OF THE EQUIVALENT NOISE BACKSCATTER COEFFICIENT AND LOCAL TERRAIN BACKSCATTER COEFFICIENT TIMES THE IPR AREA

# IMAGE QUALITY PARAMETERS (contd)

- **TERRAIN - TO - NOISE RATIO (TNR)**

$$TNR = \frac{\sigma^0}{\sigma_N + MNR \times \langle\sigma\rangle}$$

$\sigma^0$ = LOCAL TERRAIN BACKSCATTER COEFFICIENT

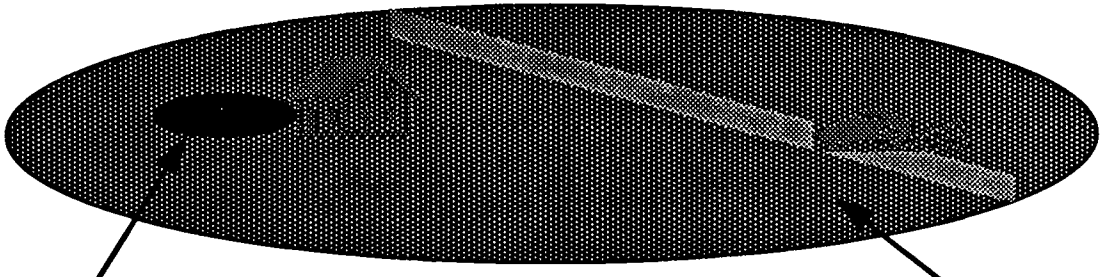
$\sigma_N$ = EFFECTIVE BACKSCATTER COEFFICIENT OF ADDITIVE NOISE

$\langle\sigma\rangle$ = AVERAGE TERRAIN BACKSCATTER COEFFICIENT

- **CONTRAST RATIO (CR)**
  - INCLUDES EFFECTS OF BOTH CLUTTER AND TOTAL NOISE
- **DYNAMIC RANGE**
  - RATIO OF LARGEST RCS FOR WHICH THE IPR AND THE IPR ENVELOPE QUALITY LEVEL HOLD, TO THE RCS EQUIVALENT TO SYSTEM NOISE AT THE SAME RANGE
  - CAN BE GREATER THAN 50 dB FOR SAR

# CONTRAST RATIO

- TWO PARAMETER CONTRAST MODEL USED TO ILLUSTRATE CONCEPT
- CONTRAST = (CLUTTER PLUS TOTAL NOISE)/(TOTAL NOISE)



$\sigma_N + MNR \times \langle\sigma^0\rangle$

$\sigma_N + \sigma^0$

$$CR = \frac{\sigma^0 + MNR \times \langle\sigma^0\rangle + \sigma_N}{MNR \times \langle\sigma^0\rangle + \sigma_N}$$

# SYSTEM NOISE

- DETERMINES SYSTEM SENSITIVITY
  - DISTINGUISH TERRAIN TYPES
  - DETECT POINT TARGETS
- ADDITIVE NOISE
  - RECEIVER THERMAL NOISE(kT)
  - PROCESSOR
  - TRANSMITTER NOISE LEAKAGE
  - PROBLEMS DISTINGUISHING TERRAIN WITH SMALL DIFFERENCE IN SCATTERING COEFFICIENTS
  - DETECTION OF WEAK POINT TARGETS IN LOW RADAR BACKSCATTERING SCENE
- MULTIPLICATIVE NOISE
  - INTEGRATED SIDELOBES
  - AMBIGUITIES

# STATISTICAL CHARACTERIZATION OF RADAR IMAGERY

- SPECKLE
  - PIXEL-TO-PIXEL VARIATION OF IMAGE INTENSITY
  - FADING STATISTICS
- TEXTURE
  - SPATIAL STATISTICS OF INTENSITY VARIATION IN SAR IMAGERY

# RADAR IMAGE EXPLOITATION AND INTERPRETATION

- **IMAGE ARTIFACTS**
  - HARMONICS
  - INTERMODULATION PRODUCTS
  - AMBIGUOUS RESPONSES
- **CHARACTERIZATION KEYS**
  - TONE/INTENSITY
  - TEXTURE
  - SPATIAL PATTERNS
  - SIZE
  - SHAPE
  - SHADOWS
  - CONTEXT
    - * *A PRIORI* INFORMATION ABOUT THE SCENE
    - * KNOWLEDGE OF OTHER OBJECTS IN THE SCENE FROM OTHER SOURCES OR SENSORS

# RADAR IMAGE EXPLOITATION AND INTERPRETATION (contd)

- TECHNIQUES FOR RADAR IMAGE ANALYSIS
  - IMAGE ENHANCEMENT
    - SPECKLE AND NOISE REDUCTION
    - SMOOTHING
  - FEATURE EXTRACTION
    - EDGE DETECTION
    - LINEAR FEATURE DETECTION
  - REGION SEGMENTATION AND CLASSIFICATION
    - TEXTURE OPERATORS
    - BOUNDARY EXTRACTION
    - NEURAL NETWORK CLASSIFIERS
  - REGISTRATION
    - MAPS, DIGITAL ELEVATION MODELS (DEM)
    - FUSION WITH OTHER SENSOR DATA (E.G., EO OR IR IMAGERY)
  - CALIBRATION
    - * POINT TARGETS AND DISTRIBUTED TERRAIN
    - * INTENSITY REMAPPING
      - LINEAR - LINEAR
      - LOG - LINEAR

# RADAR IMAGE EXPLOITATION AND INTERPRETATION (contd)

- IMAGE ANALYSIS TECHNIQUES (contd)
  - STEREO
    - * REQUIRES 2 RADAR IMAGES OF THE SAME SCENE FROM DIFFERENT LOOK ANGLES
    - * ELEVATION DETERMINATION
  - RADAR - CLINOMETRY
    - * RELATIONSHIP BETWEEN LOCAL SHADING AND LOCAL SLOPE USED TO OBTAIN TERRAIN SHAPE
  - POLARIMETRY
  - IMAGE MOSAICKING

# 3.7 RADAR POLARIMETRY

- REPRESENTATION OF POLARIZATION
  - STOKES VECTORS AND MUELLER MATRICES
  - SCATTERING MATRIX
- POLARIZATION SYNTHESIS
- POLARIZATION AND TARGET SCATTERING
  - POLARIZATION SIGNATURES
- POLARIMETRIC RADARS

# REPRESENTATION OF POLARIZATION

- CONVENTIONAL RADARS TRANSMIT AND RECEIVE ON ONLY A SINGLE POLARIZATION COMBINATION
  - EITHER: HH, VV, HV OR VH
  - RESULT OF A FIXED POLARIZATION ANTENNA FOR RECEIVE AND TRANSMIT
- SCATTERED EM FIELD IS A VECTOR QUANTITY WHICH CARRIES POLARIZATION INFORMATION
  - SINGLE POLARIZATION MEASUREMENT IS AN INCOMPLETE CHARACTERIZATION OF SCATTERED WAVE
  - FULL POLARIZATION CHARACTERIZATION REQUIRES COMPLETE VECTOR MEASUREMENT OF SCATTERED RADIATION
- POLARIMETER
  - DEVICE USED TO MEASURE THE STATE OF POLARIZATION OF AN EM WAVE
  - MEASURE COMPLETE AMPLITUDE AND RELATIVE PHASE OF ALL POLARIZATIONS FOR TRANSMIT AND RECEIVE

# REPRESENTATION OF POLARIZATION (contd)

- **FUNDAMENTAL MEASUREMENT MADE BY A RADAR POLARIMETER IS THE COMPLEX SCATTERING MATRIX**

$$[\mathbf{S}] = \begin{pmatrix} S_{h'h} & S_{h'v} \\ S_{v'h} & S_{v'v} \end{pmatrix}$$

$S_{rt}$ = complex scattering matrix element (amplitude and phase) for the receive(r) and transmit(t) polarizations

- **GENERAL BISTATIC SCATTERING GEOMETRY AND COORDINATES**
  - **COORDINATES USED TO DESCRIBE TRANSVERSE E-FIELD COMPONENTS**
  - **3 CARTESIAN COORDINATE SYSTEMS**
    - ***GLOBAL SYSTEM** $(\hat{x},\hat{y},\hat{z})$
    - *** LOCAL TRANSMITTING ANTENNA SYSTEM** $(\hat{h},\hat{v},\hat{n})$
    - *** LOCAL RECEIVING ANTENNA SYSTEM** $(\hat{h}',\hat{v}',\hat{n}')$

$$\hat{h} = \sin(\phi_i)\,\hat{x} - \cos(\phi_i)\,\hat{y}$$

$$\hat{v} = -\cos(\phi_i)\cos(\theta_i)\,\hat{x} - \sin(\phi_i)\cos(\theta_i)\,\hat{y} + \sin(\theta_i)\,\hat{z}$$

$$\hat{n} = -\cos(\phi_i)\sin(\theta_i)\,\hat{x} - \sin(\phi_i)\sin(\theta_i)\,\hat{y} - \cos(\theta_i)\,\hat{z}$$

$$\left[\text{for } i \to s,\ \hat{h} \to \hat{h}',\ \text{etc}\right]$$

# REPRESENTATION OF POLARIZATION (contd)

- FOR THE BACKSCATTERING CASE (MONOSTATIC) PRIMED AND UNPRIMED LOCAL SYSTEMS COINCIDE
- RELATE SCATTERED FIELD TO ILLUMINATING FIELD IN THIS COORDINATE SYSTEM

$$\begin{pmatrix} E_{h'} \\ E_{v'} \end{pmatrix}^{sc} = \frac{e^{ikr}}{kr} \begin{pmatrix} S_{h'h} & S_{h'v} \\ S_{v'h} & S_{v'v} \end{pmatrix} \begin{pmatrix} E_h \\ E_v \end{pmatrix}^{ill}$$

"ill" = incident field components on scatterer

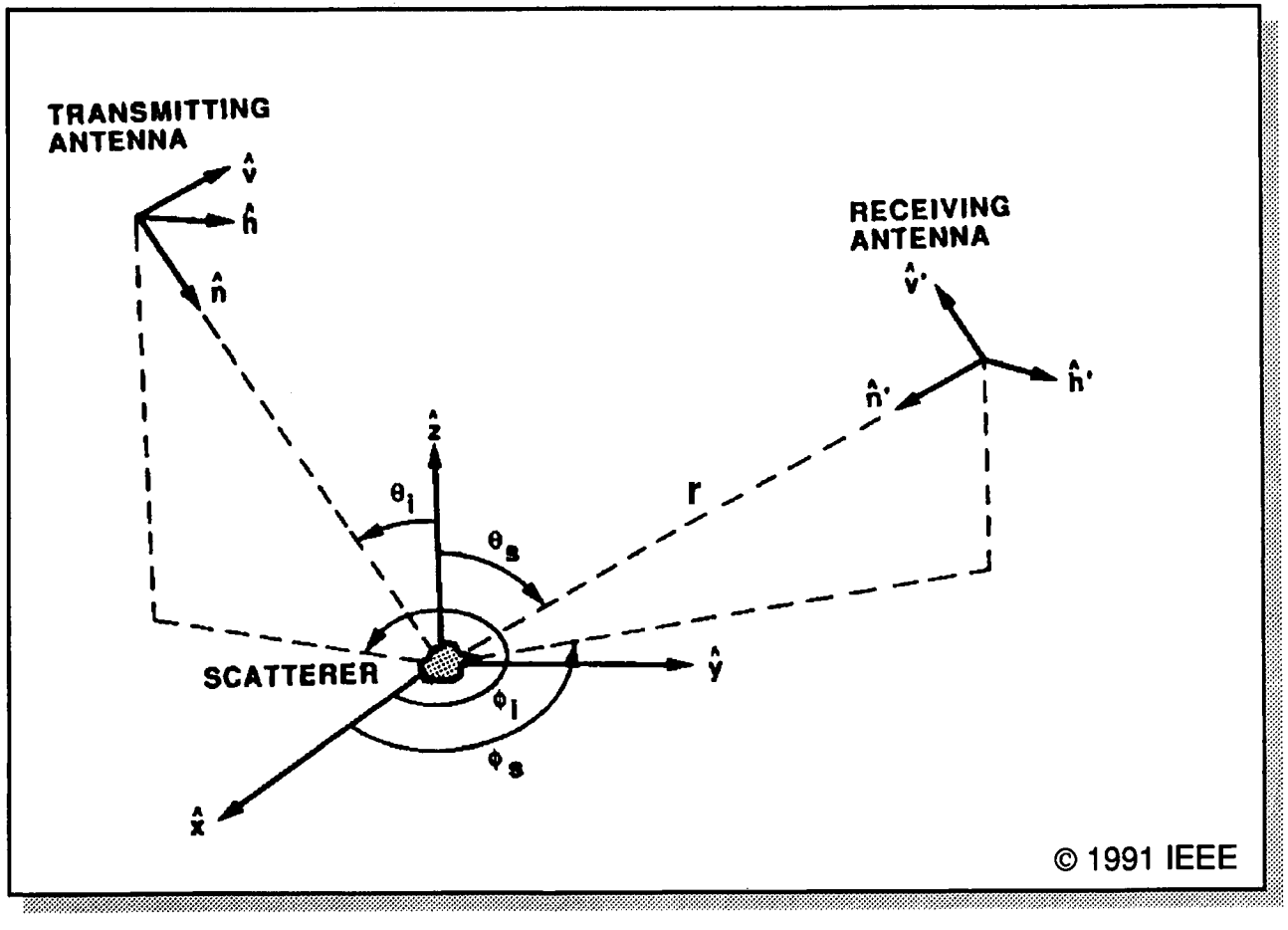
"sc" = scattered field components

$$k = \frac{2\pi}{\lambda}$$

r = distance from scatterer to receiving antenna

- IN GENERAL $S_{rt} = S_{rt}(f, \theta_i, \phi_i, \theta_s, \phi_s)$

# SCATTERING GEOMETRY AND LOCAL COORDINATE SYSTEMS




From: H. A. Zebker and J. Van Zyl, *Imaging Radar Polarimetry: A Review*, Proc. IEEE, **79(11)**,1583-1606 (1991)

# REPRESENTATION OF POLARIZATION (contd)

- **STOKES VECTORS AND MUELLER MATRIX**
  - **RECALL FROM SECTION 1.2 THE DEFINITION OF THE POLARIZATION ELLIPSE AND $\psi$ AND $\chi$**
  - **DEFINE THE STOKES VECTOR FOR A PLANE MONOCHROMATIC EM WAVE AS**

$$F_M = \begin{bmatrix} |E_v|^2 \\ |E_h|^2 \\ 2\mathrm{Re}(E_v E_H^*) \\ 2\mathrm{Im}(E_v E_H^*) \end{bmatrix} = S_0 \begin{bmatrix} \frac{1}{2}[1 + \cos(2\psi)\cos(2\chi)] \\ \frac{1}{2}[1 - \cos(2\psi)\cos(2\chi)] \\ \sin(2\psi)\cos(2\chi) \\ \sin(2\chi) \end{bmatrix}$$

# REPRESENTATION OF POLARIZATION (contd)

- THE ABOVE EXPRESSION FOR *F* DESCRIBES A DEFINITE STATE OF POLARIZATION
- FOR DISTRIBUTED OR EXTENDED TARGETS, THE SCATTERED WAVE VARIES WITH TIME, SPATIAL POSITION AND ORIENTATION, WHICH GIVES RISE TO STATES OF PARTIAL POLARIZATION
  - SCATTERING MATRIX FORMALISM CAN ONLY DESCRIBE STATES OF DEFINITE POLARIZATION
  - REQUIRE STOKES VECTORS FOR PARTIALLY POLARIZED MW RADIATION
  - NEGLECTING TIME VARIATION THE MORE GENERAL STOKES VECTOR IS DEFINED AS

$$F_M = \begin{bmatrix} \langle |E_v|^2 \rangle \\ \langle |E_h|^2 \rangle \\ 2\mathrm{Re}\langle E_v E_H^* \rangle \\ 2\mathrm{Im}\langle E_v E_H^* \rangle \end{bmatrix} = \begin{bmatrix} I_v \\ I_h \\ U \\ V \end{bmatrix}$$

$\langle \cdot \rangle$ = spatial average

  - COMPLETELY UNPOLARIZED WAVE

$$F_M = \frac{I_0}{2}\begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} \qquad I_0 = I_v + I_h$$

  - DEGREE OF POLARIZATION = POLARIZED POWER/TOTAL POWER

$$\mathrm{DOP} = \frac{\sqrt{(I_v - I_h)^2 + U^2 + V^2}}{I_v + I_h}$$

# REPRESENTATION OF POLARIZATION (contd)

- JUST AS WE USED THE SCATTERING MATRIX S TO RELATE THE INCIDENT AND SCATTERED E-FIELDS, WE CAN DEFINE A RELATIONSHIP BETWEEN THE INCIDENT AND SCATTERED STOKES VECTORS

$$F_M^s = \frac{1}{r^2} L_M F_M^i$$

- MUELLER MATRIX - REAL 4 × 4 MATRIX DEFINED FOR DISTRIBUTED TARGETS AS

$$L_M = V\langle W\rangle V^{-1}$$

$$V = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & -i & i \end{bmatrix}$$

$$W = \begin{bmatrix} S_{vv}S_{vv}^* & S_{vh}S_{vh}^* & S_{vv}S_{vh}^* & S_{vh}S_{vv}^* \\ S_{hv}S_{hv}^* & S_{hh}S_{hh}^* & S_{hv}S_{hh}^* & S_{hh}S_{hv}^* \\ S_{vv}S_{hv}^* & S_{vh}S_{hh}^* & S_{vv}S_{hh}^* & S_{vh}S_{hv}^* \\ S_{hv}S_{vv}^* & S_{hh}S_{vh}^* & S_{hv}S_{vh}^* & S_{hh}S_{vv}^* \end{bmatrix}$$

# REPRESENTATION OF POLARIZATION (contd)
## POLARIMETRIC DATA ANALYSIS

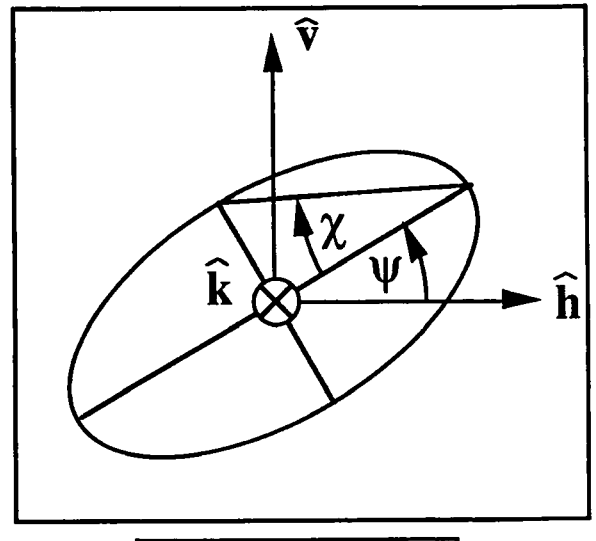
- **POLARIZATION**

  $\psi$ = **Orientation Angle**

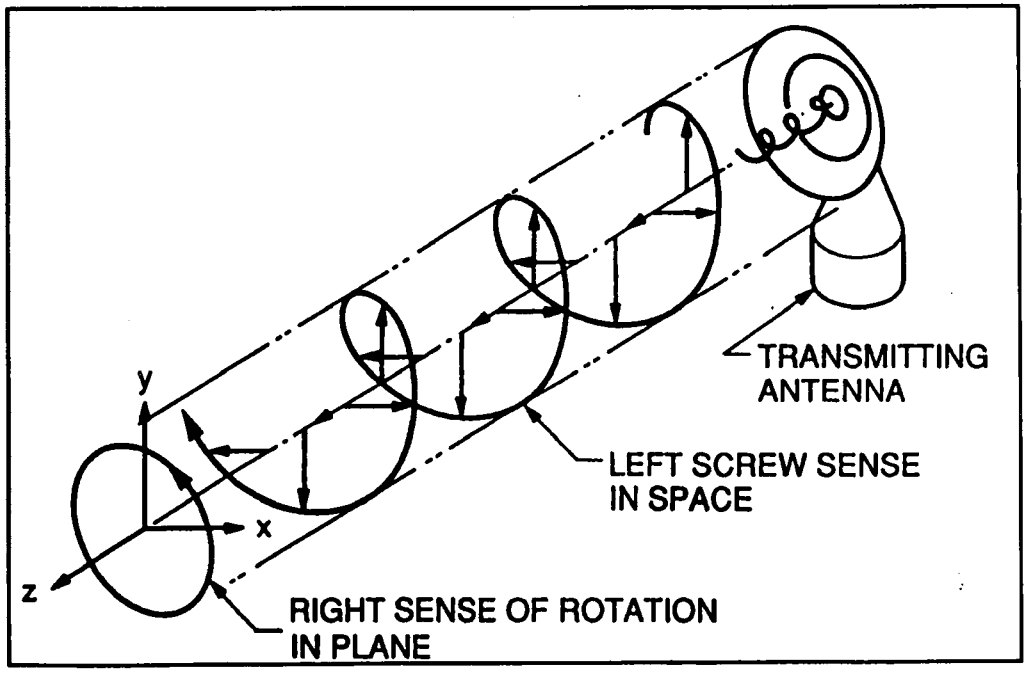
  $\chi$ = **Ellipticity Angle**

  $\chi > 0$ **left sense in plane**

  $\chi < 0$ **right sense in plane**




**POLARIZATION ELLIPSE**



# REPRESENTATION OF POLARIZATION (contd)

- **THE SCATTERING COEFFICIENT IS PROPORTIONAL TO THE MUELLER MATRIX**

$$\sigma^0_{rt}(\psi_r,\chi_r,\psi_t,\chi_t) = 4\pi\cos(\theta)\{A_r^T M'_m A_t\} \qquad M'_m \propto L_M$$

$A_p$ = normalized stokes vectors for the antenna

p = r,t

- **POLARIZATION RESPONSE**

  - **CO-POL RESPONSE PLOT**

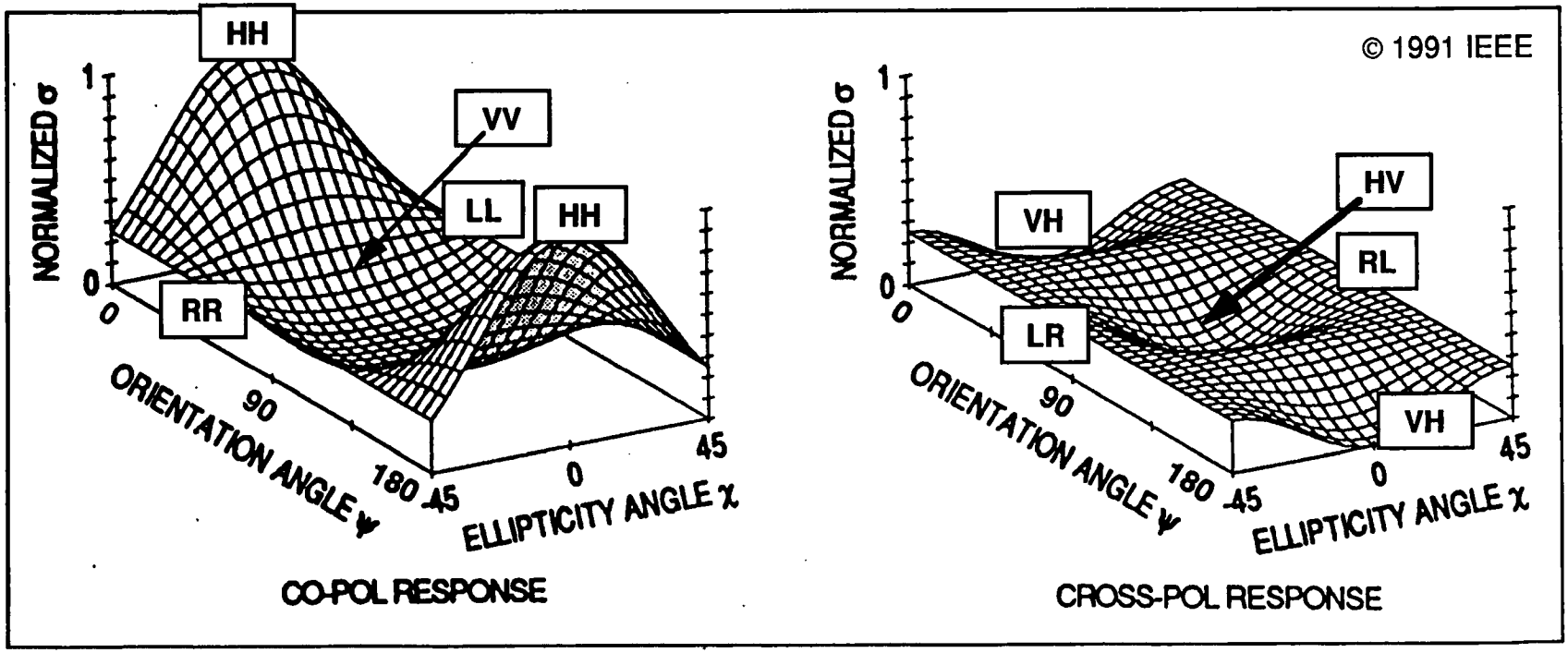
$$\sigma^0_{rt}(\psi_t,\chi_t) \text{ with } \psi_r=\psi_t \;\&\; \chi_r=\chi_t$$

  - **CROSS-POL RESPONSE PLOT**

$$\sigma^0_{rt}(\psi_t,\chi_t) \text{ with } \psi_r=\psi_t + 90^\circ \;\&\; \chi_r= -\chi_t$$

# POLARIMETRIC RESPONSE
## (OR POLARIZATION SIGNATURE)

- **CO-POL** $\sigma_{rt}(\psi_t,\chi_t)$ **with** $\psi_r = \psi_t,\ \chi_r = \chi_t$
- **CROSS-POL** $\sigma_{rt}(\psi_t,\chi_t)$ **with** $\psi_r = \psi_t + 90°,\ \chi_r = -\chi_t$
- **LINEAR-POL** $\sigma_{rt}(\psi_t,\psi_r)$ **with** $\chi_r = \chi_t = 0°$




From: H. A. Zebker and J. Van Zyl, *Imaging Radar Polarimetry: A Review*, Proc. IEEE, **79(11)**,1583-1606 (1991)

# POLARIZATION SYNTHESIS

- GIVEN $[S]$ ONE CAN COMPUTE THE RECEIVED POWER FOR ANY COMBINATION OF TRANSMIT AND RECEIVE ANTENNA POLARIZATIONS

Given $\left.\begin{array}{l}\vec{E}_t = \text{transmitted field} \\ \vec{E}_r = \text{recieved field}\end{array}\right\}$ antenna dependent

$$P_{rec} = K(\lambda,\theta,\phi)\left|\vec{E}_r \cdot [S]\vec{E}_t\right|^2$$

$$K(\lambda,\theta,\phi) = \frac{1}{2}\left(\frac{\lambda^2}{4\pi}\right)\sqrt{\frac{\varepsilon_0}{\mu_0}}\,\frac{g(\theta,\phi)}{\left|\vec{E}_r\right|^2}$$

$g(\theta,\phi)$ = antenna gain

# POLARIZATION SYNTHESIS (contd)

- THE RECEIVED POWER CAN ALSO BE EXPRESSED IN TERMS OF THE STOKES VECTORS AND MUELLER MATRIX

$$P_{rec} = K(\lambda,\theta,\phi)\,|S_r \cdot [M] S_t|^2$$

- FOR A GIVEN SCENE AND GEOMETRY ONE MEASURES [S] (OR [M])
  - RECEIVED POWER CAN THEN BE SYNTHESIZED FOR ANY TRANSMIT/RECEIVE COMBINATION

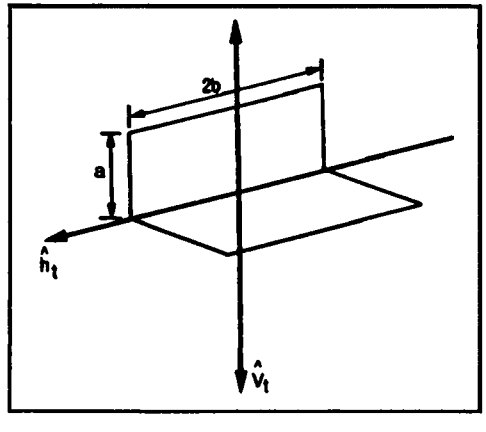
# POLARIZATION AND TARGET SCATTERING

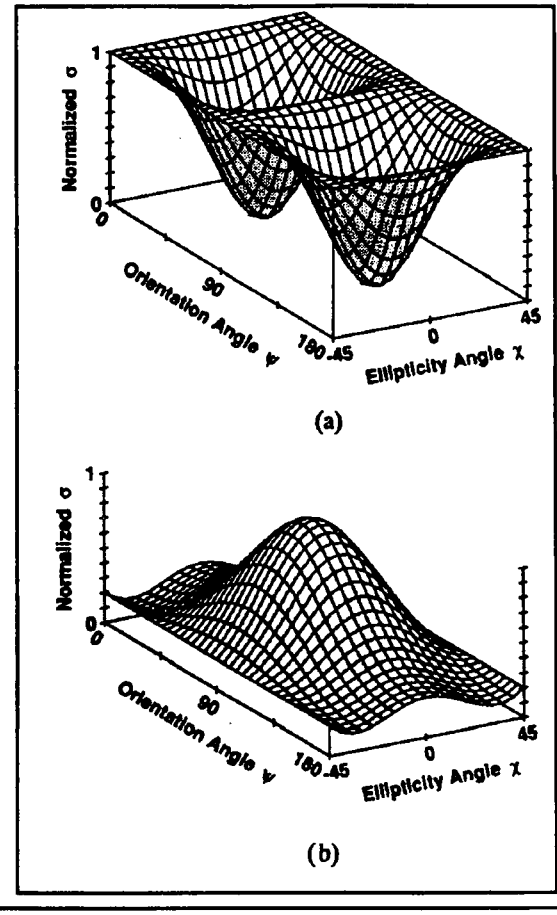
- **POLARIZATION SIGNATURE**
  - 3D SURFACE PLOT OF THE SYNTHESIZED RADAR CROSS SECTION OR SCATTERING COEFFICIENT (RECEIVED POWER) AS A FUNCTION OF ELLIPTICITY ($\chi$) AND THE ORIENTATION ($\psi$) ANGLES FOR THE TRANSMIT ANTENNA
  - USED TO CHARACTERIZE THE SCATTERING MECHANISMS FROM DIFFERENT SCATTERERS
- **EXAMPLES**
  - DIHEDRAL CORNER REFLECTOR
  - OCEAN
  - URBAN AREA AND PARK
  - SEA ICE

# POLARIZATION SIGNATURES
# DIHEDRAL CORNER REFLECTOR

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DIHEDRAL CORNER REFLECTOR




(a) Copolarized signature of a perfectly conducting dihedral corner reflector.

(b) Slightly rough surface scattering, incidence angle of 50 degrees, kh=0.5, rms slope of 30 deg., dielectric constant of 81.

From: H. A. Zebker and J. Van Zyl, *Imaging Radar Polarimetry: A Review*, Proc. IEEE, **79(11)**,1583-1606 (1991)

# POLARIZATION SIGNATURES
# OCEAN, URBAN AND PARK REGIONS

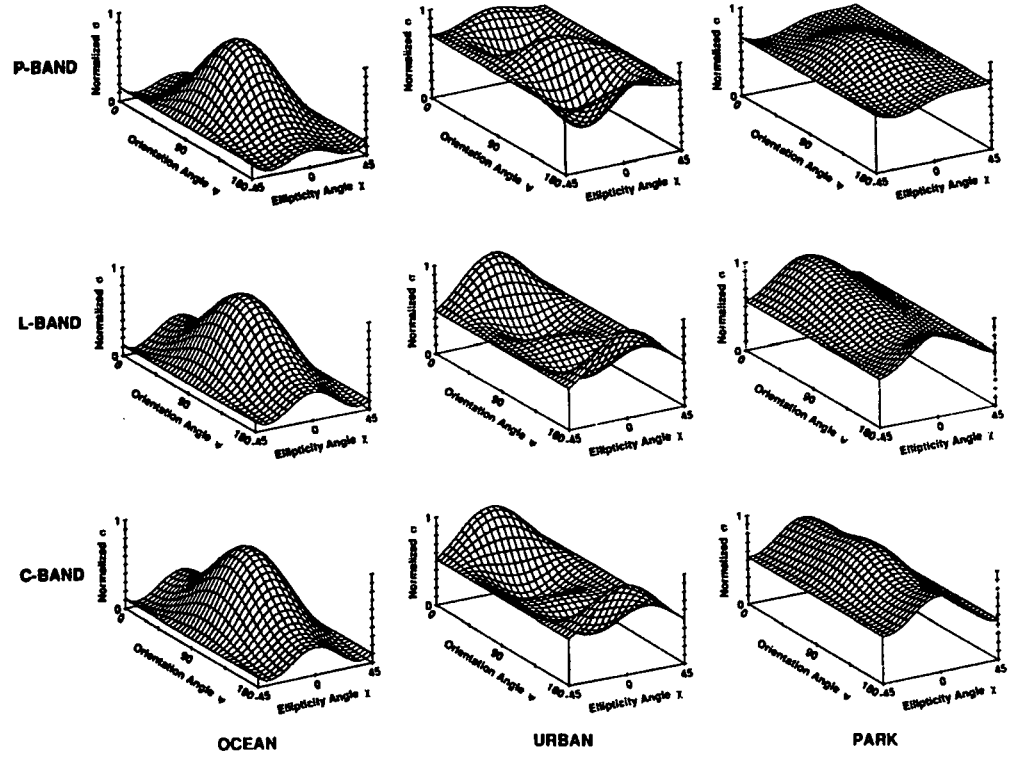



**Fig. 14.** Three-frequency polarization signatures of the ocean (incidence angle = 43.8°), an urban area (incidence angle = 44.6°) and the park (incidence angle = 44.4°) in the San Francisco image. Notice that all the signatures have distinctly different shapes, allowing one to infer that the ocean scattering is consistent with that predicted by slightly rough surface scattering models, while the urban scattering is dominated by double-reflections off the ground onto the sides of buildings before returning to the radar. The high pedestal observed in the park signals points to a high degree of variation in scattering properties from one pixel to the next for vegetated areas.

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From: H. Zebker and J. Van Zyl, *Imaging Radar Polarimetry: A Review*, Proc. IEEE, **79(11)**,1583-1606 (1991)

# POLARIZATION SIGNATURES
# SEA ICE

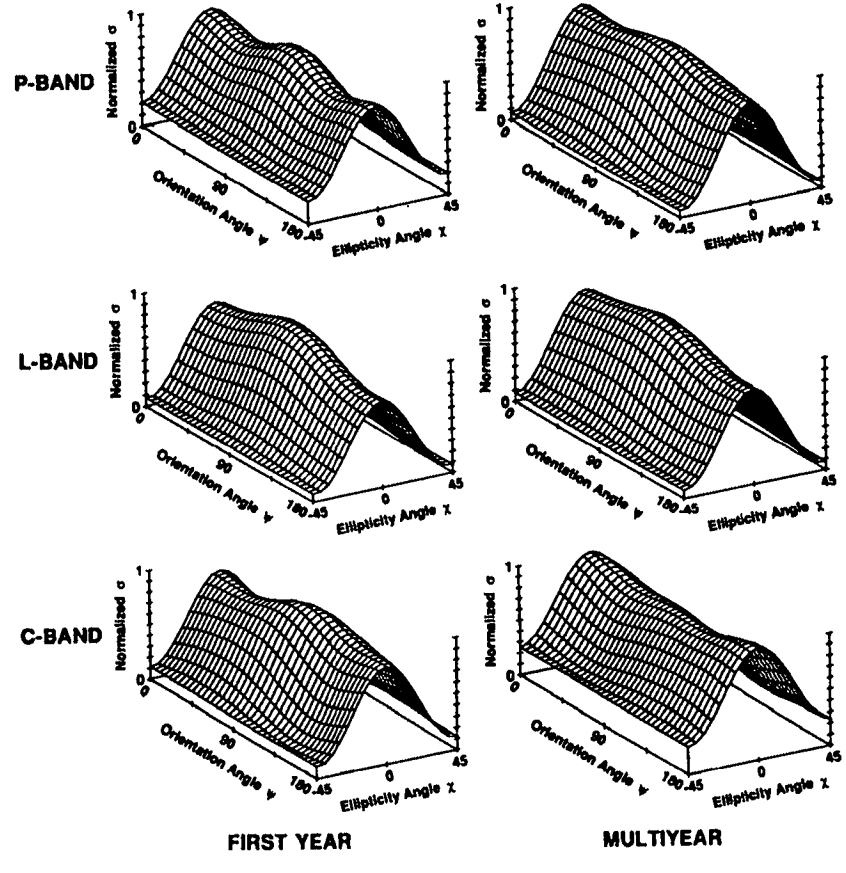



**Fig. 22.** Three-frequency polarization signatures of first year ice (incidence angle = 36.2°), and multiyear ice (incidence angle = 48.3°) in the Beaufort Sea image. Note that for the first year ice, the pedestal decreases with increasing frequency. The opposite effect is observed for the multiyear ice, in which case the pedestal increases with increasing frequency. Two different models predict the observed behavior of the multiyear ice, but at present we do not have an explanation for the observed behavior of the first year ice.

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From: H. A. Zebker and J. Van Zyl, *Imaging Radar Polarimetry: A Review*, Proc. IEEE, **79(11)**,1583-1606 (1991)

# DEGREE OF POLARIZATION

- EM WAVES SCATTERED FROM EXTENDED TARGETS ARE PARTIALLY POLARIZED

$$m(\psi_t,\chi_t) = \frac{\text{polarized power}}{\text{total power}} = \frac{\sqrt{Q^2 + U^2 + V^2}}{I_0}$$

- TWO COMPONENTS OF PARTIALLY POLARIZED EM WAVE
  - COMPLETELY POLARIZED
  - COMPLETELY UNPOLARIZED

$$F^s = (1 - m)\, F^s_{un} + m F^s_p$$

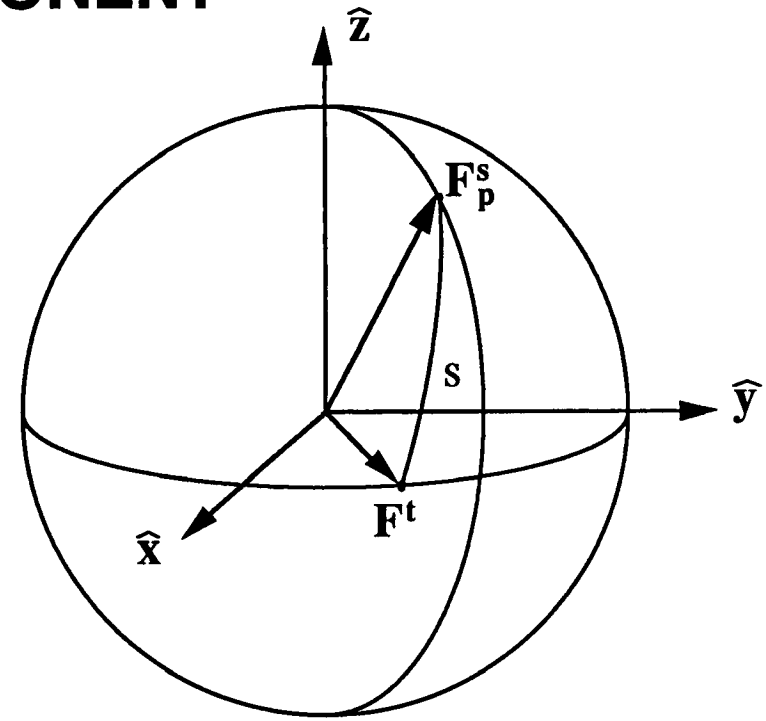
$$F^s_{un} = \begin{bmatrix} I_0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$F^s = RR^T M F^t(\psi_t,\chi_t)$$

$$RR^T = \begin{bmatrix} 2 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & -2 \end{bmatrix}$$

# DEPOLARIZATION OF THE FULLY POLARIZED COMPONENT

$$F_p^s = \begin{bmatrix} 1 \\ \cos(2\psi_p)\cos(2\chi_p) \\ \sin(2\psi_p)\cos(2\chi_p) \\ \sin(2\chi_p) \end{bmatrix}$$




POINCARE SPHERE

$S(\psi_t,\chi_t)$ = normalized arc length between $F^t$ and $F_p^s$ on the Poincare sphere

$$S(\psi_t,\chi_t) = \frac{1}{\pi}\cos^{-1}\left[F_p^s \cdot F^t - I_0\right]$$

# PHASE STATISTICS

$$E^s = \frac{\exp(jkr)}{\sqrt{4\pi}r} SE^i \qquad S = \begin{bmatrix} |S_{vv}|e^{j\phi_{vv}} & |S_{vh}|e^{j\phi_{vh}} \\ |S_{hv}|e^{j\phi_{hv}} & |S_{hh}|e^{j\phi_{hh}} \end{bmatrix}$$

- RELATIVE PHASE OF PARTIALLY POLARIZED WAVE IS A RANDOM VARIABLE IN $[-\pi,\pi]$

- ADDITIONAL INFORMATION IS PRESENT IN THE PDF OF
  - CO-POL PHASE DIFFERENCE $\phi = \phi_{hh} - \phi_{vv}$
  - CROSS-POL PHASE DIFFERENCE $\phi = \phi_{vh} - \phi_{vv}$
- PDF MAY BE FOUND FROM M OR $L_M$

$$L_M = URR^TMU^{-1} \quad \text{(MODIFIED MUELLER MATRIX)}$$

# PHASE DIFFERENCE PDF

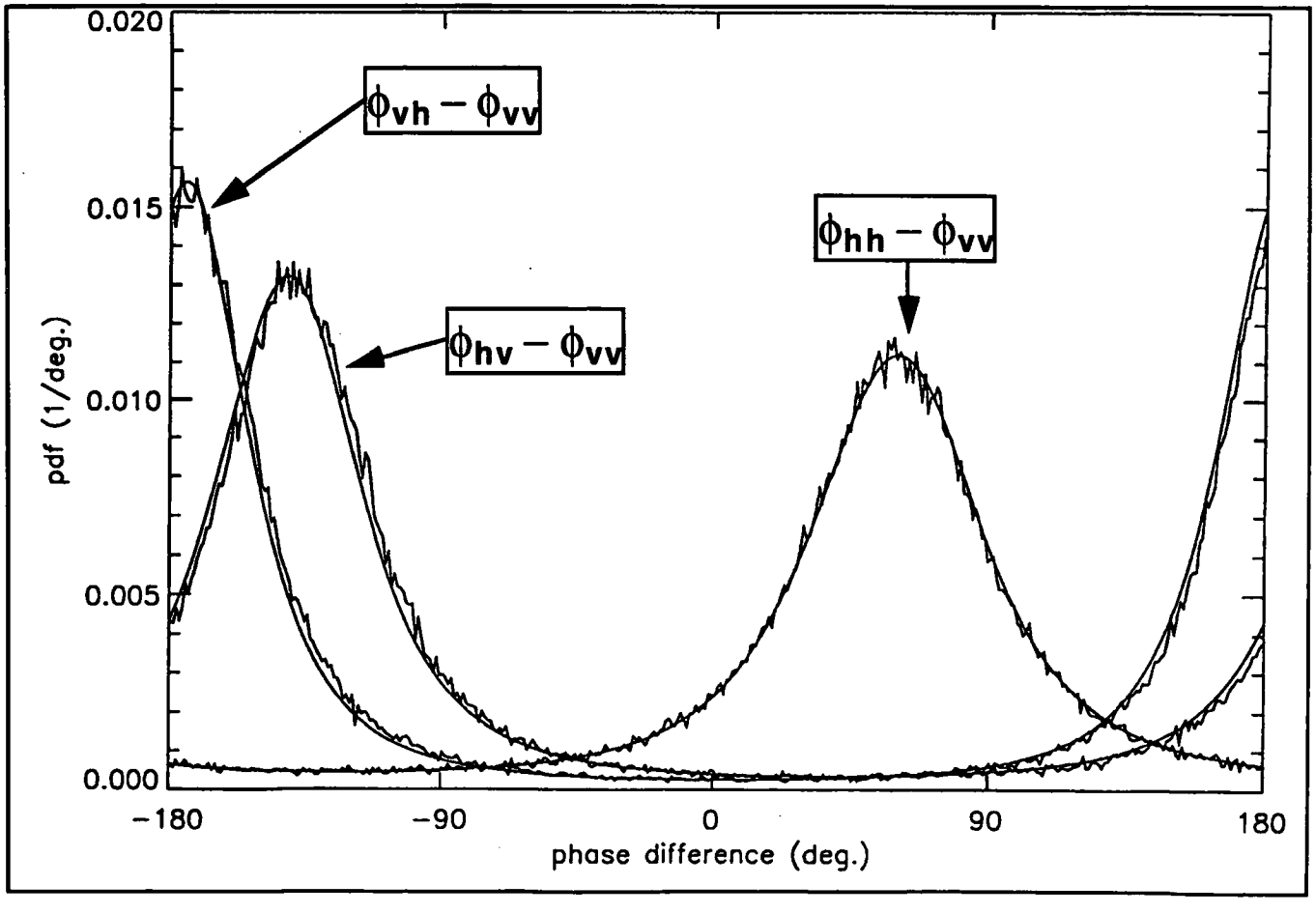
- ASSUME REAL AND IMAGINARY PARTS OF S ARE JOINTLY GAUSSIAN
- ANALYTICAL DERIVATION OF PHASE PDF GIVES

$$\alpha = \sqrt{\frac{\lambda_{13}^2 + \lambda_{14}^2}{\lambda_{11}\lambda_{33}}} \qquad \zeta = \tan^{-1}\left(\frac{\lambda_{14}}{\lambda_{13}}\right)$$

$$P(\phi) = \frac{1-\alpha^2}{2\pi[1-\alpha^2\cos^2(\phi-\zeta)]}\left\{1 + \frac{\alpha\cos(\phi-\zeta)}{\sqrt{1-\alpha^2\cos^2(\phi-\zeta)}}\left[\frac{\pi}{2} + \tan^{-1}\left(\frac{\alpha\cos(\phi-\zeta)}{\sqrt{1-\alpha^2\cos^2(\phi-\zeta)}}\right)\right]\right\}$$

| CO-POL | CROSS-POL |
|---|---|
| $\lambda_{11} = \frac{1}{2} L_{11}$ | $\lambda_{11} = \frac{1}{2} L_{11}$ |
| $\lambda_{33} = \frac{1}{2} L_{22}$ | $\lambda_{33} = \frac{1}{2} L_{12}$ |
| $\lambda_{13} = \frac{1}{4}(L_{33} + L_{44})$ | $\lambda_{13} = \frac{1}{2} L_{13}$ |
| $\lambda_{14} = \frac{1}{4}(L_{34} - L_{43})$ | $\lambda_{34} = \frac{1}{2} L_{14}$ |

# PHASE PDF FOR OCEAN BACKSCATTER



# POLARIMETRIC RADARS

- POLARIMETRIC RADARS ARE DESIGNED TO MEASURE THE COMPLETE COMPLEX SCATTERING MATRIX [S]
  - MEASURE BOTH AMPLITUDE AND PHASE OF THE SCATTERED FIELD FOR ALL LINEAR POLARIZATIONS
  - REQUIRES ABSOLUTION CALIBRATION OF AMPLITUDE AND PHASE
  - BOTH SCATTEROMETER AND SAR CONFIGURATIONS EXIST
  - SIR-C IS PLANNED TO BE A FULL POLARIMETRIC SPACEBORNE SAR
  - NASA/JPL AIRSAR IS FULLY POLARIMETRIC AT P-, L- AND C-BANDS
  - NAWC/ERIM-P3 CAN OPERATE IN A POLARIMETRIC MODE AT L-, C- AND X-BANDS

# 3.8 APPLICATIONS OF ACTIVE MICROWAVE REMOTE SENSING

- ACTIVE INSTRUMENTATION PROVIDES
  - "ALL WEATHER" – DAY/NIGHT OBSERVATIONS
- RADAR ALTIMETRY
  - 78% OF EARTH'S SURFACE IS COVERED BY WATER
  - MEASURE MEAN SEA LEVEL FOR STUDIES OF
    - * GEODESY
    - * TOPOGRAPHY
    - * LARGE-SCALE OCEAN CIRCULATION
  - CAN ALSO MEASURE SEA STATE
  - REQUIRES CAREFULLY CHOSEN ORBIT FOR SAMPLING
  - SINGLE BEAM SYSTEMS HAVE LIMITED SWATH AND COVERAGE

# OPERATIONAL ALTIMETER REQUIREMENTS

## Operational Altimeter Requirements from the National Oceanic and Atmospheric Administration

| Variable (unit) | Accuracy | Precision | Range | Resolution | Frequency | Delay | Coverage | Grid |
|---|---|---|---|---|---|---|---|---|
| **National Weather Service** | | | | | | | | |
| Wind stress) (dynes/cm²) | 0.2 | – | – | 200 km | 5 days | – | – | – |
| Currents (cm/s) | 2 | – | – | 50 | 1 week | – | – | – |
| Ice (%) | 2 | – | – | – | 1 month | – | various | – |
| **National Ocean Service** | | | | | | | | |
| Winds (m/s) | – | 0.5–2 | 0–100 | 5–20 km | 3–12 hr | 1–6 hr | regional | 10–100 |
| Topography (cm) | – | 2 | 0–50 | 10–20 | 6–12 | 3–6 | global | 10–100 |
| Wave height (m) | – | 0.5–1 | 0–50 | 5–20 | 3–12 | 1–6 | global | 10–100 |
| Tides (cm) | – | 5–10 | 0–1.5 m | 1–50 | 3–12 | 1–6 | global | 10–100 |
| Currents (cm/s) | – | 5–10% | 0–500 | 5,10,50 | 6–96 | 3–48 | global | 10–100 |
| **Office of Oceanic and Atmospheric Research** | | | | | | | | |
| Winds (m/s) | 0.5 | 0.5 | 0–75 | 100 | 1 week | 10 day | global | – |
| Topography (cm) | 1 | 1 | 1–30 | 100 | 1 week | 10 day | global | – |
| Ice (km) | 1 | 1 | – | 1 | 1 day | 12 hr | polar | – |
| Currents (cm/s) | 1,5 | 2,5 | 0–250 | 1,10,100 | 3,6,24 | 12 | coasts | 100 |
| Waves (m) | 0.3/10% | 0.2,0.3 | 0–30 | 5 | 3,6,24 | 3,12 | coasts | 10–100 |
| Winds (m/s) | 0.2,1.2 | 0.5 | 0–75 | 5 | 6,12 | 3,6 | coasts | 100 |
| Tides (cm) | 2,5,20 | 1,5 | 0–1.5 m | 0.5,100 | 3,6 | 3,24 | regions | – |
| **National Marine Fisheries Service** | | | | | | | | |
| Winds (m/s) | 2 | 0.5 | 0–75 | 50–100 | 16 | 3 | various | 20–200 |
| Waves (m) | 0.5 | 0.5 | 0–25 | 25–50 | 3 | 3 | various | 100 |
| Currents (cm/s) | 25 | – | 0–500 | 25–50 | 3 | 3 | various | 100 |

From: *A[illegible]tric System Panel Report, Earth Observing System*, Vol. IIh, NASA [illegible]987).

# ALTIMETER DESIGN REQUIREMENTS

**Summary of Design Requirements for Eos Radar Altimeters (Accuracy and Precision Refer to the Height Measurement)**

| | Accuracy | Precision | Resolution | Frequency | Grid | Repeat Precision |
|---|---|---|---|---|---|---|
| Oceanography | 10 cm | 2 cm | 5 km | 10–20 days | 50 km | 1 km |
| Geophysics | 10 cm | 2 cm | 5 km | 2 yrs | 5 km | n/a |
| Cryospherics | 10 cm | 5 cm | 100 m | 2 yrs | 5 km | 300 m |
| Geology | 10 cm | 5 cm | 100 m | 5 yrs | n/a | n/a |
| Physical climatology | n/a | n/a | 500 m(v) | 2 days | 10 km | n/a |
| Operational | 1 cm | 1 cm | 10 km | 3 hrs | 10 km | – |
| **Design goals** | **<10 cm** | **2 cm** | **~1 km** | * | * | * |

*Dependent upon the number of altimetric systems deployed and the orbit in which they are placed.

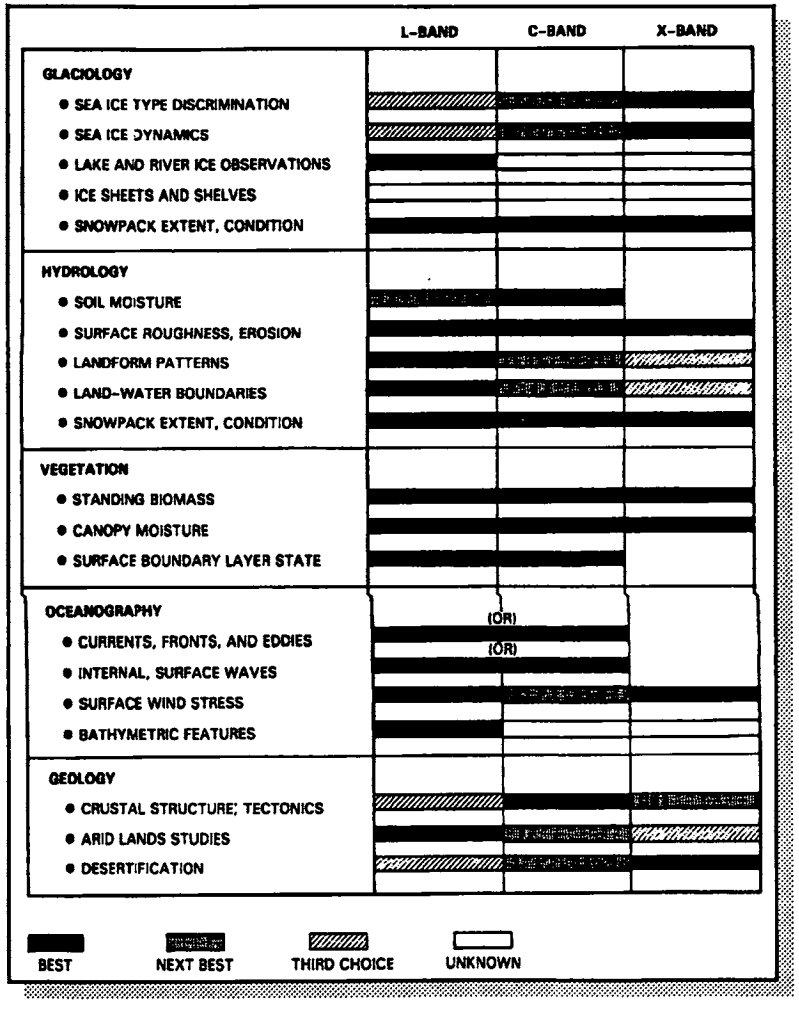
From: *Altimetric System Panel Report, Earth Observing System*, Vol. IIh, NASA (1987).

# INFORMATION REQUIREMENTS FOR SAR APPLICATIONS

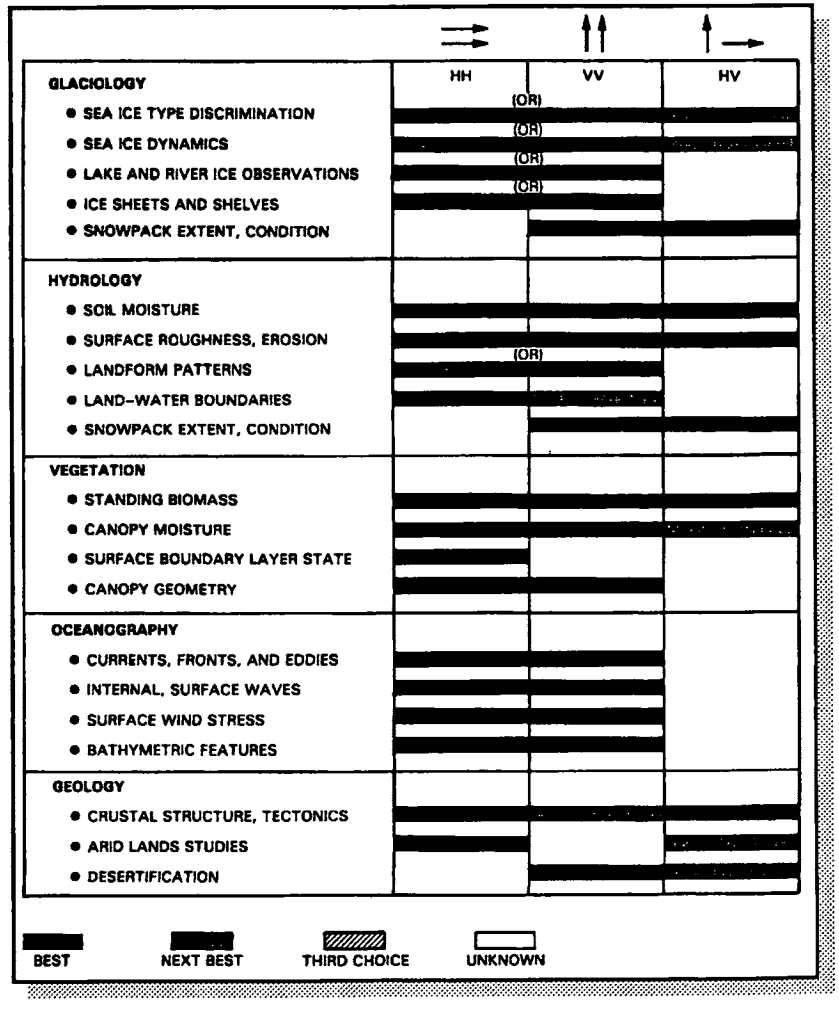
| APPLICATION | INFORMATION REQUIREMENT |
|---|---|
| TERRESTRIAL | DISTINGUISH TERRAIN TYPES |
| | DISTINGUISH VEGETATION TYPES |
| | DETECT TERRAIN OR GEOLOGICAL FEATURES |
| OCEANOGRAPHIC | DETECTION OF SPATIAL PATTERNS ON THE OCEAN SURFACE (SURFACE WAVES, ..., ETC.) |
| NAVIGATION AND GUIDANCE | LOCATE, DETECT AND CLASSIFY SPECIFIC CULTURAL OR TERRAIN FEATURES |
| | DETERMINE GEOMETRICAL RELATIONSHIPS BETWEEN SPECIFIC FEATURES AND DESTINATION |
| CHANGE DETECTION | DETECT CHANGES IN THE SCENE OF INTEREST |
| | CULTURAL SCENES, TERRAIN FEATURES, ..., ETC. |

# SCIENTIFIC APPLICATIONS OF SAR IMAGERY

## Frequency Requirements




## Polarization Requirements




From: Earth Observing System Instrument Panel Report, Volume IIF Synthetic Aperture Radar, NASA (no date given).

# SAR APPLICATIONS (contd)

- SYNTHETIC APERTURE RADAR
  - ALLOWS LARGE-SCALE AREA COVERAGE
    - * GLOBAL COVERAGE EVERY 3 DAYS AT MODERATE RESOLUTION (FEW HUNDRED METERS)
  - MULTI-SPECTRAL AND MULTI-POLARIZATION, HIGH RESOLUTION (≤ 25 meters) SURFACE IMAGING
  - SAR IMAGERY PROVIDES CHARACTERIZATION OF
    - * SURFACE MORPHOLOGY, ROUGHNESS, DIELECTRIC PROPERTIES AND GEOMETRIC SHAPE
    - * SURFACE COVER
    - * NEAR SUBSURFACE VOLUME

# GEOPHYSICAL PARAMETERS MEASURABLE WITH ACTIVE MICROWAVE SENSORS

## • OCEANOGRAPHY

- CURRENTS AND FRONTS
- RINGS AND EDDIES
- INTERNAL WAVES
- BATHYMETRIC BOUNDARIES
- SURFACE WIND FIELD
- OCEAN SURFACE TOPOGRAPHY
- OCEAN SURFACE DIRECTIONAL WAVE SPECTRA

## • GLACIOLOGY

- SEA ICE TYPE DISCRIMINATION
- SEA ICE DYNAMICS
- LAKE AND RIVER ICE EXTENT
- ICE SHEETS AND SHELF DYNAMICS
- SNOWPACK PROPERTIES
  - * EXTENT
  - * SNOW WATER EQUIVALENT
  - * WETNESS

## • HYDROLOGY

- SOIL MOISTURE
- SURFACE ROUGHNESS
- EROSION
- LANDFORM PATTERNS
- LAND-WATER BOUNDARIES
- SNOWPACK PROPERTIES

## • VEGETATION SCIENCE

- CANOPY MOISTURE
- CANOPY GEOMETRY
- CHANGE IN CANOPY BIOMASS
- SURFACE BOUNDARY LAYER STATE

## • GEOLOGY

- LANDFORMS
- DRAINAGE PATTERNS
- SURFACE COVER BOUNDARIES

# GEOPHYSICAL PARAMETERS (contd)

- ATMOSPHERIC SCIENCE AND METEOROLOGY
  - RAIN RATE
  - CLOUD TOP
  - PROFILES OF ATMOSPHERIC CONSTITUENTS AND TRACE GASES

# RESOURCE EXPLORATION

- SAR CAN PROVIDE INFORMATION FOR EARTH RESOURCE EXPLORATION
  - LARGE AREA COVERAGE
  - "ALL WEATHER", DAY/NIGHT COVERAGE
  - FOLIAGE PENETRATION
  - GROUND PENETRATION IN SOME INSTANCES
  - CHANGE DETECTION
- ANALYSIS OF SAR IMAGERY CAN YIELD
  - SURFACE PATTERNS: DRAINAGE, VEGETATION, LANDFORMS
  - POTENTIAL FOR QUANTITATIVE INFORMATION: SOIL MOISTURE, BIOMASS
  - LITHOLOGIC: ROCK TYPING, ROUGHNESS & DIELECTRIC PROPERTIES
  - STRUCTURAL: MORPHOLOGY
  - LANDFORM ANALYSIS: INFER SUBSURFACE STRUCTURE OR COMPOSITION
- POTENTIAL APPLICATIONS
  - GEOLOGIC ANALYSIS
  - HYDROCARBON & MINERAL EXPLORATION
  - HYDROLOGY

# GEOLOGIC ANALYSIS

- LITHOLOGICAL INFORMATION
- STRUCTURAL
  - LINEAMENTS, FAULTS, FOLDS
- LAND FORM ANALYSIS

# HYDROCARBON & MINERAL EXPLORATION

- **LARGE AREA SURVEY**
  - SEISMIC SURVEY LINE PLACEMENT
  - ACCESS
- **EXPLORATION PROSPECT MAPS**
  - IDENTIFY DRAINAGE, STRUCTURE, LITHOLOGY AND LINEAMENTS
- **MINERAL EXPLORATION**
  - IDENTIFY POTENTIAL AREAS OF MINERALIZATION
  - UTILITY OF MULTI-PARAMETER SAR IMAGERY (FREQUENCY & POLARIZATION)
  - EXAMPLE: DISCOVERY OF Fe, Cu and U deposits

# HYDROLOGICAL STUDIES

- **IDENTIFICATION, MAPPING AND MEASUREMENT**
  - SURFACE HYDROLOGICAL FEATURES: STREAMS, LAKES, RUNOFF, EXTENT OF FLOOD COVER, WATER LEVELS
  - SNOW AND ICE COVER MAPPING
  - GROUND WATER DETECTION

# RESOURCE EXPLORATION
# IMAGE INTERPRETATION TECHNIQUES

- **RECOGNITION ELEMENTS**
  - TONE OR INTENSITY
  - TEXTURE
  - PATTERN
  - SHADOWS
  - SIZE AND SHAPE
  - CONTEXT
- **DEVELOPMENT OF GEOLOGICAL MODELS DIRECTLY FROM RADAR IMAGE ANALYSIS DATA**
  - SAR IMAGERY
  - OTHER DATA SOURCES: LAND USE MAPS, DEM, ETC.

# IMAGE INTERPRETATION TECHNIQUES
# RECOGNITION ELEMENTS

- **TONE**
  - IMAGE INTENSITY: GREYSCALE (0-255, 8-BIT)
  - SYSTEMS DYNAMIC RANGE DEPENDENT
    - * SYSTEM NOISE
    - * MAXIMUM SIGNAL RETURN
  - RELATIVE TONE VERY USEFUL
  - ABSOLUTE OR CALIBRATED IMAGERY: MEASURE SCATTERING COEFFICIENT
  - USED TO PROVIDE FIRST ORDER CHARACTERIZATION AND DIFFERENTIATION BETWEEN SURFACE TYPES
  - REMAPPING OF IMAGE INTENSITY SCALE CAN BE USED TO ENHANCE FEATURE CONTRAST

# IMAGE INTERPRETATION TECHNIQUES
# RECOGNITION ELEMENTS (contd)

- **TEXTURE**
  - STATISTICAL VARIABILITY OF IMAGE INTENSITY
  - SPATIAL VARIABILITY OF SCATTERING COEFFICIENT IN SCENE
  - ABSOLUTE OR CALIBRATED IMAGERY: MEASURE SCATTERING COEFFICIENT
  - DIFFERENTIATE REGIONS OF VARYING HOMOGENEITY
- **SIZE/SHAPE**
  - LENGTH, WIDTH, HEIGHT, AREA AND VOLUME OF BASIC SCENE ELEMENTS
  - ABILITY TO MEASURE THESE QUANTITATIVELY DEPENDS ON: RESOLUTION AND VIEWING GEOMETRY
  - IDENTIFY AND DIFFERENTIAL OBJECTS BY SHAPE
  - STRONG DEPENDENCE ON: RESOLUTION, VIEWING GEOMETRY AND CONTRAST RATIO
  - COMPARISON OF NATURAL AND MAN-MADE FEATURES
  - GEOLOGICAL FEATURES OFTEN HAVE CHARACTERISTIC SHAPES WHICH AID IN THEIR IDENTIFICATION
    - * ALLUVIAL FORMS, VOLCANIC CONES, GLACIAL FEATURES, FOLDED STRATA, ..., ETC.

# IMAGE INTERPRETATION TECHNIQUES
# RECOGNITION ELEMENTS (contd)

- **PATTERN**
  - ARRANGEMENT OF GEOLOGIC, TOPOGRAPHIC OR VEGETATION FEATURES
  - STRAIGHT AND CURVED EDGES OFTEN USED AS A KEY
- **SHADOWS**
  - RADAR SHADOW DEPENDENT ON RELATIVE VIEWING GEOMETRY
  - MAY ALLOW FOR TARGET MENSURATION
- **CONTEXT**
  - ANCILLARY OR BACKGROUND DATABASE OF ADDITIONAL KNOWLEDGE OF AN AREA OR SCENE AND ITS SURROUNDINGS
  - GEOGRAPHIC, GEOMORPHIC OR GEOLOGIC CHARACTERIZATION
  - FIELD SURVEYS
  - SATELLITE DATA AT OTHER WAVELENGTHS (LANDSAT, SPOT, ..., ETC.)

# GROUND RANGE RESOLUTION REQUIREMENTS TREATY VERIFICATION AND CRISIS MONITORING

| OBJECTS | DETECTION | RECOGNITION | IDENTIFICATION | DESCRIPTION |
|---|---|---|---|---|
| Bridges | 6 | 4.5 | 1.5 | 0.9 |
| Radar | 3 | 0.9 | 0.3 | 0.15 |
| Radiocommunications | 3 | 1.5 | 0.3 | 0.15 |
| Material Depots | 1.5 | 0.6 | 0.3 | 0.25 |
| Troop Units or Bivouacs | 6 | 2.1 | 1.2 | 0.3 |
| Air Base Equipment | 6 | 4.5 | 3 | 0.3 |
| Artillery and Rockets | 0.9 | 0.6 | 0.15 | 0.05 |
| Aircraft | 4.5 | 1.5 | 0.9 | 0.15 |
| Headquarters | 3 | 1.5 | 0.9 | 0.15 |
| Ground-to-Ground Missiles and Anti-Aircraft Sites | 3 | 1.5 | 0.6 | 0.3 |
| Medium Sized Surface Vessels | 7.5 | 4.5 | 0.6 | 0.3 |
| Vehicles | 1.5 | 0.6 | 0.3 | 0.05 |
| Land Mine Fields | 9 | 6 | 0.9 | 0.025 |
| Ports | 30 | 15 | 6 | 3 |
| Coasts and Landing Beaches | 30 | 4.5 | 3 | 1.5 |
| Marshalling Yards & Railway Shops | 30 | 15 | 6 | 1.5 |
| Roads | 9 | 6 | 1.8 | 0.6 |
| Urban Areas | 60 | 30 | 3 | 3 |
| Military Airfields | – | 90 | 4.5 | 1.5 |
| Submarines on the Surface | 30 | 6 | 1.5 | 0.9 |
| | | | | |
| **Note: Resolution in meters** | | | | |

AFTER: *SPACE-BASED RADAR HANDBOOK*, L. CANTAFIO, ED., ARTECH HOUSE, NORWOOD (1989).

# INTEGRATED SAR AND AEROMAGNETIC MEASUREMENTS

- APPLICATION OF SAR TO EARTHQUAKE FAULT DETECTION AND MAPPING
- CANADIAN CENTER FOR REMOTE SENSING (CCRS) SAR
  - C-BAND SAR, 16 M RESOLUTION
  - DATA ACQUIRED OVER THE UNGAVA PENINSULA OF NORTHERN QUEBEC, CANADA
- AEROMAGNETIC MEASUREMENTS
  - MEASURE MAGNETIC SUSCEPTIBILITY OF BEDROCK
  - 200 M SPATIAL RESOLUTION
  - MAP MAGNETIC LINEAMENTS, REGIONAL STRUCTURE AND BEDROCK
- COMPLEMENTARY DATASETS
  - RADAR IS SENSITIVE TO TERRAIN RELIEF AND SURFACE ROUGHNESS
  - MAGETIC MEASUREMENTS ARE SENSITIVE TO SUBSURFACE MAGNETIC MATERIALS
- FIGURE
  - IHS TRANSFORMATION INTEGRATING SAR AND AEROMAGNETIC DATA
  - RGB COLOR CONTOURED MAGNETIC DATA INPUT TO IHS
  - INTENSITY REPLACED BY RADAR DATA, BACK TRANSFORM TO RGB

FROM: M. LAMONTAGNE AND D. F. GRAHAM, *REMOTE SESNING LOOKS AT AN INTRAPLATE EQRTHQUAKE SURFACE RUPTURE*, EOS, TRANS. AGU, 74(20) 353 (1993).

# 3.9 RADAR INTERFEROMETRY

# INTERFEROMETRIC SAR

- BASIC PRINCIPLE
  - ACQUIRE TWO SETS OF SAR PHASE HISTORY DATA OVER A GIVEN AREA
  - PROCESS THROUGH TO OBTAIN COMPLEX IMAGE DATA (AMPLITUDE AND PHASE)
  - MULTIPLY OR CROSS-CORRELATE THE TWO COMPLEX IMAGES TO OBTAIN PHASE DIFFERENCES OR FRINGE PATTERNS
  - EXAMINE PHASE DIFFERENCES TO EXTRACT INFORMATION ON THE SCATTERING SCENE
- ALONG-TRACK INTERFEROMETRY (ATI)
  - TWO ANTENNAS ON PLATFORM DISPLACED ALONG-TRACK
  - TRANSMIT ON AFT ANTENNA AND RECEIVE ON BOTH FORE AND AFT ANTENNAS
  - ALLOWS FOR EXTRACTION OF SCATTERER MOTION, I.E., PHASE SHIFTS DUE TO MOTION OF SCATTERER DURING DATA ACQUISITION
- CROSS-TRACK INTERFEROMETRY (CTI)
  - TWO ANTENNAS ON PLATFORM DISPLACED CROSS TRACK
  - TRANSMIT ON ONE, RECEIVE ON BOTH
  - ALLOWS FOR THE DETERMINATION OF VARIATIONS IN THE SCATTERER ELEVATION
  - USEFUL FOR TERRAIN ELEVATION MAPPING
- SAMPLE RESULTS

# RADAR INTERFEROMETRY

## THEORY OF TEMPORAL BASELINE CONFIGURATIONS
## FRONT-BACK INTERFEROMETRIC GEOMETRY AND PARAMETERS

- **TWO SAR IMAGES OBTAINED FROM FORE AND AFT ANTENNAS ARE COMPARED**
  - **PHASE DIFFERENCE AT EACH PIXEL IS RELATED TO THE VELOCITY OF THAT POINT**
  - **PHASE CHANGE GIVEN BY**

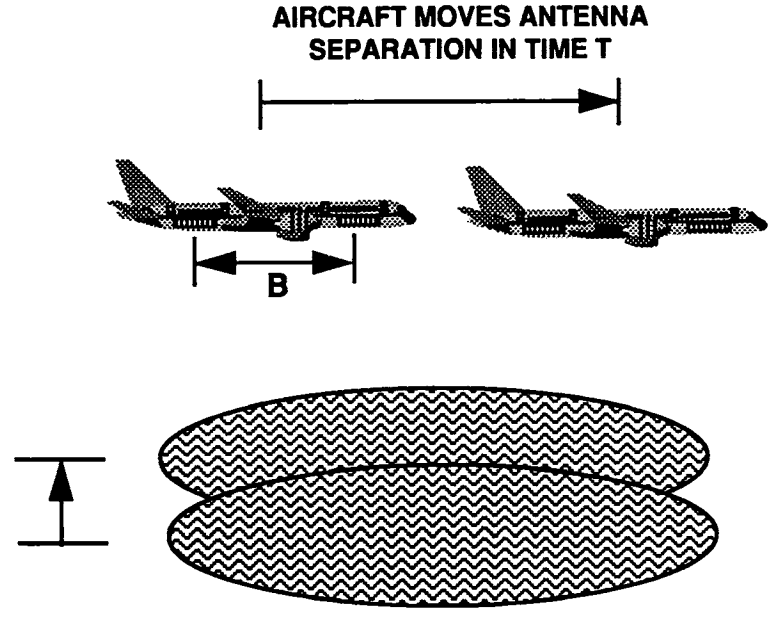
$$\varphi = \frac{4\pi UB}{\lambda V_p}$$

U = TARGET LINE OF SIGHT VELOCITY COMPONENT

$V_p$ = PLATFORM SPEED

B = ANTENNA SEPARATION (BASELINE)

$\lambda$ = RADAR WAVELENGTH




- **OCEAN IMAGING EXAMPLE**
  - **TOTAL PHASE (MOTION) DUE TO SUM OF CURRENT, SWELL AND BRAGG SCATTERER MOTIONS**
- **CORRECTIONS REQUIRED FOR AIRCRAFT ATTITUDE VARIATIONS, IN PARTICULAR ROLL**

COURTESY OF DR. RICHARD CARANDE, JPL

# 4.0 MICROWAVE REMOTE SENSING

# SPECIAL TOPICS

# 4.1 MICROWAVE REMOTE SENSING & GLOBAL CHANGE

- **GLOBAL CHANGE**

  "THE GLOBAL CHANGE PROGRAMME WILL CALL FOR COORDINATED MEASUREMENTS ON A GLOBAL SCALE OF THOSE INTERACTIVE PHYSICAL AND BIOLOGICAL PROCESSES THAT REGULATE THE EARTH SYSTEM. THE PROGRAMME WILL RELY HEAVILY ON THE EMERGING TECHNOLOGY OF REMOTE SENSING FROM AIRBORNE VEHICLES, PARTICULARLY SATELLITES. SATELLITES OFFER THE POTENTIAL OF CONTINUOUSLY VIEWING LARGE SEGMENTS OF THE EARTH'S SURFACE, THUS DOCUMENTING THE CHANGES THAT ARE OCCURRING. THE TASK, HOWEVER, IS NOT ONLY TO DOCUMENT GLOBAL CHANGE, WHICH WILL BE AN ENORMOUS JOB, BUT ALSO TO UNDERSTAND THE SIGNIFICANCE OF THESE CHANGES TO THE BIOSPHERE...THE POSSIBILITY OF MEASURING BIOSPHERE FUNCTION REMOTELY AND CONTINUOUSLY FROM SATELLITE IMAGERY MUST BE EXPLORED QUICKLY AND THOROUGHLY IN ORDER TO MEET THE CHALLENGE OF UNDERSTANDING THE CONSEQUENCES OF GLOBAL CHANGE."

  FROM: H. A. MOONEY AND R. J. HOBBS, ED., *REMOTE SENSING OF BIOSPHERE FUNCTIONING*, SPRINGER-VERLAG, NEW YORK (1990).

- **MICROWAVE REMOTE SENSING WILL PLAY AN IMPORTANT ROLE IN THE GLOBAL CHANGE PROGRAM**

  - THIS IS, HOWEVER, A SYNERGISTIC ROLE WITH MEASUREMENTS MADE BY OTHER SENSORS IN OTHER WAVELENGTH REGIONS (E.G., VISIBLE AND IR)

# GLOBAL CHANGE PROGRAMS

- WORLD CLIMATE RESEARCH PROGRAM (WCRP)
  - TROPICAL OCEAN AND GLOBAL ATMOSPHERE (TOGA)
  - GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (GEWEX)
  - WORLD OCEAN CIRCULATION EXPERIMENT (WOCE)
  - INTERNATIONAL SATELLITE CLOUD CLIMATOLOGY PROJECT (ISCCP)
- INTERNATIONAL GEOSPHERE-BIOSPHERE PROGRAMME (IGBP) CORE PROJECTS
  - INTERNATIONAL GLOBAL ATMOSPHERIC CHEMISTRY PROJECT (IGAC)
  - JOINT GLOBAL OCEAN FLUX STUDY (JGOFS)
  - BIOSPHERIC ASPECTS OF THE HYDROLOGICAL CYCLE (BAHC)
  - GLOBAL CHANGE AND TERRESTRIAL ECOSYSTEMS (GCTE)
- GENERAL ISSUES
  - SENSOR CALIBRATION IS EXTREMELY IMPORTANT FOR GC STUDIES LOOKING FOR TRENDS - SENSOR CAL BIAS COULD SHOW UP AS A FALSE TREND

# IGBP DATA NEEDS

- REQUIRE HIGH QUALITY MEASUREMENTS OVER PERIODS OF DECADES OF A LARGE NUMBER OF VARIABLES
  - PHYSICAL STATE OF THE ATMOSPHERE, OCEANS AND LAND
  - CHEMICAL CHANGES IN THE ATMOSPHERE, OCEANS AND LAND
  - BIOLOGICAL STATE OF THE LAND COVER AND UPPER LAYERS OF THE OCEAN

- IGBP NEEDS SPACE DERIVED DATA FOR 3 MAIN REASONS
  (1) DOCUMENT PRECISELY GLOBAL-SCALE CHANGES IN KEY VARIABLES TO ASSESS THE WAY THE PLANET AS A WHOLE IS EVOLVING WITH TIME
  (2) MEASURE THE LONG-TERM TRENDS IN THE FORCING FUNCTIONS OF THE GLOBAL CHANGE
  (3) SIMULTANEOUS MEASUREMENTS OF SEVERAL PARAMETERS TO STUDY INTERACTIVE PROCESSES WHICH REGULATE THE EARTH SYSTEM

# IGAC MEASUREMENT NEEDS

- TRACE GAS MEASUREMENTS
  - CONCENTRATIONS AND VERTICAL DISTRIBUTION
  - DETERMINE SOURCES AND SINKS
  - NEED IMPROVED MONITORING OF TROPOSPHERIC TRACE GASES
  - STRATOSPHERIC MEASUREMENTS ARE ALSO IMPORTANT
  - FLUXES OF TRACE GASES AT LAND AND OCEAN SURFACES
- SPECIES OF INTEREST
  - $CO_2$, CO, $CH_4$, $O_3$, $N_2O$, $NO_2$, $NH_3$, $(CH_3)_2S$, $H_2S$, OCS AND $SO_2$
- CHARACTERIZATION OF LAND COVER TYPES, CANOPY HEIGHT AND DENSITY, BIOMASS BURNING, AND NET PRIMARY PRODUCTIVITY OF LAND AND OCEANS
- MEASUREMENTS OF: TEMPERATURE, ALBEDO AND MOISTURE
- ATMOSPHERIC WATER VAPOR EXTREMELY IMPORTANT

# JGOFS MEASUREMENT NEEDS

- MEASUREMENTS OF
  - SST
  - SEA ICE COVER
  - SEA SURFACE WINDS
  - SEA LEVEL HEIGHT

- PROPERTIES INFERRED OR MEASURED
  - SURFACE WIND STRESS (SCATTEROMETER)
  - SST (MW RADIOMETER/IMAGER)
  - OCEAN CURRENTS, FRONTS AND EDDIES (ALTIMETER, SAR)
  - ICE EXTENT, SURFACE PROPERTIES AND TEMPERATURE (MW IMAGER)
  - DETAILED ICE AND OCEAN SURFACE MAPPING (SAR)

# BAHC MEASUREMENT NEEDS

- SATELLITES PROVIDE KEY SOURCE OF GLOBAL SCALE DATA NECESSARY AS INPUT TO GCM'S (100 X 100 KM GRIDS)

- PRECIPITATION MEASUREMENTS (SPACEBORNE WEATHER RADAR, ALTIMETER, MW IMAGER)

- SOIL MOISTURE (MW IMAGER)

# GCTE MEASUREMENT NEEDS

- GOAL: DEVELOP THE CAPABILITY TO INTERPRET AND PREDICT EFFECTS OF GLOBAL CHANGE PHENOMENA ON TERRESTRIAL ECOSYSTEMS
- REMOTE SENSING PROVIDES A KEY METHOD TO MEASURE CHANGES IN TERRESTRIAL ECOSYSTEMS
- BASIC DATA
  - LAND-COVER VEGETATION CHARACTERISTICS OF THE EARTH
  - SURFACE TEMPERATURE
  - SOIL MOISTURE
- MICROWAVE RADIOMETRY
  - GROSS STRUCTURAL ATTRIBUTES OF VEGETATION COVER, PARTICULARLY IN SEMI-ARID AND ARID REGIONS WHICH ARE A MIXTURE OF ROCK, SOIL AND PLANT SIGNATURES
- HIGH SPATIAL RESOLUTION AND LOW TEMPORAL FREQUENCY MEASUREMENTS OF THE PLANT CANOPY STRUCTURE ARE ALSO REQUIRED
- ALTIMETRY
  - DIGITAL ELEVATION DATA REQUIRED FOR GLOBAL MODELING OF TERRESTRIAL ECOSYSTEMS STRUCTURE AND FUNCTION CAN BE PROVIDED BY SATELLITE ALTIMETERS

# 4.2 REMOTE SENSING QUESTIONS

- WHAT ENVIRONMENTAL PARAMETERS DO I WANT TO MEASURE?
- HOW SHOULD I MEASURE A GIVEN ENVIRONMENTAL PARAMETER?
  - SENSOR?
  - FREQUENCIES AND BANDWIDTHS?
  - POLARIZATIONS?
- WHAT WILL BE THE ACCURACY AND PRECISION OF THE MEASURED ENVIRONMENTAL PARAMETERS? WHAT LIMITS THE ACCURACY AND PRECISION?
- WHAT IS THE RELATIONSHIP BETWEEN THE ENVIRONMENTAL PARAMETER WE NEED TO MEASURE AND THE PHYSICAL QUANTITIES THAT THE SENSOR(S) CAN MEASURE?

# 4.3 SPECIAL TOPICS
# ARMY REMOTE SENSING

- FOCUS DISCUSSION ON REMOTE SENSING OF PARAMETERS OF INTEREST TO ARMY
- LIST OF REMOTE SENSING AND ENVIRONMENTAL PARAMETERS
- DISCUSSION OF TECHNIQUES TO MEASURE OR RETRIEVE THESE PARAMETERS

# ARMY REMOTE SENSING PARAMETERS

- TRAFFICABILITY
  - ROADS & BRIDGES
  - SURFACE CONDITION
    - » SOIL MOISTURE
    - » ROUGHNESS
    - » RIVERS & LAKES
    - » SNOW & ICE COVERAGE
    - » FLOODING
  - VEGETATION
  - BURRIED OBJECTS
    - » LAND MINES, TUNNELS AND BUNKERS
- TOPOGRAPHY
  - SURFACE HEIGHT & SLOPES
  - BOUNDARIES
- CAMOUFLAGE, CONCEALMENT AND DECEPTION
  - DETECTION OF CAMOUFLAGE TARGETS
  - IDENTIFICATION OF TARGETS UNDER CAMOUFLAGE
  - DETECTION OF BOMB DAMAGE CONCEALMENT OR DECEPTION

# ARMY ENVIRONMENTAL PARAMETERS

- CLOUDS
  - COVERAGE
  - TYPE
  - LAYERS/THICKNESS
- VERTICAL TEMPERATURE PROFILE
- ATMOSPHERIC PRESSURE PROFILE
- ABSOLUTE HUMIDITY (PROFILE AND SURFACE VALUE)
  - LIQUID/SOLID WATER
    - » CONTENT
    - » CLOUD DROP SIZE
- WINDS
  - HORIZONTAL COMPONENT
  - VERTICAL COMPONENT
- PRECIPITATION
  - RAIN, SNOW AND HAIL
- ICE
  - SEA ICE
  - LANDLOCKED ICE COVER
- VISIBILITY
- SOIL MOISTURE
- LAND SURFACE TEMPERATURE
- VEGETATION COVERAGE/TYPE

# 5.0 SYSTEMS ENGINEERING ISSUES

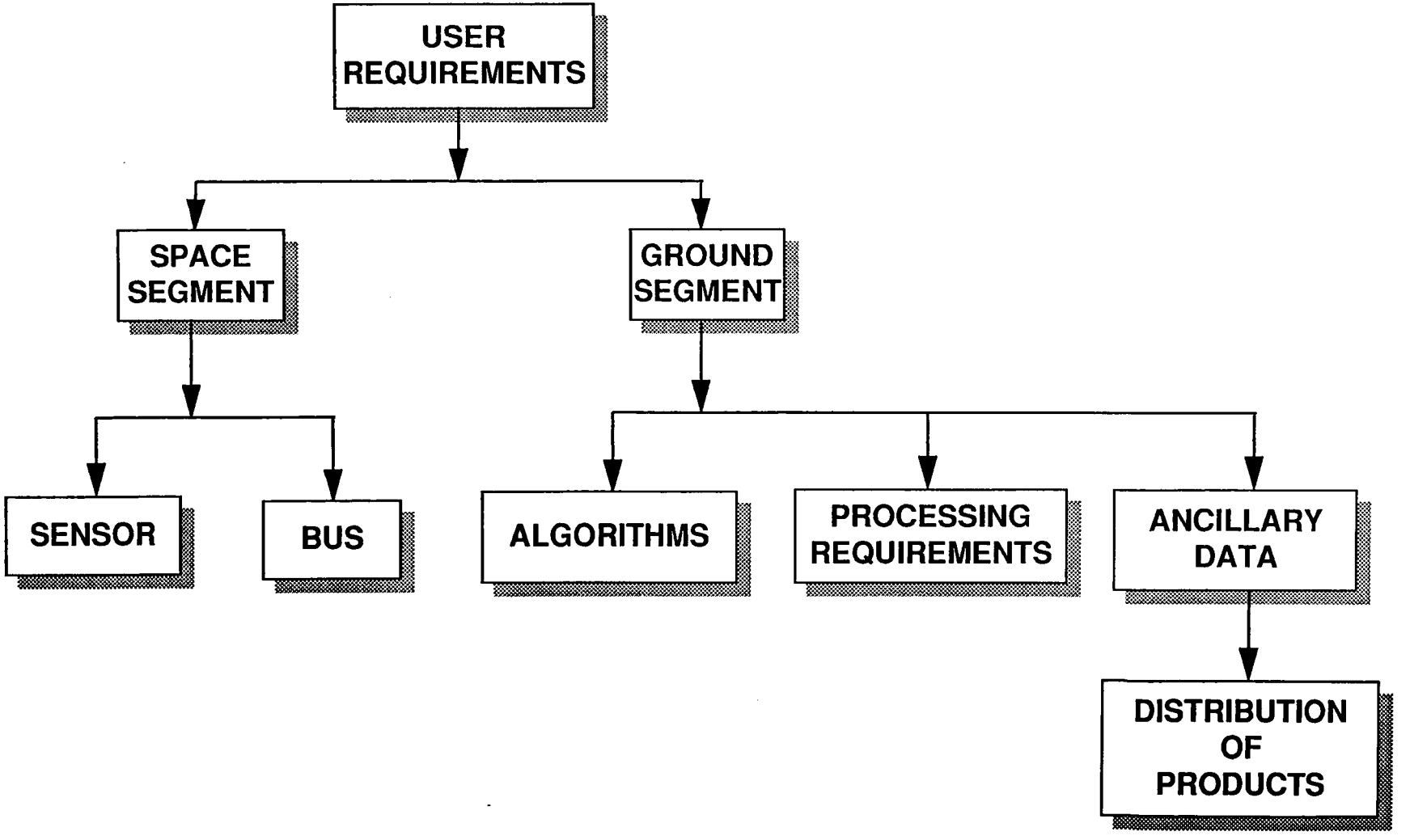
# 5.0 SYSTEMS ENGINEERING ISSUES

- REQUIREMENTS

- SYSTEMS ENGINEERING ISSUES - OVERVIEW

# SYSTEMS ENGINEERING ISSUES (contd)

- REQUIREMENTS FLOW DOWN
  - USER DEFINES REQUIREMENTS (SOMETIMES THEY NEED HELP)



# NOTES
# SSM/I SYSTEMS ENGINEERING ISSUES

The next two charts are a very brief listing of some of the systems engineering issues one must consider for a payload such as the SSM/I. These are not unique to the SSM/I and most will apply for a variety of payload types. One of the key concepts to understand is that of systems interaction. The radiometer is not an isolated instrument on the spacecraft, but rather interacts with the bus and other payloads on the DMSP bus.

# SYSTEMS ENGINEERING ISSUES (contd)

## MECHANICAL

- SIZE, WEIGHT
- STATIC
- DYNAMIC
- FIELD OF VIEW (FOV)
- POINTING STABILITY
- DEPLOY/STOW ANTENNA

## THERMAL

- HEAT LOADS
  * SOLAR
  * ELECTRONICS
- SENSOR-S/C TRANSFER
- DISSIPATION, RADIATORS, INSULATION & HEATERS

## ELECTRICAL

- POWER
- EMI & RFI

## OPERATIONAL ENV.

- SOLAR
- OUTGASSING
- RADIATION

## TELEMETRY/DATA

- DATA RATE
- COMMAND/CONTROL
- ON-BOARD PROCESSING & RECORDING

## SAFETY

- HAZARDS DUE TO FAILURES & FIRE

# SYSTEMS ENGINEERING ISSUES (contd)

## TESTING

- ENG. MODELS/PROTOTYPE
- SUBSYSTEMS
- SUBASSEMBLIES
- FULL ASSEMBLY
- QUALIFICATION TESTS
- ON-ORBIT TESTS
- CAL/VAL PROGRAM (POST LAUNCH)
- GROUND SEGMENT SOFTWARE TESTING

## RELIABILITY

- 0.8 FOR A 3 YR MISSION
- FAILURE MODE AND EFFECTS ANALYSIS

## GROUND SEGMENT

- DATA PROCESSING AND DISSEMINATION
- CALIBRATION
- ANTENNA PATTERN CORRECTION
- GEO-LOCATION
- ENVIRONMENTAL PARAMETER RETRIEVALS

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# lecture notes

# for

# Ronald G. Isaacs, MS, ME

# Earth Remote Sensing - Thursday - Day 4

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This seminar examines the physical and mathematical basis of remote sensing techniques, and applications of remote sensing systems employed in the visible, infrared and microwave portions of the spectrum including:

- simulation modeling via radiative transfer theory,
- methods for environmental product retrieval and data analysis,
- applications to meteorology and climate,
- observing system simulation approaches, and
- physical parameterizations;
- global change monitoring.

**Critical issues examined include:**

- **Evaluation of Retrieval Methods and Algorithms for Atmospheric Profiles, Cloud and Surface Properties**
- **Application of Simulation Codes based on Radiative Transfer Modeling**
- **Observing System Simulation Experiments (OSSEs) for End-to-End Remote Sensing System Simulation**
- **Dealing with Atmosphere, Ocean/Atmosphere Coupling, and Surface Properties**
- **Applications to Global Change Monitoring**
- **Tradeoffs in Sensor System Complexity and Data Retrieval Capability for Competing Candidate Sensor Technologies**
- **Data Fusion Techniques for Exploiting Multisensor, Multispectral Data Sets**

## Questions to be answered:

- What are the observational requirements for environmental parameters to support contemporary environmental modeling applications such as weather prediction and climate?

- How are the physical phenomena which contribute to the signal observed by remote sensing systems defined?

- How do these phenomena relate to environmental parameter information content required for contemporary environmental modeling applications?

- How can design tools be applied to model the response of a sensor system to changes in the earth's physical (i.e. atmospheric, oceanic, or surface) characteristics?

**Questions to be answered (continued):**

- **How can currently available sensor technologies be applied to exploit these signatures (and what are technology projections for these and novel approaches)?**

- **How can the trade-offs in sensor system complexity (weight, power, data rate) and data retrieval capability (spatial resolution, environmental parameter accuracy, coverage) be assessed for competing candidate sensor technologies?**

- **How can computer modeling simulation techniques be used to achieve an optimized, end-to-end systems approach to sensor design to meet the requirements of environmental parameter retrieval?**

- **How can data fusion techniques be employed to exploit multisensor, multispectral data sets?**

Morning

1. Forward Problem - Radiative Transfer
   - 1.1 Radiative transfer equation
   - 1.2 Multiple scattering approaches
   - 1.3 Simulation Codes: LOWTRAN, MODTRAN, FASCODE, RADTRAN)

2. Inverse Problem - Retrieval Approaches
   - 2.1 Inverse problem
   - 2.2 Smoothing methods
   - 2.3 Statistical methods
   - 2.4 Non-linear iterative (physical) methods
   - 2.5 Simultaneous method
   - 2.6 Cloud property retrieval (nephanalysis)
   - 2.7 Unified retrieval (data fusion)

**Afternoon**

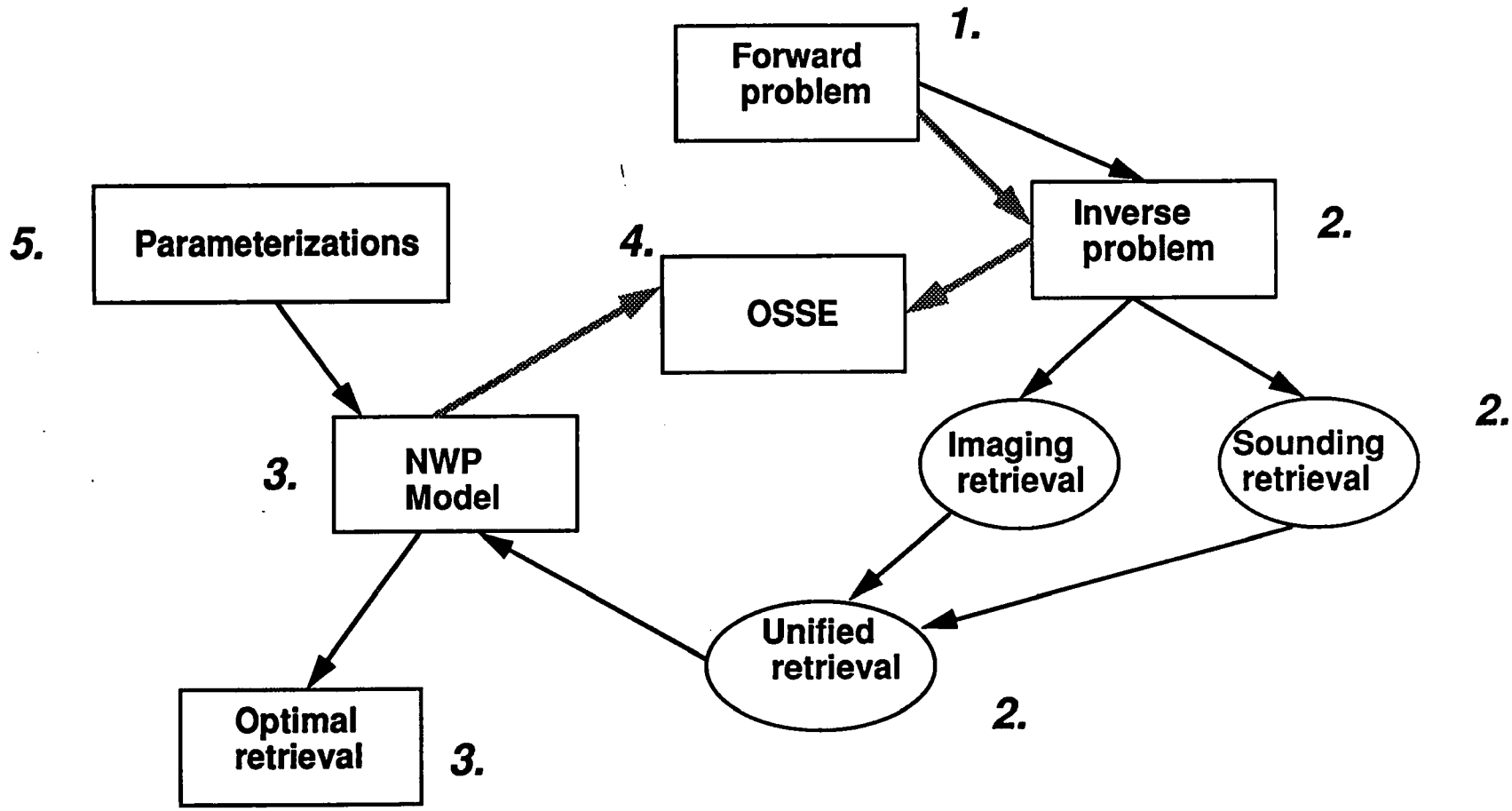
3. **Remote Sensing Applications for Meteorology and Climate**
   - **3.1 Meteorological parameters**
   - **3.2 Data assimilation techniques**
   - **3.3 Optimal retrieval**

4. **Observing System Simulation Experiments (OSSEs)**
   - **4.1 What is an OSSE**
   - **4.2 System simulation procedure**
   - **4.3 Nature run**
   - **4.4 Data sampling**
   - **4.5 OSSE procedure and comparison methodology**

5. **Physical Parameterizations**
   - **5.1 Atmosphere (clouds, convection, boundary layer)**
   - **5.2 Ocean (interaction with atmosphere)**
   - **5.3 Land (surface properties related to remotely sensed parameters)**

6. **Applications to Global Change Monitoring**

# Overview of Topics




"ZEN OF REMOTE SENSING"

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# 1. Forward Problem - Radiative Transfer

## 1.1 Radiative transfer equation

## 1.2 Multiple scattering approaches

## 1.3 Simulation Codes: (LOWTRAN, MODTRAN, FASCODE, RADTRAN)

# What is the "forward problem"?

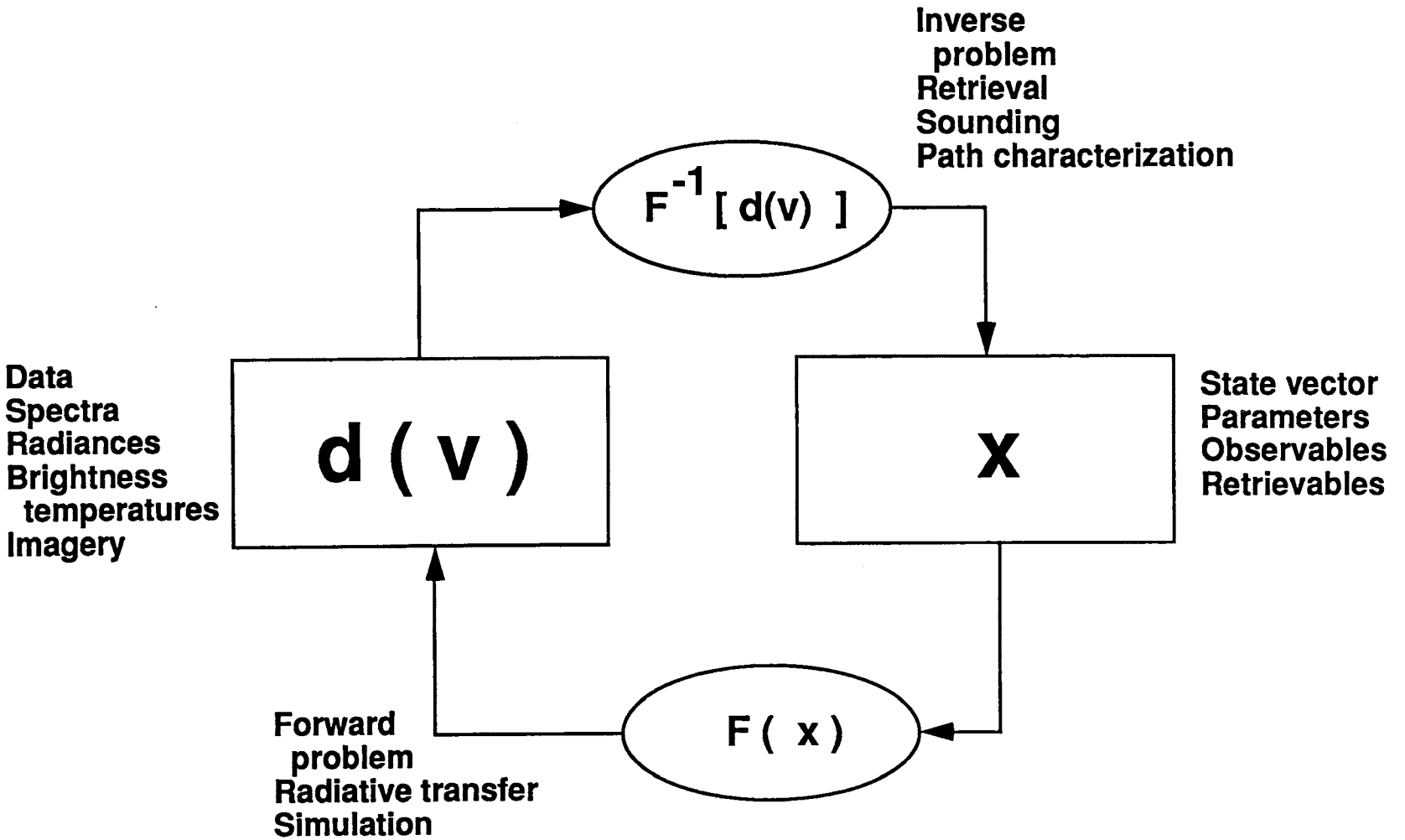
- The forward problem , F , symbolically maps the state of the atmosphere-surface system (parameter vector, x) into the electromagnetic spectrum (data vector, d):

$$d(v) = F(x)$$

- Remote sensing (i.e. the "inverse problem ") is predicated on the inference of the parameter vector from the data vector:

$$x = F^{-1}[d(v)]$$

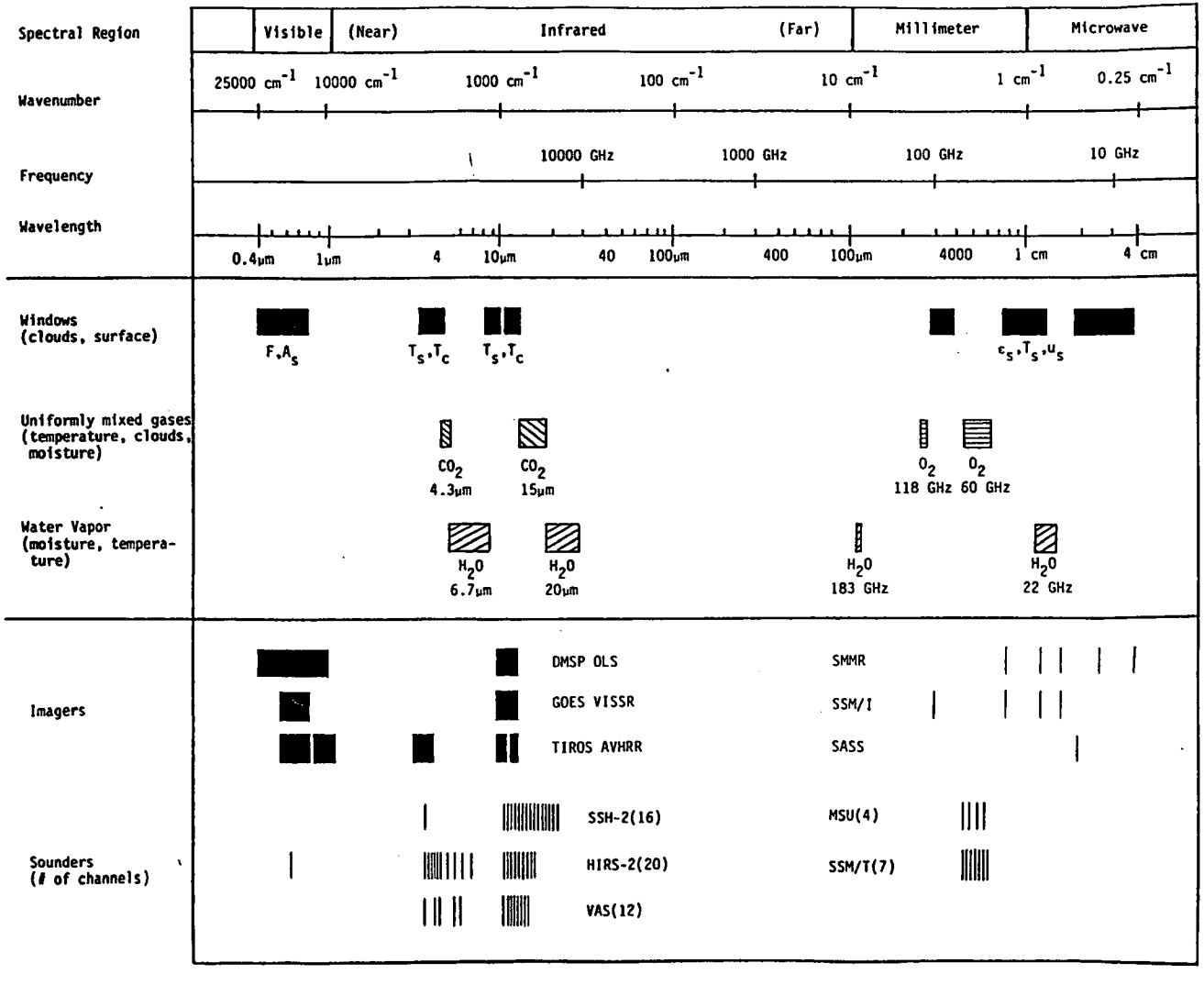
## Schematic


Inverse
problem
Retrieval
Sounding
Path characterization
$F^{-1}[\, d(v)\, ]$
Data
Spectra
Radiances
Brightness
temperatures
Imagery
d ( v )
x
State vector
Parameters
Observables
Retrievables
Forward
problem
Radiative transfer
Simulation
F ( x )

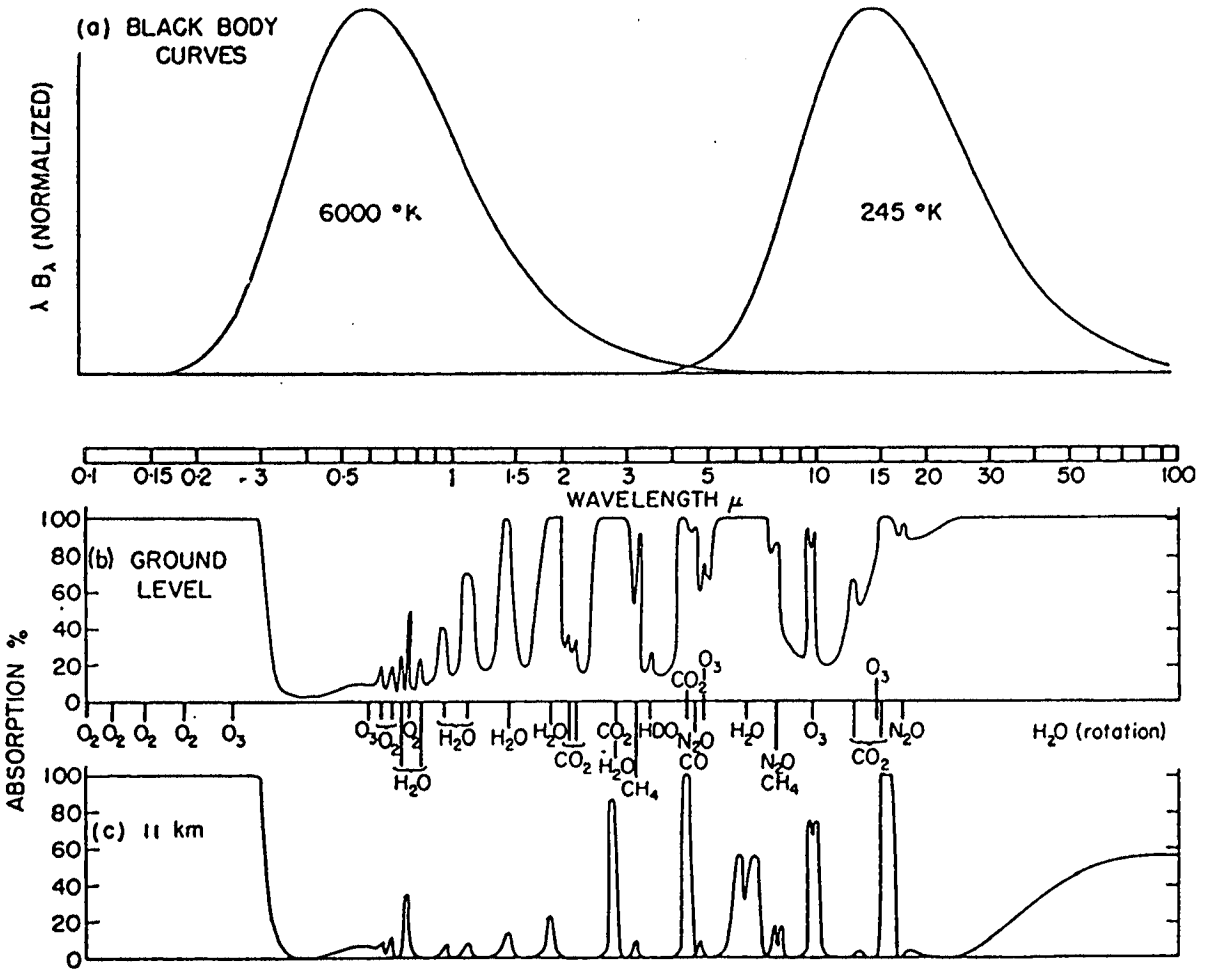
**Radiative transfer (RT) equation: a general formalism for the evaluation of the electromagnetic response of the atmosphere-surface system which depends on:**

- **frequency (or wavelength, wavenumber, etc.)**
- **surface temperature**
- **surface emissivity (or reflectivity)**
- **atmospheric temperature (as a function of path observed)**
- **absorber composition along path (abundance, number density, mixing ratio, etc.)**
- **scatterer composition along path**
- **absorber and scatterer optical properties(absorption and scattering per unit volume/amount, scattering to absorption ratio, angular scattering properties) along path**
- **can be averaged or tailored to address required spectral resolution f or given application**

# Schematic description of the spectrum



# Thermal and solar source function regions and major absorbers



## Predominant transmission windows

| Spectral Region | Windows |
|---|---|
| Microwave | 20.0+ mm |
| | 7.5–11.5 mm |
| | 3.0–3.75 mm |
| | 2.06–2.22 mm |
| Thermal infrared | 17.0–22.0 $\mu$m |
| | 10.2–12.4 $\mu$m |
| | 8.0–9.2 $\mu$m |
| Middle infrared | 4.5–5.0 $\mu$m |
| | 3.5–4.16 $\mu$m |
| Near infrared | 2.05–2.4 $\mu$m |
| | 1.55–1.75 $\mu$m |
| | 1.19–1.34 $\mu$m |
| | 1.0–1.12 $\mu$m |
| Ultraviolet and visible | 0.77–0.91 $\mu$m |
| | 0.30–0.75 $\mu$m |

## Sounding wavelengths and species

| Band | Species | Wavelength |
|---|---|---|
| Visible | $O_3$ | 0.6 $\mu$m |
| Near IR | $H_2O$ | 0.94 $\mu$m |
| | | 1.16 $\mu$m |
| | | 1.38 $\mu$m |
| | | 1.89 $\mu$m |
| | $CO_2$-$H_2O$ | 2.51 $\mu$m |
| Middle IR | $CO_2$ | 4.30 $\mu$m |
| | $H_2O$ | 6.70 $\mu$m |
| Thermal IR | $O_3$ | 9.6 $\mu$m |
| | $CO_2$ | 15.0 $\mu$m |
| | $H_2O$ | ~20 $\mu$m ← DMSP. SSH |
| Microwave | $H_2O$ | 0.16 cm (183 GHz) |
| | | 1.35 cm (22.235 GHz) |
| | $O_2$ | 0.25 cm (118 GHz) |
| | | 0.5 cm (60 GHz) |

## The Radiative Transfer Equation:

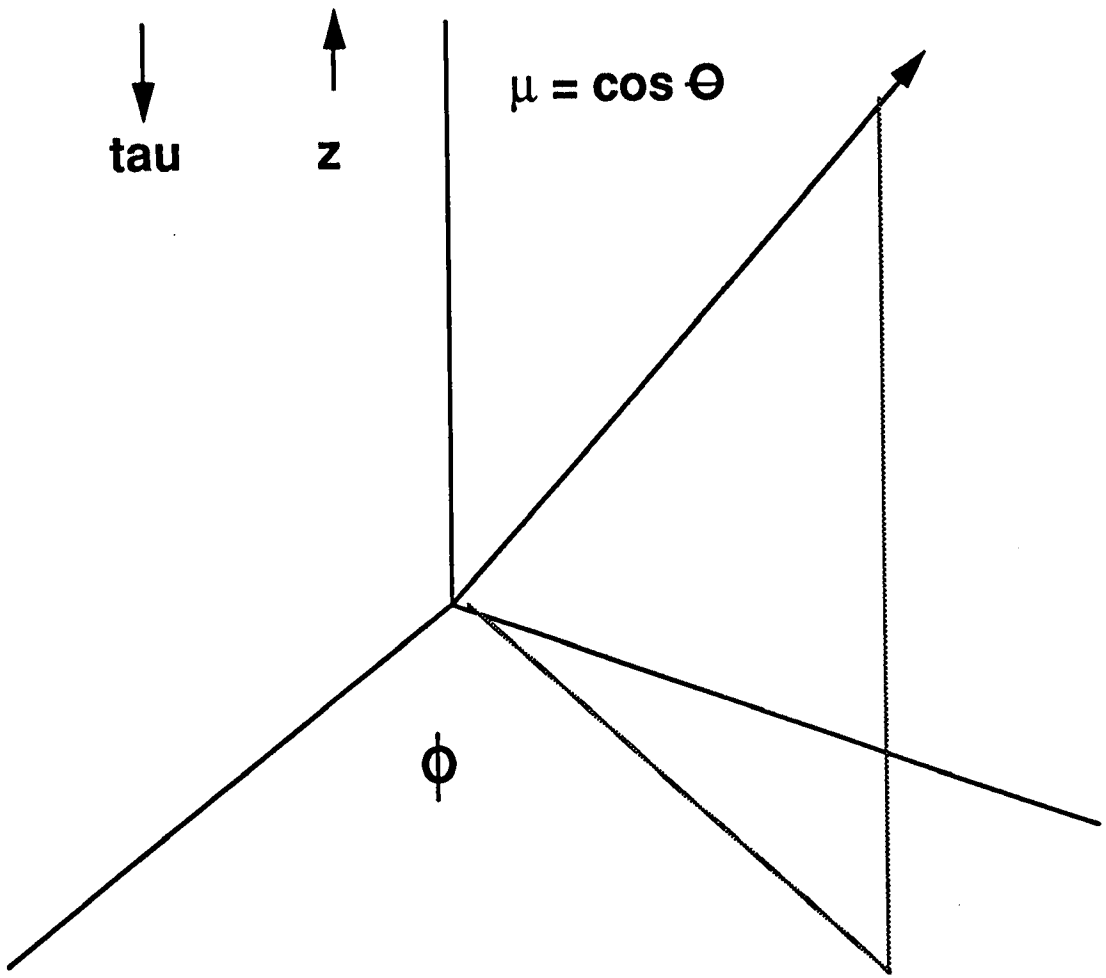
The desired path radiance I at wavenumber $\upsilon$ for an arbitrary path is given by the solution to the radiative transfer equation (RTE):

$$\mu \frac{d}{d\tau} I_\upsilon(\tau,\mu,\phi) = I_\upsilon(\tau,\mu,\phi) - J_\upsilon(\tau,\mu,\phi)$$

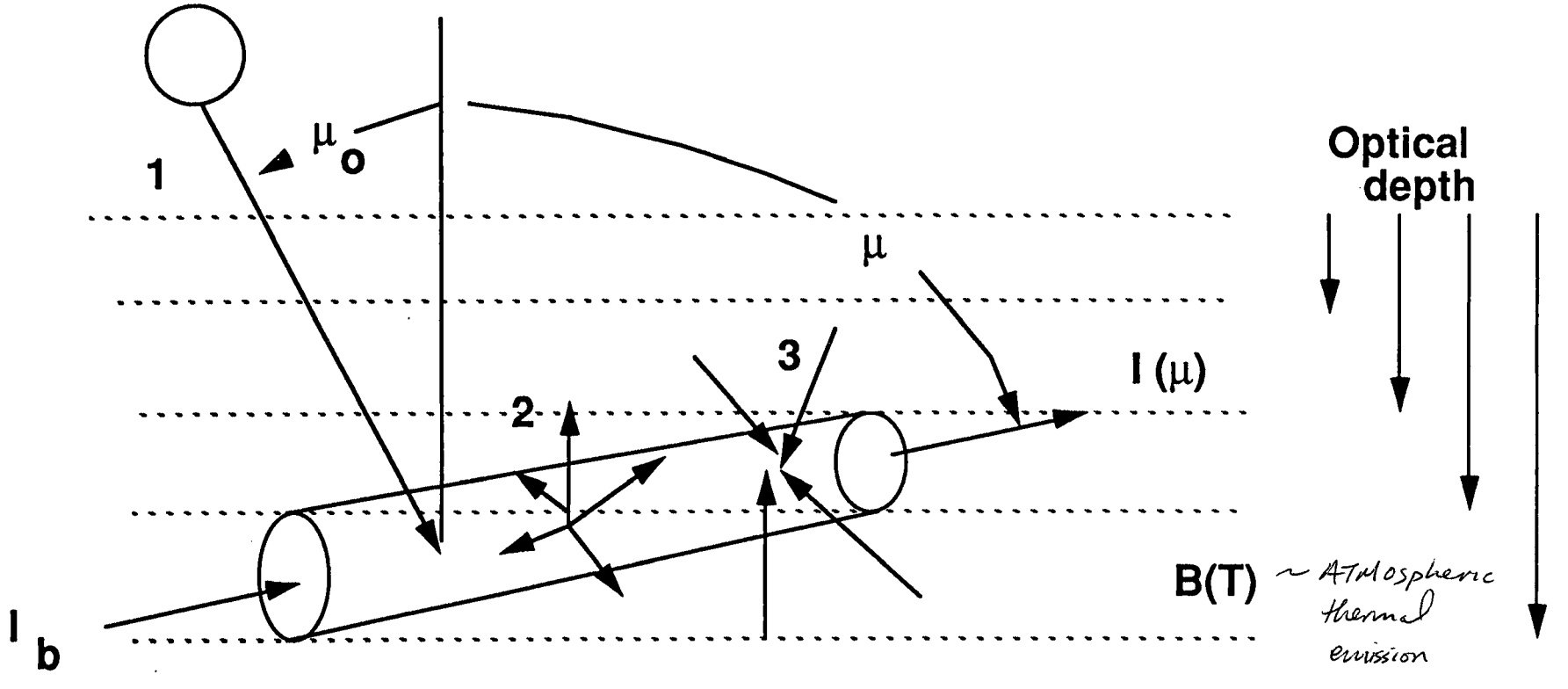
Here, $\tau$ is the vertical optical depth, $\mu$ is the cosine of the path zenith angle, and $\phi$ is the azimuth angle relative to the sun's azimuth. Optical depth, $\tau$, will depend on the relevant mechanisms determining the extinction of electromagnetic radiation for the spectral region characterized by wavenumber $\upsilon$.

Ref: Liou, K. N. , *An Introduction to Atmospheric Radiation.* Academic Press.

## Radiative transfer coordinate system



## Source function contributions to radiance path integral




1 primary solar source function
2 thermal emission
3 multiple scattering

Extinction mechanisms include: (a) molecular absorption $\kappa_a$, (b) molecular (i.e, Rayleigh) scattering $\kappa_s$, (c) particulate absorption $\sigma_a$, and (d) particulate scattering $\sigma_s$. Optical depth is given by integrating the relevant vertical extinction coefficient profiles according to:

$$\tau_v(z) = \int_z^\infty \left[\kappa_a(z) + \kappa_s(z) + \sigma_a(z) + \sigma_s(z)\right] dz.$$

The single scattering albedo is a dimensionless parameter bounded by (0, 1) which determines the relative significance of scattering and absorption mechanisms:

$$\omega_0(\tau) = \Delta\tau_s / \Delta\tau,$$

**The general source function Ju including scattering of solar radiation and thermal emission, is given by**

$$(3)\quad J(\tau,\mu,\phi) = J_0(\tau,\mu,\phi) + J_{MS}(\tau,\mu,\phi),$$

**where single scattering and local thermal emission are**

single scattering albedo — scattering phase function

$$(4)\quad J_0(\tau,\mu,\phi) = \frac{\omega_0(\tau)}{4\pi}\pi F \exp(-\tau/\mu_0) P(\Omega;-\Omega_0) + [1-\omega_0(\tau)]B[\theta(\tau)],$$

**and the multiple scattering source function is**

$$(5)\quad J_{MS}(\tau,\mu,\phi) = \frac{\omega_0(\tau)}{4\pi}\int_\Omega P(\Omega;\Omega')I(\tau,\Omega')d\Omega'.$$

# Forms of the radiative source function

TABLE 2. Radiative Source Functions: Forms of Surface, $R_i(p_b)$, and Atmospheric, $S(p)$, Contributions to Satellite-Incident Radiances, $R_i(\theta)$

source function

| Spectral Region | Surface, $R_i(p_b)$ | Atmospheric, $S(p)$ |
|---|---|---|
| Ultraviolet/visible ($\lambda < 0.7\ \mu$m) | $\pi F_i \rho_i(\Omega_0)\tau_i(\theta_0, p_b)$ | $\omega_i(p)J_i(p, \Omega)$ |
| Near infrared ($0.7 < \lambda < 4.0$) | $\pi F_i \rho_i(\Omega)\tau_i(\theta_0, p_b)$ $+ \varepsilon_i B_i[T(p_b)]$ $+ (1 - \varepsilon_i)R_i\downarrow(p_b)$ | $[1 - \omega_i(p)]B_i[T(p)]$ $+ \omega_i(p)J_i(p, \Omega)$* |
| Infrared ($4.0 < \lambda < 100\ \mu$m) | $\varepsilon_i B_i[T(p_b)]$ $+ (1 - \varepsilon_i)R_i\downarrow(p_b)$ | $B_i[T(p)]$† |
| Millimeter/microwave ($\lambda > 1000\ \mu$m) | $\varepsilon_i B_i[T(p_b)]$ $+ (1 - \varepsilon_i)R_i\downarrow(p_b)$ | $[1 - \omega_i(p)]B[T(p)]$ $+ \omega_i(p)J_i(p, \Omega)$‡ |

Legend: $F_i$ is solar irradiance; $\rho_i$ is bidirectional reflectance of surface; $\Omega_0$ and $\theta_0$ are sun/sensor reflection angle and solar zenith angle; $\varepsilon_i$ is surface emissivity; $\omega_i$ is single scattering albedo; $R_i\downarrow$ is downward atmospheric flux; $B_i$ is Planck function (thermal source function); and $J(p, \Omega)$ is scattering source function for scattering angle $\Omega$.

*Assumes scattering by aerosol or cloud.

†Assumes no scattering, if scattering same as for near infrared.

‡Assumes scattering by precipitation; if no scattering, same as for infrared.

**Flux: Boundary conditions at the surface will depend on the nature of the surface reflectance/emittance properties. The most common assumption is that of Lambert reflectance, i.e. the upward isotropic flux given by a constant surface albedo r times the downward flux. Upward and downward fluxes at optical depth t are defined, respectively, as :**

$$F^{\pm}(\tau) = \int_0^{2\pi} \int_0^1 I(\tau, \pm\mu, \phi)\mu d\mu d\phi$$

**This results in a lower boundary condition upward radiance of:**

$$I_b(\tau^*, \mu, \phi) = \frac{r}{\pi}\left[\pi F \mu_0 \exp\left(-\tau^*/\mu_0\right) + \int_0^{2\pi} \int_0^1 I(-r^*, -\mu, \phi)\mu d\mu d\phi\right]$$

$$+(1-r)B\left[\theta(\tau^*)\right].$$

**General radiance solutions to the RTE for upward and downward radiances, respectively, are:**

***Upward Radiance -***

$$I(\tau,+\mu,\phi) = I_b(\tau^*,\mu,\phi)\exp\left[-(\tau^*-\tau)/\mu\right] + \int_{\tau}^{\tau^*} J(t,\mu,\phi)\exp\left[-(t-\tau)/\mu\right]\frac{dt}{\mu},$$

***Downward Radiance -***

$$I(\tau,-\mu,\phi) = I_b(0,-\mu,\phi)\exp\left(-\tau/\mu\right) + \int_{0}^{\tau} J(t,\mu,\phi)\exp\left[-(\tau^*-\tau)/\mu\right]\frac{dt}{\mu},$$

**The forward problem for multiple scattering can be treated in one of the following ways (see Lenoble, 1985, *Radiative Transfer in Scattering and Absorbing Atmospheres: Standard Computational Methods*, Deepak Publishing):**

- **Exact analytical methods**
  - **Single scattering**
  - **H functions or X and Y functions**

- when to use each method?
- advantages and disadvantages?

- **Approximate methods**
  - **Similarity relations**
  - **Two stream methods**
  - **Asymptotic methods**

- **Numerical methods**
  - **Monte Carlo**
  - **Spherical Harmonics**
  - **Discrete Ordinates (Gaussian quadrature)**

## Multiple scattering numerical approaches:

There are a variety of numerical solutions to the radiative transfer equation when multiple scattering is an issue. In general, these seek to treat the source function integral in an appropriate manner, i.e.:

$$J_{MS}(\tau,\mu,\phi)=\frac{\omega_0(\tau)}{4\pi}\int_{\Omega}P(\Omega;\Omega')I(\tau,\Omega')d\Omega'.$$

For example, if one assumes a simple two point quadrature of this term in the RTE, obtains:

$$J_{MS}(\tau,\mu,\phi)\simeq\frac{\omega_0(\tau)}{4\pi}\Big[I^{+}(\tau)\int_{\Omega^{+}}P(\Omega,\Omega^{+})d\Omega^{+}$$

$$+\ I^{-}(\tau)\int_{\Omega^{-}}P(\Omega,\Omega^{-})d\Omega^{-}\Big].$$

The resulting two integrals can be approximated from a knowledge of the properties of the scatterers.

**Thermal emission:**

**If the single scattering albedo is zero (no scattering) the source function:**

$$J_0(\tau,\mu,\phi)=\frac{\omega_0(\tau)}{4\pi}\pi F\exp(-\tau/\mu_0)P(\Omega;-\Omega_0)+[1-\omega_0(\tau)]B[\theta(\tau)],$$

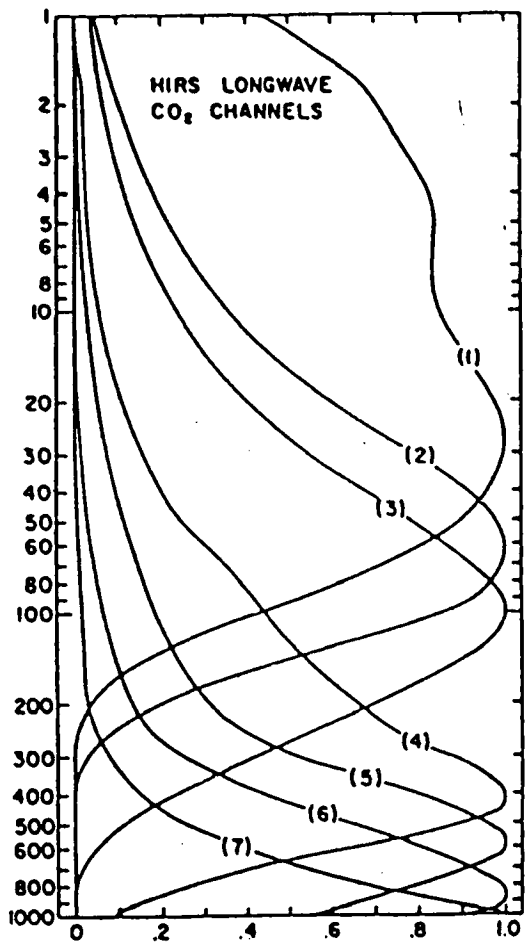
**reduces to the Planck black body function.**

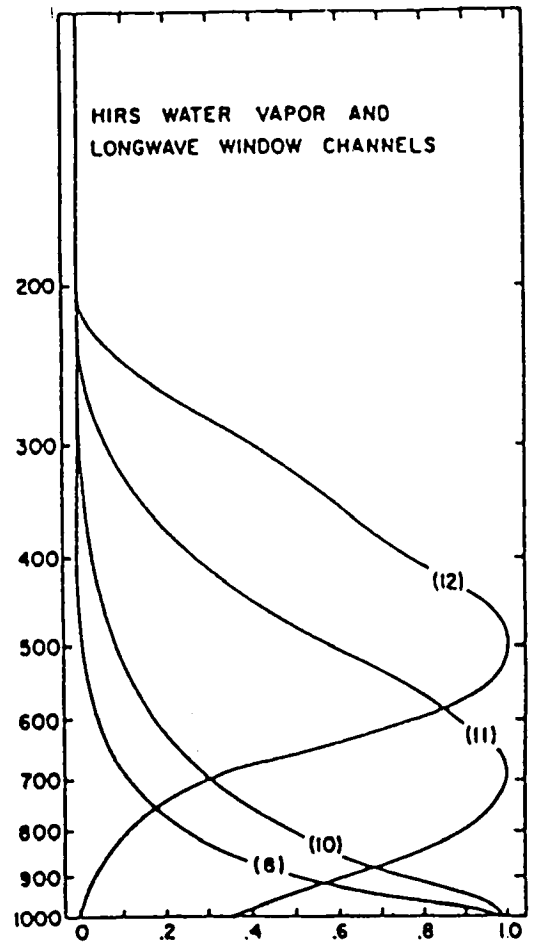
**The radiance solution then become simple line integrals of the Planck function along the path:**

$$I_i(\theta)=B_i[T(p_b)]\tau_i(\theta,p_b)+\int_{p_b}^{0}B_i[T(p)]W_i(\theta,p)d\ln p$$

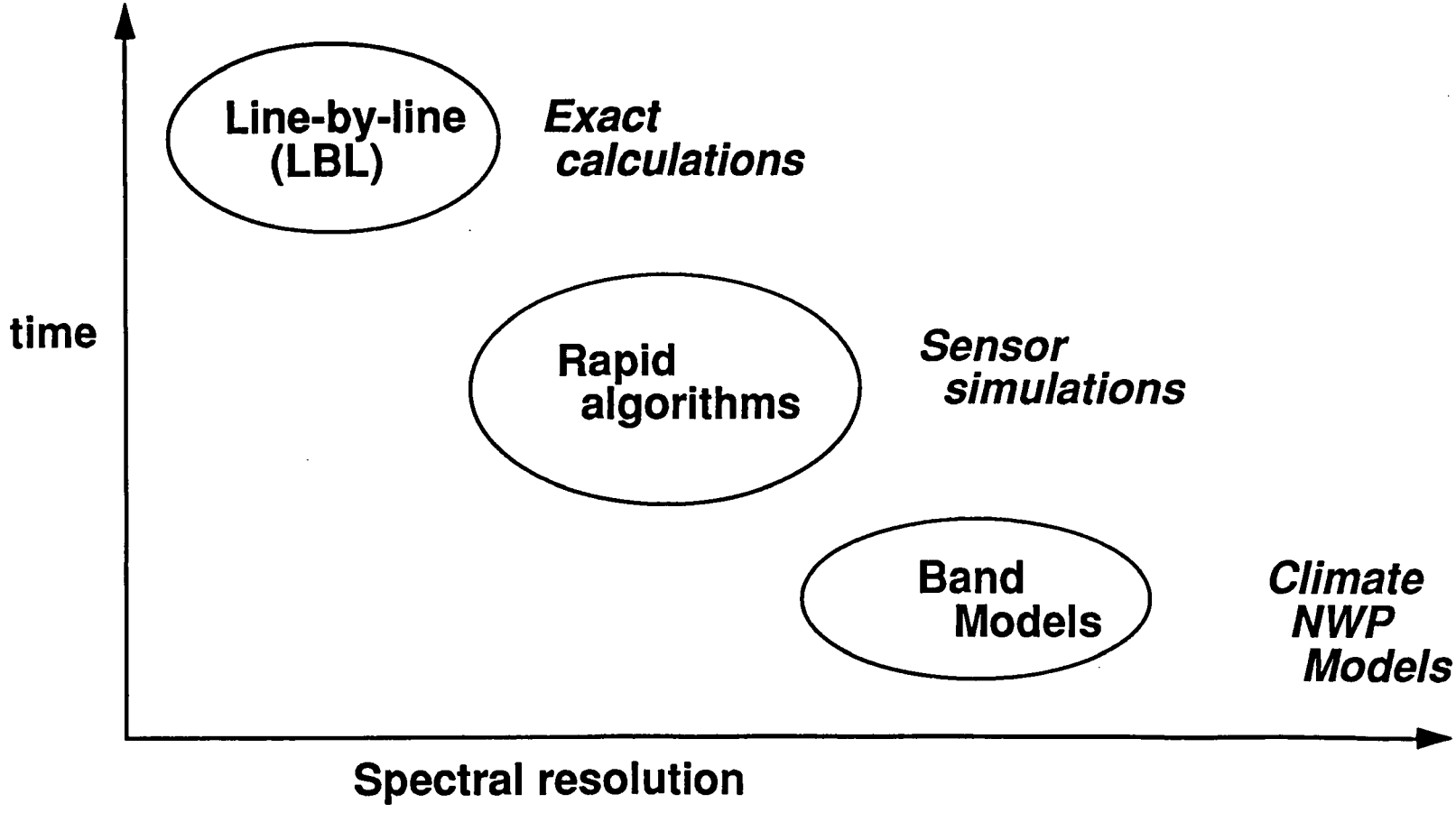
**Where W, are a set of weighting functions given by the pressure derivative of the transmittance.**

# Weighting functions for the TOVS HIRS package



**Radiative transfer approaches depend on computational resources (computer time) which are available and appropriate traded with desired spectral resolution:**



Line-by-line codes:

- Provide an exact, highly accurate computation of atmospheric transmission in the presence of gaseous absorption;
- Spectral resolution sufficient to resolve individual spectral lines.

Rapid Algorithms:

- Parameterized models based on line-by-line codes which provide efficient mean to calculate sensor bandpass transmissions and radiances;
- Spectral resolution typical of sensor 10-20 cm-1 typical in the infrared.

Band Models:

- Similar to rapid algorithms, but span large portions of the solar and infrared spectrum;
- Provide parameterized radiative transfer for numerical weather prediction and climate models;
- Spectral resolutions typically hundreds of wavenumbers.

**Line-by-line calculation:**

**Atmospheric transmittance consists of contributions by lines, , the continua, , and particulate extinction, :**

$$\tau_i(\theta,p) = \tau_{il}(\theta,p)\tau_{ic}(\theta,p)\tau_{ie}(\theta,p)$$

└ continua model depends on how lines are modeled.

**The contribution due to n discrete absorption lines is:**

$$\tau_{il}(\theta,p) = \int \phi_i(\nu) \cdot \exp -\left\{\frac{\sec\theta}{g}\sum_n \int_p^0 k_n[\nu, p', T(p')]q_n(p')dp'\right\}d\nu$$

absorption coeff.

absorber quantity

Rapid algorithm approach: Use simple expressions to calculate sensor channel bandpass weighted radiances

For the HIRS2 temperature sounding channels, transmittance at a given angle depends only on the temperature profile. The model for mean layer transmittance due to gases of fixed distribution for each reference angle is given by:

$$\tau_{iF}(pj, pj-1, \theta) = A_{ij}(\theta) + B_{ij}(\theta)\left(T_j - T_{j}^{o}\right) + C_{ij}(\theta)\left(T_{ij}(\theta) - T_{ij}^{o}(\theta)\right)$$

where Tj is the mean temperature in the layer j , between pj and pj-1, for the temperature in profile under consideration,Toj is the mean temperature in layer j in a standard temperature profile, and Tij and Toij are the effective mean temperatures for the entire profile from pj to the top of the atmosphere for the temperature profile under consideration and the standard temperature profile, respectively. The effective temperature is defined as:

$$T_{ij}(\theta) = \frac{1}{1 - \tau_{i}^{0}(p_j, \theta)} \int_0^{p_j} T(p) \frac{d\tau_i}{dp}(\theta) dp$$

where τi is the transmittance of channel i for the standard temperature profile. The coefficients Aij(q), Bij(q), and Cij(q) are determined so as to give the best fit in the least squares sense to the values of τiF obtained from LBL calculations.

**Band model approach:**

**If the channel has an effective bandpass Dj and contains a random array of lines of individual equivalent widths Wji, the average transmittance is (Kaplan, 1953):**

$$\tau_j(p,\theta)_{\text{lines}} = \exp\left[-\sum_i W_{ji}(p,\theta)/D_j\right]$$

**to the extent that the lines in Dj are representative of those in a broader bandpass. If, further, the lines have a Lorentz shape and their intensities Sji and halfwidths αji are independent of temperature and the absorbing gas in uniformly mixed in the atmosphere with volume fraction q, the individual equivalent widths have the value (Pederson, 1942):**

$$W_{ji}(p,\theta) = 2\sqrt{\pi}\left(\alpha_{0_{ji}}\, p/p_0\right)\Gamma\left(\eta_{ji}+\tfrac{1}{2}\right)/\Gamma\left(\eta_{ji}\right),$$

**where α is the halfwidth at reference pressure p0, and**

$$\eta_{ji} = \left(qS_{ji}p_0\right)/\left(2\pi\alpha_{0_{ji}}\rho_0 g\right)$$

**is independent of height with r0 being the reference density used to define Sji and g the acceleration of gravity.**

**Band model approach (continued):**

**In terms of the absorber amount**

$$m = \frac{q}{\rho_0 g} p_0$$

**This asymptotically approaches, in the weak- and strong-line limit, respectively,**

$$-\ln \tau_j(p_0,\theta)_{WL} = \lim_{Sm \to 0}\left(-\ln \tau_j(p_0,\theta) = \sum_i S_{ji}\, {}^{m}\!/_{D_j}\right.$$

$$-\ln\left(\tau_j(p_0,\theta)_{SL} = \lim_{{}^{Sm}\!/_{\alpha_0} \to \infty}\left(-\ln \tau_j(p_0,\theta) = \sum_i \sqrt{2S_{ji} m \alpha_{0ji} / D_j}\right.\right.$$

**computational efficient approximation**

$$-\ln \tau_j(p_0,\theta) = \sum_i \frac{S_{ji} m}{D_j}\left(1 + \frac{S_{ji} m}{2\alpha_{0_{ji}}}\right)^{-1/2},$$

**which is similar in form to the Goody (1952) random exponential model.**

## Simulation codes

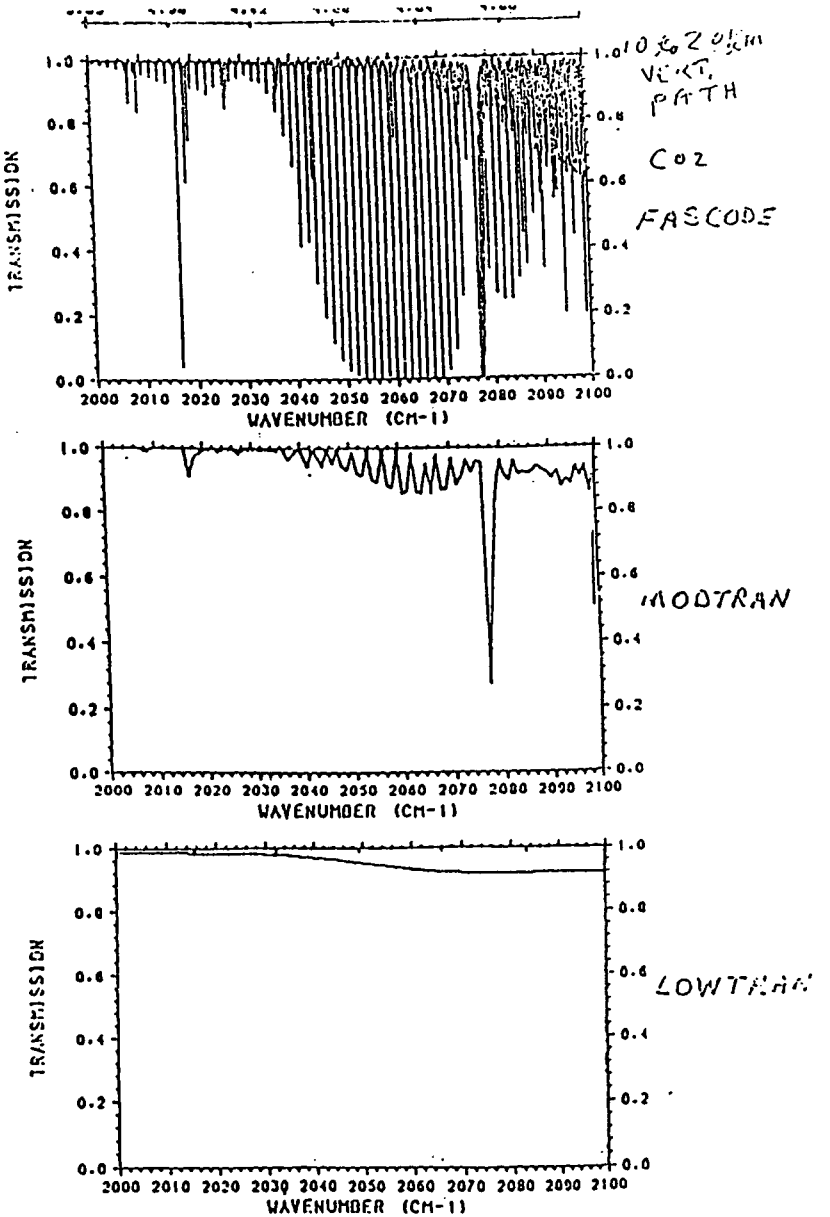
- A number of simulation (e.g. radiative transfer) codes are available in the public domain which have been used by government, university, and private investigators;
- This discussion will be limited to those developed and maintained by the Geophysics Directorate of the Air Force Phillips Laboratory summarized below:

| Code | Resolution | Applicability | Comments |
|---|---|---|---|
| - LOWTRAN | 20 cm-1 | 0-50,000 cm-1 | 1 parm band model |
| - MODTRAN | 2 cm-1 | 0-50,000 cm-1 | 2 parm band model |
| - FASCODE | LBL | 0-50,000 cm-1 | HITRAN input |
| - RADTRAN | LBL | 1-300 Ghz | self contained line file |

- These are general purpose codes which calculate transmission for general paths, radiances (or brightness temperatures), and treat multiple scattering to some degree of approximation.

Kneizys, F. X. and L. W. Abreu (eds.), 1990: *Proceeding of the 13th Annual Review Conference on Atmospheric Transmission Models.* Geophysics Laboratory (AFSC), Hanscom AFB, MA 01731

# Comparison of LOWTRAN, MODTRAN, and FASCODE for 2000-2100 cm-1 region:




$\Delta\nu \sim 0.01\ cm^{-1}$

## Model attributes of propagation models

### GL Atmospheric Propagation Models

| General Properties | FASCODE | MODTRAN | LOWTRAN |
|---|---|---|---|
| Spectral Resolution | | | |
| High | X | | |
| Moderate | X | X | |
| Low | X | X | X |
| Capabilities | | | |
| Transmittance | X | X | X |
| Background Radiance | | | |
| Thermal | X | X | X |
| Solar/Lunar | | X | X |

## LOWTRAN

- **Resolution: 20 cm-1 (low)**
- **Physics: 1-parameter band model**
- **Altitude range: ground to 40 km (limited by band model)**
- **Applications: broad band simulations, contrast, solar (direct and scattered) radiation**
- **Comments: efficient (no time penalty)**

# LOWTRAN computed reflected spectra for various surface types

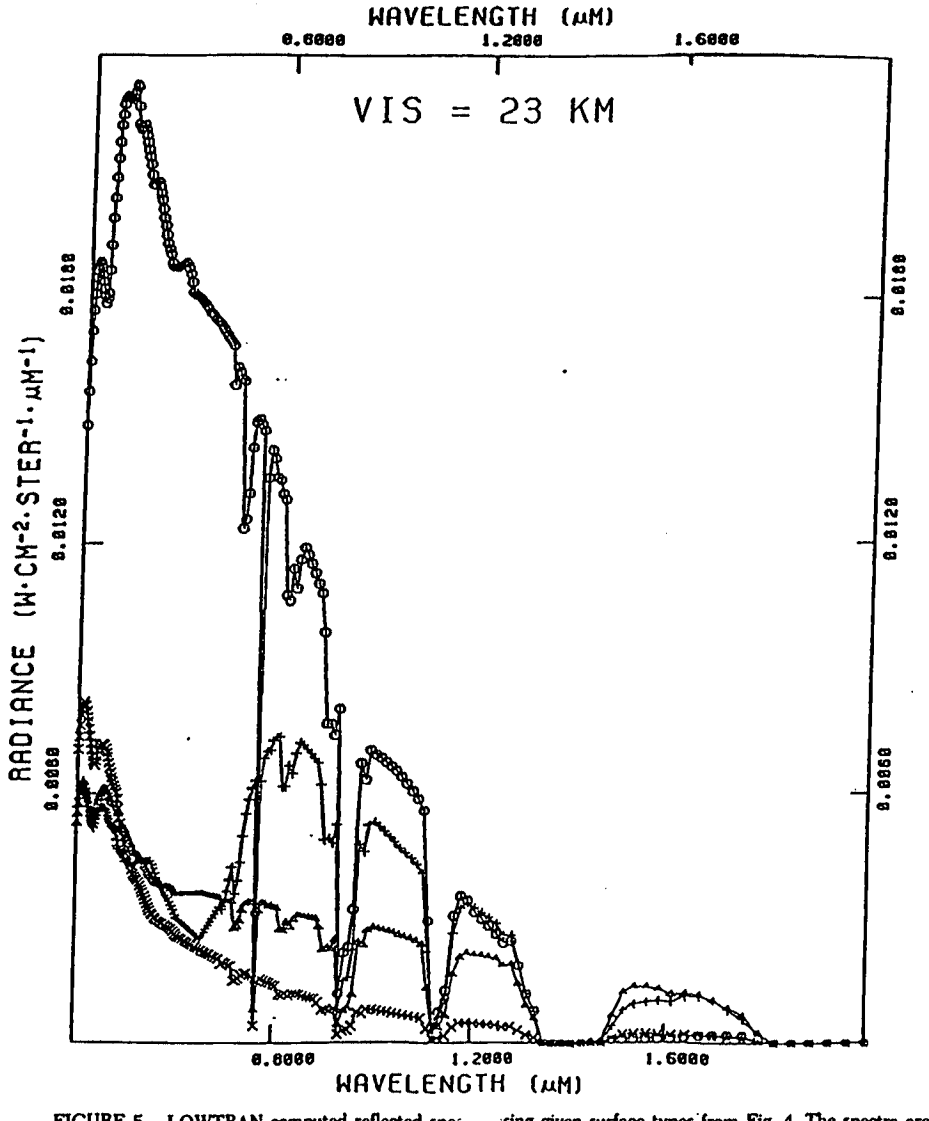



FIGURE 5. LOWTRAN computed reflected spe- sing given surface types from Fig. 4. The spectra are viewed from nadir at the top of a clear atmosphe visibility) and the solar zenith angle is 60°: (⊙) old snow; (△) plowed field; (+) plants; (×) sea.

## MODTRAN

- Resolution: 2 cm-1 (moderate)
- Physics: 2-parameter band model
- Altitude range: ground to 60 km (limited by NLTE)
- Applications: background simulations, plumes, solar (direct and scattered) radiation, better suited for high altitude paths (above 30 km)
- Comments: moderate time consumption (uses external data base in 1 cm-1 bins)

## FASCODE

- **Resolution: LBL (high)**
- **Physics: full molecular spectroscopy with high efficiency line shape decomposition approach including line coupling, NLTE, multiple scattering**
- **Altitude range: ground to 120 km**
- **Applications: laser propagation, plume signature, target contrast, remote sensing, data simulation, instrument design and development, weighting functions**
- **Comments: moderate time consumption (uses external data base in 1 cm-1 bins)**

# 2. Inverse Problem - Retrieval Approaches

## 2.1 Inverse problem

## 2.2 Smoothing methods

## 2.3 Statistical methods

## 2.4 Non-linear iterative (physical) methods

## 2.5 Simultaneous method

## 2.6 Cloud property retrieval (nephanalysis)

## 2.7 Unified retrieval (data fusion)

**Statement of the inverse problem:**

**Given a set of measurements (or observations) of the radiation emitted, scattered, and/or reflected by the atmosphere-surface system, what can be deduced about its physical state?**

**Symbolically:**

$$x = F^{-1}[\,d(v)\,]$$

**where:**

**F is the forward problem (§1)**

**d is a data vector of M observations**

**x is a state vector of N desired parameters**

## Properties of the inverse problem:

- *Ill-posed* -

  To be well posed, a solution to the problem must exist. Since the number of data points M is finite and the desired parameters are generally continuous functions, the problem is not well posed.

- *Ill-conditioned* -

  To be well conditioned (or robust), solutions must be relatively insensitive to the data. Practically, data are always somewhat uncertain due to measurement noise, i.e. small measurement errors may result in large errors in retrieved parameters.

## Partial solutions:

- **Ill-posedness -**

  **The inverse problem may be rendered well-posed by adding constraints. These may be statistical, physical, or otherwise. The type of constraints added define major retrieval approaches. Ex. a desired continuous parameter can be expanded in terms of an appropriate set of functions which reduces the number of unknowns.**

- **Ill-conditioning -**

  **Sensitivity of the inverse problem can be improved by minimizing the sum of the squared errors in the data and by overdetermining the system to the extent possible.**

Retrieval approaches:

- Sounding
  - statistical
  - smoothing (generalized inverse)
  - non-linear iterative (physical)
  - differential inversion
  - tomographic retrieval
- Imaging
  - cloud property analysis (nephanalysis)
- Data fusion (sounding + imaging)
  - unified retrieval
- Neural networks

| Retrieval Method | Characteristics | Reference |
|---|---|---|
| General | *smoothness constraint* | Twomey,Tikhonov |
| Statistical | *requires a priori data; forward problem can be used to generate statistics for a priori; efficient* | Rodgers, Westwater |
| Non-linear iterative | *requires accurate forward problem; physical and other constraints easily introduced* | Chahine |
| Simultaneous | *attributes of both generalized and iterative retrieval; solves for total state vector* | Smith |

## Smoothing (generalized inverse)

- This classical approach is associated with Phillips, Twomey, and Tikhonov;
- Can be though of as minimizing the error between the observations Ri and the forward model Fi, such that errors in the measurements and any a priori trial function are considered;
- The concept of a "penalty function" or smoother is employed to help treat ill-conditioning of problem;
- Recently, Isaacs et al (1990) have provided an updated implementation of this approach for application with the FASCODE line-by-line forward problem model.

**Minimizing the square of the differences between the observations R and the forward model F(x) such that the variance, $\sigma^2$, given by**

$$\sigma^2 = [R - F(x)]^T W[R - F(x)] + X^T \Gamma x$$

**is a minimum. Wi is a weight for the i'th observed radiance, Ri.**

**For the maximum likelihood method we have**

$$\Gamma = S_x^{-1}$$

**with Sx the error covariance of the first guess and**

$$W = S_R^{-1}$$

**with SR the error covariance of the measurements. For the ridge regression approach, $\Gamma$ is given by**

$$\Gamma_{ij} = \delta_{ij}\gamma_i$$

**where $\gamma_i$ is a damping parameter which constrains the direction and step for the non-linear problem.**

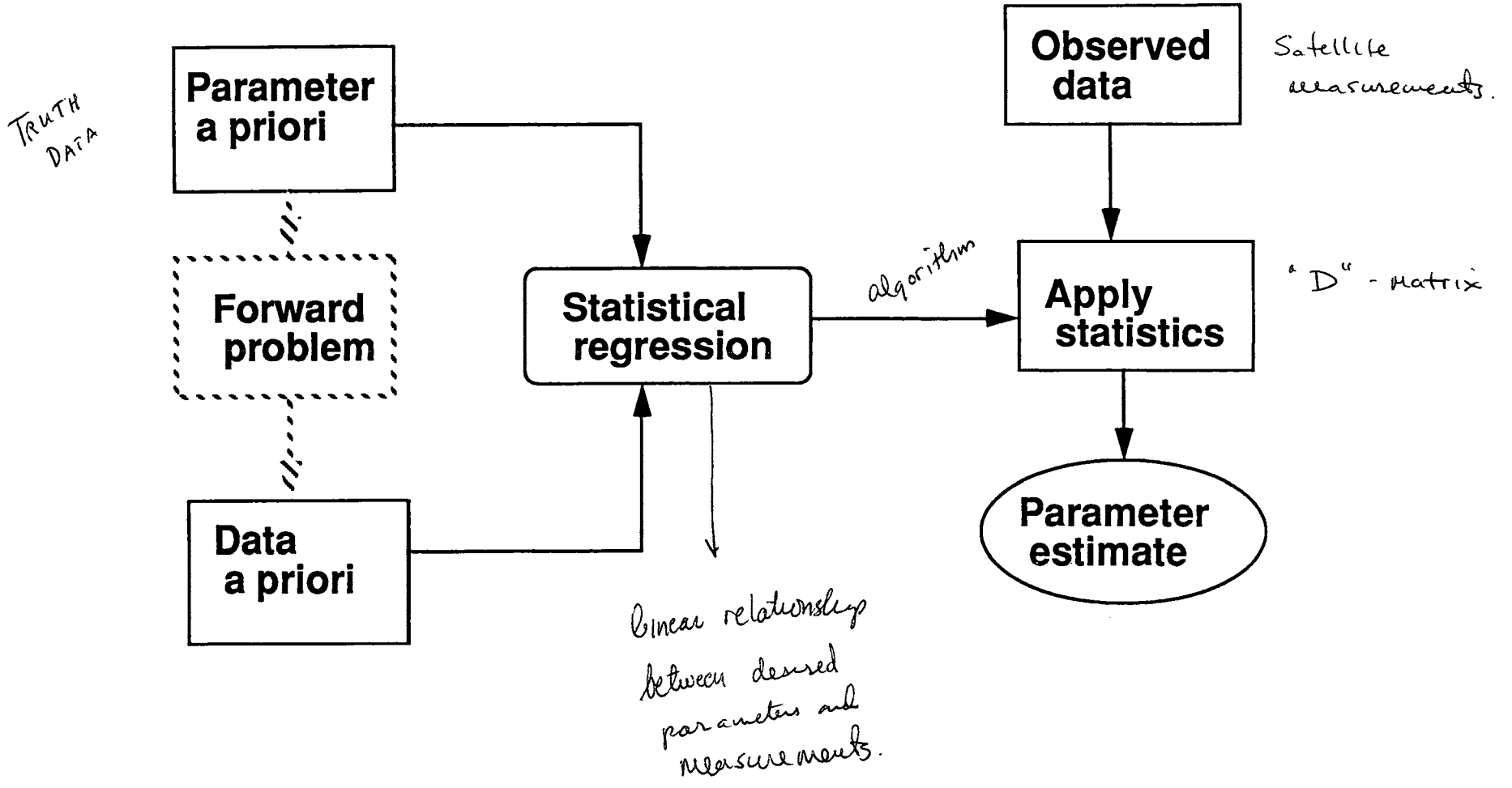
## Statistical Retrieval

ISSUES

- Basis is to choose in a statistical sense, the most probable combination of parameters which produces the observed data;
- It is most often based on a minimum least squares error estimation;
- This approach assumes an a priori data set consisting of samples of data vectors, d, and parameter vectors, p from which a statistical regression is evaluated. The coefficients of this regression are applied to infer subsequent parameter vectors from new data vectors;
- In practice, the a priori data vectors can be obtained from knowledge of the relevant forward problem by simulating data vectors from the a prior parameter vectors;
- Statistical retrievals can provide high quality first guess retrievals for non-linear iterative retrievals.

- correlations between parameters – statistical independence
- Impact of: – background conditions
  – clouds

## Statistical retrieval flow chart



matics

The estimated or inferred parameter vector is given by:

$$\bar{p} = D\bar{d}$$

with

$$D = \left(UT^t\right)\left(T*\Lambda*^{-1}\hat{T}*^t\right)$$

where:

$\bar{p}$ is the parameter vector, a vector giving a statistical estimate of the profile of the desired parameter in each layer of r layers

$\bar{d}$ is the data vector, a parameter n vector whose components are n brightness temperature or radiance

$U_{rs}$ parameter profiles matrix at r levels for s atmospheric samples

$T_{ns}$ brightness temperature or radiance matrix for n channels for s samples

$\hat{T}*$ selected eigenvectors of TTt

## Statistical retrieval mathematics (continued)

$\Lambda*$ diagonal matrix whose elements are corresponding eigenvalues

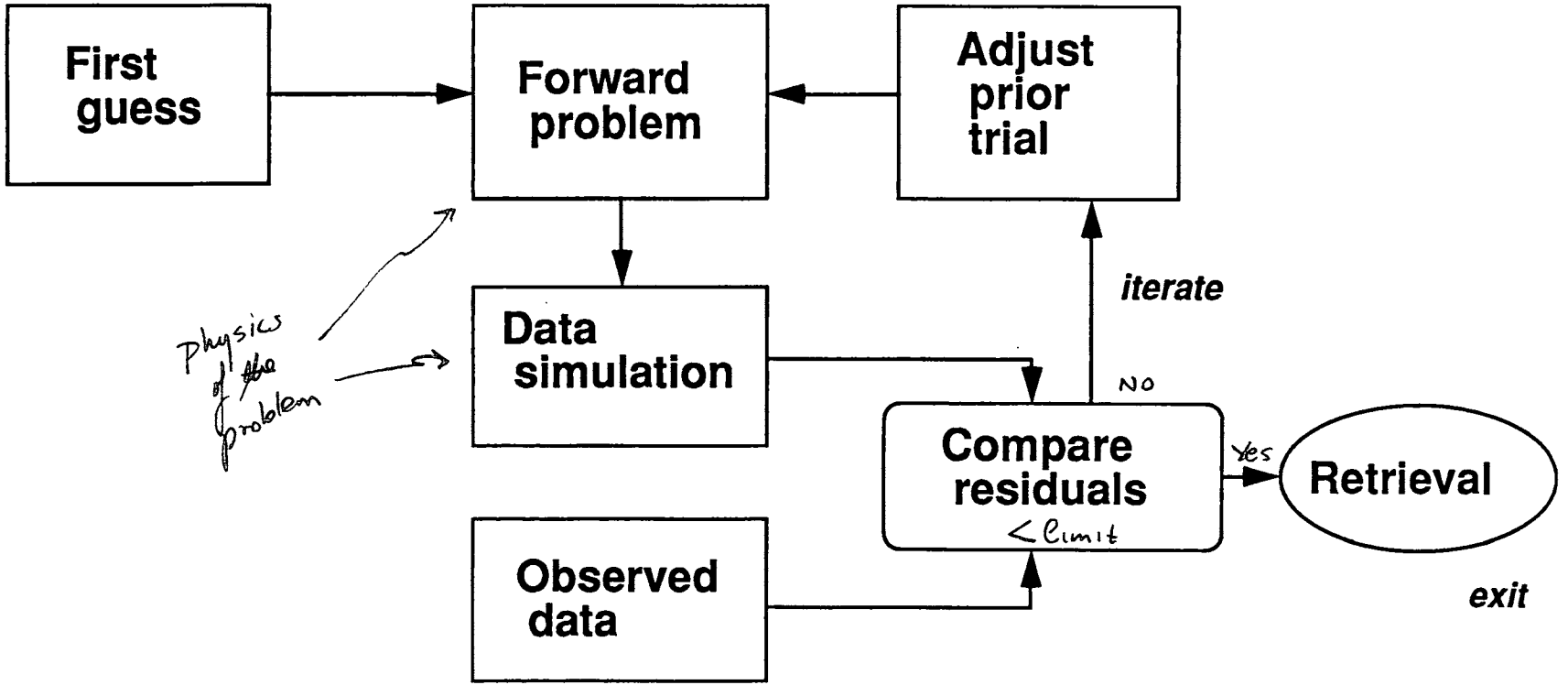
- The eigenvectors having relatively small eigenvalues (compared with the largest eigenvalue) can be discarded since they represent noise.
- The advantage of the method is that by truncating the sequence of eigenvalues, one reduces the condition number of the matrix, and therefore also the sensitivity to noise.
- In this method, if none of the eigenvectors are discarded, the problem reduces to that of solving the least squares fit problem, i.e.:

$$D = UT^t\left(TT^t\right)^{-1}$$

## Non-linear iterative

- "Chahine" type retrieval approach is designed to infer temperature and composition using little a priori information;
- Approach extended by Susskind, Chahine, et al. to apply in general to many parameters encountered in the forward problem of RTE;
- Requires accurate (or tunable) forward problem to work in practice;
- Solution obtained iteratively, adjusting a first guess by comparing observed data with results of simulation based on forward problem;
- Adjustments made to trial parameter profiles by associating each channel brightness temperature with a layer in the atmosphere based on the channel contribution functions;
- Iterations terminate when the residuals converge to levels within the noise equivalence of the sensor.

## Non-linear iterative flow chart



## Non-linear iterative mathematics

**The RTE is of the form:**

WEIGHTING FUNCTION

$$R(\upsilon_i) = B(\upsilon_i, T_s)\,\tau(\upsilon_i, p_1) + \int_{\ell np_1}^{\ell np_2} B[\upsilon_i, T(p)] \frac{\partial \tau}{\partial \ell np}\, \partial \ell np$$

**The retrieval is obtained by starting from an arbitrary initial guess for temperature or composition profile (i.e., Tn(p), qn(p); n=0). If any subsequent trial profile is a retrieval solution, then the residuals for each channel defined as:**

$$\Delta^n(\upsilon_i) = R(\upsilon_i) - R^n(\upsilon_i)$$

## Non-linear iterative (continued)

The form of the iteration depends on whether temperature or composition is being treated. For temperature, it is easy to show that a new guess (i.e., the n+1th iteration) for the Planck function (and hence, temperature profile) at each of the N path domains associated with a channel can be calculated from the nth trial Planck function and its associated simulated radiance Rn(ui) and the radiance data for that channel, R(ui), by the expression:

$$B\left[\upsilon_i, T^{n+1}(p)\right] = \frac{R(\upsilon_i) \quad B\left[\upsilon_i, T^n(p)\right]}{R^n(\upsilon_i)}$$

This expression can be simplified to obtain the following form for the relaxation equation for temperature:

$$T^{n+1}(p_i) = a_i T^n(p_i)$$

**Non-linear iterative (continued)**

**To apply the approach for composition profiles, Eqn. (11) above is integrated by parts to obtain:**

$$I(\upsilon_i) = B(\upsilon_i p_2) - \int_{\ell np_1}^{\ell np_2} \tau[\upsilon, q(p)] \frac{\partial B}{\partial \ell np} \partial \ell np$$

**From this form of the equation a similar relaxation equation for the composition profile is obtained:**

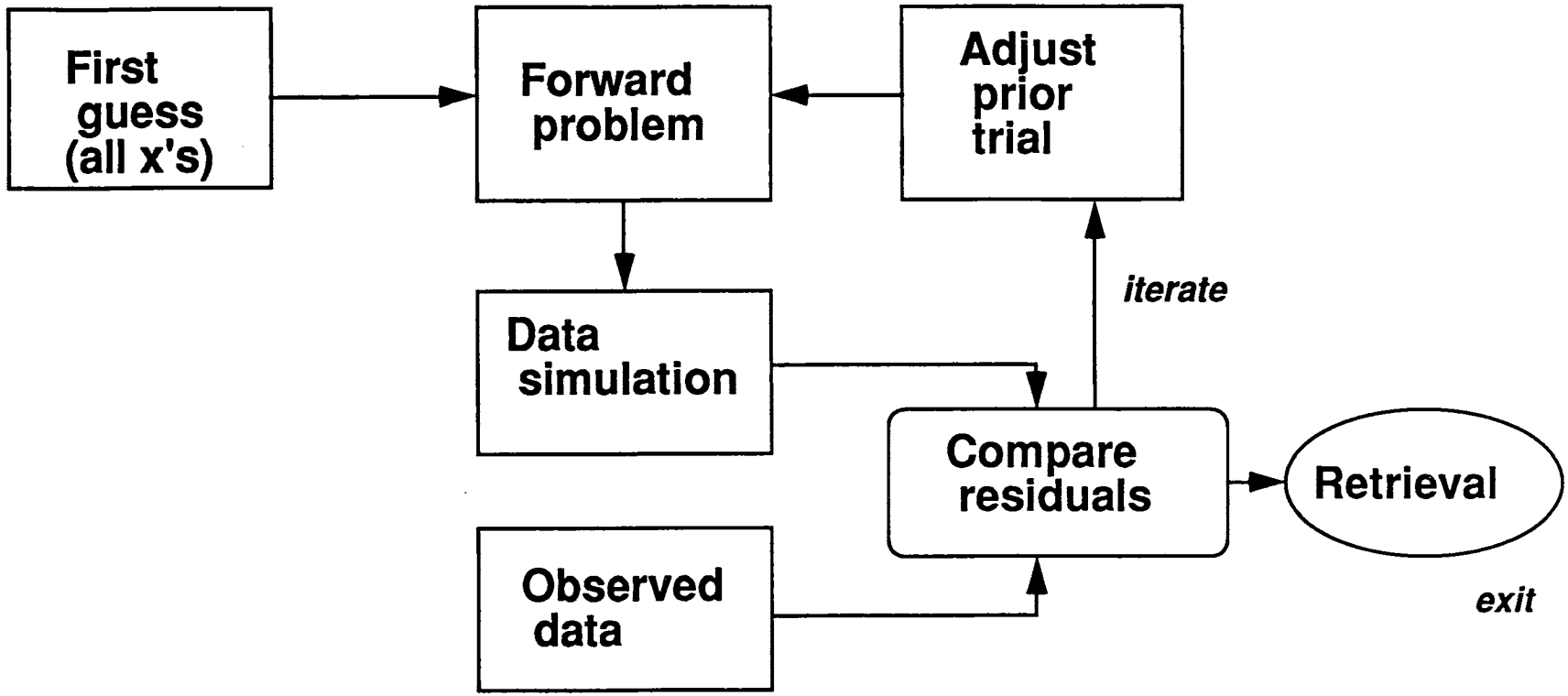
$$q^{n+1}(p_i) = a_i q^n(p_i)$$

**After each iteration and application of the relaxation equation, the adjusted profile is obtained by connecting the N path domains by a suitable interpolation formula. The relaxation is repeated until the relaxation parameters ai approach unity and the residual criteria are met.**

## Simultaneous retrieval

- Employs a perturbation form of the radiative transfer equation which relates changes in the parameter vector to changes in the data vector expressed in term of brightness temperature;
- Perturbations defined with respect to deviations from a climatological mean or trial solution;
- This relationship is inverted in a least squares sense;
- Uses all available sensor data and retrieves the total state vector accessible via the forward problem;
- Employs smoothness to improve stability.

## Simultaneous retrieval flow chart




- Similar schematic to non-linear iterative, except that all desired parameters (i.e. all x's) are treated simultaneously;
- Nonlinear often done consecutively, e.g. temperature, then constituent, etc.

## Simultaneous retrieval mathematics

**The RTE is written in a perturbation form, the change in ith channel radiance is given by:**

$$\delta R_i = \int_{p_s}^{0} \delta T \frac{\partial B}{\partial T}\frac{\partial \tau}{\partial p} dp - \int_{p_s}^{0} \delta q \frac{\partial \tau}{\partial q}\frac{\partial B}{\partial p} dp$$

$$+ \delta \varepsilon_i B_i(T_s)\tau_i(p_s)$$

$$+ \delta T_s \varepsilon_i \tau_i(p_s)\frac{\partial B}{\partial T_s}(T_s)$$

T and RH profiles

**where the deltas are changes in the temperature and moisture profiles, surface emissivity, and surface temperature for an a priori value, e.g.,**

$$\delta T(p) = T(p) - \overline{T}(p).$$

**The a prior can be a first guess or climatological value.**

**Simultaneous retrieval mathematics (continued)**

**Focusing on the temperature profile alone, the perturbation profile can be expanded about a suitable set of functions:**

$$\partial T(p) = \sum_{j=1}^{M} \alpha_j \phi_j(p).$$

**We have used empirical orthogonal functions (EOFs) of temperature and moisture in our work. (Smith uses the weighting functions.) This result is:**

└ not EOF's

$$\delta T_{B_i} = \sum_{j=1}^{M} \alpha_j \Phi_{ij}.$$

**or** $$\overline{T}_B = \Phi \overline{\alpha}$$

**where** $$\Phi_{ij} = \left(\frac{\partial B_i}{\partial T}\right)^{-1} \int_o^{ps} \phi j(p) \frac{\partial B_i}{\partial T} \frac{\partial \tau_i}{\partial p} dp$$

## Simultaneous retrieval mathematics (continued)

The inversion for the temperature profile is obtained by solving for the vector of coefficients in the EOF expansion about the a priori. This is done using least squares:

$$\overline{\alpha} = \left(\Phi^T \Phi + \sigma I\right)^{-1} \Phi^T \delta\overline{T}_B$$

where the $\sigma I$ term stabilizes the matrix inversion. This type of least squares is often called the ridge regression and s the ridge parameter. Once inverted:

$$T(p) = \overline{T}(p) + \delta T(p)$$

where

$$\delta T(p) = \sum \alpha_i \phi_i(p).$$

## Cloud property retrieval

- Clouds were among the first observed meteorological phenomena from the early TIROS satellites;
- Determination of cloud properties are important for NWP, climate, and system effectiveness predictions;
- Cloud parameters define the horizontal distribution, vertical extent, and optical properties of the clouds;

- Parameters include:

  - bulk parameters such as total cloud cover, layering, cloud top heights and thicknesses;

  - optical properties such as optical depth, albedo, and infrared emissivity;

  - cloud microphysics such as liquid water content, cloud type, cloud phase and predominant particle size.

# Cloud parameters potentially retrievable from remotely sensed data

| Variable | Definition |
|---|---|
| $F$ | cloud coverage fraction |
| $T_c$ | cloud top temperature |
| $Z_c$ | cloud top height |
| $\Delta Z_c$ | cloud thickness |
| $\varepsilon_c$ | cloud emissivity |
| $\tau_c$ | cloud optical depth |
| $A_c$ | cloud albedo |
| $N_c$ | cloud particle number density |
| $M_c$ | cloud liquid water/ice content |
| CT | cloud type |
| CP | cloud phase (ice/water) |
| CL | cloud layer information |

## Cloud analysis approaches

- Cloud analysis (or nephanalysis) approaches may be categorized by noting the type of satellite data analyzed, the data bases required to support the analysis, the computational level of effort required, and the mathematical formalism;
- Classification according to the rough physical basis of the techniques results in four general classes:
  - Threshold
  - Statistical
  - Bispectral or radiative transfer
  - Sounder - based

# Summary of cloud parameter analysis methods

| Method | Technique | Satellite Data | Supplementary Data | Cloud Parameter(s) Inferred |
|---|---|---|---|---|
| Threshold | One channel | vis | | $F$ |
| | | IR(11) | $T(Z)$ | $F$, $T_c$, $Z_c$ |
| | Two channels | vis, IR(11) | $T(Z)$ | $F$, $T_c$, $Z_c$ |
| Statistical | Regression | vis | | $F$, $A_c$ |
| | | IR(11) | $T_s$ | $F$, $\Delta Z_c$ |
| | Graphical one-dimensional histogram | vis | | $F$ |
| | | IR(11) | | $F$, $T_c$ |
| | Two-dimensional histogram | vis/IR(11) | $T(Z)$ | $F$, $T_c$, $Z_c$, CT, CL |
| | | IR(11)/WV(6) | | $T_c$, $Z_c$, CT, CL |
| | Three-dimensional histogram | vis/IR/WV | | $F$, $T_c$, $Z_c$, CT, CL |
| | Spatial coherence | IR(11) | $T(Z)$ | $F$, $T_c$, $Z_c$ |
| | | IR(11)/IR(3) | $T(Z)$ | $F$, $T_c$, $Z_c$, CL |
| Bispectral | | vis/IR(11) | $T(Z)$, $\varepsilon_s$, $T_s$, $A_s$, $\varepsilon_c$, $A_c$ | $F$, $T_c$, $Z_c$ |
| | | vis/NIR | | $F$, CP |
| Sounder | Two-channel IR | IR($2CO_2$) | | $F$, $T_c$, $Z_c$ |
| | Two-channel MW | | | $M_c$ |
| | Six-channel IR/MW | IR(11)/WV(6)/ IR($2CO_2$)/MW(2) | $T(Z)$, $RH(Z)$ | $F$, $T_c$, $Z_c$, $\Delta Z_c$, $M_c$, CL |
| | Multispectral | | | $F$, $T_c$, $Z_c$, $\Delta Zc$, $\varepsilon_c$, $\tau_c$, $A_c$, $N_c$, $M_c$, CL |

Numbers in parentheses indicate spectral region. Cloud parameters are defined in Table 7. Subscript $s$ indicates a surface quantity, $T(Z)$ and $RH(Z)$ are temperature and relative humidity profiles.

## Threshold methods

- Threshold methods are based on the observation that clouds appear brighter than most backgrounds in the visible spectrum and colder than most backgrounds in the thermal;
- This behavior is exploited by establishing a visible radiance (or albedo) or thermal brightness temperature "threshold" which defines the demarcation between cloudy and clear pixels:
  - pixels brighter than the threshold are cloudy, and
  - pixels colder than the threshold are cloudy;
- In automated analyses, this simple approach is applied by assuming the fractional cloud cover to be proportional to the difference between measured radiance and the threshold value which characterizes cloud free conditions;
- The advantage of the threshold method is its computational simplicity;
- A disadvantage is the failure to treat partial cloudiness, i.e., a pixel is either clear or cloudy;
- Single, double, and variable thresholds may be used;
- A modified threshold approach is used operationally in the Air Force global real-time (RT) nephanalysis program.

# Example of thresholded sensor data

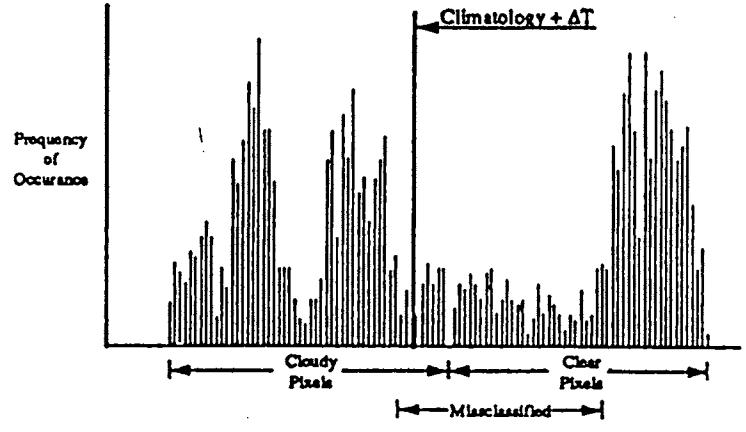



Fig. 2a. Single threshold analysis illustrating misclassified partially filled pixels.

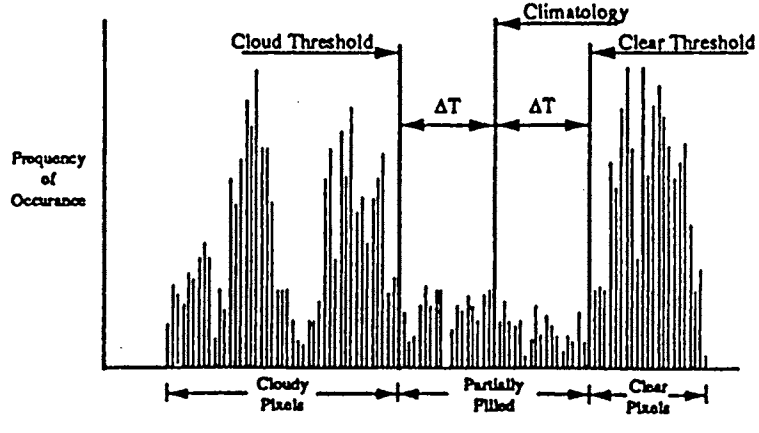
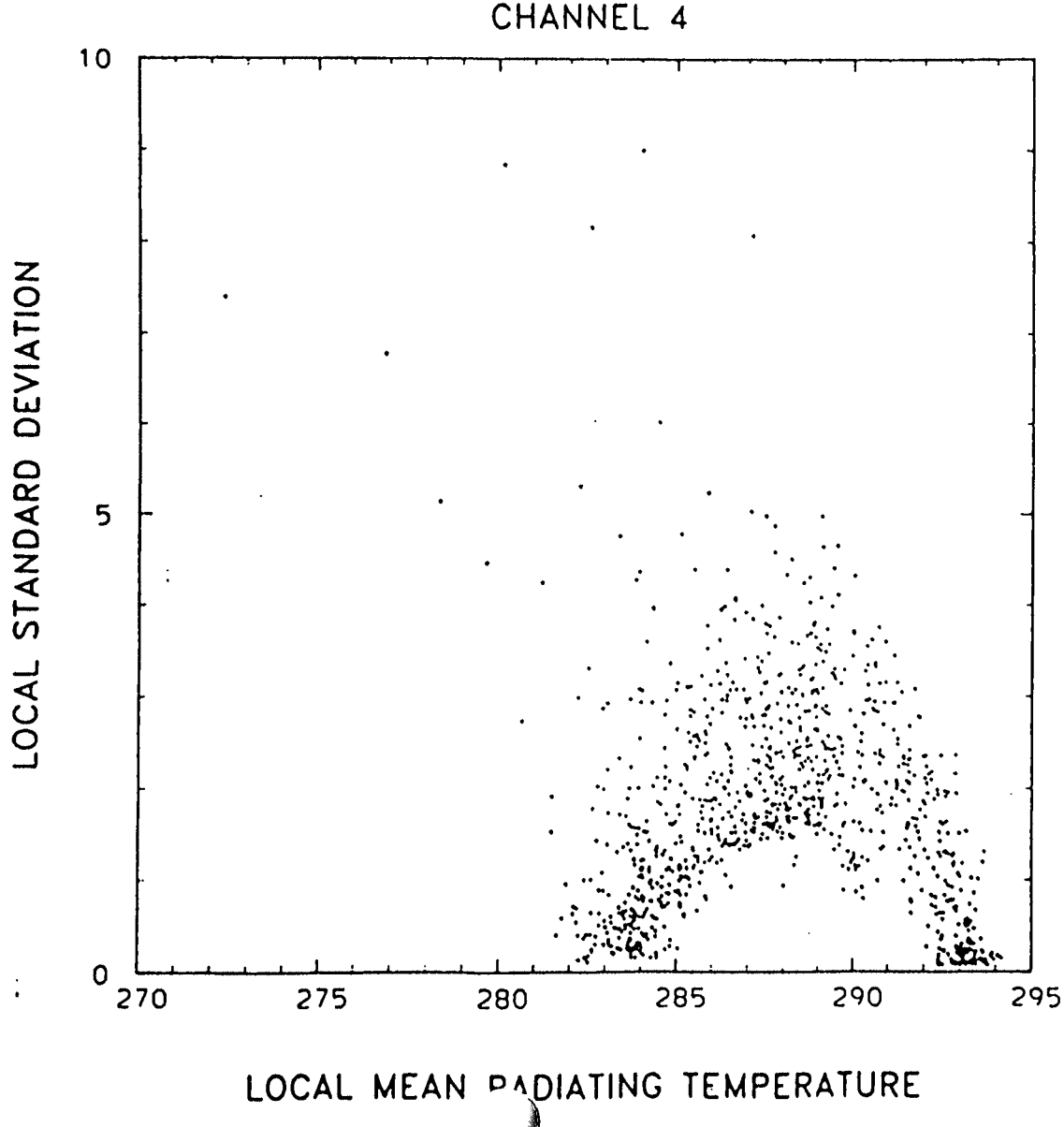



Fig. 2b. Dual threshold analysis illustrating classification of partially filled pixels.

## Statistical methods

- Cloud field imagery statistical properties are exploited to identify relevant cloud parameters;
- Statistics are used in practice to establish the appropriate thresholds discussed previously;
- Statistical regression and multivariate analysis may be used to relate properties of the cloud fields to desired parameters using "truth" defined by manual analyses (cloud typing using supervised classification techniques is one example);
- Spatial statistics can also be employed to define the local properties of the cloud field from the ensemble behavior of an image such as by investigating the spatial coherence of the field
  - spatial coherence identifies clear and cloud top layer heights,
  - treatment of partial cloudiness is implicit,
  - extensions to the method account for non-unit emissivity and sub-pixel resolution cloud.

# Application of spatial coherence approach to AVHRR imagery



## Spatial coherence

- Like the histogram approach, uses the local structure of the infrared radiance field to determine radiances associated with cloud free and completely cloudy fields-of-view;
- Technique is based on recognition of characteristic patterns in the plots of local mean radiance vs local standard deviation of radiance (or brightness temperature);
- The local values are defined for a selected window size (say 4x4 pixels) within the image;
- For an idealized single layer of cloud, the characteristic pattern is an arch:

  - the coldest cluster defining one foot of the arch is due to cloudy pixels

  - the warmest cluster defining the other arch is due to clear pixels

  - the points forming the arch itself are comprised of partially filled fields-of-view
- From this data, the surface brightness temperature, the cloud top brightness temperature and the fractional cloudiness can be determined.

## Bispectral or radiative transfer methods

- These approaches apply knowledge of the radiative transfer process to determine parameters such as cloud fraction and cloud top temperature;
- In the simple bispectral approach it is observed that visible (Rv) and infrared (Ri) radiances have the following dependence on cloud fraction F and cloud top temperature Tc:

$$Rv = [\,(1-F)\ As\ +\ F\ Ac\,]\ So$$

$$Ri = (1-F)\ B(Ts)\ +\ F\,[\,(1-e)\ B(Ts)\ +\ e\ B(Tc)\,]$$

- where As and Ac are surface and cloud albedos
  So is the solar irradiance
  Ts is the surface temperature
  and e is the cloud emissivity
- If the above variables are known, the above can be solved for F and Tc.

## Radiative transfer methods

- A sophisticated extension of the bispectral approach, radiative transfer methods are based on comparison of observed calibrated radiances to extensive look-up tables of radiances calculated using a sophisticated forward problem model which accounts for cloud properties and multiple scattering;
- All of the parameters defining cloud optical and bulk properties which enter into the forward problem are treated in parameter space;
- Retrieved properties are determined by ascertaining which combination of parameters best fits the observed data;
- This approach is currently employed in the ISCCP program.

# Retrieval of cloud mode radius and optical thickness using multispectral data

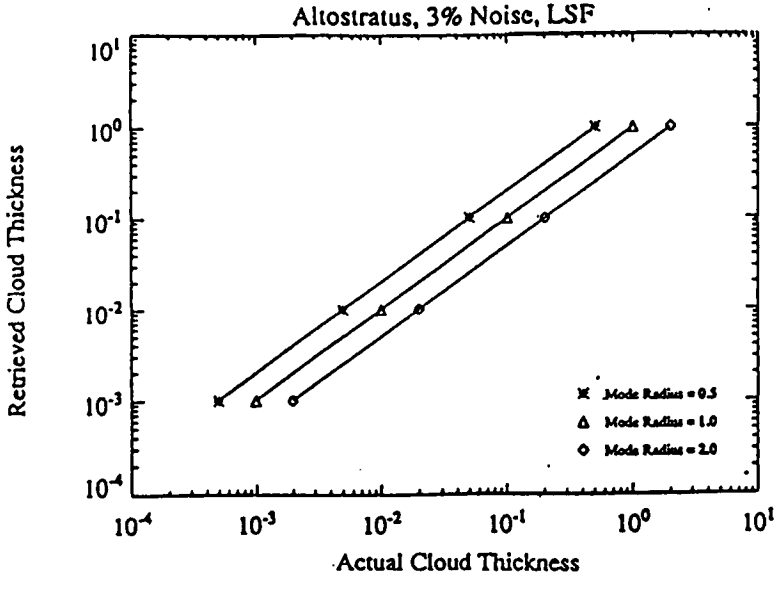



Figure 5. Retrieved versus actual cloud thickness for 3 values of mode radius, 5 μm (0.5), 10 μm (1.0), and 20 μm (2.0), offset for illustrative clarity. 3% noise has been added to "data".

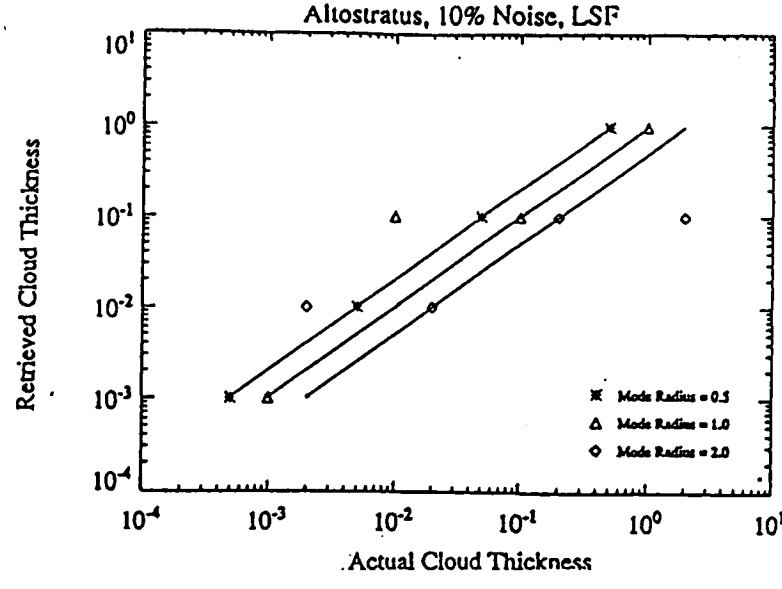



Figure 6. Same as Figure 6 except 10% noise.

## Sounder approaches

- These approaches also exploit radiative transfer theory, but differ in the data sets which are employed;
- While the previous methods are used extensively with cloud imager data, these approaches were largely developed to treat the presence of cloud in the retrieval of temperature and moisture profiles from infrared sounders;
- A fundamental assumption is that the spatial variation of cloud within the atmosphere occurs at smaller scales than that of the temperature profile;
- Window channel radiance differences in adjacent fields-of-view are assumed due to differences in cloud;
- A minimum of two channels is used to obtain cloud fraction and clear column radiances;
- The latter are processed further to obtain the desired profiles;
- In practice, multiple channels are used to obtain the ensemble of cloud and atmospheric profiles which best fit the observations.

## Hybrid Approaches:

It is unlikely that a single cloud analysis algorithm will produce optimal results everywhere (King et al, 1992); therefore, multiple approaches are necessary including those:

- that utilize cloud spectral signatures (Saunders and Kriebel, 1988);
- that exploit spatial information (Coakley and Bretherton, 1982);
- classification techniques, especially for cloud type (Garand, 1988);
- hybrid techniques which exploit all the above.

Coakley, J. and F. Bretherton, 1982: Cloud cover from high resolution scanner data: detecting and allowing for partially filled fields-of-view, *J. Geophys. Res.*, 87, 4917-4932.

Garand, L., 1988: Automated recognition of oceanic cloud patterns. Part I: Methodology and application to cloud climatology. J. Climate, 1, 20-39.

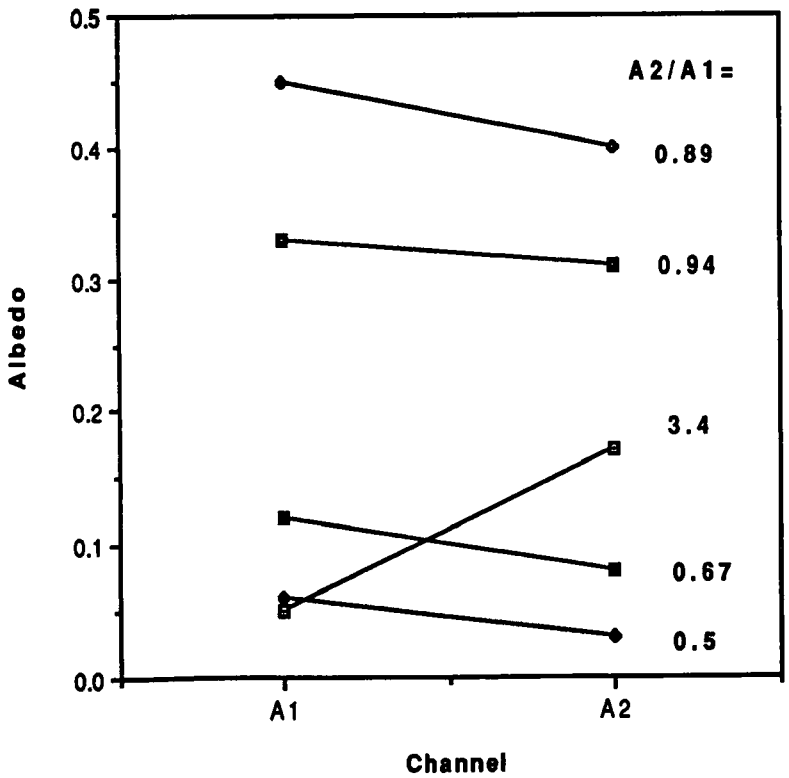
King et al., 1992: Remote sensing of cloud aerosol, and water vapor properties from the moderate resolution imaging spectrometer (MODIS), *IEEE Trans. on Geo. and Remote Sens.*, 30, 1, 1-27.

Saunders, R. and K. Kriebel, An improved method for detecting clear sky and cloudy radiances from AVHRR data. *Int. J. Remote Sens.*,7, 867-886.

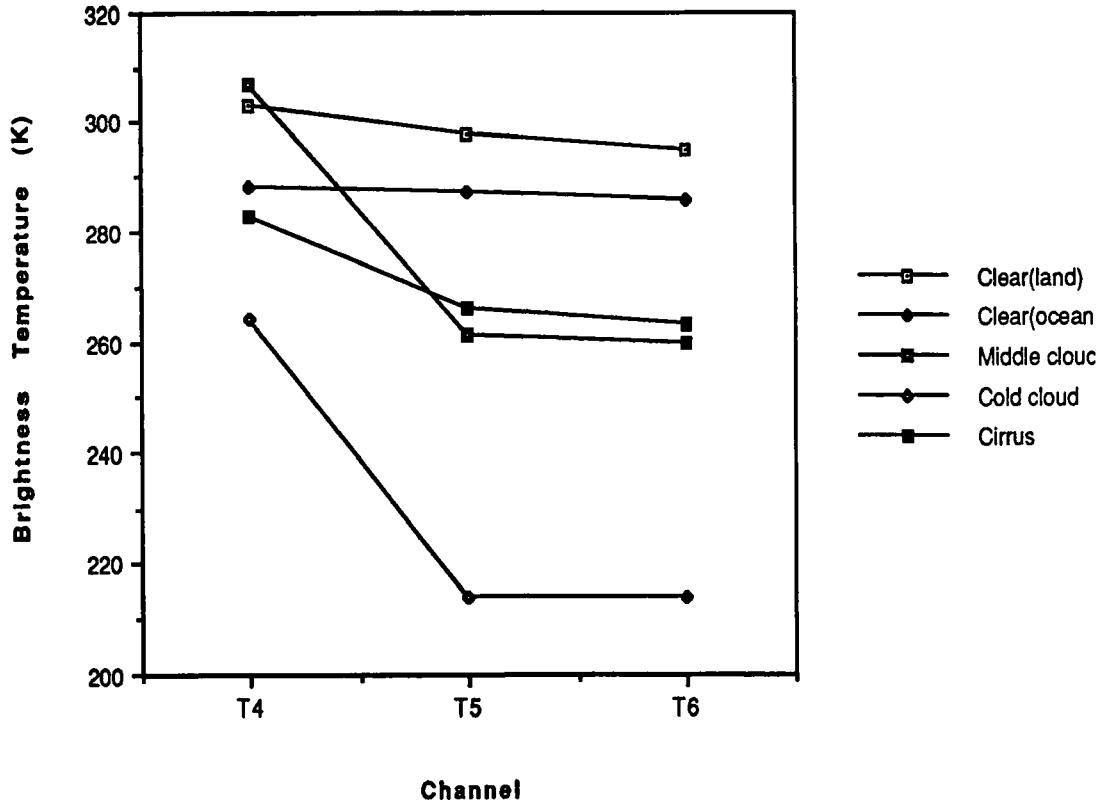
# Cloud Signatures

## AVHRR data:

### Visible Channels




### MWIR/LWIR Channels



# Typical AVHRR decision tree:

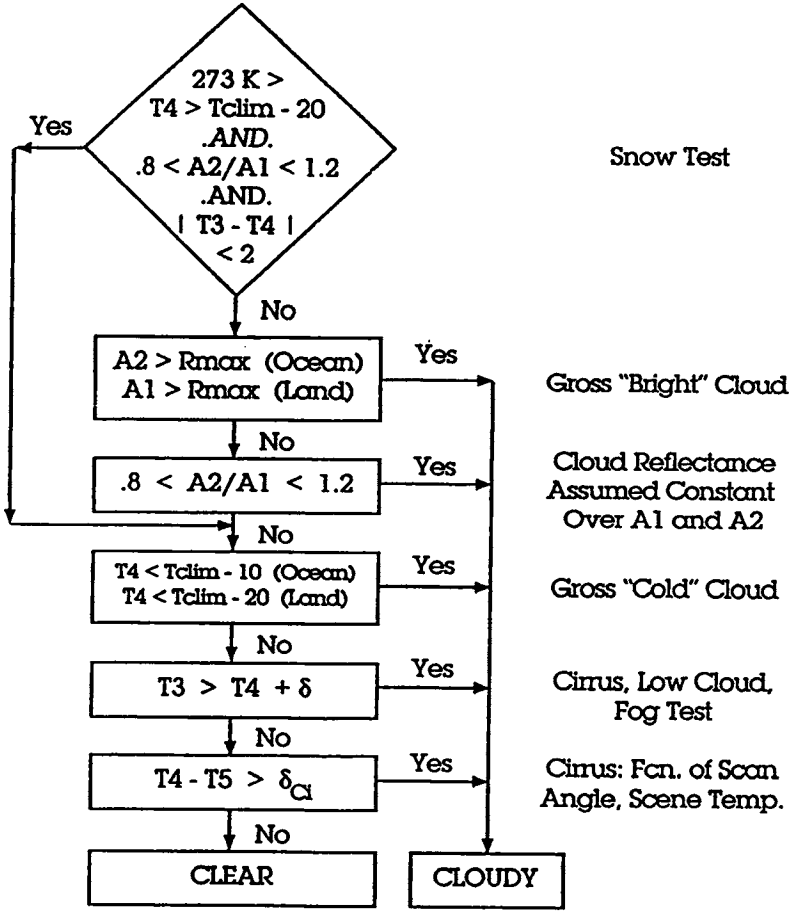



Figure 1. Sample algorithm for AVHRR multispectral cloud analysis. A1 and A2 are the visible and NIR albedos; T3, T4, and T5 are the MWIR and split-window LWIR brightness temperature measurements. The first test is for the presence of snow using thermal and visible data. Test 2 checks for "obviously bright" clouds; test 3 is a more rigorous visible / NIR ratio cloud test. Test 4 checks for "obviously cold" clouds by comparing measurements to a climatology surface skin temperature. Test 5 is a cirrus and low cloud test, and Test 6 is a cirrus / small-par[illegible]cloud test. Failing all tests results in classification of a "clear" sample.

# What is Unified Retrieval (UR) ?

- UR is a radically new algorithm concept for meteorological parameter retrieval using multiple sensor data streams which:

  - fully exploits the interdependencies of all sensor data to obtain each parameter through multispectral data fusion;

  - unifies the nephanalysis, sounding, and imaging functions of meteorological parameter retrieval;

  - optimizes the accuracy of parameters obtained by employing hybrid statistical and physical retrieval approaches.

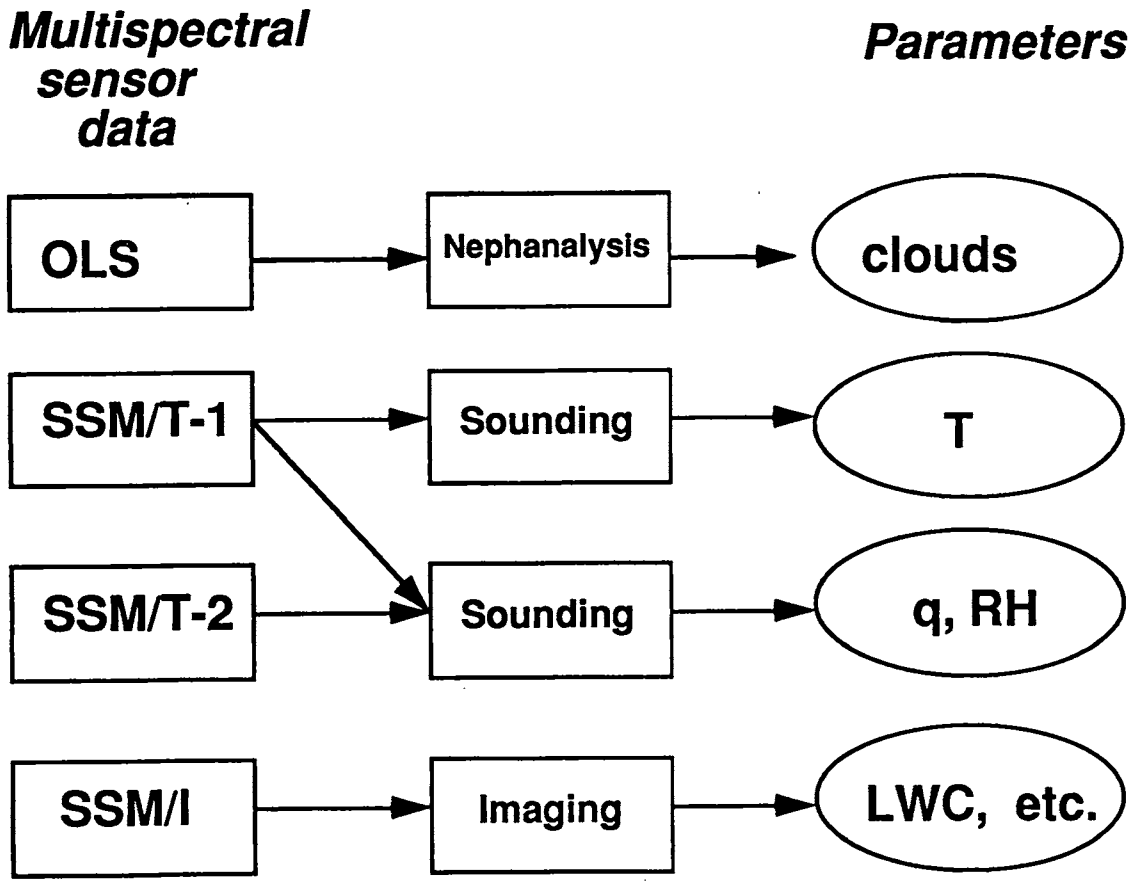
- The UR concept was developed at AER and first published in the scientific literature in "*Advances in Remote Sensing Retrieval Methods*" in 1989.

Isaacs, R.G. , 1989: A unified retrieval methodology for the DMSP meteorological sensors. in RSRM "87: Advances in Remote Sensing Retrieval Methods. A. Deepak, H.E. Fleming, J.S. Theon, (Eds.) Deepak Publishing. pp. 203-213.

# Example: DMSP

- Non-integrated, segmented, lacks multispectral perspective, does not exploit all available data for each desired parameter
- Microwave sensor soundings done using independently derived and maintained "D" matrix, statistical retrievals; ignores interdependence of sounding and nephanalysis products
- Neglect of some physics: does not treat nonlinearities in water vapor, clouds, emissivity
- Quality control of parameters can not be done in real time as needed, only retrospectively - no quality control flag for end user

# Current Operational Approach



# Innovative Attributes of Unified Retrieval

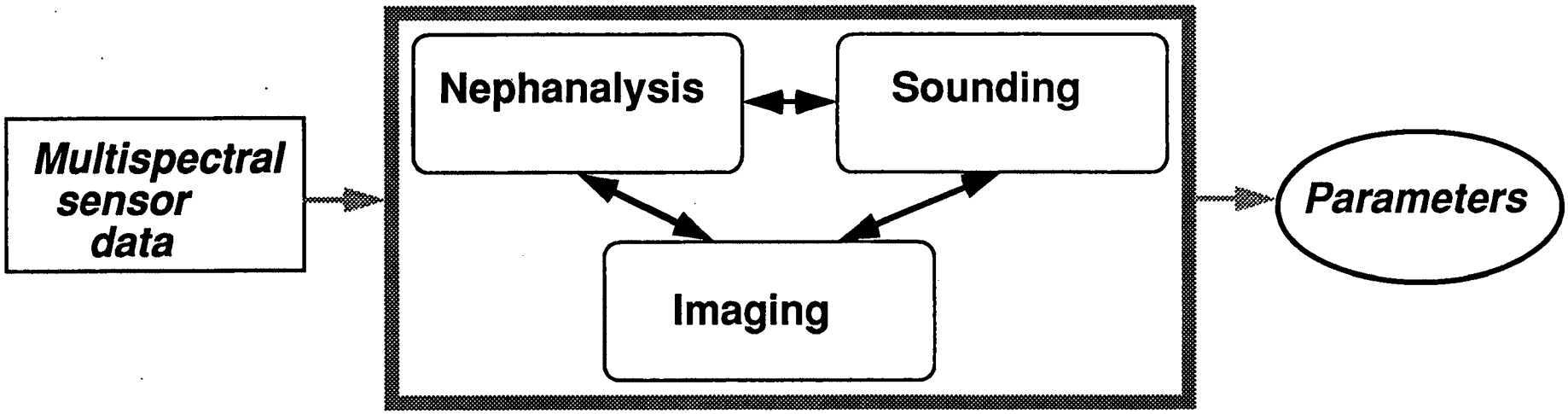
- **Provides unified treatment of all meteorological parameters exploiting the full information content of the sensor data in a multispectral sense**

- **Microwave sensor data retrievals achieved using consistent physical retrieval with statistical first guess - Integrates sounding and nephanalysis procedures (necessary since water vapor soundings depend on cloud properties which in turn depend on temperature/moisture profiles and surface temperature)**

- **Inherent non-linearities in certain parameter/brightness temperature relationships (such as water vapor, cloud, and surface emissivity) are treated explicitly through the physical retrieval procedure**

- **Provisions are available for real time quality control assessment by monitoring unified retrieval residuals (i.e. the difference between the observed sensor data and that calculated from the physical retrieval procedure)**

# Unified Retrieval



# 3. Remote Sensing Applications for Meteorology and Climate

## 3.1 Meteorological Parameters

## 3.2 Data Assimilation Techniques

## 3.3 Optimal Retrieval

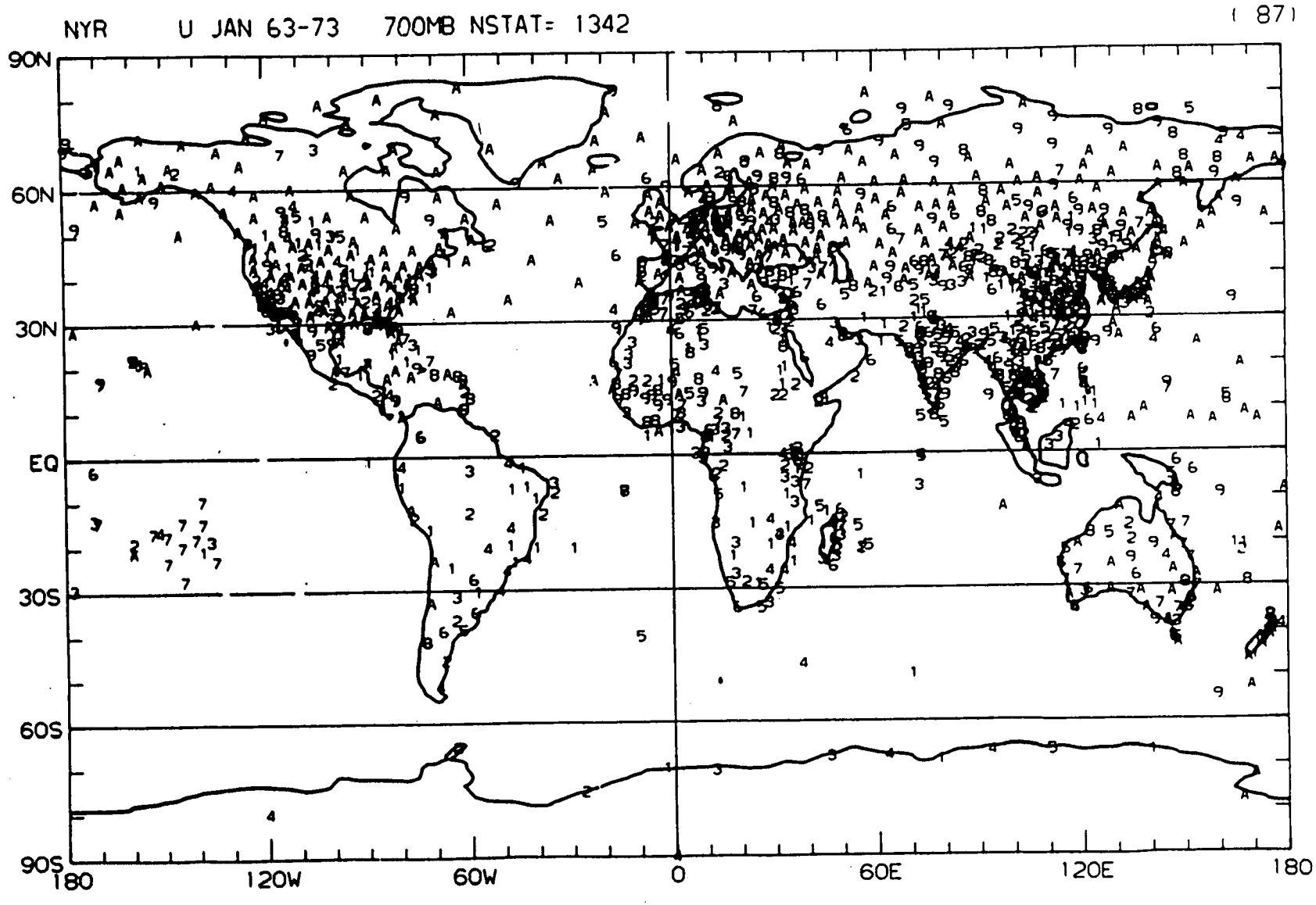
## 3.4 Interactive Retrieval

Isaacs, R.G., R.N. Hoffman, and L.D. Kaplan, 1986: Satellite Remote Sensing of Meteorological Parameters for Global Numerical Weather Prediction. *Reviews of Geophysics*, 24, 4, 701-743.

**Remote sensing helps to provide the initial conditions for numerical weather prediction - provides complementary data to conventional surface and upper air data both in space and time:**

- **Provides high horizontal resolution and global coverage - conventional data sources such as surface stations are distributed predominantly within populated land areas of the Northern hemisphere;**
- **While commercial ships and aircraft provide some data over the oceans, the atmosphere of the Southern hemisphere oceans would be virtually unknown without satellite data;**
- **Conventional data are primarily available at the synoptic times of 0000 and 1200 UT, satellite data is available as it is processed;**
- **Many meteorological parameters are potentially available from satellite based sensors.**

# Global radiosonde network geographical coverage



# Observational error for different observing systems

| Level, mbars | Radiosonde Temperature, °C | TIROS-N Temperature, °C | | Radiosonde Pilot, Aircraft Winds, m s$^{-1}$ | Cloud Drift Wind, m s$^{-1}$ | | |
|---|---|---|---|---|---|---|---|
| | | Clear/ Partly Cloudy | Microwave | | NESS and Wisconsin | ESA and LMD | JMA GMS |
| 10 | 4.5 | 2.8 | 2.8 | 6 | 8 | 8 | 13 |
| 20 | 3.8 | 2.6 | 2.7 | 6 | 8 | 8 | 13 |
| 30 | 3.2 | 2.5 | 2.6 | 6 | 8 | 8 | 13 |
| 50 | 2.7 | 2.4 | 2.5 | 6 | 8 | 8 | 13 |
| 70 | 2.3 | 2.2 | 1.4 | 6 | 8 | 8 | 13 |
| 100 | 2.1 | 2.0 | 1.6 | 6 | 8 | 8 | 13 |
| 150 | 2.1 | 2.0 | 1.7 | 6 | 8 | 8 | 13 |
| 200 | 2.0 | 1.9 | 1.8 | 6 | 8 | 8 | 13 |
| 250 | 1.8 | 1.9 | 1.9 | 6 | 8 | 8 | 13 |
| 300 | 1.6 | 1.8 | 2.0 | 6 | 8 | 8 | 13 |
| 400 | 1.5 | 1.8 | 2.2 | 5 | 7 | 8 | 10 |
| 500 | 1.2 | 1.7 | 2.2 | 4 | 7 | 8 | 10 |
| 700 | 1.1 | 1.8 | 2.5 | 3 | 5 | 8 | 6 |
| 850 | 1.1 | 2.0 | 3.9 | 2 | 4 | 7 | 6 |
| 1000 | | | | 2 | 4 | 7 | 6 |

Sea surface pressure: synoptic and ship observations, 1.0 mbar; buoy, 2.0 mbars. Temperatures given as layer means [after *Bengtsson et al.*, 1982].

## Significance to NWP

- The table lists the parameters desired in priority of potential impact on improving numerical weather prediction forecast accuracy, e.g. winds, temperature, moisture, surface pressure, etc.;
- This differs somewhat from the order in which they have been used operationally to date;
- To date it is the temperature profile which has found the most widespread use in NWP;
- Winds determined from observations of cloud drift (or cloud drift winds [CDWs]) are also commonly used;
- The use of moisture information including humidity, cloud liquid water, and precipitation are slowly developing, particularly regional and mesoscale models where these parameters play important roles in determining the atmospheric physics.

# Observational requirements for numerical weather prediction (NRC, 1985)

| Parameter | Temporal Resolution | Horizontal Resolution, km | Vertical Resolution, km | Accuracy |
|---|---|---|---|---|
| Horizontal velocity V | 12 hours | 100 | 1 | $\pm 3$ m s$^{-1}$ |
| Temperature T | 12 hours | 100 | 1 | $\pm 1$°C |
| Specific humidity $q$ | 12 hours | 100 | 1 | $\pm 1$ g kg$^{-1}$ or $\pm 10\%$ |
| Relative humifity | 12 hours | 100 | 1 | $\pm 10\%$ |
| Surface pressure $p_s$ | 12 hours | 100 | | $\pm 1$ mb |
| Sea surface temperature | 1 day | 100 | | $\pm 1$°C |
| Land surface temperature | 12 hours | 100 | | $\pm 2$°C |
| Surface moisture availability (percent of saturation) | 24 hours | 100 | | $\pm 10\%$ |
| Clouds (percent coverage) | 3–6 hours | 100 | | $\pm 5\%$ |
| Top of atmosphere radiation budget | 3–6 hours | 100 | | $\pm 5$ W m$^{-2}$ |
| Surface heat and moisture fluxes | 12 hours | 100 | | $\pm 10$ W m$^{-2}$ |
| Precipitation (total) | 1 day | 100<br>25 | | $\pm 10\%$ oceans<br>$\pm 10\%$ land |

The desired resolution and accuracy are given for measurements in the troposphere for large-scale dynamical studies and weather prediction [from *NRC*, 1985].

## Temperature

- Concepts for temperature retrieval were discussed earlier;
- Operational temperature retrievals from both the NOAA TIROS HIRS/MSU (i.e. TOVS) and DMSP SSM/T sensors provide accuracies of about 2.0-2.5 K in the free atmosphere;
- State of the art of NWP models have improved to the point where model forecast accuracies are in the 2.0 K range;
- This necessitates much more accurate satellite soundings to initialize the models (closer to the 1.0 K NRC requirement);
- Vertical resolution of the current system is about 3 km;
- Model vertical resolutions have developed to the point where this is insufficient to provide useful initialization data;
- The challenge is to try to approach the 1.0 km NRC requirement.

# Retrieval errors for TOVS

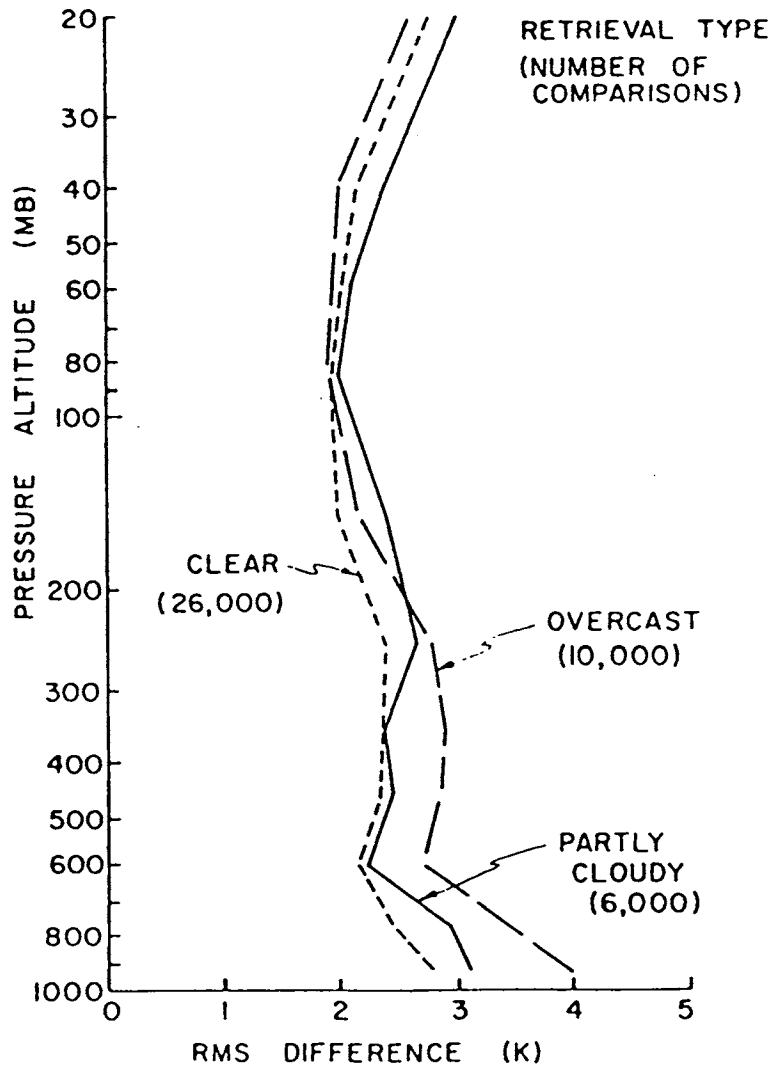



Fig. 4. Verification of satellite temperature soundings. Rms differences between radiosonde and satellite temperature soundings for April 1980 [from *Smith et al.*, 1981*a*].

## Moisture

- Moisture in its various forms (water vapor, cloud, precipitation) is radiatively the most important species in the troposphere;
- Moisture related physics includes radiation, release of latent heat, convection, precipitation, sensible heat flux, etc.;
- Satellite retrievals of moisture and cloud have not been used routinely in large scale numerical weather prediction, but studies indicate that short range forecasts (especially those of precipitation) are sensitive to initial moisture fields;
- Moisture specification is also important in the forecasting of clouds;
- Objective analysis of moisture requires special care since relative observational errors are large, length scales are small, and the variation of water vapor vertically and spatially spans many orders of magnitude;
- Water vapor retrievals are limited in vertical resolution and accuracy by the rather broad weighting functions which are characteristic of water vapor absorption bands;
- The moisture retrieval problem is also highly non-linear, e.g. the weighting functions depend on the water vapor distribution itself (as well as the temperature profile).

# TOVS water vapor weighting functions

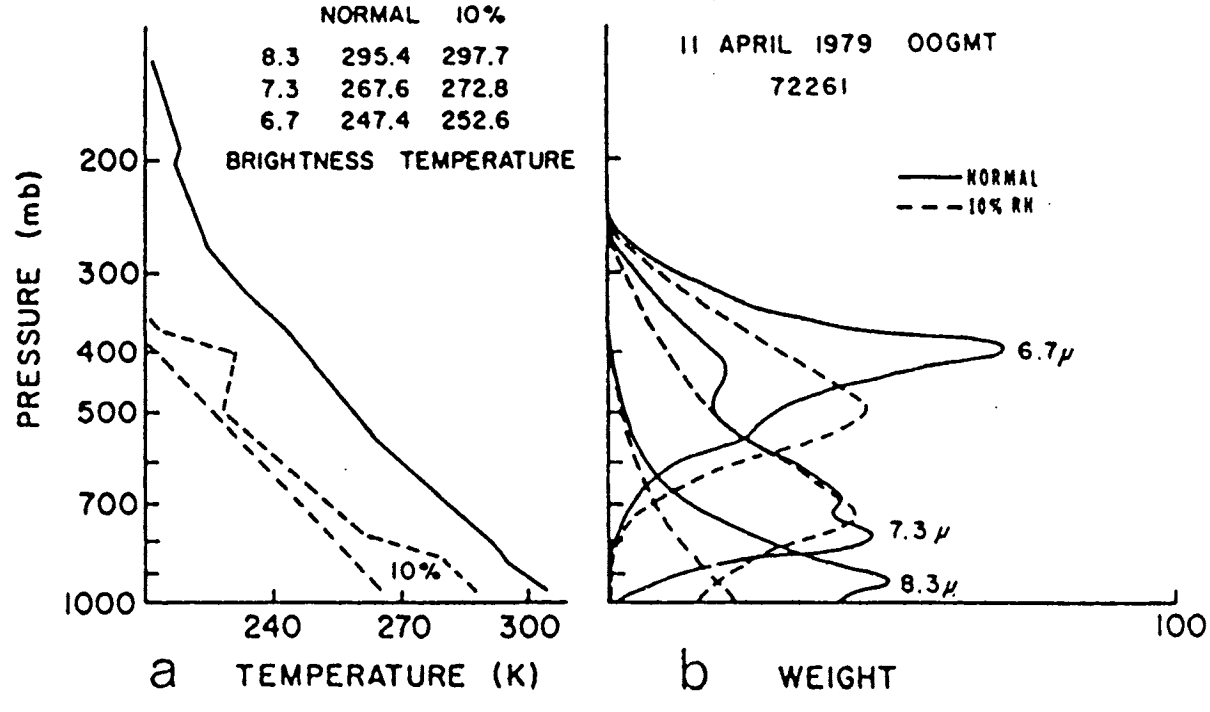



Fig. 7. TOVS water vapor weighting functions. (*a*) Radiosonde 72261 (Del Rio, Texas) atmosphere temperature and dew point profile for 0000 UT, April 11, 1979 (10% relative humidity profile also shown). (*b*) Brightness temperature weighting functions for TOVS water vapor channels for profiles shown at left [from *Hayden et al.*, 1981]. In Figure 7*b*, solid curves are for the observed profile, and dashed curves are for the 10% relative humidity profile.

## Winds

- Specification of the wind field for NWP has a large potential positive impact on forecast accuracy;
- For example, recent simulation work has examined the NWP impact of Doppler wind lidar (DWL) particularly in light of NASA Windsat/LAWS;
- LAWS measures global wind profiles down to cloud tops by exploiting aerosol backscatter;
- Accurate global wind fields improve forecast accuracy (Atlas et al, 1985 [NMC model]; Hoffman et al., 1990 [AFGWC GSM model]);
- Currently, wind profiles can be measured by the motion of features, usually clouds from geostationary satellite imagery (so-called cloud drift winds or CDWs); errors associated with CDW are due to feature extraction and cloud height assignment;
- Surface winds over the ocean can be measured passively by changes in microwave surface emissivity due to wind driven wave-slope and surface roughness effects, or actively using altimetry/scatterometry; the latter provides direction as well as speed; it is difficult to assimilate these data since surface wind is calculated by the model itself.

## Precipitation

- Precipitation (convective, stratiform, frontal, etc.) is an important determinant of atmospheric energetics;
- In particular, information on the distribution (vertical and spatial) of precipitation can be used to help initialize model latent heating in the tropics;
- Precipitation can be inferred using visible, infrared, and microwave imagery;

  - visible/infrared based on defining a statistical relationship between imagery intensity and the desired precipitation index; two classes include: indexing (independent of time) and life history method (look at time development of convective situations)

  - microwave use attenuation and scattering of microwaves by precipitation droplets (analogous to effect of clouds in the visible and infrared); brightness temperature / rainfall rate relationships used; can differentiate hydrometeor phase (rain/ice);

- Potentially, space-based radar can also be used.

# Brightness temperature vs. rain rate over ocean at (a) 19.35 and (b) 85.5 GHz using vectorized multiple scattering simulation model

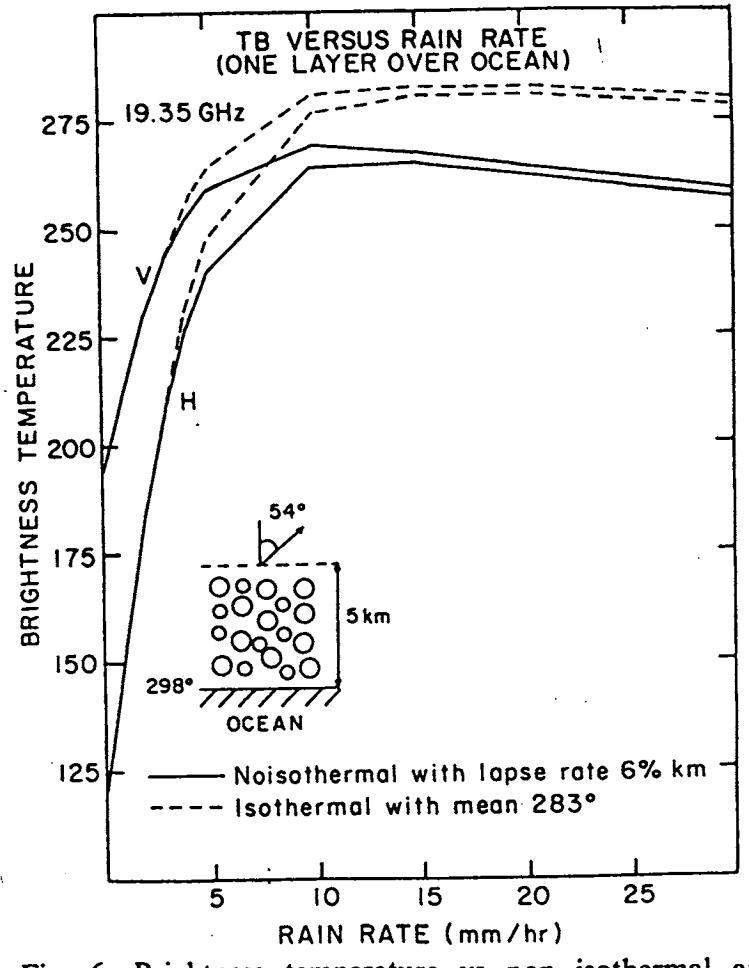



Fig. 6. Brightness temperature vs non isothermal and isothermal temperature profiles.

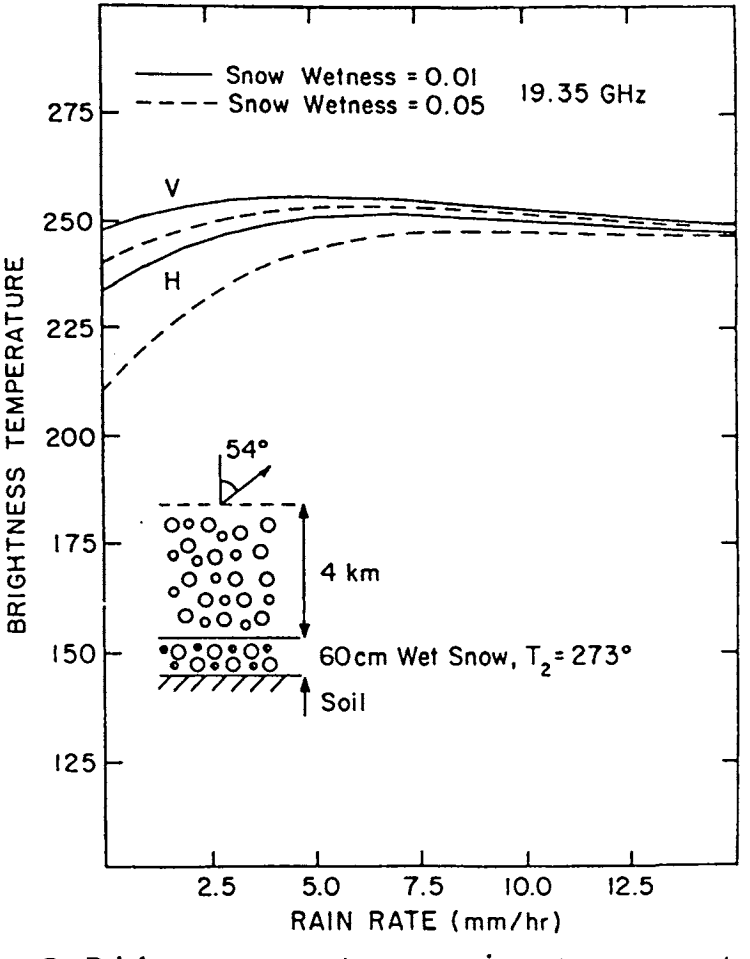



Fig. 7. Brightness temperature vs rain rates over wet snowpack.

## Other parameters

- **Soil Moisture**

  **- used in boundary layer parameterization to evaluate surface fluxes of latent and sensible heat and to act as a proxy for antecedent precipitation;**

  **- infrared retrieval approaches based on observation of diurnal variation of surface temperature, i.e. change in thermal inertia and heat capacity;**

  **- microwave approaches based on changes in surface emissivity, although this also depends on surface temperature, soil type, vegetative cover and surface roughness; long wavelength measurements required to sample depth;**

- **Albedo, snow cover, ice**

  **- used directly in model shortwave radiation parameterization; visible infrared, and microwave techniques available to infer these properties with varying degrees of accuracy.**

## Other parameters (continued)

- **Surface Temperature**

  **- driver for sensible heat flux, radiation, and evaporation, as well as of importance for cloud/clear background discrimination;**

  **- available through infrared window regions (need to account for emissivity, partial cloudiness, aerosol and water vapor effects) and microwave;**

- **Surface Fluxes**

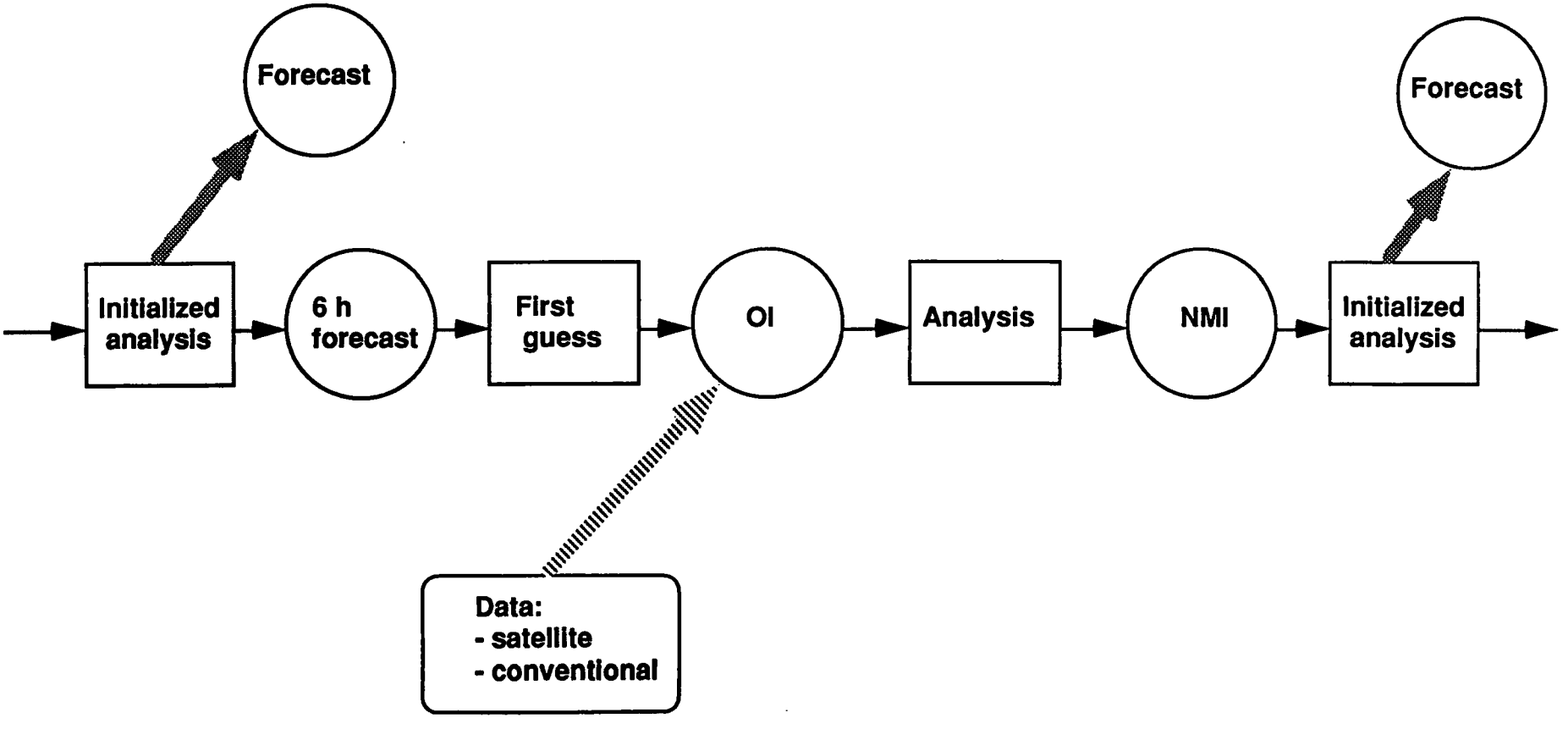
  **- related variables such as albedo, surface temperature and soil moisture allow for proxy inference of latent and sensible heat fluxes;**

  **- measurement of surface winds over the ocean provides surface stress, i.e. momentum flux.**

## Components of the NWP model:

- The forecast model is only one part of a complete NWP system;
- Component parts include:
  - an observational system
  - an observations quality control check
  - data assimilation technique to provide an objective analysis of the state of the atmosphere at a given moment in time (OI)
  - check of the consistency of the objective analysis with the constraints of the forecast model (initialization) [e.g. prevent growth of spurious gravity waves]
  - the forecast model

## NWP model cycle



## Data Assimilation:

- A complete numerical weather prediction (NWP) system incorporates a large number of individual data elements, all of which must interact with each other properly and efficiently;

  - the forecast model integrates the equations of motion supplied by the equations of state, hydrostatic balance, conservation of mass, the first law of thermodynamics, and physical parameterizations;

  - the data assimilation scheme updates the forecast with observations;

- When there is a variety of observing systems such as radiosondes, aircraft, ship, satellite data, etc., each has different error characteristics, requiring an optimal interpolation (OI) approach to data assimilation;
- Data assimilation is the process of obtaining a complete instantaneous three-dimensional state of the atmosphere from data distributed irregularly in space and time.

## 4D Assimilation (refers to space and time domains)

- Data assimilation must satisfy two requirements:
  - update the model state so that it agrees with current observations
  - initialize or balance the updated model state

- Updating techniques (determine representations of model fields from irregularly spaced observations):
  - direct insertion at grid points
  - univariate analyses (depend on one variable alone)
  - multivariate analysis (depend on more than one)

- Initialization methods:
  - static methods (geostrophic balance)
  - non-linear normal mode initialization (NL NMI) [takes into account details of the model physics]

- **Updating methods:**

  **- successive correction method (SCM) or Barnes analysis (weighted average univariate, efficient, distance, not error dependent)**

  **- optimal interpolation (OI) or Gandin analysis (regression of values on observation, accounts for magnitude and correlation structure of errors of first guess and observations, can be multivariate, analysis is optimal in a statistical sense, i.e. rms error is minimized, need to specify observational and first guess error covariances)**

  **- variational analysis method (VAM) (very flexible, also allows for time dependence to be taken into account allowing for treatment of asynoptic data, may use the adjoint of the forecast model)**

## Optimal retrieval

- This concept is a synthesis of inverse, forward problem, and NWP application;
- Optimal retrieval combines the NWP fields and observed radiances in an optimal manner using Bayesian estimation theory;
- Optimal retrieval can be thought of in two ways:

  - a retrieval scheme which uses forecast profiles as a first guess and the covariance of the forecast error as a constraint to produce retrievals compatible with the NWP analysis; or

  - a module within the NWP analysis scheme to perform the vertical analysis of the satellite radiances on the desired vertical grid points.

Eyre, J.R., 1989: Inversion of cloudy satellite sounding radiances by nonlinear optimal estimation: Theory and simulation TOVS. Quart. J. Roy. Meteor. Soc., 115(489) 1001-1026.

## Optimal retrieval mathematics

Let x be a vector representing the atmospheric state (or a NWP model's representation of it) and ym be a vector of satellite sounding measurements (radiances or brightness temperatures). Our purpose in making a 'retrieval' or 'analysis' is to find the most probable value of the atmospheric state x given the measurements ym, i.e. to maximize the conditional probability of x given ym.

$$P\left(x / y^m\right) = maximum.$$

Applying Bayesian estimation theory to the problem of NWP analysis and shows that, in the case of Gaussian error distributions, the most probable solution is that which minimizes a 'cost' or 'penalty' function

$$J(x) = \left(x - x^b\right)^T \cdot C^{-1} \cdot \left(x - x^b\right) + \left\{y^m - y(x)\right\}^T \cdot E^{-1} \cdot \left\{y^m - y(x)\right\}$$

where xb is the forecast background; C is its expected error covariance; y(x) is the radiative transfer model or 'forward model', an operator for calculating the error-free measurements corresponding to the state x; E is the expected covariance of the combined measurement and forward model errors; and superscripts T and -1 denote matrix transpose and inverse respectively.

## Optimal retrieval mathematics (continued)

To find the most probable value of x, we may either minimize Eq. (2) or, assuming there are no multiple minima, find where the gradient of J(x) with respect to x is zero.

$$J'(x) = C^{-1} \cdot \left(x - x^b\right) - K(x)^T \cdot E^{-1} \cdot \left\{y^m - y(x)\right\} = 0$$

where K(x) contains the partial derivatives of y(x) with respect to the elements of x.

- The linear case - For the linear problem, K is independent of x and we may write (This is the familiar minimum variance solution which is also the maximum probability solution in the case of Gaussian statistics):

$$x = x^b + C \cdot K^T \cdot \left(K \cdot C \cdot K^T + E\right)^{-1} \cdot \left\{y^m - y\left(x^b\right)\right\}.$$

- When attempting to retrieve from cloudy radiances and with respect to the retrieval of humidity, the problem is highly nonlinear, i.e. K changes rapidly as a function of some of the elements of x:

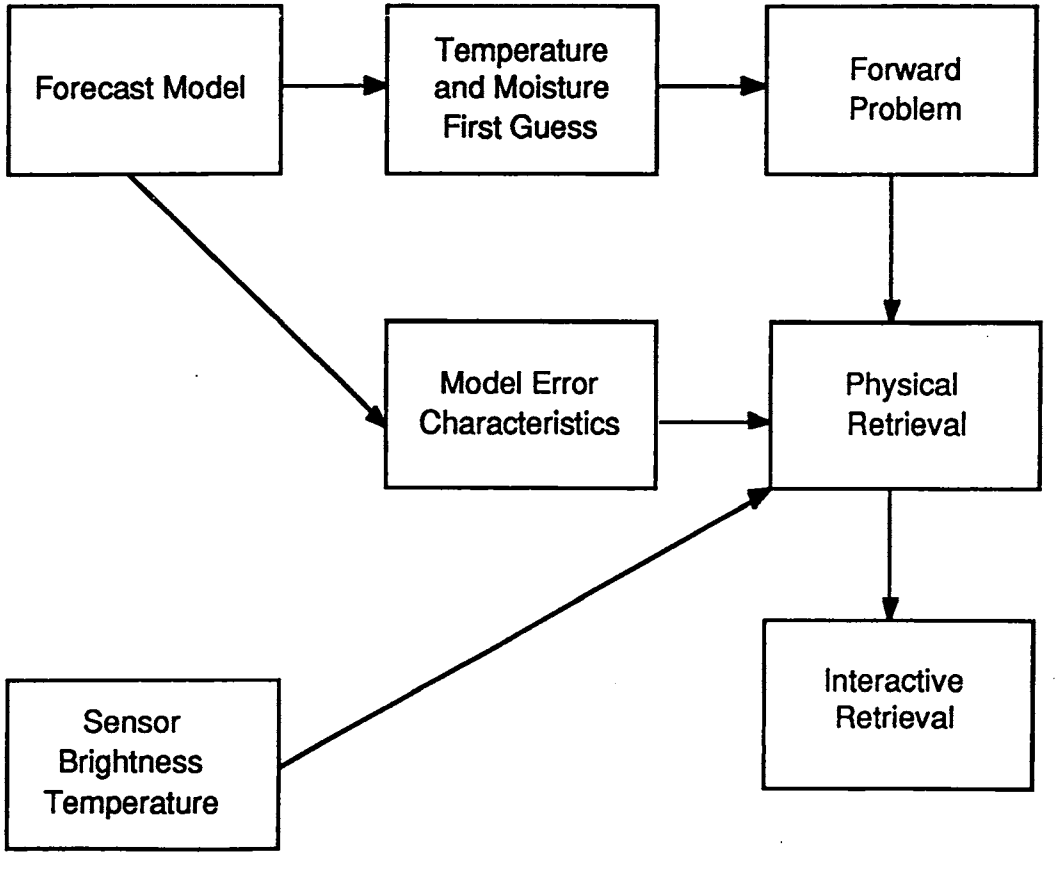
$$x_{n+1} = x_n + \left(x^b - x_n\right) + W_n \cdot \left\{y^m - y(x_n) - K_n \cdot \left(x^b - x_n\right)\right\}$$

## Interactive Retrieval

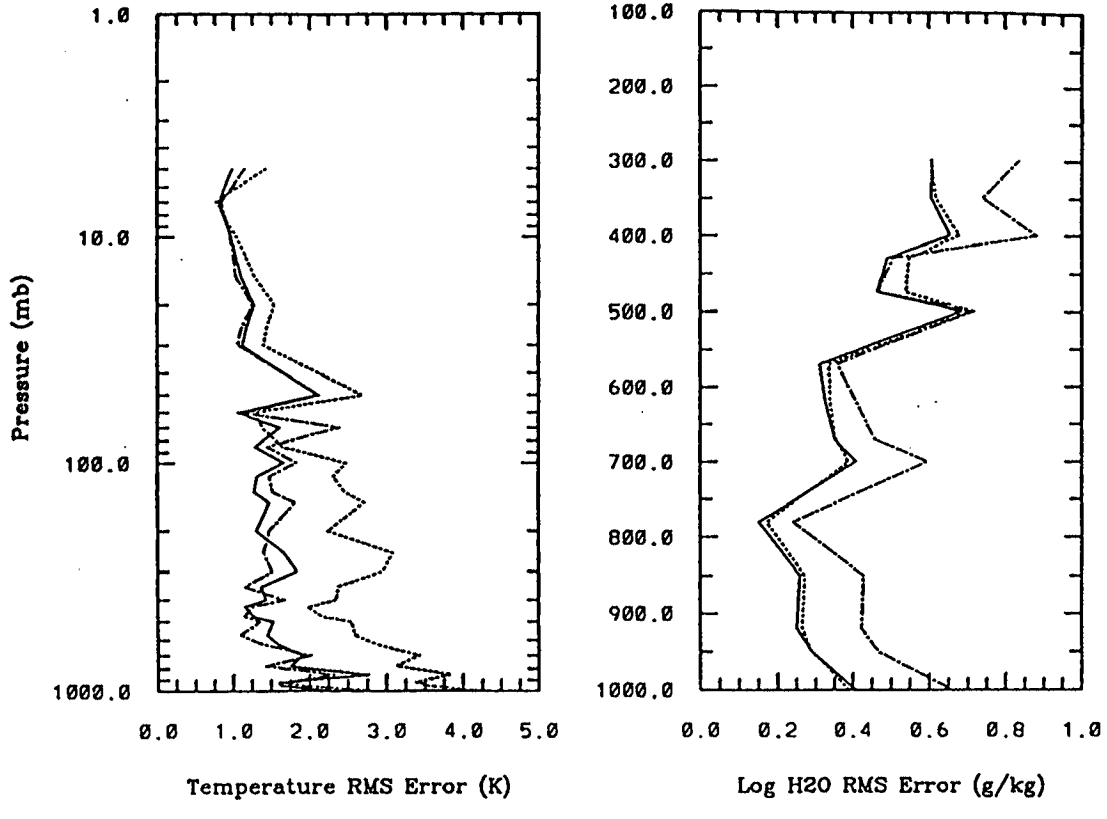
- Physical Retrieval using elements of forecast fields as a first guess.
- Operational approaches for the retrieval of temperature and moisture profiles based on regression (or "D" matrix) retrievals constrained to a solution space defined by the climatological variance (CV) of the ensemble for which the statistics are developed.
- Temperature and moisture profiles are often retrieved for assimilation within numerical weather prediction (NWP) models which themselves can provide information on the atmospheric state. NWP models dynamically constrain the possible states of the atmosphere (i.e. forecasts of temperature and moisture profiles) through their model physics.
- This reduces the solution space for the retrievals from the CV of the regression statistics to that of the model forecast error variance (FEV).

Moncet J. L. and R.G. Isaacs, 1992: Physical Retrieval of Atmospheric Profiles from the DMSP Microwave Sensor Suite Using Forecast First Guesses: Simulation Studies. Submitted to J. Appl. Meteor.

## Schematic of Interactive Retrieval



## Interactive Retrieval Results




**This figure shows the retrieval errors obtained for the independent data set when using a forecast first-guess (dot-dash), a first-guess derived from climatology (dotted), and a mixed forecast-climatological first-guess (solid)**

# 4. Observing System Simulation Experiments (OSSEs)

## 4.1 What is an OSSE

## 4.2 System simulation procedure

## 4.3 Nature run

## 4.4 Data sampling

## 4.5 OSSE procedure and comparison methodology

## What is an observing system simulation experiment (OSSE)?

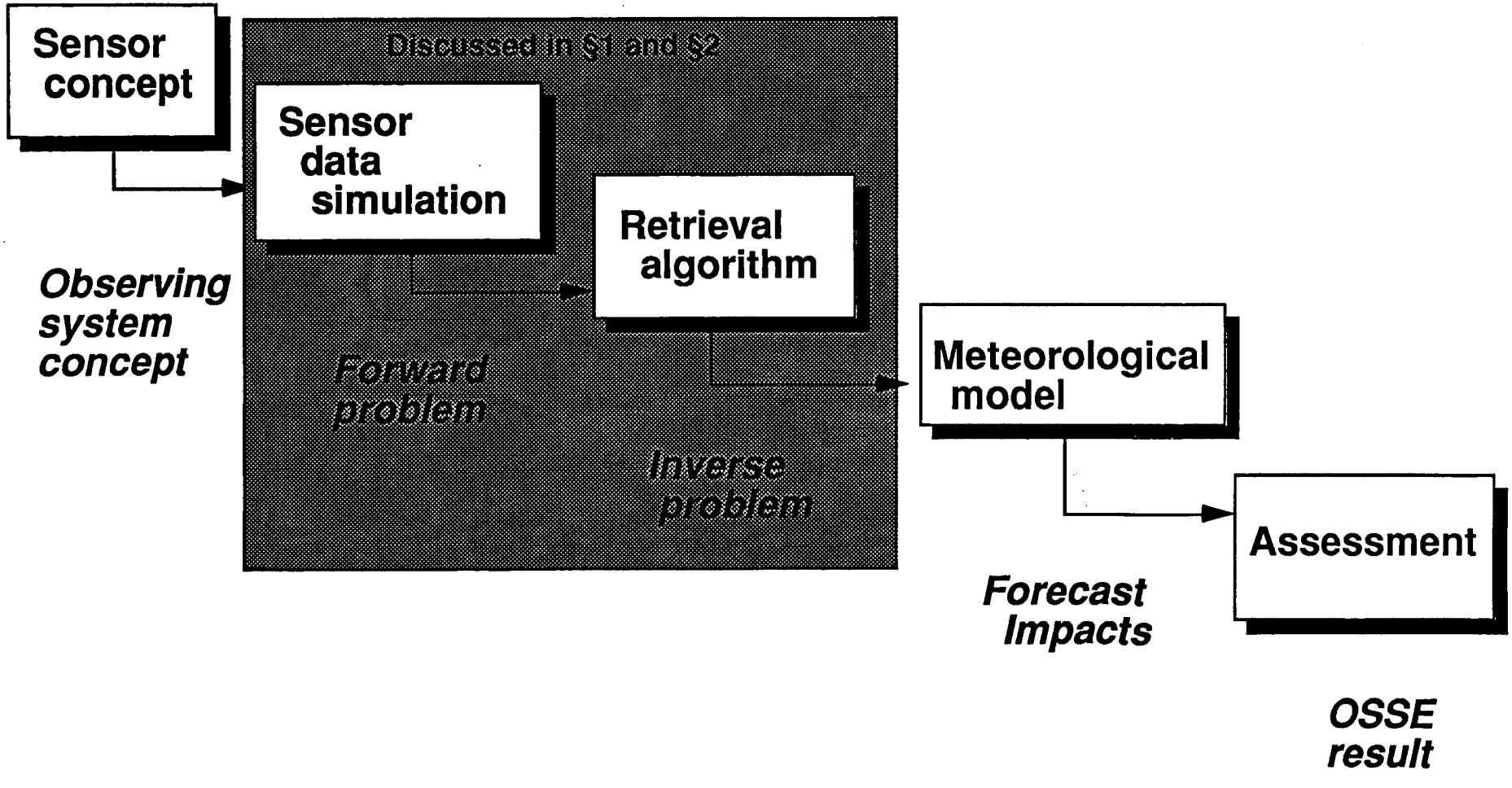
- An OSSE is an end-to-end computer simulation which assesses the sensitivity (i.e. impact of a new data source on meteorological model output.
- The goal of an OSSE is to determine the usefulness (in an objective, quantitative manner) of a new satellite data source using computer simulation of the sensor observations, model data assimilation, and model processing functions.
- OSSE technology integrates simulation (i.e. forward problem) capability, inverse problem capability, and meteorological model capability into power assessment tool.

Refs:

Hoffman, R.N., C. Grassotti, R.G. Isaacs, J.-F. Louis, T. Nehrkorn, and D.C. Norquist, 1990: Assessment of the Impact of Simulated Satellite Lidar Wind and Retrieved Water Vapor Observations on a Global Data Assimilation System. *Monthly Weather Review*, 118, 12, 2513-2542.

Isaacs, R.G., R.N. Hoffman, and L.D. Kaplan, 1986: Satellite Remote Sensing of Meteorological Parameters for Global Numerical Weather Prediction. *Reviews of Geophysics*, 24, 4, 701-743.

## OSSE end-to-end system simulation



## Uses of OSSE Results:

- Observing systems simulation experiments (OSSEs) provide a powerful tool to assess the impact of proposed satellite borne observing systems (sensors) on meteorological applications models.
- OSSEs:

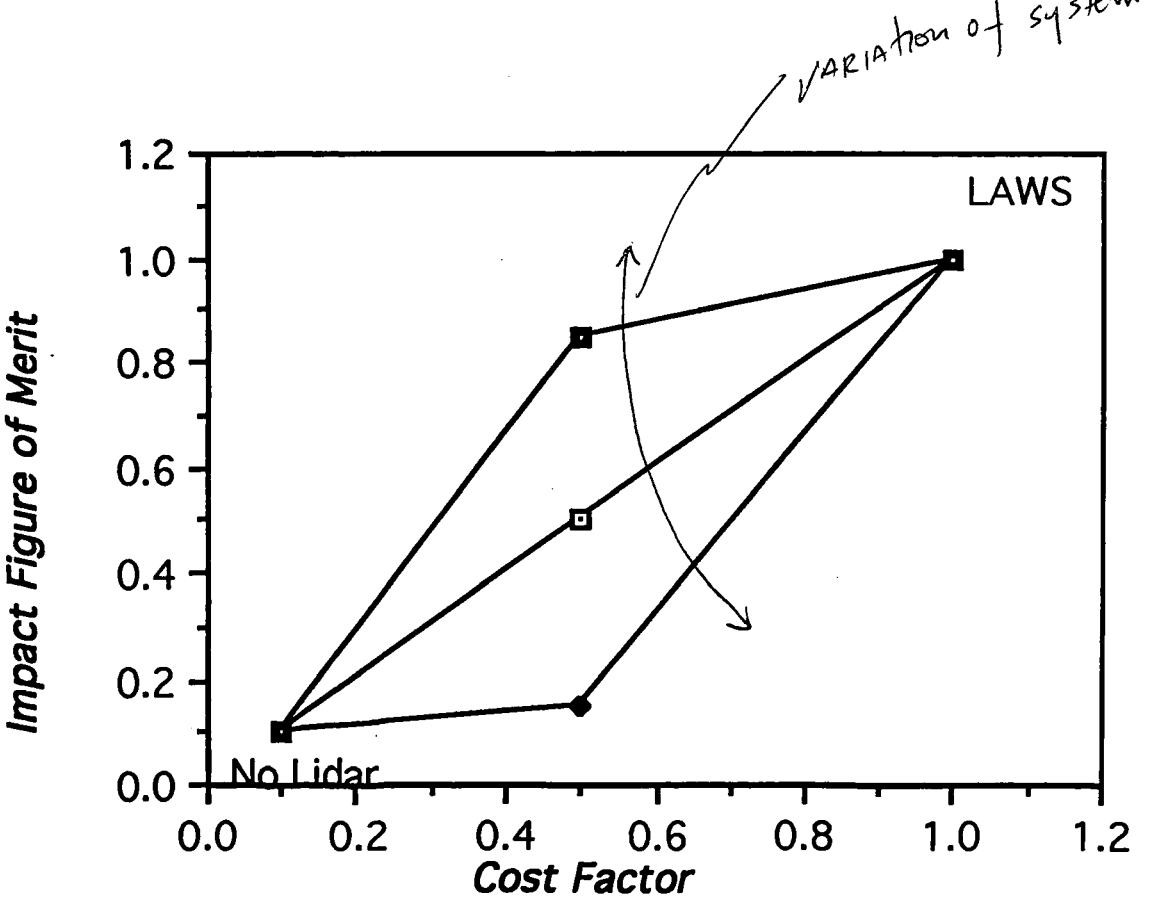
  - Help optimize the design configuration of a planned observing system by exploring the sensitivity of the resulting impact to design trade-offs;

  - Quantify sensitivity of model attributes with fixed observational input;

  - Provide assessment of benefit in cost/benefit analysis.

**Cost/Benefit Analysis:**

- **OSSE provides quantitative measure of impact on model performance figure of merit with simulated new data source;**
- **Example: is forecast accuracy better?**



- **An OSSE consists of four components:**

  **(a) a realistic simulation of the properties of the atmosphere - the "nature run";** time series to simulate temporal sampling

  **(b) a simulation of the observing system or sensor;**

  **(c) a meteorological applications model (ex. numerical weather prediction [NWP] model);**

  **(d) a comparison approach**

## The "nature" run:

- A computer data base which provides the time history state of the atmosphere for a period of time consistent with that of the meteorological applications model;

- While actual measurements of the atmospheric state parameters would be ideal, practicality dictates that a numerical model output be used; model output provides consistent fields of the total state of the system including many parameters which are not observed (measured) globally on a regular basis;

## Sensor simulation:

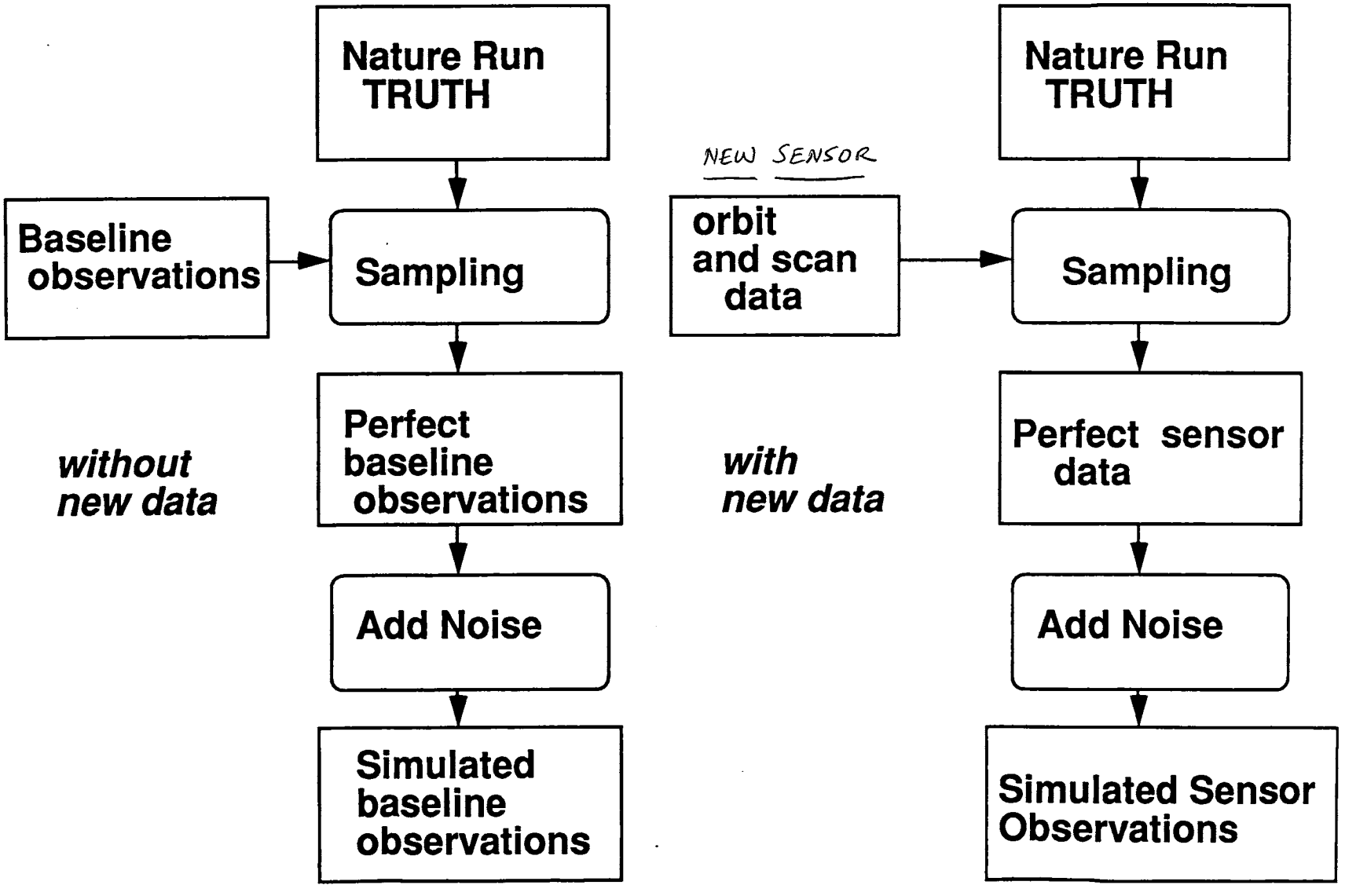
- The model requires input of simulated observations from the hypothetical sensor system, usually of one or more observables which drive the model;

- The characteristics of the simulated observations which are required include:
  - the spatial resolution;
  - the sampling frequency;
  - the error characteristics.

- All the above require assumption regarding the sensor and platform and can be simulated using forward problem/inverse problem concepts previously discussed;

- Sensor simulations in practice provided by sampling the "truth"of the nature run and producing the desired simulations.

## Data Sampling Approach



## Meteorological applications model:

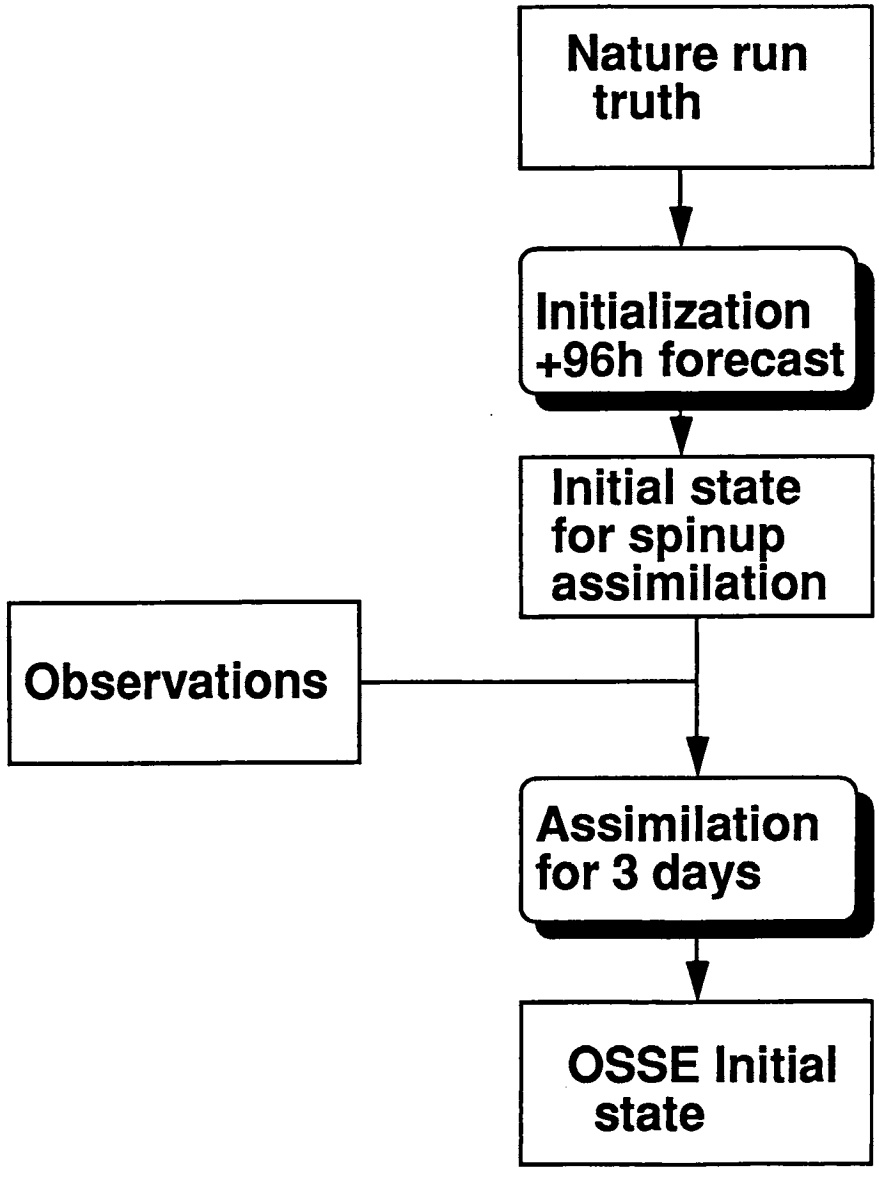
- This is a complete applications model relevant to the user;

- General attributes are the:

  - ingest or "data assimilation" of observations;
  - an analysis and initialization procedure;
  - a forecast procedure based on forward time stepping of the state of the atmosphere by applying parameterizations of the physical processes governing atmospheric motion and radiative transfer;
  - output of a forecast of atmospheric state;

- Model must be "spun-up" to provide an initial state which is distinct from that of the nature run, yet still governed by the physics of the model system (avoids identical twin characteristics).

## Spin Up Procedure



## Example of model evolution during spin up: *(Hoffman et al, 1990, MWR, 118, 12, 2513.)*

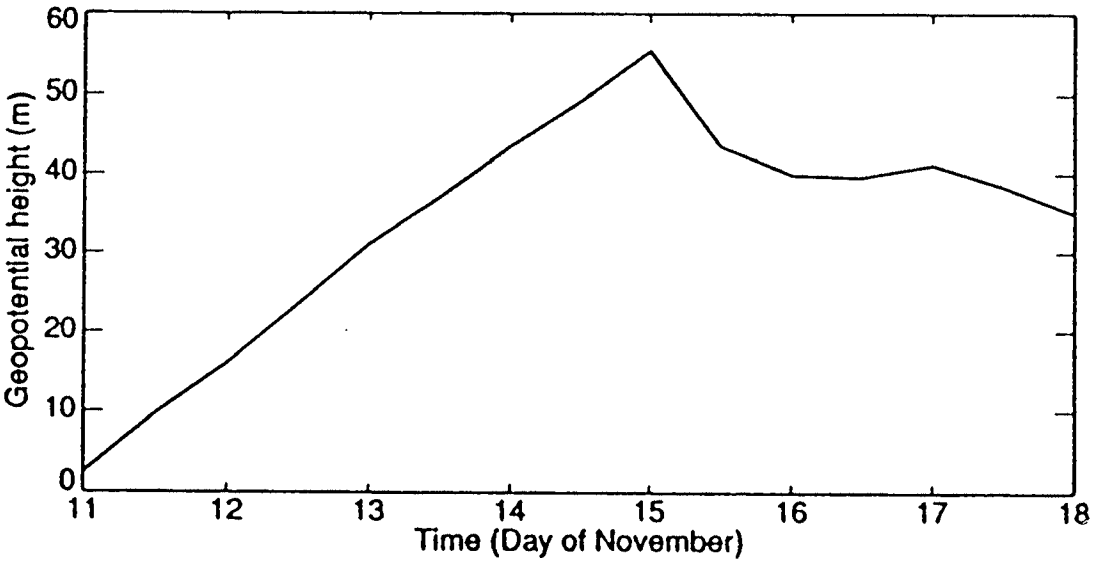


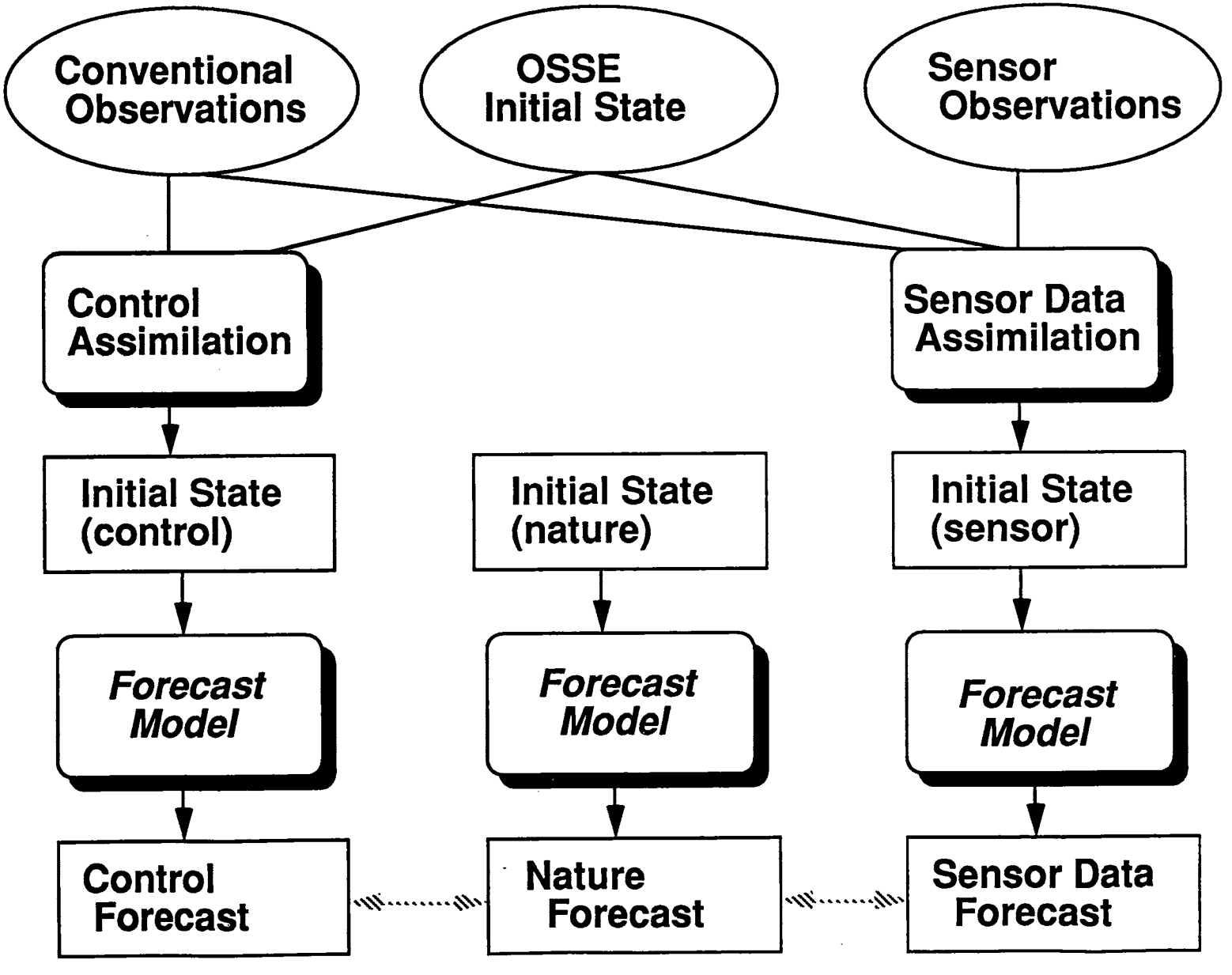

FIG. 1. Evolution of global rms 500 hPa height error during the spinup forecast and assimilation.

## Comparison methodology:

- use objective statistical methods, e.g. rms errors, skill scores, etc;

- must consider degree to which the applications model data assimilation is optimized to the existing set of observations which preclude effective use of the new data source.

# OSSE Procedure



## OSSE Results (Global NWP):

- In data sparse regions such as the southern hemispheric oceans, satellite data sources significantly improve forecast accuracy;
- In the northern hemispheric continental regions, impact is difficult to discern because of the density of conventional surface and upper air observations collected at synoptic times;
- satellite data in the northern hemisphere helps to forecast the development of synoptic systems which advect from over the oceans where conventional data is sparse.

# OSSE results: addition of moisture sounder information

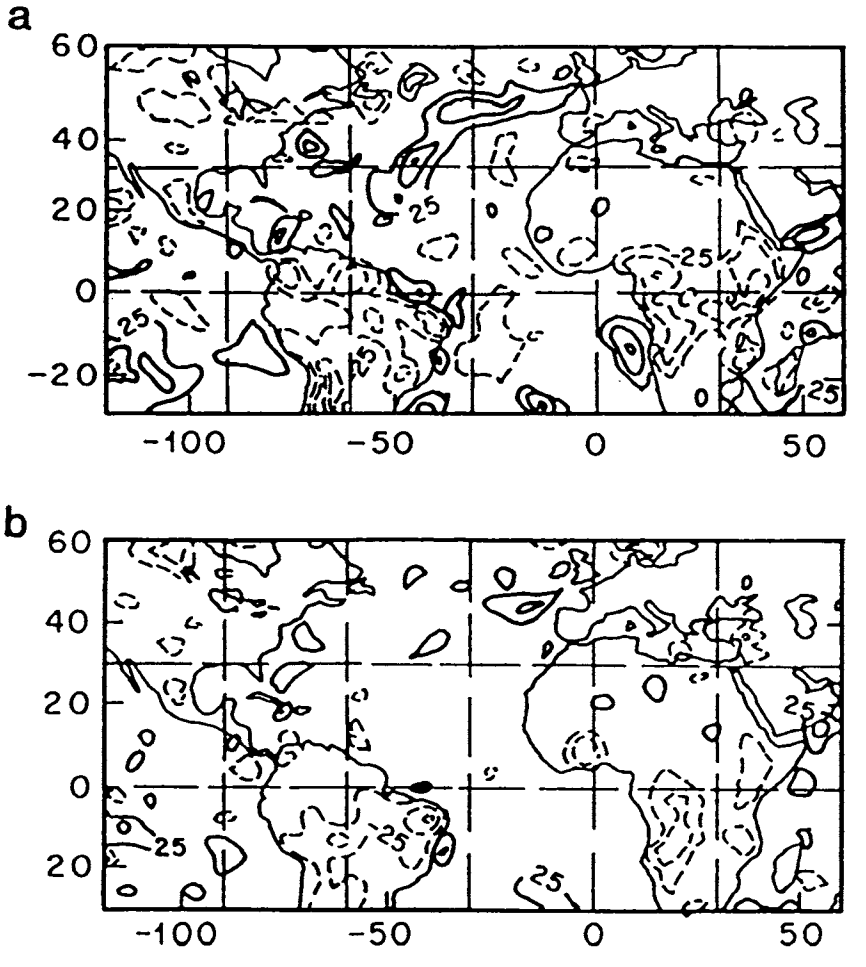



FIG. 5. Analysis error for 850 mb relative humidity valid 00 UTC 25 November. (a) STATSAT, (b) SSMSAT. Contour interval is 25% with zero line omitted. Negative values are dashed.

# OSSE results: 500 hPa error evolution with various sensor data for Northern and Southern Hemisphere.

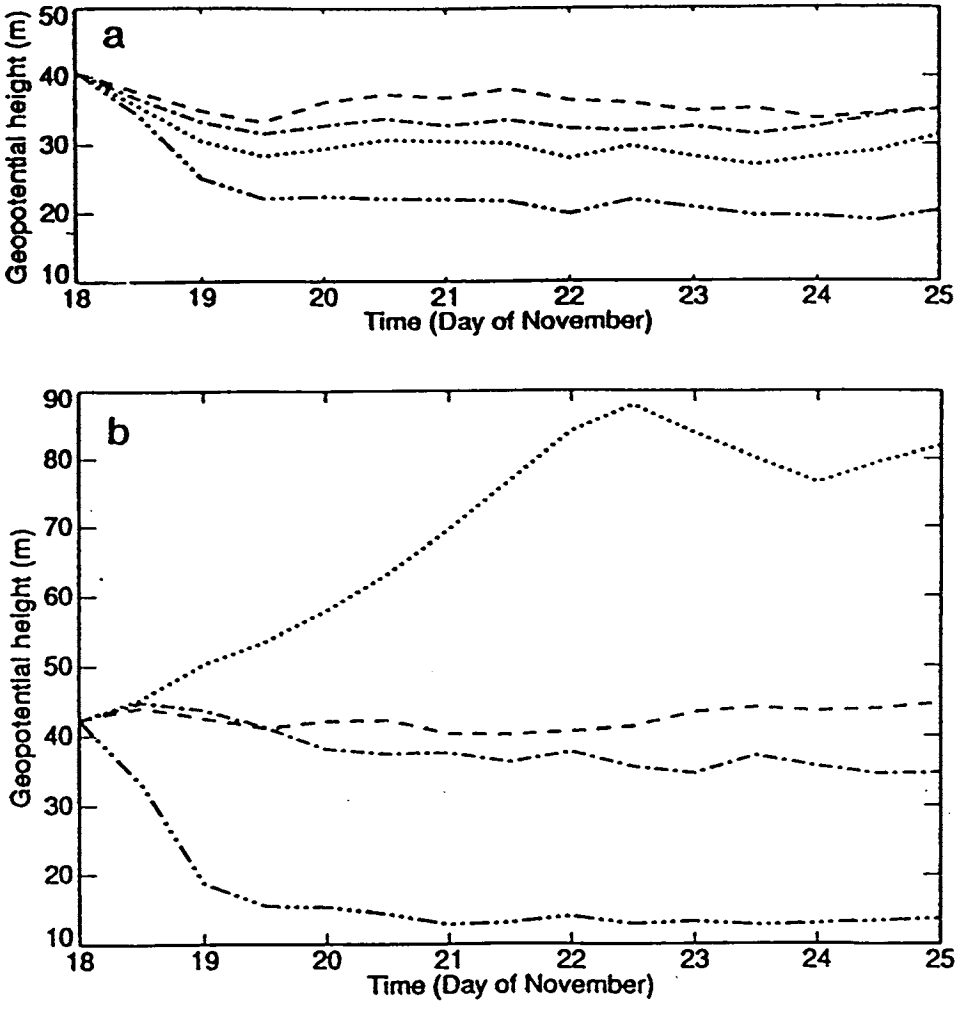



FIG. 6. Evolution of (a) Northern and (b) Southern Hemisphere rms 500 hPa height error during the STATSAT (dash), NOSAT (dot), SSMSAT (dash-dot) and WINDSAT (dash-dot-dot-dot) OSSEs.

# OSSE results: Vector wind RMSE profiles with various data sources

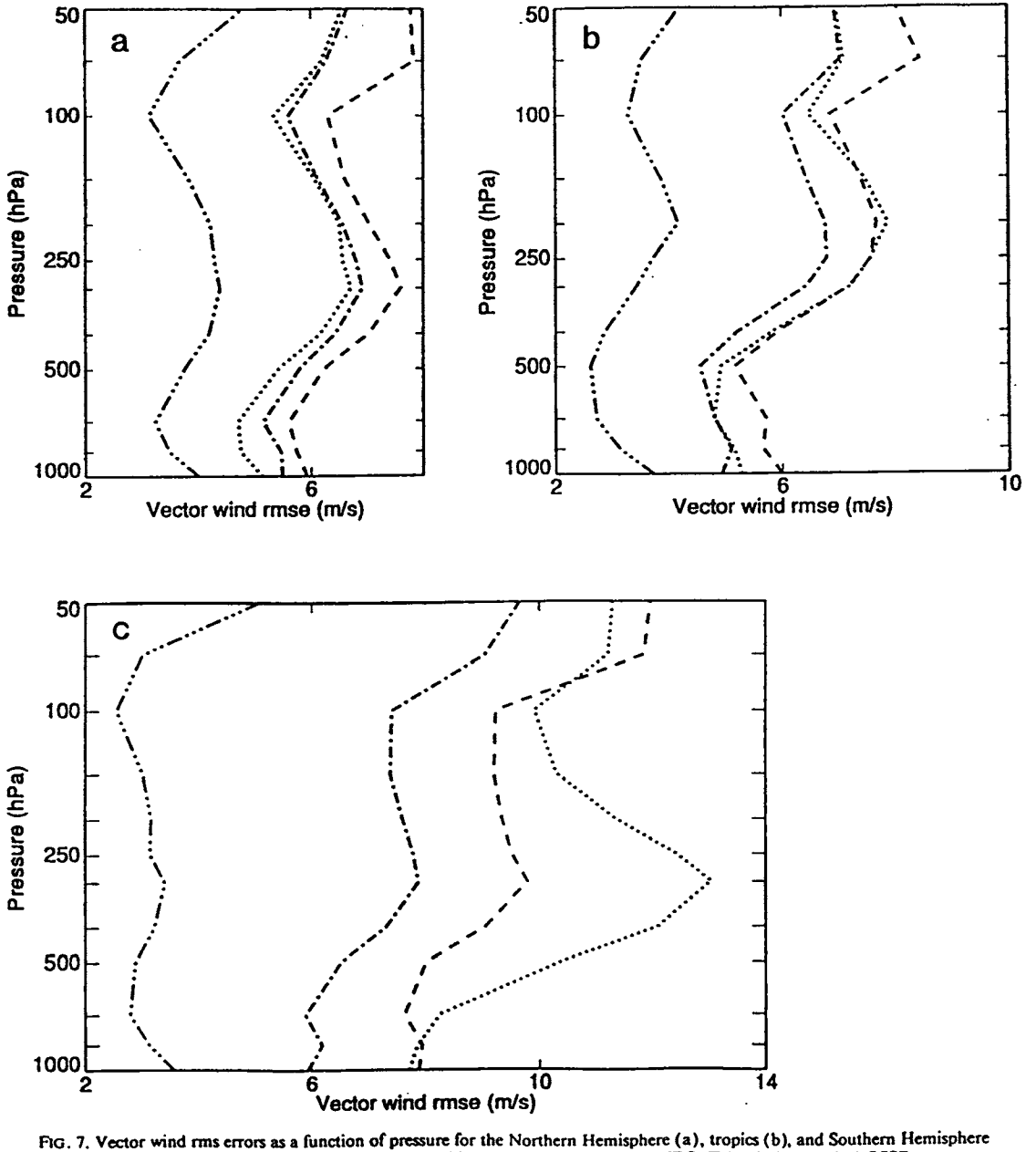
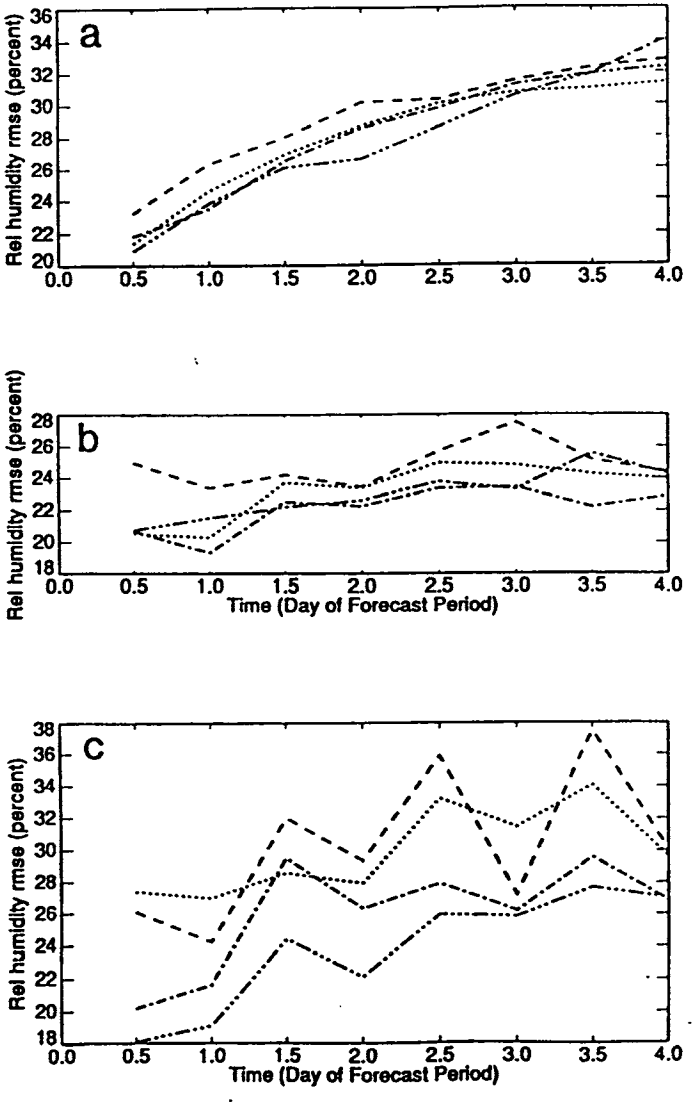



FIG. 7. Vector wind rms errors as a function of pressure for the Northern Hemisphere (a), tropics (b), and Southern Hemisphere (c) for the STATSAT (dash), NOSAT (dot), SSMSAT (dash-dot) and WINDSAT (dash-dot-dot-dot) OSSEs.

# OSSE results:Forecast RMS error growth for 850 mb relative humidity




STATSAT — TIROS

SSMSAT — DMSP

FIG. 14. Forecast rms error growth, 850 mb relative humidity. (a) Northern Hemisphere extratropics, (b) tropics, (c) Southern Hemisphere extratropics for the STATSAT (dash), NOSAT (dot), SSMSAT (dash-dot) and V SAT (dash-dot-dot-dot) OSSEs.

## Summary:

- An OSSE is an end-to-end computer simulation which assesses the sensitivity (i.e. impact of a new data source on meteorological model output.
- The goal of an OSSE is to determine the usefulness (in an objective, quantitative manner) of a new satellite data source using computer simulation of the sensor observations, model data assimilation, and model processing functions.
- OSSE technology integrates simulation (i.e. forward problem) capability, inverse problem capability, and meteorological model capability into power assessment tool.

Earth science perspective!

# 5. Physical Parameterizations

## 5.1 Atmosphere (clouds, convection, boundary layer)

## 5.2 Ocean (interaction with atmosphere)

## 5.3 Land (surface properties related to remotely sensed parameters)

**Ref:**

**Louis, J.-F., 1982: Parameterization in weather prediction models. *Rivista di Meteorologia Aeronautica*, XLII, 2/3, 219-255.**

## Physical Parameterizations

- The limitations of compute power or physical understanding often require simple formulations of physical processes which affect atmospheric motion and energy balance;
- These physical parameterizations describe diabatic processes which produce sources and sinks of energy, water vapor, and momentum;
- Important diabatic processes for numerical modeling include:
  - release of latent heat in clouds;
  - transfers of momentum, sensible heat, and moisture with the ground;
  - radiative transfer; and
  - turbulence in the boundary layer.

## Interactions Among Model Physical Processes and Parameters

- The interaction between physical processes which are quantified by model parameterizations and the model variables is complex;
- The diagram illustrates these interactions: The variables which describe the state vector of the atmosphere are in boxes (prognostic variables), while the important physical processes are in ellipses (they would be represented by the various physical parameterizations in the model). The direction of the arrows shows whether a process is affected or is modified by a variable. The thickness of the arrow indicates the relative importance of the interaction. Note the many potential "feed-back" loops;
- Significantly, remote sensing provides important information for use in both the initialization of prognostic variables (i.e. winds, temperature, etc.) and in the diagnosis of the validity of model parametrizations (e.g. is precipitation and cloud well represented);

# Physical processes and parameters

Note importance of hydrologic cycle - WATER!

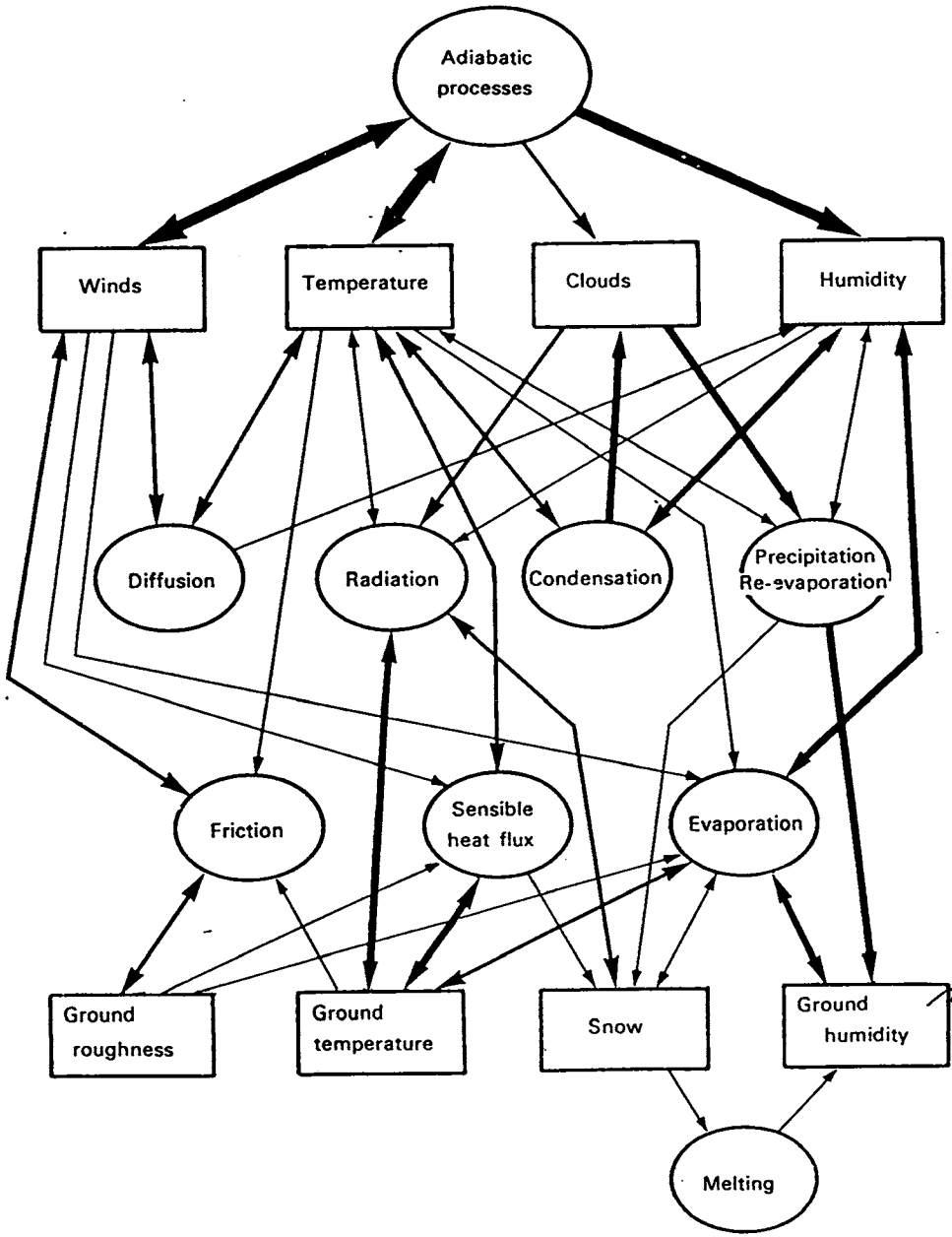



Fig. 2 - Schematic representation of processes to be included in a forecast model

## Moist processes (including clouds)

- The simplest parameterization would rain out excess moisture whenever a grid point became saturated;
- A complete account would treat condensation of water vapor, cloud droplet microphysics; formation of rain droplets, evaporation, freezing into snow hail, etc.
- Cloud schemes:

  - stratiform clouds are associated with large scale features such as frontal zones: define a critical relative humidity value which is related to cloud or liquid water

  - convective cloud strongly interacts with dynamics, depends on conditional instability of atmosphere, intensity is determined by the availability of moisture.

# Important processes within clouds

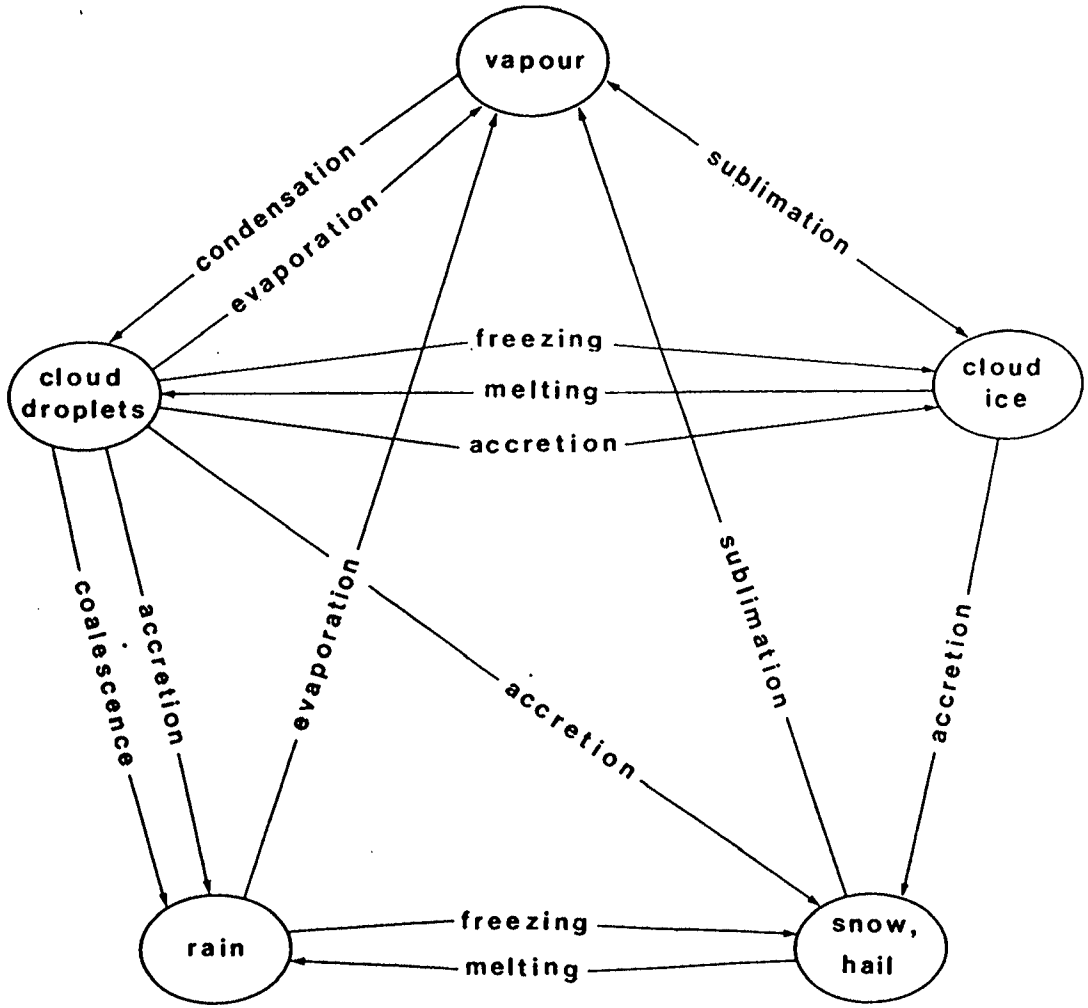



Fig. 15 - *Schematic diagram of important processes within a cloud*

## Convective cloud schemes

- **may be classified according to whether readjustment of conditional instability is stressed or availability of moisture and what happens within the cloud:**

| | *cloud* | *no cloud* |
|---|---|---|
| ***adjustment of instability*** | **Manabe** | **Arakawa-Schubert** |
| ***availability of moisture*** | **Kuo** | **Anthes** |

## Radiation

- Radiation is critical to the determination of energy balance and must be included in models of the climate;
- For NWP, radiation is important in determining the diurnal cycle which drives surface temperature and fluxes and in the interaction between clouds and radiation;
- The goal of the radiation parameterization is to treat the physics of the radiative transfer process which determines the divergence of the net flux of radiation through the atmosphere;
- The net radiative flux divergence is proportional to atmospheric heating;
- This requires consideration of the total solar and infrared bandpasses of energy;
- Hence, the use of band models.

where is atm. heating occurring.

## Ocean-atmosphere coupling

- **Major effects are:**
  - **the sea surface temperature driver**
  - **thermal heat capacity of the ocean surface**
  - **surface moisture boundary condition**
  - **ocean surface stress**
  - **ocean surface albedo**
- **These are treated in a straightforward manner by the boundary layer model;**
- **The degree of interaction between atmosphere and ocean which is required depends on the time scale of the model (less for NWP/ more for climate)**

## The boundary layer

- A boundary layer parameterization is required to provide lower boundary conditions to the model and to determine terms not available from the discretization of the nonlinear equations of motion;
- Must provide parametrizations of sensible heat flux and the transfer of momentum;
- Approaches
  - K theory (Ekman) [fluxes proportional to gradient of quantity]
  - Bulk methods [based on empirical data]
  - Mixing length theory [help determine what K is]
  - Similarity theory [Monin-Obuknov]

## Surface temperature and moisture

- **The boundary layer also provides surface temperature and (soil) moisture which are needed in the computation of surface fluxes;**

- **Ground temperature obtained by:**

  **- the energy budget of the surface, i.e. the sum of the fluxes of sensible, radiative, and latent heating are equated to the rate of change of heating of the surface layer through its thermal heat capacity**

  **- solving a temperature diffusion equation for the ground layer**

- **Similar approaches are used for soil moisture**

# "Mission to Planet Earth"

An underlying theme of earth satellite sensor applications has been monitoring weather and climate variables;

Recent concerns of the scientific community related to the question of global change has catalyzed a focus on viewing the "whole earth system": atmospheric, oceanic, terrestrial, etc.;

Weather and climate variables measured by satellite platforms and sensors are summarized in the following excellent table;

The EOS Mission integrates measurements of many of these parameters along with those characterizing the solid earth and biosphere.

Objective: "determine the extent, causes, and regional consequences of global climate change."

NASA, 1992: Report to Congress on the restructuring of the Earth Observing System. March 9, 1992.

## XI. Applications to Global Change Monitoring



# Sensors for monitoring weather and climate variables

| | Variable | Spectral region(s) | | Representative sensors (nominal spatial resolution) | Satellite platform(s) | Technique | Corroborating data | Operational products | Special programs | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| *Clouds:* | coverage; type | VIS | 0.4–0.7 $\mu$m | SR (4 km); AVHRR (1 km); VISSR (1 km); VHVIS (0.6 km); HVIS (2.7 km) | NOAA; GOES; DMSP | threshold; bi-spectral HBTM; pattern recognition | surface observer; all-sky cameras | USAF 3-D/RT Nephanalysis | ISCCP; FIRE | Schiffer and Rossow (1985) Cox *et al.* (1987) |
| | coverage; type; CTT | TIR | 8–14 $\mu$m | SR (8 km); AVHRR (1 km); VISSR (8 km); VHIR (0.6 km); HIR (2.7 km) | NOAA; GOES; DMSP | | radiosondes | | | |
| | cirrus | NEAR IR<br>NEAR IR<br>$CO_2$ | 2.6, 2.7 $\mu$m<br>1.0 $\mu$m<br>15 $\mu$m | SCR (25 km)<br>SAGE (100 km)<br>VAS (14 km) | Nimbus-5<br>Explorer<br>GOES | limb sounding<br>vertical sounding | surface obs; aircraft | | Cirrus IFO | Barton (1983b) Woodbury and McCormick (1986) Wylie and Menzel (1989) |
| *Water vapor:* | mid/upper tropospheric | water vapor | 6.3–6.7 $\mu$m | VAS (14 km); HIRS/TOVS (30 km) THIR (22 km) | GOES; METEOSAT; TIROS-N; Nimbus-4; 5; 6 | w.v. absorption | radiosondes | UTH | | Eyre (1981) |
| | column total; | water vapor | 8–9 $\mu$m | VAS (14 km) | GOES | multi-frequency sounding | | | | Chesters *et al.* (1987) |
| | cloud liquid water | passive microwave | 8, 21, 22, 31, 37GHz | SMMR (55–27 km) SSM/I (12–25 km) | Nimbus-7; Seasat; DMSP | $T_B$ Differencing | aircraft | | | Wilheit and Chang (1980 |
| | | passive microwave | 90, 183 GHz | AMSU (planned) | Eos | | | | | Wang *et al.* (1989) |
| *Precipitation:* | cumulative | VIS/TIR | | VISSR (1 km; 7 km) | GOES; METEOSAT; GMS | cloud indexing; bispectral; life history | rain gauges; radar | GPI; EPI | Winter MONEX TRMM | Arkin and Ardanuy (1989) |
| | instantaneous | passive microwave | 19GHz | ESMR (25 km): ocean only | Nimbus-5; -6 | absorption based | radar | | | Wilheit (1986) |
| | | | 18, 21, 37GHz | SMMR (55–27 km) = ocean and convective over land | Nimbus-7 | scattering based | | | | Spencer and Santek (1985) |
| | | passive microwave | +85.5GHz | SSM/I (12–25 km) | DMSP | | | | | Petty and Katsaros (1990) |
| *Winds:* | low-level | VIS | | VISSR | GOES; METEOSAT; GMS; | cloud tracking | ships; buoys | NMC analyses | | Gruber *et al.* (1971) |
| | | p. microwave; active microwave | 13.4–14GHz | SMMR (55–27 km) SASS (25 km) | Nimbus-7; Seasat Seasat; ERS-1 | scatterometry | synoptic data | | | McMurdie *et al.* (1987) |
| | high-level | TIR<br>water vapor | 8–14 $\mu$m<br>6.3 $\mu$m | VISSR; AVHRR; HIR THIR (23 km); VAS | GOES; NOAA; DMSP Nimbus; METEOSAT | cloud and water vapor feature displacement | radiosondes; aircraft | UTH | | Turner and Warren (1989) Kasiner *et al.* (1980) |
| *Sea surface temps:* | cloud-free scenes | TIR | 8–14 $\mu$m | AVHRR (1 km) | NOAA | split-window IR | ships; buoys | NOAA MCSST | TOGA | McClain *et al.* (1983) |
| | cloudy scenes | p. microwave | 6.6GHz $T_v$ | SMMR (55–27 km) | Nimbus-7; Seasat | vertical polarization | ships; buoys | | | Gloersen (1984) |

**Carleton, 1991: *Satellite Remote Sensing in Climatology.* CRC Press.**

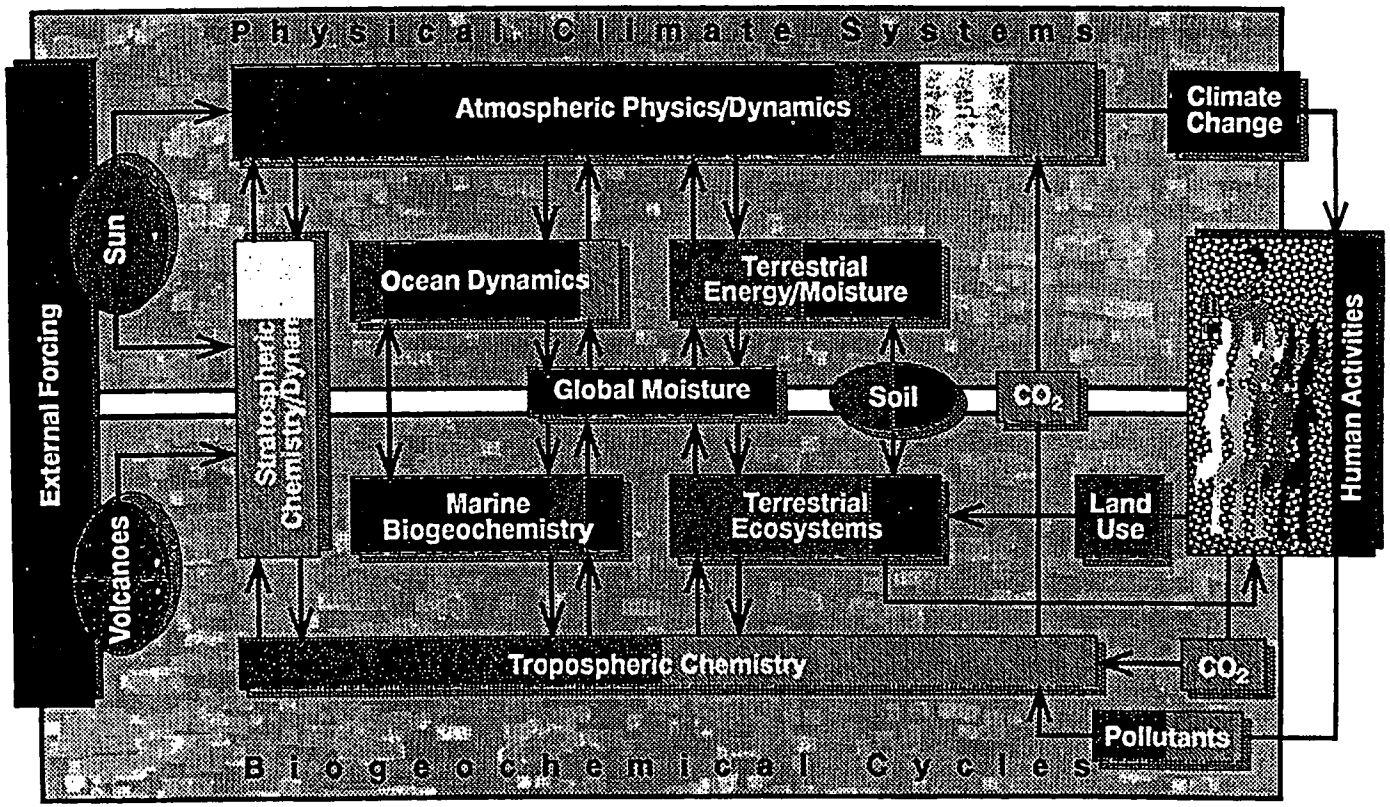
## XI. Applications to Global Change Monitoring



# Sensors for monitoring weather and climate variables (cont'd)

| | Variable | Spectral region(s) | | Representative sensors (nominal spatial resolution) | Satellite platform(s) | Technique | Corroborating data | Operational products | Special programs | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| *Snow-cover:* | extent; reflect. | VIS, NEAR-IR; TIR | | VISSR; AVHRR; HVIS | GOES; NOAA; DMSP | subjective classif.; band differencing | sfc. obs; aircraft | NOAA/NESS | SNOTEL | Matson and Wiesnet (1981)<br>Strong *et al.* (1971) |
| | depth; volume | p. microwave | 18, 37GHz $T_H$ | SMMR (55; 27 km) | Nimbus-7 | $T_B$ differencing | ground; aircraft | | | Chang *et al.* (1990) |
| | snow-cloud discrimination | Near IR<br>Near IR | 3.55–3.9 $\mu$m<br>1.51–1.63 $\mu$m | AVHRR ch. 3 (1 km)<br>HVIS, VHVIS (2.7, 0.6 km) | NOAA<br>DMSP (experimental) | narrow band sensing | aircraft | | | Kidder and Wu (1984)<br>Crane and Anderson (1984) |
| *Sea ice:* | extent | VIS, TIR (cloud-free)<br>p. microwave (cloudy) | | AVHRR (1 km); HVIS (0.6, 2.7 km)<br>ESMR (25 km); SMMR (55 km) | NOAA; DSMP<br>Nimbus-5; -7 | pattern recognition<br>$T_B$ spatial gradient | shore obs; ships; aircraft | Joint Ice Center charts (Navy-NOAA) | MIZEX | Swift and Cavalieri (19 |
| | type; concentration; surface melt | p. microwave<br>a. microwave (23 cm) | | SMMR (55 km); SSM/I (12–25 km)<br>SAR (25 m); SIR-B (25 m) | Nimbus-7, DMSP<br>Seasat; Shuttle | $T_B$ differencing<br>$T_H$ in L-band | surface; aircraft<br>surface; aircraft | | | Weaver *et al.* (1987) |
| *Vegetation:* | biomass | VIS/NEAR-IR (0.6; 0.9 $\mu$m) | | AVHRR bands 1 and 2 (1 km); MSS bands 5, 7 (80 m) | NOAA; Landsat | band ratioing | ground; aircraft | NOAA GVI/ NDVI | ISLSCP; FIFE | Tarpley *et al.* (1984) |
| | | p. microwave (37GHz) | | SMMR (27 km) | Nimbus-7 | $T_H$–$T_V$ differencing | ground; aircraft | | | Choudhury *et al.* (198 |
| *Soil moisture:* | amount; depth | TIR (8–9 $\mu$m)<br>p. microwave (8, 21, 37GHz) | | VISSR (8 km)<br>SMMR (55 km) | GOES<br>Nimbus-7 | AM/PM $T_s$ difference<br>$T_B$ polarization | rainfall (gauge)<br>ground | | | Wetzel *et al.* (1984)<br>Schmugge (1978) |
| *ERB:* | surface albedo | VIS; NEAR-IR (0.4–1.0 $\mu$m) | | SR; AVHRR; VISSR | NOAA; GOES<br>ERBS; METEOSAT | minimum brightness | pyranometer; aircraft | | ERBE; Nimbus-6; -7 | Barkstrom *et al.* (198<br>Ohring and Gruber (1983)<br>Bess *et al.* (1989) |
| | surface solar irradiance | VIS | | SR; VISSR | NOAA; GOES; METEOSAT | statistical; physical (models) | pyranometer | NOAA AgRISTARS | | Tarpley *et al.* (1979)<br>Gautier *et al.* (1980) |
| | OLR | TIR | | SR; NFOVR/WFOVR (150 km) | NOAA; ERBS; Nimbus-6; -7 | window exitance | rainfall | CAC tropical analyses | HCMM; | Stephens *et al.* (1981) |
| *Other:* | ocean color/ chloruphyll | VIS | 0.4–0.7 $\mu$m | CZCS (825 m) | Nimbus-7 | band differencing | ships | CZCS (NASA) | GOFS | Feldman *et al.* (1989) |
| | jet contrails | TIR | 11, 12 $\mu$m | AVHRR: channels 4, 5 | NOAA | band differencing | surface obs. | | | Lee (1989) |
| | aerosols | NEAR-IR | 1.0 $\mu$m | SAGE (100 km) | Explorer | limb sounding | surface obs; other satellite (VIS) | | SAGE | Woodbury and McCormick (1983) |
| | stratospheric ozone | MID-UV | 0.2–0.3 $\mu$m | SBUV/TOMS (200 km) | NOAA; Nimbus-7 | backscattered u.v. | Dobson profiles | SBUV (NOAA/ NASA) | | Ohring *et al.* (1989) |

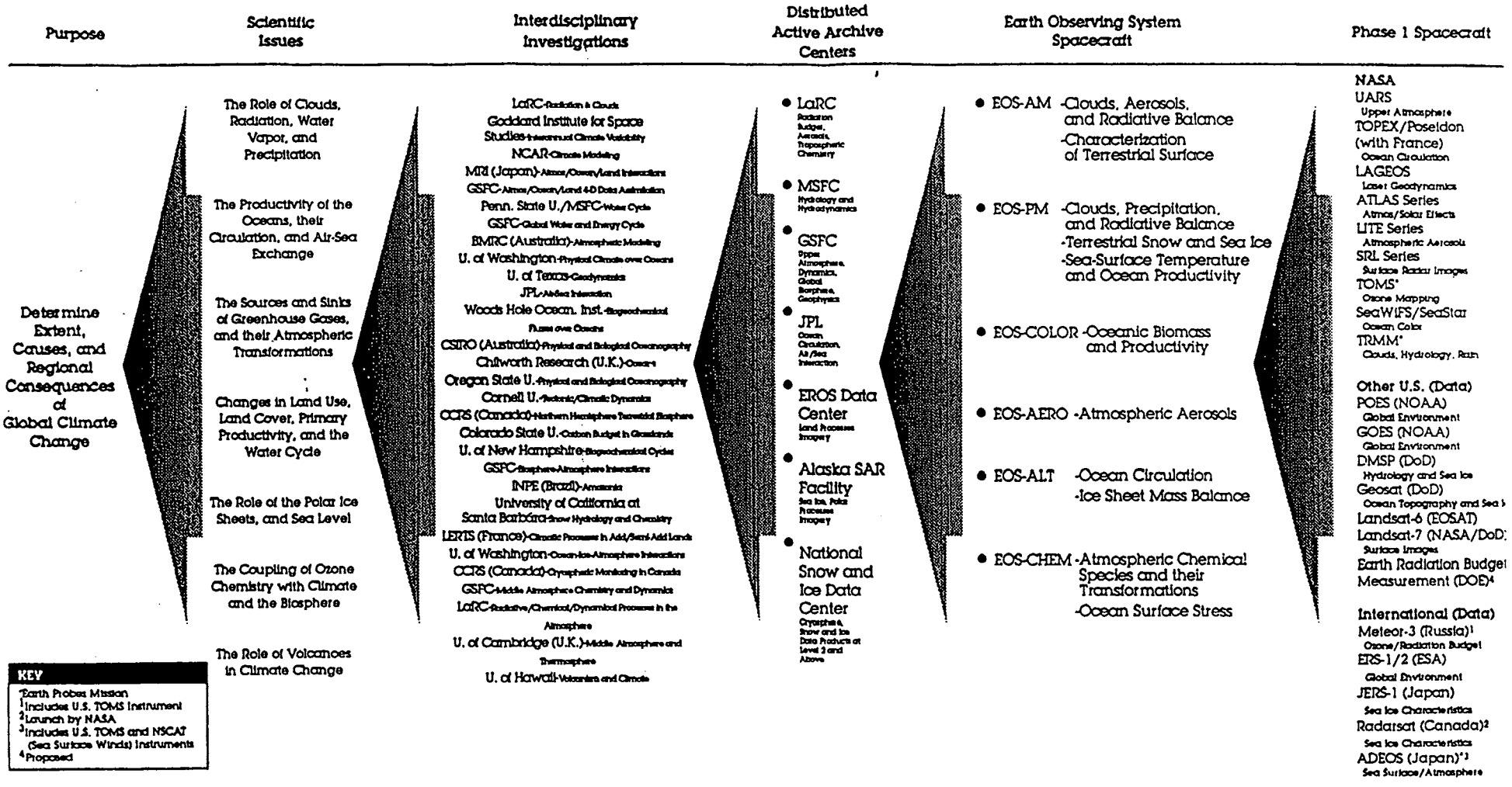
# EOS Global Climate Monitoring




**Integrated Model of the Earth System for Decadal Climate Prediction**

ARROW KEY → = INTERACTION

# EOS Mission


Purpose
Determine Extent, Causes, and Regional Consequences of Global Climate Change
Scientific Issues
The Role of Clouds, Radiation, Water Vapor, and Precipitation
The Productivity of the Oceans, their Circulation, and Air-Sea Exchange
The Sources and Sinks of Greenhouse Gases, and their Atmospheric Transformations
Changes in Land Use, Land Cover, Primary Productivity, and the Water Cycle
The Role of the Polar Ice Sheets, and Sea Level
The Coupling of Ozone Chemistry with Climate and the Biosphere
The Role of Volcanoes in Climate Change
Interdisciplinary Investigations
LaRC-Radiation & Clouds
Goddard Institute for Space Studies-Interannual Climate Variability
NCAR-Climate Modeling
MRI (Japan)-Atmos./Ocean/Land Interactions
GSFC-Atmos/Ocean/Land 4-D Data Assimilation
Penn. State U./MSFC-Water Cycle
GSFC-Global Water and Energy Cycle
BMRC (Australia)-Atmospheric Modeling
U. of Washington-Physical Climate over Oceans
U. of Texas-Geodynamics
JPL-Air/Sea Interaction
Woods Hole Ocean. Inst.-Biogeochemical Fluxes over Oceans
CSIRO (Australia)-Physical and Biological Oceanography
Chilworth Research (U.K.)-Ocean's
Oregon State U.-Physical and Biological Oceanography
Cornell U.-Botanic/Climatic Dynamics
CCRS (Canada)-Northern Hemisphere Terrestrial Biosphere
Colorado State U.-Carbon Budget in Grasslands
U. of New Hampshire-Biogeochemical Cycles
GSFC-Biosphere-Atmosphere Interactions
INPE (Brazil)-Amazonia
University of California at Santa Barbara-Snow Hydrology and Chemistry
LERTS (France)-Climatic Processes in Arid/Semi-Arid Lands
U. of Washington-Ocean-Ice-Atmosphere Interactions
CCRS (Canada)-Cryospheric Monitoring in Canada
GSFC-Middle Atmosphere Chemistry and Dynamics
LaRC-Radiative/Chemical/Dynamical Processes in the Atmosphere
U. of Cambridge (U.K.)-Middle Atmosphere and Thermosphere
U. of Hawaii-Volcanism and Climate
Distributed Active Archive Centers
LaRC Radiation Budget, Aerosols, Tropospheric Chemistry
MSFC Hydrology and Hydrodynamics
GSFC Upper Atmosphere, Dynamics, Global Biosphere, Geophysics
JPL Ocean Circulation, Air/Sea Interaction
EROS Data Center Land Processes Imagery
Alaska SAR Facility Sea Ice, Polar Processes Imagery
National Snow and Ice Data Center Cryosphere, Snow and Ice Data Products at Level 2 and Above
Earth Observing System Spacecraft
EOS-AM -Clouds, Aerosols, and Radiative Balance -Characterization of Terrestrial Surface
EOS-PM -Clouds, Precipitation, and Radiative Balance -Terrestrial Snow and Sea Ice -Sea-Surface Temperature and Ocean Productivity
EOS-COLOR -Oceanic Biomass and Productivity
EOS-AERO -Atmospheric Aerosols
EOS-ALT -Ocean Circulation -Ice Sheet Mass Balance
EOS-CHEM -Atmospheric Chemical Species and their Transformations -Ocean Surface Stress
Phase 1 Spacecraft
NASA
UARS Upper Atmosphere
TOPEX/Poseidon (with France) Ocean Circulation
LAGEOS Laser Geodynamics
ATLAS Series Atmos/Solar Effects
LITE Series Atmospheric Aerosols
SRL Series Surface Radar Images
TOMS* Ozone Mapping
SeaWiFS/SeaStar Ocean Color
TRMM* Clouds, Hydrology, Rain
Other U.S. (Data)
POES (NOAA) Global Environment
GOES (NOAA) Global Environment
DMSP (DoD) Hydrology and Sea Ice
Geosat (DoD) Ocean Topography and Sea I
Landsat-6 (EOSAT)
Landsat-7 (NASA/DoD) Surface Images
Earth Radiation Budget Measurement (DOE)[4]
International (Data)
Meteor-3 (Russia)[1] Ozone/Radiation Budget
ERS-1/2 (ESA) Global Environment
JERS-1 (Japan) Sea Ice Characteristics
Radarsat (Canada)[2] Sea Ice Characteristics
ADEOS (Japan)*[3] Sea Surface/Atmosphere
KEY
*Earth Probes Mission
[1]Includes U.S. TOMS Instrument
[2]Launch by NASA
[3]Includes U.S. TOMS and NSCAT (Sea Surface Winds) Instruments
[4]Proposed

# lecture notes

# for

# Robert O. Green, MS