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Guidelines for Spaceborne Microwave Remote Sensors

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NASA
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Scientific and Technical Information Branch

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SECTION I

INTRODUCTION

This handbook was developed to provide information and support to the spaceborne remote sensing and frequency management communities: to guide sensor developers in the choice of frequencies; to advise regulators on sensor technology needs and sharing potential; to present sharing analysis models and, through example, methods for determining sensor sharing feasibility; to introduce developers to the regulatory process; to create awareness of proper assignment procedures; to present sensor allocations adopted at the 1979 World Administrative Radio Conference (WARC); and to provide guidelines on the use and limitations of allocated bands.

This book contains four sections:

I. **Introduction**

II. **Background Information** — This section summarizes the process of frequency selection and analysis that culminated in the frequency allocations for remote microwave sensing adopted at the 1979 WARC.

Controlling Physical Factors and User Requirements, the first subsection, explains the physics and the user requirements that govern the choice of appropriate frequencies. In some cases, these factors indicate broad ranges of frequencies suitable for sensing applications; in other cases, these factors impose a uniquely fixed and immutable set of frequencies.

The second subsection, *The Regulatory Environment,* explains the procedures surrounding allocation and use of the frequency spectrum in both national and international forums.

The subsection entitled *Developing the U.S. Position* discusses the roles played by physical factors, user requirements and the regulatory environment in developing the U.S. proposals for allocations presented at the 1979 WARC.

The final subsection, *1979 WARC Results and Remaining Issues,* reviews the allocations and regulations for remote microwave sensing approved by the world's nations, and examines some of the issues requiring further study or action.

III. **Guidelines** — This section presents each sensor frequency allocation, reviewing its achievable performance and usefulness. The three subsections that follow these band-by-band analyses review procedures for national and international registration, the use of non-allocated bands and steps for obtaining new frequency allocations, and procedures for reporting interference.

IV. NASA Technical Consultation Support Services — This section describes the technical and consultation support services provided to the sensor community by NASA's Communications Division.

SECTION II

BACKGROUND INFORMATION

A. Controlling Physical Factors and User Requirements

(This section discusses the physical characteristics of spaceborne remote active and passive microwave sensing systems which govern frequency selection.)

Both active and passive microwave sensing are governed by physical laws that impose frequency requirements which present the first consideration in selecting frequencies for remote sensing.

Passive Sensors

All matter emits, absorbs and scatters electromagnetic energy. Passive sensors measure the electromagnetic energy emitted and scattered by the earth and constituents in its atmosphere.

Passive microwave sensors are radiometers – low-noise receivers patterned after radio astronomy instruments. The microwave power these sensors measure is a function of surface composition, physical temperature, roughness, and other physical characteristics. The signal power measured by the sensor varies proportionally with the equivalent blackbody temperature of the surface (the surface brightness temperature), the intervening atmospheric path, and the absorption coefficients of the atmosphere. This received power is expressed equivalently as the antenna temperature, T_A, and may be calculated from the equations of radiation transfer (Figure 1).

Passive sensors provide useful measurements because the antenna temperature depends, in certain frequency ranges, upon the physical properties of the surface or atmosphere being sensed. This dependence forms the basis on which frequencies for passive sensing are selected.

Atmospheric gases emit and absorb microwave energy at discrete resonance frequencies described by the laws of quantum mechanics. Atmospheric molecules of H_2O, for example, have resonance frequencies at 22.235 and 183.10 GHz. Other atmospheric constituents with resonant frequencies in the microwave spectrum include O_2, O_3, CO, NO_x, and ClO (Figure 2). Measurements taken near these resonance frequencies can be used to determine the amount of gas in the atmosphere and to obtain atmospheric temperature profiles.

Microwave signals are attenuated by constituents of the atmosphere. This attenuation varies according to frequency (Figure 3). Sensing at frequencies with high attenuation allows sensing of the properties of the atmosphere it-

Figure 1

For a nonscattering medium,

$$T_A(\nu) = \frac{P(\nu)}{kB} = \frac{1}{4\pi}\int_0^{4\pi} G(\Omega)\left[T_0(\nu)\, e^{-\tau(L)} + \int_0^L T(s)\beta(s)e^{-\tau(s)}ds\right]d\Omega$$

where:

T_A: antenna temperature (K)
P: received power (W)
ν: center frequency (Hz)
B: receiver bandwidth
k: Boltzmann's constant (J/K)
G: antenna gain (numeric ratio)
Ω: solid angle about the antenna (steradian)
T_0: surface brightness temperature (emission plus scattering) (K)
τ: optical depth (nepers)
β: absorption coefficient (nepers/km)
L: path length from satellite to ground (km)
s: position along the path (km)
T(s): atmospheric temperature at point s along the path (K)

The optical depth is simply related to the attenuation as follows:

$$\tau(s) = \int_0^s \beta(x)\,dx = \int_0^s \left(\frac{a(x)}{4.34}\right)dx = \frac{A(s)}{4.34}$$

where:

A: attenuation (one way)(dB)
a: specific attenuation (dB/km)

D. H. Staelin, 1969, *Passive Remote Sensing at Microwave Frequencies,* Proceedings of IEEE, Vol. 57, pp. 427-439.

self. Indeed, peaks in the attenuation curve reveal the frequencies for measurement of those atmospheric molecules that cause the attenuation. Sensing at frequencies of low attenuation allows sensing of surface land and ocean phenomena.

Frequency choice for surface measurements by passive sensors is not as constrained as for atmospheric gas measurements, since land and water surface characteristics, such as soil moisture and wind speed, affect microwave emissions over a broader range of frequencies.

However, sensing of many surface phenomena requires simultaneous measurements at several frequencies to measure any single phenomenon because the energy emitted at any frequency is determined by several overlapping phenomena. The number of phenomena affecting emissions at a certain frequency determines the number of simultaneous multi-frequency measurements needed to measure any one of those phenomena. For example, to measure sea surface temperature requires a measurement between 4 and 6 GHz, where the microwave emission is most sensitive to sea surface tem-

Figure 2
Preferred Frequency Bands for Passive Microwave Sensors

SURFACE

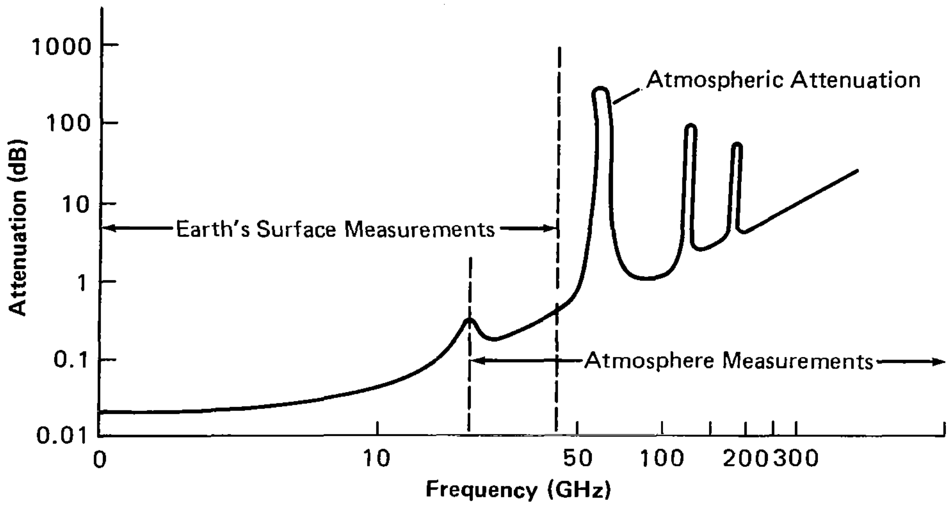
ATMOSPHERE

Frequency (GHz)	Bandwidth (MHz)	Measurements
Near 1.4	100	Soil Moisture; salinity
Near 2.7	60	Salinity; soil moisture
Near 5	200	Estuarine temperature
Near 6	400	Ocean temperature
Near 11	100	Rain; snow; lake ice; sea state
Near 15	200	Water vapor; rain
Near 18	200	Rain; sea state; ocean ice; water vapor
Near 21	200	Water vapor; liquid water
22.235	300	Water vapor; liquid water
Near 24	400	Water vapor; liquid water
Near 30	500	Ocean ice; water vapor; oil spills; clouds; liquid water
Near 37	1000	Rain; snow; ocean ice; oil spills; clouds
Near 55	250 Multiple*	Temperature
Near 90	6000	Clouds; oil spills; ice; snow
100.49	2000	Nitrous oxide
110.80	2000	Ozone
115.27	2000	Carbon monoxide
118.70	2000	Temperature
125.61	2000	Nitrous oxide
150.74	2000	Nitrous oxide
164.38	2000	Chlorine oxide
167.20	2000	Chlorine oxide
175.86	2000	Nitrous oxide
183.31	2000	Water vapor
184.75	2000	Ozone
200.98	2000	Nitrous oxide
226.09	2000	Nitrous oxide
230.54	2000	Carbon monoxide
235.71	2000	Ozone
237.15	2000	Ozone
251.21	2000	Nitrous oxide
276.33	2000	Nitrous oxide
301.44	2000	Nitrous oxide
325.10	2000	Water vapor
345.80	2000	Carbon monoxide
364.32	2000	Ozone
380.20	2000	Water vapor

*Several bands each of 250 MHz bandwidth

perature variations, and two additional measurements: near 10 and 18 GHz (Figure 4). Because the sensitivity curves, shown in Figure 4, are functions of frequency, a regression analysis can be performed on the simultaneous measurements to isolate the measurement for sea surface temperature from

Figure 3
Atmospheric Attenuation



R. K. Crane, 1971, *Propagation Phenomena Affecting Satellite Communications Systems in the Centimeter and Millimeter Wavelength Bands,* Proceedings of IEEE, Volume 59, pp. 173-188.

Figure 4
Sensitivity vs Frequency for Sensing of Ocean Phenomena

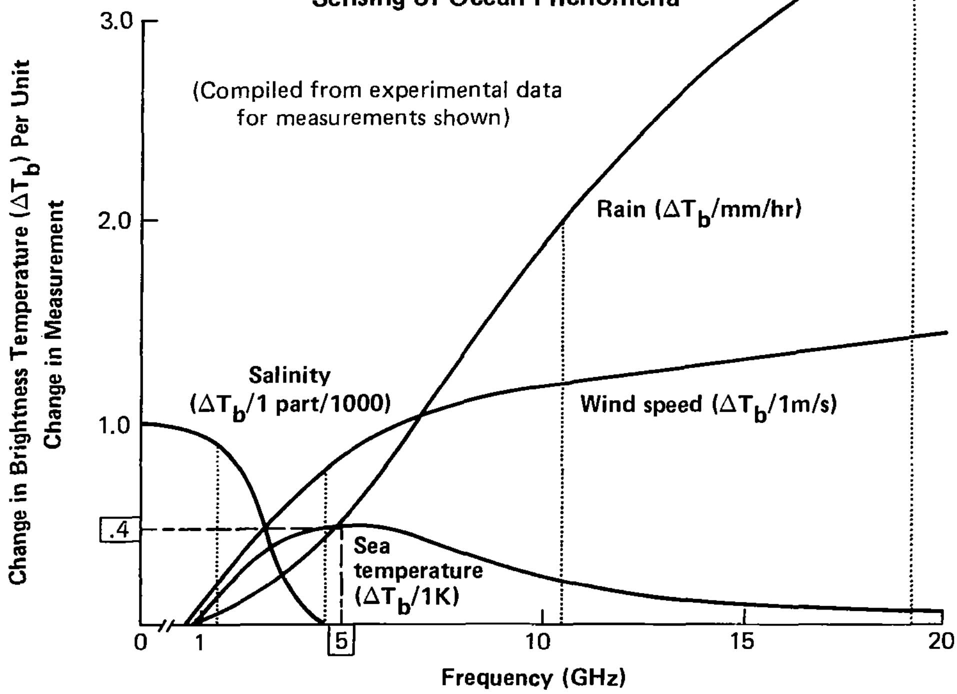
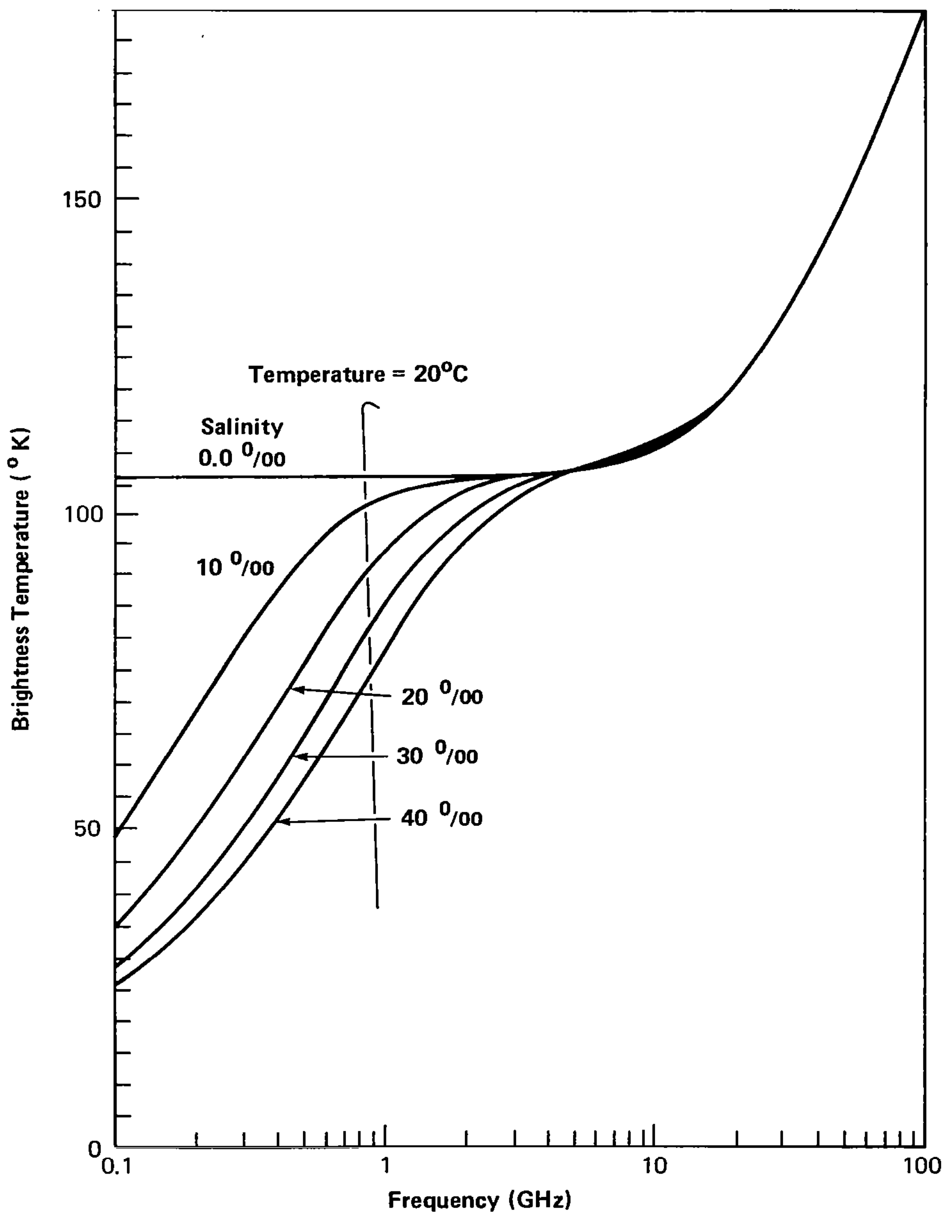


Figure 5
Brightness Temperature Variation For Constant Temperature



J. Hollinger, *Microwave Properties of a Calm Sea,* Naval Research Laboratory Report No. 7110-2, 1975.

the effects of rain and wind speed.

Frequency requirements for passive sensors are presented in Recommendation 515 of the International Radio Consultative Committee (CCIR) (Figure 2).

Figure 6
Measurement Sensitivity

$$\Delta T_e = \frac{a(T_A + T_N)}{\sqrt{Bt}}$$

Where: ΔT_e: r.m.s. uncertainty in the estimation of the total system noise, $T_A + T_N$
T_A: Antenna temperature
T_N: receiver noise temperature
B: bandwidth
t: integration time
a: receiver system constant
($a = 2$ for ideal Dicke radiometer;
$a = 1$ for an ideal total power radiometer)

J. D. Kraus, 1966, *Radio Astronomy,* McGraw-Hill, New York.

The instrument sensitivity needed to determine physical properties depends upon the required observational accuracy. For example, users determining ocean salinity over a 30-36 parts per thousand (0/00) range need an accuracy of 0.2 0/00. In the 1–2 GHz range, measurement sensitivity of 0.1 K would yield the requisite accuracy (Figure 5). Frequencies above 3 GHz are not sensitive to salinity variations. (NASA's 'Frequency Justifications for Passive Sensors,' December, 1976, presents a complete analysis of sensitivity requirements.)

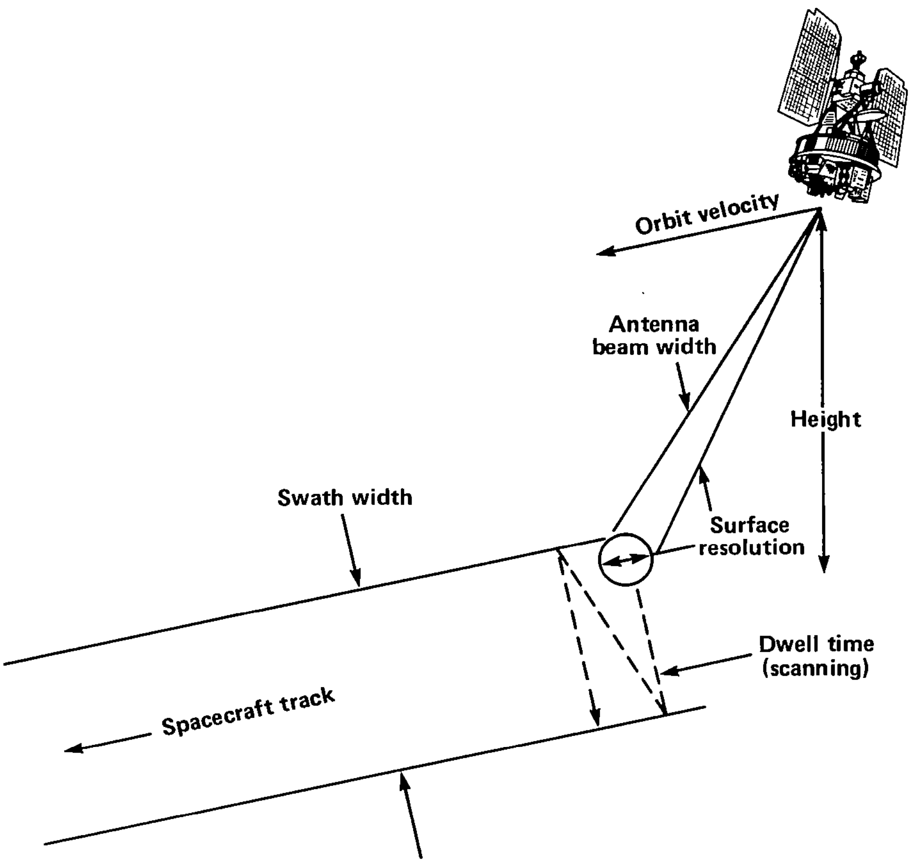
Measurement sensitivity needed to determine physical properties is achieved by integrating the received signal to reduce short term random fluctuations in the noise-like radiated energy. The radiometer sensitivity, ΔT_e, is determined by the antenna temperature, receiver noise temperature, the integration time and measurement bandwidth (Figure 6). For sensor designers, two of these four factors are pre-determined: antenna temperature is determined by the energy received, and available technology constrains receiver noise temperature. Thus, sensor designers must adjust integration time and bandwidth to achieve a given measurement sensitivity.

The time available for integration depends on the desired resolution, swath width and spacecraft velocity (Figure 7). Even among these variables, many possible combinations exist. For example, a range of resolutions may satisfy different user applications for the same measurement. Data revisit time requirements also vary, and can be satisfied through selection of an appropriate swath width.

The method used to achieve a given swath width, in turn, affects the integration time and, hence, bandwidth. A swath can be generated by a single scanning beam (Figure 7) a set of fixed, or 'pushbroom' beams (Figure 8), or a combination of scanning multibeams.

A set of sensitivity and resolution requirements has been developed to satisfy the bulk of user applications consistent with the reasonably expected technology for the next decade (Figure 9). There are some applications

Figure 7
Passive Sensor System Coverage and Resolution Considerations



Integration Time

$$t = \frac{R^2}{nVS}$$

Where:

t: Integration time
V: Velocity of spacecraft (7.6 km/s for 500 km orbit)
R: Resolution
S: Swath width
n: Number of beams

This equation assumes a contiguous scan system. The equation would be modified for other types of scan such as conical scan. The equation ignores scan flyback time.

Figure 8

'Pushbroom' Passive Sensor Concept

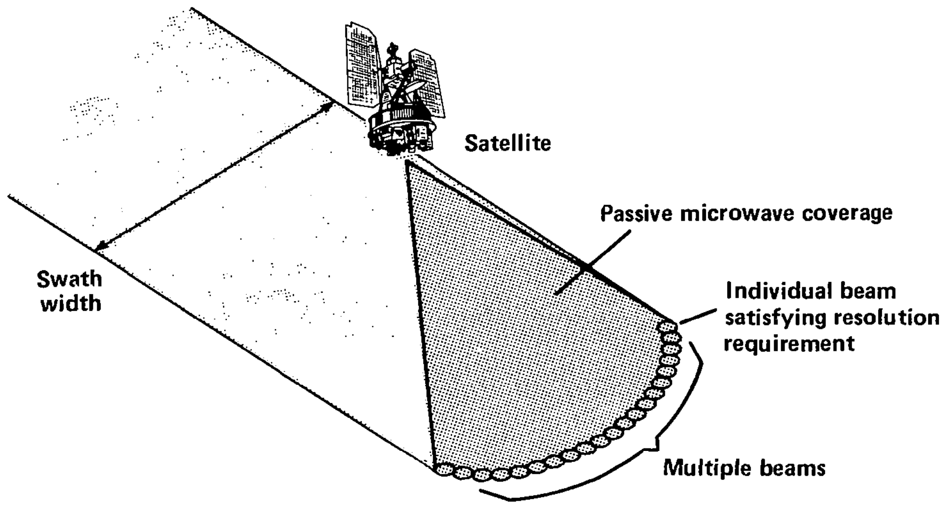


Figure 9

Sensitivity and Resolution Requirements for Passive Sensor Measurements

Measurement	Sensitivity (K)	Resolution (km)
Salinity, ocean	0.1	20
Salinity, coastal	0.1	2–5
Sea temperature, ocean	0.3	20
Sea temperature, coastal	0.3	2–5
Sea state, ocean	1.0	20
Sea state, coastal	1.0	2–5
Sea ice morphology, ocean	1.0	20
Sea ice morphology, lake	1.0	2–5
Rain	1.0	1
Snow morphology	1.0	2–5
Soil moisture	1.0	5
Water vapor		
low orbit	0.2	2
geostationary	0.2	100
Atmosphere temperature		
low orbit	0.3	10
geostationary	0.2	100
Atmospheric molecules		
(O_3, NO_x, CO, ClO)	0.2	1–2

NASA, *Frequency Band Justifications for Passive Sensors,* December, 1976.

Figure 10

Single Beam Scanner (10 GHz)

ΔT (K)	Radiometer	Resolution (km) Case 1	(Case 2)	Swath Width (km) Case 1	(Case 2)	Bandwidth (MHz)
0.5	Dicke (a=2)	2	(10)	2	(100)	100
0.5	Total power (a=1)	2	(10)	2	(100)	25
1.0	Dicke	2	(10)	8	(400)	100
1.0	Total power	2	(10)	8	(400)	25
1.0	Total power	2	(10)	32	(1600)	100

Pushbroom Mode (10 GHz)

ΔT (K)	Radiometer	Resolution (km) Case 1	(Case 2)	Swath Width (km) Case 1	(Case 2)	Bandwidth (MHz) Case 1	(Case 2)
0.5	Dicke	2	(10)	2n*	(10n)	100	(25)
0.5	Total power	2	(10)	2n	(10n)	25	(5)
1.0	Dicke	2	(10)	2n	(10n)	25	(5)
1.0	Total power	2	(10)	2n	(10n)	6	(1.2)

* n: number of beams

where requirements may exceed the values shown. For each specific application, the sensor designer must make the requisite trade-offs among sensitivity, resolution, revisit time and sensor technology to develop a usable system within allocated bandwidths. (Figure 10 gives some examples for 10 GHz radiometers in a 500 km orbit.)

In Section III, the assessment of frequency bands describes achievable sensitivity, resolution and swath width in bands allocated for remote sensing by the 1979 WARC. These calculations are based on the use of a single beam, scanning Dicke radiometer, since that instrument fairly represents the least costly, most reliable, state-of-the-art instrument type. Pushbroom-type radiometers require as many receiver/detectors as beams, a more costly, space consuming approach. Results for other types of radiometers and scan systems can be easily calculated.

Active Sensors

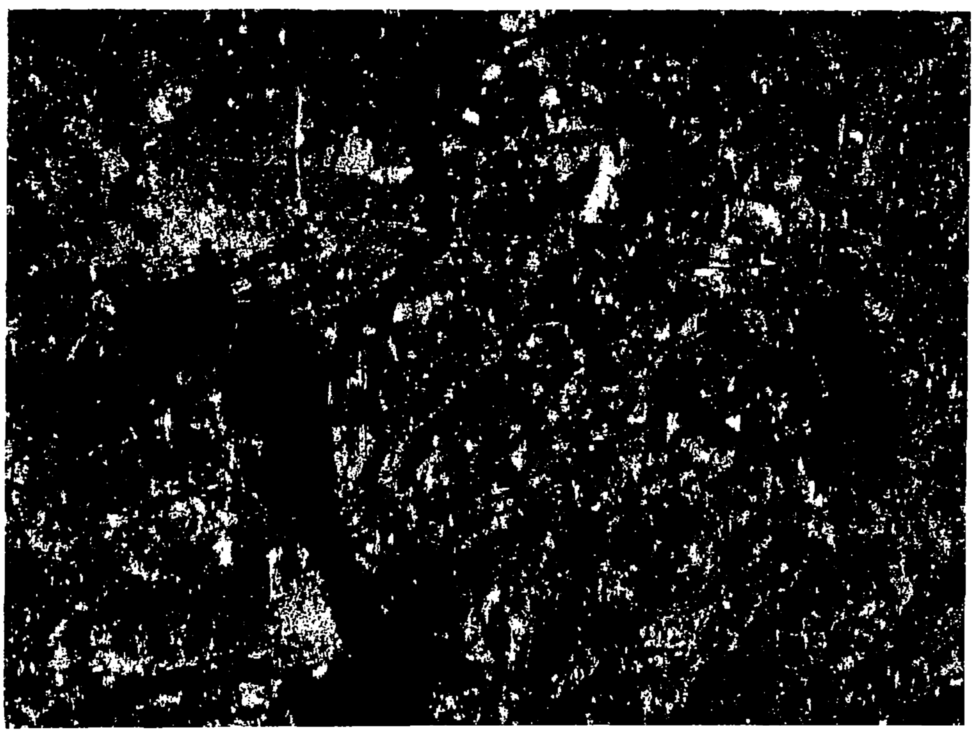
Like radars, active microwave sensors provide their own illumination: they transmit signals and then measure the signals reflected from the sensed object back to the sensor. Active sensing systems consist of an antenna, a transmitter, a receiver, an exciter, timing circuits, and a signal processor. For space applications, antenna and transmitter designs are critical because of spacecraft limitations on the antenna's size and weight and on the power consumption of the transmitter. Pulse compression designs are frequently used to reduce peak transmitter power without sacrificing measurement resolution.

Currently, there are three major types of active sensors: the radar scatterometer, radar altimeter, and image-forming radar. The scatterometer, consisting of a pulse modulator, a transmitter, an antenna, a receiver, a detector and an integrator, measures the radar backscatter coefficient over the area illuminated by the antenna. Measurements of the backscattered signals at various angles, polarization and wavelengths are used to determine roughness characteristics of the earth's surface. From these measurements, characteristics such as wind speed and direction over the oceans and surface composition of land can be inferred.

Radar altimeters measure the vertical distance between the sensor and the surface to determine the variations of the surface (surface profile). State-of-the-art altimeter design permits altitude measurements between a satellite and the ocean surface to ± 10 cm rms, allowing wave height measurements to an accuracy of 0.5 m for waves ranging from 1 to 20 m in height. Thus, sea surface depressions, major currents, tides, wind pile-up and storm surges can be determined from altimeter measurements. Altimeters are also used to measure the earth's surface — the geoid. Geoid measurements are used in study of such phenomena as crustal shift, continental drift, tidal actions, and surface location of oceanographic buoys and coastal landmarks.

Image-forming radars produce 'pictures' of the earth in a procedure analogous to camera photography (Figure 11). Radar, however, illuminates the earth at frequencies outside the visible portion of the electromagnetic spectrum, and, because it carries its own illuminating source, operates at night as well as during the day. Its ability to penetrate clouds and fog at fre-

Figure 11
Seasat SAR Image
Washington, D.C.

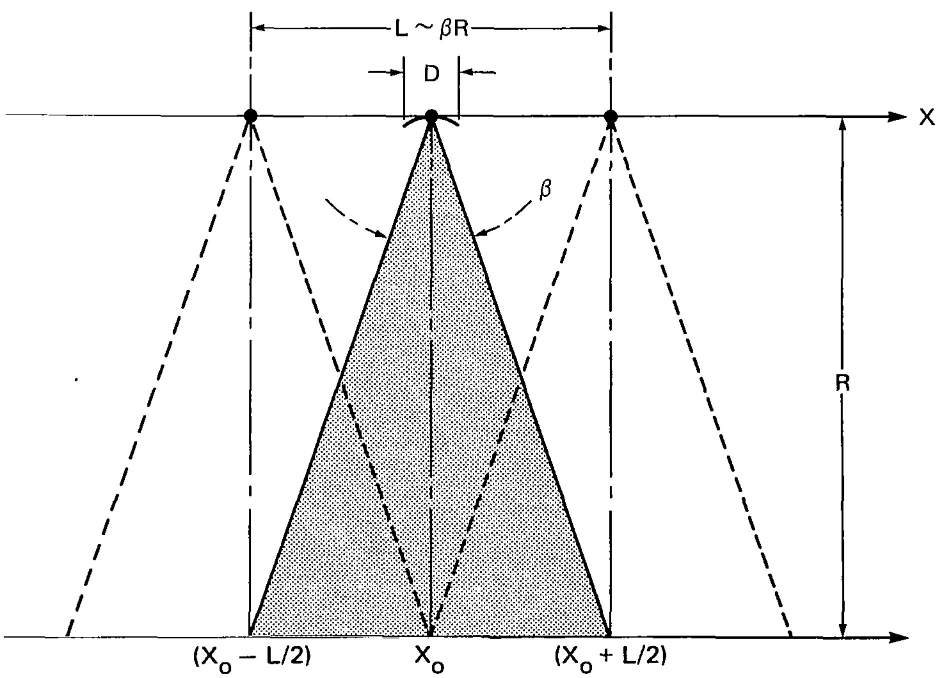


quencies below 20 GHz makes it an all-weather system. There are two types of image-forming radars: real aperture and synthetic aperture. In real aperture radar systems, antenna size and design frequency determine ground resolution. Synthetic aperture radar utilizes satellite motion and a series of phase and amplitude measurements to obtain resolution that is much greater than that achieved by real aperture systems. However, the data from synthetic aperture radars require more complex processing to construct an image than do the data from real aperture systems. The concept of obtaining high along-track resolution in a synthetic aperture is demonstrated in Figure 12. An antenna with an along-track angular beamwidth of β radians illuminates an object at slant range R and at along-track location X_0. As the sensor moves, it begins to illuminate X_0 when the sensor is at location $(X_0 - L/2)$ and ceases to illuminate X_0 when the sensor reaches $(X_0 + L/2)$. Therefore, the sensor 'sees' the object over a distance L equal to βR, which becomes the effective length of the synthetic aperture antenna.

Other active sensing instruments under development include precipitation radar, ocean wave sensors and advanced concepts such as bistatic radar.

Bandwidth requirements for active sensors vary with the type of sensor application. Scatterometers are typically narrow band, low resolution devices requiring about 1 MHz of bandwidth. Synthetic aperture radars are medium bandwidth devices and can be designed to satisfy measurement resolution requirements in less than 100 MHz of bandwidth. Altimeters, on

Figure 12
Synthetic Aperture Concept



American Society of Photogrammetry, *Manual of Remote Sensing,* Volume 1, Falls Church, Virginia, 1975.

Figure 13
Active Sensor Bandwidth

$$B=\frac{1}{t}=\left(\frac{c}{2\Delta R}\right)\left(\frac{1}{\cos\theta_d}\right)$$

Where:
- B: Bandwidth (Hz)
- ΔR: Range resolution (m)
- c: Speed of light (m/s)
- θ_d: Depression angle from satellite, or equivalently, arrival angle at earth (°)
- t: Effective pulse duration (equivalent to the inverse of the pulse compression bandwidth (s)

CCIR Report 695, (Mod I), *Feasibility of Frequency Sharing Between Spaceborne Radars and Terrestrial Radars in the Radiolocation Service,* Conclusions of the Interim Meeting of Study Group 2, Geneva, 1980.

the other hand, require wide bandwidth, up to 600 MHz, to achieve centimeter measurement accuracies. In all cases, bandwidth is determined by the user required range resolution (Figure 13).

Signals from all active sensors are attenuated twice in the atmosphere: once when transmitted, and again when reflected. Frequencies selected for active sensing must be in parts of the spectrum where attenuation is low enough to be accommodated in achievable sensor designs. Generally, active sensing has been confined to frequencies below 20 GHz, although future applications such as cloud detection and pressure sensing will require measurements at higher frequencies.

A summary of the frequency requirements for active sensors is presented in CCIR Report 693 (Mod I) adopted at the interim meeting of Study Group 2 in June, 1980. Important applications of spaceborne radar include:

soil moisture
vegetation mapping
snow distributions, depth and water content
geological mapping
land use mapping
ice boundaries, depth, type and age
ocean wave structure
ocean wind speed and direction
geodetic mapping
rain rates
cloud height and extent
surface pressure

Because the reflected signal received at the sensor depends on the dielectric properties of the surface and the roughness of the surface, the preferred frequency for active sensing depends upon the phenomenon to be measured. CCIR Report 693 identifies a number of frequency bands needed for the cited applications (Figure 14).

Figure 14

Preferred Frequency Bands for Active Microwave Sensors

Frequency (GHz)	Suggested Bandwidth (MHz)	Usage
Near 1	60	Wave structure
Near 3	100	Geology
Near 5	100	Soil moisture
Near 10	100	Precipitation
Near 14	600	Wind/ice/geoid
Near 17	100	Vegetation
Near 35	100	Snow
Near 76	100	Cloud monitoring

CCIR Report 693 (Mod I), *Preferred Frequency Bands for Active and Passive Microwave Sensors,* Conclusions of the Interim Meeting of Study Group 2, Geneva, 1980.

B. The Regulatory Environment

(This section describes the international and national regulatory structures and the processes involved in attaining allocations and protection for spaceborne sensors at the 1979 WARC.)

Use of the frequency spectrum is regulated nationally and internationally through radio regulations which designate specific uses for discrete frequency bands (frequency allocation) and establish technical criteria for using the allocated bands. Technical criteria include a variety of regulations such as limits for power flux densities, regulations for equivalent isotropic radiated power (EIRP) and standards for antenna sidelobe patterns.

International Regulation

Internationally, the International Telecommunication Union (ITU), an agency of the United Nations, administers the Radio Regulations. The regulations can be modified by administrative radio conferences; agreements reached at an administrative radio conference are published as the final acts of that conference. These acts require ratification by ITU member countries. In the United States the acts, like all treaties, must be ratified by the President with the advice and consent of the U.S. Senate before they constitute a binding commitment.

Frequency bands are allocated and technical criteria are developed for use by stations in specific radio services (Figure 15). Radio services — radio applications of radio networks which possess similar overall characteristics and are operationally compatible — are defined by the ITU. For example, microwave radio relay stations operating terrestrially between fixed points are in the Fixed Service, whereas telephone service links relayed via satellite are in the Fixed-Satellite Service. Spaceborne remote sensors belong to the Space

Figure 15
Radio Services

Fixed Service
Fixed-Satellite Service
Aeronautical Fixed Service
Inter-Satellite Service
Space Operation Service
Mobile Service
Mobile-Satellite Service
Land Mobile Service
Land Mobile-Satellite Service
Maritime Mobile Service
Maritime Mobile-Satellite Service
Port Operations Service
Ship Movement Service
Aeronautical Mobile Service
Aeronautical Mobile-Satellite Service
Broadcasting Service
Broadcasting-Satellite Service
Radio Determination Service
Radio Determination-Satellite Service
Radionavigation Service
Radionavigation-Satellite Service
Maritime Radionavigation Service
Maritime Radionavigation-Satellite Service
Aeronautical Radionavigation Service
Aeronautical Radionavigation-Satellite Service
Radiolocation Service
Meteorological Aids Service
Earth Exploration-Satellite Service
Meteorological-Satellite Service
Standard Frequency and Time Signal Service
Standard Frequency and Time Signal-Satellite Service
Space Research Service
Amateur Service
Amateur-Satellite Service
Radio Astronomy Service
Safety Service
Special Service

From Section III, Article 1, Final Acts of the World Administrative Radio Conference, Geneva, 1979

Research Service or the Earth Exploration-Satellite Service.

Administrative radio conferences are scheduled by the ITU's Administrative Council, composed of a representative group of ITU member nations. Sometimes, the Council limits conference topics to certain areas, regulations or radio services (Figure 16). Periodically, a general world administrative radio conference (WARC) convenes to review and update all ITU Radio Regulations. The 1979 WARC in Geneva was the most recent of these general conferences; its results will comprise the new ITU Radio Regulations, which are scheduled to become effective January 1, 1982.

Technical advice about matters considered by the administrative radio conferences comes from the International Radio Consultative Committee (CCIR), the ITU's technical arm composed (presently) of 11 study groups, each dealing with specific topics (Figure 17). Remote sensing is dealt with in Study Group 2, Space Research and Radio Astronomy. The study groups meet twice in a four year cycle to examine such questions as appropriate technical parameters for particular radio services, and sharing between services. Every four years, after approval by a CCIR plenary meeting, thirteen volumes of recommendations, reports, decisions, resolutions, and opinions — one volume for each study group, one volume for the two joint CCIR/CCITT (International Telephone and Telegraph Consultative Committee) study groups, plus a general information volume — are published. These documents serve as the primary source for technical references on pertinent topics usually compiled by the appropriate CCIR study group(s) prior to an upcoming administrative radio conference.

Once allocated by an administrative radio conference, discrete frequency bands may be used only by the specified radio services. (Radio Regulation

Figure 16
Past Administrative Radio Conferences

Year	Location	Subject
1903	Berlin	General
1906	Berlin	General
1912	London	General
1927	Washington	General
1932	Madrid	General
1938	Cairo	General
1947	Atlantic City	General
1959	Geneva	General
1963	Geneva	Space
1966	Geneva	Aeronautical
1967	Geneva	Maritime
1971	Geneva	Space
1974	Geneva	Maritime
1978	Geneva	Aeronautical
1979	Geneva	General

Planned Conferences

Tentative Date (Duration)	Subject
9 November, 1981 (6 weeks)	Region 2 MF-BC RARC, Second Session
23 August, 1982 (4 weeks)	Region 1 FM-BC RARC, First Session
28 September, 1982 (6 weeks)	ITU Plenipotentiary Conference
23 February, 1983 (3½ weeks)	Mobile Services WARC (limited agenda)
13 June, 1983 (5 weeks)	Region 2 Broadcasting Satellite RARC
January, 1984 (5 weeks)	HF-Broadcasting WARC, First Session
October, 1985 (6 weeks)	Region 1 FM-BC RARC, Second Session
July, 1985 (6 weeks)	Space Services, WARC, First Session
January, 1986 (7 weeks)	HF-Broadcasting WARC, Second Session
September, 1986 (4 weeks)	Region 2 MF-Broadcasting RARC (New Bands)
January, 1987 (4 weeks)	African VHF/UHF-Broadcasting RARC
September, 1987 (6 weeks)	Space Services WARC, Second Session
March, 1988 (6 weeks)	Region 3 VHF/UHF Bands RARC
September, 1988 (6 weeks)	Mobile Services WARC (broad agenda)

3279 provides that stations may be assigned in derogation of the table of allocations on the express condition that harmful interference will not be caused to services carried on by stations operating in accordance with the Radio Regulations.) Three types of allocations exist: primary, indicated in the allocation table by listing entirely in upper case; permitted, listed in 'Grotesque light' style typeface; and secondary, indicated by listing in normal characters with initial capital letters. A station in a service with a secondary allocation may not interfere with, nor claim protection from, a station in a service with a primary or permitted allocation. A frequency band may be allocated for use around the world or limited to use in only one or two of the ITU's three regions (Figure 29).

Figure 17
CCIR Study Groups

Study Group 1	Spectrum utilization — monitoring
Study Group 2	Space Research and Radioastronomy Services
Study Group 3	Fixed service at frequencies below about 30 MHz
Study Group 4	Fixed Service using satellites
Study Group 5	Propagation in non-ionized media
Study Group 6	Propagation in ionized media
Study Group 7	Standard frequency and time-signal services
Study Group 8	Mobile services
Study Group 9	Fixed service using radio-relay systems
Study Group 10	Broadcasting service (sound)
Study Group 11	Broadcasting service (television)
CMTT	CCIR/CCITT Joint Study Group for Television and Sound Transmissions
CMV	CCIR/CCITT Joint Study Group for Vocabulary

Footnotes to the allocation tables contain further information about a band's allowable use. Some footnotes provide additional allocations, indicating the status of the allocation through the wording of the footnote. For example, some footnotes contain allocations that refer to Article 14 (formerly Article N13A), which provides primary status, but only after a system has been fully coordinated. Other footnotes grant primary or secondary status directly or they indicate intended operation in a frequency band with minimal, or no, protection rights. Footnotes may also provide allocations in a few countries as opposed to a whole region. Finally, footnotes may impose restrictions or special conditions of operation in a frequency band.

To gain international recognition of the use of a frequency, stations must be registered with the ITU's International Frequency Registration Board (IFRB); see *Section III* for the registration procedures. Enforcement of ITU Radio Regulations depends, as do most international agreements, upon the good will and mutual cooperation among member nations. Among users of the frequency spectrum, the motivating mutual benefit is the protection, provided by general compliance, from interference and disruption of service.

National Regulation

In the United States, the duties of frequency management are divided into regulation of frequency use by the federal government and frequency use by all other domestic users. The President, through the National Telecommunications and Information Administration (NTIA), regulates frequency use by the federal government. Non-government telecommunications are regulated by the Federal Communications Commission (FCC).

The Interdepartment Radio Advisory Committee (IRAC), one of the NTIA's advisory bodies, is composed of representatives from the major federal users of the frequency spectrum (Figure 18). Non-federal users are represented in the IRAC by a liaison representative from the FCC.

International responsibilities are coordinated and carried out by the U.S. Department of State, with the advice of the FCC and the NTIA. Formu-

Figure 18
IRAC Members

Department of Agriculture
Department of the Air Force
Department of the Army
Department of Commerce
Department of Energy
Federal Aviation Administration (DOT)
General Services Administration
Health, Education and Welfare
Department of the Interior
International Communication Agency
Department of Justice
National Aeronautics and Space Administration
National Science Foundation
Department of the Navy
Department of State
Department of the Treasury
United States Coast Guard (DOT)
United States Postal Service
Veterans Administration
Federal Communications Commission*
Federal Emergency Management Agency

*Liaison representation

Report of the Interdepartment Radio Advisory Committee, NTIA, July, 1980-December 31, 1980.

lation of U.S. proposals to international administrative radio conferences is based on a national consensus. The U.S. position on frequency allocations for remote sensors, which was the basis for U.S. proposals to the 1979 WARC, was developed by the IRAC and FCC over a period of several years. Potential technical and economic constraints on users of frequency bands that might be shared with the sensors required study and discussion. To accommodate these legitimate concerns, a variety of compromises was reached. Sometimes the bandwidth requested for the sensors was reduced; in other cases the proposed sensor frequency was adjusted to another band. These compromises enabled the IRAC and FCC to reach consensus on U.S. proposals for allocations to remote sensing at the 1979 WARC.

The U.S. allocation proposals underwent a similar compromise process in the international forum of the WARC.

Allocations made by the WARC must be incorporated into the national radio regulations before they may be used within the United States. International allocations are not necessarily adopted for national use. A single band in the international Table of Frequency Allocations may be broken into several domestic bands and allocated for specific services or reserved for government or non-government use. Special domestic footnotes may be added. In addition, national regulations may provide levels of allocation status that differ from the ITU regulations, such as a secondary rather than a primary allocation (Figure 19).

Formulating the national table involves consideration of the competing

Figure 19
Section of Pre-WARC National Allocation Table

International			United States				
Region 1 GHz	Region 2 GHz	Region 3 GHz	Band GHz 1	National Provisions 2	Government Allocation 3	Non-Government Allocation 4	Remarks 5
12.75–13.25	FIXED MOBILE		12.75–13.25	NG		FIXED 'MOBILE NG11 NG53	
13.25–13.4	AERONAUTICAL RADIONAVIGATION 406 407 407A		13.25–13.4	G, NG 406	AERONAUTICAL RADIONAVIGATION Space Research (Earth-to-space)	AERONAUTICAL RADIONAVIGATION Space Research (Earth-to-space)	
13.4–14	RADIOLOCATION 407 407A 408 409		13.4–14.0	G, NG US110	RADIOLOCATION Space Research (Earth-to-space) G59	Radiolocation Space Research (Earth-to-space)	See Part 7.18 of Manual of Regulations and Procedures
14–14.3	FIXED–SATELLITE (Earth-to-space) RADIONAVIGATION 408A		14.0–14.2	G, NG US207	RADIONAVIGATION Space Research (Earth-to-space)	FIXED-SATELLITE (Earth-to-space) RADIONAVIGATION Space Research (Earth-to-space)	
	407 407A		14.2–14.3	G, NG US207	RADIONAVIGATION	FIXED-SATELLITE (Earth-to-space) RADIONAVIGATION	
14.3–14.4	FIXED–SATELLITE (Earth-to-space) RADIONAVIGATION–SATELLITE 408A		14.3–14.4	G, NG US206 US207	RADIONAVIGATION-SATELLITE	FIXED-SATELLITE (Earth-to-space) RADIONAVIGATION-SATELLITE	
14.4–14.5	FIXED FIXED–SATELLITE (Earth-to-space) MOBILE 408B 408C		14.4–14.5	G, NG US203 US207	FIXED MOBILE Space Research (Space-to-Earth)	FIXED-SATELLITE (Earth-to-space) Space Research (Space-to-Earth)	

Tables of Frequency Allocations and other abstracts from *Manual of Regulations and Procedures for Radio Frequency Management,* NTIA.

needs and operating requirements of numerous federal and non-federal users. A review of the results of the 1979 WARC and generation of proposals for appropriate modifications to the national table is currently in progress within an IRAC ad hoc committee. The FCC will present the proposed new table to the public for comment prior to adopting the new table through FCC rulemaking procedures.

C. Developing the U.S. Position

(This section reviews the criteria considered in determining which frequency band allocations the United States sought at the 1979 WARC)

The U.S. proposals on spaceborne microwave remote sensors to the 1979 WARC evolved from a preliminary set of preferred frequency bands based upon the controlling physical factors and user requirements. Consideration of obvious conflicts with other services, and judicious selection of bands within the range permitted by physical factors that might help circumvent those conflicts, guided the initial selections. Then, these initial preferences were analyzed in detail to determine sharing compatibility with other services already allocated or proposed in each shared band. Sensor sharing criteria were developed to determine acceptable degradation of sensor operations in shared bands. In several bands in which allocated services had not yet implemented systems, the sharing criteria developed included limits needed on the other services to permit sharing by the sensors.

Figure 20

Minimum Discernible Power Change

$$\Delta P = k \Delta T_e B$$

Where:

- k: Boltzmann's constant, 1.38×10^{-23} J/K
- ΔT_e: sensor sensitivity (given in Figure 6)
- B: receiver bandwidth

CCIR Report 694, *Sharing Considerations and Protection Criteria Relating to Passive Microwave Sensors,* Recommendations and Reports of the CCIR, Kyoto, 1978.

From these studies came detailed justifications used in developing the U.S. position. In 1978, reports on sharing models and analyses for passive and active sensors which were based upon this work were adopted by the CCIR Plenary Assembly XIV as Reports 694 and 695 respectively. Recommendation 516 on active sensor sharing was also adopted by the CCIR.

Passive Sensor Analysis

The antenna of a passive sensor can receive radiation from all points on the earth and in the atmosphere within the satellite's line of sight. Interference varies over time as the sensor orbits the earth. As the sensor 'couples' with an interferor, the amount of interference varies according to the gain of the sensing antenna in the interferor's direction, as well as the gain of the interferor antenna in the sensor's direction. The difference in response between interference received via the main-beam and the sidelobe can be greater than 100,000 to 1.

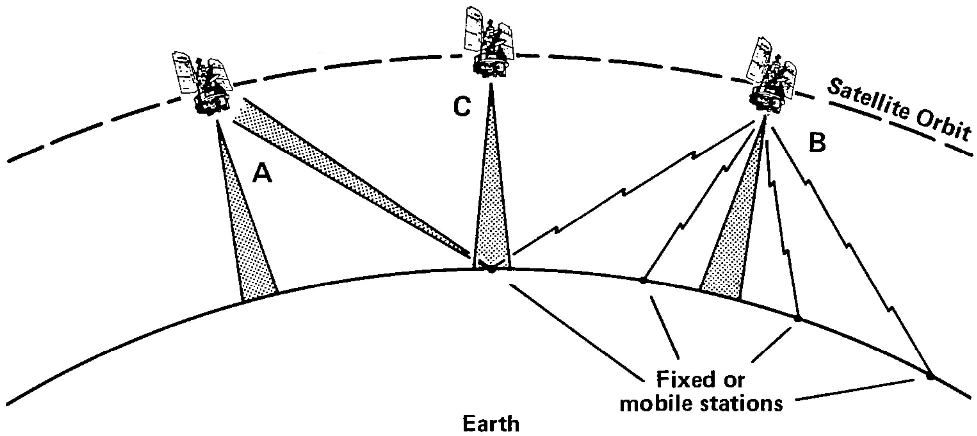
Harmful interference to a passive sensor occurs when the unwanted signal at the receiving antenna approaches the sensor threshold, or minimum discernible power change, ΔP (Figure 20).

The criterion used for defining the level of interference as harmful is 20% of ΔP. (Standard engineering practice normally sets measurement uncertainties at 10% of the required measurement accuracy. The CCIR, in Report 694, *Sharing Considerations and Protection Criteria Relating to Passive Microwave Sensors,* Geneva, 1978, adopted 20% of ΔP as the criterion for determining passive sensor interference thresholds.)

A second criterion defines acceptable data loss for remote sensing measurements as 5%. In other words, data from up to 5% of the area scanned by the sensors may be unusable due to interference. This data loss, discussed below, occurs when the sensor antenna points directly at an interference source, or conversely, when the sensor is within the main beam of an interfering source.

To determine whether frequency bands for passive sensors can be shared with active services, the typical equipment characteristics and geographic dispersion of each service operating in the bands must be analyzed. For services in which equipment has not yet been developed or standardized, applicable CCIR guidelines indicate operating parameters of the services. This information can be combined with parameters of the passive sensor

Figure 21
Interference from Fixed and Mobile Services



A. Fixed and mobile antenna main beams pointed at the sensor's antenna sidelobes
B. Cumulative effect of sidelobe to sidelobe interference
C. Sensor antenna mainbeam pointed at the sidelobes of the terrestrial source of interference

Figure 22
Sensor Interference Thresholds And Required Sensitivities

Frequency (GHz)	Interference Threshold (dBW)	Bandwidth (MHz)	Required Sensitivity ΔT_e (K)
Near 1.4	−165	100	0.1
Near 2.7	−166	60	0.1
Near 5	−158	200	0.3
Near 6	−158	400	0.3
Near 11	−156	100	1.0
Near 15	−160	200	0.2
Near 18	−160	200	0.2
Near 21	−160	200	0.2
22.237	−155	300	0.4
Near 24	−157	400	0.2
Near 30	−156	500	0.2
Near 37	−146	1000	1.0
Near 55	−157	250	0.3
Near 90	−138	6000	1.0
Above 100	−150	2000	0.2

CCIR Report 694, op cit

to determine how much interference the passive sensor may encounter.

Sharing With Fixed and Mobile

There are three potential modes of interference to passive sensors from terrestrial fixed and mobile services which must be considered (Figure 21).

Some interference is unavoidable, but not particularly harmful. For example, in all shared frequency bands the sensor will receive erroneous readings when pointed directly at man-made sources on earth; but this interference is normally limited to a short time period in a relatively small area. While undesireable, the loss of data from up to 5% of the area scanned is acceptable for remote sensing measurements.

Wide area interference is less benign and occurs when sidelobe emissions of a number of earth transmitters cumulatively cause interference, a situation that commonly arises in frequency bands below 10 GHz in which fixed and mobile services operate. In wide area interference, an entire area will be lost to sensing whenever the total number of transmitters in that area exceeds a certain limit.

Main beam emissions from terrestrial transmitters, either singly or through overlapping beams, can also produce wide area interference. This type of interference occurs when the sensor is near the horizon with respect to terrestrial transmitters. Because of the geometrical relationships, main beam interference can occur only when the sensor is several thousand miles from the interferor.

For viable sharing, the total interference reaching the sensors via all modes (and from all services sharing a band) cannot exceed the interference threshold (Figure 22).

For example, in the 10.6-10.7 GHz band, where the interference threshold is -156 dBW, expected interference levels for a passive sensor in a 500 km orbit are calculated by the methods set forth in CCIR Report 694:

Fixed Service

Sidelobe Contribution:

Transmitter power	-3 dBW
Transmitter antenna sidelobe gain	-10 dBi
Atmospheric loss	-0.1 dB
Spreading loss (Ave.)	130 dBm^{-2}
Sensor antenna effective area (sidelobe)	-56 dBm^2
10,000 transmitters	+40 dB
Interference received	-159.1 dBW

Fixed Service

Mainbeam Contribution:

Transmitter e.i.r.p.	35 dBW
Spreading loss	-139 dBm^{-2}
Atmospheric loss	-3 dB
Sensor antenna effective area (sidelobe)	-56 dBm^2
3 transmitter mainbeam overlaps	+5 dB
Interference Received	-158 dBW
Total Received Interference	-156 dBW

The calculated interference level of -156 dBW would allow sensors operating in the 10.6-10.7 GHz band to remain within the acceptable data loss limit of 5%. Based on a uniformly random distribution of 10,000 interfering transmitters, four or more overlaps at the satellite's orbit would occur and cause interference 2% of the time. The 2% is added to a 3% area loss from the sensor's pointing directly at the terrestrial sources of interference:

Area loss from one interferor	17.8 dBkm^2
10,000 potential visible sources	40.0 dB
Earth area of satellite visibility	72.8 dBkm^2
% of total visibility lost	3%

If the fixed service EIRP or transmitted power exceed the threshold levels, data loss would exceed 5% and sharing would not be possible. To permit sharing, the WARC adopted +40 dBW transmitter EIRP and -3 dBW transmitter power as mandatory limits on the fixed services in the 10.6-10.7 GHz band. These limits are satisfactory on the assumption that the number of fixed transmitters will not exceed the population of 10,000 used in the model calculation.

A random interference analysis program has been developed to determine the cumulative interference effects of multiple terrestrial transmitters simultaneously visible to a spaceborne sensor. This program uses a random number generator to place terrestrial stations within the view of the sensor. The terrestrial stations are located randomly at great circle distances from the sensor satellite's sub-satellite point and are assigned random pointing directions. Calculation of the interference power at the sensor receiver is then based upon the terrestrial and sensor antenna patterns and range to the satellite.

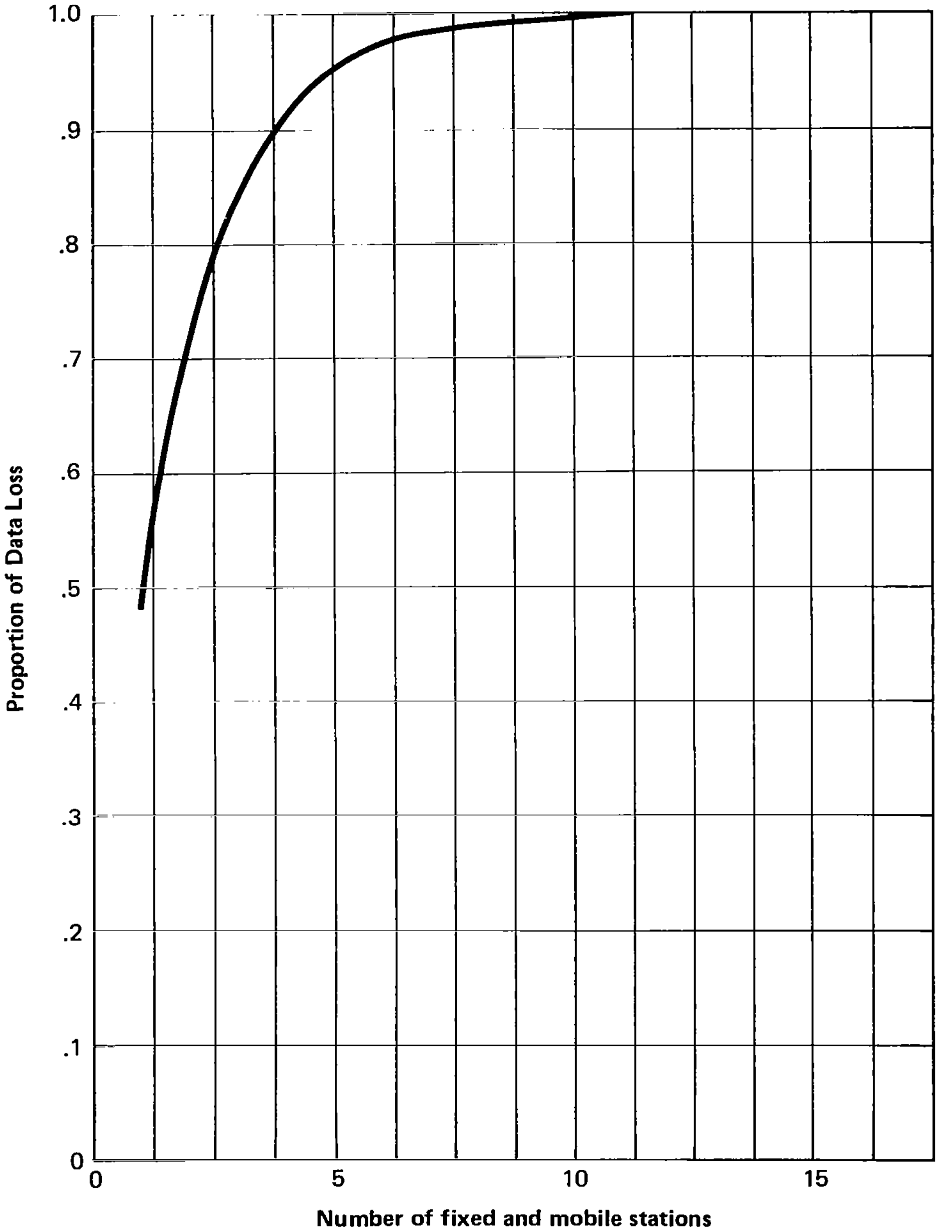
The random interference analysis program can determine the probability of interference to a sensor as a function of the population and characteristics of the interfering transmitters. The program generates two products: graphs showing data loss versus the number of transmitters and maps that show loss of coverage areas. For example, in the case of passive sensors sharing with existing fixed and mobile services in the 4950-5000 MHz band, these products show that sharing in that region of the spectrum is not feasible in large areas of the world (Figures 23 and 24).

Sharing with Active Space Services

Space services such as the Fixed-Satellite or Broadcasting-Satellite Services can generate wide area interference when they serve large geographical areas. In serving the United States or Europe, for example, the main beams from these satellites must cover the service area, causing wide area interference for a sensor flying through the main beam if the power flux density (PFD) produced by the transmitting satellite exceeds a threshold level. Since the interference power reflected from the earth's surface can enter the main beam of a spaceborne sensor, this interference mode is more limiting than the direct interference into the sensor back lobes from the interfering satellite (Figure 25).

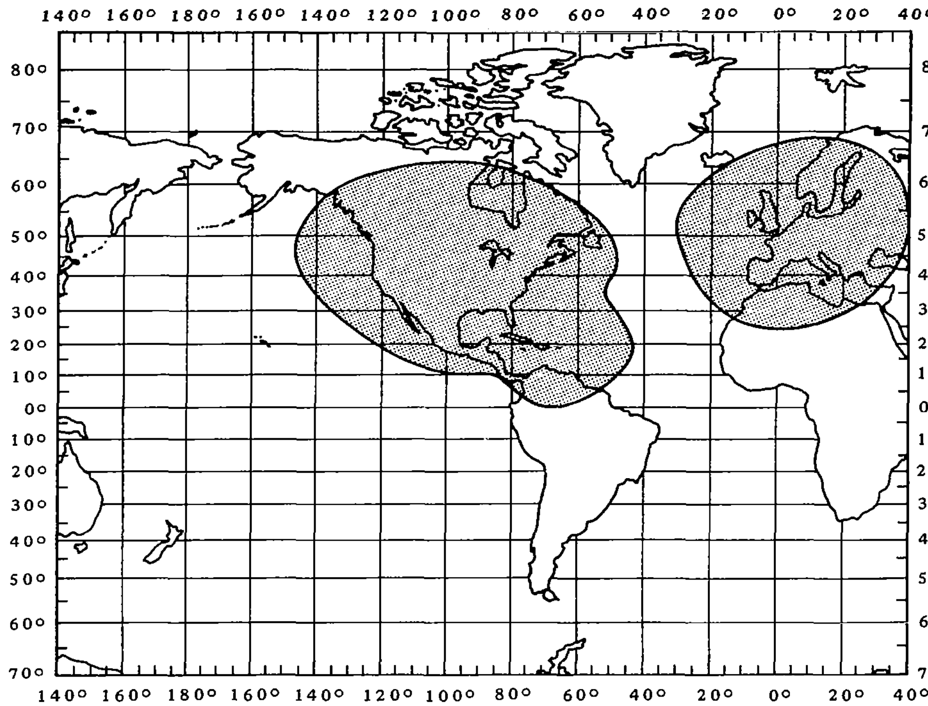
The PFD level at which the transmitting satellite produces harmful interference in this case is a function of the scattering coefficient (σ_o), which is determined by several factors: angle of incidence, sea surface roughness,

Figure 23
Example of Data Loss Versus Number of Fixed and Mobile Stations (4950-5000 MHz)



NASA, *Frequency Band Justifications for Passive Sensors,* December, 1976

Figure 24
Loss of Coverage Area Due to Fixed and Mobile Service (4950-5000 MHz)



NASA, *Frequency Band Justifications for Passive Sensors,* December, 1976

soil wetness, soil roughness, vegetation cover, soil type and terrain slope. The level of interference received by a passive sensor will depend on how closely the sensor antenna axis is aligned with the specular direction of the reflected signal from a fixed satellite (Figure 26). A PFD of -101 dB [W/(m^2)] would result in interference at the sensor interference threshold when the scattering coefficient exceeds -3 dB and would limit area loss for sensing to small values.

More study is needed to determine the percentage of time that alignment of a passive sensor antenna to the specular direction of the fixed satellite reflected signal will occur.

Further studies should also provide a basis for determining the maximum PFD level acceptable for sharing and, perhaps, to specify a range of incidence angles for the passive sensor antenna which would minimize interference.

General Sharing Guidelines

The sharing potential of each frequency band requires individual analysis. However, certain general conclusions can be made regarding sharing with other services (CCIR report 694):

Sharing with the Fixed and Mobile Services

— appears feasible above 20 GHz without limitations;

— can be feasible between 10-20 GHz only with sharing criteria which limit the fixed and mobile equipment parameters; and

Figure 25

Reflected Path Interference From Fixed Satellites

The interference power received by the sensor is:

$$P_R = \left[\frac{P_T G_T}{4\pi R^2_{TG}}\right]\left[\frac{\sigma_o}{4\pi}\right]\left[\frac{A_S}{R^2_{GR}}\right] A_R$$

Where:

$P_T G_T$: fixed-satellite EIRP
R_{TG}: range from the fixed-satellite to earth
σ_o: scattering coefficient
A_S: footprint of the sensor antenna on the earth
R_{GR}: range from the earth to the sensor
A_R: effective area of the sensor antenna

The above equation can be expressed as:

$$P_R = \left[\frac{P_T G_T}{4\pi R^2_{TG}}\right]\left[\frac{\lambda^2 \pi}{64 \cos \theta_i}\right] \sigma_o$$

where θ_i is the incidence angle of the sensor antenna.

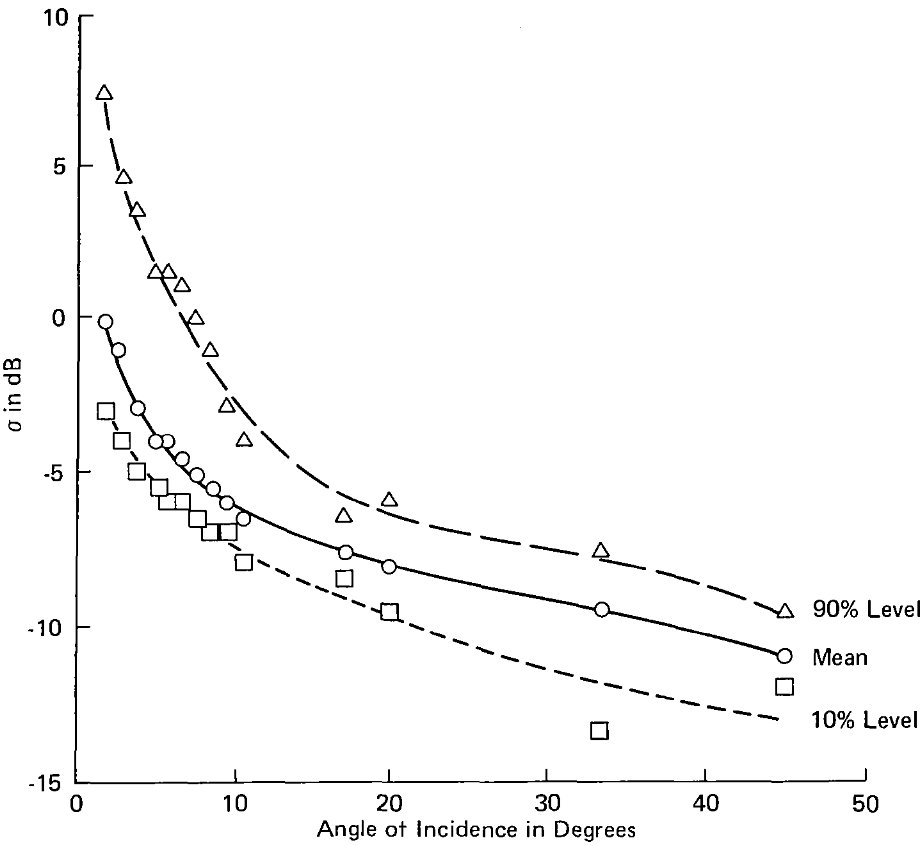
Since the first term on the right side of the above equations is the PFD produced by the fixed-satellite, the maximum PFD which will not cause interference can be determined from:

$$PFD = \frac{P_R (64 \cos \theta_i)}{\lambda^2 \pi \sigma_o}$$

The value of σ_o is a function of the angle of incidence, soil wetness, soil roughness, vegetation cover, soil type and terrain slope.

T. Hines and J. Nicholas, *Frequency Sharing Between Passive Sensors and the Fixed Satellite Service in the Band 17.7-19.7 GHz,* Systematics General Corporation, 1981

Figure 26
Differential Scattering Coefficient Measured at Various Sites In the U.S. with Skylab S-193 Scatterometer



Stephen Purduski, *Distribution Tests Five Percentile Values and Autocorrelation Coefficients of Skylab S-193 Overland Radar Data,* RSL Tech memo 2923-9, University of Kansas, Lawrence, Kansas, June, 1978.

— is not feasible below 10GHz. (Although large areas of the oceans would currently be interference free, future growth in developing countries will eventually render these bands useless for passive sensing.)

Sharing with Fixed-Satellite and Mobile-Satellite space-to-Earth links between 15-20 GHz is feasible with appropriate PFD sharing criteria

Sharing with Fixed-satellite and Mobile-satellite Earth-to-space links has limited feasibility and should be avoided if possible

Sharing with the Broadcasting-Satellite Service is not feasible

Sharing with the Radiolocation and Aeronautical Radionavigation Services is feasible only in bands used exclusively for radio altimeters

Sharing with the Broadcasting Service is not feasible

Sharing with the Inter-Satellite Service is feasible

Active Sensor Analysis

Because the power flux densities produced by spaceborne radars pointed toward earth exceed levels acceptable for sharing with terrestrial communications services, sharing possibilities for active sensors are confined to the radiolocation bands, in which radars already operate. Studies (CCIR Report 695, *Feasibility of Frequency Sharing Between Spaceborne Radars and Terrestrial Radars in the Radiolocation Service,* Geneva, 1978; J. J. Nicholas, Jr., *Cochannel Interference Analysis Between Spaceborne and Terrestrial Radars,* IEEE Transactions, Aerospace Electronic Systems, Volume AES-14, pp. 803, 812, September, 1978) indicate that all three types of active sensors – imaging radars, scatterometers and altimeters – could feasibly operate in bands shared with terrestrial radars.

To evaluate sharing feasibility, the potential for sharing between terrestrial and spaceborne radars most susceptible to interference was examined. The SEASAT-A synthetic aperture radar (SAR) was chosen for study since the SAR will probably be the most common and also the most susceptible of the spaceborne radars. If sharing is feasible for the SAR, it would most likely be feasible for other active sensors. The terrestrial radar chosen for analysis was a long range surveillance radar. It included four modes of operation – normal, moving target indicator (MTI), integration and digital processing – and had a large interference potential: 5 MW of transmitter power. In terms of interference, these modes ranged from very susceptible to insensitive.

The terrestrial radar sharing analysis showed no interference to the terrestrial radar in two of its modes – integration and digital processing – because of processor discrimination against the unwanted signal. Discernible interference occurred in the normal and MTI modes; however, this interference resembled interference caused by other terrestrial radars and airborne radars operating in the same band, and was of a form commonly handled by operational procedures. The interference would occur less than 0.08% of the time. This percentage would vary according to the number of orbiting radars, the spaceborne radar's power, and the terrestrial radar's receiver sensitivity (or minimum detectable signal) (Figure 27).

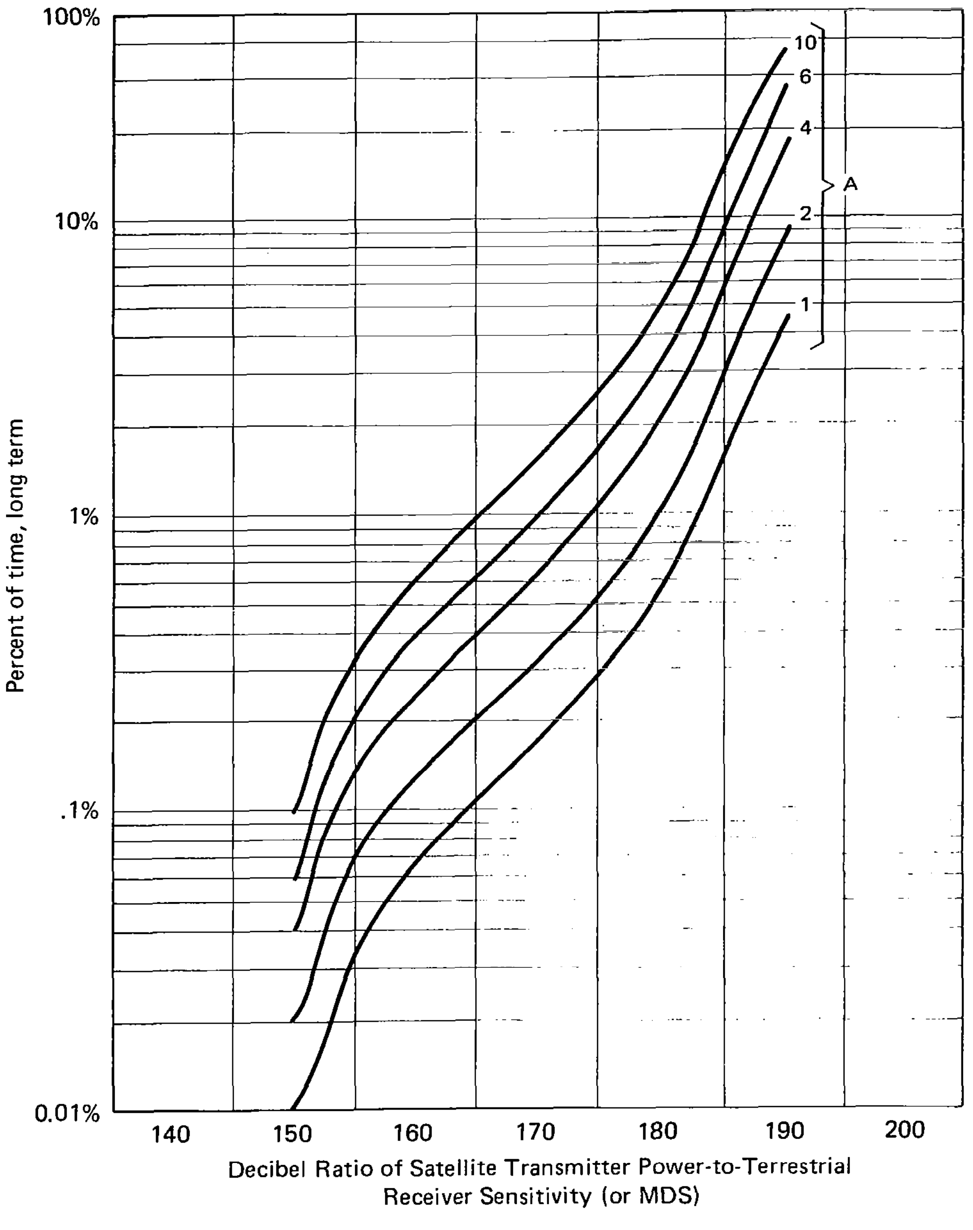
The spaceborne radar sharing analysis showed that the SAR received no interference in the low gain mode. Perceptible interference that occurred in the high gain mode was similar to that encountered by airborne imaging radars currently operating in radiolocation bands. Lowering the SAR receiver's power saturation level in the high gain mode would make interference-free operation possible, but the dynamic range of the SAR would be reduced.

Another analysis concluded that scatterometers would be even less sensitive to interference than the SAR is (Figure 28). The acceptable interference level increases when the scatterometer signal level increases above its minimum, as it does for incidence angles less than the maximum of 55°; conservatively, allowable interference levels would be -7 dB above the scatterometer's noise level. Of course, different scatterometer designs must be analyzed individually to determine their susceptibility to interference.

The U.S. Position

The intense competition by various services for spectrum use, particularly below 20 GHz, necessitated a number of compromises in developing the U.S. position on sensor allocations for the 1979 WARC. These compromises in-

Figure 27
Parametric Interference Curves



A: Number of satellites carrying a spaceborne radar

CCIR Report 695, *op cit.*

Figure 28
SEASAT Scatterometer Interference Analysis

The received signal power at the scatterometer is given by the two-way radar return equation:

$$P_S = \frac{P_T G_T}{4\pi R^2} \cdot \frac{\sigma^0 A}{4\pi R^2} \cdot \frac{G_T \lambda^2}{4\pi} \cdot L_S$$

Where:

- P_T: transmitter power
- G_T: transmitter antenna gain
- $4\pi R^2$: spreading loss (one way), R = range
- σ^0: normalized radar scattering cross-section
- λ: wavelength
- A: instantaneous resolution element area
- L_S: all other losses, such as atmospheric losses

The variance of σ_z^2, including noise plus interference is given by:

$$\sigma_z^2 = \frac{1}{B\tau_n}\left(\sigma_n^2 + \sigma_i^2\right)^2 + \frac{1}{B\tau_{s+n}}\left(\sigma_n^2 + \sigma_i^2 + \sigma_s^2\right)^2$$

Where:

- B: Scatterometer IF bandwidth
- τ_n: noise integration time
- τ_{s+n}: signal and noise integration time
- σ_n^2: noise variance (AC power)
- σ_i^2: interference variance (AC power)

The quantity to be measured is the sea's σ°, which then can be related to wind speed. Since all other right-side factors are known, only P_s needs to be determined in order to calculate σ°. The return signal power, P_s, can be estimated by averaging the signal plus noise, then subtracting the average noise power. However, this approach only yields the 'mean' value for P_s. There is some variance to this mean due to the statistical nature of the signal and the noise.

Based on the minimum σ° of -28 dB (-167 dBw received signal), -161 dBw of noise and a 50% accuracy requirement at 55° incidence angle, leads to an allowable interference of -154 dBw for SEASAT. As the signal level increases, even more interference could be tolerated. Hence, a conservative allowance for interference would be 7 dB above the scatterometer's receiver noise level. Of course, different scatterometers must be individually analyzed in order to determine the correct interference allowance. However, this analysis has shown that the scatterometer, relative to a SAR, is less sensitive to interference.

J. Nicholas, *NOSS Scatterometer Interference Analysis,* Technical Memorandum, Systematics General Corporation, May, 1980.

cluded acceptance of bandwidths that were narrower than those desired, consolidation of some bands, sharing of non-vital bands with incompatible services, and acceptance of secondary status for active sensors in many of the proposed bands.

For passive sensors, the U.S. effort emphasized two vital requirements: the adoption of the frequency bands needed to make atmospheric measurements at the discrete frequencies determined by gaseous molecular resonances; and adoption of a viable set of bands for simultaneous multi-frequency measurements needed to determine land and ocean surface parameters.

For active sensors, the U.S. position emphasized adoption of a set of bands for multi-frequency measurements between 1 and 100 GHz. The band selection had to permit viable sharing situations, and at least one band had to have sufficient bandwidth (600 MHz) to accomodate altimeter operations.

D. 1979 WARC Results and Remaining Issues

(This section summarizes the results of the 1979 WARC and presents the frequency allocations tables pertaining to microwave remote sensors.)

The 1979 WARC approved over fifty allocations for microwave sensors: ten for active and over forty for passive. The conference accommodated most sensor requirements: One group of bands particularly suited to simultaneous measurement of surface phenomena was allocated for passive sensors. A second group of bands provides for passive sensing of the atmosphere, including water vapor resonance frequencies and multiple resonance frequencies for oxygen, nitrous oxide, ozone, carbon monoxide and chlorine oxide. A third group of bands allocated for passive sensor surface measurements is less useful due to predicted high interference levels and/or limited bandwidth.

In addition to the allocations, the conference established protection criteria in the 10.6-10.7 GHz band to protect passive sensors from the fixed and mobile services. Some issues, however, require further attention.

The new allocations created several sharing situations which have not been analyzed in CCIR studies. The 1260-1300 MHz band was allocated to the Amateur-Satellite Service (Earth-to-space) and active sensing. Potential interference to spaceborne radars operating in the band requires analysis and, if necessary, protection criteria should be established.

In the 4.2-4.4 GHz band, passive sensors share the allocation with the Aeronautical Radionavigation Service and its associated ground transponders. Sharing with the ground transponders has not been analyzed and requires particular attention since a new footnote (789) specifies that no protection from radio altimeters will be provided to passive sensors in this band.

No agreement was reached for protection in the 18.6-18.8 GHz band. Further study to determine power limits for the Fixed and Fixed-Satellite Services to protect passive sensing in the band should be conducted in the CCIR (1979 WARC Recommendation 706).

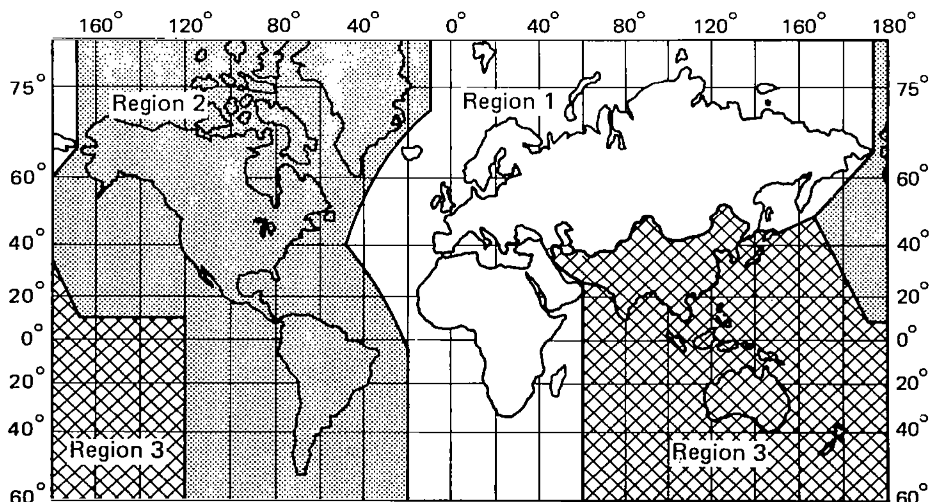
High powered services in adjacent bands, such as the Broadcasting-Satellite Service, present potential interference to passive sensors. Criteria for protection — in the form of out-of-band filtering requirements for both the broadcasting satellite and the passive sensor — should be developed.

Future conferences may raise new matters of concern. Planning for the geostationary-satellite orbit is scheduled for the 1985/1987 space WARC, which is charged with planning space services and frequency bands to guarantee equitable access by all countries to the geostationary-satellite orbit. The first session of the conference will determine which services should be planned and will establish the principles, technical parameters and criteria for such planning. A second session of the WARC will follow two years later, and will implement the decisions of the first session. In bands which microwave sensors share with geostationary satellite services — such as the 18.6—18.8 GHz band, shared with the Fixed-Satellite Service — the Space WARC could have significant impact on remote microwave sensing.

Frequency Allocation Tables

The pages that follow contain sections of the allocation tables adopted by the 1979 WARC which pertain to spaceborne microwave sensing, denoted in the tables as the Earth Exploration-Satellite Service (passive) or (active) and the Space Research Service (passive) or (active). The world map in figure 29 shows the three ITU regions. Primary allocations are designated by listing services in upper case; secondary allocations are indicated by listings with initial capital letters. Footnotes affecting remote sensing are highlighted by boxes in the tables. For convenience, the text of only those footnotes is included here. Frequencies for data readout were also allocated but are not presented here.

Figure 29
ITU Regions



ITU, *Final Acts of the World Administrative Radio Conference,* Geneva, 1979.

Passive Sensor Allocations from the 1979 WARC

<table>
<tr><th colspan="3">Allocation to Services</th></tr>
<tr><th>Region 1</th><th>Region 2</th><th>Region 3</th></tr>
<tr><td>1 350 – 1 400
FIXED
MOBILE
RADIOLOCATION
719 $\boxed{720}$ 718</td><td colspan="2">1 350 – 1 400
RADIOLOCATION
714 718 $\boxed{720}$</td></tr>
<tr><td>1 400 – 1 427</td><td colspan="2">EARTH EXPLORATION-SATELLITE (passive)
RADIO ASTRONOMY
SPACE RESEARCH (passive)
722 $\boxed{721}$</td></tr>
<tr><td>1 660.5 – 1 668.4</td><td colspan="2">RADIO ASTRONOMY
SPACE RESEARCH (passive)
Fixed
Mobile except aeronautical mobile
739 738 737 722 736</td></tr>
</table>

ADD 720 The bands 1 370 – 1 400 MHz, 2 640 – 2 655 MHz, 4 950 – 4 990 MHz and 15.20 – 15.35 GHz are also allocated to the space research (passive) and earth exploration-satellite (passive) services on a secondary basis.

ADD 721 All emissions in the band 1 400 – 1 427 MHz are prohibited.

Allocation to Services		
Region 1	**Region 2**	**Region 3**
2 500 – 2 655 FIXED MOBILE except aeronautical mobile BROADCASTING-SATELLITE 764 762 763 757 $\boxed{720}$ 753 756 759 758 760	2 500 – 2 655 FIXED FIXED-SATELLITE (space-to-Earth) MOBILE except aeronautical mobile BROADCASTING-SATELLITE 755 $\boxed{720}$ 764 762 761 757 760	2 500 – 2 535 FIXED FIXED-SATELLITE (space-to-Earth) MOBILE except aeronautical mobile BROADCASTING-SATELLITE 764 762 761 757 760 754 2 535 – 2 655 FIXED MOBILE except aeronautical mobile BROADCASTING-SATELLITE 764 762 757 760 $\boxed{720}$
2 655 – 2 690 FIXED MOBILE except aeronautical mobile BROADCASTING-SATELLITE Earth-Exploration Satellite (passive) Radio Astronomy Space Research (passive) 759 765 763 764 762 757 760 758	2 655 – 2 690 FIXED FIXED-SATELLITE (Earth-to-space) (space-to-Earth) MOBILE except aeronautical mobile BROADCASTING-SATELLITE Earth Exploration-Satellite (passive) Radio Astronomy Space Research (passive) 761 764 762 757 760 765	2 655 – 2 690 FIXED FIXED-SATELLITE (Earth-to-space) MOBILE except aeronautical mobile BROADCASTING-SATELLITE Earth Exploration-Satellite (passive) Radio Astronomy Space Research (passive) 766 761 764 762 757 760 765

ADD 720 The bands 1370 – 1400 MHz, 2640 – 2655 MHz, 4950 – 4990 MHz and 15.2 – 15.35 GHz are also allocated to the space research (passive) and earth exploration-satellite (passive) services on a secondary basis.

Allocation to Services		
Region 1	Region 2	Region 3
2 690 – 2 700	EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) $\boxed{768}$ 767 769	
4 200 – 4 400	AERONAUTICAL RADIONAVIGATION $\boxed{789}$ 791 790 788	
4 800 – 4 990	FIXED MOBILE Radio Astronomy 793 778 794 $\boxed{720}$	
5 925 – 7 075	FIXED FIXED-SATELLITE (Earth-to-space) MOBILE 791 $\boxed{809}$	
7 075 – 7 250	FIXED MOBILE 811 $\boxed{809}$ 810	

ADD 720 The bands 1 370 – 1 400 MHz, 2 640 – 2 655 MHz, 4 950 – 4 990 MHz and 15.20 – 15.35 GHz are also allocated to the space research (passive) and earth exploration-satellite (passive) services on a secondary basis.

ADD 789 Use of the band 4 200 – 4 400 MHz by the aeronautical radionavigation service is reserved exclusively for radio altimeters installed on board aircraft and for the associated transponders on the ground. However, passive sensing in the earth exploration-satellite and space research services may be authorized in this band on a secondary basis (no protection is provided by the radio altimeters).

ADD 809 In the band 6 425 – 7 075 MHz, passive microwave sensor measurements are carried out over the oceans. In the band 7 075 – 7 250 MHz, passive microwave sensor measurements are carried out. Administrations should bear in mind the needs of the earth exploration-satellite (passive) and space research (passive) services in their future planning of this band.

ADD 768 All emissions in the band 2690 – 2700 MHz are prohibited, except those provided for by Nos. 767 and 769.

Allocation to Services		
Region 1	**Region 2**	**Region 3**
10.6 – 10.68	EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY SPACE RESEARCH (passive) Radiolocation 832 $\boxed{831}$	
10.68 – 10.7	EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) 834 $\boxed{833}$	
14.8 – 15.35	FIXED MOBILE Space Research $\boxed{720}$	

ADD 833 All emissions in the band 10.68–10.7 GHz are prohibited, except for those provided for by No. 834.

ADD 720 The bands 1 370 – 1 400 MHz, 2 640 – 2 655 MHz, 4 950 – 4 990 MHz and 15.20 – 15.35 GHz are also allocated to the space research (passive) and earth exploration-satellite (passive) services on a secondary basis.

ADD 831 In the band 10.6 – 10.68 GHz, the fixed and mobile, except aeronautical mobile, services shall be limited to a maximum equivalent isotropically radiated power of 40 dBW and the power delivered to the antenna shall not exceed -3 dBW. These limits may be exceeded subject to agreement obtained under the procedure set forth in Article 14. However in Afghanistan, Saudi Arabia, Bahrain, Bangladesh, China, the United Arab Emirates, Finland, India, Indonesia, Iran, Iraq, Japan, Kuwait, Lebanon, Nigeria, Pakistan, the Philippines, Qatar, Syria and the U.S.S.R., the restrictions on the fixed and mobile, except aeronautical mobile, services are not applicable.

<table>
<tr><th colspan="3">Allocation to Services</th></tr>
<tr><th>Region 1</th><th>Region 2</th><th>Region 3</th></tr>
<tr><td>15.35 – 15.4</td><td colspan="2">RADIO ASTRONOMY
EARTH EXPLORATION-SATELLITE (passive)
SPACE RESEARCH (passive)
865 $\boxed{864}$</td></tr>
<tr><td>18.6 – 18.8
FIXED
FIXED-SATELLITE (space-to-earth)
MOBILE except aeronautical mobile
Earth-Exploration-Satellite (passive)
Space Research (passive)
$\boxed{872}\boxed{871}$</td><td>18.6 – 18.8
EARTH EXPLORATION-SATELLITE (passive)
FIXED
FIXED-SATELLITE (space-to-earth)
MOBILE except aeronautical mobile
SPACE RESEARCH (passive)
$\boxed{872}\boxed{871}$</td><td>18.6 – 18.8
FIXED
FIXED-SATELLITE (space-to-earth)
MOBILE except aeronautical mobile
Earth Exploration-Satellite (passive)
Space Research (passive)
$\boxed{872}\boxed{871}$</td></tr>
<tr><td>21.2 – 21.4</td><td colspan="2">EARTH EXPLORATION-SATELLITE (passive)
FIXED
MOBILE
SPACE RESEARCH (passive)</td></tr>
</table>

ADD 864 All emissions in the band 15.35 – 15.4 GHz are prohibited, except those provided for by No. 865.

ADD 871 In making assignments to stations in the fixed and mobile services, administrations are invited to take account of passive sensors in the earth-exploration satellite and space research services operating in the band 18.6 – 18.8 GHz. In this band, administrations should endeavour to limit as far as possible both the power delivered by the transmitter to the antenna and the e.i.r.p. in order to reduce the risk of interference to passive sensors to the minimum.

ADD 872 In assigning frequencies to stations in the fixed-satellite service in the direction space-to-Earth, administrations are requested to limit as far as practicable the power flux-density at the Earth's surface in the band 18.6 – 18.8 GHz, in order to reduce the risk of interference to passive sensors in the earth exploration-satellite and space research services.

<table>
<tr><th colspan="3">Allocation to Services</th></tr>
<tr><th>Region 1</th><th>Region 2</th><th>Region 3</th></tr>
<tr><td colspan="3">22.21 – 22.5
EARTH EXPLORATION-SATELLITE (passive)
FIXED
MOBILE except aeronautical mobile
RADIO ASTRONOMY
SPACE RESEARCH (passive)
875 $\boxed{876}$</td></tr>
<tr><td colspan="3">23.6 – 24
EARTH EXPLORATION-SATELLITE (passive)
RADIO ASTRONOMY
SPACE RESEARCH (passive)
$\boxed{880}$</td></tr>
<tr><td colspan="3">31.3 – 31.5
EARTH EXPLORATION-SATELLITE (passive)
RADIO ASTRONOMY
SPACE RESEARCH (passive)
$\boxed{887}$</td></tr>
<tr><td>31.5 – 31.8
EARTH EXPLORATION-SATELLITE (passive)
RADIO ASTRONOMY
SPACE RESEARCH (passive)
Fixed
Mobile except aeronautical mobile
889 888</td><td>31.5 – 31.8
EARTH EXPLORATION-SATELLITE
RADIO ASTRONOMY
SPACE RESEARCH (passive)
$\boxed{888}$</td><td>31.5 – 31.8
EARTH EXPLORATION-SATELLITE (passive)
RADIO ASTRONOMY
SPACE RESEARCH (passive)
Fixed
Mobile except aeronautical mobile
888</td></tr>
</table>

ADD 880 All emissions in the band 23.6 – 24 GHz are prohibited.

ADD 887 All emissions in the band 31.3 – 31.5 GHz are prohibited.

ADD 876 The use of the band 22.21 – 22.5 GHz by the earth exploration-satellite (passive) and space research (passive) services shall not impose constraints upon the fixed and mobile, except aeronautical mobile services.

ADD 888 In Region 2, all emissions in the band 31.5 – 31.8 GHz are prohibited.

Allocation to Services		
Region 1	**Region 2**	**Region 3**
36 – 37	EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive) 898	
50.2 – 50.4	EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive)	
51.4 – 54.25	EARTH EXPLORATION-SATELLITE (passive) SPACE RESEARCH (passive) $\boxed{907}$ 906	
54.25 – 58.2	EARTH EXPLORATION-SATELLITE (passive) FIXED INTER-SATELLITE MOBILE 909 SPACE RESEARCH (passive) 908	
58.2 – 59	EARTH EXPLORATION-SATELLITE (passive) SPACE RESEARCH (passive) $\boxed{907}$ 906	
64 – 65	EARTH EXPLORATION-SATELLITE (passive) SPACE RESEARCH (passive) $\boxed{907}$ 906	

ADD 907 In the bands 51.4 – 54.25 GHz, 58.2 – 59 GHz, 64 – 65 GHz, 86 – 92 GHz, 105 – 116 GHz and 217 – 231 GHz all emissions are prohibited.

Allocation to Services		
Region 1	**Region 2**	**Region 3**
86 – 92	EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) $\boxed{907}$	
100 – 102	EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive) 722	
105 – 116	EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) $\boxed{907}$ 722	
116 – 126	EARTH EXPLORATION-SATELLITE (passive) FIXED INTER-SATELLITE MOBILE SPACE RESEARCH (passive) 909 916 915 722	
150 – 151	EARTH EXPLORATION-SATELLITE (passive) FIXED FIXED-SATELLITE (space-to-Earth) MOBILE SPACE RESEARCH (passive) 919	

ADD 907 In the bands 51.4 – 54.25 GHz, 58.2 – 59 GHz, 64 – 65 GHz, 86 – 92 GHz, 105 – 116 GHz and 217 – 231 GHz, all emissions are prohibited.

Allocation to Services		
Region 1	**Region 2**	**Region 3**
164 – 168	EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive)	
174.5 – 176.5	EARTH EXPLORATION-SATELLITE (passive) FIXED INTER-SATELLITE MOBILE SPACE RESEARCH (passive) 909 919	
182 – 185	EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) 920 $\boxed{921}$	
200 – 202	EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive) 722	
217 – 231	EARTH EXPLORATION-SATELLITE (passive) RADIO ASTRONOMY SPACE RESEARCH (passive) $\boxed{907}$ 722	

ADD 921 In the band 182 – 185 GHz all emissions are prohibited except for those under the provisions of No. 920.

Allocation to Services		
Region 1	Region 2	Region 3
235 – 238	EARTH EXPLORATION-SATELLITE (passive) FIXED FIXED-SATELLITE (space-to-Earth) MOBILE SPACE RESEARCH (passive)	
250 – 252	EARTH EXPLORATION-SATELLITE (passive) SPACE RESEARCH (passive) 923	
275 – 400	(Not allocated) $\boxed{927}$	

ADD 927 The frequency band 275 GHz – 400 GHz may be used by administrations for experimentation with, and development of, various active and passive services. In this band a need has been identified for the following spectral line measurements for passive services:

Radio astronomy service: 278 – 280 GHz and 343 – 348 GHz;

Space research service (passive) and earth exploration-satellite service (passive): 275 – 277 GHz, 300 – 302 GHz, 324 – 326 GHz, 345 – 347 GHz, 363 – 365 GHz and 379 – 381 GHz.

Future research in this largely unexplored spectral region may yield additional spectral lines and continuum bands of interest to the passive services. Administrations are urged to take all practicable steps to protect these passive services from harmful interference until the next competent World Administrative Radio Conference.

Active Sensor Allocations from the 1979 WARC

Allocation to Services		
Region 1	**Region 2**	**Region 3**
1 215 – 1 240	RADIOLOCATION RADIONAVIGATION-SATELLITE (space-to-Earth) 712 711 710 $\boxed{713}$	
1 240 – 1 260	RADIOLOCATION RADIONAVIGATION-SATELLITE (space-to-Earth) Amateur 712 711 710 $\boxed{713}$ 714	
1 260 – 1 300	RADIOLOCATION Amateur 664 712 711 $\boxed{713}$ 714	
3 100 – 3 300	RADIOLOCATION $\boxed{713}$ 777 776 778	
5 255 – 5 350	RADIOLOCATION 798 $\boxed{713}$	
8 500 – 8 750	RADIOLOCATION 820 $\boxed{713}$ 819	
9 500 – 9 800	RADIOLOCATION RADIONAVIGATION $\boxed{713}$	
13.4 – 14	RADIOLOCATION Standard Frequency and Time Signal-Satellite (Earth-to-space) Space Research $\boxed{713}$ 853 854 855	

ADD 713 In the bands 1 215 – 1 300 MHz, 3 100 – 3 300 MHz, 5 250 – 5 350 MHz, 8 550 – 8 650 MHz, 9 500 – 9 800 MHz and 13.4 – 14.0 GHz, radiolocation stations installed on spacecraft may also be employed for the earth exploration-satellite and space research services on a secondary basis.

Allocation to Services		
Region 1	**Region 2**	**Region 3**
17.2 – 17.3	RADIOLOCATION Earth Exploration-Satellite (active) Space Research (active) 866 867	
24.05 – 24.25	RADIOLOCATION Amateur Earth Exploration-Satellite (active) 881	
35.2 – 36	METEOROLOGICAL AIDS RADIOLOCATION $\boxed{897}$ 894	
76 – 81	RADIOLOCATION Amateur Amateur-satellite $\boxed{912}$	

ADD 897 Radars located on spacecraft may be operated on a primary basis in the band 35.5 – 35.6 GHz.

ADD 912 In the band 78 – 79 GHz radars located on space stations may be operated on a primary basis in the earth exploration-satellite service and in the space research service.

SECTION III

THE GUIDELINES

A. Introduction to Guidelines For Spaceborne Microwave Remote Sensors

Section III details the procedures for using the spectrum for remote microwave sensing according to the rules and regulations of the frequency management community. The initial subsection summarizes the sharing potential and the achievable user performance in each band allocated for passive and active sensing by the 1979 WARC. The second subsection presents registration requirements for spaceborne sensors, and the third subsection explores the use of non-allocated bands and procedures for obtaining new frequency allocations. The final subsection outlines procedures for reporting interference.

Allocations for Remote Sensing

The 1979 WARC allocated over fifty frequency bands for remote microwave sensing and the transmission of the resulting data from space to earth, including transmission via data relay satellites.

The frequency bands proposed by the United States and allocated by the WARC were chosen to satisfy requirements imposed by physical factors and, for the most part, to insure feasible sharing situations with other radio services allocated in the same bands. A few of the allocated bands, however, are expected to be of limited utility. The WARC allocated a group of bands particularly suited to simultaneous measurement of surface phenomena by passive sensors (Figure 30). These frequency

Figure 30

Principal Allocations for Surface Measurements By Passive Sensors

Frequency Band (GHz)	Principal Measurements
1.40–1.427	Soil moisture, salinity
4.2–4.4	Sea surface temperature
10.6–10.7	Rain, snow, ice, sea state
18.6–18.8	Sea state, rain, ice
31.3–31.8	Ice, oil spills, clouds, liquid water
36–37	Rain, snow, ice, oil spills, clouds
86–92	Clouds, oil spills, ice, snow

ITU, *ibid.*

bands all have adequate measurement bandwidth, lie in regions of low atmospheric attenuation, and can be feasibly shared with other allocated services.

For atmospheric measurements by passive sensors, allocations include the important water vapor resonance frequencies at 22.235 GHz and 183.31 GHz and many of the oxygen resonance frequencies between 50 GHz and 65 GHz, and at 118.7 GHz (Figure 31). Allocated bands for other gases encompass 8 nitrous oxide resonance frequencies, 4 ozone, 3 carbon monoxide, and 2 chlorine oxide resonance frequencies lying between 100 and 300 GHz. Some of these bands have been allocated exclusively to passive sensors and radio astronomy. In the shared bands, sharing is feasible with all allocated services.

Ten frequency bands between 1.2 GHz and 79 GHz were allocated for active microwave sensors (Figure 32). All of the allocated bands are shared with the Radiolocation Service, with which sharing is feasible.

Sharing Criteria

Sensor developers and regulators should understand the bases on which sharing is feasible and then develop equipment and regulatory provisions which insure that the conditions for sharing are met.

The levels of permissible interference to passive microwave sensors are based on studies that determined measurement sensitivities required to meet the projected needs of the discipline sciences (NASA, *Frequency Band Justifications for Passive Sensors,* 1976). For example, sharing criteria at 10.6–10.7 GHz were based on a measurement sensitivity of 1 Kelvin. A sensor designed to be more sensitive than 1 K might be unable to achieve full accuracy due to fixed and mobile transmitters producing interference at levels that can be tolerated by less sensitive systems.

Figure 31

Principal Allocations For Atmospheric Measurements

Frequency Band (GHz)	Principal Measurements
21.2–21.4	Water vapor; liquid water
22.21–22.5	Water vapor; liquid water
23.6–24	Water vapor; liquid water
50.2–50.4	Oxygen (atmospheric temperature)
51.4–59	Oxygen (atmospheric temperature)
64–65	Oxygen (atmospheric temperature)
100–102	Nitrous oxide
105–126	Ozone; carbon monoxide; oxygen (atmospheric temperature)
150–151	Nitrous oxide
164–168	Chlorine oxide
174.5–176.5	Nitrous oxide
182–185	Water vapor, ozone
200–202	Nitrous oxide
217–231	Nitrous oxide; carbon monoxide
235–238	Ozone
250–252	Nitrous oxide

ITU, *ibid.*

Interference is considered harmful when it causes signal levels that exceed 20% of the required measurement sensitivity (ΔT_e). Sensor operators must accept a data loss in shared bands of up to 5% of the area scanned due to interference. In bands shared with Fixed and Mobile Services, such as 10.6–10.7 GHz, high levels of interference will be encountered whenever the sensor antenna points directly at a terrestrial transmitter. Also included in the 5% total loss is the loss that occurs when multiple terrestrial transmitter main beams illuminate the sensor as it crosses the horizon with respect to the transmitters (See *Developing the U.S. Position* in Section II).

While a 5% data loss is considered tolerable for remote sensing applications, designers must be aware of these limitations, which result from the adopted sharing criteria.

Competition between services for the spectrum below 20 GHz precluded WARC allocation of the very wide bands needed to satisfy all combinations of spatial resolution, sensitivity and coverage with a single antenna and radiometer. Radiometer sensitivity is a function of bandwidth and integration time. When bandwidth is limited, the dwell time must be increased, which decreases the size swath that can be scanned. Because of bandwidth limitations, sensor designers may be forced in the future to multiple antenna beam and multiple radiometer designs to achieve projected requirements in the spectrum below 20 GHz.

Also, the measurement calculations in the Assessment of Frequency Bands, which follows, are based on the use of a Dicke-switched radiometer (a=2); however, a total power radiometer (a=1), which is, technologically, a more difficult instrument due to required component stability, could improve the sensor's performance. For example, a total power radiometer could quadruple the achievable swath width in any given band. Sensor designers must consider how to best satisfy the requirements of particular applications and choose from among the many possible combinations of sensitivity, resolution, sensor technology and swath width.

Sharing feasibility is based on the known characteristics of operating active systems and the assumed characteristics of planned active radio services. A major change in these systems can cause incompatibility, depending upon how such a change affects the total interference power

Figure 32
Allocations for Active Microwave Sensors

Frequency Band (GHz)
1.215–1.3
3.1–3.3
5.25–5.35
8.55–8.65
9.5–9.8
13.4–14.0
17.2–17.3
24.05–24.25
33.5–35.6
78–79

ITU, *ibid.*

seen by the sensor. For example, digital termination radio systems are planned in the United States for operation in parts of the 10.6–10.7 GHz band. Although these systems will use many transmitters, sharing will be feasible as long as each transmitter's power remains well below the limits set by the WARC, to insure that the total interference power received by the sensor does not reach the harmful interference threshold.

The WARC was unable to agree on sharing criteria which would protect passive sensors from interference in the 18.6–18.8 GHz band. A decision on this matter was deemed premature, and it was referred to the CCIR for further study. Administrations were merely urged to limit the characteristics of fixed, mobile and fixed-satellite systems to minimize the risk of interference. In the next few years, it will become technically feasible to design active radio systems which would render this important band useless for remote sensing. Mandatory sharing criteria are required to protect remote sensing in this band.

The WARC's actions have laid the foundation for protecting remote sensing measurements that can contribute to the solution to urgent problems that confront the world. Both designers and regulators must now insure that future sensing systems and radio systems evolve in ways that allow realization of the potential benefits of those systems.

B. Assessment of Frequency Bands Allocated for Passive Sensors

1370–1427 MHz

Allocation Status

1370–1427 MHz

From 1370 to 1400 MHz, passive sensors are allocated on a secondary basis by footnote. The primary services in the band are the Radiolocation, Fixed and Mobile Services.

In the 1400–1427 MHz portion of the band, passive sensors are allocated on a primary basis with the Radioastronomy Service.

Sharing Criteria and Interference Potential

In the footnoted 1370–1400 MHz band, no protection is provided from the primary services. In the U.S., over 100 high powered radars operate in the band; international listings also indicate extensive use. Radiolocation Service transmitters cause sensors a 100% loss of coverage area when the satellite is in view. One Fixed Service transmitter causes a 94% data loss.

In the 1400–1427 MHz region, all emissions are prohibited worldwide to provide for radio astronomy and passive sensing measurements.

The interference threshold for determining sharing feasibility in this band is −165 dBW in a 100 MHz reference bandwidth.

User Requirements and Attainable Measurements

The proposals and the WARC allocation were based on sensor requirements for ocean salinity and soil moisture content measurements. Measurement parameters accomodated by the WARC allocation of 1370–

1427 MHz are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km)	Swath Width (km)
Ocean Salinity	0.2 0/00*	0.1	57	20	20
Soil Moisture	1–2%	1.0	57	5	170

*Parts per thousand

Sensor requirements accommodated in the 1400–1427 MHz interference-free portion of the allocation are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km)	Swath Width (km)
Ocean Salinity	0.2 0/00*	0.1	27	30	30
Soil Moisture	1–2%	1.0	27	5	85

Relaxing the ΔT_e requirement would allow other attainable combinations of spatial resolution and swath width.

Assessment

The 1400–1427 MHz portion of the band is extremely important for land and ocean surface measurements; no interference should be encountered in this region, and it is recommended for passive sensing. Due to the relatively narrow bandwidth, some required combinations of ΔT_e, resolution and swath width may be unattainable using a single antenna and radiometer, and multiple antenna beams and radiometers may be needed to satisfy measurement requirements.

Sensing in the 1370–1400 MHz portion of the band should be avoided, since high levels of interference will be encountered in most of the world.

1660.5–1668.4 MHz

Allocation Status

1660.5—1668.4 MHz

Passive sensing shares a primary allocation of this band with the Radioastronomy Service. The Fixed and Mobile Services are allocated on a secondary basis.

Sharing Criteria and Interference Potential

Since passive sensors have a primary allocation, terrestrial services may not produce interference harmful to passive sensors which have been notified to the IFRB in this band.

User Requirements and Attainable Measurements

This allocation was not proposed by the U.S., and its specific utility for passive sensing has not yet been analyzed. The limited bandwidth (8 MHz) would restrict its utility.

Assessment

From a regulatory standpoint, the 1660.5–1668.4 MHz allocation is well protected since the other services in the band that present interference potential are secondary. Equipment characteristics of terrestrial systems operating in the band are unknown. The very limited 8 MHz bandwidth restricts the band's utility.

2640–2700 MHz

Allocation Status

2640–2700 MHz

From 2640–2655 MHz, passive sensors are allocated on a secondary basis by footnote. This portion of the band is allocated on a primary basis to the Fixed, Mobile and Broadcasting-Satellite Services and to Fixed-Satellite downlinks in Regions 2 and 3. Fixed Service systems operating in Region 1 may include troposcatter systems which use high power transmitters, though RR 762 states that administrations shall make all practicable efforts to avoid developing new troposcatter systems in the 2500–2690 MHz band.

In the 2655–2690 MHz band, passive sensors are allocated on a secondary basis. The Fixed, Mobile and Broadcasting-Satellite Services, and the Fixed-Satellite Service (Earth-to-space) in Regions 2 and 3, have primary status. In addition, the Mobile-Satellite Service (Earth-to-space) is allocated in Region 3 by a footnote.

Passive sensors and radio astronomy share a primary allocation in the 2690–2700 MHz band. This band is allocated by footnote to Fixed and Mobile on a primary basis in 40 countries in Eastern Europe, Africa, Middle East, and the Far East for equipment in operation before January, 1985.

Sharing Criteria and Interference Potential

In the 2640–2690 MHz band, harmful interference from the Fixed and/or Mobile Service will be encountered by passive sensors operating simultaneously in the coastal areas of the United States, Europe and the Mediterranean and over the land areas of the United States, Europe, Asia Minor and North Africa. Sixty-five Instructional Television Fixed Service (ITFS) stations operate in the U.S.; over 100 line-of-sight (LOS) systems and 9 troposcatter systems worldwide have been notified to the IFRB. (A single assignment may include multiple transmitters within the registering administration.) One ITFS transmitter within the sensor's line-of-sight would cause a 27% data loss; one troposcatter transmitter would cause a 100% data loss.

Harmful interference from simultaneous operation of the Broadcasting Satellite Service (space-to-Earth) would be encountered by passive sensors over the entire ground 'footprint' area of the beam, which will be quite extensive if such systems are implemented in this band. However, they are more likely to be implemented in the 12 GHz band, which is also allocated for broadcasting satellites.

Harmful interference would be encountered by passive sensors over large areas surrounding fixed satellite earth stations, causing a 15% data loss from each earth station. Although no systems are currently operating, some commercial and several international administrations are considering 'thin-route' communication links for remote areas.

In the 2690–2700 MHz band, sharing between passive sensors operating simultaneously with the Radioastronomy Service is feasible. The feasibility of sharing with the Fixed and Mobile Services in this band will be determined by the extent of their use of the band by 1985. Extensive use is doubtful, however, due to the historical use and vociferous opposition to interference sources by the radio astronomy community.

The interference threshold used to determine sharing feasibility in this band is −166 dBW in a 60 MHz reference bandwidth.

User Requirements and Attainable Measurements

The proposal and allocation in the 2640–2700 MHz band were based on the user requirements for coastal salinity and soil moisture measurements. The sensing parameters that can be accommodated in the allocated bandwidth are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km) Case 1	Resolution (km) (Case 2)	Swath Width (km) Case 1	Swath Width (km) (Case 2)
Ocean Salinity	2 0/00	0.1	60	20		20	
Soil Moisture	1–2%	1.0	60	2	(5)	20	(125)

Sensor parameters accomodated by the 2690–2700 MHz portion of the allocation, which presents less interference potential, are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km) Case 1	Resolution (km) (Case 2)	Swath Width (km) Case 1	Swath Width (km) (Case 2)
Ocean Salinity	2 0/00	0.1	10	110		110	
Soil Moisture	1–2%	1.0	10	2	(5)	4	(20)

Relaxing the ΔT_e requirement would permit additional attainable combinations of spatial resolution and swath width.

Assessment

The secondary status and high probability of extensive interference from primary services limit the usefulness of the allocation to passive sensors in the 2640–2690 MHz band. This band is not recommended for passive sensing. Although little or no interference is expected in the 2690–2700 MHz portion of the band, the limited bandwidth restricts this band's utility. Other nearby bands (1400–1427 and 4200–4400 MHz) providing greater usable bandwidth can be used for the same measurements and are recommended over the 2640–2700 MHz band.

4200–4400 MHz

4200–4400 MHz

Allocation Status

Passive sensors are allocated on a secondary basis by footnote in the 4200–4400 MHz band. This band is also allocated on a secondary basis to the Fixed Service in five countries. The Aeronautical Radionavigation Service has a primary allocation.

Sharing Criteria and Interference Potential

It is specified by footnote that no protection will be provided by radio altimeters to the passive sensors. However, up to 3000 aircraft simultaneously in view of the sensor would not exceed the passive sensor interference threshold, and that number is well above the predicted number of aircraft expected to be in view over coastal and ocean areas.

The feasibility of sharing with transponders associated with the aeronautical radionavigation systems is currently under study, but is not expected to present a problem.

The interference threshold used to determine sharing feasibility is −158 dBW in a 200 MHz reference bandwidth.

User Requirements and Attainable Measurements

The proposal and WARC allocation were based on sea surface temperature measurements in this band. Requirements that can be accommodated by the WARC allocation of 4200–4400 MHz are:

Measurement	Measurement Accuracy	$\Delta T_e(K)$	Band Width (MHz)	Resolution (km) Case 1	(Case 2)	(Case 3)	Swath Width (km) Case 1	(Case 2)	(Case 3)
Sea Surface Temperature	0.5° C	0.3	200	2	(5)	(20)	6	(35)	(600)

Assessment

Due to its larger interference-free bandwidth, this band is the best of the three bands (4.2–4.4, 5 and 6 GHz) usable for sea surface temperature measurements. Sharing is feasible with the radio altimeters in the band. Sharing with the associated transponders is under study. The 4200–4400 GHz band is the only allocated band below 10 GHz with both the adequate bandwidth to meet user requirements and the freedom from harmful interference necessary for passive sensing, and the band is recommended for use. The other recommended band below 10 GHz, 1400–1427 MHz, has too limited a bandwidth to fully meet some required combinations of resolution and swath width.

4950–5000 MHz

4950–5000 MHz

Allocation Status

The 4950–4990 MHz band is allocated to passive sensors on a secondary basis by footnote. The band is allocated to the Fixed and Mobile (except aeronautical) Services on a primary basis and to the Radioastronomy Service on a secondary basis.

The 4990–5000 MHz band is allocated on a primary basis to the Fixed and Mobile (except aeronautical) and Radioastronomy Services. Passive sensors are allocated on a secondary basis.

Sharing Criteria and Interference Potential

Passive sensors have secondary allocation and receive no protection from the primary Fixed and Mobile Services in the 4950–5000 MHz band. Due to the large number and distribution of systems using the band, harmful interference will be encountered by a passive remote sensor in coastal and estuarine areas of North America, South America and large portions of Europe, North Africa and Asia Minor. A single Fixed Service transmitter in this band may result in a 48% data loss.

The interference threshold for determining sharing feasibility is −158 dBW in a 200 MHz reference bandwidth.

User Requirements and Attainable Measurements

In the early development of passive sensor frequency requirements, this band was considered for measuring sea surface temperature. Due to the difficulties of sharing with existing fixed systems, however, the U.S. proposed the 4200–4400 MHz band (discussed earlier) for those measurements. Operating requirements accommodated by the WARC allocation of 4950-5000 MHz are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km) Case 1	Resolution (km) (Case 2)	Swath Width (km) Case 1	Swath Width (km) (Case 2)
Sea Surface Temperature	0.5°C	0.3	50	2	(20)	2	(200)

Relaxing the ΔT_e requirements would permit additional attainable combinations of spatial resolution and swath width.

Assessment

The 4950–5000 MHz secondary allocation provides no protection for passive sensors, and extensive interference is expected from the primary services. Interference and bandwidth considerations make the 4200–4400 MHz allocation superior to this band for the measurement of sea surface temperature; thus the 4950–5000 MHz band is not recommended for passive sensing.

6425–7250 MHz

Allocation Status

From 6425 to 7075 MHz, passive sensors are noted in a footnote as operating over the oceans. In the 7075–7250 MHz region, the same

6425–7250 MHz

footnote indicates that passive measurements are being carried out and 'administrations should bear in mind the needs of the passive sensors.'

The 6425–7075 MHz band is allocated on a primary basis to the Fixed, Mobile and Fixed-Satellite (Earth-to-space) Services. From 7075–7250 MHz, the Fixed and Mobile Services are allocated on a primary basis; portions of this band are allocated by footnote to the Space Research Service (deep space; Earth-to-space), Space Research (near Earth, Earth-to-space) and Space Operations (Earth-to-space).

Sharing Criteria and Interference Potential

In the 6 GHz region, sharing by passive sensors operating simultaneously with the Fixed and Mobile Services is not feasible, since this band is used extensively throughout the United States and in all other regions of the world. The international registration files indicate approximately 5000 worldwide frequency assignments, and each assignment may include multiple transmitters. Many of the systems appear to be line-of-sight microwave links or high-power troposcatter systems, located mostly in the United States, Canada, Uruguay, Argentina, most of Europe and Mexico. The large number of terrestrial transmitters in this frequency band indicates that at least 40–100 terrestrial transmitters will be simultaneously visible to the passive sensor when it is near coastal areas. Although some ocean areas will be free from interference, even open ocean temperature measurements would be subject to extensive interference within line of sight to the sensor, an assessment corroborated by Scanning Multichannel Microwave Radiometer (SMMR) measurements on Seasat and Nimbus 7. One high power transmitter causes a data loss of at least 41%.

The interference threshold for determining sharing feasibility in this band is −158 dBW in a 400 MHz reference bandwidth.

User Requirements and Attainable Measurements

The proposals and WARC allocation in this band were based on sea surface temperature measurements. Operational requirements accommodated by the WARC allocation of 6425–7250 MHz are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km) Case 1	(Case 2)	Swath Width (km) Case 1	(Case 2)
Sea Surface Temperature	0.5°C	0.3	825	2	(20)	24	(2400)

Assessment

The 6425–7075 MHz allocation has more than sufficient bandwidth to accommodate measurement requirements, but the allocation's secondary status and the expected interference over large areas from primary services limits the band's usefulness. However, the band may be useful for passive sensing of some interference-free areas of open ocean.

The 4200–4400 MHz band, as discussed previously, is more useful for sea surface temperature measurements and is recommended over the 7425–7075 band.

10.6–10.7 GHz

10.6–10.7 GHz

Allocation Status

From 10.6 to 10.68 GHz, passive sensors share a primary allocation with the Fixed, Mobile (except aeronautical) and Radioastronomy Services. The Radiolocation Service is allocated on a secondary basis.

In the 10.68 to 10.7 GHz portion, passive sensors and the Radioastronomy Service are allocated on a primary basis. In 27 countries, Fixed and Mobile Services are also allocated primary status but are restricted to equipment in operation prior to January 1, 1985.

Sharing Criteria and Interference Potential

The WARC adopted a footnote that restricts the maximum e.i.r.p. (40 dBW) and power delivered to the antenna of fixed and mobile stations (−3 dBW) in the 10.6–10.68 GHz band, except in 20 countries that have taken exception to the footnote. This restriction makes simultaneous operations feasible except in areas near those excepting countries, which include the USSR, China, Middle East and the Indian Sub-Continent. However, little use is presently made of the 10.6–10.68 GHz band and, even in the excepting countries, significant development of high power fixed and mobile systems is unlikely because the bandwidth is too limited for economically viable systems.

Development of fixed and mobile systems in the little used 10.68–10.7 GHz portion of the band prior to the cutoff date of January 1, 1985 is equally doubtful; thus, the sharing potential in the 10.6–10.7 GHz band is good.

The interference threshold for determining sharing feasibility in this band is −156 dBW in a 100 MHz reference bandwidth.

User Requirements and Attainable Measurements

The proposals and WARC allocation were based on sea state measurements to determine wind speed over oceans and on high rain rate measurements. The operational requirements accommodated by the WARC allocation for the measurements are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km)			Swath Width (km)		
				Case 1	(Case 2)	(Case 3)	Case 1	(Case 2)	(Case 3)
Wind Speed	1.5 m/s	1	100	2	(5)	(20)	8	(50)	(800)
Snow Water Content	2%	1	100	2	(5)		8	(50)	
Rain Rate	20%	1	100	1	(5)		2	(50)	
Ice Morphology	—	1	100	2	(5)	(20)	8	(50)	(800)

Assessment

The 10.6–10.7 GHz band is critical for land and ocean surface measurements.

Restricted e.i.r.p. and power in the Fixed and Mobile Services assures sharing feasibility in and around conforming countries; the small likelihood of development of high power fixed and mobile systems in the remaining areas extends the sharing feasibility worldwide.

The 10.6–10.7 GHz band is recommended for surface measurements by passive sensors.

15.2–15.4 GHz

Allocation Status

15.2–15.4 GHz

The 15.2–15.35 GHz region is allocated to passive sensing on a secondary basis by footnote. The Fixed and Mobile Services have a primary allocation and Space Research has a secondary allocation (for telemetry and telecommand).

The 15.35–15.4 GHz band is allocated to passive sensors and the Radioastronomy Service on a primary basis. A footnote provides a secondary allocation for Fixed and Mobile Services in approximately 20 countries; except for those countries, all emissions in this band are prohibited.

Sharing Criteria and Interference Potential

Since the Fixed and Mobile Services have a primary allocation in the 15.2–15.35 GHz band, they are not obligated to protect passive sensors, which have a secondary allocation. Sharing would not be feasible near developed countries due to the high density and high power of transmitters operating over large geographical areas.

From 15.35 to 15.4 GHz, the primary allocation protects passive sensors from interference. Fixed and mobile units located in the Middle East could cause interference, but those systems have secondary status; in addition, it is unlikely that fixed and mobile systems will be developed for use in this band.

The interference threshold for determining sharing feasibility in this band is –160 dBW in a 200 MHz reference bandwidth.

User Requirements and Attainable Measurements

The proposals and WARC allocation were based on user requirements for water vapor and rain measurements in this band. Operational requirements for these measurements accommodated by the WARC allocation of 15.2–15.4 GHz are:

Measurement	Measurement Accuracy	$\Delta T_e(K)$	Band Width (MHz)	Resolution (km)	Swath Width (km)
Water Vapor	0.3 g/cm^2	0.2	200	7	7
				(over land)	
				20	60
				(over oceans)	
Rain Rate	20%	1.0	200	1	4

Requirements accommodated by the more useful 15.35–15.4 GHz region of the band are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km)	Swath Width (km)
Water Vapor	0.3 g/cm^2	0.2	50	25 (over land)	25
				25 (over oceans)	25
Rain Rate	20%	1.0	50	1	1

Assessment

The 15.2–15.35 GHz portion of the 15.2–15.4 GHz band has limited utility near developed countries due to interference and the secondary status of passive sensors.

From 15.35 to 15.4 GHz, passive sensors have a primary allocation and are protected from interference. With the exception of some Mid-Eastern nations, all emissions in this band are prohibited.

The 15.35–15.4 GHz band is well-suited to passive sensing from an interference standpoint, but the 50 MHz bandwidth is not sufficient for most planned applications using available sensing technology.

18.6–18.8 GHz

Allocation Status

In the 18.6–18.8 GHz band, passive sensors have a primary allocation in Region 2 and a secondary allocation in Regions 1 and 3. The Fixed, Mobile (except aeronautical) and Fixed Satellite (space-to-Earth) Services are allocated on a primary basis in all three regions. **18.6–18.8 GHz**

Sharing Criteria and Interference Potential

A footnote adopted by the WARC requests that stations in the Fixed, Mobile and Fixed-Satellite Services minimize their transmitting power to reduce the risk of interference to passive sensors. The U.S. proposed specific constraints (35 dBW, e.i.r.p., with −3 dBW of maximum transmitter power for the Fixed Service, and −101 dBW/m^2 maximum PFD for the Fixed Satellite Service) at the WARC, which were not adopted. The U.S., however, is expected to adopt these criteria and, as the world's largest telecommunications market, may influence other nations to follow.

Due to economic factors, future systems in the Fixed, Mobile and Fixed-Satellite Services will probably not require power that exceeds the U.S. proposed limits. The CCIR is conducting technical analyses to develop sharing criteria acceptable to all services for the 18.6–18.8 GHz band.

The interference threshold for determining sharing feasibility in this band is −155 dBW in a 200 MHz reference bandwidth.

User Requirements and Attainable Measurements

The proposal and WARC allocation were based on user requirements for rain, sea state (wind speed) and ocean ice morphology measurements in this band. Requirements for each measurement as accommodated by the 18.6–18.8 GHz WARC allocation are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km)			Swath Width (km)		
				Case 1	(Case 2)	(Case 3)	Case 1	(Case 2)	(Case 3)
Wind Speed	1.5 m/s	1.0	200	2	(5)	(20)	16	(100)	(1600)
Ice Morphology	–	1.0	200	2	(5)	(20)	16	(100)	(1600)
Rain Rate	20%	1.0	200	1	(5)		4	(100)	

Assessment

The 18.6–18.8 GHz band is critical for land and ocean surface measurements.

The present electromagnetic environment is conducive to passive sensing. The sharing criteria that the U.S. is expected to adopt, coupled with economic considerations that affect transmitting power designs by shared services throughout the world, are expected to promote an interference-free sensing environment in most areas.

Efforts to develop acceptable worldwide, mandatory sharing criteria in order to insure an interference-free sensing environment are continuing.

21.2–21.4 GHz

Allocation Status

21.2–21.4 GHz

In the 21.2–21.4 GHz band, passive sensors share primary status with the Fixed and Mobile Services.

Sharing Criteria and Interference Potential

All allocated services in this band share equal status, which entitles passive sensors to some protection. Sharing by simultaneously operating passive sensors and the Fixed and Mobile Services is expected to be feasible due to: 1) the low required e.i.r.p. envisioned for digitally encoded fixed and mobile systems operating above 20 GHz; and 2) high atmospheric absorption.

The interference threshold for determining sharing feasibility in this band is –160 dBW in a 200 MHz reference bandwidth.

User Requirements and Attainable Measurements

The proposals and WARC allocation were based on user requirements for water vapor measurements in this band. Sensor parameters accommodated by the WARC allocation of 21.2–21.4 GHz are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km) Case 1	Resolution (km) (Case 2)	Swath Width (km) Case 1	Swath Width (km) (Case 2)
Water Vapor	0.3 g/cm^2	0.2	200	7	(20)	7	(60)

Assessment

Passive sensors share the 21.2–21.4 GHz band with the Fixed and Mobile Services on an equal basis; the sharing is considered feasible. This band is well-suited for atmospheric water vapor measurements and is recommended for passive sensing.

22.21–22.5 GHz

22.21–22.5 GHz

Allocation Status

In the 22.21–22.5 GHz *band, the passive sensors share a primary* allocation with the Fixed, Mobile (except aeronautical) and Radio-astronomy Services.

Sharing Criteria and Interference Potential

Passive sensors and the terrestrial services are allocated on an equal basis and are thus entitled to some protection. However, a footnote states that use of this band by satellite passive sensors shall not impose constraints upon the Fixed and Mobile services. Sharing by simultaneously operating passive sensors and the Fixed and Mobile Services is expected to be feasible due to: 1) the low required e.i.r.p. envisioned for digitally encoded fixed and mobile systems operating above 20 GHz; and 2) high atmospheric absorption.

The interference threshold for determining sharing feasibility in this band is –155 dBW in a 300 MHz reference bandwidth.

User Requirements and Attainable Measurements

The proposal and WARC allocation were based on user requirements for water vapor measurements in this band. Operational requirements accommodated by *the* WARC *allocation* of 22.21–22.5 GHz for water vapor measurements are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km) Case 1	Resolution (km) (Case 2)	Swath Width (km) Case 1	Swath Width (km) (Case 2)
Water Vapor	0.3 g/cm^2	0.2	290	5	(20)	5	(80)

Assessment

Passive sensors sharing the 22.21–22.5 GHz band with the other primary services is considered feasible. This band is suited for atmospheric water vapor measurements and is recommended for passive sensing.

23.6–24.0 GHz

Allocation Status

23.6–24.0 GHz In the 23.6–24.0 GHz band, passive sensors are allocated on a primary basis with the Radioastronomy Service. All emissions are prohibited in this band.

Sharing Criteria and Interference Potential

Since all emissions in this band are prohibited, passive sensors will receive no interference. Sharing with the Radioastronomy Service is, as always, feasible.

User Requirements and Attainable Measurements

The proposal and WARC allocation were based on user requirements for water vapor measurements. The operational requirements for water vapor measurements accommodated by the WARC allocation of 23.6–24.0 GHz are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km)	Swath Width (km)
Water Vapor	0.3 g/m^2	0.2	400	3	3
				(over land)	
				20	120
				(over ocean)	

Assessment

Since emissions are prohibited, the 23.6–24.0 GHz band presents the ultimate in protection to passive sensors. This band is well-suited to atmospheric water vapor measurements and is recommended for passive sensing.

31.3–31.8 GHz

Allocation Status

31.3–31.8 GHz From 31.3 to 31.5 GHz, passive sensors share a primary allocation with the Radioastronomy Service.

From 31.5 to 31.8 GHz, the passive sensors again share a primary allocation with the Radioastronomy Service. In Regions 1 and 3, the

Fixed and Mobile (except aeronautical) Services are allocated on a secondary basis.

Sharing Criteria and Interference Potential

Sharing with the Radioastronomy Services is, as always, feasible. As previously noted for frequencies above 20 GHz, sharing with the Fixed and Mobile Services in the 31.5–31.8 GHz band is feasible.

The interference threshold for determining sharing feasibility in this band is −156 dBW in a 500 MHz reference bandwidth.

User Requirements and Attainable Measurements

The proposal and WARC allocation were based on user requirements for ocean ice morphology measurements. The operational requirements for this measurement as accommodated by the WARC allocation of 31.3–31.8 GHz are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km) Case 1	(Case 2)	(Case 3)	Swath Width (km) Case 1	(Case 2)	(Case 3)
Ice Morphology	–	1.0	500	2	(5)	(20)	40	(250)	(4000)

Assessment

The wide (500 MHz) bandwidth and exclusive allocation in large portions of the band make the 31.3–31.8 GHz band very attractive for passive sensing for land and ocean surface measurements, and it is recommended for that use.

36–37 GHz

Allocation Status

In the 36–37 GHz band, passive sensors share a primary allocation with the Fixed and Mobile Services. **36–37 GHz**

Sharing Criteria and Interference Potential

All services are allocated on a primary basis and thus entitled to some protection. As previously noted, sharing by simultaneously operating passive microwave sensors and the Fixed and Mobile Services is feasible above 20 GHz.

The interference threshold for determining sharing feasibility in this band is −146 dBW in a 2000 MHz reference bandwidth.

User Requirements and Attainable Measurements

The primary measurements in this band are for rain, snow and ocean ice morphology. The operational requirements for these measurements accommodated by the WARC allocation of 36–37 GHz are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km) Case 1	(Case 2)	(Case 3)	Swath Width (km) Case 1	(Case 2)	(Case 3)
Rain Rate	20%	1	1000	1	(5)		5	(125)	
Snow Water Content	2%	1	1000	2			20		
Ice Morphology	–	1	1000	2	(5)	(20)	20	(125)	(2000)

Assessment

The 36–37 GHz band is very important for passive sensing of land and ocean surfaces. The 1000 MHz bandwidth makes it particularly attractive for remote sensing.

50.2–50.4 GHz

Allocation Status

50.2–50.4 GHz

Passive sensors share a primary allocation with the Fixed and Mobile Services in the 50.2–50.4 GHz band.

Sharing Criteria and Interference Potential

All services in this band share primary allocation and are thus entitled to protection. As noted, sharing by sensors operating simultaneously with the Fixed and Mobile Services is feasible above 20 GHz.

The interference threshold for determining sharing feasibility in this band is −157 dBW in a 250 MHz reference bandwidth.

User Requirements and Attainable Measurements

As at other frequencies between 50 and 65 GHz, the primary user requirement in this band is the measurement of oxygen to develop atmospheric temperature profiles. Atmospheric temperature can be measured from the nadir or along the limb path. Operational requirements accommodated by the WARC allocation of 50.2–50.4 GHz are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km)	Swath Width (km)
Atmospheric Temperature, Nadir	1°C	0.3	200	10	Not applicable
Atmospheric Temperature, Limb	1°C	0.3	200	2	Not applicable

Assessment

Frequencies between 50 and 65 GHz are used to determine atmospheric temperature profiles. The 50.2–50.4 GHz band is used by NOAA operational meteorological satellites. Sharing with the Fixed and Mobile Services in the band is feasible and the band is recommended for use.

51.4–59 GHz

51.4–59 GHz

Allocation Status

From 51.4–54.25 and from 58.2–59 GHz, passive sensors have a primary allocation. All emissions are prohibited in both bands.

In the 54.25–58.2 GHz band, passive sensors share primary status with the Fixed, Mobile and Intersatellite Services.

Sharing Criteria and Interference Potential

Since all emissions are prohibited in the 51.4–54.25 and 58.2–59 GHz bands, passive sensors and Radioastronomy have exclusive use of the band and are fully protected. As previously noted, sharing with the Fixed and Mobile Services is feasible in frequencies above 20 GHz. Sharing with the Intersatellite Service is feasible, although intersatellite use at these frequencies is not expected in the near future.

The interference threshold for determining sharing feasibility in this band is −157 dBW in a 250 MHz reference bandwidth.

User Requirements and Attainable Measurements

This band is used to determine atmospheric temperature profiles. User requirements for oxygen measurements are the same as shown in the 50.2–50.4 GHz allocation and repeated here:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km)	Swath Width (km)
Atmospheric Temperature, Nadir	1°C	0.3	200	10	Not applicable
Atmospheric Temperature, Limb	1°C	0.3	200	2	Not applicable

Assessment

This band is critical for determining atmospheric temperature profiles and provides the greatest bandwidth for multi-frequency temperature profiling. Sensors on NOAA meteorological satellites are operating at 53.74, 54.95 and 57.95 GHz. Sharing is feasible and the 51.4–59 GHz band is recommended for use.

64–65 GHz

Allocation Status

64–65 GHz

Passive sensors have a primary allocation in the 64–65 GHz frequency band.

Sharing Criteria and Interference Potential

All emissions are prohibited in the 64–65 GHz band, fully protecting passive sensors.

User Requirements and Attainable Measurements

This band is used in conjunction with several other bands to measure atmospheric temperature profiles. The operating requirements are the same requirements shown for the 50.2–50.4 GHz band.

Assessment

The 64–65 GHz band is suited to obtaining atmospheric temperature profiles at low altitudes. Since all emissions are prohibited, sensors should encounter no interference.

The band is recommended for passive sensing.

86–92 GHz

Allocation Status

86–92 GHz

Passive sensors share a primary allocation with the Radioastronomy Service.

Sharing Criteria and Interference Potential

All emissions in this band are prohibited. As always, passive sensors can share with the Radioastronomy Service.

User Requirements and Attainable Measurements

The primary measurements conducted in this band are for clouds, ice and snow, and the band is particularly useful for geostationary orbit sensors. The operational requirements for these measurements accommodated by the WARC allocation of 86–92 GHz are:

Measurement	Measurement Accuracy	ΔT_e(K)	Band Width (MHz)	Resolution (km) Case 1	(Case 2)	Swath Width (km) Case 1	(Case 2)
Clouds	0.1 g/m^3	1	6000	1	(5)	30	(750)
Ice Morphology	–	1	6000	2	(5)	120	(750)
Snow Water Content	2%	1	6000	2	(5)	120	(750)

Assessment

This is an important band for surface measurements. It has the highest frequency and largest bandwidth of any band likely to be used for surface measurements. Since all emissions are prohibited, it is interference free.

The 86–92 GHz band is recommended for passive sensing.

100 GHz and above

Allocation Status

100 GHz and above

All allocations for passive sensors above 100 GHz are primary allocations (Figure 33). Other primary services with which they share include the Fixed, Mobile, Fixed-Satellite (space-to-Earth), Radioastronomy and Intersatellite Services (see Section II).

Sharing Criteria and Interference Potential

Some of the bands above 100 GHz are allocated exclusively to passive sensors and radio astronomy while others are shared with compatible services, including the Fixed, Mobile, Fixed-Satellite (space-to-Earth) and Intersatellite Services. In the shared bands, expected equipment characteristics, atmospheric absorption and use indicate that sharing with the other allocated services is feasible.

The interference threshold for determining sharing feasibility in these bands is −150 dBW in a 2000 MHz reference bandwidth.

Figure 33

Preferred Frequencies and Allocations For Passive Sensors Above 100 GHz

Preferred Frequency (GHz)	Measurements	Allocations (GHz)
100.49	Nitrous oxide	100–102
110.80	Ozone	105–126
115.27	Carbon monoxide	105–126
118.70	Temperature	105–126
125.61	Nitrous oxide	105–126
150.74	Nitrous oxide	150–151
164.38	Chlorine oxide	164–168
167.20	Chlorine oxide	164–168
175.86	Nitrous oxide	174.5–176.5
183.31	Water vapor	182–185
184.75	Ozone	182–185
200.98	Nitrous oxide	200–202
226.09	Nitrous oxide	217–231
230.54	Carbon monoxide	217–231
235.71	Ozone	235–238
237.15	Ozone	235–238
251.21	Nitrous oxide	250–252
276.33	Nitrous oxide	275–277

ITU, *op cit;* CCIR Report 693, *op cit.*

User Requirements and Attainable Measurements

Figure 29 shows the preferred frequency lines for specific atmospheric measurements by passive sensors. For atmospheric molecular (O_3, NO, CO and ClO) line measurements above 100 GHz, a sensitivity of 0.2 K and a resolution of 2 km are required. For measurements of H_2O (183 GHz) and atmospheric temperature (118 GHz) from a geostationary orbit, a sensitivity of 0.2 K and a resolution of 100 km are required. The WARC allocations accommodated all requirements.

Assessment

Eleven bands are allocated to passive sensors on a primary basis above 100 GHz for 18 line frequency measurements. An additional six bands in unallocated spectrum between 275 and 400 GHz are identified as important for passive sensing for spectral line measurements. The allocations permit critically important measurements of atmospheric temperature, water vapor, ozone and several polluting gases, including nitrous oxide, carbon monoxide, and chlorine oxide. No interference is anticipated in any of these bands and their use for passive sensing is recommended.

C. Assessment of Frequency Bands Allocated For Active Sensors

Allocation Status

Ten bands were allocated for active spaceborne sensors (Figure 34). Eight were allocated on a secondary basis; two bands — at 35 and 78 GHz — are primary allocations. In general, the active sensors share the bands with the Radiolocation and/or Radionavigation Services.

Sharing Criteria and Interference Potential

Analysis of three types of spaceborne radars — imaging (e.g. SAR), scatterometers and altimeters — showed that sharing is not feasible with terrestrial communication services but is feasible with terrestrial radar systems (See *Developing the U.S. Position* in Section II). There are essentially no terrestrial radars now operating above 17 GHz, and few are expected in the near future. There is extensive terrestrial radar use below 17 GHz in the bands allocated to spaceborne radars for active sensing. Although some mutual interference can be expected for short periods of time, the small data loss (less than 1%) that results will be acceptable to sensor operators. Because little harmful interference is expected in anticipated systems, no sharing criteria have been developed. Thus, secondary allocation is no handicap to active sensing in the bands in which terrestrial radar services have primary status.

WARC Results

The WARC allocations accommodated all the active sensor requirements proposed by the U.S.

Figure 34
Preferred Frequencies and Allocations for Active Sensing

Preferred Frequency (Ghz)	Suggested Bandwidth (MHz)	Use	Allocation
Near 1	60	Wave structure; geology	1215–1300 MHz
Near 3	100	Geology	3100–3300 MHz
Near 5	100	Soil moisture	5250–5350 MHz
Near 10	100	Precipitation; wave structure	8550–8650 MHz; 9500–9800 MHz
Near 14	600	Wind; ice; geoid	13.4–14.0 GHz
Near 17	100	Vegetation; snow	17.2–17.3 GHz; 24.05–24.25 GHz
Near 35	100	Snow	35.5–35.6 GHz
Near 76	100	Cloud monitoring	78–79 GHz

ITU, *op cit;* CCIR Report 693, *op cit.*

Assessment
The allocations present a highly useful set of bands that are nearly octavely related. These bands are all recommended for active sensing.

D. Registration Requirements

(This section explains the procedures for registering sensing systems according to national and international regulations.)

To receive the protection from interference that national and international regulations provide, active and passive sensor use of the frequency spectrum must be registered. In addition, active sensors — as transmitters — fall under the requirement that all transmitters be registered. The latter requirement also applies to the spacecraft transmitters used to transmit the accumulated data to an earth station.

Both national and international registration procedures include furnishing a description of system characteristics, some compatibility analysis (coordination), and a proposed timetable for operation. In the United States, the forms for international registration are generally prepared at the same time as those for national registration.

Government agencies have frequency managers who handle the administrative and technical work involved in registration of sensor systems. Within NASA, the Office of Space Tracking and Data Systems (OSTDS/Code T) submits the applications for frequency assignment to the IRAC (Interdepartment Radio Advisory Committee) and other appropriate governing bodies and represents NASA at government meetings. Each NASA center has a frequency manager who initiates the applications and sends them to the OSTDS to submit to the appropriate regulatory agencies. Prior to initiation of requests for frequency support, sensing instruments are coordinated with the Communications Division (Code EC) of the Office of Space and Terrestrial Applications (OSTA) so that the interference potential and suitability of the planned frequency use can be determined.

National Registration

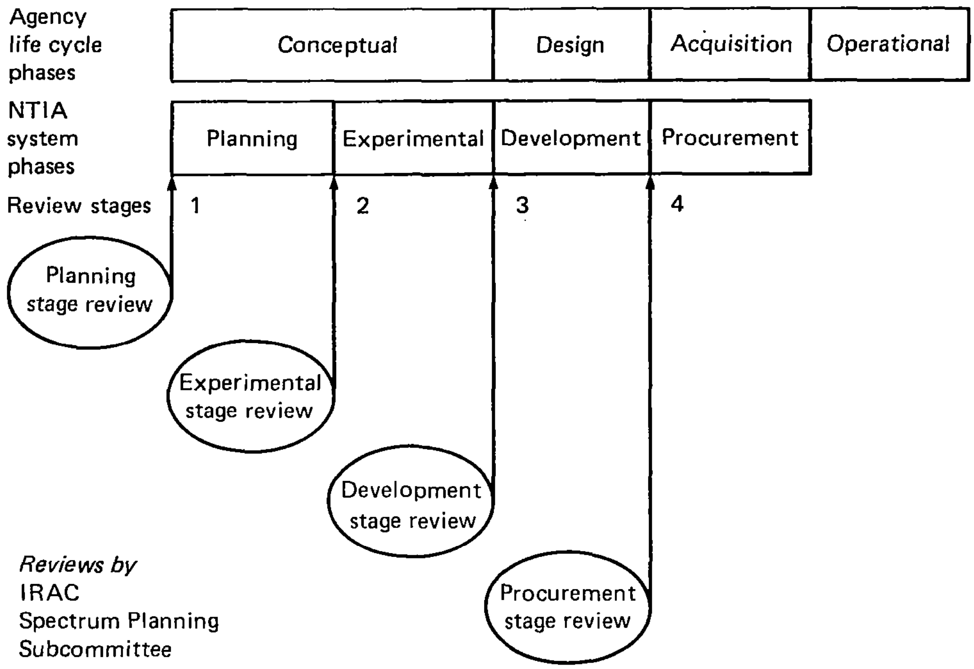
The National Telecommunications and Information Administration (NTIA) conducts frequency registration for government systems through the Interdepartment Radio Advisory Committee (IRAC). Commercial systems are registered through the Federal Communications Commission (FCC).

The registration process for new government telecommunications systems and subsystems, and major changes in technical or operating characteristics of existing systems, begins with a four stage review procedure by the IRAC's Spectrum Planning Subcommittee (SPS). The four reviews correspond to initiation of planning, experimental, development and procurement stages in development of a system (Figure 35). A request for review by the SPS is conveyed by letter explaining the stage of review requested, the system's purpose and a variety of proposed technical and operating characteristics (Figure 36). Section 8.3.6 of the NTIA Manual of Regulations sets out the requirements of each review stage, including corresponding electromagnetic compatibility analyses for each stage. The SPS, which meets semi-monthly to review new government systems, determines the availability of spectrum for these systems. Technical support is supplied to the SPS by the Systems Review Branch of NTIA. The SPS review takes an average of six months, but varies depending upon the compatibility of the frequency requirement with other users in the band. The stage one (planning stage) review must be completed no later than one year prior to the initial date of operation. After reviewing the system, the SPS makes recommendations regarding spectrum supportability to the NTIA, which in turn provides guidance to the requesting agency. In conjunction with the stage 2, 3, and 4 reviews, the Space Systems Group of SPS initiates the advance publication, coordination and notification of space systems within the ITU forum.

After a space system receives system review approval, applications for frequency assignment are sent to the Frequency Assignment Subcommittee (FAS) by the applying agency. The FAS reviews the application for frequency assignment (Figure 37) to ensure that the assignment conforms to national and international regulations and is compatible with existing and planned frequency uses. After reviewing the application, the FAS recommends either approval or disapproval of the assignment to the NTIA. Approved assignments then appear in the Government Master File (GMF).

Because no commercial sensors have been developed to date, the FCC has not yet developed regulations for sensors. Under present regulations, active sensors could be licensed under the experimental licensing rules of the FCC's Frequency Liaison Branch by filing FCC form

Figure 35
Relationship Between NTIA Systems Review And Federal Agency Life Cycle Phases



Buss, Leo A. and Cutts, Robert L., *U.S. National Spectrum Management,* Telecommunications Journal, Volume 47, No. VI, June, 1980, p. 320.

442 (available from the FCC). This registration, however, only permits operation on a non-interference basis, and provides no protection to the active sensor.

There is no domestic procedure within the FCC to protect passive sensors. The United States has a policy of not licensing receive-only stations, although some receive-only earth stations are contained in the FCC data base and are considered when fixed stations are licensed in the same band. In addition, registration of radio astronomy sites is now required by Article 36 of the International Radio Regulations and new procedures to register receive-only sites may be developed by the FCC.

To assure protection for non-government sensors, the FCC would have to establish new rules for both active and passive sensors. New rules may be proposed to the FCC in accordance with Part I, sub-part C of the FCC Rules, *How to File Rulemaking Proceedings.*

International Registration

The International Frequency Registration Board (IFRB) oversees international registration of space systems in accordance with Articles 11 and 13 of the ITU Radio Regulations (formerly Article 9A).

Figure 36
Application Requirements For SPS System Review

1. A cover letter with the following information:

   a. *Stage of Review Requested* – Indicate the stage of review requested.

   b. *Purpose of the System* – Submit for all stages a summary description of the function of the system or subsystem, e.g., collect and disseminate meteorological data using satellite techniques, transmission of radar data for air traffic control, a remote control of ATC radars.

   c. *Information Transfer Requirement* – Submit for all stages the required character, quantities, data rates, and circuit quality/reliability.

   d. *Estimated Termination Date (*where applicable*).*

   e. *Estimated Initial Cost of the System* – This item is for information to show the general size and complexity of the system. It is not intended to be a determining factor in system reviews.

   f. *Target Date* – Submit dates on which spectrum-related decisions must be made relative to system planning, development, procurement and employment.

   g. *System Relationship and Essentiality* – Submit for all stages a statement of the relationship between the proposed system and the function of operation it is intended to support. Include a brief statement of the essentiality to the supported function or operation.

   h. *Replacement Information* – Identify the existing system(s) and associated frequency assignments to be replaced by the proposed system, where applicable.

2. Attachments to the cover letter shall provide:

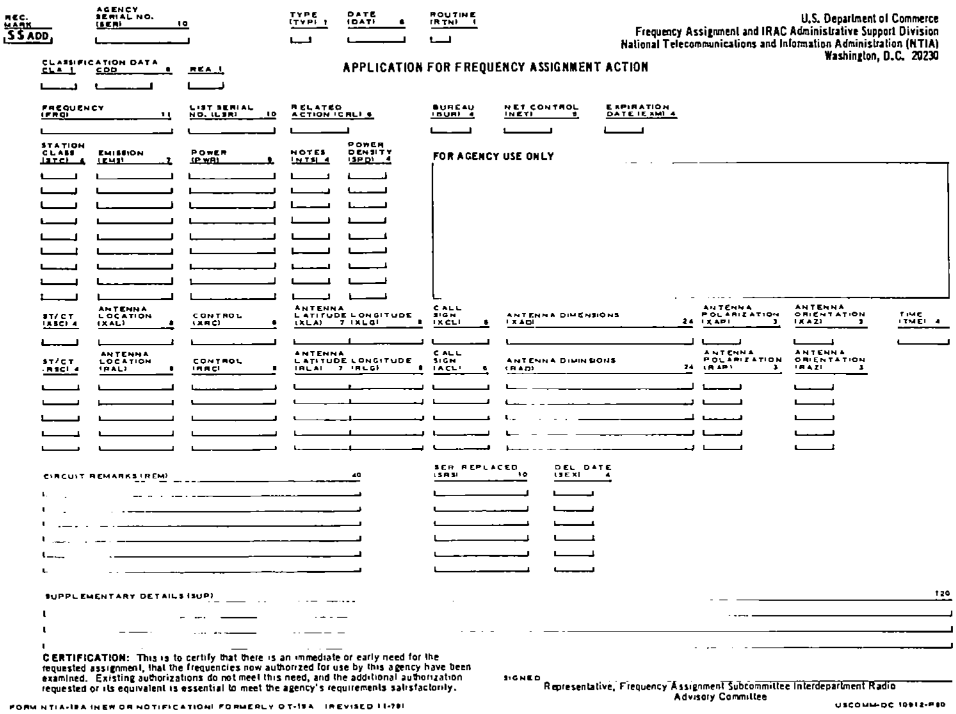
   Attachment 1 – line diagram(s) showing the links, direction of transmission, and frequency band(s).

   Attachment 2 – Space Systems

   a. Stage 1 – the information specified in Appendix 1B to the ITU Radio Regulations. (This information will also be used to comply with the provisions of No. 639AA, ITU Radio Regulations, if appropriate.) Instructions for the provision of information required by Appendix 1B are contained in the *Manual of Instructions for Notifying U.S. Radio Frequency Assignment Data to the International Frequency Registration Board.*

   b. Stages 2, 3, and 4 – the information specified in Appendix 1A to the ITU Radio Regulations submitted on FCC Forms 130A, 130B, 130E, 130S. (This information will also be used to comply with the provisions of Nos. 639AA, 639AJ, 639AN, and 639BA, ITU Radio Regulations, if appropriate.) If FCC Forms 130A, 130B, 130E, and 130S were submitted for a previous review of the same system, and the information is the same, the forms need not be submitted again for a subsequent higher level stage of review. In this case, a reference will be made indicating that FCC Forms 130A, B, E, and S were previously submitted. Instructions for completing these forms are contained in the *Manual of Instructions for Notifying U.S. Radio Frequency Assignment Data to the International Frequency Registration Board.*

Figure 37
Application for Federal Government Frequency Assignment



REC. MARK SS ADD | AGENCY SERIAL NO. (SER) 10 | TYPE (TYP) 1 | DATE (DAT) 6 | ROUTINE (RTN) 1

U.S. Department of Commerce
Frequency Assignment and IRAC Administrative Support Division
National Telecommunications and Information Administration (NTIA)
Washington, D.C. 20230

CLASSIFICATION DATA CLA 1 | CDD 6 | REA 1

APPLICATION FOR FREQUENCY ASSIGNMENT ACTION

FREQUENCY (FRQ) 11 | LIST SERIAL NO. (LSR) 10 | RELATED ACTION (CRL) 6 | BUREAU (BUR) 4 | NET CONTROL (NET) 5 | EXPIRATION DATE (EXM) 4

STATION CLASS (STC) 4 | EMISSION (EMS) 7 | POWER (PWR) 9 | NOTES (NTS) 4 | POWER DENSITY (SPD) 4

FOR AGENCY USE ONLY

ST/CT (XSC) 4 | ANTENNA LOCATION (XAL) 8 | CONTROL (XRC) 8 | ANTENNA LATITUDE (XLA) 7 | LONGITUDE (XLG) 8 | CALL SIGN (XCL) 6 | ANTENNA DIMENSIONS (XAD) 24 | ANTENNA POLARIZATION (XAP) 3 | ANTENNA ORIENTATION (XAZ) 3 | TIME (TME) 4

ST/CT (RSC) 4 | ANTENNA LOCATION (RAL) 8 | CONTROL (RRC) 8 | ANTENNA LATITUDE (RLA) 7 | LONGITUDE (RLG) 8 | CALL SIGN (ACL) 6 | ANTENNA DIMENSIONS (RAD) 24 | ANTENNA POLARIZATION (RAP) 3 | ANTENNA ORIENTATION (RAZ) 3

CIRCUIT REMARKS (REM) 40 | SER REPLACED (SRS) 10 | DEL DATE (SEX) 4

SUPPLEMENTARY DETAILS (SUP) 120

CERTIFICATION: This is to certify that there is an immediate or early need for the requested assignment, that the frequencies now authorized for use by this agency have been examined. Existing authorizations do not meet this need, and the additional authorization requested or its equivalent is essential to meet the agency's requirements satisfactorily.

SIGNED
Representative, Frequency Assignment Subcommittee Interdepartment Radio Advisory Committee

FORM NTIA-19A (NEW OR NOTIFICATION) FORMERLY OT-19A (REVISED 11-78) USCOMM-DC 10912-P80

International registration consists of three steps: advance publication, coordination and notification. Advance publication is initiated when the user supplies the IFRB with the system information specified in Appendix 4 (formerly Appendix 1B) of the Radio Regulations. This information is the same needed to apply to the SPS for national registration; generally, users apply for advance publication during Stage 2 (experimental stage review) of the SPS process. The Radio Regulations require that this information be received between five and two years prior to date of operation. The data are submitted to the Space Systems Group of SPS and, after approval, are forwarded to the IRAC's International Notification Group (ING). The ING, chaired by the FCC, which acts as the U.S. focal point for international notification activities, forwards the data to the IFRB.

Within two months of receiving it, the IFRB publishes the information in its weekly circular. (Subscriptions to IFRB weekly circulars are available from the ITU Secretariat in Geneva, Switzerland.) Following publication, administrations of other nations have four months in which to comment on possible interference to their own space systems. These comments go directly to the initiating body (in this country, the NTIA, via the FCC), with copies to the IFRB. The concerned administrations then resolve their potential interference problem by mutually acceptable adjustments, such as modification of transponder antenna gains or transmitter power. The IFRB is advised of progress every six months.

About six months after the advance publication is circulated, the coordination procedure begins. Coordination determines how closely geostationary satellites in the same band can be located, or how closely terrestrial stations can be placed to earth stations. Appendix 29 coordination deals with inter-satellite interference while Appendix 28 involves the coordination between earth stations and terrestrial stations. Appendix 29 applies only to geostationary satellites and thus does not apply to low-orbit satellites. However, sensor systems on geostationary spacecraft are subject to coordination requirements.

Earth stations for low-orbiting satellites do require coordination with terrestrial stations, which involves forwarding data specified in Radio Regulations Appendix 3 (formerly Appendix 1A) to administrations located in the coordination area according to Appendix 28.

After advance publication and coordination, if appropriate, notification data specified in Appendix 3 are sent to the IFRB. Standard forms for this information are available from the FCC and are normally completed during stages 3 and 4 of the SPS process. NTIA policy requires international notification before it will give a frequency assignment.

Notification data, which differ from the contents of the advance publication, must be submitted between three years and three months prior to beginning operation. This information is published by the IFRB in a weekly circular.

The IFRB performs an examination of the notified data and if it reaches a favorable finding, the space system is registered in the Master International Frequency Register. Comments concerning conformance with the Radio Regulations, interference, or other considerations may accompany the registration.

Within thirty days of the date specified as the first date of operation, the IFRB should receive confirmation of operation.

Notifications can receive favorable findings only if they conform with the Radio Regulations in such matters as operating in allocated bands and conformance with power flux density limits. Out-of-band and other types of non-conforming operations can be notified only on a non-interference basis; this type of registration provides no protection, and any harmful interference caused by such an operation must be eliminated.

E. Use of Non-Allocated Bands and Procedures for Obtaining New Frequency Allocations

(This section describes the reasons for using non-allocated bands and obtaining new allocations.)

The international frequency allocations for remote microwave sensing approved by the 1979 WARC are the result of a complex national and international effort based upon a thorough examination of all the data about physical requirements and sharing considerations available at the time. The advantages of using the allocated bands which resulted from such a comprehensive effort are impressive. They include:

Protection from interference
Suitability for sharing
Sensor uniformity
Development of data bases at specific frequencies
Suitability of the bands for future operational use
Establishment of the need for the allocated bands
Establishment of the credibility and responsibility of the sensor community

Obviously, using non-allocated bands should be a choice of last resort. Such use involves disadvantages directly opposed to the advantages shown above: users of non-allocated bands have no protection against interference, they operate from an inadequate data base, sharing criteria are unknown or untenable, etc.

Despite these difficulties, however, it is likely that users will eventually need to use some non-allocated bands, since remote sensing is a young science in which development of new applications should be expected. The physics governing the science may dictate use of a certain frequency to perform a particular measurement. For example, the requirements of pressure sounding in the atmosphere, of great interest to meteorologists, were not identified in time to be included in preparations for the 1979 WARC. Data since then may indicate a need to use a frequency band that was not allocated.

Under Radio Regulation 342 (formerly Regulation 115), active sensors could operate in non-allocated frequency bands, but would be forced to stop operating if harmful interference is detected. Since passive sensors cannot cause interference, they can operate anywhere in the frequency spectrum. In both cases, however, sensor operators have no protection against interference that could prevent their obtaining meaningful data. The only way to provide that protection is through allocation of the needed frequency band by the ITU and subsequent notification of the actual application. Therefore, the process for obtaining a new frequency allocation should begin immediately whenever the need for a new frequency band is identified.

Experience indicates a series of steps necessary to obtaining desired frequency allocations. The process begins with studies defining usable frequency bands, followed by sharing studies. Proposed allocations of bands that would displace existing services and thereby cause economic or social impact are considerably harder to justify than allocation of bands that can be reasonably shared. Users would have to convince both national and international authorities that impressive social or economic benefits would result from such an allocation.

Technical reports on preferred frequencies and sharing analyses are submitted to the CCIR, the ITU's technical arm. Acceptance of these studies and sharing analyses by the CCIR is a major milestone in the allocation process, since international acceptance of technical requirements is extremely important at an administrative radio conference.

The actual proposals for international frequency allocations are submitted first to national planning bodies (the NTIA and the FCC in the U.S.) as they prepare for the next scheduled WARC competent to deal with the subject. Active participation in the CCIR, national planning processes, international technical planning for the WARC, the WARC itself, and formulation of national regulations is critical to a successful effort. The involved national and international bodies generally make their decisions and recommendations on a consensus basis. A strong advocate in each of the forums is vital to obtain that consensus.

F. Reporting Interference

(This section discusses national and international procedures for reporting interference and their applicability to sensor operators.)

Conventional Reporting of Harmful Interference

Both national and international procedures for dealing with interference begin with identification of the source. In the United States, FCC district offices and monitoring stations can help determine the source of harmful interference. Then, according to Section 8.2.30 of the NTIA manual, government users should contact the operators of the source to try to eliminate the harmful interference. If these efforts are impractical or unsuccessful, government users should report the interference to their agency's frequency manager. The report should include transmission and reception information about the user's station, the source of interference and the receiving station (Figure 38).

Non-government users report harmful interference to the nearest FCC field office. A directory of those offices is included in Volume I, part 0.121 of the FCC Rules and Regulations.

International procedures are contained in Article 22 (formerly Article 15) of the ITU Radio Regulations.

Reporting Interference to Remote Sensors

Because sensor operators cannot identify interference until after the sensor data have been processed and analyzed, they cannot normally identify the source of harmful interference at all. A cooperative effort within the sensor community is necessary to deal with interference to sensor systems.

Government users should supply as much information as they have about the suspected interference — time, date, frequency, geographical locations and any other pertinent facts — to their agency frequency managers. They should also forward a copy of this report to NASA's Communications Division, Code EC-4, so that that office can compile a sensor data base which will help in identifying the source of future interference and in determining levels of acceptable interference. In frequency bands with primary allocations to sensors, protection is

Figure 38

Suggested Information for Interference Report

(from NTIA Manual, Section 8.2.30)

1. Particulars concerning the station causing the interference:
   a. Name or call sign
   b. Frequency measured
   c. Class of emission
   d. Bandwidth
   e. Station class
   f. Bearing
   g. Nature of interference

2. Particulars concerning the transmitting station whose transmissions are being interfered with:
   a. Name or call sign
   b. Frequency assigned
   c. Frequency measured
   d. Class of emission
   e. Bandwidth
   f. Station class
   g. Geographic location

3. Particulars furnished by the receiving station experiencing the interference:
   a. Name or call sign
   b. Station class
   c. Geographic location
   d. Dates and times of occurrence of harmful interference

4. Other supporting data:
   a. Reporting agency
   b. Canadian coordination data
   c. Other information

assured if the sharing criteria are accurate. Such accuracy cannot be determined, however, until a data base sufficient for analysis exists. The data base will also be useful in assessing the adequacy of existing allocations and sharing criteria in preparation for future WARCs.

SECTION IV

NASA TECHNICAL AND CONSULTATION SUPPORT SERVICES

The Communications Division, NASA Headquarters, provides assistance in determining spaceborne remote sensing frequency requirements and performing coordination studies. The work needed to develop the remote sensing frequency allocation requirements described in this handbook, and to develop national and international support for remote sensing allocations at the 1979 WARC, was performed by the Division. In the areas of NASA environmental and resource observation programs, the Communications Division has been assigned specific management responsibilities for radio frequency requirements by NASA's Associate Administrator, Office of Space and Terrestrial Applications (OSTA).

Prior to the submission of requests for frequency assignments through established channels, frequency requirements for OSTA remote sensing projects must be coordinated with the Communications Division. This coordination will help assure that, whenever possible, NASA remote sensing satellites are operating in frequency bands allocated by the 1979 WARC for active and passive microwave sensors and associated data readout frequencies. In this way, sensing operations are protected from harmful interference and from the interruption of operation that occurs when satellites operating in non-allocated bands cause harmful interference and must cease transmitting. In cases in which the allocated bands do not meet mission requirements, the Communications Division can advise NASA managers, engineers and scientists and help them examine alternatives.

Active participation of satellite and sensor developers at the NASA Centers is needed for the Communications Division to discharge its responsibilities. The Communications Division should be included in the early study and development phases of satellite projects involving sensors and frequency use. While the established procedures for applying for frequency assignments through the Center Frequency Managers is unchanged, they should not be initiated until after coordination within OSTA has been accomplished.

The Communications Division maintains a handbook of guidelines to frequencies for sensor use, and a separate sensor handbook which contains descriptions and technical data on all NASA remote sensors. Within resource limitations, the services provided by the Division are available to all of NASA and to other government agencies upon request.

To achieve its own program objectives concerning remote sensing (Figure 39), the Communications Division provides a number of specific

Figure 39

Objectives of the Communications Division's Technical and Consultation Support Services

- Assist sensor developers and program managers within NASA in selecting radio frequency bands and in resolving frequency problems that affect NASA programs.
- Represent the remote sensing community on government telecommunication committees.
- Represent the remote sensing community on international telecommunications committees and at world administrative radio conferences.
- Provide understanding and analysis of spectrum requirements for remote sensing satellites and remote sensors.
- Analyze the sharing potential between remote sensors and other radio services operating in common frequency bands.
- Develop frequency allocation and sharing criteria requirements.

services. The Division performs frequency selection analyses and interference analyses, and prepares frequency use plans. During the frequency assignment process, the Division will provide compatibility analyses and make presentations to the appropriate IRAC Committees (SPS, FAS, and TSC). When necessary, the Division develops responses to proposals for frequency assignments for non-sensor transmission in bands allocated to remote sensing.

The Communications Division maintains a close working relationship with the NASA Frequency Management Office (NASA HQ Code TS) and represents much of the sensing community on government telecommunications committees such as the IRAC ad hoc committee responsible for domestic implementation of the Final Acts of the 1979 WARC. The Communications Division also provides representation for much of the sensor community on international telecommunications committees and at radio conferences. This representation entails introducing frequency requirements and sharing criteria into the International Radio Consultative Committee (CCIR), and participating in the development of protection criteria acceptable to both the sensor community and other radio services sharing the same bands or operating in adjacent bands. Criteria for adjacent band protection, for example, currently concern development of filter characteristics for both remote sensors and broadcasting satellites that would protect sensors operating in bands adjacent to the broadcasting satellites.

For future WARCs, the Division will develop and document sensing requirements (frequencies, bandwidths, protection criteria) which appear appropriate for inclusion in the Radio Regulations, present and support those requirements on U.S. WARC preparatory committees, and participate in developing U.S. proposals and position papers for the WARC. The Communications Division, with State Department authorization, will represent remote sensing interests at these conferences.

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Technical Officer: John W. Kiebler

16. Abstract This handbook was developed to provide information and support to the spaceborne remote sensing and frequency management communities: to guide sensor developers in the choice of frequencies; to advise regulators on sensor technology needs and sharing potential; to present sharing analysis models and, through example, methods for determining sensor sharing feasibility; to introduce developers to the regulatory process; to create awareness of proper assignment procedures; to present sensor allocations adopted at the 1979 World Administrative Radio Conference (WARC); and to provide guidelines on the use and limitations of allocated bands.

This book is organized in three principal sections. The Background Information section discusses controlling physical factors and user requirements, the regulatory environment, developing the U.S. position for the 1979 WARC, and 1979 WARC results and remaining issues. The Guidelines section presents each sensor frequency allocation, reviewing its achievable performance and usefulness. Procedures for national and international registration, the use of non-allocated bands and steps for obtaining new frequency allocations, and procedures for reporting interference are discussed. The NASA Technical Consultation Support Services section describes the technical and consultation support services provided to the sensor community by NASA's Communications Division.

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