NASS- 23434
Mod 7..
Systematics General

FREQUENCY BAND JUSTIFICATIONS FOR PASSIVE SENSORS

1 to 10 GHz

(NASA-CR-155531) FREQUENCY BAND JUSTIFICATIONS FOR PASSIVE SENSORS, 1 TO 10 GHz (Systematics General Corp., McLean, Va.) 218 p HC A10/MF A01 CSCL 17B N78-15327
Unclas G3/32 58012

December 1976

NASA

National Aeronautics and Space Administration

Washington, D.C. 20546

FREQUENCY BAND JUSTIFICATIONS FOR PASSIVE SENSORS

1 to 10 GHz

December 1976

NASA

National Aeronautics and Space Administration

Washington, D C 20546

PREFACE

This document presents the frequency allocation requirements for passive sensors utilized in the Earth Exploration Satellite and the Space Research Services. The document is organized into Chapters I and II, Parts A and B.

Chapter I, Part A presents the applications and, in some cases, potential benefits which are applicable to various microwave remote measurements. Since measurements are required simultaneously in multiple frequency bands to adequately determine values of some phenomena, these relationships between frequency bands are presented. The various measurement accuracies, dynamic range, resolutions and frequency needs are also discussed.

Chapter I, Part B presents a band-by-band summary of requirements, unique aspects and sharing analyses of the required frequency bands for passive sensors.

Chapter II, Part A discusses sensitivity requirements of the various measurements and microwave radiometry techniques while Part B provides the detailed band-by-band sharing analyses.

In addition, Appendices I-IV, describe the analytical techniques applied to the detailed sharing analyses. Appendix V, presents a bibliography of publications pertinent to the scientific justification of the frequency requirements for passive microwave remote sensing.

TABLE OF CONTENTS

CHAPTER I — Page

PART A - FREQUENCY BAND REQUIREMENTS -------------------- IA-1

1. INTRODUCTION ------------------------------------ IA-3
2. APPLICATIONS AND MEASUREMENTS ------------------- IA-5
   2.1 Agriculture, Forestry and Range Resources -- IA-5
   2.2 Land Use Survey and Mapping ---------------- IA-10
   2.3 Water Resources ---------------------------- IA-12
   2.4 Weather and Climate ------------------------ IA-15
   2.5 Environmental Quality ---------------------- IA-26
   2.6 Marine Resources, Estuarine and Oceans ----- IA-30
   2.7 Summary ------------------------------------ IA-41
3. MEASUREMENT CONSIDERATIONS AND FREQUENCY REQUIREMENTS ------------------------------------ IA-43

PART B - SUMMARY OF REQUIREMENTS, UNIQUE ASPECTS AND SHARING ANALYSES OF REQUIRED FREQUENCY BANDS ------------ IB-1

SECTION 1 - FREQUENCY BAND 1.3-1.427 GHz --------------- IB-1-1
SECTION 2 - FREQUENCY BAND 2.640-2.700 GHz ------------- IB-2-1
SECTION 3 - FREQUENCY BAND 4.950-5.000 GHz ------------- IB-3-1
SECTION 4 - FREQUENCY BAND 6.425-7.250 GHz ------------- IB-4-1

CHAPTER II

PART A - MICROWAVE RADIOMETRY --------------------------- IIA-1

PART B - USER REQUIREMENTS AND DETAILED SHARING ANALYSES - IIB-1

SECTION 1 - FREQUENCY BAND 1.300-1.427 GHz ------------- IIB-1-1
SECTION 2 - FREQUENCY BAND 2.640-2.700 GHz ------------- IIB-2-1
SECTION 3 - FREQUENCY BAND 4.950-5.000 GHz ------------- IIB-3-1
SECTION 4 - FREQUENCY BAND 6.425-7.250 GHz ------------- IIB-4-1

APPENDIX I - GAIN-RANGE QUOTIENT ANALYSIS ------------- X-1
APPENDIX II - RANDOM INTERFERENCE ANALYSIS PROGRAM ----- X-7
APPENDIX III - ANTENNA PATTERNS ------------------------ X-11
APPENDIX IV - INTER-SATELLITE SYSTEM DEVELOPMENTS ------ X-15
APPENDIX V - BIBLIOGRAPHY ----------------------------- X-35

LIST OF FIGURES

FIGURE		PAGE
1 -	Zenith Attenuation vs. Frequency	IIA-4
2 -	Theoretical vertical one-way attenuation from specified height to top of the atmosphere for a moderate humid atmosphere (7.5 g/m^3 at the surface)	IIA-6
3 -	Temperature Weighting Functions	IIA-8
4 -	Water Vapor Weighting Functions	IIA-9
5 -	Attenuation Coefficient for Liquid-Water Scatterers	IIA-10
6 -	Attenuation Coefficient for Ice Scatters (Spherical)	IIA-11
7 -	Scattering Albedo vs. Frequency	IIA-13
8 -	Change in Brightness Temperature with Salinity	IIA-15
9 -	Change in Brightness Temperature with Surface Temperature	IIA-16
10 -	Change in Brightness Temperature with Wind Speed	IIA-17
11 -	Brightness Temperatures of Ice at Various Frequencies	IIA-19
12 -	Apparent Temperature of a Uniformly Vegetated Smooth Surface for Various Frequencies	IIA-20
13 -	Measured Dry Snow Brightness Temperatures at Various Frequencies and Polarizations	IIA-21
1-1 -	Loss of Coverage Area Due to Single High Power Emitter - Fixed and Mobile Service	IIB-1-10
1-2 -	Loss of Coverage Area Due to Single Medium Power Emitter - Fixed and Mobile Service	IIB-1-11
1-3 -	Loss of Coverage Area Due to Single Low Power Emitter - Fixed and Mobile Service	IIB-1-12
1-4 -	Data Loss vs. Number of Fixed and Mobile Stations	IIB-1-13
1-5 -	Loss of Coverage Area Due to Fixed and Mobile, and Aeronautical Radionavigation	IIB-1-14
2-1 -	Distribution of Channel G and H ITFS Systems in the U.S.	IIB-2-4
2-2 -	Data Loss vs. Number of ITFS Stations Visible	IIB-2-6
2-3 -	Loss of Coverage Area for Salinity Measurements Due to ITFS Operation	IIB-2-8
2-4 -	Data Loss vs. Number of Fixed and Mobile Stations Visible	IIB-2-11
2-5 -	Location of Tropospheric Scatter Systems in IFRB Listing	IIB-2-12
2-6 -	Loss of Coverage Area for Coastal Salinity or Soil Moisture Measurements Due to Tropo-Scatter Systems	IIB-2-14

PRECEDING PAGE BLANK NOT FILMED

LIST OF FIGURES (cont.)

FIGURE			PAGE
2-7	-	Multibeam Time Zone Coverage of a Typical Broadcast-Satellite ------------------------------	IIB-2-20
2-8	-	Loss of Coverage Area Due to Fixed Satellite Earth Station Operations (Control Station) ------	IIB-2-24
3-1	-	Number of Terrestrial Systems Transmitting vs. Data Loss ------------------------------------	IIB-3-6
3-2	-	Approximate Loss of Coverage for Estuarine Surface Temperature Measurements -----------------	IIB-3-7
4-1	-	Approximate Loss of Coverage Area for Sea Surface Temperature Measurements ------------------------	IIB-4-6

CHAPTER I

PART A

FREQUENCY BAND REQUIREMENTS

1. INTRODUCTION

Some of the most difficult problems facing humanity today are the assuring of adequate supplies of food and energy, while at the same time improving and safeguarding the physical environment and the quality of life. The use of remote sensor observations from experimental and operational aircraft and spacecraft platforms is assisting in the solution of these problems by providing data on phenomena that affect the earth and its environment.

Technological advances in the state-of-the-art in remote sensor systems in recent years, coupled with the desire for greater information on the earth, its oceans, and atmosphere, have led to the development and increasing use of a new generation of remote sensor systems operating in the microwave region of the frequency spectrum. These new sensors, called passive microwave sensors, have the capability of providing information heretofore unobtainable with basic imaging techniques such as photography, television, or multispectral imaging used in past remote observations.

In addition to measuring phenomena and collecting data on a number of phenomena important in studies of the earth, oceans and atmosphere, passive microwave sensors can successfully make measurements in virtually any weather conditions, through clouds and during both day and night time periods. Such measurements are possible since the microwave emissions from the atmosphere, and land and ocean surfaces are frequency-dependent. Furthermore, more economical and repetitive measurements can be made over larger geographical areas using spaceborne microwave passive sensors than with the limited, more costly, techniques currently employed.

Passive microwave sensors can provide the quantitative and qualitative data needed by scientists, engineers, managers and users to help solve mankinds' truly great and pressing problems. Microwave applications are numerous, and the information acquired from the microwave passive sensor data can be used for improving and protecting earth and water resources; planning, preserving and utilizing land resources; and monitoring the environment. More specifically, the data from passive microwave sensors can be used for predicting the weather and long-term climatology changes for detecting, quantifying and monitoring water and atmospheric pollution; and for understanding the earth, ocean and atmospheric dynamics. Each of these is important to the sustenance of life on our planet, and space technology and microwave remote sensors can make significant contributions toward this important objective.

2. APPLICATIONS AND MEASUREMENTS

Experiments conducted with passive microwave sensors have indicated specific applications areas which may benefit from analysis of the data acquired with passive microwave sensing observations. These include:

1) Agriculture, Forestry and Range Resources
2) Land Use Survey and Mapping
3) Water Resources
4) Weather and Climate
5) Environmental Quality
6) Marine Resources, Estuaries and Oceans

In the following paragraphs of this section, specific user needs and problem areas of concern are addressed, along with economic benefits and measurement phenomena, to exemplify the important contributions of spaceborne passive microwave observations in solving many of the problems of the earth.

2.1 Agriculture, Forestry and Range Resources

The need for agricultural, forest and range resources to satisfy a growing population generally have been met throughout history, through intensive development of the available land and through technology advances. To keep up with the worlds' population growth and expanding demands, mankind will have to depend on continued technological progress and further development of land resources. Earth-oriented satellites with advanced sensor systems offer an opportunity to provide potential users with informative and useful data concerning world agriculture, forest and range resources.

Agriculture, forestry and range applications are concerned with the planning of land use for food and fiber production, and the management of those resources for the ultimate benefit of producers and users.

Remote sensing technology can assist in the efficient management of the nation's renewable food and fiber resources and provide relevant information on world-wide agricultural conditions. Timely inventory and production estimates are critical to the distribution and consumption of food and fiber resources. Such estimates require knowledge of not only the types, amounts and location of specific commodities of interest, but information regarding the factors which influence the eventual quality and quantity of the output. These factors include the physical conditions of the plants, such as vigor, density, damage, disease and maturity; and environmental parameters such as availability of water, soil type, moisture, salinity and insect infestations.

Potential applications of satellite data in forest management include inventories of forest type, timber volumes by species and size, inventory of logging residues, and evaluation of forest stresses such as insects, diseases and pollution damage. Other potential applications for range management are vegetation mapping, forage production estimation, monitoring effects of range fires, and encroachment of undesirable vegetation.

The annual economic benefits which may be realized by improving crop forecasts, based on yielding better distribution and import/export decisions, is estimated to be from $247 million to $549 million dollars; while the savings for improving rangeland management, timber harvest management and multiple use allocations are reported to be $54.5 million annually.

Continued advancements in sensor technology should provide capabilities for more frequent coverage, increased resolution, and better sensor signature identification to assure maximum user participation. Passive microwave sensors can provide data on several phenomena which will directly contribute to our i formation needs in this application area. For example, mea ments of soil moisture and rain would be invaluable data for farmers, hydrologists, meteorologists and a variety of other users.

The moisture content of the surface soil layer is a key factor in the determination of plant growth and must be known for the effective mangement of crop production and for use as an input to crop yield forecasts. An accurate knowledge of the soil moisture will allow foresters and agronomists to manage crop irrigation and to provide more accurate forecasts of food and forest production. As an indication of the value of conserving moisture or of utilizing an economical irrigation program, it is estimated that the conservation of an additional inch of available water in the state of North Dakota during the growing season could provide $100 million in direct benefits through increased crop production, plus an additional $200 million in indirect income within the state economy.* In addition, moisture content is a prime determinant of the way water is utilized in water sheds and hydrologists must be knowledgeable of this parameter for the management of consumable water, hydroelectric power and for the preparation of flood forecasts.

The production of crops such as corn, sorghum, sugar beets, wheat and potatoes, and the utilization by beef of marginal land, can be increased by more than 30 times** by irrigation. In many regions, irrigation water is provided by underwater aquifiers. If the underwater aquifiers are not replenished, the resource will be depleted. By adequately monitoring soil moisture over a region, irrigation may be scheduled to maximize its effectiveness and conserve valuable water resources. A limited number of programs to schedule irrigation using soil moisture measurements are currently underway. These programs have reduced water consumption by one third in comparison with irrigation on a fixed time schedule -- an

*The Effects of Added Rainfall During the Growing Season in North Dakota, North Dakota State University, June 30, 1974.

**W. E. Splinter "Center-Pivot Irrigation", Scientific American 234, No. 6, 90-00 (June 1976).

estimated potential savings of $100 million annually. The use of spaceborne microwave systems for soil moisture measurements provides a means for management of water resources on a global basis.

The results of previous application studies, and stated user requirements, have identified the measurement parameters considered desirable for obtaining the needed soil moisture data. The repeat coverage needs for soil moisture measurements are one per day with an accuracy goal of 2 percent and a spatial resolution of 2-5 km. The optimum frequencies for soil moisture measurements using passive microwave techniques are in the 1.4 and 2.7 GHz regions. A range of 0-30 percent (dry weight) has been established as the measurement objective.

Rain is another important factor for the agriculture, forestry and range resources management, and measurements from passive microwave sensors can provide much useful data. Rain measurements are also directly associated with soil moisture. Based on user information and measurement studies of rain using microwave sensing techniques, the stated accuracy and resolution requirements for rain measurements are 20 percent and 1 km, respectively. The desired measurement range is from 0-100 mm/hr with a required update rate being from once per hour to once per day. For optimum rain measurements, multiple frequency measurements are needed at the frequencies of 10.7, 15.5, 19.9 and 37 GHz in order to measure different rain rates and achieve the desired 0-100 mm/hr dynamic measurement range.

2.2 Land Use Survey and Mapping

Recent years have seen a growing realization that land is a valuable resource, finite in amount, and that, in the public interest, there should be better planning of the manner in which land is used now and in the future. Some examples of concern are: whether land that is suitable for growing food should be be developed for alternate uses; whether sufficient land is being reserved for parks or other public uses; where to locate power plants, with due consideration for the effects that plants will have on the locality, and for the needs of plants, such as cooling water and access to fuel; and what the long term effects of converting wetlands to human use are.

For land resource management, satellite data may be applied to the inventorying of agriculture land-use, forest type mapping, suburban and urban mapping, soil erosion studies, cartographic mapping, identification and measurement of wetlands, and pollution mapping.

Land applications are concerned with the inventory of land use as an aid in planning for the most effective use of the land and other resources. It involves the production of land use and other thematic maps and charts, and statistical inventory information along with appropriate prediction models that provide information to a variety of users. Such information will be of use to many international, federal, state, and local agencies, and private and public institutions. The degree of usefulness will be dependent upon the availability, accuracy and timeliness of the information. According to land use planners, the current limiting factor in the process of effective land use management and planning is the timely acquisition of relevant data. Specifically, data gathered by current means have limited usefulnesss in the land use planning process because of incomplete coverage, inappropriate scale, poor reliability or lack of timeliness.

Land use planners have estimated that it would cost states, regional authorities and cities approximately $250 million per year over the next decade if conventional means are used for collecting land use information. Remote sensing systems could supply the necessary information at significantly lower cost. For example, recent economic studies in land use planning indicate that economic benefits attributable to satellites over alternative data gathering systems would be in the range from $7.9 to $17 million annually.

Although many of the information needs of users and land use planners can be satisfied with visible and near infrared measurements, the information obtainable by microwave sensors, with the high resolution, all weather, day/night capability they offer, is desired.

The multiple frequency measurement by passive microwave sensors will assist in land mapping and cartography. Lower frequency measurements will provide specific information for vegetation-free cartographic mapping, whereas the higher frequencies will enable differentiation between vegetation zones, non-vegetation and vegetation density. Such information can be closely tied to the determination of land types such as forest or wooded areas, mountain areas, roads, cities, park land, etc., which are primary use designations required by land-use planners.

2.3 Water Resources

Fresh water is one of the nation's most important assets. It is a renewable resource, but must be wisely conserved if we are to have adequate supplies to meet increasing demands. Sound management of water utilization is also necessary if we are not to affect our environmental and ecological balances.

Water quality and water use data are collected throughout the nation by many agencies, for use in water resources management and operational programs.

Water resources applications are concerned with managing the development, use and conservation of water to assure availability for power generation, irrigation, industrial use, municipal water supply and recreation. Included in this application area are water run-off predictions for flood prediction, hydroelectric power generation, irrigation and water consumption management.

The primary application of remote sensing is to provide information for developing and improving hydrologic models. This includes locating ground water discharges and underground sources; monitoring lake and river ice, monitoring lakes, river, and reservoir water quality, assessing flood damage, mapping flood plains, watershed mapping and modeling, snow mapping and monitoring, wetlands mapping and monitoring, and surveying waterways for navigational hazards.

The potential economic benefits of remote sensing from space have been documented in recent studies. For example, it has been estimated that the annual cost savings and increased value in power generation and agricultural water supply based on improved water run-off forecasts would approximate $54.6 million annually.

Passive microwave sensors can make important contributions in this application area. Sensor measurement techniques can be used to determine precipitation volumes, water content, snow melt rate, and changes in soil moisture. Each of those can be important. For example, snow represents a vast hydrologic resource. In the Western United States, up to 80 percent of the usable water comes from snow melt. Snow melt provides the water resource for hydro-electric power generation, irrigation, industrial use, public consumption, and recreation. Accurate monitoring of the amount of water in the snowpack and the rate of release is required for streamflow forecasting. Adequate streamflow forecasts during snow melt are required for the management of reservoir levels to store water and prevent flooding.

In regions where the primary water resource is snowmelt, water that is lost due to inadequate storage facility management cannot be recovered for future use. Remote means are required to determine snow water content and the amount of water within the snow pack. These measurements must be made separately for each drainage basin. Satellite borne radiometers with a 2-5 km spatial resolution are required to provide the service on a global basis.

Multiple frequency measurements are desired for snow depth, extent and water content measurements. The desired frequencies for passive microwave sensing of snow include 1.4, 2.7, 10.7, 19.9 and 37 GHz. Users have indicated an update rate of one per day with an accuracy of 2 percent, and a range from 0-20 percent free water content.

Lake ice measurements represent another potential information source for water resource scientists, managers, and users. Large lakes such as the Great Lakes are valuable national resources, not only as water sources, but as key transportation routes for bulk commodities. In northern regions, the lakes may be frozen for a significant period of time, a factor which limits their usefulness. A better understanding of the lake ice morphology is necessary to develop techniques to extend the shipping season; an extension of the St. Lawrence Seaway season for even a few weeks would have a significant economic impact.* Remote observations of the thickness and structural changes in the ice are required to forecast ice breakup and weak points for ice breakers. Microwave radiometers provide a means of sensing the structural properties of the ice under both clear and cloudy conditions,** thus providing a means for the effective management of this aspect of water resources. The spatial resolution required for measurements is 2-5 km, with a daily update rate.

2.4 Weather and Climate

The use of satellites in the observation and prediction of the earth's weather represents one of the earliest of all space applications. Many advances have been made in long range weather and climate forecasting and weather hazard prediction on the basis of the satellite acquired data, but significant improvements in this discipline area can be realized through microwave remote sensor systems capable of performing long term observations.

---

* Helewicz, J., 1976: "Arctec Would Corral Sea Ice", The Baltimore Sun, June 27, 1976 (Section K).

** J. C. Blinn, III, "Microwave Measurements of Ice Thickness", Environmental Research & Technology, Inc., Final Report JPL Contract 953748, Concord, Mass. 01742, February 1975.

Long range predictions are now receiving much attention, and their importance justifies continued emphasis. Information from satellite systems, combined with earth-based observations, will make it possible to monitor, on a long-term basis, many of the physcial factors considered by climatologists to be critical in establishing the mean and statistical states of the atmosphere. Many of these factors are manifested in effects on the radiation balance of the land-ocean-atmosphere system -- included are the measurement of solar radiation, the determination of the earth's radiant energy retention capability (albedo), the measurement of outgoing infrared emissions, and the heat content of the mixing layer at the surface of the oceans. These measurements will ultimately be needed to relate the earth's energy budget to measurements of the states of the atmosphere, such as the nature and the distribution of cloud cover, and the vertical structure of temperature and water vapor.

Prediction of local weather for periods of up to two hours is also becoming increasingly important to the decision-making processes of a wide variety of users in the construction, off-shore drilling and other industries. Knowledge of weather and climate also is essential in assuring adequate food supplies. For example, prediction of soil moisture, rainfall, snow, snow melt and run-off would be useful in agriculture and hydrology.

The wide demand for present weather data and the willingness of users to invest in the necessary ground equipment has been demonstrated by the extensive use of the Automatic Picture Transmission (APT) system, now part of the NOAA satellite series. Over 1000 users purchased or constructed specialized ground equipment in order to receive APT pictures. This represents a total voluntary expenditure of approximately $10 million. Because this information is obtained from low altitude satellites, it is available at any given location about twice daily. The continuous flow of data from planned geostationary satellite systems could increase many fold the availability of present weather information. The requirement for rapid response essentially precludes the centralized processing now in use. Many users will need low-cost receiving and processing terminals of their own. An advanced geostationary satellite, with high resolution imaging and sounding capability (for which the technology is being developed), would permit such applications.

New needs and economic benefits related to weather and climate prediction are much broader than heretofore believed, and involve a much broader range of users than just the weather forecasting community. The weather not only affects individuals on a daily basis, but affects groups of users as well. For example, in agriculture, farmers throughout the world are concerned with weather and a number of decisions are made by farmers daily regarding planting, spraying, irrigating, plowing and harvesting. In a localized case study, it was found that the economic benefits to hay users in the state of Wisconsin alone was $88 million per year. These figures are based on optimum predictions and decisions that are weather dependent. Another example is the highway construction industry which needs accurate predictions for decisions such as when to pour concrete, do earth work and when construction workers cannot work due to weather conditions.

In another benefit study, cargo and shipping losses caused by weather were estimated to be $500 million annually. Representatives of the maritime community involved in the study concluded that improved wave and weather forecasts, which space systems might make possible, could permit important reductions in these losses. They further concluded that improved routing which space-based navigation could make possible, would permit important additional savings in the $450 million fuel cost currently experienced in transatlantic service by the U.S. flag fleet. World-wide, such benefits could be accrued by all shipping nations.

Weather and climate applications include the three major areas of: 1) Weather Prediction, 2) Climate Monitoring and Prediction, and 3) Weather Danger and Disaster Warning. Remote sensing techniques can be used to determine the actual structure of the atmosphere globally which, when supplemented by simulation techniques, models and other observations, will provide the required data for weather forecasts. Other applications include monitoring indicators of regional and global climate changes, including solar inpout, radiation budget, ocean-atmosphere interactions and atmospheric gas and particulate variability. For Weather Danger and Disaster Warning, remote sensing systems can be used for continuous observations of atmospheric features to permit early identification and quantitative measurement of atmospheric conditions condusive to the formation of tornadoes, thunderstorms and hurricanes.

Important measurement parameters that microwave sensing systems can contribute to the weather and climate applications are discussed in the following paragraphs along with the specific requirements.

Microwave observations at frequencies below 30 GHz are relatively insensitive to clouds and are useful for surface observations under both clear and cloudy conditions. Clouds, especially large areas of stratiform clouds, are detectable at higher microwave frequencies; these cloud observations are required for use in weather and climate forecasts. The effects of clouds on measurements made at the higher microwave frequencies must also be known in order to interpret the measurements correctly.

Cloudiness provides a tracer of atmospheric motion; it is important for studying climatic changes and is an important input for studies of atmospheric dynamics. Information on cloudiness is equally important for the development of future short-range forecasting schemes. Current infrared temperature sounding systems are adversely affected by clouds, and information from combined microwave and infrared sensors are required to interpret the data adequately in order to provide temperature profiles.

Cloud measurement requirements specified by users include a desired range of 0-3 $gm/m^2/km$ and an accuracy of 0.3 $gm/m^2/km$. A spatial resolution of 1 km is required. The desired frequencies for passive sensing are 37 and 90 GHz, and update information is needed every 6 hours. A number of competing effects which must be corrected for are soil moisture, snow, lake ice, sea state, surface temperature, water vapor and atmospheric temperature.

Rain is another important phenomena that can be measured by passive microwave sensors. Rain is an important water resource for agriculture and provides water for industrial use, public consumption, and recreation; it can also represent a potential hazard due to flooding. Rain is an important tracer of atmospheric processes, and provides an indication of the latent heat energy release that drives atmospheric circulation. Rainfall data are required overland for water management and over the oceans for weather and climate forecasts.

The accurate measurement of rainfall on a global basis is possible using multifrequency microwave radiometers that provide nearly constant surveillance of all areas.* Observations of rain as a tracer of atmospheric dynamics can be routinely made using microwave observations both overland and over the oceans. These latter measurements are required only one to four times per day for input to weather forecasting schemes.

Multiple frequency measurements for differing rain rates are desired. Measurements can be performed at 10.7, 15.5, 19.9 and 37 GHz. The user requirements include an overall range requirement of 0-100 mm/hr with a 20 percent accuracy. A spatial resolution of 1 km is desired with an update rate of once per hour to once per day. Other parameters or effects relating to these measurements include soil moisture, snow, lake ice, sea state and surface temperature.

Water vapor also plays an important role in the energetics of the atmosphere and climate behavior. Water vapor profile measurements are required for short-range forecasts, and total integrated water content measurements are required for long-range and climatological forecasts.

*Radiometric measurements at a single frequency have a limited dynamic range. To extend the dynamic range simultaneous measurements must be made at a number of frequencies between 10 and 37 GHz. If overland measurements are to be made, observations should be made at even lower frequencies.

Water vapor profiles may be remotely measured by either infrared or microwave radiometers. Microwave radiometers provide the only means for making observations during periods of cloudiness. For adequate inversion or interpretation of the microwave water vapor observations, radiometric measurement of cloud water content is also required. Also, since absorption and emission by atmospheric water vapor occurs with varying intensity over the entire microwave frequency region, observations of the surface at other frequencies are affected by water vapor, and measurements of at least the total precipitable water are required for the correction of other measurements.

There are classes of satellite observation systems that are required for weather and climate applications. Low orbiting satellite observations with downward (nadir) viewing radiometers in the 15-32 GHz range are necessary to provide data with high spatial resolution close to the earth's surface. Geostationary satellite observations in the 182-185 GHz range are necessary to provide data with high update rates and adequate spatial resolutions. Limb scanning (above the horizon) observations on low orbiting satellites are also required in order to provide water vapor profiles in the stratosphere. Limb scanning observations will utilize the 182-185, 320-330 and 375-585 GHz ranges.

The requirements for low orbiting nadir observations include a 0-7 gm/cm^2 range for total precipitable water, with an accuracy of 0.3 gm/cm^2, and a spatial resolution of 2 km for over-land measurements and 20 km for measurements over the ocean. Multiple frequency measurements are essential to nadir profile measurements, and the bands of interest include 15.5, 17.9, 19.9, 21.2, 22.2, 24.0, and 31.5 GHz. The desired update rate for these measurements is twice per day. There are several competing effects which must be considered which include soil moisture, snow morphology, lake ice, sea state, sea ice, clouds, rain and atmospheric temperature.

The observation requirements for geostationary nadir measurements are somewhat different although the range and accuracy are the same as in low orbiting nadir observations. A spatial resolution of from 20-100 km is adequate with an update rate of four times per day. Multiple frequency measurements are required within the band of 182-185 GHz to provide profile data. Competing effects with these measurements include temperature, clouds and rain.

Measurement requirements for the low orbiting limb sounder observations include a range of .001-.1 gm/m^2 and an accuracy of 0.001 gm/m^2. A spatial resolution of 100 x 300 km (horizontal) and 1 km (vertical) is required. Multiple frequency measurements within the band are desired over the range of 182-185, 320-330, and 375-385 GHz. The update rate specified is four times per day. The only strong competing effect for these measurements is temperature, which is discussed in the following paragraphs.

A large number of temperature and wind profile measurements at locations distributed uniformly over the surface of the earth are required for weather forecasting. At a minimum, temperature profile measurements are required at a large number of locations. At present, balloon carried sensors (radiosondes) provide the required observations over land areas, and satellite-borne infrared radiometers are used to generate temperature profiles over the oceans. However, infrared observations are often contaminated by clouds, while microwave data can provide the required data under all weather conditions.

Temperature soundings are calculated by inverting radiometric observations made simultaneously at a number of frequencies within the molecular oxygen rotation lines between 50 and 70 GHz or near the isolated line at 118.75 GHz. Observations are required at different frequencies to provide different altitude weighting functions* for sensing temperature variation with height. Observations made at frequencies with high absorption values (near the peak of the lines) provide information about

*Staelin, D. H. (1969): "Passive Remote Sensing at Microwave Wavelengths", Proc. IEEE, 57 427-439.

temperature high in the atmosphere; observations at frequencies with less absorption (further from the peaks of the lines and typically in the valleys between the lines) provide information about temperature at lower altitudes.

There are three classes of satellite observation systems that are required. Low orbiting satellite observations with downward (nadir) viewing radiometers in the 50-70 GHz region are necessary to provide data with high spatial resolution close to the earth's surface. Geostationary satellite observations at frequencies between 114 and 124 GHz are necessary to provide data with high update rates and adequate spatial resolution. Limb scanning (above the horizon) observations on low orbiting satellites are required to provide temperature profiles in the stratosphere. Limb scanning observations will utilize frequencies in the 50-70 GHz region as well as those above 100 GHz

The requirements for the low orbiting nadir observations include a range of -70 to +30°C with an accuracy of 1°C. A spatial resolution of 2-20 km is desired with an update rate of twice per day. Multiple frequency measurements are required, and more than four separate frequency bands in the 50-70 GHz band are needed to provide a range of weighting functions for different altitude measurements. Effects which compete with these low orbiting nadir observations include clouds, rain and water vapor.

For the geostationary nadir observations a -70° to +30°C range is required with an accuracy of 1°C. A spatial resolution of 20-100 km is essential, with an update rate of four times per day. Multiple frequency measurements within the band of 114-124 GHz are essential for profiling. Several competing effects exist which include water vapor, clouds, and rain.

The requirements for low orbiting limb sounding include a range of -70° to +10°C with an accuracy of 1°C. A spatial resolution of 100 x 300 km (horizontal) and 1 km (vertical) is required, with an update rate of once per day. Multiple measurements are required within the bands of 50-70 GHz and 110-126 GHz for profiling. The primary competing effect in these measurements is water vapor.

2.5 Environmental Quality

There is major evidence that the earth's environment is being adversely affected by man. The growth of the earth's population, the tremendous increase in industrial activity, and the concentration of people in cities and expanding metropolitan areas have brought major problems in maintaining the quality of the physical atmosphere and an adequate supply of quality water.

Laws recently enacted at the federal and state levels, together with action programs at the federal, state and local government levels and by industries, are moving the nation at an accelerated rate to a cleaner physical environment. An implementation schedule has been established that calls for most of the goals to be met within 10 years. It has been estimated by environmental specialists that in excess of $100 billion will be spent during the next decade for pollution control.

Current and evolving remote sensor systems could contribute to achieving the national environmental goals, and meet the needs of major users of environmental quality data. Substantial progress has been made in developing sensors and systems for air quality monitoring in the stratosphere. In contrast, however, progress in developing sensors and systems for monitoring the lower atmosphere and monitoring water quality is lagging. There is an immediate need to use state-of-the-art technology and to place in operation improved and expanded air and water quality monitoring programs to meet regulatory requirements.

The troposphere is the lowest major layer of the atmosphere, extending from the earth's surface to an altitude of about 12 km. It is in this lower layer of the atmosphere that most of the important processes affecting atmospheric pollution, as well as weather, occur. Most of the first-order effects of airborne pollutants experienced by man, plants, and animals are highly dependent upon the dispersion and dilution capacity of the troposphere. A temperature inversion layer just above the troposphere acts to some extent as a cap or lid on the mixing layer. The most immediate air quality problems involve sensing and controlling the pollutants in the layer of the troposphere nearest the earth.

Sensors on the earth's surface, in aircraft and in spacecraft can be used for monitoring the troposphere to assess, on both regional and global scales, the impact of air pollution and of air quality control. Passive microwave sensors can provide capabilities for all weather, day and night measurements, and for measuring the vertical distribution of pollutants from the ground up.

In the stratosphere, the region of the atmosphere from about 12 km to 50 km above the surface of the earth, space-borne sensors can also contribute valuable data. The stratospheric ozone layer filters ultraviolet radiation from the sun that is harmful to most forms of earth life. There are growing concerns about the potential for effecting significant changes in the world-wide climatic conditions through the introduction of both trace gases and particulates into this protective barrier of the planet. Several basic properties of the stratosphere make it sensitive to the injection of trace gases and particulates of both man-made and natural origin. Since photochemical processes that determine the ozone content are not well understood, it is conceivable that the introduction of new materials, or the increase in quantity of chemical forms, leading to new equilibrum values could significantly alter the protective ozone barrier.

Over the next decade, emphasis must be given to monitoring the environmental quality of the stratosphere on a global scale with emphasis on measurements of stratospheric species, both gases and aerosols, and on the species involved in ozone chemistry. Additional measurements should be directed at determining the impact of man-made pollutants on significant stratospheric natural processes.

Measurements of the concentrations of atmospheric trace constituents and their variation in space and time are required to evaluate the effects of man on the stratosphere and troposphere. Passive microwave remote sensing can provide information about ozone (O_3), nitrous oxide (N_2O) and carbon monoxide (CO). The current controversy over the use of aerosol sprays and the depletion of the ozone layer arises in part from a lack of data on ozone content and variation. A real depletion of the ozone layer may cause an increase in the occurrence of skin cancer. Microwave observations are required to provide daily observations of ozone concentrations. Similarly, the trace constituents N_2O and CO should be monitored to establish background levels to assess the effects of these pollutants.

Molecular oxygen, water vapor, ozone, nitrous oxide, and carbon monoxide all have rotation lines in the 100 to 300 GHz region. Limb scanning observations of emissions at frequencies centered on the rotation lines and in the valleys between lines are required to provide altitude distributional information on the trace constituents in the stratosphere and troposphere. The spatial resolution requirements for limb scanning of ozone, nitrous oxide and carbon monoxide measurements are 100 x 300 km (horizontal) and 1 km (vertical). Update rates required for ozone are 1 per day, while the specified rate for nitrous oxide and carbon monoxide are once per week. The required line frequencies for ozone are 110.83, 124.09, 184.38, 235.71, 237.15, 239.09, and 364.43 GHz. For nitrous oxide, measurement frequencies include 125.61, 150.7, 175.86, 200.97, 226.1, 251.2, 276.3 and 301.4 GHz. The required line frequencies for carbon monoxide are 115.3, 230.5, 345.80 GHz. The primary competing effect for each of these is water vapor.

2.6 Marine Resources, Estuarine and Oceans

Water has a fundamental impact on the welfare of mankind and its very existence. Water covers more than two-thirds of the earth's surface. The oceans dominate the earth's weather systems and are the source of vast quantities of food and other natural resources. Furthermore, ocean commerce is of crucial importance to man's capacity to maintain or enhance his quality of life.

Remote sensing technology can provide data for, and assist in:

(1) the efficient management of living marine resources,

(2) the efficient and effective management of activities within estuarines and coastal zone regions,

(3) the effective use of the oceans as transportation routes, and

(4) the meaningful contribution toward the advancement of the basic sciences of marine biology and oceanography.

Estuaries and coastal zones play an important role in the productivity of coastal regions by serving as home, nursery, and breeding grounds for many species of fish and shellfish that are important as food crops. Practically all sports fish and 65 percent of all commercial fish are estuarine dependent,* spending at least some of their life in estuarine waters. The habitat for these species is principally determined by the salinity and temperature of the waters. Oysters, for example, can tolerate a wide range of salinity but produce best within a limited salinity range. Large influxes of fresh water stimulate shrimp stock perhaps by salinity change, and perhaps by the nutrients carried by the fresh water.

* Report by the Secretary of the Interior to the U.S. Congress, "National Estuarine Pollution Study", Senate Doc. 91-58 (1970).

From 1959 to 1969, imports of fishery products accounted for 19 percent of the total deficit in the U.S. balance of payments. In the late 1950's, the annual deficit was on the order of several hundred million dollars. Currently about 70 percent of fishery products used in the U.S. are imported, and the deficit is about $1.5 billion per year. An increase in the productivity and protection of fisheries in our own coastal waters would reduce U. S. dependency on other nations. Remote sensing techniques can be of benefit in (1) understanding fisheries-related biology to conserve fish stock and establish maximum sustainable yields for the stocks, (2) enforcing international and other conventions and agreements related to fisheries, and (3) forecasting environmental conditions best suited for specific species of fish to determine the most likely location of schools.

Remote measurements of salinity are required to monitor habitat change and to forecast fish and shellfish population levels. Microwave measurements are required to provide the salinity data under both clear and cloudy conditions. Measurements of surface salinity within the small confines of estuaries implies a spatial resolution limitation for the sensors. However, microwave systems can provide salinity data integrated over areas with a characteristic length of 2-5 km, and the observations are useful for assessing and monitoring habitat change.

In the open ocean, salinity shows relatively small change with time and location. Local changes, however, can occur after major storms or as a result of large-scale circulations. Salinity and temperature serve as tracers of these large-scale ocean currents, and their measurement is important for climate forecasts. Microwave radiometry provides the only routine method for the acquisition of salinity data of the open oceans on a global basis.

The specified range for estuarine salinity measurements is 10-35 parts per thousand, with an accuracy of 2-5 parts per thousand, a spatial resolution of 2-5 km. The optimum frequency is 2.7 GHz. An update rate of once per week is required. For ocean salinity the range is 30-36 parts per thousand with an accuracy of 0.2 parts per thousand. The optimum frequency for these measurements is 1.4 GHz, with a 20 km spatial resolution. The competing effects for such measurements include surface temperature, sea state, water vapor, clouds and rain.

Microwave passive remote sensors can also provide data on surface temperature. The habitat of fish and shellfish within an estuary and coastal zones is determined principally by the salinity and temperature. The preferences of some commercial fish species for a limited range of water temperatures is well known to fishermen. The rapid detection of coastal water mass boundaries (ocean fronts) and coastal upwellings of nutrient rich, cold subsurface water is required for the optimum deployment of fishing vessels. Detection of thermal anomalies is also required for warning of natural hazards to coastal regions such as the so-called "red tide", a sudden growth of toxic dinoflagellate blooms which seriously affect the economy of the shellfish industry. Also, water temperature is a tracer of water circulation, and as such can be used for the detection of thermal pollution and the enforcement of environmental regulations.

Ocean surface temperatures are also measureable. These temperatures act as a tracer of ocean circulation and can be used to identify or mark upwellings where colder, nutrient rich water is forced to the surface. Temperature distributions affect the abundance and distribution of marine organisms, which in turn affect the commercial fish population. Routine, clear and cloudy weather observations of the variations in sea surface temperature are needed for the optimum deployment of fishing vessels. The data are also required for long-range weather forecasts. Satellite-borne microwave passive remote sensing of sea surface temperature can provide the routine observations over the entire globe that are needed for weather forecasting and ocean fishery resource management.

Estuarine, coastal and ocean surface temperature measurements are needed over a range of 0-30°C to an accuracy of 0.5°C. The spatial resolution for estuarine measurements is 2-5 km at a frequency of 5.0 GHz. Update rates of once per day are essential. For ocean surface temperature measurements, a 20 km spatial resolution is required, with the optimum frequency being in the 6.5-7.0 GHz region. The competing effects in these measurements are sea state, water vapor, clouds, and rain.

The term "sea state" has been used widely for describing the characteristics of the ocean surface as modified by the wind. It is also known that a marked variation in microwave brightness temperature results from variations in the ocean surface conditions. Thus, there is the potential for huge savings through the use of microwave radiometers for mapping the sea state over large areas on a routine basis. For example, fixed installations such as offshore drilling platforms placed in estuaries or in the vicinity of continental shelves are exposed to the huge stresses caused by high seas. Thus, sea state data are needed for hazardous situation warning and for the compilation of statistical data for the design of structures to withstand the stress. The current high failure rate of offshore structures is a testimony to the requirement for improved data. Passive microwave sensing systems have the capability of providing the required sea state data under nearly all weather conditions on a routine, global basis. Moreover, since the sea state affects measurements of salinity and temperature and the detection of oil slicks, sea state measurements must be made in order to interpret correctly the observations at other frequencies.

Microwave remote passive sensing of sea state at a number of frequencies over the open ocean can provide surface wind speed data under all weather conditions for long- and short-range forecasts of weather and wave conditions. It is known that rough seas can seriously reduce the speed of ocean transports. Many of these ships have operation costs in excess of $50,000 per day; consequently, knowledge and forecasts of sea state which result in more rapid and improved transportation is of enormous economic benefit.

Major ocean storms such as typhoons and hurricanes can be remotely sensed and their position determined from the spatial wind speed pattern. This information is critical for typhoon and hurricane warning. The general clouds and rain patterns associated with tropical storms can be sensed with visual, infrared and microwave radiometers. Only microwaves, however, provide all the weather surface windspeed sensing capability required to assess the severity of the storm. As noted previously, sea state measurements are required to correct measurements of salinity and water surface temperature, and overwater observations of clouds, water vapor profiles, and atmospheric tempratures.

The optimum frequencies for sea state (wind speed) measurements are 10.7 and 19.9 GHz. The measurement range for estuarine sea state (wind speed) measurements has been specified to be 0-30 m/sec. with an accuracy of 2 m/sec. A spatial resolution of 2-5 km is needed, with an update rate of once per day. For ocean sea state measurements, a range of 0-40 m/sec. at an accuracy of 2 m/sec. is required. A 2-20 km spatial resolution is needed, with an update rate of once per every 6 hour period. The basic competing effect in these measurements is rain.

Ice extent, thickness and type are also measurable at microwave frequencies. Ice presents a hazard to marine transportation in various parts of the continental U.S. and in Alaska. The Great Lakes, the U.S. central river system, and New England are becoming increasingly important to the transportation of commodities. Nearly all iron ore which moves in the Great Lakes region is carried by ship. Significant amounts of wheat, oil products, coal, and finished goods also move across the region by ship. Most vessels operating in the U.S. are not designed to operate unaided through ice-covered waters, and ice-breaking service is provided, usually by the federal government (U.S. Coast Guard). Therefore, capabilities to determine ice coverage, clear water passages, pressure ridges, and ice thickness are important to success in extending the navigation season. An interim report* on the extension of the St. Lawrence and Great Lakes navigation season beyond the December 15 closing date shows the following estimated economic gains:

*U.S. Army Corps of Engineers. Great Lakes Navigation Season Extension. Winter Navigation Board, Special Status Reports, U.S. Army Corps of Engineers, July 1974.

Navigation season extended to	Gain in Millions of Dollars: Jan. 31	Feb. 28	Year round
By 1975	40	58	68
By 1985	85	123	145

These gross estimates are based on a number of factors including improved ice surveillance, better data analysis and better prediction, all-season aids to navigation, and increased icebreaking activity.

In the Arctic and Antarctic, ice-breaking has historically been conducted in support of scientific investigations and, to a limited degree, in military operations. Recent discovery of oil deposits on the Alaskan north slope, coupled with the political and economic ramifications of a dependency on Middle East oil supplies, has spurred activity in the far north. Scientific and geological surveys, commercial oil drilling, ocean transport, and supporting icebreaking requirements in high latitudes will place increasing emphasis on all-weather sensing to predict ice extent, polynyas, ice thickness, pressure ridges, and the discrimination of new ice from multi-year ice.

Microwave measurements can provide ice thickness observations under both clear and cloudy conditions. Remote sensing at visual and infrar · frequencies provide information on ice location, but only microwave sensors can provide observations during the period of ice breakup when clouds regularly obscure the surface. Microwave measurements provide the only means to sense ice thickness quantitatively. Data is required to provide this information on a routine basis for all global regions north of 50°N and south of 50°S, where sea ice is important to navigation.

The measurement requirements for ice thickness include a range of 0-1 meter and an accuracy of 0.2 meters. A 20 km spatial resolution is needed and an update rate of once per day is desired. The optimal frequency for ice thickness measurements is 1.4 GHz. Ice type measurements are also desired. A spatial resolution of 2-20 km has been specified, with a once per day update rate. Multiple frequency measurements are needed for ice type discrimination, with the primary frequencies being 10.7, 19.9 and 37.0 GHz. The primary competing effects in ice thickness and ice morphology measurements are rain and snow cover.

Some forms of sea pollution are also measureable at microwave frequencies. An example is marine oil spills, an important form of pollution. The oil affects the production of the smaller marine organisms that develop near the ocean surface. These small marine organisms are important links in the food chain leading to commercial fish stocks.

Also, oil floating on estuarine water is an insidious form of pollution that affects commercial fishing, wildlife habitat, and recreation.

The USCG has observed marked decreases -- up to 25 percent -- in the number of oil spills when continued surveillance of critical areas has been employed.* Although much of this decrease can be attributed to increased attention to handling and transfer methods, the fact that better and more complete surveillance is being conducted tends to dissuade the intentional polluter. The cost of daily observation of certain harbors and waterways with existing vessels and aircraft by the USCG is estimated to be between $2 million and $4 million annually. The cost may exceed $18 million annually if a dedicated system for surveillance of pollution is extended to all major U.S. continental lakes and coastal waters. At present, high-resolution radar, imaging microwave radiometers, and multispectral low-light-level television are being installed on aircraft for surveillance in low-altitude flights. It is estimated that yearly costs could be decreased by about one-third or one-half through the use of sensor systems which can detect surface oil of 1,000 m^2 or greater.

Passive microwave sensors on low orbiting satellites are capable of detecting and measuring the thickness of oil spills* of more than 0.2 km spatial extent. Microwave measurements can

---

*Gerhard, Glen: A Study of the Cost Effectiveness of Remote Sensing Systems for Ocean Slick Detection and Classification. National Sea Grant Program, U.S. Coast Guard, Washington, D.C., 1972.

make timely oil spill detection under both clear and cloudy conditions. Timely detection is important in remote regions, both for the effective enforcement of environmental regulations and for the initiation of effective corrective action.

Passive microwave observations with a resolution of 2 km are required to monitor the occurrence of marine oil spills on a daily basis. The frequencies necessary for these measurements are 37.0 and 90.0 GHz. The competing effects are sea state, rain and water vapor.

2.7 Summary

A review of the applications, remote sensor needs and measurement requirements for passive microwave sensors outlined in the previous paragraphs indicates that a natural relationship can be established. Table 1 is a matrix of the relationships of the various applications areas and the types of information which would benefit each application area. From this chart it can be seen that much of the data from the measurements and phenomena of interest can be used in a number of applications areas.

TABLE 1

Relationship of Measured Phenomena to Major Applications Areas

MAJOR APPLICATIONS AREAS	Terrain Imaging	Soil Moisture	Snow Morphology	Lake Ice	Salinity	Surface Temperature	Sea State	Oil Slick	Ice Thickness	Ice Morphology	Clouds	Rain	Water Vapor	Temperature	H_2O	CO	N_2O	O_3
Agriculture, Forestry and Earth Resources		●	●	●							●	●	●					
Land Use Survey and Mapping	●																	
Water Resources		●	●	●	●	●	●	●			●	●	●					
Weather and Climate						●	●				●	●	●	●				
Environmental Quality					●			●							●	●	●	●
Marine Resources, Estuaries and Oceans			●	●	●	●	●	●	●	●	●	●		●				

Measurement Phenomena

3. MEASUREMENT CONSIDERATIONS AND FREQUENCY REQUIREMENTS

Remote sensing is the observation, measurement and interpretation at a distance of the physical environment through the use of electromagnetic radiation. Physical parameters that can be determined remotely are spatial distribution, spectral distribution, polarization, temporal variation, and variations of the above factors with angle of observation.

In the microwave region, 1.0 to 300 mm (300 GHz to 1 GHz), thermal emission, which is dependent on the emissivity and physical temperature of matter, can be observed.

Radiometers measure the apparent temperature averaged over all objects within the antenna's coverage. Apparent temperature is the overall measured "brightness" temperature from all objects. Considering only one object at temperature T, and no intervening atmosphere, the brightness temperature T_B equals:

$$T_B = \varepsilon T$$

where ε is the emissivity of the object.

Since an earth-viewing radiometer measures radiation emitted and reflected from the earth and the atmosphere, measurement of one is complicated by the other's presence. Also, every form of matter has a differing emission spectrum. Molecules, for example, have emission (and absorption) spectrum relatively narrowly confined about a frequency which is determined by the quantum mechanic relationships for that molecule. On the other hand, matter which is composed of many molecules, such as land, has a very broad emission spectrum which is the sum of the complex interactions of all the molecules in the particular matter.

Theoretically, the best method of recognizing various forms and concentrations of matter, would be to utilize a spectrum analyzer that covers the whole microwave spectrum. Since this is impossible, sensing is necessary in frequency areas where the phenomena exhibit high responses relative to competing effects. For example, when measuring surface phenomena such as soil moisture or sea state, the time varying absorption effects of atmospheric water vapor can mask the desired measurements. If, however, the water vapor concentrations and hence absorption effects, were measured separately, then such masking effects could be removed. Consequently, there is an interrelationship between all phenomena that if accounted for, would improve the accuracy and utility of the measurements. Table 2 illustrates the interrelationships for various phenomena. The letter P in the Table indicates that the phenomena exhibits a strong emission at the designated frequency and, hence, is considered a primary measurement. Table 3 presents a matrix of these desired measurements and various competing effects which need to be simultaneously measured in order that highly accurate primary measurements can be made.

TABLE 2
FREQUENCY BANDS FOR THE INVESTIGATION OF SURFACE AND ATMOSPHERIC PHENOMENA

MEASUREMENTS

FREQUENCY BAND GHz	Land			Estuary				Ocean						Atmosphere				Trace Constituents		
	Soil Moisture	Snow Morphology	Lake Ice	Salinity	Surface Temperature	Sea State	Oil Slick	Salinity	Surface Temperature	Sea State	Ice Thickness	Ice Morphology	Oil Slick	Cloud	Rain	Water Vapor	Temperature	CO	N_2O	O_3
1.300-1.427	P	P						P		P	P									
2.64 -2.70	P	P		P																
4.95 -5.00					P															
6.425-7.250									P											
10.6-10.7		P	P			P				P		P			P					
15.3-15.5															P	P				
17.7-17.9																P				
19.7-19.9		P	P			P				P		P			P	P				
21.0-21.2																P				
22.1-22.4																P				
23.6-24.0																P				
31.3-31.5																P				
36.0-37.0		P	P				P					P	P		P					
50.2-50.4																	P			
52.0-54.25																	P			
54.9-55.1																	P			
56.05-56.55																	P			
57.5-58.5																	P			
62.4-63.0																	P			
85.0-92.0							P						P	P						
100.0-102.0																			P	P
115.0-126.0																	P	P	P	P
150.0-151.0																			P	
174.5-176.5																			P	
182.0-185.0																P				P
200.0-201.5																			P	
225.0-240.0																		P	P	P
250.0-252.0																			P	
275.0-277.0																			P	
300.0-303.0																			P	
320.0-330.0																P				
340.0-350.0																		P		
360.0-370.0																				P
375.0-385.0																P				

TABLE 3
COMPETING EFFECTS IN THE INVESTIGATION OF SURFACE AND ATMOSPHERIC PHENOMENA

COMPETING EFFECT

MEASUREMENT	Soil Moisture	Snow Morphology	Salinity	Surface Temperature	Sea State	Ice Thickness	Ice Morphology	Oil Slick	Cloud	Rain	Water Vapor	Temperature	CO	N_2O	O_3
Soil Moisture									X	X	X				
Snow Morphology									X	X	X				
Lake Ice		X							X	X	X				
Salinity				X	X				X	X	X				
Surface Temperature					X				X	X	X				
Sea State									X	X					
Ice Thickness		X					X								
Ice Morphology		X								X					
Oil Slick					X					X	X				
Cloud	X	X		X	X		X			X	X	X			
Rain	X	X		X	X		X								
Water Vapor	X	X			X		X		X	X		X			
Temperature									X	X	X				
H_2O											X				
CO															
N_2O											X				
O_3											X				

Those frequencies in the 20-24, 50-70, and above 100 GHz provide atmospheric measurements. The frequencies chosen allow for the profiling of the constituent of interest through measurement on and around molecular resonance lines. Profiling measurements allow for determination of vertical distributions of molecules of interest. Such profiles provide information on such phenomena as fluorocarbon migration to the stratosphere and the consequent interaction, and depletion, of ozone.

A number of frequencies are also specified for rain measurements - these are required to provide an adequate dynamic range for high spatial resolution observation over a wide range of rain rates.

Since land and sea phenomena to be measured produce broadband responses, the frequency of the center of each band is not critical. What is important is the general location of each band in the frequency domain, due to the high sensitivity to the phenomena, and the number of separate frequency bands. Only 11 bands have been requested for land and sea phenomena.

In conclusion, passive microwave remote sensing is a powerful new tool for the management and conservation of the earth's resources. It is important for future generations that the required frequency bands be protected, to the highest practical limit, from significant contamination. The following sections address this problem through sharing analyses with current and proposed services in the requested passive sensing bands.

CHAPTER I

PART B

SUMMARY OF REQUIREMENTS, UNIQUE ASPECTS AND SHARING ANALYSES OF REQUIRED FREQUENCY BANDS

SECTION 1

FREQUENCY BAND 1.3-1.427 GHz

ANALYSIS OF PASSIVE REMOTE SENSING REQUIREMENTS IN THE 1.3-1.427 GHz BAND

1.1 ALLOCATIONS

The existing allocations and proposed changes in the 1.3-1.427 GHz frequency band are given below for ITU Regions 1, 2, and 3. Underlined items indicate proposed additions, and dashed items indicate proposed deletions.

Region 1	Region 2	Region 3
	NON-GOVERNMENT	
1300-1350	AERONAUTICAL RADIONAVIGATION MOD 346 Radiolocation 346A 347 348 MOD 349A 349B	
1350-1370 FIXED MOBILE RADIOLOCATION 346A 349 MOD 349A 349B	RADIOLOCATION 346A 346B 349 MOD 349A 349B	
1370-1400 FIXED MOBILE RADIOLOCATION 349 349A	RADIOLOCATION 349 349A	
1400-1427	EARTH EXPLORATION SATELLITE (Passive) SPACE RESEARCH (Passive) RADIO ASTRONOMY	

1.2 MEASUREMENT

Thermal microwave earth emissions to determine:

1) Ocean salinity (primary)
2) Soil moisture content (primary)
3) Snow morphology (primary)
4) Sea ice thickness (primary)
5) Ocean sea state (primary)

1.3 APPLICATION

More effective and efficient management of:

1) Agricultural production
2) Marine food production
3) Water resources
4) Hazard warning
5) Ship routing
6) Weather forecast

1.4 GEOGRAPHICAL COVERAGE REQUIREMENTS

Geographical coverage requirements include worldwide ocean areas for salinity, sea state, and ice thickness measurements, and worldwide land masses for soil moisture and snow morphology measurements.

1.5 SENSOR PERFORMANCE AND OPERATIONAL REQUIREMENTS

- **Ocean Salinity**

Range:	30-36 parts per thousand
Accuracy:	0.2 parts per thousand
Sensitivity:	0.1 K
Resolution (Swath):	20 km (60 km)
Update Rate:	1 per week
Integration Time:	0.66 seconds
Bandwidth:	127 MHz
Sensor Interference Threshold:	-165 dB(W)
Competing Effects:	Surface temperature (7.0 GHz) Sea state (10.7, 19.7 GHz) Rain, clouds (19.7, 37.0 GHz)

- **Soil Moisture**

Range:	0-30% (dry weight)
Accuracy:	1-2% by weight
Sensitivity:	1.0 K
Resolution (Swath):	5 km (200 km)
Update Rate:	1 per day
Integration Time:	0.012 seconds
Bandwidth:	64 MHz
Sensor Interference Threshold:	-158 dB(W)
Competing Effects:	Soil roughness (10.7 GHz) Vegetation (37.0 GHz) Water vapor (22.2 GHz) Rain (19.7, 37.0 GHz)

- Snow Morphology

Range:	0-20% free water content
Accuracy:	2%
Sensitivity:	1.0 K
Resolution (Swath):	5 km (200 km)
Update Rate:	1 per day
Integration Time:	0.012 seconds
Bandwidth:	64 MHz
Sensor Interference Threshold:	-158 dB(W)
Competing Effects:	Water vapor (22.2 GHz) Rain and clouds (19.9, 37.0 GHz)

- Ocean Sea State

Range:	0-40 m/sec
Accuracy:	2 m/sec
Sensitivity:	1 K
Resolution (Swath):	20 km (800 km)
Update Rate:	1 per 6 hours
Integration Time:	0.05 seconds
Bandwidth:	16.2 MHz
Sensor Interference Threshold:	-164 dB(W)
Competing Effects:	Rain (19.7, 37.0 GHz)

- **Sea Ice Thickness**

Range:	0-1 m
Accuracy:	0.2 m
Sensitivity:	1 K
Resolution:	20 km
Update Rate:	1 per day
Integration Time:	0.05 seconds
Bandwidth:	16.2 MHz
Sensor Interference Threshold:	-164 dB(W)
Competing Effects:	Ice morphology (10.7, 19.9, 37.0 GHz) Snow cover (2.7, 10.7, 19.7, 37.0 GHz)

- **Spacecraft Parameters**

Orbital Altitude:	500 km, circular
Inclination:	70-110° (for worldwide coverage)
Antenna:	20 meter (5 km resolution) 5 meter (20 km resolution)

- **Operational Requirements**

Salinity and soil moisture contours are required once per week and once per day respectively. Ice and snow observations are required on a daily basis. Sea state measurements are required every 6 hours to track hurricanes and typhoons. Continuous spacecraft measurements are required to compile the above data.

Data acquired in this frequency band must be used in conjunction with measurements in other bands to eliminate competing effects.

1.6 STATUS OF TECHNOLOGY AND USE

L-Band Radiometers have flown on SKYLAB and are in current usage on research aircraft. The Shuttle Imaging Microwave System will be placed on the Shuttle. Operational use is expected in the mid-1980's for Shuttle, Landsat and Seasat follow-on missions.

1.7 REASONS FOR SELECTION OF THIS FREQUENCY AND BANDWIDTH

Soil moisture and snow morphology radiometric measurements can be obtained at frequencies below 5 GHz. Salinity can only be observed at frequencies below 3 GHz. For these phenomena, measurement sensitivity increases as the frequency decreases.

The sensor resolution requirement of 20 km preclude the use of lower frequency bands due to antenna aperture size constraints.

Sea state observations are desired in this band because the effects of rain and clouds are small.

Therefore, for salinity, soil moisture, snow, and sea state measurements, this band is a good compromise based solely on the application.

The required bandwidth (127 MHz) is determined by radiometer sensitivity, receiver noise temperature and integration time, all of which are fixed by the application. A derivation of the bandwidth value is contained in Chapter II, Part B, Section 1.

1.8 SHARING ANALYSIS RESULTS

Portions of the 1.3-1.427 GHz band are currently allocated to the Fixed, Mobile, Aeronautical Radionavigation, Radiolocation, and Radioastronomy Services. Since passive spaceborne sensors can inherently share with the Radioastronomy Services, the analysis is concerned only with the other three above mentioned services.

The results, presented herein, are based on information contained in U. S. and international frequency assignment data files.

The assumptions underlying the analysis are that:

- Present use of the 1.3-1.4 GHz band for Radiolocation and Aeronautical Radionavigation is extensive, both in the U. S. and on a worldwide basis.

- Since the Radiolocation and Aeronautical Radionavigation Services are safety related services, operation on a 24-hour basis is presumed.

- In Region I there are a substantial number of registrations in the fixed service. In all probability these transmitters are associated with national PTT systems, which operate on a 24-hour basis.

- Use of the 1400-1427 MHz portion of the spectrum is exclusive to the Radioastronomy Service.

The results of the sharing analyses are presented below as well as in Table 1-1.

- <u>Aeronautical Radionavigation and Radiolocation Services</u>

  - Sharing on a simultaneous operational basis between spaceborne passive sensors and the Aeronautical Radionavigation and Radiolocation Services in the 1.3-1.4 GHz band is not feasible.

  - Time sharing with these services is not a viable alternative.

- <u>Fixed and Mobile Services</u>

  - Sharing on a simultaneous operational basis between spaceborne microwave sensors and the Fixed and Mobile Services in the 1.35-1.4 GHz band is not feasible.

  - Time sharing with these services is also not feasible.

1.9 SHARING CONCLUSIONS

Sharing on a simultaneous operational basis between spaceborne passive microwave sensors and the Fixed, Mobile, Aeronautical Radionavigation and Radiolocation Services in the 1.3-1.4 GHz band is considered not feasible.

TABLE 1-1

SUMMARY OF SHARING ANALYSIS RESULTS

		AERONAUTICAL RADIONAVIGATION & RADIOLOCATION	FIXED AND MOBILE
MAXIMUM RECEIVED POWER (dB RELATIVE TO THE INTERFERENCE THRESHOLD) FOR ONE INTERFEROR		57.7	47
MINIMUM RECEIVED POWER (dB RELATIVE TO THE INTERFERENCE THRESHOLD*) FOR ONE INTERFEROR		13.2	-17
LOSS OF COVERAGE AREA FROM SINGLE INTERFERENCE SOURCE	km^2 %**	31.2×10^6 100%	29.3×10^6 94%
SIMULTANEOUS SHARING FEASIBLE		NO	NO
TIME SHARING FEASIBLE		NO	NO

*(-)Indicates below interference level of -165 dB(W).
**Percentage number is percent of area lost to the radiometer when in view of the interferor.

ORIGINAL PAGE IS OF POOR QUALITY

Sharing on a simultaneous operational basis between spaceborne microwave sensors and the Fixed and Mobile Services in the 1.35-1.4 GHz band is not feasible. Time sharing with these services is also not feasible.

Sharing on a simultaneous operational basis between the spaceborne passive services and the Radioastronomy Service in the 1.4-1.427 GHz band is feasible.

SECTION 2

FREQUENCY BAND 2.640-2.700 GHz

ANALYSIS OF PASSIVE REMOTE SENSING REQUIREMENTS IN THE 2.640-2.700 GHz BAND

2.1 ALLOCATIONS

The existing allocations and proposed changes in the 2.640-2.700 GHz frequency band are given below for ITU Regions 1, 2, and 3. Underlined items indicate proposed additions, and dashed items indicate proposed deletions.

Region 1	Region 2	Region 3
	NON-GOVERNMENT	
2550-2655	FIXED 364C MOBILE except aeronautical mobile BROADCASTING-SATELLITE MOD 361B 362 363 364 364F	
2655-~~2690~~ 2670		
FIXED 364C 364D MOBILE except aeronautical mobile BROADCASTING-SATELLITE MOD 361B MOD 364H 363 364 364F ~~364G~~	FIXED 364C 364D FIXED-SATELLITE (Earth and Space) MOBILE except aeronautical mobile BROADCASTING-SATELLITE MOD 361B MOD 364H 364E 364F ~~364G~~	
2670-2690		
MOBILE except aeronautical mobile FIXED 364C 364D ~~BROADCASTING-SATELLITE 361B 364H~~ RADIO ASTRONOMY 363, 364, 364F, 364G, MOD 233B	RADIO ASTRONOMY MOBILE except aeronautical mobile FIXED 364C 364D ~~BROADCASTING-SATELLITE 361B 364H~~ FIXED SATELLITE (Earth and Space) 364E 364F 364G MOD 233B	
2690-2700	SPACE RESEARCH (Passive) RADIO ASTRONOMY EARTH EXPLORATION SATELLITE (Passive) MOD 233B 363 364A 364B	

2.2 MEASUREMENT

Thermal microwave earth emissions to determine:

1) Salinity of estuarine and coastal waters (primary)
2) Soil moisture content (primary)
3) Snow morphology (primary), and
4) Estuarine sea state (secondary).

2.3 APPLICATION

More effective and efficient management of:

1) Marine food production
2) Agricultural production, and
3) Water resources

2.4 GEOGRAPHICAL COVERAGE REQUIREMENTS

Geographical coverage requirements include worldwide estuarine and coastal areas for salinity measurements, and worldwide land masses for soil moisture and snow morphology measurements.

2.5 SENSOR PERFORMANCE AND OPERATIONAL REQUIREMENTS

- Coastal Salinity

Salinity Range:	10-35 parts per thousand
Accuracy:	2-5 parts per thousand
Sensitivity:	0.15-0.3 K
Resolution:	2-5 km

● <u>Coastal Salinity</u> (cont.)

Update Rate:	1 per week
Integration Time:	0.2 seconds
Bandwidth:	60 MHz
Sensor Interference Threshold:	-166 dB(W)
Competing Effects:	Surface temperature (5.0 GHz) Sea state (10.7, 19.9 GHz), Water vapor (22.4 GHz), Clouds and Rain (19.9, 37.0 GHz).

● <u>Soil Moisture</u>

Range:	0-30% (dry weight)
Accuracy:	1-2% by weight
Sensitivity:	1.0 K
Resolution (Swath):	2-5 km (200 km)
Update Rate:	1 per day
Integration Time:	0.002 seconds
Bandwidth:	60 MHz
Sensor Interference Threshold:	-158 dB(W)
Competing Effects:	Soil Roughness (10.7 GHz), Vegetation (37.0 GHz), Water vapor (22.4 GHz), and Rain (19.9, 37.0 GHz)

- Snow Morphology (primary)

Range:	0-20% free water content
Accuracy:	2%
Sensitivity:	1.0 K
Resolution:	2-5 km
Update Rate:	1 per day
Integration Time:	0.2 sec
Bandwidth:	60 MHz
Sensor Interference Threshold:	-158 dB(W)
Competing Effects:	Water vapor (22.4 GHz), Rain and Clouds (19.9, 37.0 GHz)

- Spacecraft Parameters

Orbital Altitude:	500 km, circular
Inclination:	70-110° (for worldwide coverage)
Antenna:	10-25 meter diameter

- Operational Requirements

Salinity and soil moisture contours are required once per week and once per day. Due to the small required resolution (2-5 km), continuous spacecraft measurements over applicable areas are required to compile the contours.

Nighttime operations are possible in this frequency band due to low data update rates.

The data acquired in this frequency band must be used in conjuction with radiometric data gathered simultaneously at other frequencies, in order to eliminate competing effects (i.e., sea surface temperature, sea surface foam, water vapor, vegetation, etc.).

2.6 STATUS OF TECHNOLOGY AND USE

Experimental equipment such as the S-Band Microwave Radiometer has been developed, tested and flown aboard aircraft. The Shuttle Imaging Microwave System will be placed on the Shuttle. Additional operational use is expected in the mid 1980's on Shuttle, Landsat, and Seasat follow-on missions.

2.7 REASONS FOR SELECTION OF THIS FREQUENCY AND BANDWIDTH

Soil moisture and snow morphology radiometric measurements can be obtained at frequencies below 5 GHz.* For salinity measurements, radiometric responses degrade rapidly above 3 GHz. Measurements in the 1-3 GHz region are not affected by cloud cover.

The sensor resolution requirements of 2-6 km precludes the use of lower frequency bands, due to antenna aperture size constraints.

Therefore, for salinity, soil moisture and sea ice measurements, the 2.64 to 2.7 GHz band is a good compromise, based solely on the application.

*See Chapter II, Part A.

The required bandwidth (60 MHz) is determined by radiometer sensitivity, receiver noise temperature and integration time, all of which are fixed by the application. A derivation of the bandwidth value is contained in Chapter II, Part B, Section 2.

2.8 SHARING ANALYSIS RESULTS

Portions of the 2.64 to 2.70 GHz spectral region are currently allocated to the Fixed, Mobile, Fixed Satellite (Earth-to-Space) Broadcast Satellite (Space-to-Earth), and Radio Astronomy Services.

The results presented are based on information contained in U.S., as well as international, frequency assignment data files and, in some cases, anticipated future use of the band. The assumptions underlying the sharing analyses are that:

- The Fixed and Mobile Service use of this band in the United States is primarily for Instructional Television Fixed Service (ITFS) as well as for safety and industrial operations, and is not normally required between the hours of 11 p.m. and 7 a.m. local time.

- The Broadcast-Satellite-Service operation will not be required between the hours of 11 p.m. and 7 a.m. local time.

- The Fixed-Satellite Service up-link for thin route communications will be required on a low duty cycle.

The results of the sharing analyses are presented below and in Table 2-1. The detailed sharing analyses can be found in Chapter II, Part B, Section 2.

- Fixed and Mobile Services

  - Harmful interference, on a simultaneous operational basis, will be encountered in the coastal areas of the United States, Europe and the Mediterranean; and the land areas of the United States, Europe, Asia Minor and North Africa. No terrestrial systems were identified, or are known to be planned, for other regions of the world.

  - Time sharing is considered feasible with the Fixed Service in the United States, but is not feasible in the other areas mentioned above.

- Broadcast Satellite Service (Space-to-Earth)

  - Harmful interference, on a simultaneous operational basis, will be encountered over extensive areas of the earth due to broadcast satellite operations. However, only the United States is known to be seriously considering broadcast satellites in this band.

  - Time sharing is considered feasible with this service.

	BROADCAST SATELLITE	FIXED SATELLITE (Earth-To-Space)	FIXED AND MOBILE
MAXIMUM RECEIVER POWER (dB RELATIVE TO INTERFERENCE THRESHOLD) IN MAIN BEAM OF ONE INTERFEROR	+33	+24	+27
MINIMUM RECEIVED POWER (dB RELATIVE TO INTERFERENCE THRESHOLD*) FOR ONE INTERFEROR	-6	-12	-11
LOSS OF COVERAGE AREA FROM SINGLE INTERFERENCE SOURCE (KM^2/%**)	2×10^8 / ~ 100%	2.8×10^6 / 15%	5×10^6 / 27%
SIMULTANEOUS SHARING FEASIBLE	NO	NO	NO
TIME SHARING FEASIBLE	YES	YES	LIMITED***

* (-) Indicates below interference threshold of -166 dB(W).
** Percentage number is per cent of area lost to the radiometer when in view of the interferor.
*** Not in portions of Region I.

TABLE 2-1 Summary of Sharing Analyses Results

ORIGINAL PAGE IS OF POOR QUALITY

- <u>Fixed Satellite Service (Earth-to-Space)</u>

  - Harmful interference, on a simultaneous operational basis, will be encountered over large areas surrounding a fixed satellite earth station.

  - Time sharing, however, is considered feasible with this service.

2.9 SHARING CONCLUSIONS

Sharing on a simultaneous operational basis between spaceborne passive microwave sensors of the Earth Exploration Satellite or Space Research Services, and other services currently allocated in the 2.64-2.70 GHz band is not feasible below 2.69 GHz. Time sharing in certain ITU regions, however, is feasible.

Sharing on a simultaneous operational basis between the space passive services and the Radioastronomy Service in the 2.69-2.70 GHz band is feasible. Consequently, the Radioastronomy Service and the space passive services can be allocated on a primary, co-equal basis in the 2.69-2.70 GHz band.

SECTION 3

FREQUENCY BAND 4.950-5.000 GHz

ANALYSIS OF PASSIVE REMOTE SENSING REQUIREMENTS IN THE 4.950-5.000 GHz BAND

3.1 ALLOCATIONS

The existing allocations and proposed changes in the 4.950-5.000 GHz frequency band are given below for Regions 1, 2, and 3. Underlined items indicate proposed additions, and dashed items indicate proposed deletions.

Region 1	Region 2	Region 3
	NON-GOVERNMENT	
4950-4990	EARTH EXPLORATION SATELLITE (Passive) FIXED MOBILE RADIO ASTRONOMY SPACE RESEARCH (Passive) MOD 233B ~~354~~ ~~382A~~ 382B 382C	
4990-5000		
~~FIXED~~ ~~MOBILE~~ RADIO ASTRONOMY SPACE RESEARCH (Passive) EARTH EXPLORATION SATELLITE (Passive) 233B		~~FIXED~~ ~~MOBILE~~ RADIO ASTRONOMY SPACE RESEARCH (Passive) EARTH EXPLORATION SATELLITE (Passive) 233B
RADIO ASTRONOMY SPACE RESEARCH (Passive) EARTH EXPLORATION SATELLITE (Passive) 383A		

3.2 MEASUREMENT

Thermal microwave earth emissions to determine:

1) Estuarine surface temperature (primary)
2) Soil moisture content (secondary)
3) Ocean surface temperature (secondary)
4) Rain (secondary).

3.3 APPLICATION

More effective and efficient management of:

1) Marine food production
2) Fish and shellfish economy
3) Deployment of fishing vessels
4) Warning systems for natural hazards to coastal regions, and
5) Thermal pollution and environmental regulations.

3.4 GEOGRAPHICAL COVERAGE REQUIREMENTS

Geographical coverage requirements include worldwide estuarine and coastal areas for estuarine surface temperature measurements.

3.5 SENSOR PERFORMANCE AND OPERATIONAL REQUIREMENTS

- Estuarine Surface Temperature

Temperature Range:	273-300 K
Accuracy:	0.5 K
Sensitivity:	0.3 K
Resolution:	2-5 km

- <u>Estuarine Surface Temperature (cont)</u>

Update Rate:	1 per day
Integration Time:	0.2 seconds
Bandwidth:	50 MHz
Sensor Interference Threshold:	-164 dB(W)
Competing Effects:	Sea State, Water Vapor, Clouds, Rain

- <u>Spacecraft Parameters</u>

Orbital Altitude:	500 km, circular
Inclination:	70-110° (for world-wide coverage)
Antenna:	15 meter

- <u>Operational Requirements</u>

Estuarine surface temperature contours are required once per day. Continuous spacecraft measurements over estuarine areas are required to compile this contour.

The data acquired in this frequency band must be used in conjunction with radiometric data gathered simultaneously at other frequencies, in order to eliminate competing effects (i.e., sea state, water vapor, clouds, rain, etc.).

3.6 STATUS OF TECHNOLOGY AND USE

The Passive Microwave Imaging System has been developed and flown on aircraft. Current development and testing is proceeding on the Swept Frequency Radiometer passive sensor. Operational use is expected in the mid 1980's on the Shuttle and SEASAT follow-on missions.

3.7 REASONS FOR SELECTION OF THIS FREQUENCY AND BANDWIDTH

The change in received apparent brightness temperature, as a function of estuarine surface temperature, is a maximum near this frequency.

Observations in this band are relatively insensitive to salinity variations.

This band is optimum for all-weather sensing, since the effects of liquid water (precipitation) in the atmosphere are minimized, while the sensitivity to estuarine surface temperature change is maximized.

The required bandwidth (50 MHz) is determined by radiometer sensitivity, receiver noise temperature and integration time, all of which are fixed by the application. A derivation of the bandwidth value is contained in Chapter II, Part B, Section 3.

3.8 SHARING ANALYSIS RESULTS

Portions of the 4.95-5.00 GHz band are currently allocated to the Fixed, Mobile and Radio Astronomy Services.

The sharing analysis results presented below are based on information contained in the United States, as well as international frequency assignment data files. Table 3-1 presents these results in tabular form for a single interferor. The detailed sharing analyses can be found in Chapter II, Part B, Section 3.

- Harmful interference, on a simultaneous operational basis, will be encountered in the coastal and open ocean areas approximately 2000-2400 km from the shore lines of North America, Puerto Rico and a large portion of Europe. No extensive use of the band was identified for other regions of the world.
- Time sharing is generally considered infeasible with the Fixed and Mobile Services in this band.

3.9 SHARING CONCLUSIONS

Sharing on a simultaneous operational basis between spaceborne passive microwave sensors and the Fixed and Mobile Services in the 4950-4990 MHz band is not feasible. Time sharing in this band is also considered infeasible.

Sharing on a simultaneous operational basis between the space passive services and the Radio Astronomy Service in the 4990-5000 MHz band is feasible.

TABLE 3-1

SUMMARY OF SHARING ANALYSES RESULTS

		FIXED AND MOBILE
MAXIMUM RECEIVED POWER (dB RELATIVE TO THE INTERFERENCE THRESHOLD) FOR ONE INTERFEROR		+49 (1)
MINIMUM RECEIVED POWER (dB RELATIVE TO THE INTERFERENCE THRESHOLD*) FOR ONE INTERFEROR		-22 (2)
LOSS OF COVERAGE AREA FROM SINGLE INTERFERENCE SOURCE	(km^2)	8.6×10^6
	%**	48%
SIMULTANEOUS SHARING FEASIBLE		NO
TIME SHARING FEASIBLE		NO

(1) Based on larger of two types of terrestrial systems operating in the band (1 kw)

(2) Based on smaller of two types of terrestrial systems operating in the band (5 W)

*(-) Indicates Below Interference Threshold of -164 dB(W).
** Percentage number is percent of area los to the radiometer when in view of the interferor.

SECTION 4

FREQUENCY BAND 6.425 - 7.250

ANALYSIS OF PASSIVE REMOTE SENSING

REQUIREMENTS IN THE

6.425 - 7.250 GHz BAND

4.1 ALLOCATIONS

The existing allocation and proposed changes in the 6.425 - 7.250 GHz frequency band are given below for Region 1, 2, and 3. Underlined items indicate proposed additions, and dashed items indicate proposed deletions.

Region 1	Region 2	Region 3
	NON-GOVERNMENT	
6425-~~7250~~ 6925	FIXED MOBILE FIXED SATELLITE (Earth-to-Space) 379A ~~392AA~~ ~~392B~~ 393	
6925-7250	FIXED MOBILE ~~379A~~ ~~392AA~~ MOD 392B ~~393~~ MOD 392AA	

ORIGINAL PAGE IS
OF POOR QUALITY

4.2 MEASUREMENT

Thermal microwave earth emissions to determine:

1) Ocean surface temperature (primary),
2) Soil moisture content (secondary),
3) Estuarine surface temperature (secondary),
4) Ocean sea state (secondary),
5) Sea ice thickness (secondary).

4.3 APPLICATION

More effective and efficient management of:

1) Fishery resources,
2) Deployment of fishing vessels, and
3) Long range weather forecasting.

4.4 GEOGRAPHICAL COVERAGE REQUIREMENTS

Geographical coverage requirements include worldwide ocean areas for ocean surface temperature measurements.

4.5 SENSOR PERFORMANCE AND OPERATIONAL REQUIREMENTS

- Ocean Surface Temperature

Range:	273-300K
Accuracy:	0.5K
Sensitivity:	0.3K
Resolution (Swath):	20 km (800 km)
Update rate:	1 per day
Integration time:	0.05 seconds

Bandwidth:	200 MHz
Sensor Interference Threshold:	-158 dB(W)
Competing Effects:	Sea state (10.7, 19.9 GHz), Water vapor (22.4 GHz), Clouds and Rain (19.9, 37.9 GHz)

- Spacecraft Parameters

Orbital Altitude:	500 km, circular
Inclination:	70-110° (for world-wide coverage)
Antenna:	<1 meter

- Operational Requirements

Ocean surface temperature contours are required once per day. Due to the small required resolution (2-5 km), continuous spacecraft measurements over applicable ocean areas are required to compile these contours.

The data acquired in this frequency band must be used in conjunction with radiometric data gathered simultaneously at other frequencies, in order to eliminate competing effects (i.e., sea state, water vapor, clouds, rain, etc.)

4.6 STATUS OF TECHNOLOGY AND USE

Current development and testing are proceeding on the Scanning Multichannel Microwave Radiometer for flight on the Nimbus-G (1978) and Seasat-A (1977) spacecraft. The Shuttle Imaging Microwave System will be placed on the Shuttle. Operational use is expected by the mid-1980's on Shuttle and Seasat follow-on missions.

4.7 REASONS FOR SELECTION OF THIS FREQUENCY AND BANDWIDTH

The change in received apparent brightness temperature, as a function of sea surface temperature change, is a maximum near this frequency.

Also the required spatial resolution for estuarine and coastal measurements can be achieved with practical spacecraft antennas. Therefore, the 6.425-7.25 GHz region is well suited for spaceborne remote sensing based solely on the application.

The required bandwidth (200 MHz) is determined by radiometer sensitivity, receiver noise temperature and integration time, all of which are fixed by the application. A derivation of the bandwidth value is contained in Volume II, Part B, Section 4.

4.8 SHARING ANALYSIS RESULTS

The 6.425-7.250 GHz band is currently allocated to the Fixed and Mobile Services on a worldwide basis. The following sharing analysis results are based on a sharing analysis of a 200 MHz portion of the 6.425-7.250 GHz spectral region - namely the 6.500-6.700 GHz band. The specific frequency region chosen is based on sensor hardware currently under development.

The analysis is based on information contained in the United States, as well as in international frequency assignment data files. A summary of the results is presented below and in Table 4-1. The detailed sharing analysis can be found in Volume II, Part B, Section 4.

- Due to the large population and spatial distribution of systems currently 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.

- Time sharing in this band is generally considered infeasible due to the anticipated operational nature of the Fixed and Mobile Services.

4.9 SHARING CONCLUSIONS

Sharing on a simultaneous operational basis between space-borne passive microwave sensors and the Fixed and Mobile Services in the 6.5-6.7 GHz region is not feasible. Time sharing is also considered infeasible.

TABLE 4-1

SUMMARY OF SHARING RESULTS

		FIXED AND MOBILE
MAXIMUM RECEIVED POWER (dB RELATIVE TO INTERFERENCE THRESHOLD) IN MAIN BEAM OF ONE INTERFEROR		35 (1)
MINIMUM RECEIVED POWER (dB RELATIVE TO INTERFERENCE THRESHOLD)* FOR ONE INTERFEROR		-22 (2)
LOSS OF COVERAGE AREA FROM SINGLE INTERFERENCE SOURCE	(km^2) %**	7×10^6 (1) 41%
SIMULTANEOUS SHARING FEASIBLE		NO
TIME SHARING FEASIBLE		NO

(1) Based on 1 watt interferor
(2) Based on 40 watt interferor
* Indicates below interference threshold of -158 dB(W)
** Percentage number is percent of area lost to the radiometer when in view of the interferor.

CHAPTER II

PART A

MICROWAVE RADIOMETERY

MICROWAVE RADIOMETRY

Energy at microwave frequencies is emitted and absorbed by the surface of the earth and the atmosphere above the surface. The transmission properties of the absorbing atmosphere vary as a function of frequency as shown in Figure 1. This figure depicts calculated one way zenith (90° elevation angle) attenuation values for oxygen and water vapor.[1]. The calculations are for a path between the surface and a satellite. These calculations reveal frequency bands for which the atmosphere is effectively opaque and others for which the atmosphere is nearly transparent. The regions or windows that are nearly transparent may be used to sense surface phenomena; the regions that are opaque are used to sense the top of the atmosphere.

The power received by a radiometer on a satellite looking down at the earth may be calculated from the equations of radiative transfer[1,2]. For a nonscattering medium,

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

where T_A = antenna temperature

P = received power

ν = center frequency

B = receiver bandwidth

κ = Boltzmann's constant

G = antenna gain

Ω = solid angle about the antenna

T_o = surface brightness temperature (emission plus scattering)

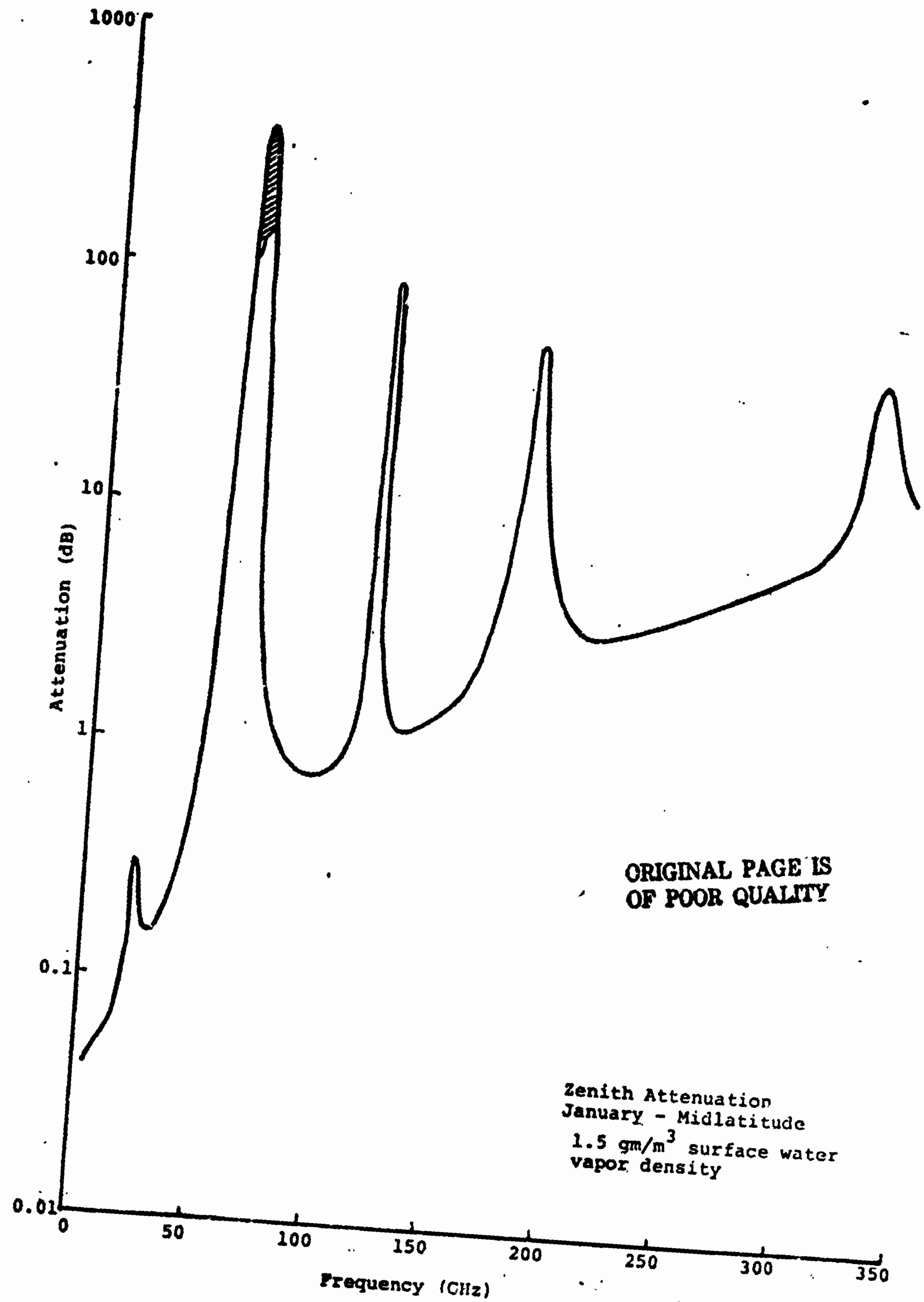
τ = optical depth

β = absorption coefficient

L = path length from satellite to ground

s = position along the path

and $T(s)$ = atmospheric temperature at point s along the path



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 1. Zenith Attenuation vs. Frequency

The optical depth is simply related to the attenuation as

$$\tau(s) = \int_0^s \beta(x)dx = \int_0^s \left(\frac{a(x)}{4.34}\right)dx = \frac{A(s)}{4.34} \quad (2)$$

where A = attenuation (one way)
and a = specific attenuation.

Equations (1) and (2) display the essential features of remote sensing using microwave frequencies. The surface brightness temperature, the atmospheric temperature at points, s, along the path and the absorption coefficients are unknowns to be determined from measurements of the antenna temperature, T_A. The surface brightness temperature and the absorption coefficients in turn depend on the physical properties of the surface or atmosphere that are to be sensed. A single observation at a single frequency cannot be used to estimate a single physical parameter. Observations must be made simultaneously at a number of frequencies and combined with models for the frequency dependence and physical parameter dependence of the surface brightness temperature and of the absorption coefficient before the integral equation, equation (1), may be solved.

The equation may be simplified for application at frequencies in the atmospheric windows where the attenuation is less than 1 dB. For an antenna system with a narrow beam and for an absorber at a constant temperature, T_s the equation reduces to

$$T_A \approx T_0 \ell + T_s(1-\ell)$$

$$\ell = \int_0^L \frac{a(x)}{4.34}\,dx = \frac{A}{4.34}$$

This result shows that even in the windows, the effect of the atmosphere above the surface must be considered.

Atmospheric Absorption

The attenuation does not occur within a single atmospheric layer of constant temperature. Figure 2 displays the variation

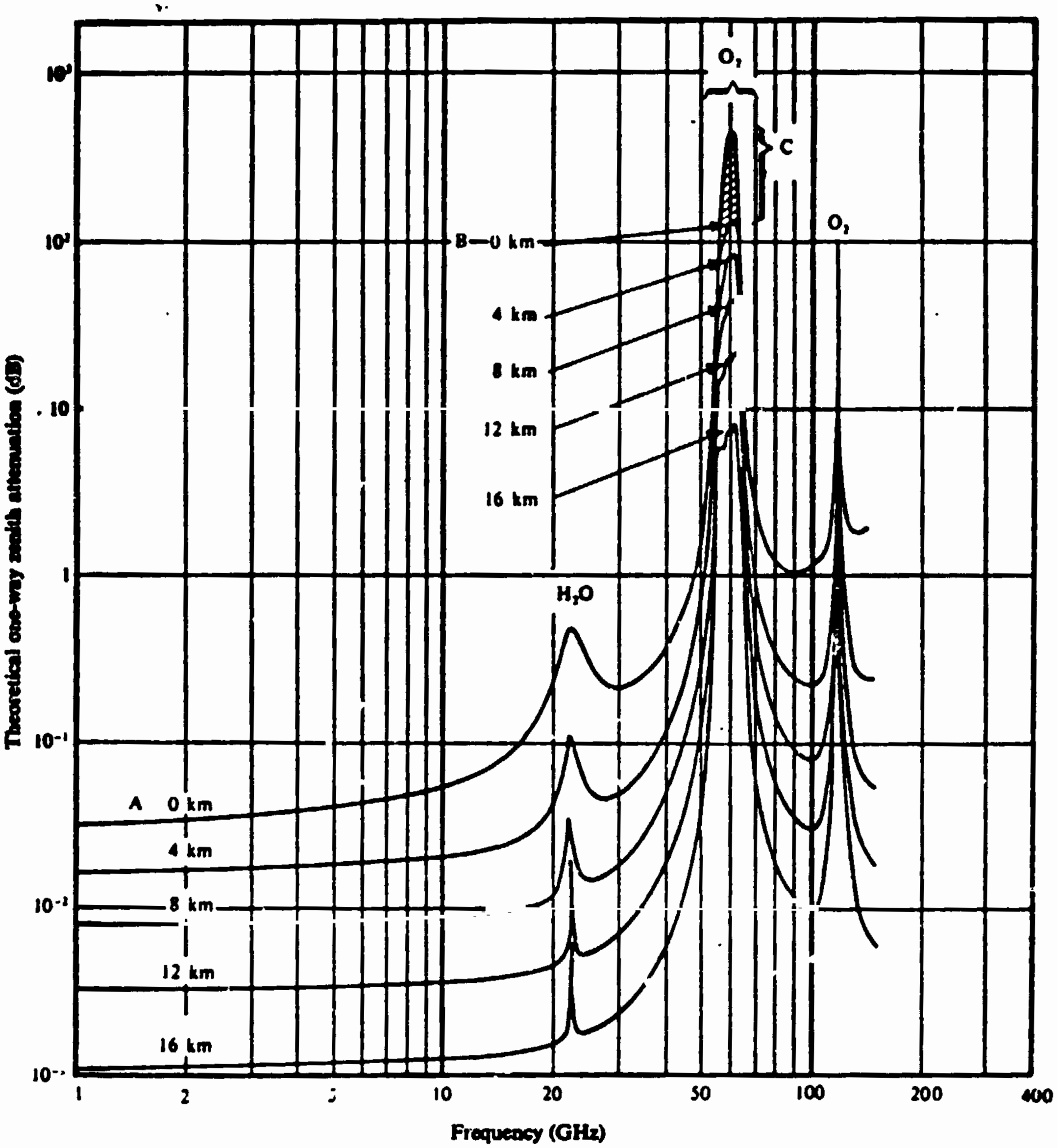


Figure 2. Theoretical vertical one-way attenuation from specified height to top of the atmosphere for a moderate humid atmosphere (7.5 g/m^3 at the surface).

A: Starting heights (km)
B: Minimum values for paths starting at indicated heights (km)
C: Range of values for the path from the surface to 80 km

ORIGINAL PAGE IS OF POOR QUALITY

of attenuation with frequency and height. Equation 1 indicates that the measured antenna temperature depends most upon the temperature in the region along the path where the attenuation (total to the satellite) is less than 10 dB and little on temperatures in regions where the attenuation is very small or the total attenuation to the satellite is large. The temperature values can be sensed at different heights or distances along the path by selecting frequencies near the edges of the opaque regions with different attenuations which provide different weighting functions or multipliers of $T_{(s)}$ in equation (1). The broad opaque region between 50 and 70 GHz is composed of a number of narrow absorption (opaque) lines and observations may be made either at the edges of the complex of lines or in the valleys between the lines. The range of attenuation values - peak to valley for the complex of lines are indicated as shaded areas on Figs. 1 and 2.

A number of different frequencies may be chosen to provide a reasonable set of weighting functions for atmospheric temperature and water vapor profile measurements. Sample calculations for a set of frequencies in the oxygen line complex[3] are given in Figure 3 and for water vapor[4] in Figure 4. Calculations for the channels corresponding to the lowest five frequencies on Figure 3 performed using a statistical procedure for inverting equation (1)[4] show that for a 0.3°K radiometer sensitivity the expected rms uncertainty in the estimated temperatures is less than 2°C for heights above 1 km at midlatitudes over the ocean.

Clouds and rain can provide additional attenuation when they occur along the path. Figures 5 and 6 [illegible] the frequency variation of attenuation due to liquid water and ice in precipitation. These curves show that both rain and clouds may be sensed in the atmospheric windows between 5 and 150 GHz. Multiple observations over a wide frequency range are required to separate rain from cloud and to separate these effects from surface emission[4].

The rain and cloud droplets scatter a part of the energy

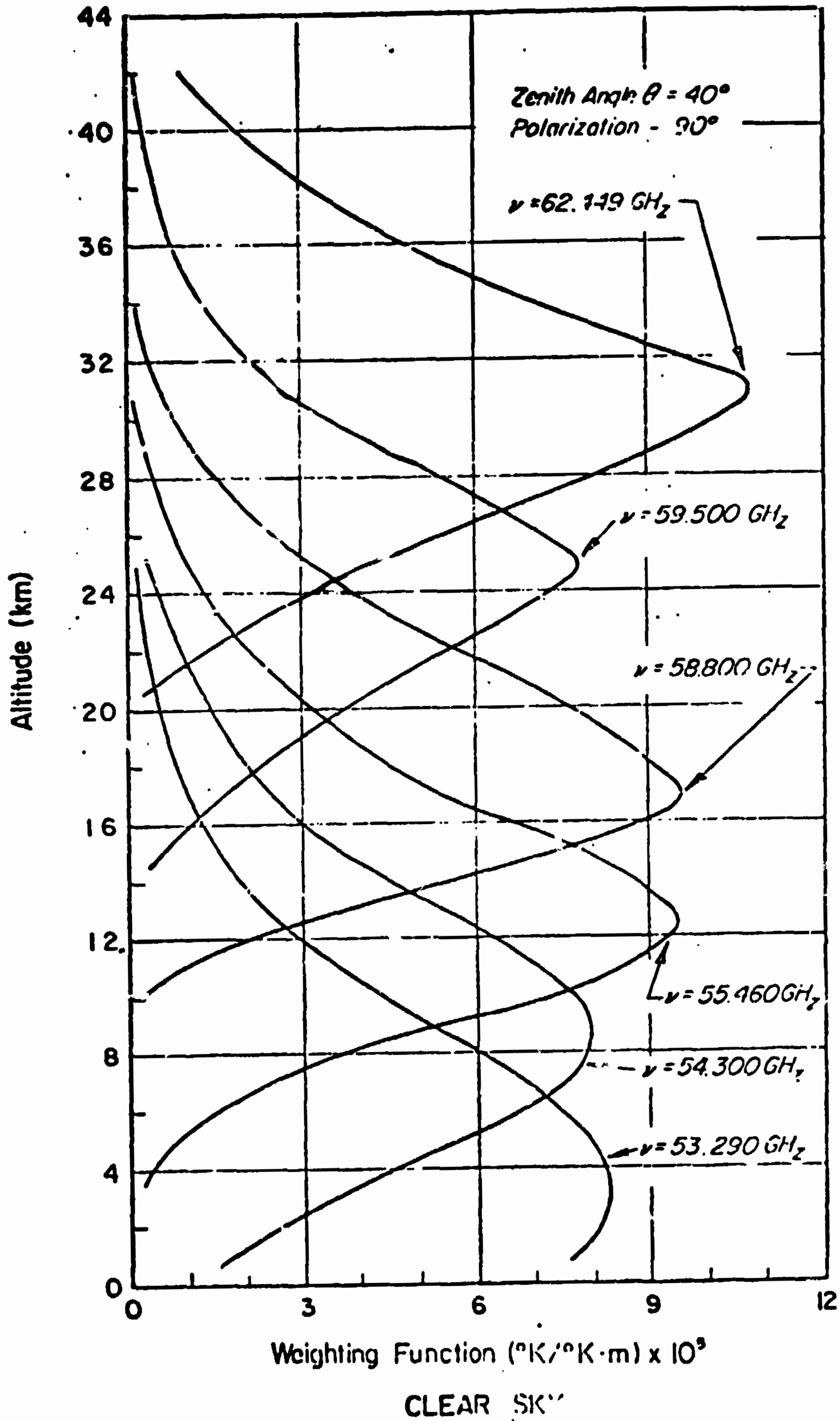


Figure 3. Temperature Weighting Functions

ORIGINAL PAGE IS
OF POOR QUALITY

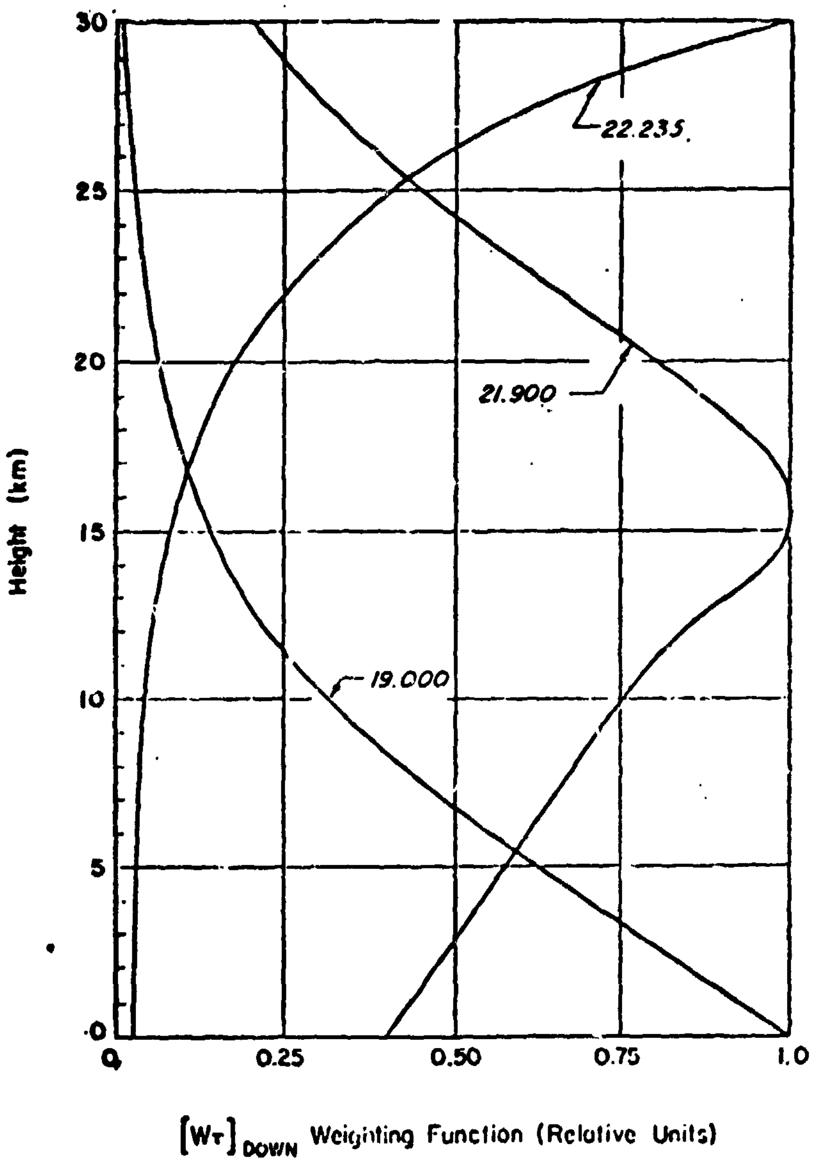


Figure 4. Water Vapor Weighting Functions

C-2

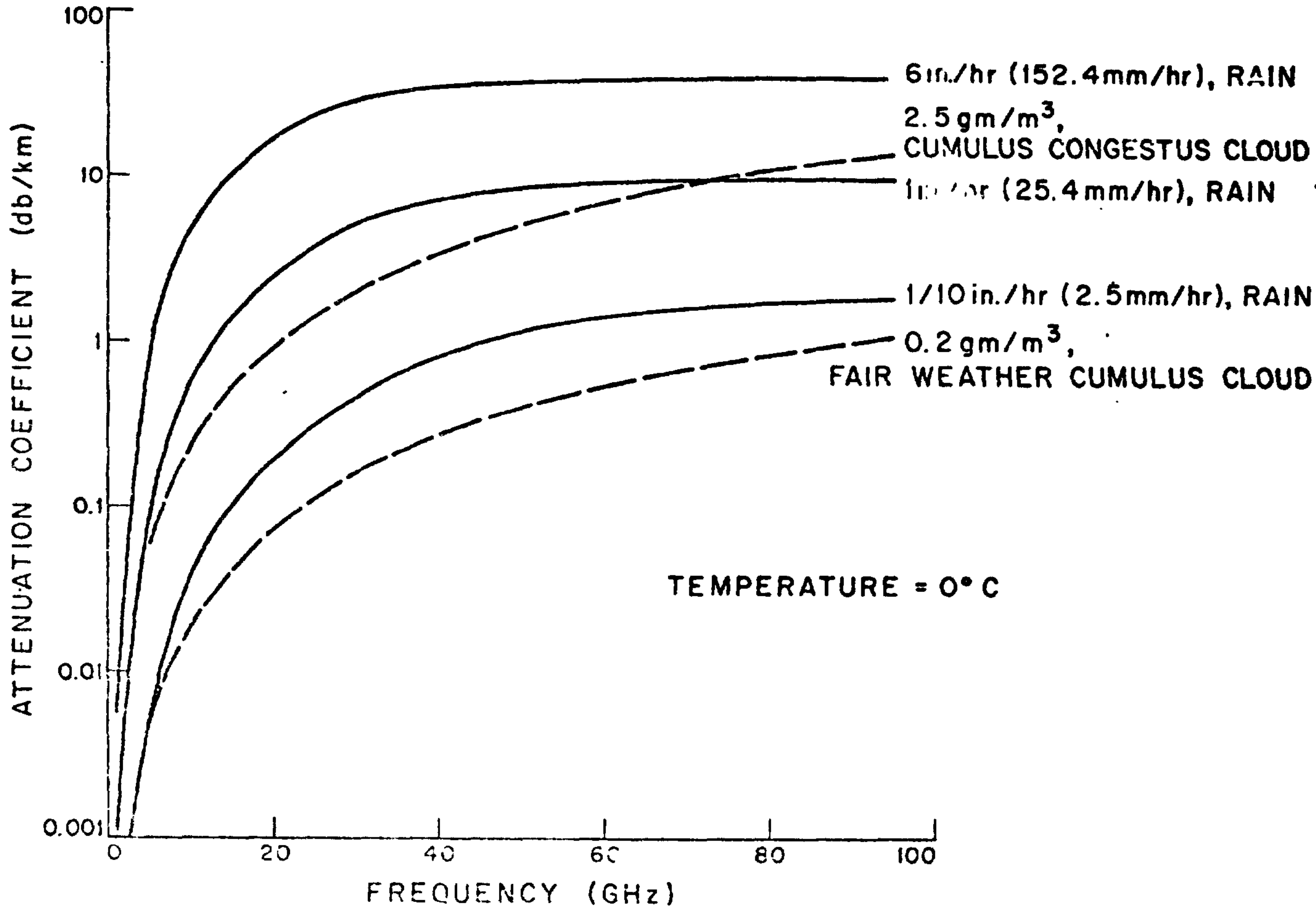


Figure 5. Attenuation Coefficient for Liquid-Water Scatterers

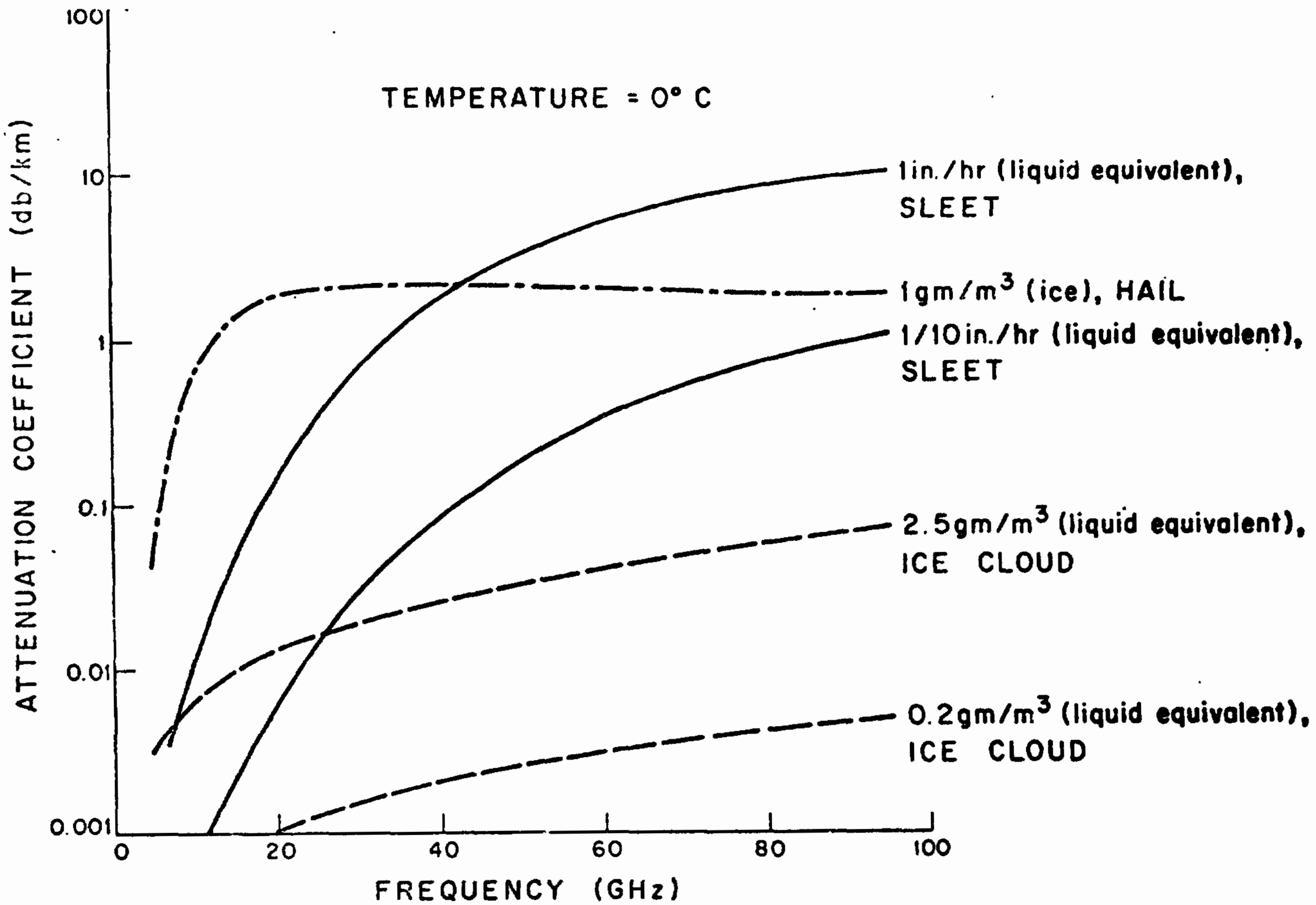


Figure 6. Attenuation Coefficient for Ice Scatters (Spherical)

that is lost due to attenuation. The ratio of energy scattered to that lost by absorption is called the single scattering albedo[1]. Figure 7 depicts the single scattering albedo as a function of frequency for liquid and ice scatterers. If the single scattering albedo is zero, equations (9) and (2) hold but when the single scattering albedo is not zero the effect of scattering must be included in the radiative transfer equation. When the single scattering albedo is near one, attenuation is primarily due to scattering and not to absorption. Under these conditions, little emission is generated by the scatterers although the scatterers still attenuate the emission upwelling from lower regions of the atmosphere and from the surface.

Surface Emission

Emission from the surface of the earth is transmitted through the atmosphere to the satellite. When the attenuation values are high, this emission cannot be sensed. When it is low, as required to sense the temperature of the lowest layer of the atmosphere, both the surface and atmospheric contributions are combined. Additional measurements within the window channels are required to separate the two types of contributions. Surface emission is proportional to the temperature and emissivity of the surface. The latter are related to the dielective properties of the surface and to the roughness of the surface. If the emissivity is less than unity, the surface both emits and scatters radiation. The scattered radiation originates from downward atmospheric emission from above the surface. In a window channel with very small attenuation values this latter contribution is negligible; otherwise it must be considered in the solution of equation (1).

Surface brightness temperatures do not show the rapid variation with frequency exhibited by emission from atmospheric absorption lines. The relatively slow frequency variations of the effects of surface parameters requires simul-

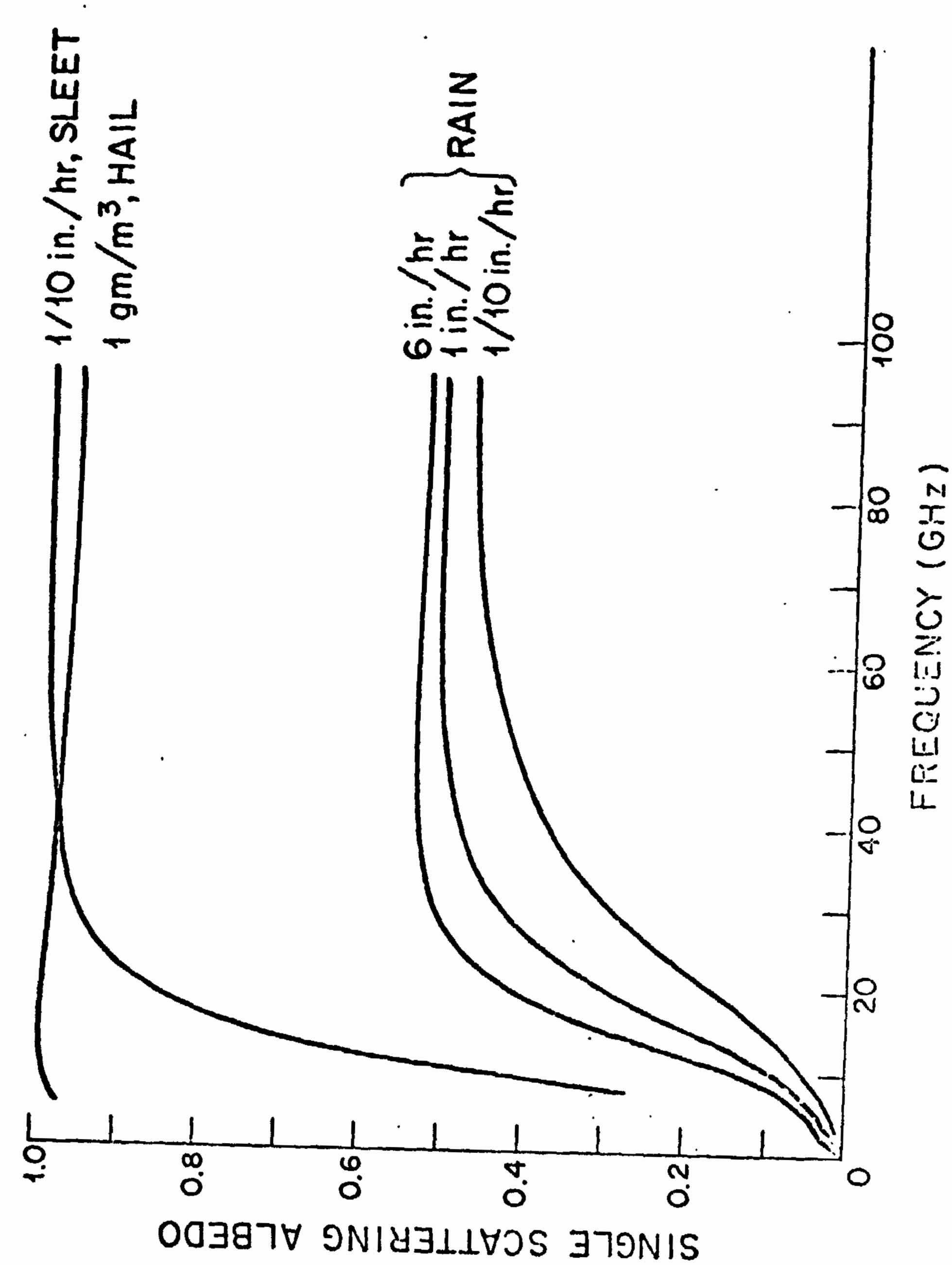


Figure 7. Scattering Albedo vs. Frequency

ORIGINAL PAGE IS
OF POOR QUALITY

taneous observations over a broad frequency range within the atmospheric windows to determine their values. Separation of the parameters can only be accomplished when the parameters have different frequency dependences[4,5]. Figs. 8, 9 and 10 depict the frequency dependence of the several parameters that affect the brightness temperature of the ocean surface, salinity, temperature, and wind. The wind affects the brightness temperature by roughing the surface and by producing foam which has dielectric properties different from the underlying water. These figures show that salinity is best sensed at frequencies below 3 GHz and, if extreme measurement accuracy is required, at frequencies below 1.5 GHz. Sea surface temperature is best sensed using frequencies in the 3 to 10 GHz range with 5 GHz being optimum. Wind affects observations at all frequencies but is best sensed at frequencies above 15 GHz.

Surface layers of ice or oil that float on the surface have dielectric properties different from water and can be sensed due to the resultant change in brightness temperature. Oil slicks can change the brightness temperature above 30 GHz by more than 50°K[6] and ice can change the brightness temperature by more than 50° at frequencies from 1 to 40 GHz[7]. Although ice and oil spills can provide a large change in brightness temperature, a number of observations in each of the atmospheric windows are required to separate the effects of ice and snow from rain and clouds.

The moisture content of the surface layers can be detected at microwave frequencies[8]. The brightness temperature of snow and of soil both change with moisture content and with frequency. In general, the lower the frequency, the thicker the layer that can be sensed. Since the moisture at the surface is related to the profile of moisture below the surface, observations at higher frequencies can also be useful. In sensing the melting of snow near the surface, observations at 37 GHz and higher provide the most information. For sensing soil, especially soil under a vegetation canopy,

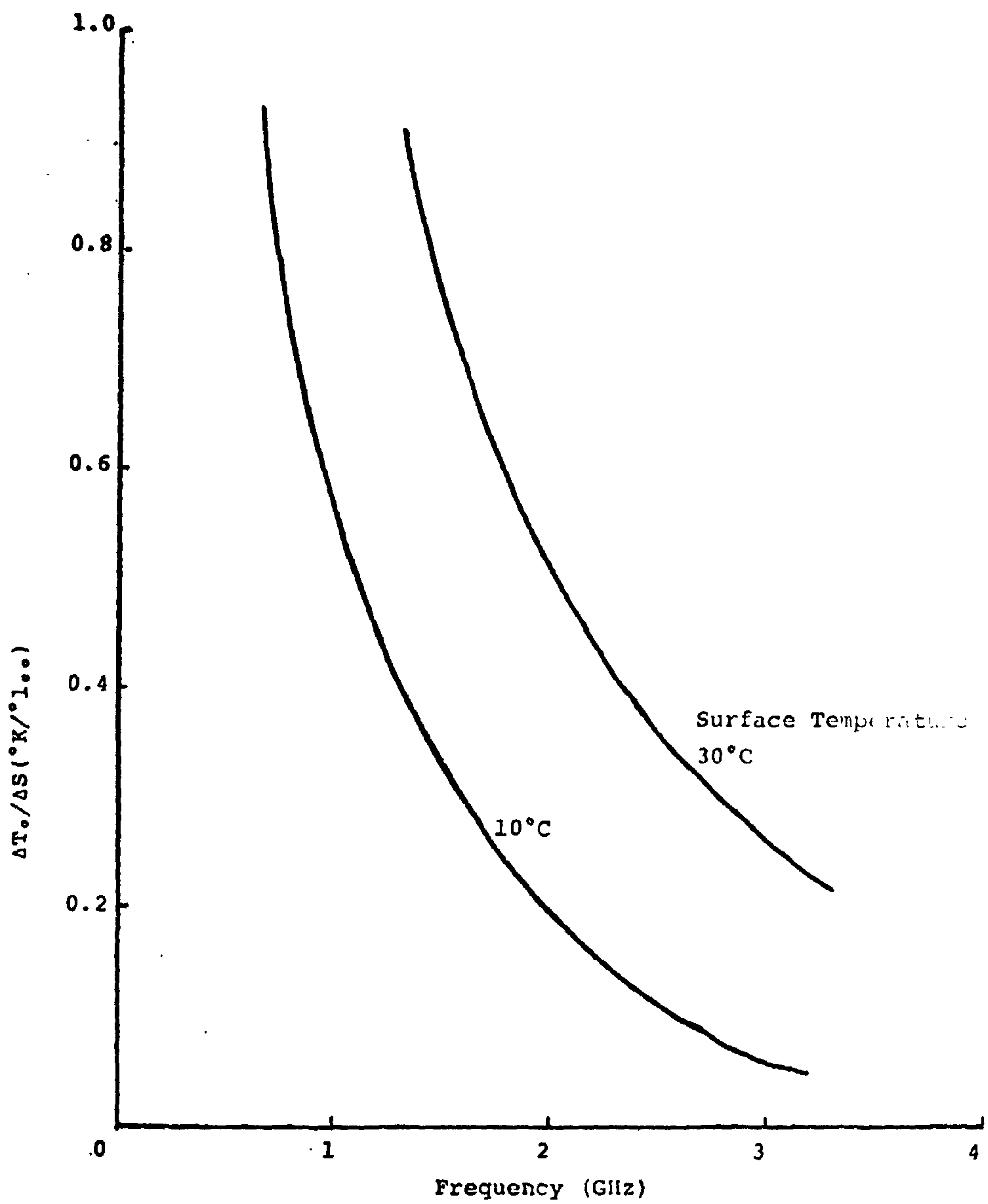


Figure 8. Change in Brightness Temperature with Salinity

ORIGINAL PAGE IS
OF POOR QUALITY

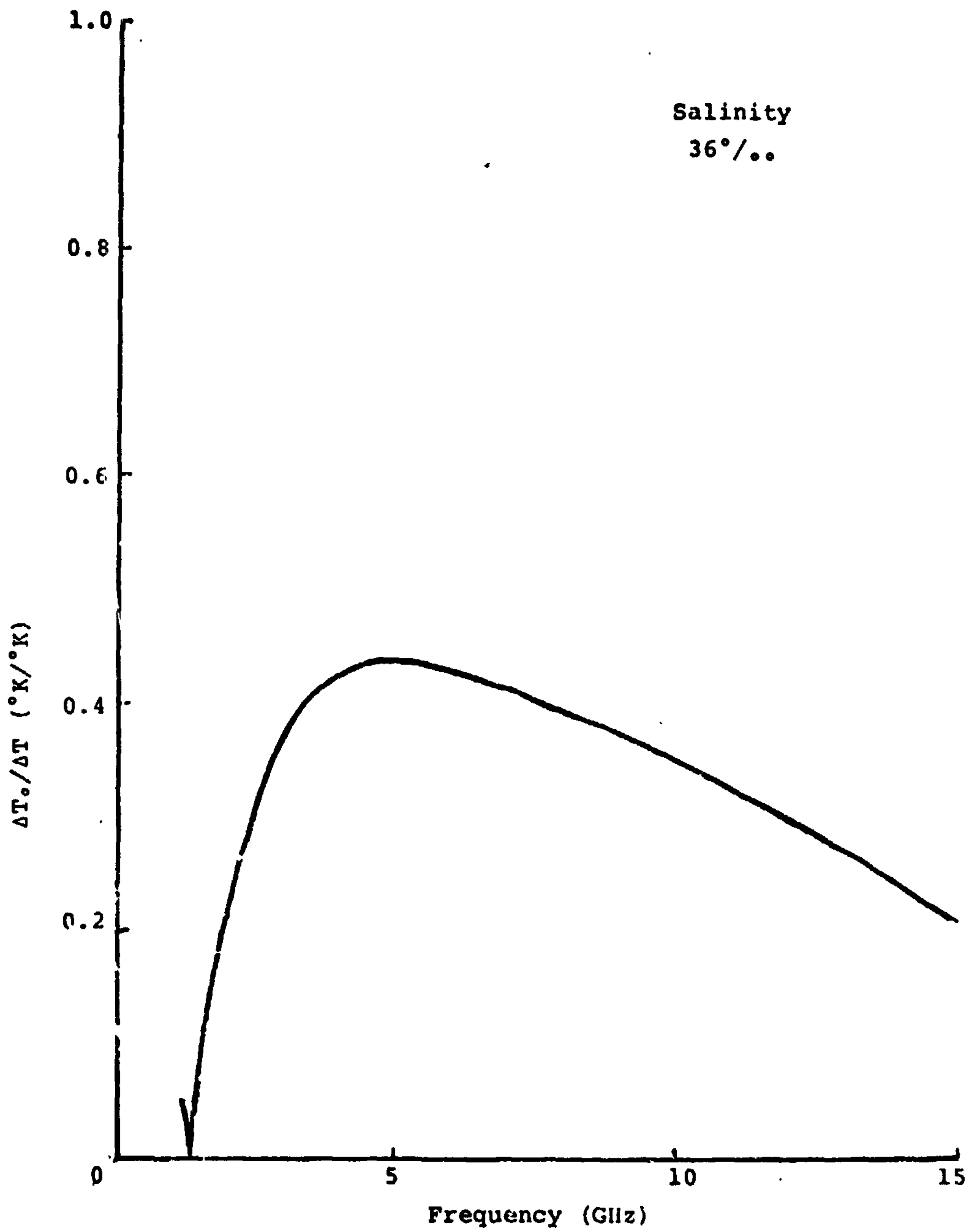


Figure 9. Change in Brightness Temperature with Surface Temperature

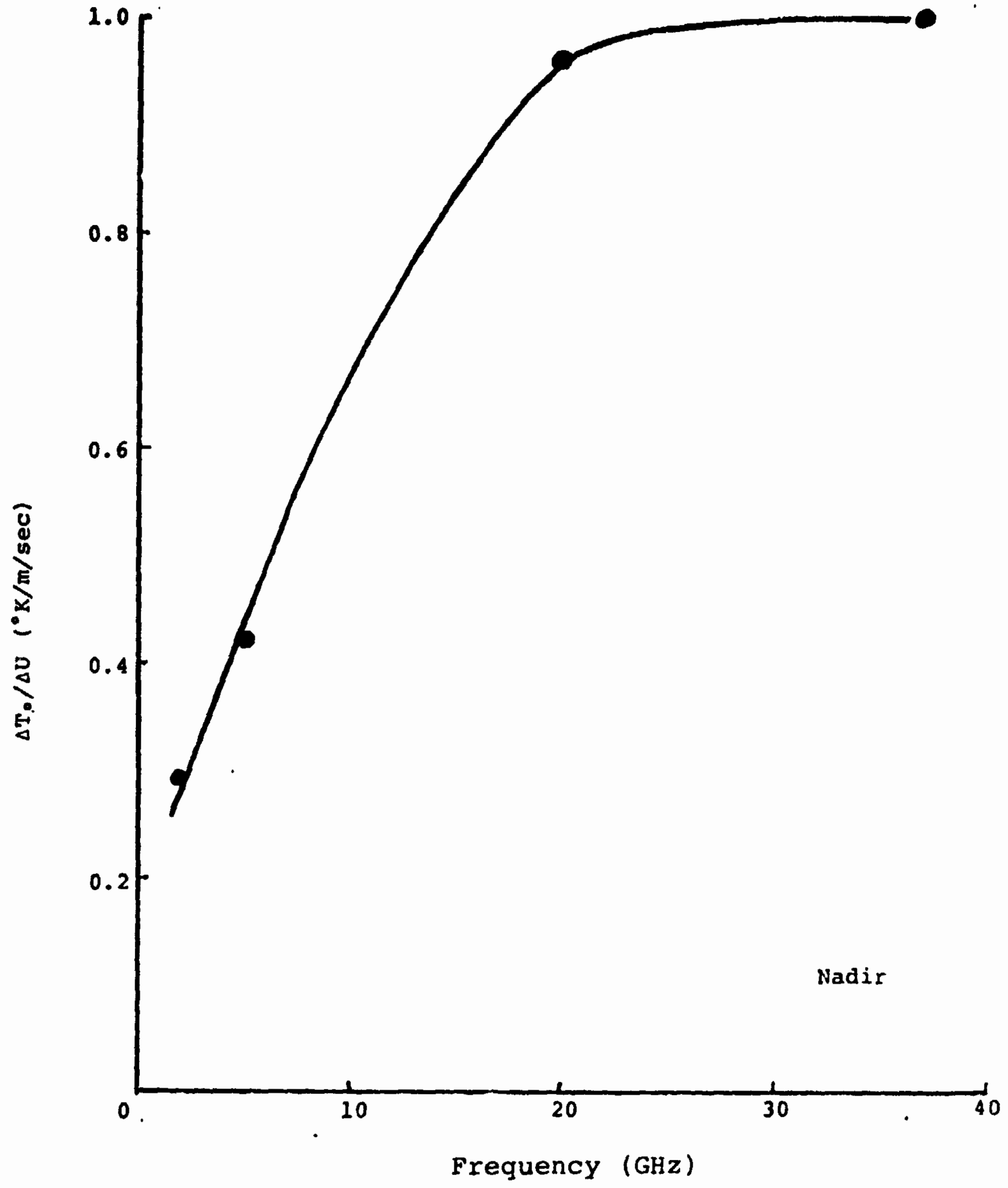


Figure 10. Change in Brightness Temperature with Wind Speed

ORIGINAL PAGE IS
OF POOR QUALITY

frequencies below 3 GHz are of most interest. In practice a number of frequencies are required first to classify the surface as to roughness, vegetation cover, sea ice age, etc., and second to measure parameters such as ice thickness or moisture content. Figures 11, 12, and 13 present sensitivity curves versus frequency for ice[10], soil moisture[11], and snow[12].

Radiometer Sensitivity

Radiometric receivers sense the noise like thermal emission collected by the antenna and the thermal noise of the receiver. By integrating the received signal the random noise fluctuations can be reduced and accurate estimates can be made of the sum of the receiver noise and external thermal emission noise power. Expressing the noise power per unit bandwidth as an equivalent noise temperature, the effect of integration in reducing measurement uncertainty can be expressed as[9]

$$\Delta T = \frac{\alpha(T_A + T_N)}{\sqrt{B\tau}}$$

where ΔT = rms uncertainty in the estimation of the total system noise, $T_A + T_N$

T_A = antenna temperature

T_N = receiver noise temperature

B = bandwidth

τ = integration time

α = receiver system constant.

There are two types of microwave radiometers--total power and Dicke[10]. Total power radiometers measure the noise power received by the antenna, as well as that generated by the receiver system. However, they are subject to calibration errors due to receiver system drift. Dicke radiometers, on the other hand, rapidly switch the input of

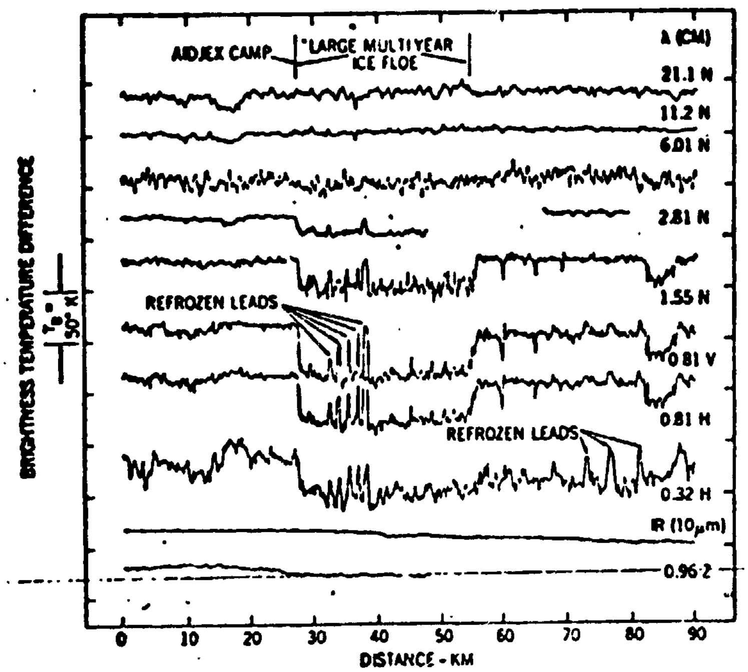


Figure 11. Brightness Temperatures of Ice at Various Frequencies

ORIGINAL PAGE IS OF POOR QUALITY

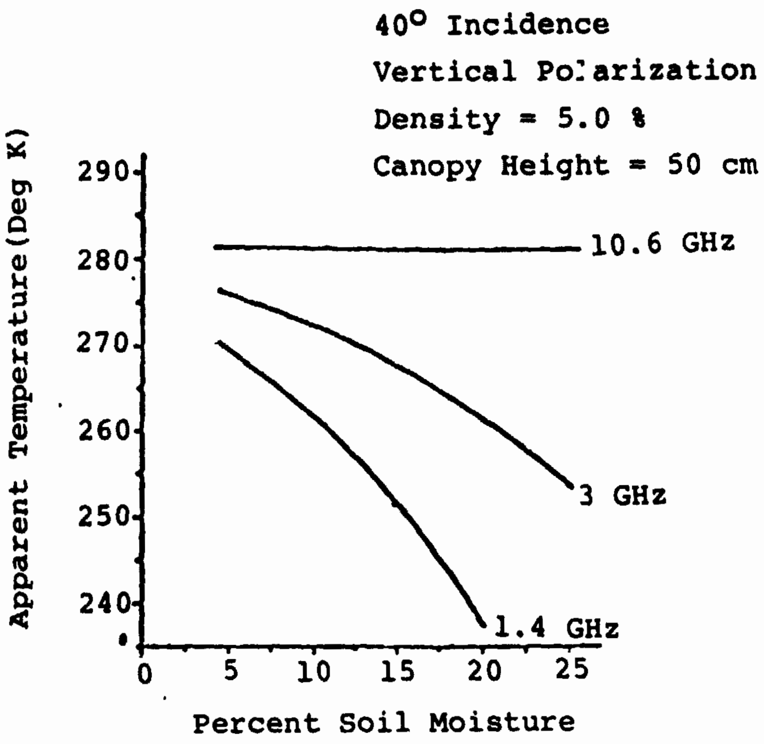


Figure 12. Apparent Temperature of a Uniformly Vegetated Smooth Surface for Various Frequencies

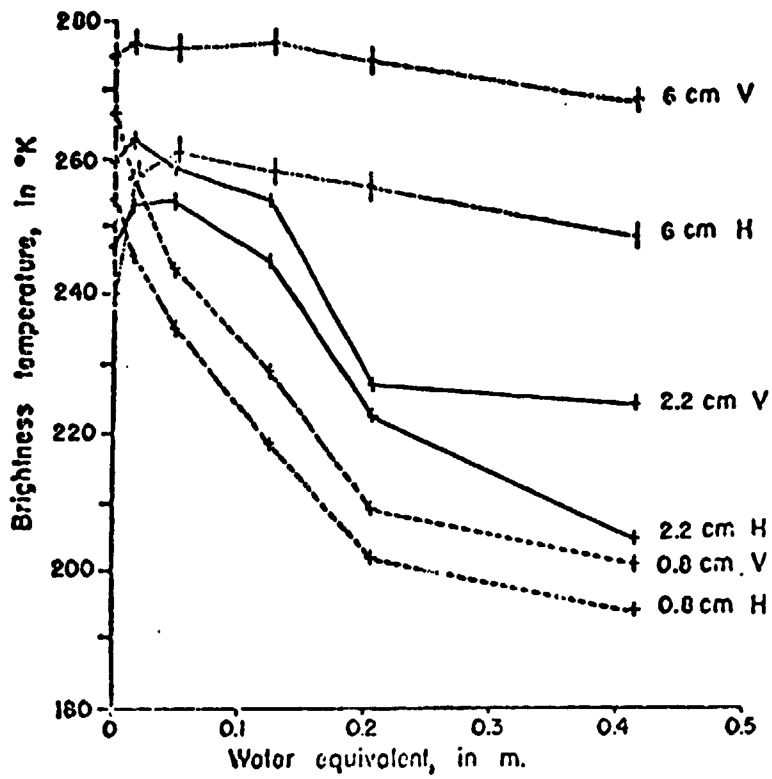


Figure 13. Measured Dry Snow Brightness Temperatures at Various Frequencies and Polarizations

ORIGINAL PAGE IS OF POOR QUALITY

the receiver system between the antenna and a load at a known temperature in order to secure proper calibration. The Dicke receiver output is detected synchronously with the input switching rate and the difference between the two signals is amplified and averaged to provide an output proportional to the difference between the antenna temperature and load temperature. The Dicke radiometer is sensitive to gain changes, but less so than a total power radiometer since amplification at the critical stages in the Dicke receiver system can be performed with ac coupled stages tuned to the switching rate rather than by dc coupled stages. In practice, Dicke radiometers are easier and less expensive to construct, operate and maintain than total power radiometers that provide the same protection against reciver system drift calibration errors.

For an ideal total power radiometer, $\alpha = 1$; for an ideal Dicke radiometer, $\alpha = \sqrt{2}$; and for a practical Dicke radiometer $\alpha = 2$. The bandwidth calculations made for Chapter I and Chapter II, Part B, assumed $\alpha = 2$ unless otherwise stated.

REFERENCES

1. R.K. Crane; 1971 "Propagation Phenomena Affecting Satellite Communication Systems Operating in the Centimeter and Millimeter Wavelength Bands" Proc. IEEE 59 173-188.

2. D.H. Staelin; 1969 "Passive Remote Sensing at Microwave Frequencies" Proc. IEEE 57 427-439.

3. N.E. Gaut. E.C. Reifenstein III, D.T. Chang, and J.C. Blinn III; 1973 "Analysis of Microwave Sounding Systems" Final Report ERT Project P-553, Environmental Research & Technology, Inc., Lexington, Mass.

4. N.E. Gaut, E.C. Reifenstein III, and D.T. Chang; 1972 "Microwave Properties of the Atmosphere, Clouds and the Oceans" Final Report ERT Project P-280, NASA Contract NAS5-21624, Environmental Research & Technology, Inc., Lexington, Mass.

5. M.G. Fowler, J.H. Willand, D.T. Chang, and R.G. Isaacs; 1976 "Estimation of the Geophysical Properties of the Ocean Surface Using Aircraft Microwave Measurements" Final Report ERT Project 1143, NASA Contract NAS5-20619, Environmental Research & Technology, Inc., Concord, Mass.

6. J.P. Hollinger and R.A. Mennella; 1973 "Oil Spills: Measurements of Their Distributions and Volumes by Multifrequency Microwave Radiometry" Science 181 54-56, 6 July 1973.

7. J.C. Blinn III; 1975 "Microwave Measurements of Ice Thickness" Final Report ERT Project P-791, JPL Contract No. 953748, Environmental Research & Technology, Inc., Lexington, Mass.

8. T. Schmugge, P. Gloersen, T. Wilheit, and F. Geiger; 1974 "Remote Sensing of Soil Moisture With Microwave Radiometers" J. of Geophys. Res. 79 317-323.

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

10. R.H. Dicke, R. Beringer, R.L. Kyhl, and A.B. Vane; 1946; "Atmospheric Absorption Measurements with a Microwave Radiometer" Phys. Rev. 70 340-348.

CHAPTER II

PART B

USER REQUIREMENTS AND

DETAILED SHARING ANALYSES

SECTION 1

FREQUENCY BAND 1.3-1.427 GHz

USER REQUIREMENTS

The primary measurements in this band are soil moisture, snow morphology, ocean salinity, sea state, and ice thickness. The principal measurements that constrain system design are ocean salinity and soil moisture.

Salinity measurements over the open ocean require spatial resolutions on the order of 20 km. For a satellite in a 500 km circular orbit, a 20 km resolution (2° beam) requires the use of a 5 meter antenna, depending upon the pointing angle. Since the antenna beam traverses a point on the surface in less than two seconds, the integration time must be less than two seconds.

Salinity in the open ocean changes little with space and time; the ocean salinity range is between 30-36 parts per thousand, and to make adequate measurements, a measurement accuracy of 0.2 parts per thousand is required. Using the sensitivity curves presented in Part A, the required radiometer sensitivity is 0.1 K. For a Dicke radiometer, with system noise temperature of 450 K, a 0.1 K sensitivity and 2 second integration time, the minimum bandwidth is 42 MHz. To map the ocean regions in a reasonable time frame, a minimum swath of 60 km is necessary. This can be obtained by scanning. The integration time for such a scanning system is 0.66 seconds and a bandwidth of 127 MHz is required.

Soil moisture measurements require higher resolutions than salinity measurements. However, due to spacecraft antenna constraints, antennas larger than 20 meters are impractical. In this band a 20 meter antenna will produce a ground resolution of 5 km when a 0.5 second integration time is used.

Soil moisture measurements are required over a 0-30% (dry weight) range with a 1-2% accuracy by weight. Using the sensitivity curves presented in Part A, the required radiometer sensitivity is 1.0 K. For a Dicke radiometer with a system noise temperature of 450 K, 1.0 K sensitivity and 0.5 second integration time, the required bandwidth is 1.6 MHz. To map land areas, however, requires imaging a swath on the order of 200 km. This swath implies an integration time of 0.012 seconds and a 64 MHz bandwidth.

Salinity in the open ocean is affected by storms and the meander of larger scale features such as the Gulf Stream. These change slowly, and worldwide observations on a once per week basis are adequate. Soil moisture is required to provide input to scheduled irrigation and water resources control, and observations are required once per day. Sea ice measurements are used for ship routing, and are required on a once per day basis.

SHARING ANALYSIS

Portions of the 1.300-1.427 GHz band are currently allocated to the Aeronautical Radio Navigation, Radiolocation, Fixed, Mobile, and Radio Astronomy Service. Fixed and Mobile Service allocations are confined to Region 1.

Since radio astronomy (1.400-1.427 GHz) can inherently share with another passive service, the following sections discuss the frequency sharing potential between the Earth Exploration Satellite Service and the Aeronautical Radionavigation, Radiolocation, Fixed and Mobile Services in the 1.3 to 1.4 GHz frequency range.

1.1 Aeronautical Radionavigation and Radio Location Services

Current U.S. and International frequency assignments reveal extensive use of the frequency range 1300-1400 MHz for Aeronautical Radionavigation and Radiolocation. U.S. data files alone reveal about 100 transmitters in the frequency range of 1300-1350 MHz. The transmitters have powers of up to 5 MW peak. Foreign listings appear to be quite similar to the U.S. listings as to power and gain. Since no information is given in the foreign listings concerning duty cycle, the detailed sharing analysis given in the following paragraphs is based largely on U.S. system characteristics.

1.1.1 Technical Characteristics

Transmitters in the Aeronautical Radionavigation and Radiolocation Services are typically pulsed radars. Essential characteristics representative of the vast majority of registered systems are as follows:

Transmitter power (peak)	67 dB(W)
Antenna Gain	34.5 dB(i)
Pulse Repetition Rate	310 to 364 pps
Pulse Duration	2 μsec
Transmitter Bandwidth	14.4 MHz

The effect of a pulsed signal on the apparent radiometer measurement is a function of its average power rather than peak power.

Using a pulse repetition rate of 333 pps, which is typical of long range radars, the average power output of the radar transmitter is found to be 35.2 dB(W).

The radar characteristics used in the sharing analysis are as follows:

Transmitter Power (average)	35.2 dB(W)
Transmitter Antenna Gain	34.5 dB(i)
Transmitted Power (average)	69.2 dB(W) e.i.r.p.

1.1.2 Sharing Considerations

1.1.2.1 Simultaneous Operations

The maximum interference level occurs when the radiometer is located in the main beam of the interference source. This occurs at low elevation angles as seen from the radar station.

The level of the interference would be:

Transmitter Power	35.2 dB(W)
Transmitter Antenna Gain	34.5 dB(i)
Spreading Loss	-139 dB(i)
Radiometer antenna effective area (sidelobe)	- 38 dB(m^2)
Received Interference Power	-107.3 dB(W)

or 57.7 dB above the interference threshold of -165 dB(W).

It is known that there are nearly one hundred such transmitters in the U.S. alone. Analysis of international listings indicates that this band is used extensively for radiolocation and/or radionavigation purposes. The Gain-Range Quotient Analysis Program* was utilized to simulate the couplings between the radiometer and transmitter antennas as the spacecraft orbits the earth. The loss of coverage area was found to be 100% of the visibility sphere as seen from the terrestrial station.

---

* See Appendix I

Consequently, sharing on a simultaneous operational basis is considered infeasible.

1.1.2.2 Time Sharing

Aeronautical Radionavigation and Radiolocation installations transmit on a 24-hour basis, and must continue to do so, since this operation is required for aeronautical safety. Time sharing of the frequency spectrum is therefore infeasible.

1.1.3 Conclusions on Sharing with Aeronautical Radionavigation and Radiolocation Services

Due to large required e.i.r.p.'s and numerous transmitters in these services, sharing on a simultaneous operational or time basis in the 1300-1400 MHz spectral region is considered infeasible.

1 2 Fixed and Mobile Services

Fixed and mobile operations in the 1.3-1.4 GHz band are confined to Region I. Inspection of the IFRB listings for this region reveals a substantial number of registrations in Europe. All of the registrations are in the Fixed Service. No registrations were found in Africa. Based on the powers specified in the registrations it is possible to group the existing stations into low, medium and high power categories. The interference analysis detailed in the following paragraphs is predicated on an assumed mix of the three categories.

1.2.1 Technical Characteristics

The Fixed Service transmitters located in the IFRB Files fall into the following categories:

A. High Power (25% of users)

Transmitter Output Power	23 dB(W)
Antenna Gain	32 dB (i)
Transmitted e.i.r.p.	55 dB(W)

B. Medium Power (35% of users)

Transmitted Output Power	17 dB(W)
Antenna Gain	30 dB(i)
Transmitted e.i.r.p.	47 dB(W)

C. Low Power (40% of users)

Transmitted Output Power	5 dB(W)
Antenna Gain	32 dB(i)
Transmitted e.i.r.p.	37 dB(W)

The major locations of these transmitters are the European countries in Region 1.

1.2.2 Sharing Considerations

1.2.2.1 Simultaneous Operation

The maximum interference level occurs when the sensor is in the main beam of a terrestrial station; for the Fixed and Mobile Services this takes place when the spacecraft is on the horizon as seen from the terrestrial station. The interference level from a single terrestrial transmitter is computed as follows:

A. High Power

Transmitter Output Power	23	dB(W)
Transmitter Antenna Gain	32	dB(i)
Spreading Loss	-139	dB(m^{-2})
Radiometer Effective Area (sidelobe)	-38	dB(m^2)
Received Interference Power	-122	dB(W)

or 47 dB above the interference threshold -165 dB(W).

B. Medium Power

Transmitter Output Power	17	dB(W)
Transmitter Antenna Gain	30	dB(i)
Spreading Loss	-139	dB(m^{-2})
Radiometer Antenna Effective area (sidelobe)	-38	dB(m^2)
Received Interference Power	-130	dB(W)

or 39 dB above the interference threshold -165 dB(W).

C. Low Power

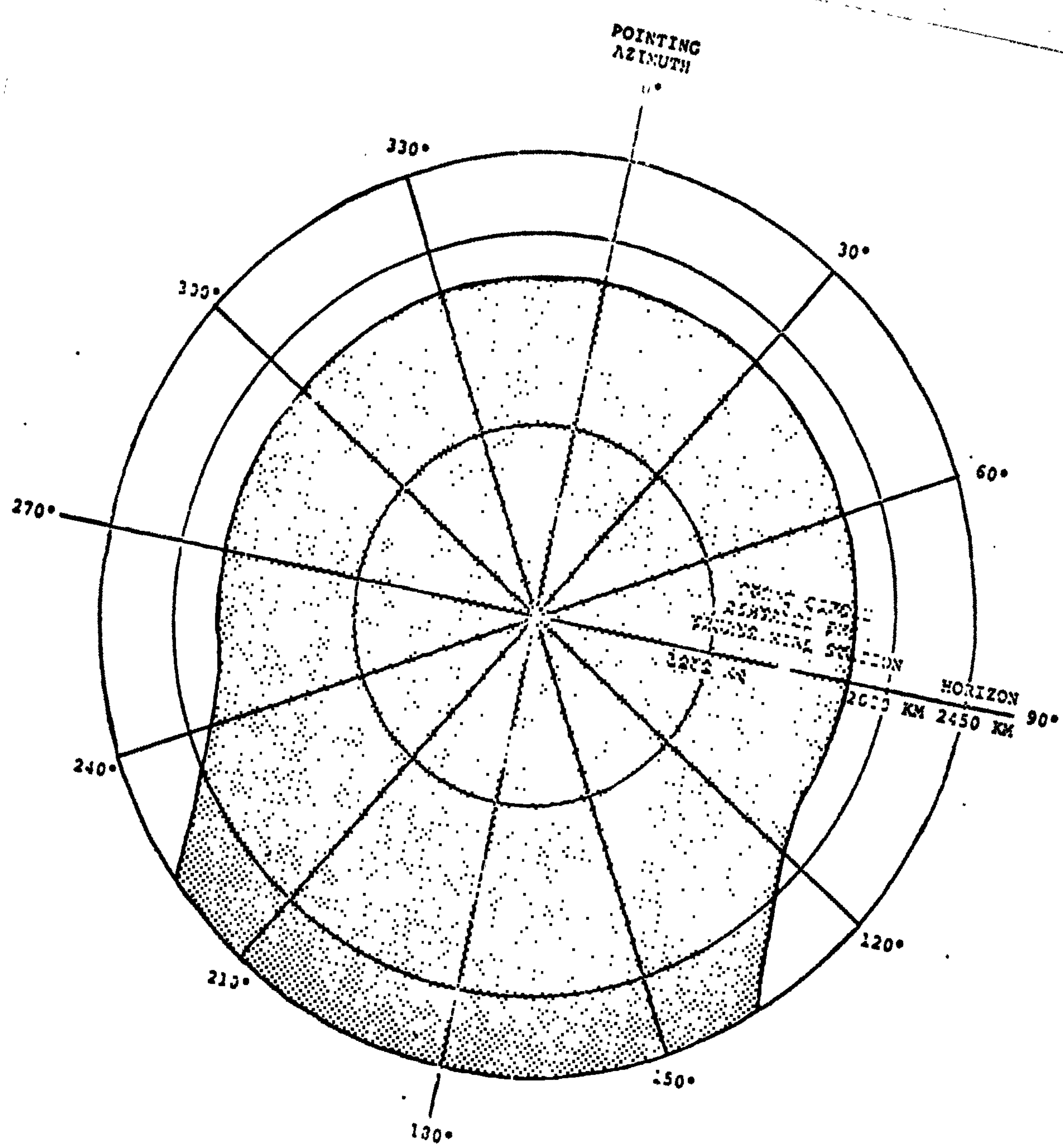
Transmitter Output Power	5 dB
Transmitter Antenna Gain	32 dB(i)
Spreading Loss	-139 dB(m^{-2})
Atmospheric Loss	0 dB
Radiometer Antenna Effective Area (sidelobe)	-38 dB(m^2)
Received interference power	-140 dB(W)

or 25 dB above the interference threshold.

Figures 1-1, 1-2, and 1-3 illustrate the loss of coverage area resulting from operation of a single Fixed or Mobile Service station having high, medium, and low power, respectively. The area lost due to operation of a high power station corresponds to 94% of the visibility sphere around the earth station. For a medium power station, the loss of coverage area is about 37% of the visibility sphere, and for a low power station, 5%.

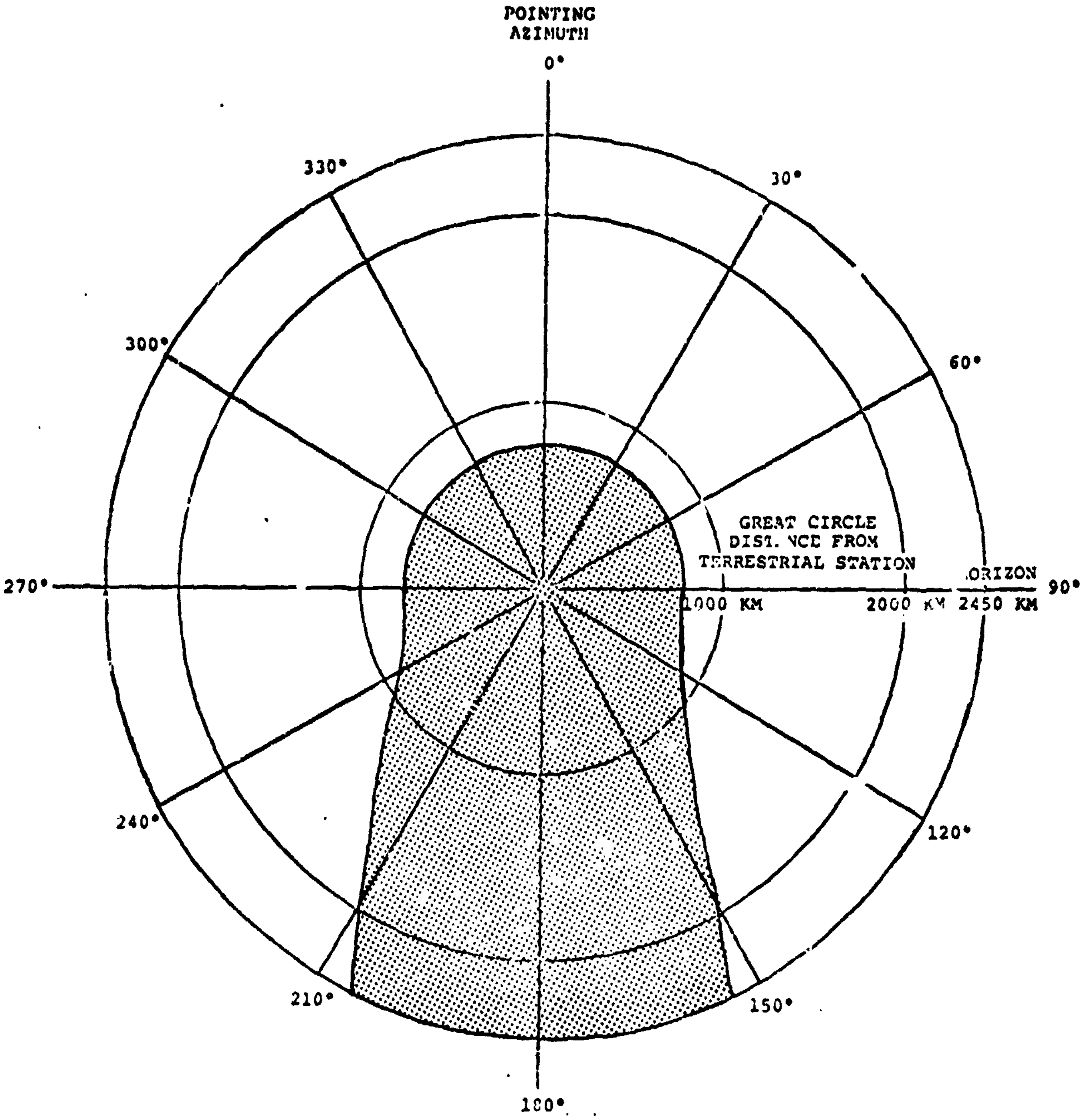
The Random Interference Analysis Program* was utilized to simulate the multi-interferor interference environment based on the expected system parameters. Figure 1-4 presents the results of this analysis for a mix of high-, medium-, and low-power transmitters. The figure relates the probability of data loss to the number of terrestrial transmitters simultaneously operating and visible to the radiometer. Only a few transmitters, simultaneously in view of the radiometer, will produce a total loss of data. The total overall world interference situation for Fixed and Mobile Services, as well as Aeronautical Radionavigation, is illustrated in Figure 1-5.

*See Appendix II.



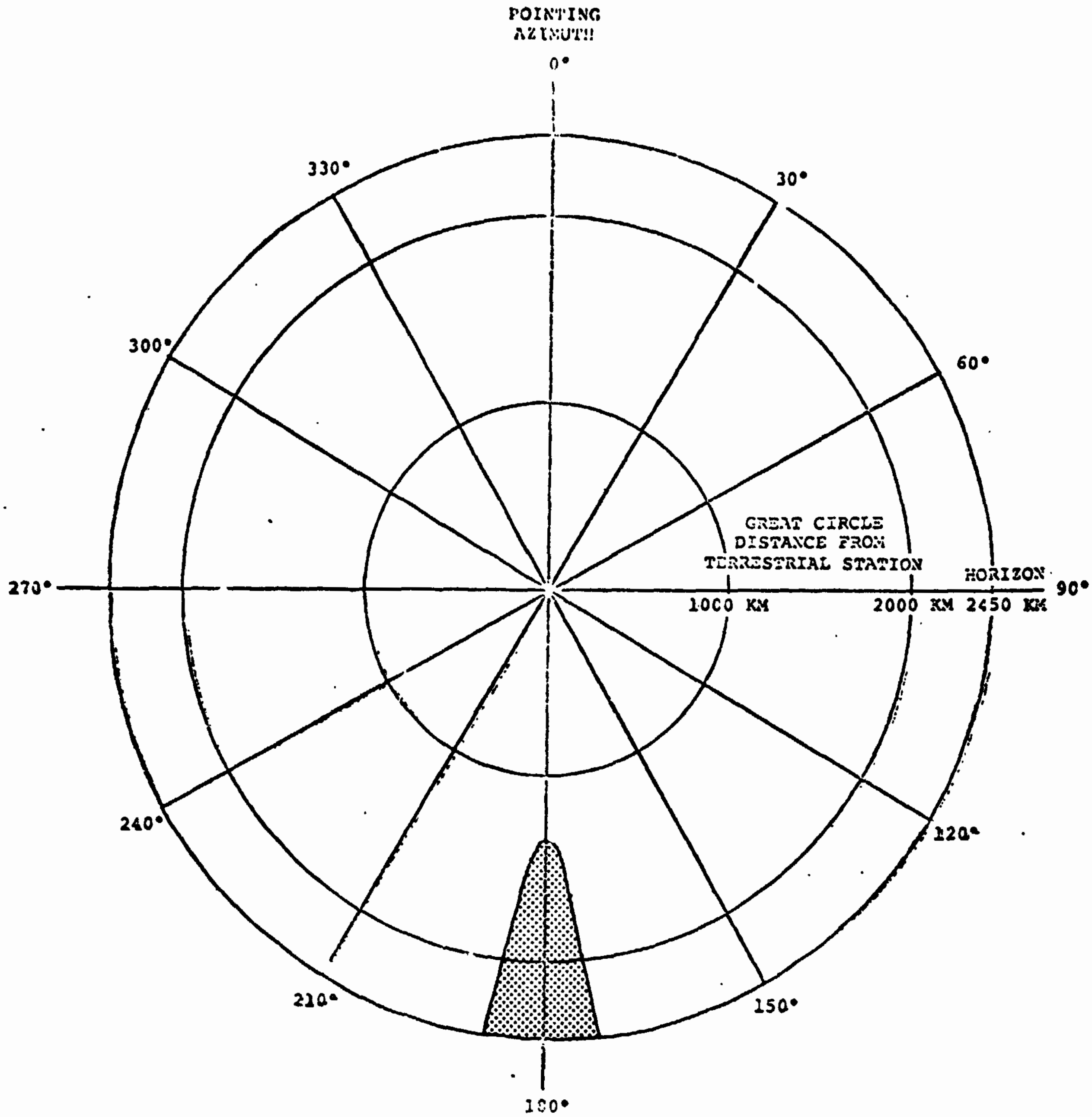
Note: Shaded areas indicate region where interference and, therefore, loss of coverage occurs. Terrestrial station is located in center.

Figure 1-1. Loss of Coverage Area Due to Single High Power Emitter - Fixed and Mobile Service



Note: Shaded areas indicate region where interference, and therefore, loss of coverage occurs. Terrestrial station is located in center.

Figure 1-2. Loss of Coverage Area Due to Single Medium Power Emitter - Fixed and Mobile Service



Note: Shaded areas indicate region where interference and, therefore, loss of coverage occurs. Terrestrial station is located in center.

Figure 1-3. Loss of Coverage Area Due to Single Low Power Emitter - Fixed and Mobile Service

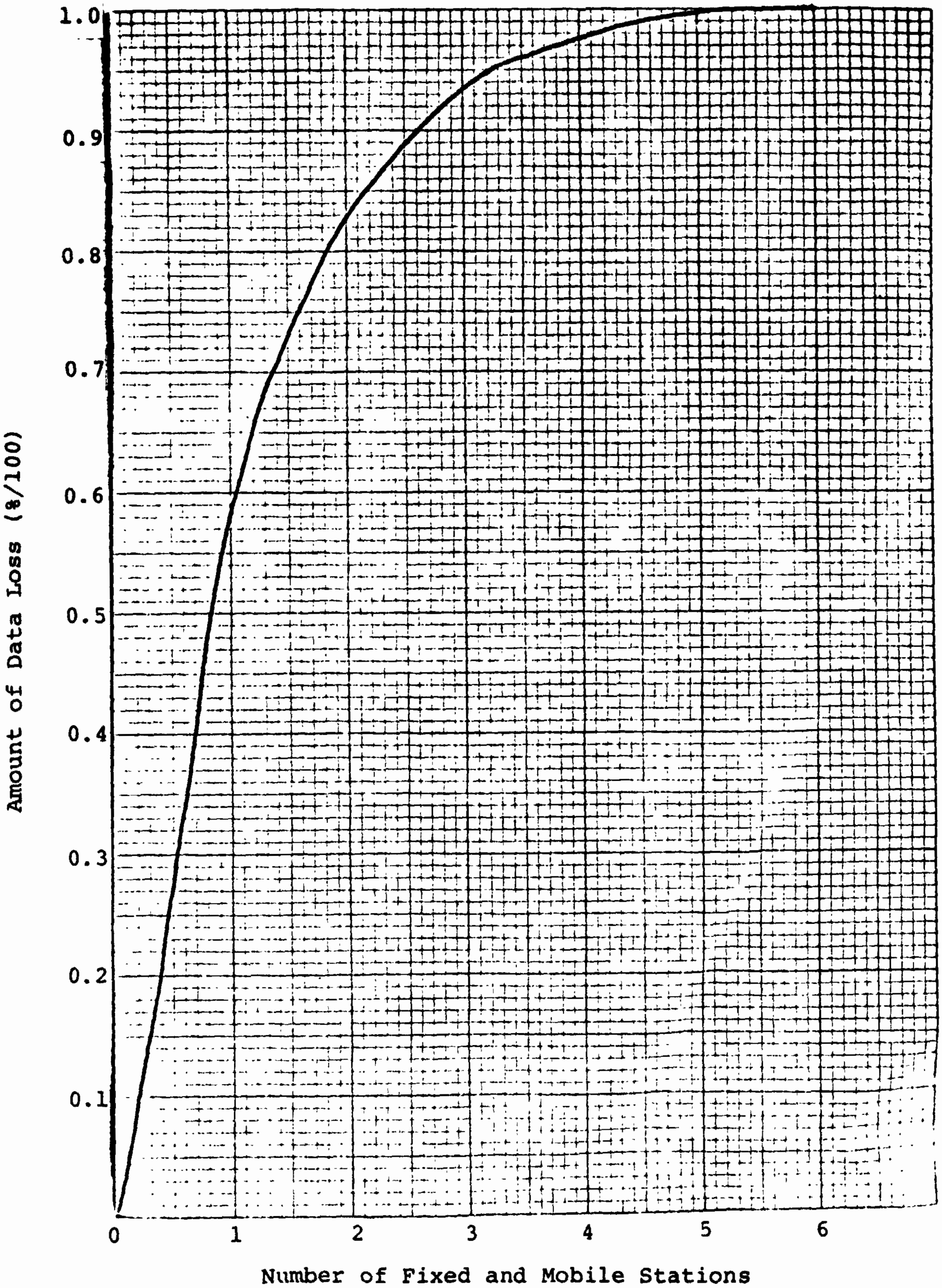


Figure 1-4. Data Loss vs. Number of Fixed and Mobile Stations

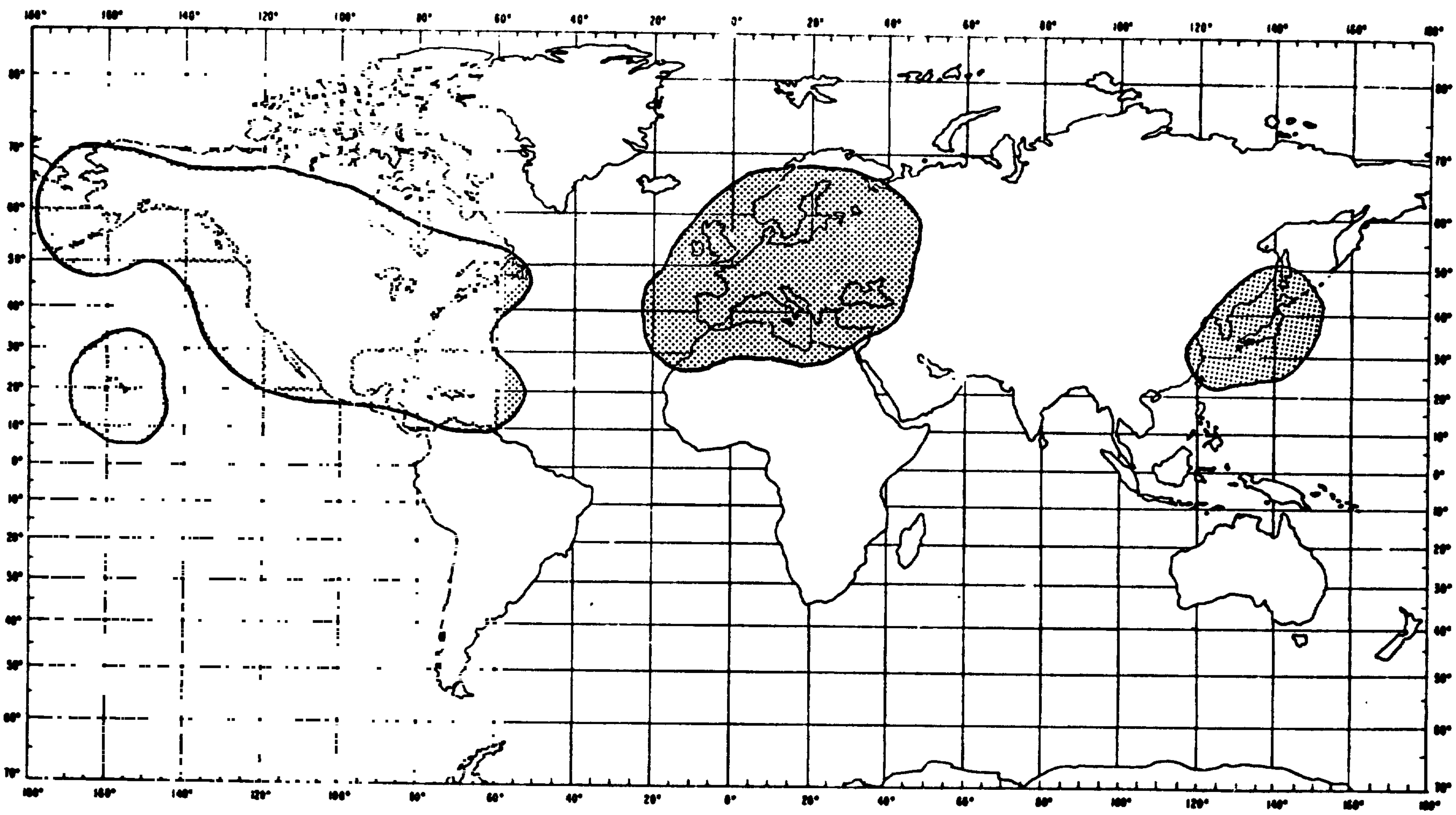


Figure 1-5 Loss of Coverage Area Due to Fixed and Mobile, and Aeronautical Radionavigation

1.2.2.2 Time Sharing

Analysis of IFRB listings indicates that the fixed transmitters registered in Region 1 are largely operated by National PTT agencies, and, as such, are used for common carrier point-to-point service. Such operations are generally full period in nature, rendering time sharing, as a means of sharing the band, infeasible.

1.2.3 Conclusions on Sharing with Fixed and Mobile Services

Due to the large e.i.r.p.'s and numerous transmitters in the Fixed and Mobile Services in the 1300-1400 MHz spectral region, sharing on a simultaneous operational or time basis is considered infeasible.

SECTION 2

FREQUENCY BAND 2.640-2.700 GHz

USER REQUIREMENTS

The principal measurement for this band is estuarine salinity. Estuaries are relatively small bodies of water with a wide range of salinity. In this band, the primary measurement requirement is to limit the satellite beam pattern on the ground to a small percentage of the total estuarine area. For small estuaries, a 2-5 km maximum spatial dimension of the beam on the ground is adequate and requires a 10-25 meter antenna. For a satellite in a 500 km circular orbit, the beam will move one spatial resolution element in 0.2 seconds. The integration time, therefore, must be 0.2 seconds or less.

The total salinity ranges to be sensed within an estuary are 10 to 35 parts per thousand. The required measurement accuracy is 2-5 parts per thousand. Using the sensitivity curves given in Part A, the required radiometer sensitivity is 0.2 to 0.5 K for a 10 C water temperature, and 0.6 to 1.5 K for a 30 C water temperature. The minimum sensitivity requirement to span all surface temperature values of interest is 0.1 to 0.3 K.

The minimum radiometer bandwidth required to obtain a 0.1 K radiometer sensitivity with a 0.2 second integration time is 60 MHz if a total power radiometer is used, and 240 MHz if a Dicke switched radiometer is used.

Salinity within an estuary is affected by storms and, on a longer time scale, by runoff of fresh water from rivers and streams feeding into the estuary. Marine organisms tolerate the rapid salinity changes associated with the storms, but are not tolerant to long term changes. Observations must be made with sufficient frequency to track changes caused by variations in runoff. Therefore, observations would be required once per week throughout each season.

SHARING ANALYSIS

There are five services currently allocated within the 2.64 to 2.7 GHz spectral region - these are the Fixed, Mobile, Broadcasting-Satellite, Fixed-Satellite (earth-to-space only), and Radioastronomy Services.

Since the Radioastronomy Service can inherently share with another passive service, the following sections analyze the sharing potential between the Earth Exploration Satellite Service (passive) and each of the existing allocated services occupying the band. The Fixed and Mobile Services are treated together, due to the commonality of technical characteristics relevant to sharing. For the purposes of this analysis, the Fixed and Mobile Services category has been subdivided into the United States region and the International Telecommunications Union region.

A.1 Fixed and Mobile Service - United States

2.1.1 Instructional Television Fixed Service (ITFS)

Within the United States, the primary user of the 2.64 to 2.69 GHz band is the Instructional Television Fixed Service (ITFS). The ITFS consists of a large number of small transmitter/receiver systems utilized to relay video and audio communications between educational institutions, or between a series of individual buildings at a single institution.

The spectrum region available for use by the ITFS is divided into 31 separate channels, the assignments of which are controlled by the FCC. Seven of the 31 channels lie within the 2.64 to 2.69 GHz region. These channels are designated as the ITFS G and H* channels. Figure 2-1 shows the approximate physical locations of the 65 ITFS systems presently operating on the G and H channel assignments. Fifty-four of the systems are located in the eastern United States, and eleven are located in California.

2.1.1.1 Technical Characteristics

The technical characteristics of the ITFS transmitters depend upon the separation between the institutions being served, and upon the number of receivers being accommodated by a single originating or relaying transmitter. The following two ITFS transmitter models appear to be representative:

---

* "H" channels are used primarily by a few point-to-point systems which are "grandfathered" in the 2500-2690 MHz band.

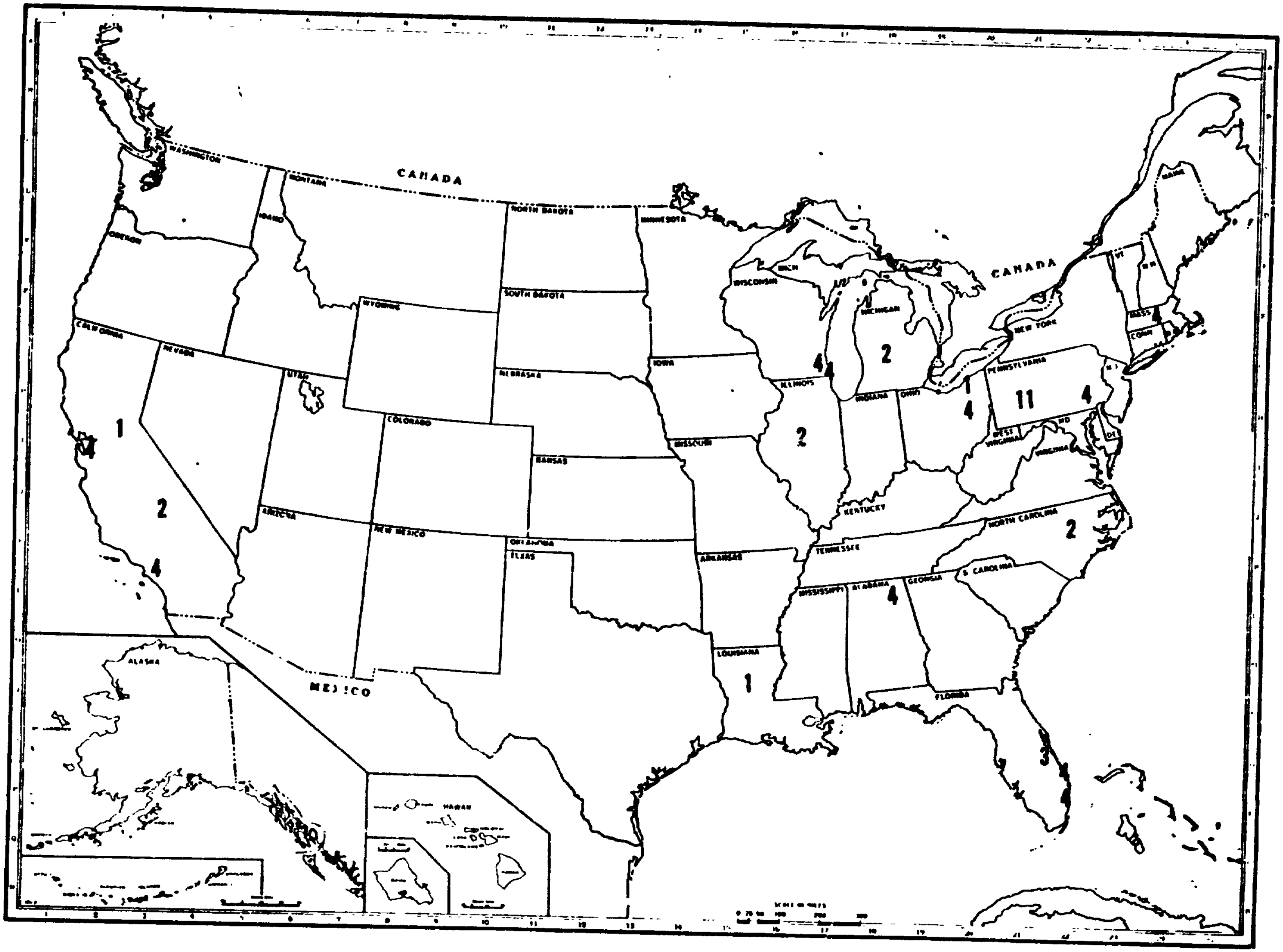


Figure 2-1 Distribution of Channel G and H ITFS Systems in the U.S.

(1) Antenna Type = Vertical stacked-array

Antenna Pattern = 13 dB(i) horizontal gain, omni

Transmitter Power = 7 to 10 dB(W)

(2) Antenna Type = paraboloid

Antenna Gain = 26 dB(i)

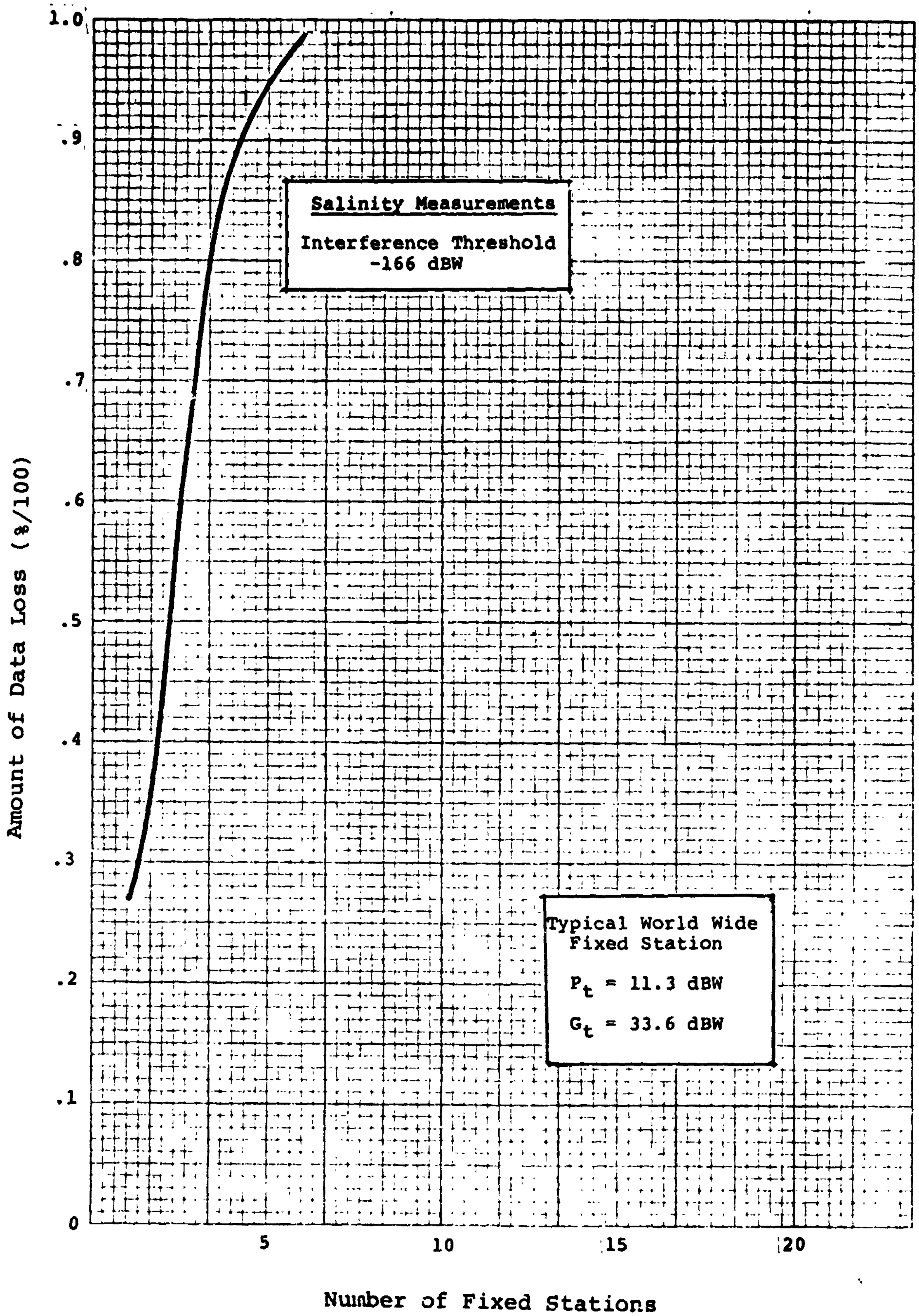
Transmitter Power = 8.5 dB(W)

Approximately two-thirds of the 64 systems operating employ parabolic antennas.

2.1.1.2 <u>Sharing Considerations</u>

2.1.1.2.1 <u>Simultaneous Operations</u>

Figure 2-2 relates the probability of data loss as a function of the number of ITFS stations simultaneously visible to an Earth Exploration Satellite for salinity measurements. The curves were generated using the Random Interference Analysis Program outlined in Appendix II. Figure 2-2 indicates that a radiometer used for salinity measurements (interference threshold = -166 dB(W)) will, on the average, experience a 27% data loss while within view of a single ITFS transmitter.



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 2-2 Data Loss vs. Number of ITFS Stations Visible

The approximate areas of complete (100%) data loss due to interference from ITFS transmitters is shown in Figure 2-3 for salinity measurements.

The implications of Figures 2-2 and 2-3 are that simultaneous sharing between ITFS and spaceborne radiometers could not be accomplished over the eastern United States. Salinity measurements would not be feasible.

2.1.1.2.2 <u>Time Sharing</u>

The ITFS is generally used as a small area distribution system to transmit educational material from either a central source, such as drop-point of the Public Broadcasting Network, or from one classroom to another. The latter type of distribution often includes two-way communications, with a voice feedback channel (usually channel G4).

ITFS systems are not used on a continuous basis. Typical schedules include transmission during the public school day (i.e., 8 a.m. to 4 p.m.), and possibl evening transmissions (i.e., 6 p.m. to 10 p.m.) to accommodate evening and night classes at Universities or Adult Education Centers.

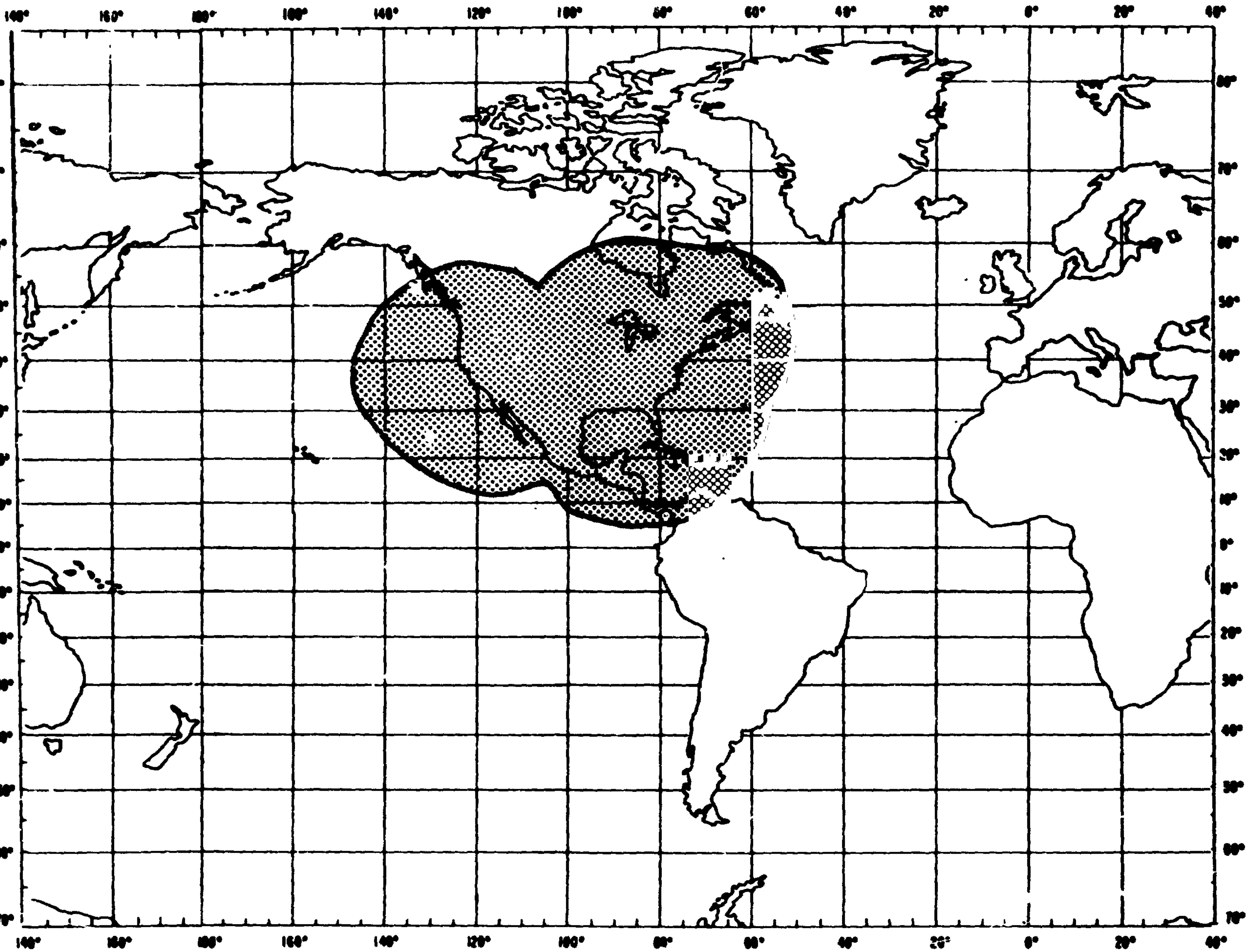


Figure 2-3 Loss of Coverage Area for Salinity Measurements Due to ITFS Operation

FORM NSL-75012M

The systems would not be expected to transmit between the hours of 10 p.m. and 8 a.m., local time. Consequently, allowing for a 1-hour buffer zone, there should be no interference between the hours of about 11 p.m. and 7 a.m. local time. If the radiometer is flown in a clock-synchronous orbit whose local time of passage is between about 2 a.m. and 4 a.m., continuous nighttime coverage for coastal salinity measurements would be possible. Therefore, time sharing is feasible, if ITFS channels G and H are restricted from operating during the period 8 a.m. to 10 p.m., local time.

2.1.2 Fixed and Mobile Services - Worldwide

A search of IFRB data files has indicated that the majority of fixed and mobile systems operating in this frequency band are located in Region 1, principally in Europe and the USSR. The systems characteristics indicate that both line-of-sight (LOS) and troposcatter systems are in use. There are approximately 100 LOS and 9 troposcatter registered assignments. A single assignment may, however, imply multiple systems within the registering administration.

2.1.2.1 Technical Characteristics

Although individual system parameters vary considerably, a typical LOS system would have the following characteristics:

Transmitter Power = 11.3 dB(W)

Antenna Gain = 33 dB(i)

and characteristics typical of troposcatter systems in the region are:

Transmitter Power = 40 dB(W)

Antenna Gain = 32 dB(i)

2.1.2.2 Sharing Considerations

2.1.2.2.1 Simultaneous Operations

Figure 2-4 relates the probability of encountering interference, while making salinity measurements, to the number of LOS fixed and mobile stations visible to an EES satellite. Figure 2-4 indicates that a radiometer used for salinity measurements (i.e., interference threshold = -166 dB(W)) will, on the average, lose 27% of its data while in view of a single fixed or mobile transmitter. Implications of the figure are that a 100% loss of salinity data would occur if LOS stations are simultaneously in view of the radiometer.

Nine of the listings in the IFRB files are apparently troposcatter communication systems. These systems are located in the European-Mediterranean area as indicated in Figure 2-5. The minimum interference power thac a system of this type would generate at a 500 km orbital altitude can be determined as follows:

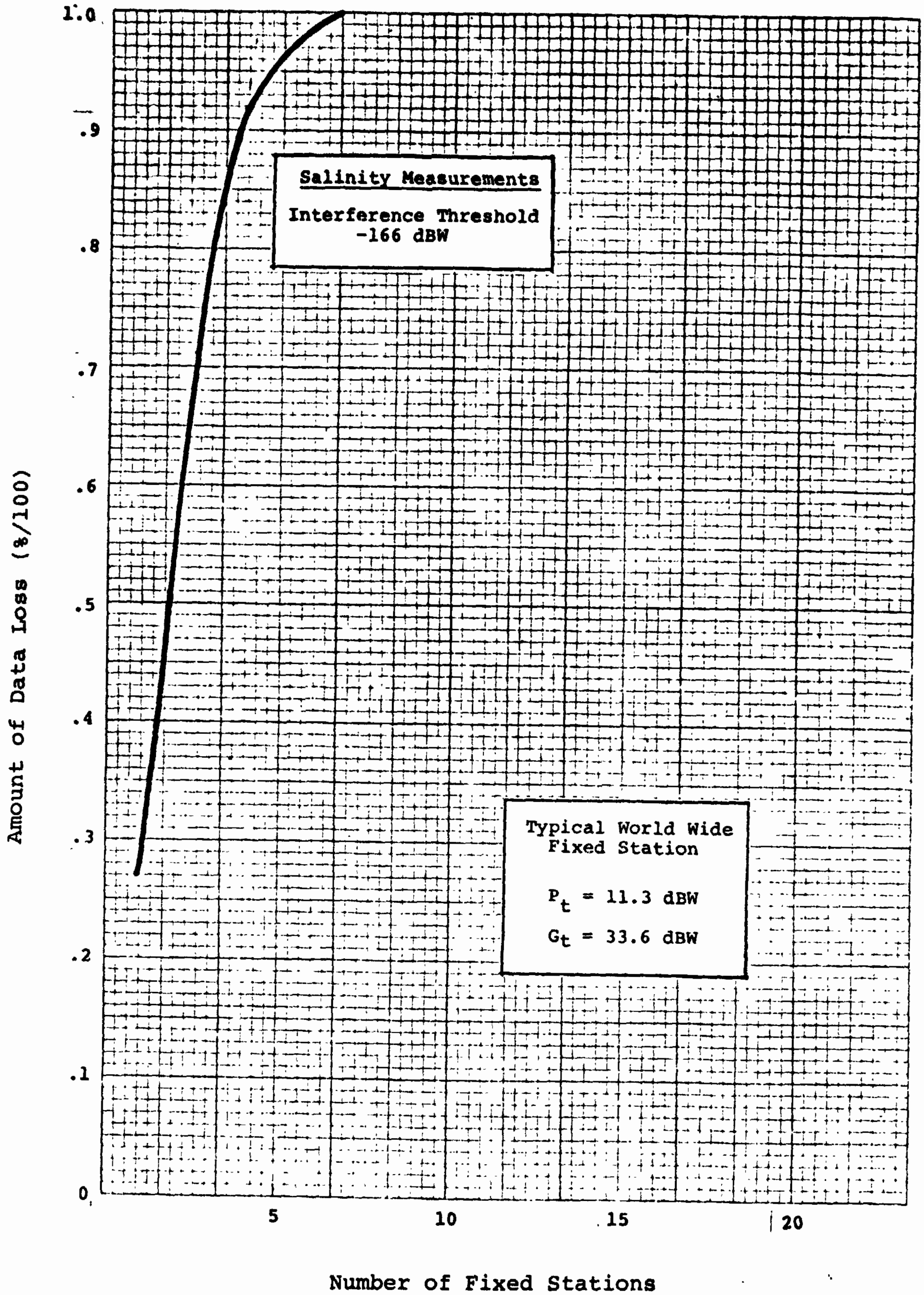


Figure 2-4 Data Loss vs. Number of Fixed and Mobile Stations Visible

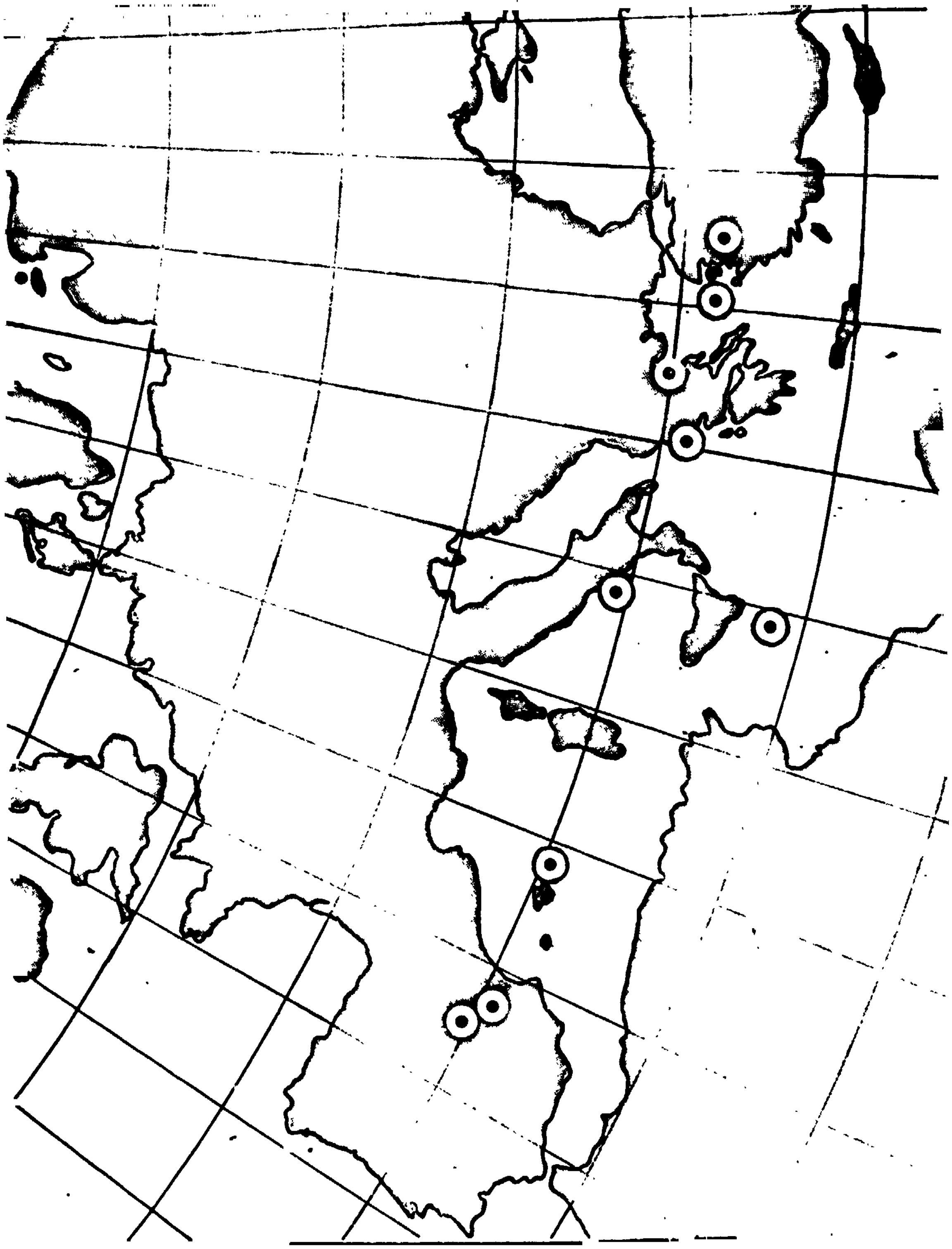


Figure 2-5 Location of Tropospheric Scatter Systems in IFRB Listing

Transmitter Power	=	40 dB(W)
Antenna Gain (backlobe)	=	- 10 dB(i)
Spreading Loss (slant range - 2500 km)	=	-139 dB(m^{-2})
Effective Aperture Area of Radiometric Antenna	=	-44 dB(m^2)
Interference Power at the Radiometer Receiver Input	=	-153 dB(W)

Figure 2-6 shows the loss of coverage area resulting from the 9 troposcatter systems. This figure indicates that the radiometer will receive interference whenever a troposcatter system is within the radiometer's field of view.

It should be noted, however, that Footnote 364D of the Radio Regulations states as follows:

> "Administrations shall make all practicable effort to avoid developing new tropospheric scatter systems in the band 2655-2690 MHz".

It is therefore anticipated that the use of the troposcatter systems in Region 1 may gradually decline as communication needs are satisfied by other techniques.

However, the overall analysis indicates that simultaneous sharing is not feasible.

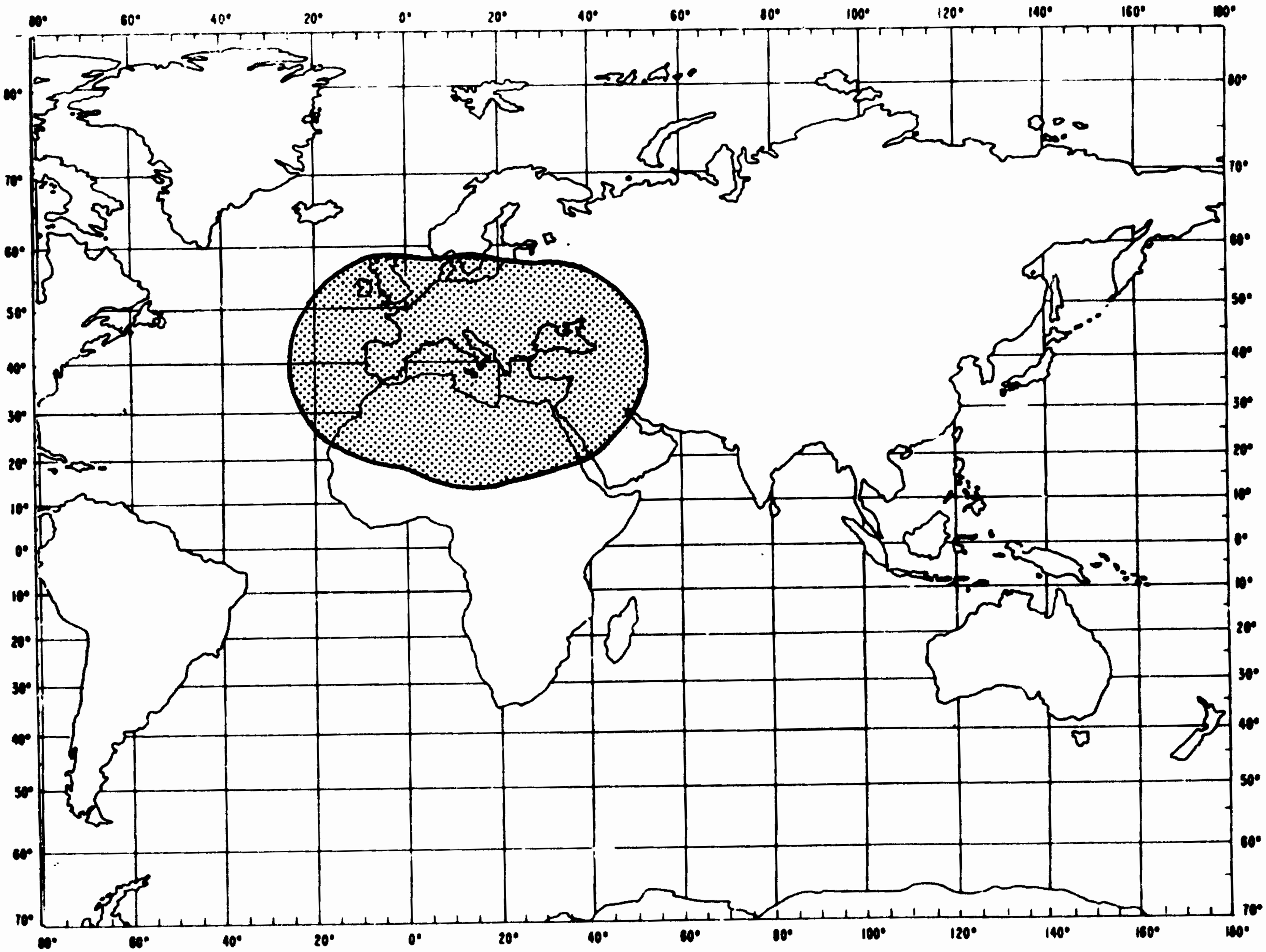


Figure 2-6 Loss of Coverage Area for Coastal Salinity or Soil Moisture Measurements Due to Tropo-Scatter Systems

FORM NSL-75011M

2.1.2.2.2 Time Sharing

It is difficult to obtain detailed information regarding the duty cycles of world-wide fixed and mobile operations for both LOS and troposcatter systems. It cannot be assumed, however, that these systems will be inoperative during late night-early morning hours. Accordingly, time sharing in Region 1 is considered infeasible. Obviously, time sharing could be accomplished if nighttime restrictions on operating times could be imposed.

2.1.2.3 Conclusions on Sharing with Fixed and Mobile Services

In Region 1, operations of the Fixed and Mobile Service preclude sharing with EES (passive) on an equal allocation basis. However, EES (passive) allocations based on a non-interference basis (secondary or footnoted) would allow for limited remote sensing coverage now and in the foreseeable future. Unlimited coverage would require either a dedicated allocation or time-sharing, neither of which is considered to be practicable in light of the operational nature of current fixed and mobile systems.

In Region 2 (specifically the United States), sharing on a primary basis with current services is feasible. The only technical criterion for sharing is that current services be restricted from operating between 11 p.m. and 7 a.m.

Based on available data few, if any, fixed and mobile systems are currently operating in Region 3 in this band. Consequently, there are two alternatives for sharing on a primary basis: 1) restrict operations of currently allocated services from 11 p.m. to 7 a.m.; or 2) allocate the 2.64-2.70 GHz band to the passive services, and delete the Fixed and Mobile allocation from the 2.64-2.69 GHz band.

2.2 Broadcasting-Satellite Service

With the exception of the experimental ATS-6 spacecraft, most of today's interest in broadcasting-satellite operations is in the 11.7-12.2 GHz region, due to the economical viability of smaller individual and community receiver antennas. Hardware has been developed and tested for this application in the United States, Europe (within the European Broadcasting Union) and in Japan. Consequently, it is anticipated that most broadcast-satellite operations will occur in the 11.7-12.2 GHz band, rather than in the 2 GHz region. However, since the allocation is in existence, and since some U. S. use remains a possibility, sharing with the Broadcasting Service in the 2.64-2.69 GHz band is analyzed below.

2.2.1 Technical Characteristics

Broadcast-satellites in the 2 GHz region would employ large (20-30 ft.) reflector antennas with high output powers (100-200 W), in order to serve community receivers (additionally, Footnote 361B restricts broadcast-satellite operation to community reception in this band). Emission bandwidths would be approximately 40 MHz. In this band, broadcast-satellites are limited by Article 7 of the Radio Regulations to power flux densities (PFD's) of:

- $-152\ \mathrm{dB}(\mathrm{W/m^2/4\ kHz})$ for $0° \leq \delta \leq 5°$
- $-152\ \mathrm{dB}(\mathrm{W/m^2}+3(\delta-5)/4\ \mathrm{kHz})$ for $5° \leq \delta \leq 25°$
- $-137\ \mathrm{dB}(\mathrm{W/m^2/4\ kHz})$ for $25° \leq \delta \leq 90°$

where δ is the angle of the incoming radiation, viewed from the ground station.

2.2.2 Sharing Considerations

2.2.2.1 Simultaneous Operations

There are two possible interference paths from a broadcasting-satellite to a low orbiting satellite. Interference could either be received through the low-orbiting satellite antenna backlobe, or through reflection from the surface of the earth into the radiometer mainbeam.

Assuming that 50%* of the radiation from a broadcast-satellite incident upon the earth is isotropically reflected, the equivalent radiated power from one square meter of the earth's surface would be approximately -140 dB(W/4 kHz). A remote sensor directed at 1 square meter of the earth's surface would sense:

---

* National Bureau of Standards, Technical Note 101, May 1, 1966.

Reflected power density	=	-140 dB(W/4 kHz)
Spreading Loss (500 km orbital altitude)	=	-125 dB(m^{-2})
Effective area of Radiometric Antenna	=	+ 15 dB(m^2)
Received Power Density from a Square Meter of Earth	=	-250 dB(W/4 kHz)

The area within the main beam of a 10-meter spacecraft antenna at 500 km orbital altitude is approximately +78 dB(m^2). Therefore, the interference power at the input to the spacecraft receiver would be approximately -173 dB(W/4 kHz). Since it is assumed that the emission bandwidth of the broadcast-satellite falls completely within the sensor receiver's bandwidth, the total power received would be on the order of -133 dB(W). This level is well above the threshold interference for salinity measurements (-166 dB(W)), and would preclude land as well as coastal region sensing where, for instance, time zone shaped broadcast-satellite antenna patterns will overlap the coastal waters.

Interference entering the low-orbit spacecraft through the backlobes (-17 dB(i) gain) constitutes a similar level of interference, as seen from the following calculation:

PFD at 500 km altitude	=	-137 dB(W/m^2/4 kHz)
Effective aperture area of radiometer antenna	=	- 47 dB(m^2)
		-184 dB(W/4 kHz)

or -144 dB(W) in the sensor receiver's bandwidth. Again, this is an intolerably high level of interference.

Both of the above interference paths assume the radiometer to be located within the main beam of the broadcast-satellite.

The following is a calculation of the interference seen at a radiometer sensing coastal salinity over the east coast from sidelobe emissions of a broadcast-satellite serving the Pacific Time Zone. Figure 2-7 shows the coverage of a typical broadcast-satellite shaped beam to serve the west coast (shaded area). The "X" on the figure indicates the location of the spacecraft bearing the passive sensor. The angular separation of the two as seen from the broadcast-satellite is approximately 3 times the 3 dB beamwidth of the broadcast-satellite. The relative sidelobe gain discrimination of the broadcast-satellite antenna is taken in this analysis to be:

$$G_D = 12.5 + 25 \log (\Phi/\Phi_0)^*$$

where G_D = Gain down from main beam (dB)

Φ = Off axis angle to radiometer

Φ_0 = 3 dB beamwidth of Pacific Time Zone coverage beam (1.8°)

This indicates that 24.5 dB of discrimination is provided by the broadcast-satellite. Referring back to the reflected interference path previously calculated, the same analysis applies, and the interference level at the radiometer from the reflected path would be:

* CCIR Draft Report AF/10-11, Geneva, 1976.

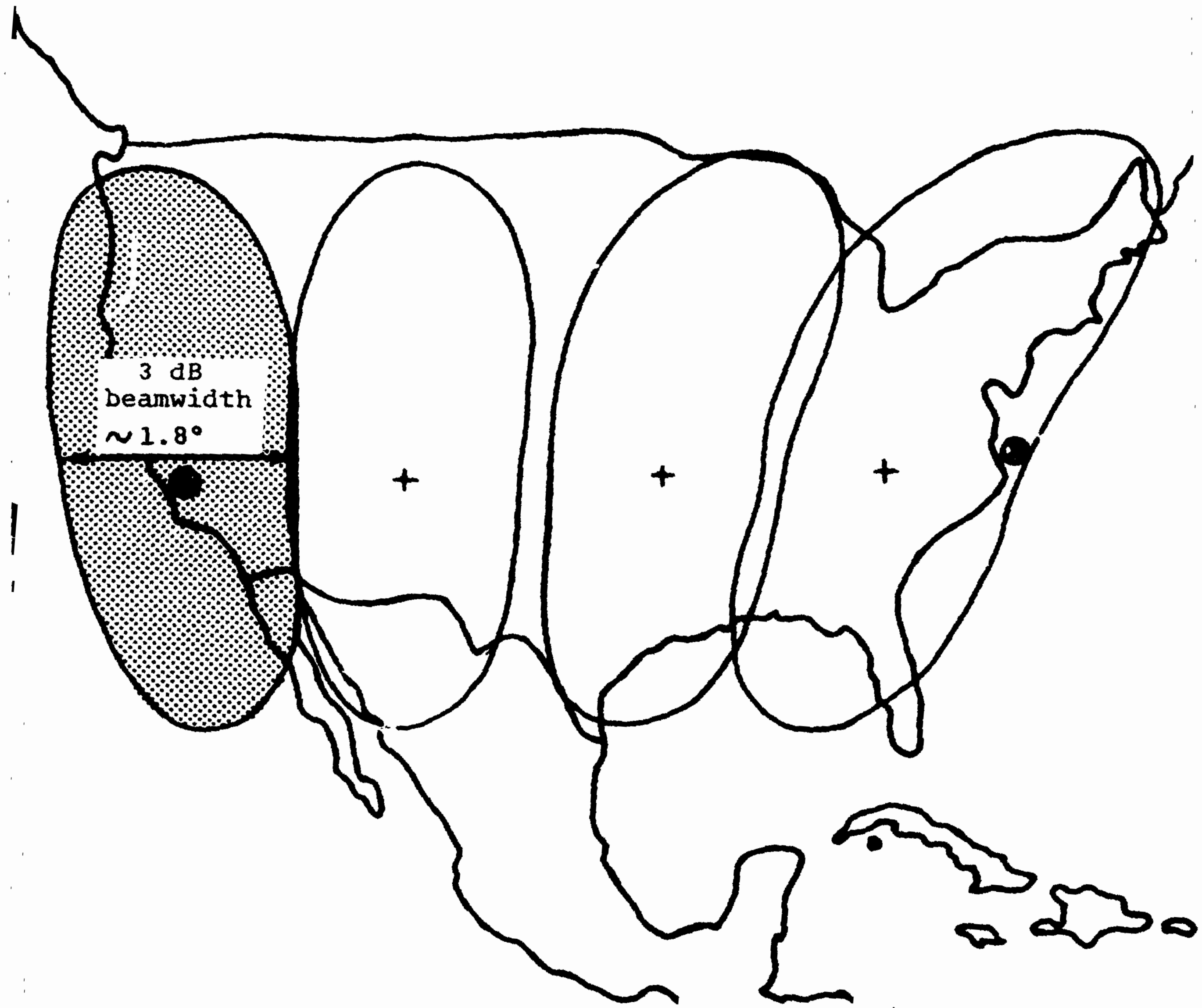


Figure 2-7 Multibeam Time Zone Coverage of a Typical Broadcast-Satellite

Reflected Path = -133 - 24.5 = -157.5 dB(W)

Sharing on a simultaneous operation basis is therefore infeasible.

2.2.2.2 Time Sharing

Time sharing with broadcasting-satellites is more difficult than time sharing with ITFS systems. A passive sensor attempting to obtain data over the east coast of the United States would be illuminated by a broadcast-satellite operating to service the west coast. This restricts time sharing possibilities to between 2-4 a.m. local time, assuming normal broadcasting-satellite operations are from 7 a.m. to 11 p.m. local time. Thus, time sharing with the Broadcasting-Satellite Service is considered feasible only if a properly chosen sun-synchronous orbit is employed and if broadcast-satellite emissions are restricted to between 7 a.m. and 11 p.m. local time.

The above hours of time sharing feasibility are determined using the reference radiation diagram proposed for broadcasting-satellites in CCIR Draft Report AF/10-11. This reference pattern was derived based on antennas of current design, employing little sidelobe radiation control. It is technically feasible, if care is taken in antenna design, to provide up to 30-35 dB first and second sidelobe discrimination. An effort such as this would substantially alleviate the narrow time span during which time sharing is feasible allowing remote sensing of areas two time zones away from a broadcast-satellite service zone.

2.2.3 Conclusions on Sharing with the Broadcasting-Satellite Service

Although only Region 2 is expected to use the 2.64-2.69 GHz band for broadcasting-satellite application, it appears that the operational scenario of a typical broadcast link would allow for time sharing with the passive spaceborne microwave radiometry.

2.3 FIXED-SATELLITE SERVICE (EARTH-TO-SPACE)

Use of the Fixed-Satellite Service in the 2.64 to 2.69 GHz band is envisioned to be primarily for "thin route" communication links to remote parts of the earth. Experiments performed with the NASA ATS-6 spacecraft have shown the practicality of providing communications to sparsely populated areas via space links. This type of service is presently under review by various commercial organizations and several administrations. The majority of thin-route communication networks would not operate 100 percent of the time, but would be operated only when necessary. The only station with a 100% duty cycle would be the control station.

2.3.1 Technical Characteristics

Based on the assumption that use of the band for fixed satellite operation <u>may</u> occur, the following characteristics are hypothesized as representation of systems which may use the band.

Single channel per carrier

Antenna size = 1-2 meters*

Antenna gain = 22 dB(i)

Transmitter Power = 10 dB(W)

2.3.2 Sharing Considerations

2.3.2.1 Simultaneous Operations

A typical earth station with the above operational characteristics operating at 40°N latitude and pointed to the geostationary orbit produces a power flux at the 500 km orbital altitude of approximately -95 dB(W/m^2). In the backlobes of the earth station antenna, this power flux may be as low as -135 dB(W/m^2). In the backlobes of the radiometer antenna, the highest allowable power level is -122 dB(W/m^2).

Figure 2-8 shows the area surrounding such a transmitting fixed satellite earth station which would be lost to radiometer measurements. If this station is assumed to be a control station, the area would be permanently lost to the radiometer. The maximum number of such earth stations which could simultaneously be in view and still allow for limited data collection would be 6-8. Beyond this number 100% data loss would occur from cumulative sidelobe interference.

* The use of small apertures is intended to circumvent accurate pointing requirements.

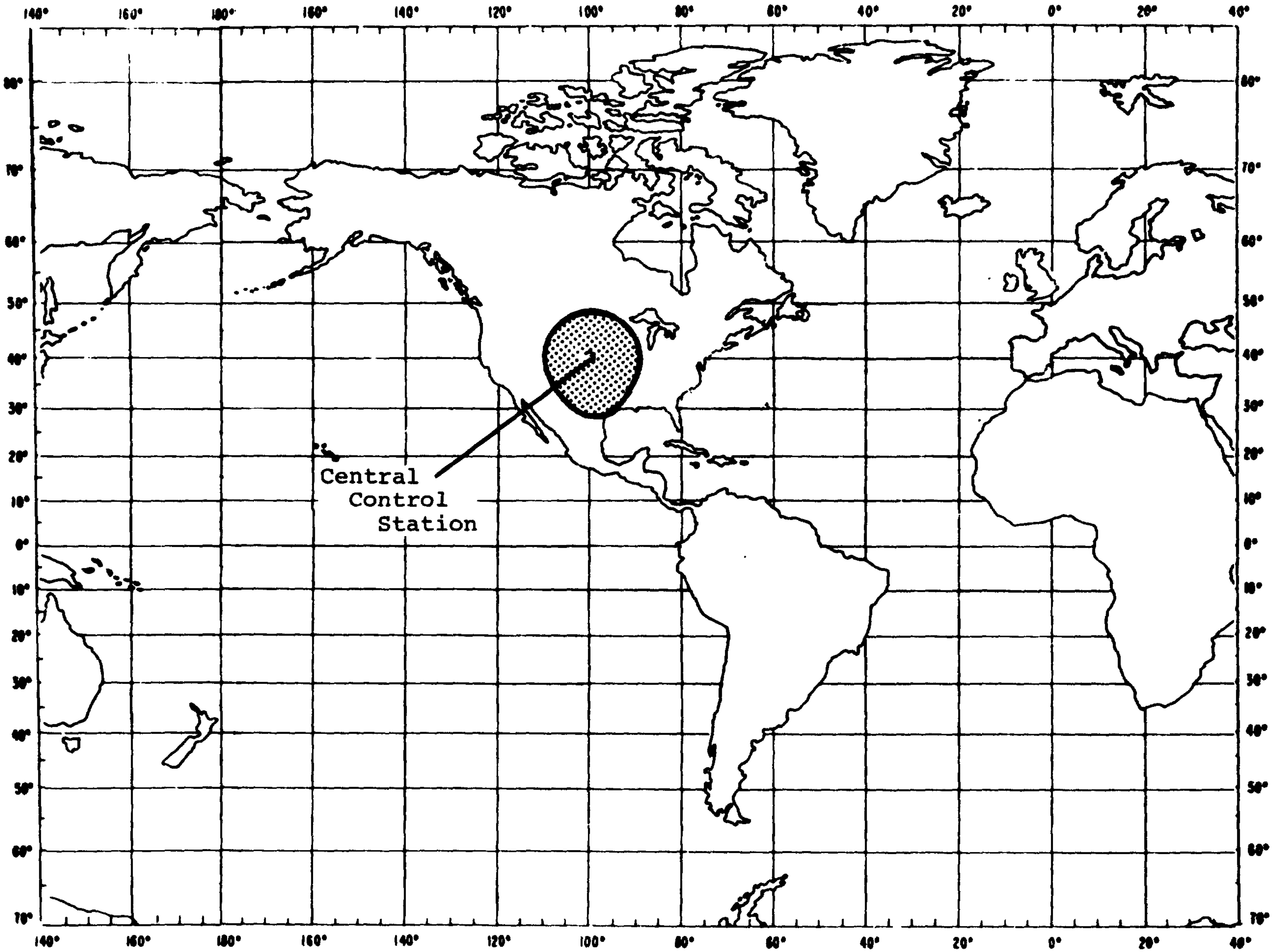


Figure 2-8 Loss of Coverage Area Due to Fixed Satellite Earth Station Operations (Control Station)

FORM NSL-75012M

If extensive use is made of the Fixed-Satellite Service earth-to-space allocation in this band, sharing on a simultaneous operation basis would be considered infeasible.

2.3.2.2 Time Sharing

Under the assumption that this band will be used only for thin-route, on-demand, low duty cycle operation, time sharing with passive remote sensors should be feasible.

2.3.3 Conclusions on Sharing with Fixed-Satellite Service

Since simultaneous operations with the Fixed-Satellite Service (earth-to-space) operations is untenable, the only alternative is time sharing. Current indications are that time sharing would be possible in all regions since the number and duty cycles of fixed-satellite systems expected to be operating in this band will be small.

SECTION 3

FREQUENCY BAND 4.950-5.000 GHz

USER REQUIREMENTS

The principal measurement in this frequency band is estuarine surface temperature. This band was selected to maximize the response of the radiometer to surface temperature changes. Selecting a frequency for maximum response minimizes the integration time and bandwidth required to measure the phenomenon.

Satellite measurements of estuarine surface temperature require small antenna beamwidths in order to separate the water surface from the land. The maximum dimension of the beam footprint on the water surface is 5 km for observations of large estuaries. A 2 km resolution is optimum, as this maintains a balance between antenna size and the number of estuaries that can be sensed. For a satellite in a 500 km circular orbit, a 2 km resolution (0.2° beam) requires a 15-20 meter antenna, depending upon the pointing angle. Since the beam traverses a point on the surface in less than 0.2 seconds, the integration time must be less than 0.2 seconds.

The measurement range of surface temperature is 0-30 C. Measurements with a 2 percent accuracy (0.5 C) are required to map the smaller changes that occur within an estuary. The sensitivity values of Part A indicate that the required radiometer sensitivity is 0.3 K. Using the equation relating integration time to bandwidth for a Dicke switched radiometer with a 300 K noise temperature, the required bandwidth is in excess of 45 MHz.

To map an estuarine region, a swath of at least 50 km wide is needed. A 50 km swath requires a minimum of 25 beam positions. For a scanning radiometer, the minimum integration time for each beam position would be 0.08 seconds, and would require a bandwidth of 1.13 GHz. Since the maximum available possible bandwidth is 50 MHz, a multibeam antenna with a 0.2 second integration time would be required if a Dicke switched radiometer is used.

Surface temperature observations are used to detect nutrient rich regions, which indicate thermal pollution, and observe water circulation within the estuary. These observations must be made often in order to map the rapid time fluctuations of the phenomena. This requires observations on a daily basis. Daily observations are also required for the enforcement of environmental regulations.

SHARING ANALYSIS

Portions of the 4.95-5.00 GHz band are currently allocated to the Fixed, Mobile and Radio Astronomy Services on a world-wide basis.

Since radio astronomy (4990-5000 MHz) can inherently share with another passive service, the following sections discuss the frequency sharing potential between the Earth Exploration Satellite Service (passive), and the Fixed and Mobile Service in the 4.95-4.99 GHz region.

3.1 Technical Characteristics

3.1.1 United States Operations

Within the United States, the primary users of the 4.95-5.00 GHz band are the U. S. Navy and Air Force, employing fixed and mobile systems for transportable radio communications. Geographically, these systems are located primarily in the eastern and western extremes of the United States.

Although the technical characteristics of these fixed and mobile systems may vary, the following two system characteristics predominate:

System 1

Transmitter Power = 7 dB(W)

Antenna Gain = 38 dB(i)

System 2

Transmitter Power = 30 dB(W)

Antenna Gain = 38 dB(i)

The United States frequency assignment data files indicate that there are approximately 50 assignments for each of the above generic systems. However, many of the individual assignments indicate multiple transmitter system networks.

3.1.2 World-Wide Operations

Although a large number of assignments have been identified in IFRB data files, little information exists as to their operational nature. Additionally, many of the assignments do not have antenna gains specified.

There are 24 assignments in Europe, primarily in France, Holland and Germany, which are in the 68 dB(W) e.i.r.p. range, and 28 assignments in the 45 dB(W) e.i.r.p. range.

3.2 Sharing Considerations

Assuming the typical output power levels of U.S. and world-wide systems to be similar, the Random Interference Analysis Program (Appendix II) outputs are applicable to both systems.

3.2.1 Simultaneous Operations

Figure 3-1 presents the results of the output of the Random Interference Analysis Program. The program simulation assumed an equal mix of high and lower power systems.

Figure 3-1 relates the number of terrestrial transmitters visible to a radiometer at a 500 km orbital altitude to the probability of data or coverage loss. As shown in the figure, a 100% data loss would occur if approximately 10 or more transmitters are simultaneously in view.

Figure 3-2 shows the anticipated areas of data loss due to simultaneous operation of the terrestrial systems. The interference regions represent areas within which it is anticipated that 10, or more, terrestrial transmitters will be simultaneously in view from the radiometer.

This analysis indicates that sharing on a simultaneous operation basis is infeasible.

3.2.2 Time Sharing

Although it is expected that operations of terrestrial systems in this band will decrease during the nighttime hours, it cannot be assumed that this is, or will be, the normal operational schedule. Time sharing, therefore, is considered infeasible. Obviously, time sharing could be accomplished if nighttime restrictions could be imposed.

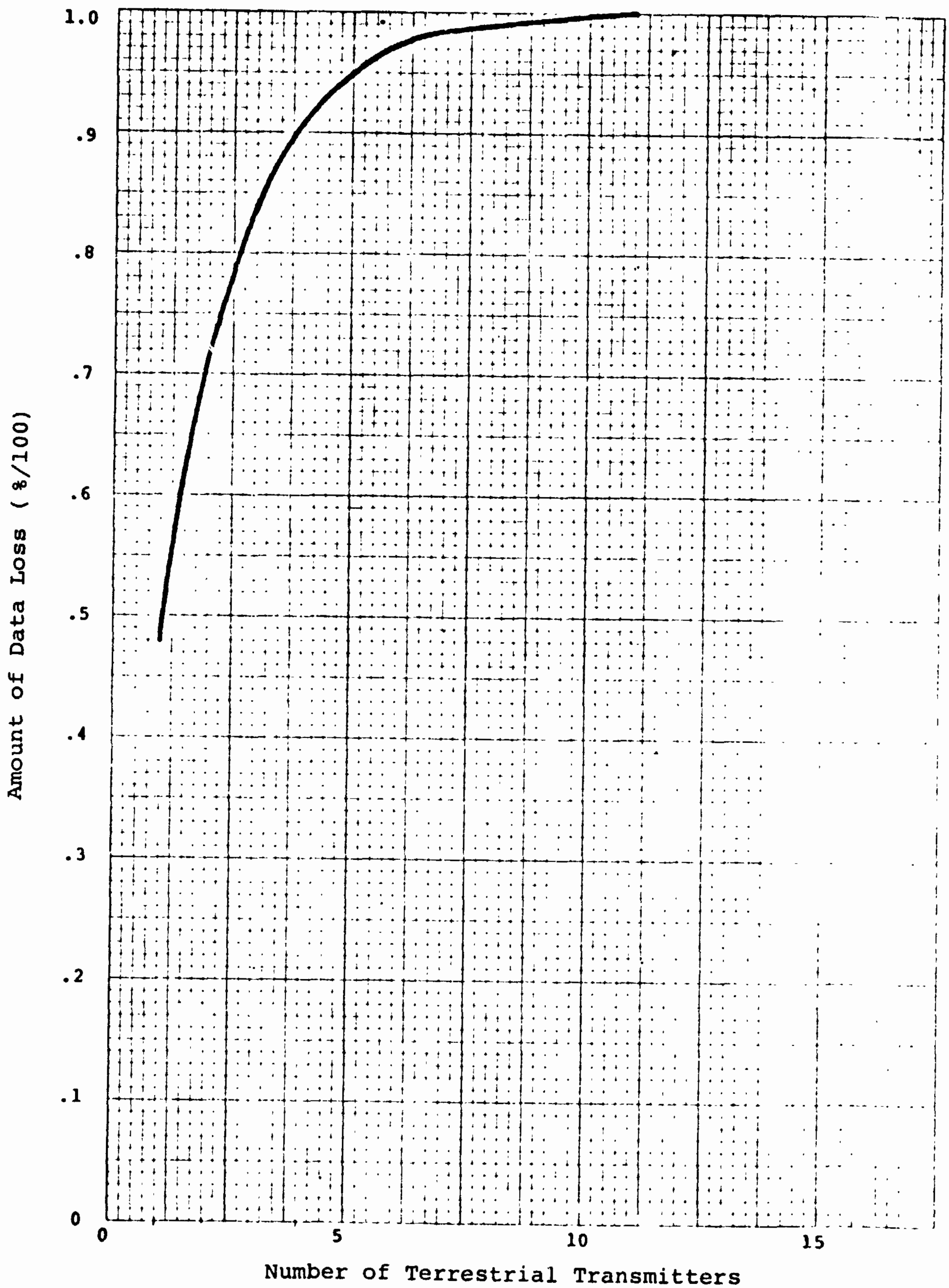


Figure 3-1 Number of Terrestrial Systems Transmitting vs. Data Loss

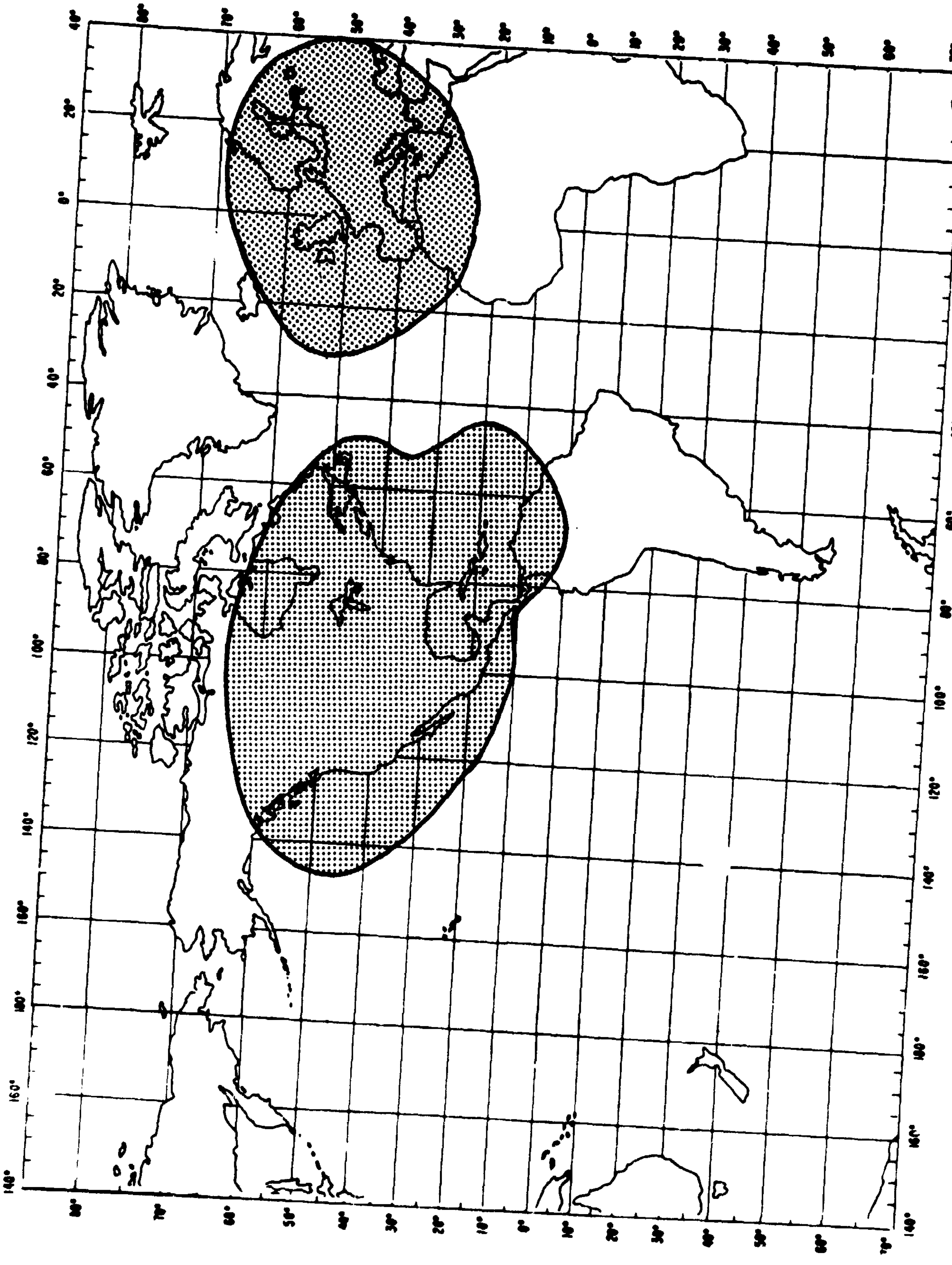


FIGURE 3-2 Approximate Loss of Coverage for Estuarine Surface Temperature Measurements

FORM NSL-75012M

ORIGINAL PAGE IS
OF POOR QUALITY

3.3 Conclusions on Sharing with Fixed and Mobile Services

Sharing on a simultaneous operational basis between spaceborne passive microwave sensors and the Fixed and Mobile Services in the 4950-4990 MHz band is not feasible. Time sharing in this band is also considered infeasible.

Sharing on a simultaneous operational basis between the space passive services and the Radio Astronomy Service in the 4990-5000 MHz band is feasible.

SECTION 4

FREQUENCY BAND 6.425 - 7.250

USER REQUIREMENTS

The principal measurement in this frequency band is ocean surface temperature. Although this band does not correspond to the frequency which maximizes sensitivity to surface temperature, the frequency is adequate for ocean temperature measurements.

Surface temperature measurements over the open ocean require spatial resolutions on the order of 20 km. A 20 km resolution is adequate for detecting movements of the Gulf stream and to delineate regions for fishing operations. For a satellite in a 500 km circular orbit, a 20 km resolution (2° beam) requires the use of a 1-2 meter antenna, depending upon the pointing angle. Since the beam traverses a point on the surface in less than two seconds, the integration time must be less than two seconds.

The measurement range of surface temperatures is 0-30 C. Measurements with a two percent accuracy (0.5 C) are required to differentiate Gulf stream movement and areas of fishing importance. The sensitivity curves of Part A indicate that the required radiometer sensitivity is 0.3 K. Using the equation relating integration time to bandwidth for a Dicke Switched radiometer with a 300 K noise temprature, the required bandwidth is in excess of 5 MHz.

In order to map an ocean region, a swath width of 800 km, utilizing 40 beam positions, is required. For a scanning system, the minimum integration time would then be 0.05 seconds per beam position. The minimum bandwidth for a 0.05 second integration time is 200 MHz.

Ocean surface temperatures change relatively slowly, and one observation per week is adequate.

SHARING ANALYSIS

The only world-wide primary allocation currently in the 6.425-7.250 GHz band is for the Fixed and Mobile Services. In Brazil, Canada and the United States, however, the band 6625-7125 MHz is also allocated, on a secondary basis, to the Fixed-Satellite Service for space-to-earth transmissions.

The following sections analyze the sharing potential between the Earth Exploration Satellite Service (passive) and the Fixed and Mobile Services for sharing on a primary basis.

4.1 Technical Characteristics

Use of this band throughout the United States, as well as all other regions of the world, is quite extensive. IFRB data files indicate approximately 1000 world-wide frequency assignments*, and each assignment may indicate multiple transmitter systems. Many of the systems appear to be line-of-sight microwave links with transmitter powers on the order of 1-20 watts. Antenna gains for these systems are in the 38 to 42 dB(i) range. Additionally, there are numerous assignments in the multi-kilowatt output power range, which appear to be tropcscatter

*This analysis concerns itself with a specific 200 MHz band within the 6.425-7.250 GHz spectral band - namely 6.500-6.700 GHz. The specific frequency region chosen is based on hardware currently under development.

systems. The major locations of these line-of-sight and tropo systems are the United States, Canada, Uraguay, Argentina, most of Europe and Mexico.

4.2 Sharing Considerations

4.2.1 Simultaneous Operations

The harmful interference level experienced by a coastal temperature measurement radiometer in this frequency band is -158 dB(W). Interference occurs when the passive sensor is in view of any number of emitters whose output powers total 2.0 kW or, equivalently, 33 dB(W). This is seen from the following calculation:

Output Power	=	33 dB(W)
Antenna Gain	=	- 5 dB(i)*
Spreading Loss	=	-134 dB(m^{-2})**
Effective Area of Radiometer Antenna	=	- 52 dB(m^2) (antenna side-lobe)
		-158 dB(W)

In order to sense the surface temperatures of coastal and estuarine regions of a given continent, the passive sensor will, of necessity, be in view of transmitters approximately 2500 km inland from the coast (this is equal to about halfway across the United States). If a typical terrestrial transmitter

*Small CCIR reference antenna pattern.
**Average spreading loss.

in this band employs 40-100 watts of output power, then interference will occur to coastal temperature measurements when 20-50 of these systems are operating and simultaneously visible to the passive sensor. The large population of terrestrial transmitters in the U. S. and world-wide in this frequency band indicates that at least 40-100 terrestrial transmitters will be simultaneously visible to the passive sensor when near coastal areas. Figure 4-1 presents the approximate areas of the world where interference would be experienced. This figure shows that even ocean temperature measurements would experience extensive interference.

Simultaneous operation with this service is therefore infeasible.

4.2.2 Time Sharing

Due to the expected operational nature of line-of-sight and troposcatter communication systems, and the large population of these systems world-wide, time sharing in this band is considered infeasible.

4.3 Conclusions on Sharing with Fixed and Mobile Services

Simultaneous operations between spaceborne passive microwave sensors and the Fixed and Mobile Services in the 6.5-6.7 GHz region is not feasible. Time sharing is also considered infeasible.

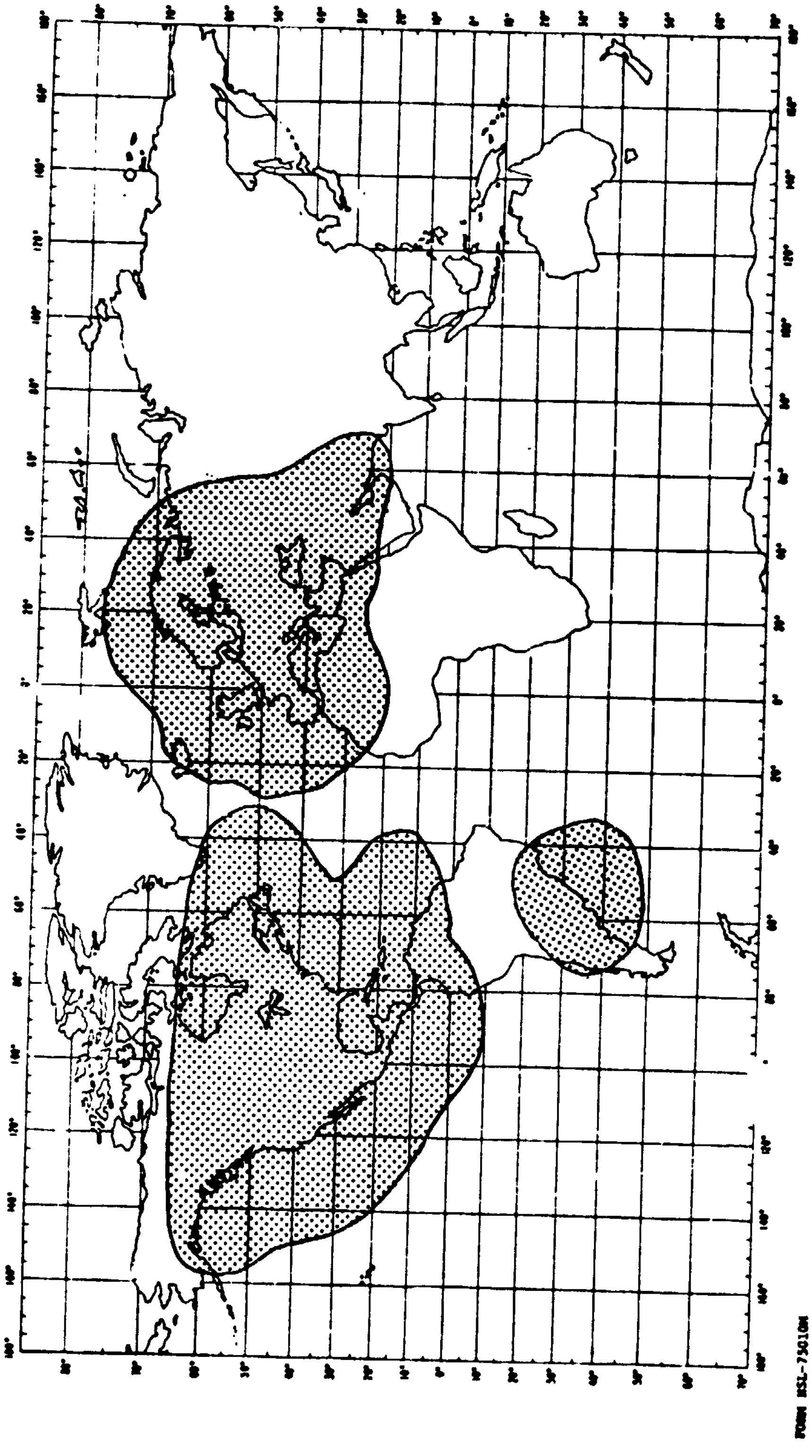


FIGURE 4-1 Approximate Loss of Coverage Area for Sea Surface Temperature Measurements

ORIGINAL PAGE IS
OF POOR QUALITY

APPENDICES I - V

APPENDIX I

GAIN-RANGE QUOTIENT ANALYSIS

Gain-range quotient calculations permit the generation of a map that pictorially describes the loss of coverage area that results from interference to a passive sensor.

The gain-range model is based upon a parametric analysis of potential interference situations. The harmful interference power, ΔP_H, seen at the passive radiometric input is given by:

$$\Delta P_H = 0.2\ k \Delta T\ B\ (W) \qquad (1)$$

where k = Boltzmann's constant (Watts/K/Hz)

ΔT_{rms} = Receiver minimum discernible temperature differential (K)

B = Receiver bandwidth (Hz)

In relation to the interfering source,

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

where: G_t = Gain of transmitting antenna

P_t = Power of transmitting source (Watts)

G_R = Gain of receiver antenna

λ = Wavelength (meters)

R = Range (meters)

Rearranging Equation (2)

$$\frac{\Delta P_H (4\pi)^2}{P_t \lambda^2} = \frac{G_t G_R}{R^2} \qquad (3)$$

In this analysis, the right hand side of Equation 3 is termed the "gain-range quotient" and may be calculated independently of ΔP_H, P_t and λ as follows. The area of the spacecraft's orbital sphere visible to a given terrestrial station is divided into small incremental regions called "bins", (e.g. 2° x 2° latitude-longitude regions, see Figure I-1). For each of these regions, the gain of the spacecraft antenna in the direction of the terrestrial station, the gain of the terrestrial station in the direction of the spacecraft, and a range between the spacecraft and the terrestrial station may be calculated. With these values determined, the gain-range quotient is known. Under the assumption that the bins are small and the functions are slowly varying, the gain-range quotient for each bin is assumed to apply over that entire bin area.

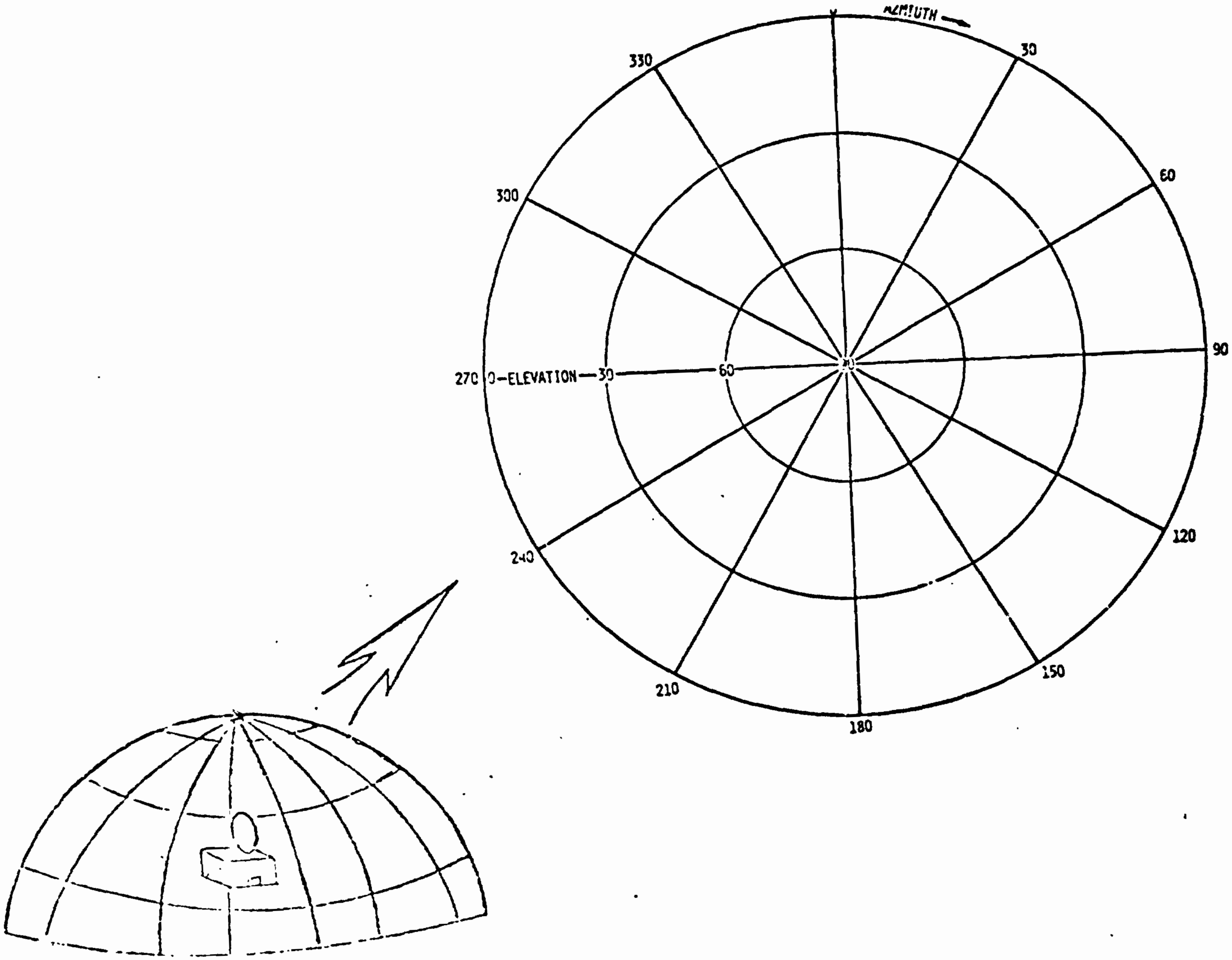
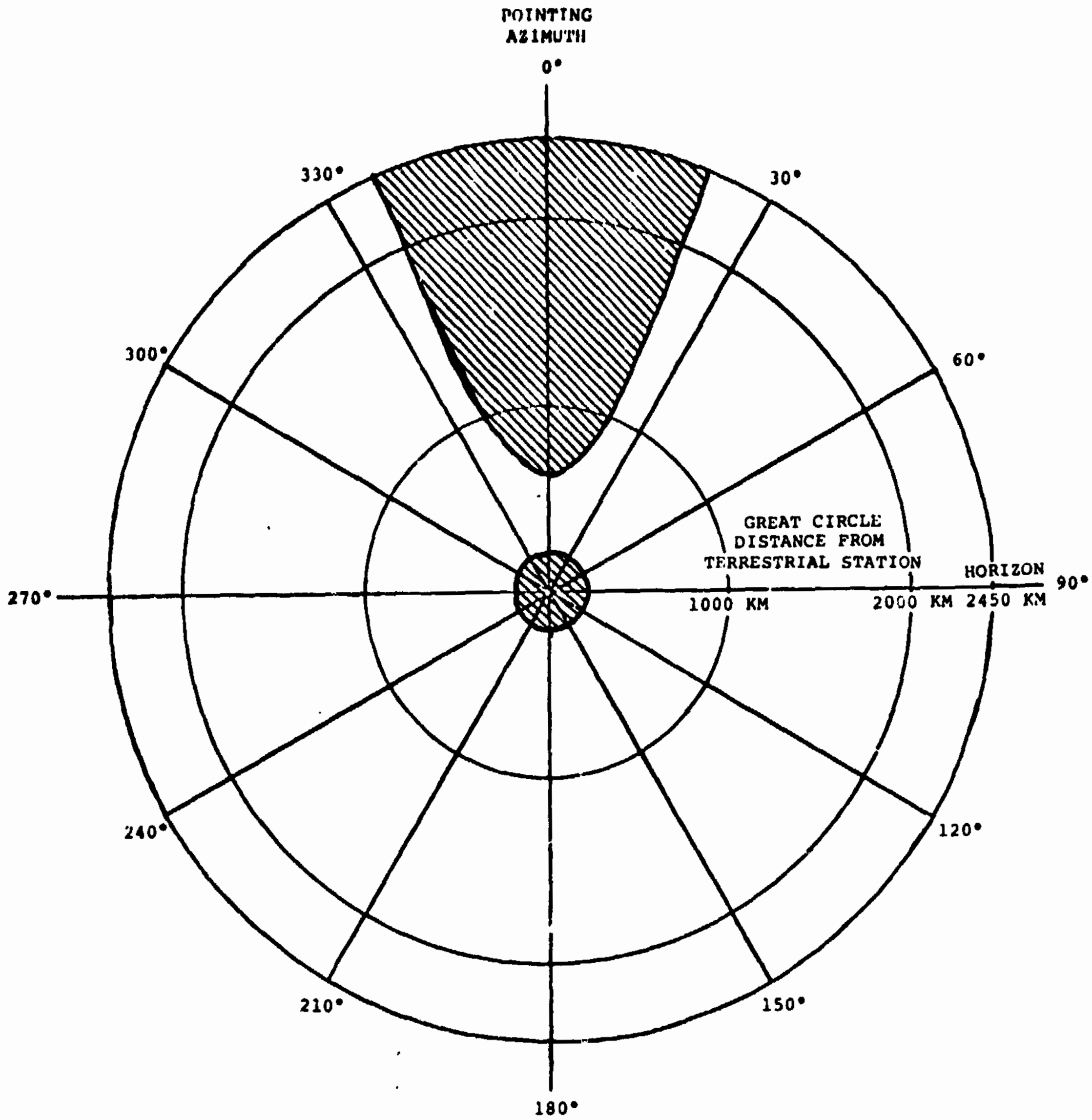


Figure I-1 AZ-EL Bin Structure Surrounding Terrestrial Station

If this process is repeated for each bin, a map of gain-range quotients vs. spacecraft location is achieved. It should be noted that the gain-range quotient map is, at this point, independent of frequency, transmit power and harmful interference power. It is dependent only on the orbital altitude and specific antenna patterns used for the spacecraft and terrestrial station. If the antenna patterns used closely represent the terrestrial and space systems, then all that need be done to determine approximate interference regions on the map is to calculate the minimum tolerable gain-range quotient using ΔP_H, P_t, λ, etc. from Equation 3.

The utility of this approach lies on the map-like presentation of potential interference regions. Passive spaceborne sensors, are generally used to produce radiance maps of the earth's surface or atmosphere. The interference maps indicate regions of the earth's surface which are unavailable for sensor operation. Figure I-2 presents an example map. The gain-range program differs from the Random Interference Analysis Program (Appendix II) in that it is intended to generate the areas of geographical coverage lost to a spaceborne radiometer when in view of a single terrestrial station.



Note: Shaded areas indicate region where interference and therefore, loss of coverage occurs. Terres:cial station is located in center.

Figure I-2 Sample Loss of Coverage Area Map

ORIGINAL PAGE IS
OF POOR QUALITY

APPENDIX II

RANDOM INTERFERENCE ANALYSIS PROGRAM

The Random Interference Analysis Program was developed to determine the cumulative effects of numerous terrestrial stations simultaneously visible to a spaceborne radiometer.

This technique utilizes a random number generator to place terrestrial stations within the field of view of the radiometer. The terrestrial stations are located at random great circle distances from the spacecraft subsatellite point, and assigned a random pointing direction. Based upon the terrestrial transmit power, gain patterns of both the terrestrial and radiometer antennas, and range to the spacecraft, the interference power at the input to the radiometer is calculated. If the calculated level of interference is above the radiometer threshold, the program notes that one station caused interference. If the level is not above threshold, a second station is randomly placed in the region visible to the radiometer, and its interference power is calculated and added to that of the first station. The result is again compared to the radiometer threshold. This process is continued until the radiometer interference threshold is exceeded.

X-6

In order for this process to generate meaningful results, it is necessary to repeat the above procedure a large number of times to obtain a statistically significant number of samples.

Table II-1 presents an example output of the program, at the point where the cumulative interference exceeds the radiometer threshold. Column two indicates the number of times that the interference threshold was reached or exceeded for the number of stations in Column 1. For example, row 1 of Table II-1 indicates that interference from a single station, placed and pointed randomly, exceeded the radiometer threshold 132 times. This corresponds to a 13.2% (based on 1000 total samples) probability. In 319 samples, interference from two stations exceeded the interference threshold corresponding to a 31.9% probability. For these 1000 data samples, the radiometer could tolerate no more than 10 stations and radiometer data was lost whenever 10 or more were simultaneously in view.

TABLE II-1

Example Output of
Random Interference Analysis Program

No. Stations	Number of Times Interference Experienced	Probability of Interference (%)
1	132	13.20
2	319	31.90
3	532	53.20
4	718	71.80
5	859	85.90
6	925	92.50
7	972	97.20
8	991	99.10
9	998	99.80
10	1000	100.00

APPENDIX III

ANTENNA PATTERNS

Due to the nature of the multifrequency analyses performed, it has not been possible to obtain actual measured antenna patterns. Therefore, it has been necessary to utilize several mathematical envelope patterns approximating actual antenna patterns.

1. Passive Radiometer Antenna Patterns

An under-illuminated antenna envelope pattern was developed to model narrow "pencil" beams, used by radiometers for obtaining high resolution maps of the earth's surface. A 90% beam efficiency (90% of the energy entering the antenna enters within the -20 dB points) is postulated. The first sidelobe level is assumed to have a fixed level extending to 5 times the 3 dB half angle, and receives 7% of the energy. The secondary sidelobe region extends to an off-axis angle of 90°, and receives 2% of the energy. These sidelobe gain levels are a reasonable approximation of an under-illuminated pencil beam antenna. The development of this pattern is based on conservation of energy principles (i.e., the gain summed over the entire antenna must equal that of an isotrope.) Figure III-1 shows the envelope pattern of the simulated antenna.

X-10

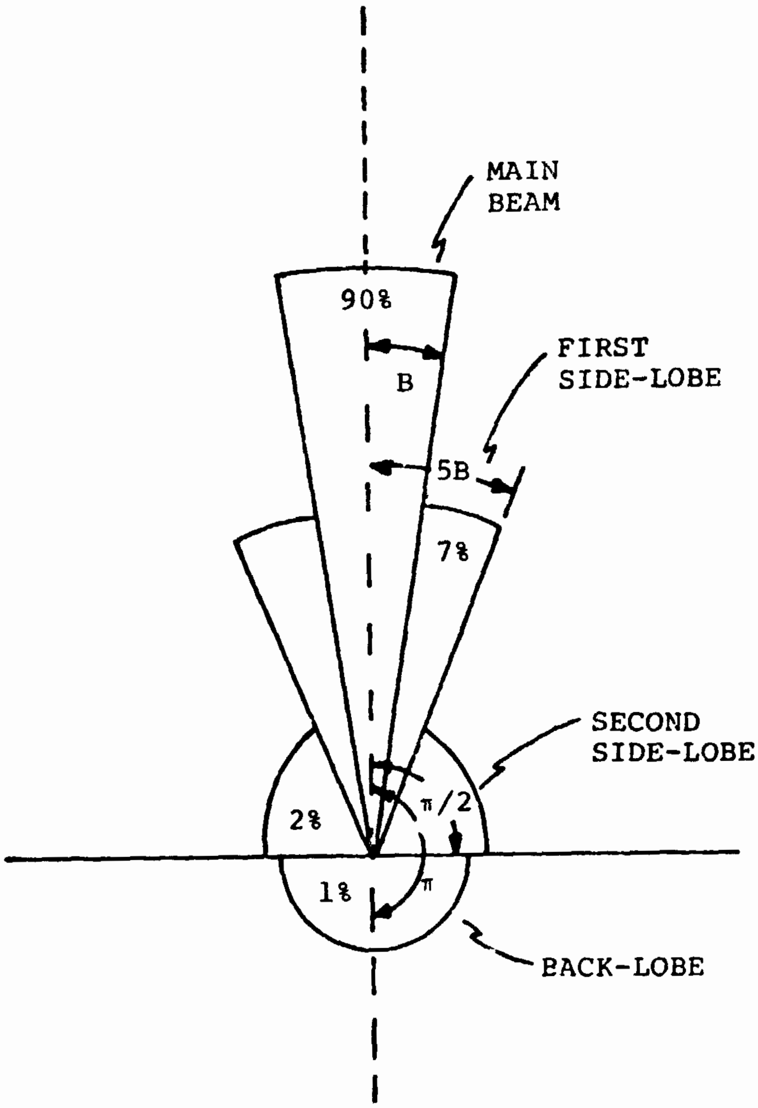


Figure III-1. Under-Illuminated Antenna Radiation Pattern

2. Terrestrial and Earth Station Antenna Patterns

The parabolic terrestrial and earth station antenna patterns used in the sharing analyses were based on CCIR recommended patterns. Specifically, CCIR 95th percentile peak side-lobe gain patterns given by:

$$G(\theta) = 32-25 \log(\theta) \text{ for } D/\lambda > 100$$

$$G(\theta) = 38-25 \log(\theta) \text{ for } D/\lambda < 100$$

where: $G(\theta)$ = the side-lobe antenna gain referenced to an isotropic (dB(i))

θ = off-axis angle as seen at the antenna (deg.)

D = antenna dimeter (m), and

λ = wavelength (m)

3. Fixed-, Mobile- and Broadcasting-Satellite Antenna Patterns

The reference radiation antenna patterns recommended for use for broadcasting-satellite antennas is contained in CCIR Draft Report AF/10-11 Geneva, 1976 and is as follows:

$$G_D = -12\left(\frac{\phi}{\phi_o}\right)^2 \text{ for } 0 \leq \phi \leq 1.44\phi_o$$

$$G_D = -25 \text{ for } 1.44\phi_o < \phi \leq 3.16$$

$$G_D = -\left[12.5+25 \log_{10}\left(\frac{\phi}{\phi_o}\right)\right] \text{ for } 3.16\ \phi_o < \phi$$

where: ϕ_o = 3 dB beamwidth (deg.)

ϕ = off-axis angle (deg.)

G_D = gain discrimination

This pattern very closely approximates that pattern currently accepted for the Fixed-Satellite Service and therefore it has been used for all the geostationary spacecraft sharing analyses.

APPENDIX IV

INTER-SATELLITE SYSTEM DEVELOPMENTS

1. INTRODUCTION

This annex describes the generalized models used to determine transmission parameters for satellite links in the Inter-Satellite Service and presents sample interference analyses for the 54.9 to 55.1 GHz band. Two types of system models are considered, a non-tracking communication system utilizing antennas which are fixed to the body (or despun portion) of the spacecraft, and a system utilizing tracking-antennas, i.e., antennas which may be pointed independently of the spacecraft attitude perturbations. The principal difference between these two models is that the antenna beamwidth of the non-tracking system must be large enough to accommodate the relative angular motions of both the transmitting and receiving spacecraft.

2. GEOSTATIONARY-TO-GEOSTATIONARY SATELLITE MODELS

2.1 Non-Tracking Inter-Satellite Systems

One of the models used to describe the non-tracking geo-stationary-to-geostationary inter-satellite systems is based on information contained in CCIR Document 451-1 (rev 76). This document gives values for expected satellite relative station-keeping errors of future inter-satellite systems and are as follows:

Altitude variation	$\pm$ 12 km
North/South	$\pm$ 8 km
East/West	$\pm$ 73 km

These values are relative in that it is expected that the phase of the cyclic orbital perturbation of the two inter-satellites would be as closely matched as possible, in order to reduce the apparent angular motion of one spacecraft as seen from the other. Figure 1 illustrates the effect of the relative station-keeping errors in terms of apparent angular displacements as a function of the geocentric orbital separation of the two spacecraft.

Figure 1 indicates that for relatively small angular separations, (e.g., up to about 30°) the altitude variation causes the largest uncertainty in the location of the spacecraft, while at large separation angles the dominant factor is the east-west station-keeping capability.

Since, for the non-tracking system, the antenna beamwidths must be wide enough to encompass the relative satellite station-keeping errors, in addition to compensating for the transmitting satellites attitude errors, Figure 1 implies that narrowbeam high-gain antennas can only be utilized when the two satellites are sufficiently separated in orbit.

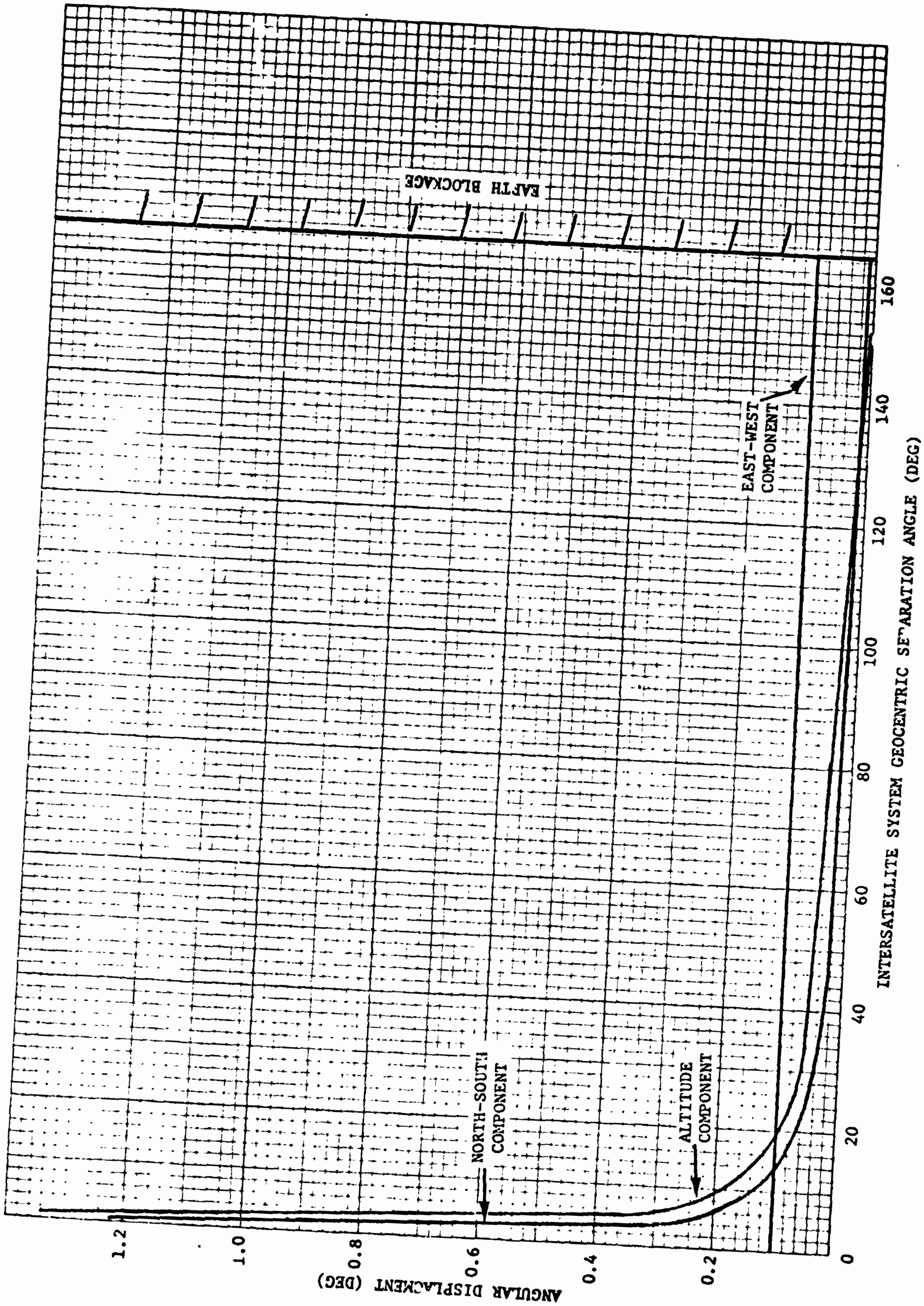


FIGURE 1. RELATIVE ANGULAR ERROR DUE TO STATIONKEEPING UNCERTAINTIES

Equation 1 gives the power required by the transmitting satellite as a function of the satellite separations, antenna diameters, frequency and other link and physical parameters of the inter-satellite system.

$$P = \frac{(C/N)\ KT(f)b}{G_R G_T} \left(\frac{\lambda}{4\pi R}\right)^{-2} \qquad (1)$$

where: G = main beam gain = $\left(\frac{\pi D}{\lambda}\right)^2 \eta$

f = frequency (GHz)

λ = wave length (m)

T = receiver temperatue = $9000\sqrt{f/55}$

p = power (Watts)

D = antenna diameter (m)

R = range (m) = $R_g\sqrt{2(1-\text{Cos}\ \phi)}$

R_g = geostationary distance to center of Earth

ϕ = geocentric separation angle (deg)

K = 1.38×10^{-23} dBW/K/Hz Boltzmann's constant

b = bandwidth (Hz)

C/N = carrier-to-noise ratio

Three of the terms shown in Equation (1) require elucidation. The receiver noise temperature variation with frequency is based on a noise figure of 15 dB at 55 GHz. The bandwidth and carrier-to-noise ratio chosen for the non-tracking model are 100 MHz and 30 dB respectively. These values are typical of communication links that may be used by Intelsat type traffic (i.e., generally multiplexed voice-traffic). Since the service requirements for commercial traffic are generally quite high, it is felt that these requirements represent a practical worst case for development of the transmit power for non-tracking systems, and therefore for interference to a spaceborne radiometer.

It should be noted that one of the principal reasons put forth by the fixed-satellite community for utilizing inter-satellite links is the reduction of the time delay which would occur over a fixed satellite two-hop link. This time delay could be considerably reduced by utilizing close inter-satellite relays between spacecraft. However, two inter-satellite spacecraft having an orbital separation of 30° would have 66% of the time delay of full two-hop system. For this reason, it would be expected that the commercial voice traffic would be restricted to inter-satellite communications between relatively closely space spacecraft.

2.2 Tracking Inter-Satellite Systems

It is possible that inter-satellite systems which do not utilize "Intelsat-type" traffic will come into existance. For example, earth resource images, or other types of wide band digital data, may be relayed between geostationary spacecraft.

Such systems would require greater information bandwidths than the previously discussed systems but would carry digital traffic which is not impacted by propagation delays. For the purposes of this analysis a digital signal, with a 200 MHz information bandwidth, is assumed.

Further it is assumed that a post-detection S/N ratio of 20 dB would be sufficient and that this would be accomplished via a first detection C/N of 10 dB and a modulation technique (spread spectrum) yielding 10 dB processing gain. This implies that the original 200 MHz information bandwidth would be spread on the order of 10:1 and therefore the transmitted bandwidth would be approximately 2 GHz.

2.3 Transmitter Power Requirements

Figure 2 presents the inter-satellite transmit power requirement for the tracking-antenna system model and for two different non-tracking system models as a function of spacecraft orbital separation. The non-tracking system models are developed by utilizing an antenna beamwidth large enough to encompass the maximum angular area of uncertainty (shown in Figure 1) in addition to a 0.1° attitude uncertainty. Figure 2 presents the required power for non-tracking systems with antenna diameter upper limits of 1.2 and 2 meters. The tracking system is assumed to utilize a 0.1° beamwidth antenna.

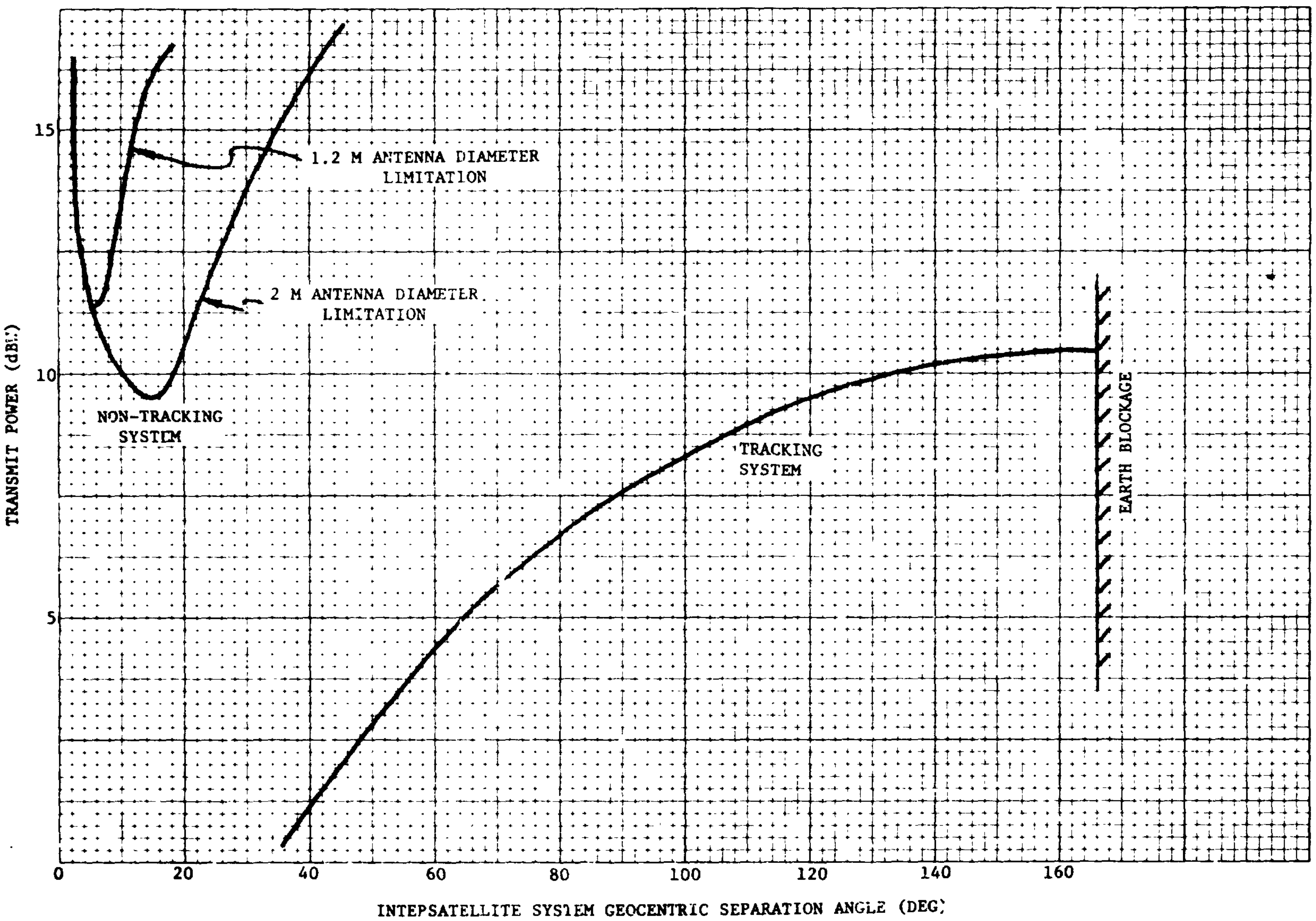


FIGURE 2. 54 GHz INTERSATELLITE SYSTEM REQUIRED TRANSMIT POWER

These models lead to parameters which may be reasonable for inter-satellite systems in the 50 to 60 GHz portion of the spectrum; that is, maximum antenna sizes of either 2 meters for the non-tracking system (i.e., compatible with large launch vehicles) or 4 meters for the tracking systems (compatible with shuttle-type payloads).

Figure 2 indicates that at 54 GHz the non-tracking system has an optimum (i.e., minimum power) angular separation. This occurs because the increased achievable gain as the spacecraft are separated, more than compensates for the increasing range between the spacecraft. The minimum power requirement is reached at the point where the antenna size reaches the indicated limit even though the relative angular motions of the spacecraft are still decreasing. From this point on, the antenna gain remains constant and the transmit power must be increased to compensate for the increased spreading loss as the spacecraft separations are increased. At geocentric spearation angles beyond about 30° the transmitting power requirements for non-tracking systems rapidly become prohibitive.

Since worst case interference to a low orbiting radiometer would occur from geostationary spacecraft communications across large orbital arcs (and therefore grazing the earth's limb), the technical parameters of tracking geostationary-to-geostationary inter-satellite systems are utilized in all sharing analyses to which this Appendix applies.

2.4 Interference Analysis Procedure

In order to assess potential interference from geostationary-to-geostationary satellite links it is necessary to make certain assumptions as to the technical characteristics of the link. A method by which an upper bound on the potential interference may be placed is described below.

Since the level of interference received by either a limb sounder or a nadir-looking radiometer is a function of the orbital separation of the geostationary spacecraft (which determines the required transmit power and off-axis antenna gains), the following figures present the interference level as a function of orbital separation angle of the geostationary spacecraft.

Figure 3 illustrates the worst case interference level received by a nadir-looking radiometer when two geostationary satellites are communicating with one another. Additionally, the interference threshold for the radiometer is shown by the dashed line. As illustrated in the Figure, no interference will occur. Interference threshold is approached only when the main beam of the transmitting inter-satellite spacecraft ap-proaches the earth - even in this case, the interference is 10.7 dB below the threshold of the radiometer.

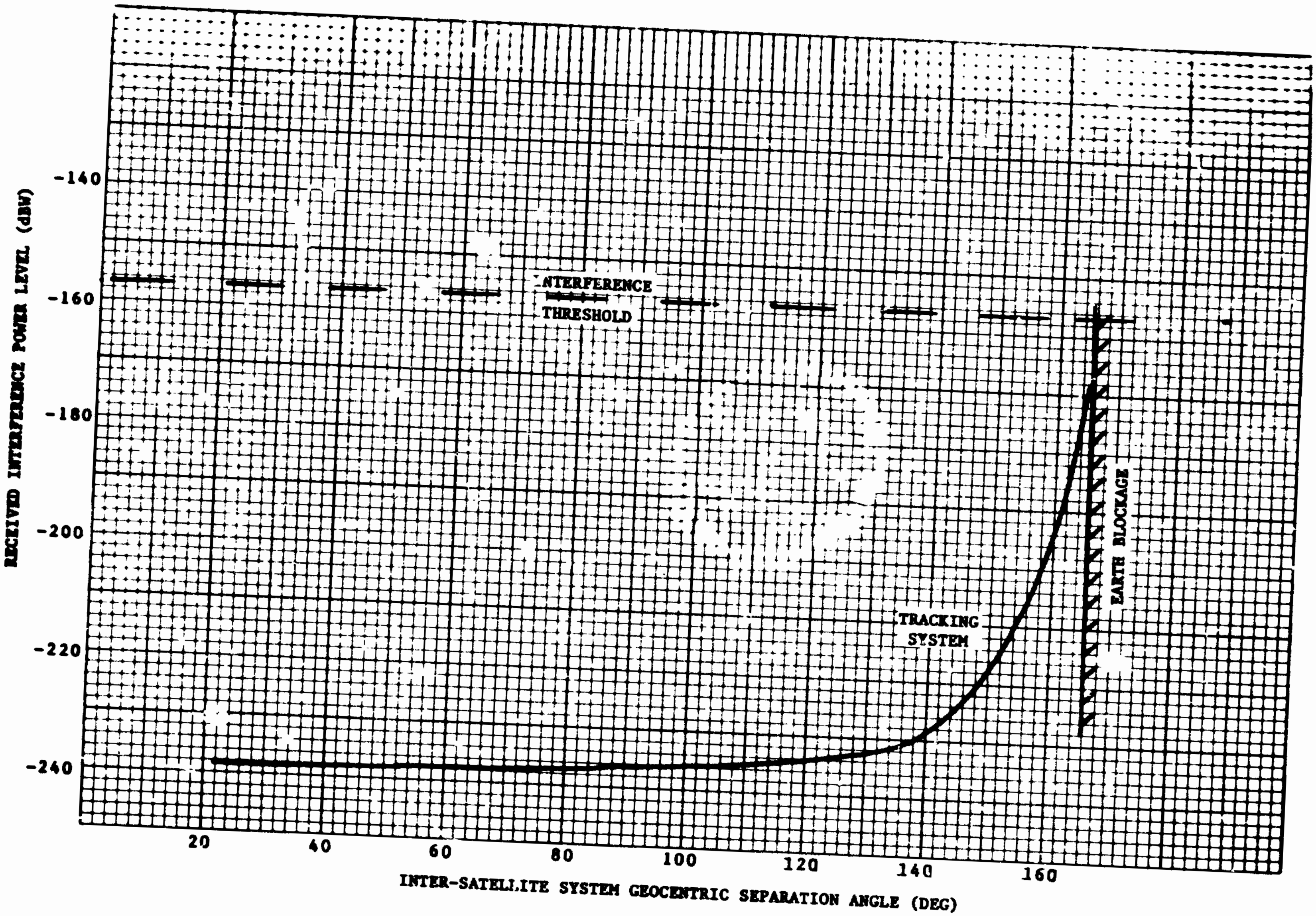


FIGURE 3. WORST CASE INTERFERENCE POWER RECEIVED BY NADIR-LOOKING RADIOMETER AT 54.9-55.1 GHz

It should be noted that there has been no allowance made for atmospheric loss in the interference path in this portion of this analysis. These losses, however, will provide additional margin against interference.

The conclusion, then, is that nadir-looking radiometers should experience no interference from geostationary-to-geostationary communication links in the 54.9-55.1 GHz inter-satellite band.

Figure 4 illustrates the power received by a limb-sounding radiometer under worst case* conditions as a function of the separation of the inter-satellite spacecraft. The interference level for the radiometer is indicated by a dashed line in the figure.

The peak interference level presented in Figure 4 represents a main-beam to main-beam coupling situation between the geostationary spacecraft and the limb sounder. Although this situation in reality would not occur for anticipated Earth Exploration Satellite orbits, it is presented only to set an upper bound on potential interference. In this example, a maximum interference level of 68 dB above threshold could be encountered.

In order to bound the area of the orbital sphere in which interference above threshold would occur, it is necessary to determine the relative position of the radiometer spacecraft to provide antenna discriminations equal to 68 dB.

---

*This worst case condition is defined as the main beam of the radiometer pointing directly at the transmitting inter-satellite system.

C-3

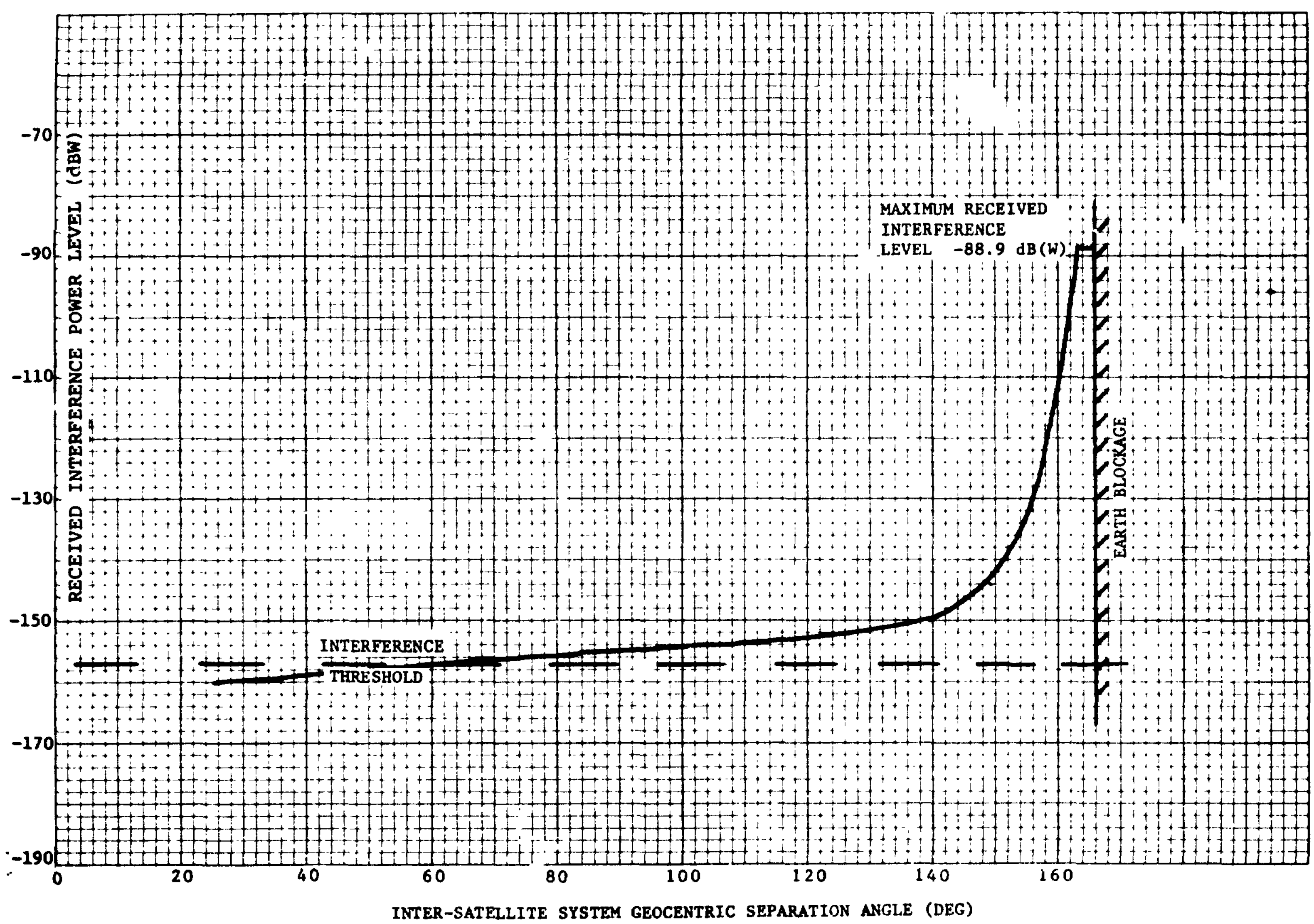


FIGURE 4. WORST CASE INTERFERENCE POWER RECEIVED BY LIMB-SOUNDING RADIOMETER AT AT 54.9-55.1 GHz

Figure 5 presents minimum combined antenna discrimination as a function of east-west and north-south relative motion of the radiometer away from the point* of maximum interference. It can be seen from this figure that an east-west motion of the radiometer of only 0.5° yields the required discrimination, while a north-south motion of 12° is required. These angles then, respectively, represent the semi-minor and semi-major axis of a pseudo-elliptical region lying on the equator with the long axis (12° x 2 = 24° in length) oriented in the north-south direction. This region represents about 3% of the total 500 km orbital sphere.

This 3% loss represents the worst case and for all other geometrical configurations the interference area would significantly be diminished. Additionally, for geostationary satellite spacings of less than 70°, no interference would be encountered by the radiometer, whether nadir looking or limb sounding.

Since this worst case 3% loss of sensing area would occur only for an inter-satellite system communicating across a 160° arc of the geostationary orbit, and a much reduced interference region would occur from inter-satellite systems operating across less than 150° of the geostationary orbit, this situation* would not occur in practice and therefore it is concluded that limb-sounders can share with geostationary-to-geostationary inter-satellite links.

---

*Refers to hypothetical situations of 1) a polar orbit/side-looking limb sounder and 2) an equatorial orbit with a long track pointing of the limb sounder.

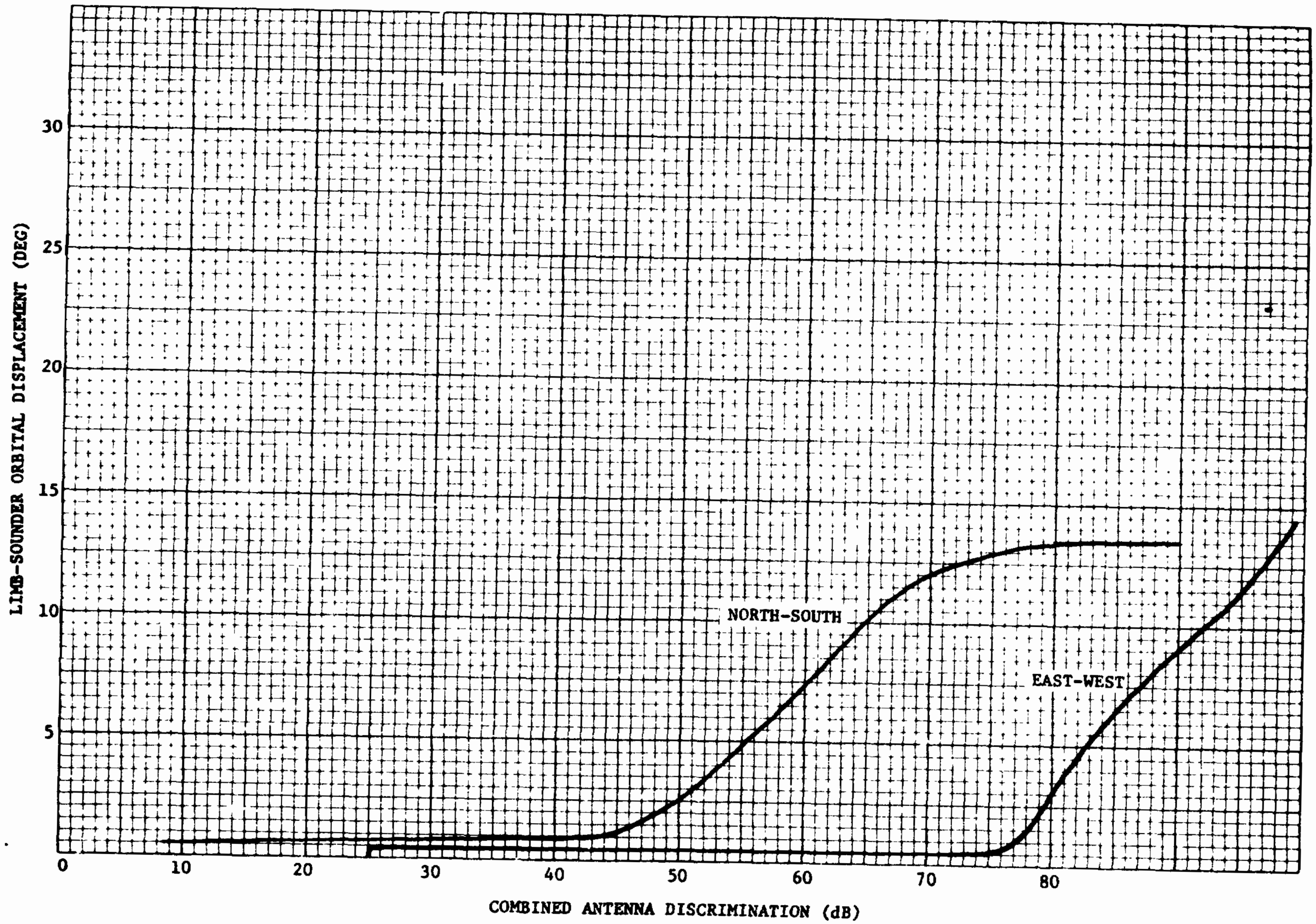


FIGURE 5. AVAILABLE ANTENNA DISCRIMINATION VS. LIMB-SOUNDER ORBITAL DISPLACEMENT

3. GEOSTATIONARY/LOW-ORBIT SATELLITE MODELS

3.1 Sytem Model

The communication system parameters for a geostationary/ low orbit satellite, a 200 MHz information bandwidth spread over a 2 GHz transmission bandwidth and a required receive C/N of 10 dB, are assumed to be the same as for geostationary-to-geostationary inter-satellite systems (see Section 2.2.). However, because of the more demanding tracking capabilities required for the up- and down-links, wider beamwidth antennas must be utilized.

3.2 Transmit Power Requirements

The technical characteristics of geostationary/low orbit links in the Inter-satellite Service have been estimated using an assumed design employing spread spectrum techniques. The design parameters are as follows:

- Required predetection carrier to noise ratio - 10 dB
- Receiver noise - 15 dB
- Transmission bandwidth - 2 GHz
- Geostationary satellite antenna gain - 60 dB(i)
- Low orbit satellite antenna gain - 50 dB(i)

The satellite transmitter power required to permit communications over the link can be computed by the following relationship:

$$P_t = N + 10\ \text{dB} - G_t - A_R + L$$

where: N = receiver noise power

G_t = transmitting antenna gain

A_R = receiving antenna effective

L = spreading loss

For the 54.9 to 55.1 GHz band the required transmitter power is 23.1 dB(W).

The worst case interference geometry would occur if the radiometer, while scanning the earth's limb, received a main beam signal from a geostationary satellite within the radiometer main beam. The interference level in this instance is computed as follows:

Transmitted e.i.r.p.	83.1 dB(W)	
Bandwidth conversion factor	- 9.3 dB	(235 MHz/2 GHz)
Spreading loss	-163.0 dB(m^{-2})	
Radiometer antenna effective area (main beam)	+ 8.7 dB(m^2)	
Received interference power	- 80.5 dB(W)	

or 76.5 dB above the interference threshold of -157 dB(W). For nadir-looking radiometers, the interference level would be 2.5 dB below the radiometer interference threshold. This interference would occur only when the geostationary satellite points at the limb.

The probability of occurrence and the duration of this interference situation is very small. For instance, a typical polar orbit adjusted for global repetitive coverage would cause the limb sounder to point to a geostationary satellite only twice per month. The maximum duration of interference in this case would be approximately three minutes and constitute less than 0.8 of one percent of the time. The interference situation therefore will be an infrequent occurrence and the loss of data would be negligible.

A limb sounding radiometer will experience interference whenever its main beam is directed at the sidelobes of the geostationary satellite as seen from the following calculations:

Transmitted e.i.r.p. (0 dB/i gain)	23.1 dB(W)
Bandwidth conversion factor	- 9.3 dB (235 MHz/2 GHz)
Spreading loss	-163.0 dB (m^{-2})
Radiometer antenna effective area (main beam)	+ 8.7 dB(m^2)
Received interference power	-140.5 dB(W)

or 16.5 dB above the interference threshold. Although this level does constitute interference to the radiometer, the length of time that interference would be above threshold is of negligible impact to data measurements. For instance, a typical polar orbit adjusted for global repetitive coverage would cause the limb sounder to point at the geostationary

satellite at most twice per month and the duration of interference would be on the order of 20 seconds maximum (.01% of the orbital time). Additionally, the value calculated is conservative in that no account is taken for potential atmospheric attenuation at the earth's limb.

Another potential interference situation is whenever the radiometer passes through the main beam of a geostationary satellite. In this instance, coupling of the signal would be via the side lobe of the radiometer antenna (for both nadir and limb sounding) and the resulting interference level is computed as follows:

Transmitted e.i.r.p.	83.1 dB(W)
Bandwidth conversion factor	- 9.3 dB (235 MHz/2 GHz)
Spreading loss	-163 dB(m^{-2})
Radiometer antenna effective area (side lobe)	- 70.3 dB(m^2)
Received interference power	-159.5 dB(W)

or 2.5 dB below the radiometer interference threshold of -157 dB(W).

Consequently, for the two interference geometries presented above, no significant interference will be experienced by the radiometer due to the geostationary to low orbit link.

3.4 Interference Analysis (Low Orbit Satellite Transmitting)

The amount of interference received by the radiometer from a transmitter located on a low orbit spacecraft is highly dependent upon the distance between the two spacecraft, which can vary from tens to thousands of kilometers. The spreading loss therefore may fluctuate as much as 60 to 70 dB.

Since any main beam to main beam couplings are extremely remote, the only significant potential for interference results from side lobe to side lobe coupling.

The following calculation determines the distance required between the two spacecraft in order that side lobe coupling does not cause interference.

Transmitted e.i.r.p. (0 dB gain)	23.1 dB(W)
Bandwidth conversion factor	- 10.0 dB (235 MHz/2 GHz)
Radiometer antenna effective area (side lobe)	- 56.3 dB(m^2)
Interference threshold	-(-158 dB(W))
Required spreading loss	114.8 dB(m^{-2})

or a distance of 155 km.

In order for the spacecraft to pass within this distance the orbital altitude of the two spacecraft must be within 155 kilometers. If the two spacecraft are to remain within this distance of each other for a significant amount of time, the basic orbital parameters must be nearly identical. It is highly improbable that two spacecraft would be launched into such similar orbits unless it were a matter of design. Clearly, large areas of interference would not occur.

APPENDIX V

BIBLIOGRAPHY

SALINITY

Dillinger, A. and J. Paris, 1972, Salinity and temperature analysis program: Project 4699, Houston Aerospace System Division, Lockheed Electronics Company, Inc. Houston, Texas, p. 107.

Droppleman, J. and D. Evans, 1972, Salinity surveys using an airborne microwave radiometer: 4th Ann. Earth Resources Prog. Rev., Vol. I, NASA/JSC.

Paris, J., 1969, Microwave radiometry and its application to marine meteorology and oceanography: Ref. No. 69-IT, Dept. of Oceanography, Texas A & M University, College Station, Texas.

Thomann, G.C., 1973, Remote measurement of salinity in an estuarine environment: Remote Sensing of Environment, v.2, no. 4, pp. 249-259.

Zdanovich, V.G., 1972, Salinity surveys using an airborne microwave radiometer: 8th Internat. Symp. on Remote Sensing of Environment, Ann Arbor, Michigan.

SEA SURFACE TEMPERATURE

Gurvich, A. ad S. Egorov, 1966: Determination of the surface temperature of the sea from its thermal radio emission: Izv. Atm. and Oceanic Phys., v. 2, pp. 305-307.

Hanson, K., 1972: Remote sensing of the ocean: Remote Sensing of the Troposphere, Chapter 22, USDC-NOAA, Wave Propagation Lab., Boulder, Colorado, p. 56.

Hidy, G., W. Hall, W. Hardy, W. Ho, A. Jones, A. Love, M. VanMelle, H. Wang, and A. Wheeler, 1971: Development of a satellite microwave radiometer to sense the surface temperature of the world's oceans, S-band radiometer: Final Report, Contract No. NAS 1-10106, Space Division, North American Rockwell.

Paris, J., 1969: Microwave radiometry and its application to marine meteorology and oceanography: Ref. No. 69-IT, Dept. Oceanography, Texas A & M University, College Station, Texas.

Stogryn, A., 1967: The apparent temperature of the sea at microwave frequencies: IEE Trans. Ant. Prop., V. 29, pp. 776-782.

SOIL MOISTURE

Basharinov, A.E., L.F. Borodin, and A.M. Shutko, 1974: "Passive Microwave Sensing of Moist Soils", in Proc. Ninth International Symposium on Remote Sensing of Environment, Univ. of Michigan, Ann Arbor, 363-367.

Cihlar, J. and F.T. Ulaby, 1975: "Microwave Remote Sensing of Soil Water Content", Univ. of Kansas, CRINC Remote Sensing Laboratory, Tech. Rept. 264-6, Contract NAS 9-14052.

Eagleman, J.R., 1974: Moisture Detection from Skylab. Ninth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, Ann Arbor, 701-705.

Eagleman, J.R., and F.T. Ulaby, 1974: "Remote Sensing of Soil Moisture by Skylab Radiometer and Scatterometer Sensors", Advances in the Astronautical Science, The Skylab Results, Vol. 31, Part 2, 681.

Eagleman, J.R. and W.C. Liu, 1976: "Remote Sensing of Soil Moisture by a 21-cm Passive Radiometer", J. Geophys. Res., 81, 3660-3666.

Schmugge, T., P. Gloersen, T. Wilheit and F. Geiger, 1974: "Remote Sensing of Soil Moisture with Microwave Radiometers", Journal of Geophysical Research, 79, 317-323.

SNOW

American Society of Photogrammetry, 1975: Manual of Remote Sensing: Volumes I and II, Falls Church, Virginia.

Barnes, J.C., C.J. Bowley, and D.A. Simmes, 1974: The Application of ERTS Imagery to Mapping Snow Cover in the Western United States, Final Report under Contract NAS 5-21803, Environmental Research and Technology, Inc., Concord, MA, 77 pp.

Barnes, J.C., J.L. Cogan, and M.D. Smallwood, 1975: A Study to Develop Improved Spacecraft Snow Survey Methods Using Skylab/EREP Data: Final Report under Contract NAS 9-13305, Environmental Research and Technology, Inc., Concord, MA, 92 pp.

Barnes, J.C., and C.J. Bowley, 1974: Handbook of Techniques for Satellite Snow Mapping, Report Prepared under Contract NAS 5-21803, Environmental Research and Technology, Inc., Concord, MA, 95 pp.

Committee on Polar Research, 1970: Polar Research, A Survey, National Research Council, National Academy of Sciences, Washington, D. C., 204 pp.

Linlor, W., M. Meier, and J. Smith, 1974: "Microwave Profiling of Snowpack Free-Water Content", Proc dings of Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources, National Academy of Sciences, Washington, pp. 729-736.

Salomenson, V.V., 1974: "Water Resources", in Proceedings of Third ERTS Symposium, Volume II, NASA SP-356, Goddard Space Flight Center, pp. 126-137.

Strong, A.E., E.P. McClain, and D.F. McGinnis, 1971: "Detection of Thawing Snow and Ice Packs through the Combined Use of Visible and Near-Infrared Measurements from Earth Satellites", Monthly Weather Review, 99, (11), pp. 828-830.

Wiesnet, D.R., 1974: "The Role of Satellites in Snow and Ice Measurements," Proceedings of Interdisciplinary Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources, National Academy of Sciences, Monterey, California, December 2-6, 1973, pp. 447-456.

Wiesnet, D.R., and D.F. McGinnis, 1973: "Hydrologic Applications of the NOAA-2 Very High Resolution Radiometer," Symposium on Remote Sensing and Water Management, Burlington, Ontario, Canada (June).

SEA STATE

Blanchard, D., 1963: Electrification of the atmosphere by particles from bubbles in the sea: Progress in Oceanography, Vol. I, New York, Pergamon Press.

Cardone, V., 1969: Specification of the wind field distributio in the marine boundary layer for wave forecasting: Report TR 69-1, New York, New York Univ., Geophysical Sciences Lab.

Conway, J., 1970: Laser and microwave observations of sea-surface conditions for fetch-limited 17-25 m/s winds: IEEE Trans. Geosci. Electronics. v. GE-8, p. 326-336.

Cox, C. and W. Munk, 1954a: Measurement of the roughness of the sea surface from photographs of sun's glitter: Jour. Optical Soc. of America, v. 44, p. 838-850.

Cox, C. and W. Munk, 1954b: Statistics of the sea surface derived from sun glitter: J. Marine Res., v. 13, pp. 198-227.

Droppleman, J., 1970: Apparent microwave emissivity of sea foam: Jour. Geophys. Res., v. 75, pp. 696-698.

Hall, F., 1972: Microwave brightness temperature of a wind blown sea: 4th Annual Earth Resources Program Review, Vol. I, NASA Johnson Space Center, Houston, Texas.

Monahan, E., 1969: Freshwater whitecaps: Jour. Atmos. Sci., v. 26, pp. 1026-1029.

Nordberg, W., J. Conaway, D. Ross, and T. Wilheit, 1971: Measurement of microwave emission from a foam covered, wind driven sea: Jour. Atmos. Sci., v. 28, pp. 429-435.

Ross, D. and V. Cardone, 1972: Observations of oceanic whitecaps for moderate to high wind speeds: 4th Ann. Earth Resource Prog. Rev., NASA Johnson Space Center (formerly Manned Spacecraft Center), Houston, Texas.

Williams, G., Jr., 1969: Microwave radiometry of the ocean and the possibility of marine wind velocity determination from satellite observations: Jour. Geophys. Res., v. 74, pp. 4591-4594.

SEA ICE

Blinn, J.C. III, 1975: "Microwave Measurements of Ice Thickness", Environmental Research & Technology, Inc., Final Report under JPL Contract No. 953748.

Campbell, W.J., P. Gloersen, W. Nordberg, and T.T. Wilheit, 1973: Dynamics and Morphology of Beaufort Sea Ice Determined from Satellites, Aircraft, and Drifting Stations, NASA Publication X-650-73-194, NASA/GSFC.

Fletcher, J.O., 1966: "Forward", Proc. of the Symposium on the Arctic Heat Budget and Atmospheric Circulation, Memorandum RM-6233-NSF, The RAND Corporation.

Gloersen, P., T. Wilheit, and T. Schmugge, 1972: "Microwave Emission Measurements of Sea Surface Roughness, Soil Moisture, and Sea Ice Structure:, Fourth Annual Earth Resources Progress Review, Vol. 1, NASA/JSC, Houston, Texas.

McClain, E.P., 1974: "Some New Satellite Measurements and their Application to Sea Ice Analysis in the Arctic and Antarctic", Proceedings of Interdisciplinary Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources, National Academy of Sciences, Washington, pp. 457-466.

McClain, E.P. and M.D. Baliles, 1971: "Sea Ice Surveillance from Earth Satellites:, Mariners Weather Log, 15 (1), pp. 1-4.

Meeks, D.C., R.O. Ramseier and W.J. Campbell, 1974: "A Study of Microwave Emission Properties of Sea Ice - AIDJEX 1972", in Proc. Ninth International Symposium on Remote Sensing of Environment, pp. 307-322, Univ. of Michigan, Ann Arbor.

NASA, 1973: US-USSR Bering Sea Expedition Convair-990 Navigational Flight Data, Prepared, Programming Methods, Inc. for the Laboratory for Meteorology and Earth Sciences, Goddard Space Flight Center, NASA, under contract NAS5-11930, Greenbelt, Maryland.

Wilheit, J., J. Blinn, W. Campbell, A. Edgerton, and W. Nordberg, 1971: Aircraft Measurements of Microwave Emission from Arctic Sea Ice, X651-71-417, NASA/GSFC, Greenbelt, Maryland.