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# RADIOMETER MISSION REQUIREMENTS
# FOR
# LARGE SPACE ANTENNA SYSTEMS

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# NOMENCLATURE

$f$ = frequency
$F$ = footprint; resolution element
$D$ = diameter of antenna (aperture)
$A_e$ = effective aperture
$\lambda$ = wavelength
$h$ = orbital altitude
$\frac{C_D A}{m}$ = ballistic drag coefficient
FOV = field-of-view
IFOV = instantaneous field-of-view
$Q$ = orbits per day
$i$ = orbital inclination
$P$ = power level at the antenna
$T$ = temperature
$B$ = predetection bandwidth
ERIP = equivalent isotropic radiated power
$\varepsilon$ = beam efficiency
$\delta$ = rms antenna surface deviations
HPBW = half-power bandwidth
$\Delta T$ = radiometer sensitivity
$T_{sys}$ = radiometer system temperature
$\gamma$ = post detection integration time
$\tau$ = dwell time
$S$ = swath width
$V$ = orbital velocity

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## SUMMARY

Requirements are defined for Earth observational microwave radiometry for the decade of the '90's using Large Space Antenna (LSA) systems with apertures in the 50 to 200 meter range. General Earth observational needs, specific measurement requirements, orbital mission guidelines and constraints, and general radiometric requirements are defined. This requirements definition has been assembled by a NASA interCenter committee for the purpose of guiding the Langley Research Center's spacecraft technology development work which has LSA systems as its "focus." However, technologists and space data application specialists at other NASA centers, as well as those in academia and in industry, can use this information also, particularly, in assessing its technology impact along with similar requirements information for space communications and astronomy disciplines.

General Earth observational needs are derived from NASA's basic space science program. Specific measurands include soil moisture, water surface temperature, water roughness, ice boundaries, salinity, and water pollutants. Measurements with 10 to 1 km spatial resolution and 3 to 1 day temporal resolution are required. The primary orbital altitude and inclination ranges are 450-2200 km and 60° - 98°, respectively. Contiguous large-scale coverage of several different areas of the globe dictates large (several hundred meters) swaths.

Radiometrically the measurements are made in the 1-37 GHz range preferrably with dual polarization radiometers with >90 percent beam efficiency. Reflector surface rms deviations in the range from $\lambda/30$ - $\lambda/100$ are required. Accuracy and resolution requirements for brightness temperature are in the order of 2 K and 0.5 K, respectively, dictating radiometer sensitivity of < 0.5 K. System implications point toward multiple beam configurations used in either "whisk or "push" broom modes.

# I. INTRODUCTION AND BACKGROUND

Langley Research Center's spacecraft research program is aimed at developing the technical foundation for future high performance, cost effective spacecraft systems through research at the discipline level (e.g., structures and electronics) and at the systems level. Large Space Antenna (LSA) systems have been chosen as the "focus" for this work. Activities will include:

(1) Basic research and technology development in the appropriate disciplines;

(2) Systems studies to define advanced concepts and to identify critical technology requirements; and

(3) Systems level hardware research and development;

and will culminate in providing technical data and advice to the appropriate project organizations.

Although it is not expected that the Langley Research Center will deliver LSA systems for operational spaceflight missions, it is appropriate to define measurements and missions that may need or utilize LSA systems and to delineate the corresponding performance and system requirements in order to guide the spacecraft and LSA systems research. Three generic applications are considered to be "technology drivers": (1) narrow-band communications, (2) radio astronomy from space, and (3) Earth observational radiometry. Appropriate efforts are being made to keep the "requirements definitions" for those three applications up to date and properly related. This report addresses only the "requirements" for Earth observational radiometry. Establishing their relationship to the requirements for communications and astronomy represents a follow-on activity. Let it suffice to say that although the requirements for the three applications may be similar in many ways and a basic LSA system may respond to all of them, there may be other ways (e.g., orbital parameters and beam efficiencies) in which they may be markedly different, and that the impact of such differences on the research and technology efforts must be assessed. This report can serve as a primary input to that assessment.

In establishing an NASA interCenter committee (see Appendix for membership) to "produce an updated set of radiometer mission requirements," the guidelines specified an antenna aperture range of 50-200 meters and "early 1990 mission considerations." The "new" information in this report, therefore, is simply the committee's assessment and selection of the requirements for this size range projected to circa 1990. An attempt has been made to summarize the rationale for selection of these requirements in a progressive fashion, starting with Earth observational needs and measurement needs addressable by an LSA radiometer and concluding with LSA system radiometric, orbital, and performance requirements. In addition, major references are included.

## II. EARTH OBSERVATIONAL NEEDS

### General Needs

The following statements taken from reference 1 are a succinct summary of NASA's Earth Observational Program objectives and future emphases:

"The Resource Observation Program objectives include forecasting of agricultural production, exploration for mineral and energy resources, management of land use and water resources, and assessment of geodynamic hazards (such as earthquakes). Current efforts are concentrated in utilizing medium-to-low resolution instruments in a few spectral regions. Further emphasis will be on high-resolution (temporal, spatial, and spectral) studies in truly multispectral fashion, including magnetic, microwave, IR, visible, and stereo data."

"The Global Environment Program objectives include monitoring and forecasting of global weather and local severe storms, assessment and forecasting of climate, monitoring and forecasting of ocean conditions, and assessment of air and water quality. The future emphasis will be on multi-instrument systems to measure a variety of phenomena simultaneously, and on geosynchronous observations."

The important feature of these statements regarding LSA requirements is that high resolution sensing in the microwave portion of the spectrum is needed "to measure a variety of phenomena simultaneously," and that these measurements would be particularly useful in agriculture, hydrology, and weather and climate forecasting applications. Examining the microwave sensing data in Table II-1 in response to these expressed needs, it is obvious that there is potential with various microwave frequencies for remote sensing of atmospheric, sea surface, and land surface parameters. A first order assessment of this potential is portrayed by Table II-2 which charts observables (in order of frequency best suited for sensing) desirable for the various application disciplines with an indicator of the importance of the individual observables to each application.

For the observables listed, high resolution generally means spatial resolution elements or footprints whose largest dimensions range from

TABLE II-1.- Microwave Sensing Data

| A. Microwave Bands | | |
|---|---|---|
| Band | Frequency (GHz) | Wavelength (cm) |
| P | 0.3 - 1.0 | 30.00 - 100 |
| L | 1.0 - 2.0 | 15.00 - 30.0 |
| S | 2.0 - 4.0 | 7.50 - 15.0 |
| C | 4.0 - 8.0 | 3.75 - 7.5 |
| X | 8.0 - 12.5 | 2.40 - 3.75 |
| Ku | 12.5 - 18.0 | 1.67 - 2.40 |
| K | 18.0 - 26.5 | 1.10 - 1.67 |
| Ka | 26.5 - 40.0 | 0.75 - 1.10 |
| V (mid freq.) | 50.0 | 0.58 |

| B. Microwave Spectrum Characteristics | |
|---|---|
| Characteristics | Frequency (GHz) |
| Atmosphere | |
| Windows | 1-18, 35, 93, 150 |
| $O_2$ Lines (Temp. Sounding) | 50-70, 118 |
| Water Vapor Lines | 22, 183 |
| Cloud Absorption (Rayleigh) | $\propto f^2$ |
| Sea Surface | |
| Temperature Sensitive | 2-6, 12 |
| Salinity Sensitive | 1-2 |
| Wind Speed Sensitive | 2-50 |
| Ice Coverage and Age Sensitive | 10-50 |
| Land Surface | |
| Spatial Resolution of Surface Features | $\propto f^2$ |
| Soil Moisture Sensitive | 1-10 |

TABLE II-2.- Potential Microwave Observations Important for Various Applications

OBSERVABLE

| APPLICATION | FREQ (GHz) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1-37 | 1-2 | 1-10 | 1-10 | 1-8 | 22 | 30-40 | 10-50 | 50-70 | 130-140, 183, 93, 118 |
| | WATER ROUGHNESS - SEA STATE (WINDS) | SEA SURFACE SALINITY | WATER POLLUTANTS | SOIL MOISTURE | SEA SURFACE TEMP. | ATMOS. WATER VAPOR | LAND SURFACE IMAGING | ICE MAPPING (COVERAGE AND AGE) | ATMOS. TEMP. PROFILE | SURFACE IMAGE AND ATMOSPHERIC SOUNDING |
| AGRICULTURE | - | - | - | + | - | - | + | - | - | 0 |
| HYDROLOGY | - | - | - | + | - | - | + | - | - | 0 |
| WEATHER AND CLIMATE | + | 0 | - | + | + | + | 0 | + | + | + |
| COASTAL PRODUCTIVITY | + | + | - | - | + | - | - | 0 | - | - |
| COASTAL DYNAMICS | + | - | - | - | + | - | + | + | - | 0 |
| WATER QUALITY | - | - | + | 0 | - | - | 0 | - | - | 0 |

- NOT APPLICABLE
0 HELPFUL
+ IMPORTANT
+ CRITICAL

approximately 20 km to 1 km and temporal resolution elements or revisit intervals which range from approximately 4 days to 1 hour. Thus, the elements necessary to determine microwave frequencies (Earth observable phenomena), antenna aperture size (spatial resolution) and orbital parameters (revisit intervals) requirements for LSA systems have been defined in a preliminary fashion by the needs of the basic NASA Earth Observational Program. It should be noted, however, that major non-NASA "users" of data obtained by observing the Earth with LSA systems may have other requirements and these should be addressed also. This task is reserved for a later effort and is not included in this requirements definition.

## Key Measurements

Microwave radiometry applications in the 20-cm band have long been identified as the driver in the development of Large Space Antennas. In particular, soil moisture content, sea surface temperature, and salinity are the key geophysical parameters of interest for remote sensing in this wavelength region. Physical models and experimental demonstrations have already validated the concepts relating the microwave brightness temperature to these geophysical quantities. The issues for the development of future systems involve tradeoffs between required spatial resolution, swath width, revisit time, data rate, and the issues of radar versus radiometer systems. Table II-3 lists requirements given in reference 2, "High Resolution Passive Microwave Satellites." These data were generated by scientists studying configurations of a multifrequency microwave radiometer.

The 20 to 50-km resolution spread for sea surface temperature (SST) was later investigated by the Navy for a classified application. The 20 km was found to be the largest footprint that was usable, i.e., the minimum needed resolution, with 10 km being the desired resolution. It was decided that an IR sensor could meet the resolution needs and that the cloud penetrating advantages of the microwave radiometer were not essential for this application. The U.S. Navy is interested in other applications which may require microwave measurements of 10 km or better resolution, however, unclassified descriptions of these applications and associated requirements have not been prepared for this report.

TABLE II-3.- Key Measurement Requirements
(Derived from ref. 2)

| | RESOLUTION (KM) | SWATH (KM) | TEMPORAL HRS. |
|---|---|---|---|
| SST | 20-50 | 500-1000 | 76 |
| SALINITY | 5-10 | 500 | 76 |
| SOIL MOISTURE | 25 (3 for watershed) | | |

High resolution salinity measurements (better than 1 km) for estuarine applications can adequately be met by remote sensing aircraft, consequently salinity observations from space are reduced in priority and call for global-scale moderate resolution measurements.

The 25-km soil moisture resolution identified in reference 2 is not very definitive. A more specific and accurate statement of resolution needs is given in the "Plan of Research for Integrated Soil Moisture Studies" (ref. 3). A range of resolutions from 1 km to 200 km was proposed (Table II-4) with the highest resolutions (10 km and 1 km) needed by agricultural and hydrological uses and the lowest resolution for climate applications. Apparently in this plan the requirements were not set wholly independent of sensing methods because it specified greater resolutions for active (1 km) than for passive (10 km) techniques. Certainly if 1-km resolution measurements can be made with passive sensors, they would also be used in agriculture.

TABLE II-4.- Soil Moisture Requirements
(Derived from ref. 3)

| SENSOR | SPATIAL (KM) | | | TEMPORAL (DAYS) | | |
|---|---|---|---|---|---|---|
| | AGRIC | CLIMATE | HYDROL | AGRIC | CLIMATE | HYDROL |
| PASSIVE | 10 | 100-200 | 10,25 | 1-3 | 3-6 | 3 |
| ACTIVE | 1 | 100-200 | 1,5 | 1-3 | 3-6 | 3 |

Recent studies by Environmental Research and Technology, Inc. (ERT) and the University of Kansas are summarized in Table II-5. In essence, ERT states that the soil moisture content is proportional to the rainfall amounts over an area. In an analysis of over 400 central United States storm systems, 10 km was shown to be the characteristic scale size for rainfall amount. Further, an analysis of Landsat images showed that land features were accurately represented by a 10-km scale size. For a small number of users (those with regions approximately 25 km$^2$) resolutions of 1 km were important. In summary, for soil moisture determinations, a spatial resolution of 10 km is adequate for the majority of agricultural, hydrological, and climate applications. A 1-km resolution will make the data useful to additional users (approximately 10 percent). (Historically, additional applications of higher resolution data, whether directly derived or serendiptiously encountered, seem to gain acceptance as the technology for obtaining the data matures.)

TABLE II-5.- Soil Moisture Resolution

| STUDY | FINDINGS |
|---|---|
| Evaluation of the Spatial Resolution Soil Moisture Information, ERT Document #P7505-F, March 1981 (ref. 4) | Rainfall amounts from most storms in central U.S. can be resolved on a 10 km scale with a 20-percent underestimate of the peak. |
| | For land features in midwestern U.S., 10-km radiometer resolution provides useful and representative soil moisture measurements. |
| | Most crop yield forecasts can be accomplished and improved by a 10-km resolution. One km would benefit a small number of groups concerned with details of soil moisture over regions where ponds and lakes cause radiometric ambiguities. |
| Evaluation of the Soil Moisture Prediction Accuracy of a Space Radar Using Simulation Techniques, University of Kansas, Report 429-1, May 1981 (ref. 5) | Image simulation techniques were used to generate SAR images for a space SAR using a Kansas test site. One-km resolution (the largest studied) gave the best soil moisture retrievals. |

Whether or not the costs of a 1-km resolution system can be economically justified remains to be studied.

The other side of the sensing problem is temporal resolution. The desired intervals between revisits range from 1 to 6 days with most of the applications satisfied within 3 days. Irrigation scheduling, reservoir control, crop forecasting, and flood assessment demands frequent revisits. It is critical that the swath width be sufficiently large to meet this need, and maintain contiguous coverage over large geographic areas vital to full utilization of the various measurements, e.g., soil moisture measurements over major farm belts in the 30°N to 50°N latitude band. An extremely large angular radiometer field-of-view (60 degrees or more) is required to meet the contiguous mapping/wide swath requirements which, in turn, means microwave radiation from the Earth's surface is sensed with large off-normal angles. Validated physical models referred to earlier apply only if the polarization of the emitted radiation is considered in the measurements and the corresponding retrieval models. Measurements can be made with horizontal polarization only, but dual polarization is very desirable. This is especially important for angles off-normal of 30 degrees of more. Polarization requirements are discussed further in section IV and the impact of limiting the microwave emission angle on orbital altitude is discussed in section III. Regarding system implications and tradeoffs of these requirements, it should be noted first that LSA radiometry is not the only way to obtain the desired measurements. A viable alternative, for example, may be the synthetic aperture radar. Recent recognition of the inability to calibrate accurately, however, means further R&D is still required. Second, it appears to be more important to examine approaches which give global coverage in about 3 days than to perform detailed tradeoffs on configurations for 1 to 10-km resolution. For some concepts, the same aperture can be used for higher resolutions with smaller swaths and, hence, less frequent visits. Third, the system should accommodate multiple wavelengths. For example, both 20-cm and 10-cm wavelengths are useful in soil moisture measurements. The $\lambda = 10$ cm is somewhat more attenuated by dense vegetation than $\lambda = 20$ cm, but it still provides a sensitive soil moisture channel. Perhaps the $\lambda = 10$ cm could be used for the high resolution and the $\lambda = 20$ cm would provide lower resolution and better sensitivity.

## Measurement Needs Summary

Having established a general need for the measurements and having addressed three key measurements, a matrix similar to that of Table II-2 is developed to summarize the specific measurement needs or "requirements." In the completed matrix (not shown), measurement parameters such as range, accuracy, spatial resolution, geographic coverage, temporal repeat, and experiment lifetime are entered in each applicable box of the matrix. The important "requirements" are tagged, and the most critical (yet reasonable for LSA applications) "requirements" for each measurand are used as pacing "requirements." This technique (adapted from ref. 6) provides a means for synthesizing overall missions. The results for an LSA mission are shown in Table II-6. The measurands are listed at the top of the table from left to right in order of their estimated importance for an LSA radiometric mission. Underneath are listed the selected critical/pacing measurement requirements for range, accuracy, resolution, temporal repeat, etc.

Range. Range is listed in terms of the geophysical quantity and varies with each measurand. Soil moisture range requirements are set by agricultural needs, while water pollutant requirements are paced by the sensing of oil spill thickness, and ice measurements by being able to determine boundaries. In section IV these ranges are converted to, and listed in, terms of "brightness temperature," the quantity actually measured by the LSA radiometer.

## TABLE II-6.- Measurement Requirements for LSA Radiometer

MEASURANDS

| | SOIL MOISTURE | WATER SURFACE TEMPERATURES | WATER ROUGHNESS (WINDS) | ICE | SALINITY | WATER POLLUTANTS | LAND SURFACE IMAGING | ATMOSPHERIC WATER VAPOR |
|---|---|---|---|---|---|---|---|---|
| RANGE | 5-40% 5-10 cm depth | 270-310 K | 0-60 m/s | boundaries | 0-40 ppt | 0-1 cm oil thickness | TBD | TBD |
| ACCURACY | 20% wet/ 50% dry | 1 K | 3 m/s | 0.5 km linear | 1 ppt | 1 mm thickness | TBD | TBD |
| RESOLUTION | 10 km (mandatory) to approx. 1 km (desired) | | 1 km | 1 km | 10 km (mandatory) to approx. 1 km (desired) | 1 km | 10 km - 1 km | 20 km |
| COVERAGE | Farm belts | oceans | oceans | coastal zones, inland waters | coastal zones | coastal zones | continental | global |
| TEMPORAL REPEAT INTERVALS | primarily 3 days, some 1 day | | 3 days to 1 week | 3 days to 1 day | primarily 3 days, 1 day | 1 day | primarily 3 days | 1 day to 1 week |
| EXPERIMENT LIFETIME | several years | several years | several years | several years | several years | several years | several years | several years |

Accuracy. Accuracy also is listed in terms of the geophysical parameter. Again soil moisture requirements for agricultural applications are the critical ones. In section IV accuracy (including precision and sensitivity) requirements are translated into allowable error and noise tolerances in terms of brightness temperature.

Experiment Lifetime. Climate applications have the greatest need for measurements over a long period of time. A precise specification is not needed for technology development purposes, so the requirement for experiment lifetime is simply stated as "several years."

Coverage. Large geographic regions must be surveyed. Contiguous coverage of these areas is vital to the full utilization of the various measurements, i.e., contiguous soil moisture measurements over major farm belts. In section III this requirement is translated into swath width and orbital requirements.

Temporal Repeat. The needs of most applications are met with temporal repeats (sampling or revisit intervals) of approximately every 3 days. A few applications, however, require repeats as often as once every day. Therefore, 3 days is considered the primary requirement for temporal resolution and 1 day is the secondary requirement. In section III this requirement (along with coverage) is translated into orbital and swath width requirements.

Resolution. Many application needs are met with approximately 10-km resolution. A number of applications, however, require resolutions as fine as 1 km. Therefore, the selected spatial resolution requirement ranges from 10 km mandatory to 1 km desired. In section III these, spatial resolution requirements are translated into orbit altitude requirements and in section IV to main beam efficiency and antenna aperture size specifications.

An extremely wide range of measurement needs have been expressed by data users, especially for spatial resolution, temporal repeats, and geographic coverage. In fact, as will be shown later, LSA radiometers have severe limitations that force tradeoffs regarding the requirements imposed by resolution and coverage needs on orbital parameters, swath width, antenna aperture size, and accuracy. Even with an ideal system, LSA radiometers in the 50 to 200-meter range can promise only relatively moderate spatial resolution. Therefore, a prime measurement scenario is envisioned in which high resolution optical thematic mappers and synthetic aperture radars which have limited coverage, slow temporal repeat and high data rates are complemented by moderate resolution (10 km to 1 km) LSA radiometers, which provide full Earth coverage (large swaths) with fast temporal repeats (1 to 3 days) at modest data rates.

## III. LARGE SPACE ANTENNA RADIOMETER ORBITAL REQUIREMENTS

### Orbital Altitude

Selecting the operating altitude for an LSA Earth radiometric system is a rather complex task. The LSA spacecraft must be high enough to insure long experiment measurement lifetimes and the specified coverage and low enough to satisfy spatial resolution requirements with the smallest possible antenna. The factors affecting the choice of altitude and their impact on the space observation system are listed in Table III-1.

TABLE III-1.- Factors Affecting the Choice of Orbital Altitude

| MEASUREMENT REQUIREMENT | | IMPACT ON SPACE OBSERVATION SYSTEM |
|---|---|---|
| Experiment/Measurement Lifetime (Orbital Mission Duration) | Several Years | $C_D A/m$, Drag Makeup Capability |
| Spatial Resolution | 10 km - 1 km | $\lambda$, D (for a Single Beam) |
| Line of Sight - Local Vertical Incidence Angle Limits | < 30°<br>$\geq$ 30°- < 75° | Single Polarization<br>Dual Polarization |
| Repeat Intervals | 3 days - 1 day | Swath Width Choice, FOV, Scanning or Multiple Beam Design |
| Global Contiguous Coverage | Full - Partial | |
| Resolution Element Distortion<br>- Due to Earth Curvature<br>- Associated with Large FOV's | Tolerance After Corrections ± 5% | Design or Data Reduction Corrections |

The angular resolution, $\theta_r$, requirement for an LSA in terms of the required spatial resolution or footprint, F, at the Earth's surface and the orbital altitude, h, is $\theta_r = \tan^{-1} F/h$, which for small angles is $\theta$ (radians) = F/h. The ideal angular resolution capability of a circular antenna of diameter, D, and operating wavelength, $\lambda$, is $\theta_c$ (radians) = $1.22\lambda/D$. Consequently, to meet the requirement means that $h \leq FD/1.22\theta$. For a single beam, 200-meter LSA sensing at $\lambda = 20$ cm (e.g., soil moisture) with the 10-km mandatory resolution, the orbital altitude must be less than approximately 8000 km. Operation at geosynchronous altitudes-- more than four times higher-- is prohibited; only low Earth orbits (LEO) are possible. For this requirements definition, 8000 km is considered to be the maximum orbital altitude. Similarly, for a single beam, 50-meter

LSA, sensing soil moisture at 20 cm with 1-km resolution, the orbital altitude must be less than approximately 200 km. Therefore, 200 km is considered to be the absolute minimum orbital altitude.

The experiment lifetime is set by those applications such as climate prediction which require long duration measurements. "Several years" was the descriptor used for experiment lifetime in Table II-2. (Design lifetimes for the sensor components may be two to three times this number.) The ballistic drag coefficient, $C_D A/m$, of the spacecraft affects the orbital lifetime and, thus, establishes a practical lower limit on orbital altitudes, as illustrated in figure III-1 (from ref. 7). The $C_D A/m$ ratio for a large aperture microwave radiometer spacecraft will probably be in the range from 0.2 to 20, depending on configuration, and, thus, may allow acceptable long-life orbits as low as 450 km without any significant orbit boost adjustment capability (ref. 8). For this requirements definition, 450 km is considered to be the practical lowest orbital altitude for long lifetime missions.

In section II the need was established for contiguous coverage (implying wide swaths) with repeat intervals of 1 to 3 days. Furthermore, it was established that if this requirement can be met with microwave emission angles of less than 30 degrees off the normal to the Earth's surface then single horizontal polarization sensing is sufficient to make the desired geophysical measurements. Global contiguous coverage can be obtained with a 3-day repeat interval sensing with line of sight-Earth local vertical incidence angles of less than 30 degrees for any altitude above the practical 450 km minimum altitude (ref. 9). The minimum altitude for contiguous coverage with a 1-day repeat interval, however, is approximately

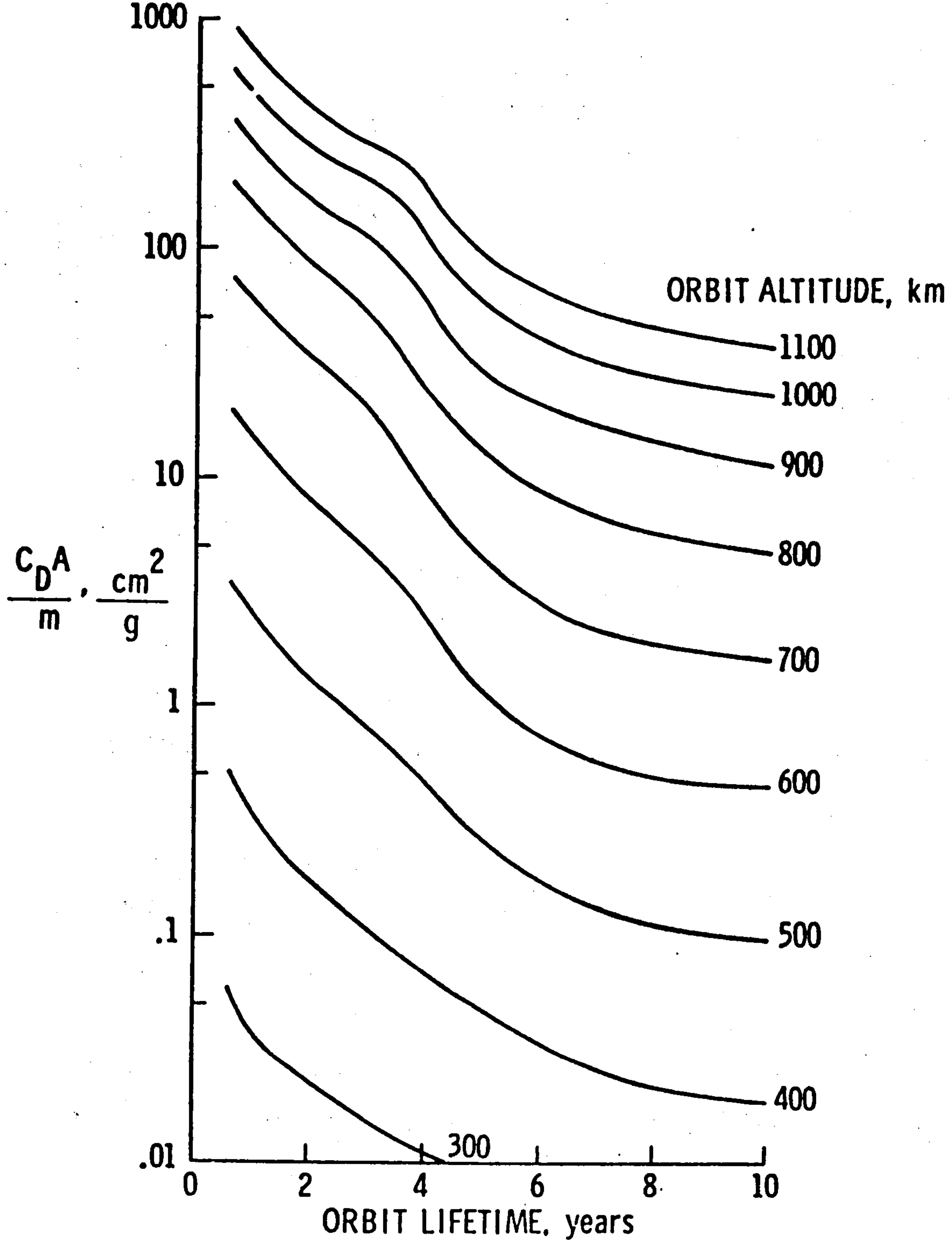

Fig III-1 Lifetimes in Low Earth Orbit
(from ref. 7)

2200 km. Such an altitude penalty, five times the practical minimum, is probably not acceptable since it means that the antenna diameter, D, must increase five times. In order to show the impact of lower altitude alternatives on the space observation system, Table III-2 lists the approximate viewing parameters for several cases.

TABLE III-2.- Approximate Viewing Parameters for Global Contiguous Coverage

| CASE | ALTITUDE (km) | INCIDENCE ANGLE (°) | ORBITS (no./day) | REPEAT INTERVAL (days) | SWATH (° Longitude/ km) | TOTAL FOV (°) |
|---|---|---|---|---|---|---|
| Reference | 2200 | 30 | 11 | 1 | 17/2000 | 43 |
| 1 | 450 | 30 | 15 | 3 | 4/500 | 56 |
| 2 | 450 | >>30 | 15 | 1 | 12/1500 | Very Large |

Case 1. In this case the need for measurements with a 1-day repeat interval is ignored, which results in being able to fly as low as 450 km, reducing the swath width and mildly increasing the field-of-view.

Case 2. In this case the incidence angle limit of approximately 30 degrees for single polarization is ignored, which also results in being able to operate as low as 450 km. The swath width required is somewhat smaller than the reference case because more viewing opportunities (i.e., orbits per day and number of days) occur at the lower altitude. The system sacrifices are the probable need for dual polarization sensing, and the use of very large fields-of-view.

Earth curvature effects over wide swaths distort the "footprint;" likewise, large field-of-view systems have inherent distortions. The LSA design and/or the data reduction algorithms must correct such distortions to within tolerances (See Table III-1). After field-of-view and swath design choices are made, the final part of the orbit altitude selection process determines the exact fractional number of orbits per day, Q, required to fix exactly the revisit times and to guarantee proper swath pattern overlap margins. Figure III-2 (adapted from ref. 9) gives the orbital altitude, h, necessary to achieve the specified orbit repetition factors, Q's. For example, for 1 day repeats with Q's of 15 and 14, the corresponding altitudes are approximately 540 and 850 Km, respectively. For 3-day repeats with Q's of 15-1/3, 14-2/3, 14-1/3, and 13-2/3 the altitudes are approximately 460, 640, 775 and 975 km, respectively.

In summary (see Table III-3) altitude choices are driven by different requirements and three altitude regimes, all in low-Earth-orbit, are possible: (1) a very high orbit regime, 2200 - 8000 km where useful measurements can potentially be made with single polarization, but for which larger antenna apertures are required for spatial resolution; (2) a very low orbit regime, 200-450 km where the drag makeup capability necessary for long experiment lifetimes is a significant design consideration (this regime is usually reserved for proof testing onboard shuttle sortie missions); and (3) intermediate orbital altitude regime, 450-2200 km where long life can be obtained more easily and where some tradeoffs regarding resolution, field-of-view angles, swath width, spacecraft drag, etc., are possible. Finally, within each altitude regime the repeat interval requirements dictate a selection from several discrete altitudes and generally the lowest altitude is selected in light of the better spatial resolution with smaller aperture advantage. For example, the lowest altitude in the intermediate regime for a 3-day repeat (Q = 14 2/3)

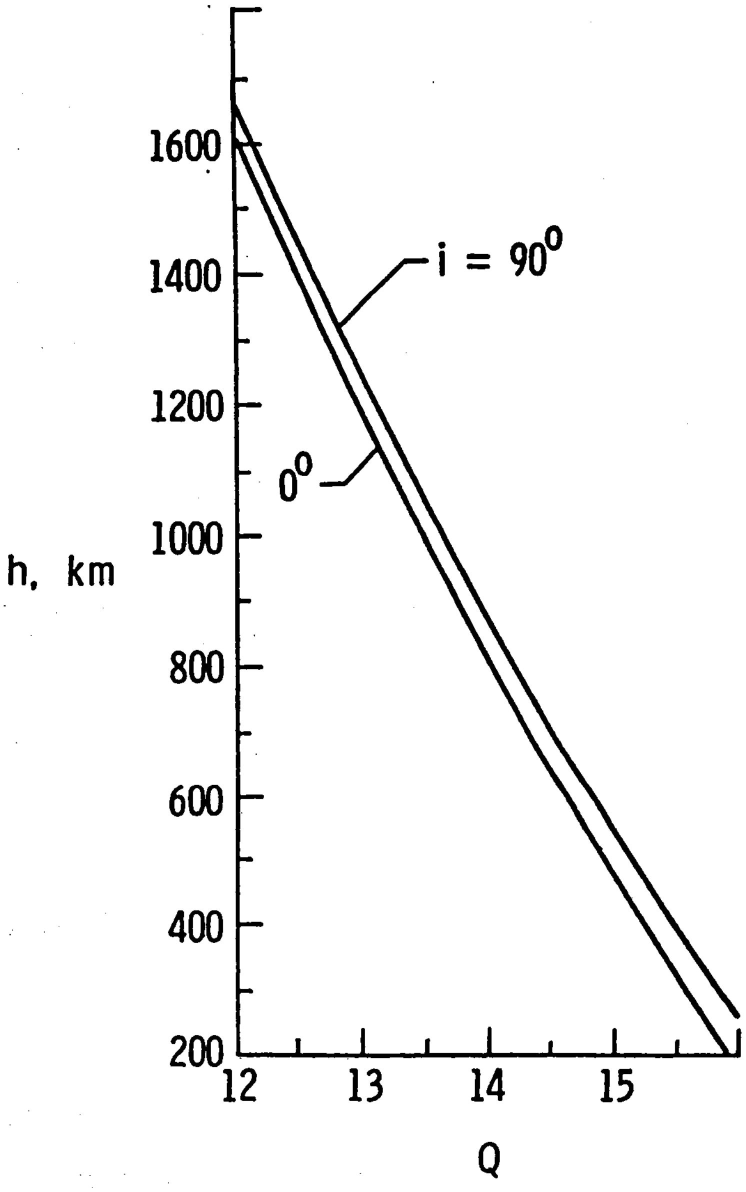

Fig. III-2 Orbital Altitude vs. Orbit Repetition Rate (from ref. 9) is approximately 640 km, and the lowest altitude for a 1-day repeat is approximately 540 km.

TABLE III-3.- Orbit Altitude

| Altitude Descriptor | Driving Requirement |
|---|---|
| Maximum - 8000 km | Single beam resolution of 10 km with 200 m aperture at λ = 20 cm |
| Minima | |
| 200 km | Single beam resolution of 1 km with 50 m aperture at λ = 20 cm |
| 450 km | Lowest practical long lifetime orbit |
| 2200 km | Lowest orbit for global contiguous sensing with 1-day repeat using incidence angles of < 30°. |
| Practical operating and design tradeoff range 450 - 2200 km | Long duration, high resolution, global coverage with smallest antenna |

## Orbital Inclination

Orbit inclination, i, has a small effect on altitude (see fig. III-2); its greatest effect is on geographic coverage. Orbital inclinations in the range from 60° to 98° can best satisfy the geographic coverage requirements. An orbit inclination of 60° provides good coverage over the temperate zones and farm belts and consequently is about the lowest orbital inclination that can satisfy the coverage required for soil moisture and

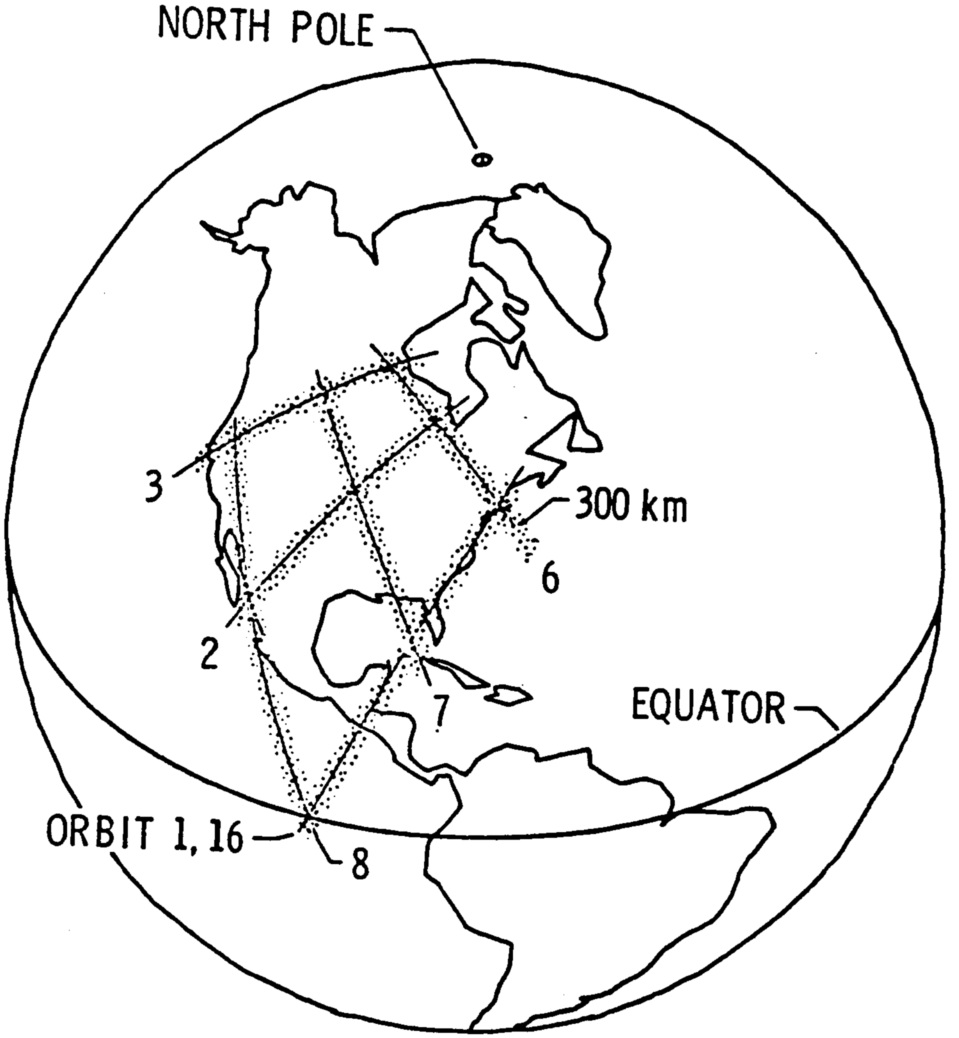

Fig. III-3 Geographic Coverage for a 1-Day Orbital Repeat Interval
(∿ 600 km Altitude)
(from ref. 8)

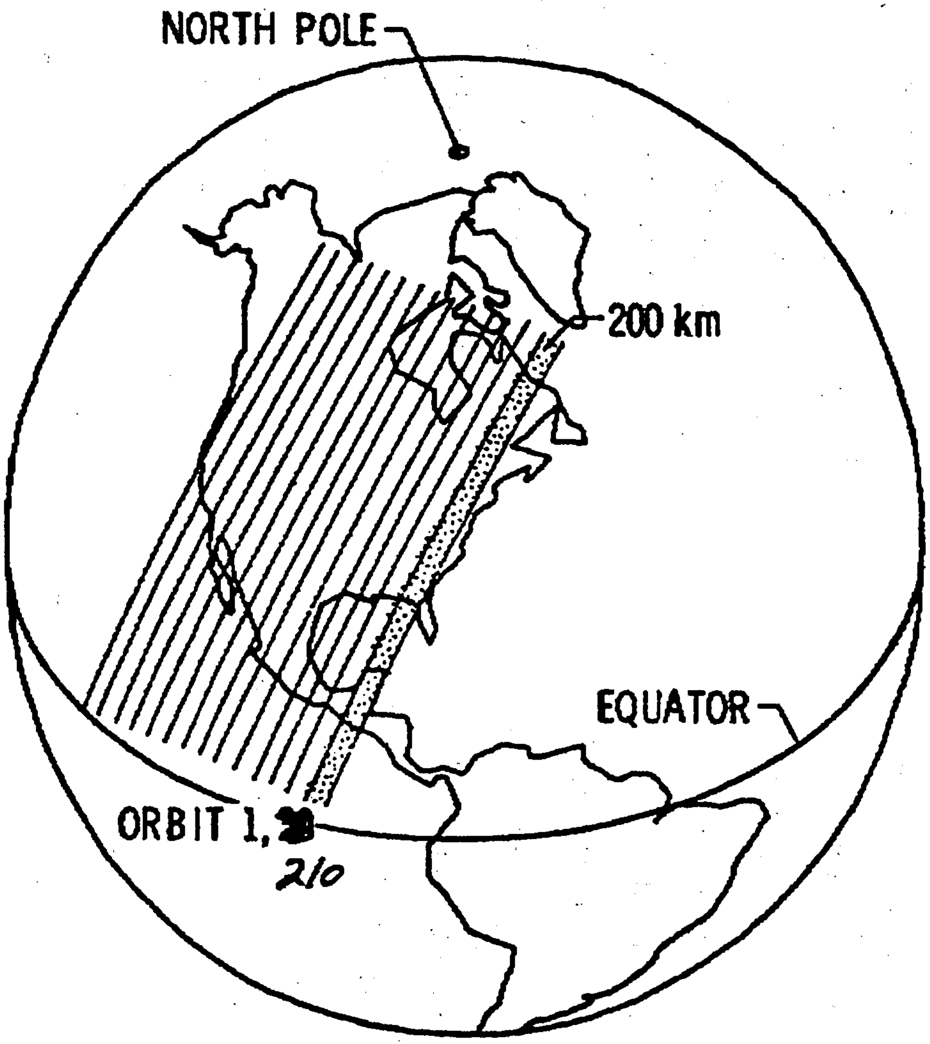

Fig. III-4 Geographic Coverage for a 14-Day Orbital Repeat Interval
(∿ 600 km Altitude)
(from ref. 8)

sea surface temperature measurements. For 60° inclinations, portions of two coverage plots of the United States are shown on fig. III-3. With a repeat interval of 1 day, only approximately 25 percent of full coverage is obtained using a 300 km swath. A 3-day repeat yields approximately 60-percent coverage of the United States and approximately 40 percent of equatorial areas. To meet the requirements for full global contiguous coverage, a wider swath, in the order of 500-2000 km, is required (See Table III-2) or the interval between revisits must be increased further. With a 14-day repeat, 100 percent or full contiguous coverage can be obtained with a swath of 200 km (fig. III-3b). The feasibility of meeting the requirement of contiguous coverage of major geographic areas vital to the various measurements, with a repeat interval approaching 1-3 days is impossible to assess at this point, for it will depend on the particular radiometer spacecraft design and the corresponding orbit parameters. In particular, designs for wide angle off-nadir viewing and for low atmospheric drag must be developed for systems whose resolution performance may depart significantly from the ideal diffraction limited case. Such system implications and limitations are addressed in the next section.

## Orbital Maintenance

Orbital inclination variations are small and Earth measurements are relatively insensitive to such variations, so orbit maintenance is primarily concerned with altitude maintenance. Orbital altitude changes affect the spatial resolution, swath width, geographic coverage and sampling repetition. Orbital altitude changes are caused by solar radiation

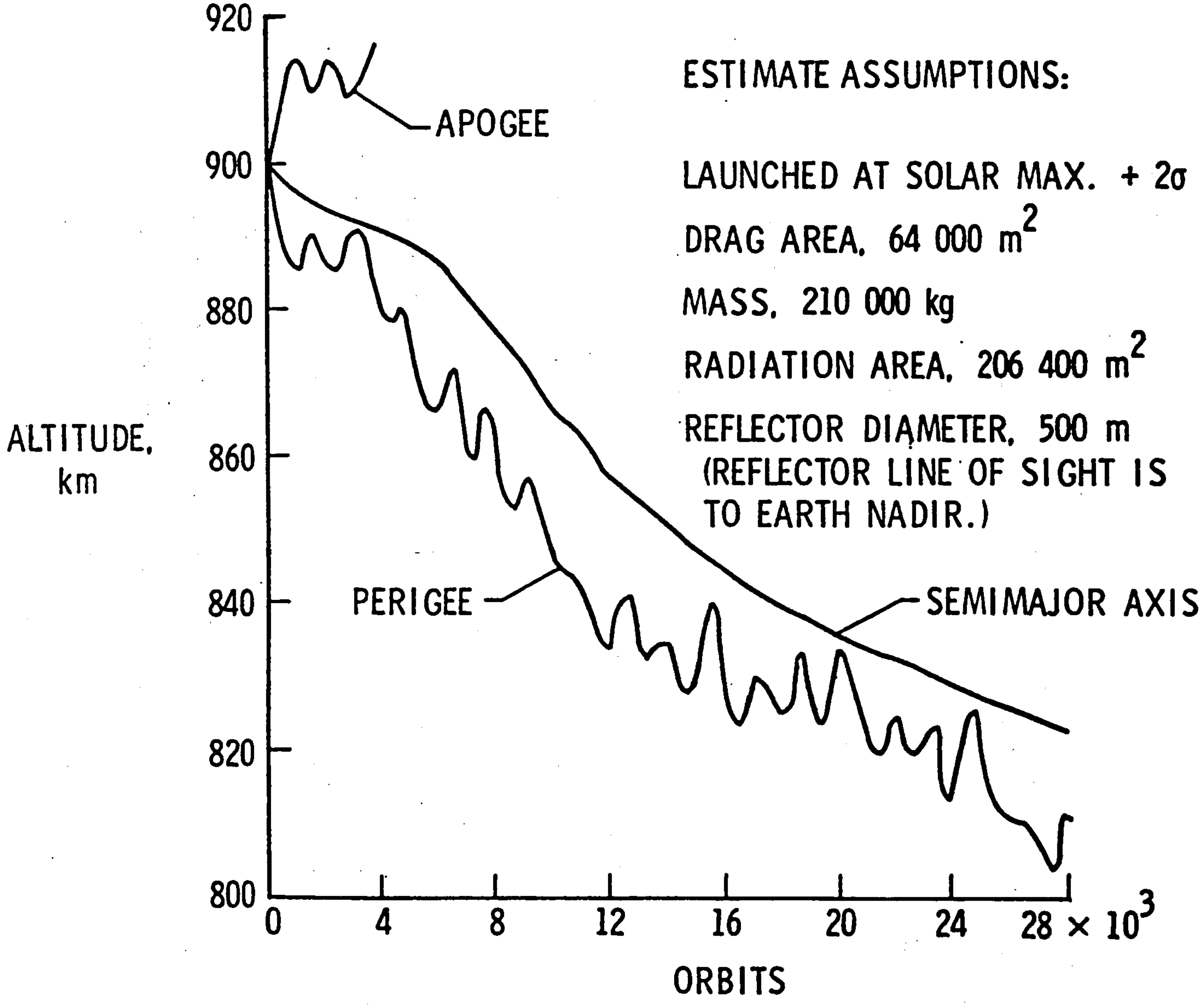

Fig. III-5 Example Estimate of Orbit Altitude Variations and Decay
(from ref. 8)

pressure on the spacecraft and by the atmospheric drag of the spacecraft. For example, at 900 km, using conservative estimates of antenna size, mass, cross-sectional area and atmospheric density (solar-cycle maximum), the atmospheric drag of an example spacecraft is estimated and orbital decay (semimajor axis) is calculated (fig. III-4). This decay is relatively smooth as compared to the cyclic fluctuations in the perigee and apogee altitudes, also shown in figure III-4, which are due to solar radiation pressure effects on the spacecraft. Microwave radiometry data users must be guaranteed that a particular orbit pass occurs with some degree of precision over the programed area and during the programed time. For LSA missions these specifications are expressed as follows:

Lateral drift of orbit <± 0.1 swath width

Sampling time drift <± 15 minutes for Sun-sync orbit
<± 1 hour for 60° orbit

For a particular spacecraft design, these can be translated into propulsion system performance requirements and onboard propellant needs.

## Orbital Requirements Summary

Geosynchronous orbits are not possible with the 10-km resolution requirement and the 200-meter aperture upper limit. Most observational requirements, however, can be satisfied by operating within the 450-2200 km altitude regime. In this regime many design tradeoffs are possible. Discrete altitude selections are associated with the number of orbits per day and the revisit interval requirements. For example, approximately

640 km is the lowest altitude for 14-2/3 orbits per day required for a 3-day repeat cycle.

Contiguous large-scale coverage of important farm belts and ocean areas dictates orbit inclination choices in the 60° to 98° range and swath widths of 300 km or more.

Strict orbit maintenance is required to insure contiguity and geodetic precision of mapped data products.

## IV. LARGE SPACE ANTENNA RADIOMETRIC REQUIREMENTS

In Section II, Earth observational requirements and in Section III orbital requirements were defined for LSA space flight missions. This section summarizes the resulting requirements imposed on the LSA radiometer system itself. These include requirements for frequency selection, filtering and polarization; beam efficiency, angular resolution and aperture size; brightness temperature range, accuracy and resolution; and predetection bandwidth, system noise and integration time.

### Frequency

From Table II-2 and Table IV-1 it can be seen that all of the Earth remote sensing requirements, except atmospheric humidity and temperature profiling, can be met in the frequency range between 1 and 37 GHz. The atmospheric humidity and temperature measurements are specialized measurements which can be best accomplished with dedicated instruments such as the Advanced Microwave Sounder Unit (AMSU). Five discrete frequencies near 1.4, 6.6, 10.7, 21, and 37 GHz could satisfy the remaining sensing requirements. A sixth frequency at 18 GHz would be of some benefit.

This set of frequencies, except for 1.4 GHz, was used in the Scanning Multifrequency Microwave Radiometer (SMMR) flown on the SEASAT and NIMBUS-G spacecraft. While this particular set of frequencies is not unique it is felt that it best represents the minimum set required for the measurements listed in Table II-6 for circa 1990 systems. Eventual selection of LSA radiometer operating frequencies will depend somewhat on demonstrated capability for retrieving the desired geophysical measurands, but final precise selection will likely be based primarily on avoidance of external interferences. Specific frequency allocations were made for current systems by World Administrative Radio Conference. Regulations for power flux densities, equivalent isotropic radiated power, and standard radiating antenna sidelobe patterns are established and administered internationally (ref. 10). Unfortunately, interference free frequency bands for radiometry are scarce and radio frequency interference (RFI) filtering may be required. For example, the relationship between antenna temperature, $T_{ant}$, and the power level at the antenna, P, is given by

$$P = k\ T\ B$$

where k = Boltzmans constant = $1.23 \times 10^{-23}$ W $K^{-1}$ $Hz^{-1}$
and B = prediction bandwidth ≈200 MHz.

For a signal level equivalent to a radiometer noise level of 0.2° the power at the antenna terminals would be -123 dbm. Any external interference must be kept below this level. Assuming the antenna was not pointed toward the interfering signal, a spatial filtering by the antenna of at least 30 db can be used. Assuming the maximum size antenna of 180 m and an aperture efficiency of 50 percent, the equivalent isotropic radiated power, EIRP, from the ground can be calculated from

## Table IV-1 Application Areas and Observable Parameters
(from National Guidelines for Remote Microwave Sensors, NASA Review Copy)

| APPLICATION AREAS AND OBSERVABLE PARAMETERS | DESIRED SPECIFICATIONS | | | SPOT SIZE (KM) AT CRITICAL FREQUENCY HEIGHT (KM) | | | $\Delta T_{rms}$ AT DESIRED RESOLUTION HEIGHT (KM) | | | [SPOT SIZE (KM)]/[DESIRED SIZE] HEIGHT (KM) | | | [$\Delta T_{rms}$ (AVAILABLE)]/[$\Delta T_{rms}$ (REQUIRED)] HEIGHT (KM) | | | FREQUENCY (GHz) SMMR TIROS-N | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SPOT SIZE (KM) | $\Delta T_{rms}$ | REVISIT TIME (HR) | 400 | 900 | 1200 | 400 | 900 | 1200 | 400 | 900 | 1200 | 400 | 900 | 1200 | 1.4 | 3.0 | 6.6 | 10.7 | 18 | 21 | 37 | 55 | 90 | 183 |
| **SYNOPTIC METEOROLOGY & CLIMATOLOGY** | | | | | | | | | | | | | | | | | | | | | | | | | |
| Temperature Profile | 50 | 0.3 | 3-12 | 1.5 | 3.3 | 4.3 | 0.2 | 0.3 | 0.4 | 0.03 | 0.06 | 0.08 | 0.8 | 1.1 | 1.2 | | | | | | | ● | ⊕ | | |
| Water Vapor Profile | 15 | 0.5 | 3-12 | 4.1 | 8.6 | 11.2 | 0.4 | 0.6 | 0.7 | 0.3 | 0.6 | 0.8 | 0.9 | 1.2 | 1.4 | | | | | + | ● | + | | | + |
| Water Vapor Profile (Non-Tropical) | 15 | 0.5 | 3-12 | 0.5 | 1.0 | 1.3 | 2.1 | 3.0 | 3.4 | 0.03 | 0.06 | 0 08 | 4 2 | 6.0 | 6.7 | | | | | | | | | + | ⊕ |
| Liquid Water Abundance, Rain Rate | 2-10 | 2 | 3-12 | 2.3 | 4.9 | 6.3 | 0.9 | 1.3 | 1.4 | 0.2 | 0.5 | 0 6 | 0 4 | 0.6 | 0.7 | | ● | ● | ● | + | + | ⊕ | ● | + | |
| Sea Surface Temperature | 50 | 0.3 | 6-36 | 13 | 28 | 36 | 0.08 | 0.1 | 0.1 | 0.3 | 0.6 | 0.7 | 0.3 | 0.4 | 0.4 | ● | + | ⊕ | ● | + | ● | + | | | |
| Sea Surface Wind (Magnitude) | 50 | 1 | 3-12 | 7.9 | 17 | 22 | 0.1 | 0.1 | 0.2 | 0.1 | 0.3 | 0.4 | 0 1 | 0.1 | 0.2 | + | ● | + | ⊕ | | | + | | | |
| Sea Surface Wind (No Precipitation) | 50 | 1 | 3-12 | 2.3 | 4.9 | 6.3 | 0.2 | 0.2 | 0.3 | 0.05 | 0.1 | 0.1 | 0.2 | 0.2 | 0.3 | | | | | + | + | ⊕ | | | |
| **SEVERE STORMS** | | | | | | | | | | | | | | | | | | | | | | | | | |
| Temperature Profile | 3-30 | 0.3 | 1-6 | 1.5 | 3.3 | 4.3 | 0.4 | 0.6 | 0.6 | 0.05 | 0.11 | 0.14 | 1 3 | 1.9 | 2.1 | | | | | | | ● | ⊕ | | |
| Water Vapor Profile | 3-15 | 0.5 | 1-6 | 4.1 | 8.6 | 11.2 | 0.4 | 0.6 | 0.7 | 0.3 | 0.4 | 0.6 | 0.9 | 1.2 | 1.4 | | | | | + | ⊕ | + | | | + |
| Water Vapor Profile (Non-Tropical) | 3-15 | 0.5 | 1-6 | 0.5 | 1.0 | 1.3 | 2.1 | 3.0 | 3.4 | 0.03 | 0.06 | 0.08 | 4.2 | 6.0 | 6.7 | | | | | | | | | + | ⊕ |
| Liquid Water Abundance, Rain Rate | 2-10 | 2 | 1-6 | 2 3 | 4.9 | 6.3 | 0.9 | 1 3 | 1.4 | 0.2 | 0.5 | 0.6 | 0.4 | 0.6 | 0.7 | | ● | ● | ● | + | + | ⊕ | ● | + | |
| Sea Surface Temperature | 3-30 | 0.3 | 2-6 | 13 | 28 | 36 | 0.1 | 0.2 | 0.2 | 0.4 | 0.9 | 1 2 | 0.5 | 0.6 | 0.7 | ● | + | ⊕ | ● | + | ● | + | | | |
| Sea Surface Wind (Magnitude) | 3-30 | 1 | 1-6 | 7.9 | 16.9 | 22 | 0.2 | 0.2 | 0.2 | 0.3 | 0.6 | 0.7 | 0.2 | 0.2 | 0 2 | + | ● | + | ⊕ | | | + | | | |
| Sea Surface Wind (No Precipitation) | 3-30 | 1 | 1-6 | 2.3 | 4.9 | 6.3 | 0.3 | 0 4 | 0.5 | 0.1 | 0.2 | 0.2 | 0.3 | 0.4 | 0.5 | | | | | + | + | ⊕ | | ● | |
| **OCEAN SURFACE** | | | | | | | | | | | | | | | | | | | | | | | | | |
| Surface Wind Velocity | 2-50 | 1 | 3-12 | 7.9 | 16.9 | 22 | 0.1 | 0.1 | 0.2 | 0 2 | 0.3 | 0.4 | 0 1 | 0.1 | 0.2 | + | ● | + | ⊕ | | | + | | | |
| Surface Wind Velocity (No Precipitation) | 10-50 | 1 | 3-12 | 2.3 | 4.9 | 6.3 | 0.2 | 0.2 | 0.3 | 0.05 | 0.1 | 0.1 | 0 2 | 0.2 | 0 3 | | | | | + | + | ⊕ | | + | |
| Sea Surface Temperature | 1-50 | 0.3 | 6-36 | 13 | 28 | 36 | 0.08 | 0.1 | 0.1 | 0.3 | 0.6 | 0.7 | 0.3 | 0.4 | 0.4 | ● | ● | ⊕ | ● | + | ● | + | | | |
| Salinity | 0.5-10 | 0.3 | 3-12 | 60 | 130 | 168 | 0.3 | 0.5 | 0.5 | 6 1 | 13 0 | 16.8 | 1 1 | 1.6 | 1.8 | ⊕ | ● | ● | ● | + | | + | | ● | |
| Oil Slicks, etc (No Precipitation) | 0.5 | 0.3 | 1-12 | 2.3 | 4.9 | 6.3 | 18 | 25 | 28 | 4.6 | 9.8 | 12.7 | 60 | 84 | 94 | ● | ● | ● | | + | | ⊕ | | + | |
| **LAND PARAMETERS** | | | | | | | | | | | | | | | | | | | | | | | | | |
| Soil Moisture (Low Frequency) | 3-25 | 1 | 6-36 | 61 | 130 | 168 | 0.1 | 0.2 | 0.2 | 2.4 | 5.2 | 6.7 | 0 1 | 0.2 | 0.2 | ⊕ | | + | | | | | | | |
| Soil Moisture (Higher Frequency) | 3-25 | 1 | 6-36 | 13 | 28 | 36 | 0.2 | 0.2 | 0.3 | 0.5 | 1.1 | 1 4 | 0 2 | 0.2 | 0.3 | ● | | ⊕ | | | | ● | | | |
| Snow Cover and Type, Frozen Ground | 3-25 | 1 | 6-12 | 2.3 | 4.9 | 6 3 | 0.4 | 0.5 | 0.6 | 0.1 | 0.2 | 0 2 | 0.4 | 0.5 | 0.6 | | ● | + | | + | | ⊕ | | + | |
| **SEA AND LAND ICE** | | | | | | | | | | | | | | | | | | | | | | | | | |
| Sea Ice Concentration | 1-5 | 2 | 3-12 | 2.3 | 4.9 | 6.3 | 1.8 | 2.5 | 2.8 | 0.5 | 1.0 | 1.3 | 0.9 | 1 3 | 1.4 | | | | | + | | ⊕ | | ● | |
| Sea Ice Type | 1-5 | 1 | 6-12 | 2.3 | 4.9 | 6.3 | 1.8 | 2.5 | 2 8 | 0 5 | 1.0 | 1.3 | 1.8 | 2 5 | 2.8 | | ● | ● | + | + | | ⊕ | | ● | |
| Land Ice Properties (e g , Firn) | 10-50 | 1 | 12-36 | 2.3 | 4.9 | 6.3 | 0.2 | 0.2 | 0.3 | 0.05 | 0.1 | 0.1 | 0.2 | 0.2 | 0.3 | | ● | ● | + | + | | ⊕ | | ● | |

⊕ Critical

\+ Important

● Helpful

$$(-123 \text{ dbm} + 30 \text{ db}) + \text{EIRP} \times \frac{A_e}{2\pi R^2}$$

where $A_e$ is the effective aperture of the antenna and R is the distance from the interfering source (≈1000 km).

$$\text{EIRP} = 6.3 \times 10^{-10} \text{ mw} \times \frac{2\pi\ (10^6)^2}{\pi/2(90)^2} = 0.3 \text{ mw}$$

That is, an isotropic radiator in the surface of the Earth transmitting 0.3 mw, not in the antenna beam, would just be detectable. Any higher power would require filtering in the radiometer.

## Polarization

Polarization of the antenna feed is important since the emissivity of the surface is both a function of polarization angle and incidence angle of the sensing beam received by the LSA. The emissivity of the surface must be modeled so that antenna temperature can be converted to the physical temperature of the surface. The modeling is made easier if both the polarization angle and incidence angle are fixed. However, this is not always consistent with physically realizable antenna scanning and feed systems. Table IV-2 lists polarization options.

TABLE IV-2. Possible Combinations of Polarization in Decreasing Desirability

| | | |
|---|---|---|
| 1. | Dual Linear, Fixed Angle | Most Desirable |
| 2. | Single Linear, Fixed Angle | |
| 3. | Dual Linear, Rotating Angle | |
| 4. | Single Linear, Rotating Angle | Least Desirable |

Circular polarization is not listed since measuring two orthogonal linear polarizations is equivalent to measuring circular polarization. Options 1 or 2 should be the minimum requirement.

Wide swath systems necessary for Earth coverage cannot have the same line of sight - Earth local vertical incidence angle for all sensing beams, but the various angles are fixed by the viewing geometry. As noted in Section III on orbital requirements, the imposition of a limit on the beam line of sight - Earth local vertical incidence angle can impose a severe altitude operating penalty.

Cross polarization effects caused by the LSA itself, e.g., offset feed, should be minimized. A -60 to -70db criterion appears to be quite adequate for measurand retrieval purposes.

## Spatial Resolution

Spatial resolution requirements were given in Table II-6 as "10 km mandatory to 1 km desired" as reflecting the needs of the community of "Users" of Earth geophysical data that are acquired remotely from space. Such statements about resolution are often ambiguous. In image evaluation, resolution refers to the size of the smallest discernible feature. In radiometry, the Rayleigh criterion states that "two components of equal intensity should be considered resolved when the principal maximum of one coincides with the first minimum of the other." In remote sensing of Earth parameters, a number of terms have been used to describe the resolution element; e.g., pixel, footprint, field-of-view (FOV), instantaneous field-of-view (IFOV), beam width, spot size, and tessera. As used herein, the resolution element is pragmatically defined as the "assigned" field-of-view at the Earth's surface during a single measurement sequence. It is appropriate to examine how this assignment is made.

In Section III the angular resolution capability of a circular antenna of diameter, D, and operating wavelength, $\lambda$, was stated as $\theta_C$ (radians) = $1.22\lambda/D$, and this IFOV at the Earth's surface was considered the assigned FOV. This did not account for the movement of the IFOV during a measurement sequence (discussed in paragraph on Modeling Radiometer Sensitivity). Furthermore, its characteristic dimension (in this case, a diameter) is defined by the 3-db power contour of the main beam, when the "edge" of the main beam is actually about 2.5 times larger. This assignment disregarded part of the main beam, along with the side lobes and back lobes which together supply half of the power received. Obviously, therefore, precision radiometry requires a knowledge of both the size and the energy of the full sensing beam.

Beam Efficiency. Beam efficiency, $\varepsilon$, or more properly, main beam efficiency is defined as the integral of power over the main beam out to the first minimum divided by the integral over the complete antenna pattern. It represents the fraction of the power received through the main beam if the antenna was in an isothermal enclosure. The power received from all angles other than the main beam, $1 - \varepsilon$, comes from sources other than the scene being observed and, in general, is not accurately known. The effective antenna temperature then consists of two parts

$$T_{ant} \simeq \varepsilon T_{scene} + (1 - \varepsilon)\ T_{other}.$$

The second term must be removed by assuming a temperature distribution for $T_{other}$ and integrating over all the side lobes and back lobes. This process is simple if most of the power is in the first side lobe and the scene is homogeneous such as the ocean. On the other hand, the main beam may be on the ocean and the side lobes partially viewing land. In this case, the correction may be impossible to make to the required accuracy. In any case, the larger the beam efficiency is, the easier it is to correct for the unwanted received radiation. If, for example, $1 - \varepsilon = 0.02$ (main beam efficiency of 98 percent), the maximum value of the second term would be $0.02 \times 300° = 6°$ which could be calculated to within ± 0.2 degree with a knowledge of $T_{other}$ to within ± 10 degrees.

The required beam efficiency is highly dependent on the required measurement accuracy, side lobe structure and scene heterogeneity. Experience in using data from the SEASAT and NIMBUS-6 SMMR radiometers has shown that for main beam efficiencies less than 90 percent, it is difficult to correct for the power received from the side lobes and back lobes to the accuracy required for sea surface temperatures determination. Main beam efficiences, $\varepsilon$, of 99 percent with certain types of horn antennas to as low as 60 percent for a uniformly illuminated reflector antenna are possible. With the required main beam efficiency being dependent on the particular observation, it is difficult to specify a general requirement on $\varepsilon$ for a broad range of measurements other than to say that $\varepsilon$ should be as high as possible. In order to provide guidance to designers and technologists, however, this requirements definition will adopt (to guarantee data inversion) as a general requirement $\varepsilon > 90$ percent for a homogeneous scene.

Beam Size and Antenna Diameter. In Table IV-3 optical and microwave beams are compared with regard to radiation source, beam size, and beam efficiency for perfect diffraction limited designs. (Scattering of energy outside the main beam is covered in the paragraph on surface roughness.) Case 1 is the classic optics case which uses the Rayleigh resolution criterion. The maximum possible energy in the main beam, called the Airy disk, is 84 percent (ref. 10). An extended source, Case 2, however, applies more directly to remote sensing of the Earth with sensors such as those on LANDSAT. The 84-percent maximum occurs in the disk (or main beam) which is twice the classic size (ref. 11). Case 3 applies to the traditional microwave antenna half-power beam width used for communications,

TABLE IV-3.- Diffraction Limited Beams

| RADIATION SOURCE | BEAM SIZE (radians) | BEAM EFFICIENCY (%) |
|---|---|---|
| Optical, incoherent, nonpolarized, point source | $\approx 1.22\ \lambda/D$ to first minimum | 84 (full Airy disk) |
| Optical, incoherent, nonpolarized, extended source | $\approx 2.44\ \lambda/D$ to first minimum | 84 (full Airy disk) |
| Microwave, coherent, polarized point source | $\approx 1.22\ \lambda/D$ to half-power points | 50 (half-power beam) |
| Microwave, partially coherent, partially polarized, extended source | $\approx 3\lambda/D$ | > 90 (full main beam, side lobes depressed) |

radar, and similar applications while Case 4 applies more directly to passive microwave remote sensing. In this last case the effect of the side and back lobes must be suppressed in order to increase the main beam efficiency to 90 percent or more. The size of this main beam is approximately 2.5 times the half-power size or $3\lambda/D$.

In actual practice, the size of the "assigned" resolution elements varies from the half-power beam size, $1.22\lambda/D$, to twice the size of the main beam, $6\lambda/D$. (Twice the main beam size allows for one beamwidth translation during a measurement sequence.) This ambiguity of approximately a factor of five exists in statements of both measurement requirements and measurement capabilities. In this requirements definition, therefore, we build in a degree of conservatism by using the criterion that the maximum dimension of the main beam should be equal to or smaller than one-half the resolution requirement. Using this criterion, the maximum altitude is reduced from 8000 km given in section III to approximately 1700 km. And, at the practical minimum altitude of 450 km, the antenna diameter, D, required for 10-km resolution at $\lambda = 20$ cm is 54 m, while the best resolution possible with a 200-m antenna is 2.7 km.

Figure IV-1 shows the required antenna diameter as a function of wavelength for a 600-km orbit. Both the optimistic and conservative criteria are used for the 10-km mandatory and the 1-km desired resolutions. For the mandatory 10-km resolution, the full 200-m aperture is not required for a single beam; but for 1-km resolution, the 50-m aperture is adequate only at the upper end of the frequency range.

Surface Roughness. In addition to diffraction, scattering from a reflector surface also reduces main beam efficiency. That is, any deviation from a perfect geometric surface figure will scatter radiation out of the main beam. The direction in which the radiation is scattered is determined by the size and distribution of the errors. However, the magnitude of the energy gain of the main beam is given by the well-known Ruze formula $g = g_0 e^{-(4\pi\delta/\lambda)^2}$ (ref. 12). The exponential represents the energy attenuation factor due to the rms surface errors, $\delta$, for a reflector operating at a wavelength $\lambda$; e.g., if $\delta = \lambda/16$ beam efficiency is reduced to approximately 50 percent. If the beam efficiency must be greater than 90 percent and surface roughness is budgeted for only one-half of the 10 percent allowable beam energy loss, then the surface irregularities must be maintained such that $\delta < \lambda/55$.

The performance limits of large groundbased antennas used for radio astronomy and communications are determined primarily by the accuracy of the reflecting surfaces. Figure IV-2 plots antenna diameter as a function of minimum usable wavelength, $\lambda_{min}$, for some of the world's best radio telescopes. The criterion used for $\lambda_{min}$ was the half-power antenna gain criterion. It can be seen that there is a definite correlation between antenna diameter and $\lambda_{min}$. The solid line on the figure approximates the correlation and corresponds to $D = 6000\lambda_{min}$. Applying this correlation to LSA's at 37 GHz, the corresponding diameter is approximately 50 meters. Using this criterion, antennas larger than 50 meters would have to operate at less than 37 GHz. The half-power criterion used for radio telescopes corresponds to $\delta = \lambda/16$. If $\delta = \lambda/55$ is used as the criterion for Earth radiometry, high frequency operation is further restricted. Alternative modes of operation are envisioned, however, where only a small portion of the total available aperture is used at the higher frequencies, or where the $D/\lambda$ limit is raised by reducing $\delta$ through better engineering and manufacture of the reflecting surface and by the use of mechanically active surface controllers. Thus, the practical maximum operating frequency is somewhat configuration and technology dependent, but 37 GHz remains as the requirement.

## Brightness Temperature Range and Accuracy

Earth emitted radiation is the actual quantity sensed in the prescribed resolution element with a corresponding beam efficiency. It depends on both temperature and emissivity and is referred to as brightness temperature. The physical temperature over the Earth is approximately 290 ± 50 K. The emissivity varies from 1 to 0.2 giving a brightness temperature range of 48 K to 340 K. The cold sky is often used as a calibration source so the radiometers should have a dynamic range of approximately 3 K to 340 K. The brightness temperature ranges for the various measurands are shown in Table IV-4. Also shown are the measurement accuracy and resolution requirements. The accuracy requirement, or more properly, the tolerance for uncorrected errors, varies drastically with the user's application. Generally, 1 percent of the brightness temperature or 2 K to 3 K is a typical requirement, but some specific applications require absolute accuracies that approach the precision and temperature resolution requirements. Accurate radiometers must minimize systematic errors such as nonunity emissivity of the

Fig. IV-1 Minimum Required Antenna Diameter at 600 km Orbital Altitude for Various Spatial Resolution Requirements

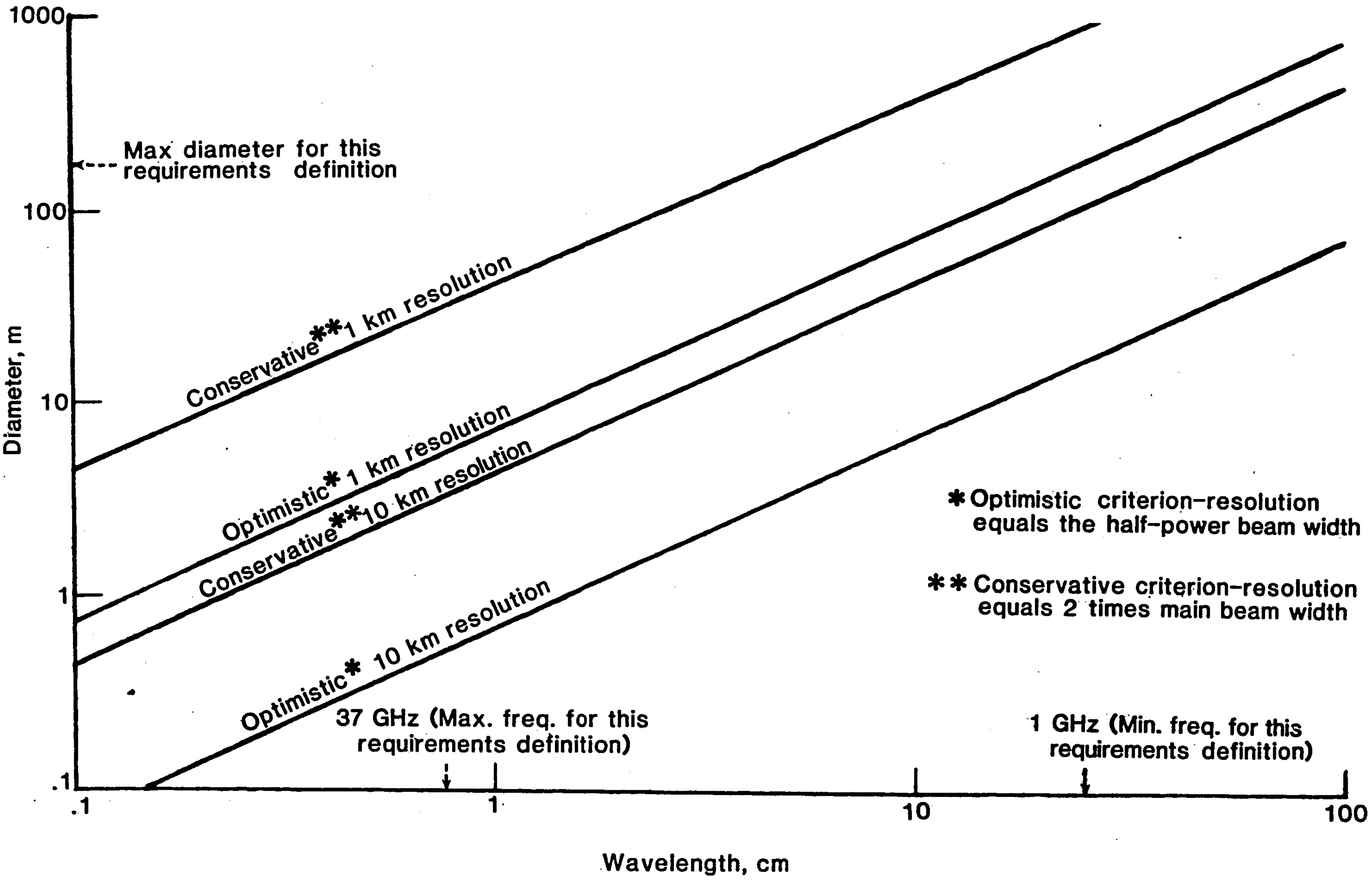

Fig. IV-2 Diameter vs. Operating Wavelength Comparison for Earth-Based Large Antenna Systems

1. U.TEXAS
2 OVRO 10 m

3 NRAO 11 m
3A NRAO 11 m, DOME CLOSED
4 CRIMEA
5 NRAO VLA
6 OVRO 40 m

7 BONN 100 m
8 NASA DSM 64 m
9 NRAO 90 m
10 PARKES 64 m

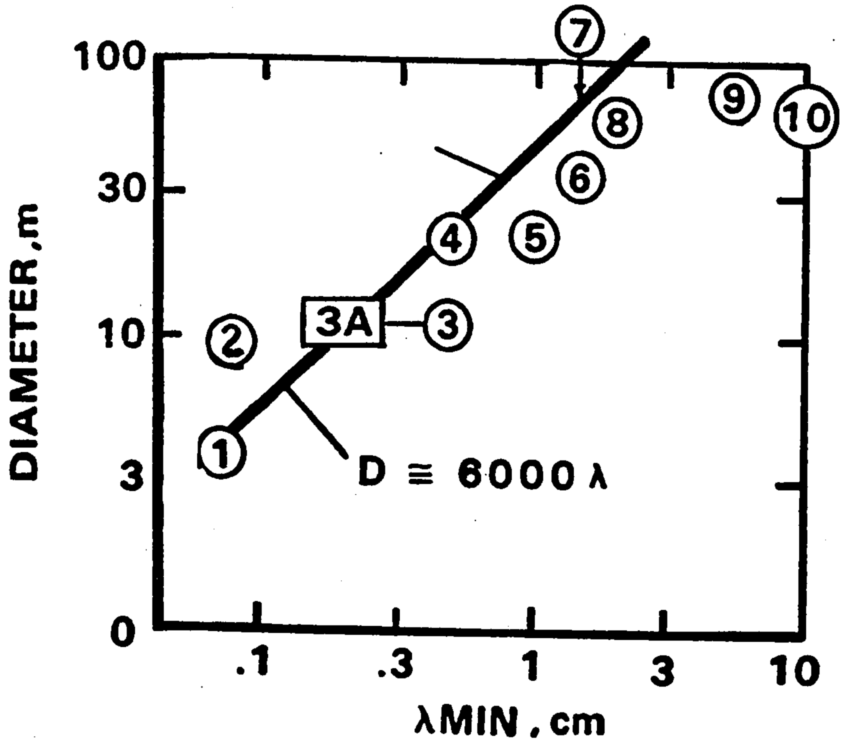

TABLE IV-4.- Brightness Temperature Radiometric Requirements

| GEOPHYSICAL PARAMETER | SOIL MOISTURES | WATER SURFACE TEMP. | WATER ROUGHNESS (WIND) | ICE | WATER SALINITY | WATER POLLUTANTS (OIL) |
|---|---|---|---|---|---|---|
| Frequency Range | 1-10 GHz | 2-6 GHz | 2-50 GHz | 10-50 GHz | 1-2 GHz | 1-30 GHz |
| Wavelengths | 30-3 cm | 15-5 cm | 15-0.6 cm | 3-0.6 cm | 30-15 cm | 30-1 cm |
| Brightness Temperature Range | 200-300 K | 85-120 K | 85-300 K | 100-250 K | 50-100 K | 5-200 K |
| Brightness Temperature Accuracy | General Requirement Approximately 1% of Brightness Temperature (2-3°) | | | | | |
| Brightness Temperature Resolution (Precision) | 2 K | 1 K | 0.5-2 K | 0.2-1 K | 0.3 K | 0.5 K |

calibration targets, antenna side lobes, and reflector surface scattering which can produce biases in the brightness temperature that are difficult to quantify or isolate.

Brightness Temperature Resolution. The brightness temperature resolution requirement is related to the accuracy and precision requirements for the measurands. It is often used interchangeably with radiometer sensitivity, $\Delta T$. However, in determining geophysical properties, sea surface temperature for instance, the uncertainty in the measurement of brightness temperature is often larger than $\Delta T$. (Radiometer calibrations include the same noise as the signal, consequently, the uncertainty in brightness temperature after calibration is larger than $\Delta T$.) Harrington et al. (ref. 14) model the variance of the measurements as

$$\sigma_{TA}^2 = C + \frac{(\Delta T)^2}{(1 - \alpha)^2 (1 - R_i)^2} .$$

$\sigma_{TA}^2$ = variance of the antenna temperature for a desired measurand

C = additive constant

$\alpha$ = attenuation factor for the radiometer front end

$R_i$ = power reflection coefficient of the input wave in the forward direction

In this formulation measurement uncertainties are related directly to $\Delta T$, but other antenna and radiometer characteristics produce a multiplicative factor and an additive constant, C. At low values of $\Delta T$, generally $< 0.5$ K, C becomes important. Currently, C is difficult to estimate, and may increase variances by, perhaps, an order of magnitude. To illustrate these points further, and to show the logic for choosing a "reasonable" requirement for $\Delta T$ for LSA systems, the following discussion of radiometer sensitivity is included.

Modeling Radiometer Sensitivity. The temperature sensitivity of a switched radiometer is modeled by

$$\Delta T = \frac{2T_{sys}}{\sqrt{B\gamma}} \tag{IV-1}$$

where

$T_{sys}$ = system noise temperature (received radiation plus internal noise)

B = predetection bandwidth

$\gamma$ = postdetection integration time

As can be seen by equation (IV-1), $\Delta T$ can be minimized by decreasing the system noise temperature or maximizing the bandwidth and/or integration time.

Typical radiometer bandwidths at the lower frequencies are set at 200 mHz or less in order to reduce RFI from band-allocated active radiometers. This number can be larger at the higher frequencies.

In order to keep from smearing the measurement results, the integration time should be smaller or equal to the time that the sensing beam dwells on a resolution element. Most Earth viewing microwave instruments (ESMR, SCAMS, SMMR, MSU) use a scan approximately perpendicular to the ground track with continuous coverage within the scan limits, that is, the footprints are contiguous in both along track and cross track directions. The observed region between the scan limits is called the swath. As the footprint is made smaller, the time available for a single measurement becomes shorter and the temperature radiometer sensitivity, $\Delta T$, consequently degrades. With a single receiver instrument, there is always a tradeoff between footprint size and sensitivity if complete surface coverage is maintained within each swath measurement zone.

It can be shown that the dwell time, $\tau$, the time available for a single measurement is given by

$$\tau = \frac{F^2}{SV} \qquad \text{(IV-2)}$$

where F is the footprint diameter, S is the edge-to-edge swath containing S/F individual footprints, and V is the orbital velocity (Earth rotation is ignored).

The system noise temperature, $T_{sys}$, is composed of the receiver temperature and the signal (antenna) temperature. For a precision null-balance dicke radiometer,

$$T_{sys} = T_o + T_{rcr} \qquad \text{(IV-3)}$$

where

$T_o$ = ambient temperature of the reference load

$T_{rcr}$ = receiver input noise temperature

$T_o$ is typically 300 K and $T_{rcr}$ is generally the input noise temperature of the front-end low noise amplifier (FET or parametric amplifier) and the preceding loss contribution. For L and S bands an average value of 100 K is assumed.

Setting $\gamma = \tau$ and using typical values in equations (IV-1, IV-2, and IV-3), $\Delta T$ is calculated for footprints of 10 km and 1 km over a swath width range of 100 km to 2000 km. These results are plotted in figure IV-3. Also displayed in the border of the plot are the measurement requirements for brightness temperature resolution from Table IV-4 and swath width requirements from Table III-2.

Radiometer Sensitivity Requirement. In Table IV-4 the smallest brightness temperature resolution value required is 0.2 K so it appears that the radiometer sensitivity requirement, $\Delta T$, should be less than that by some factor. But in the expression for measurement variance, for such small values of $\Delta T$, the C factor tends to be dominant so that reducing $\Delta T$

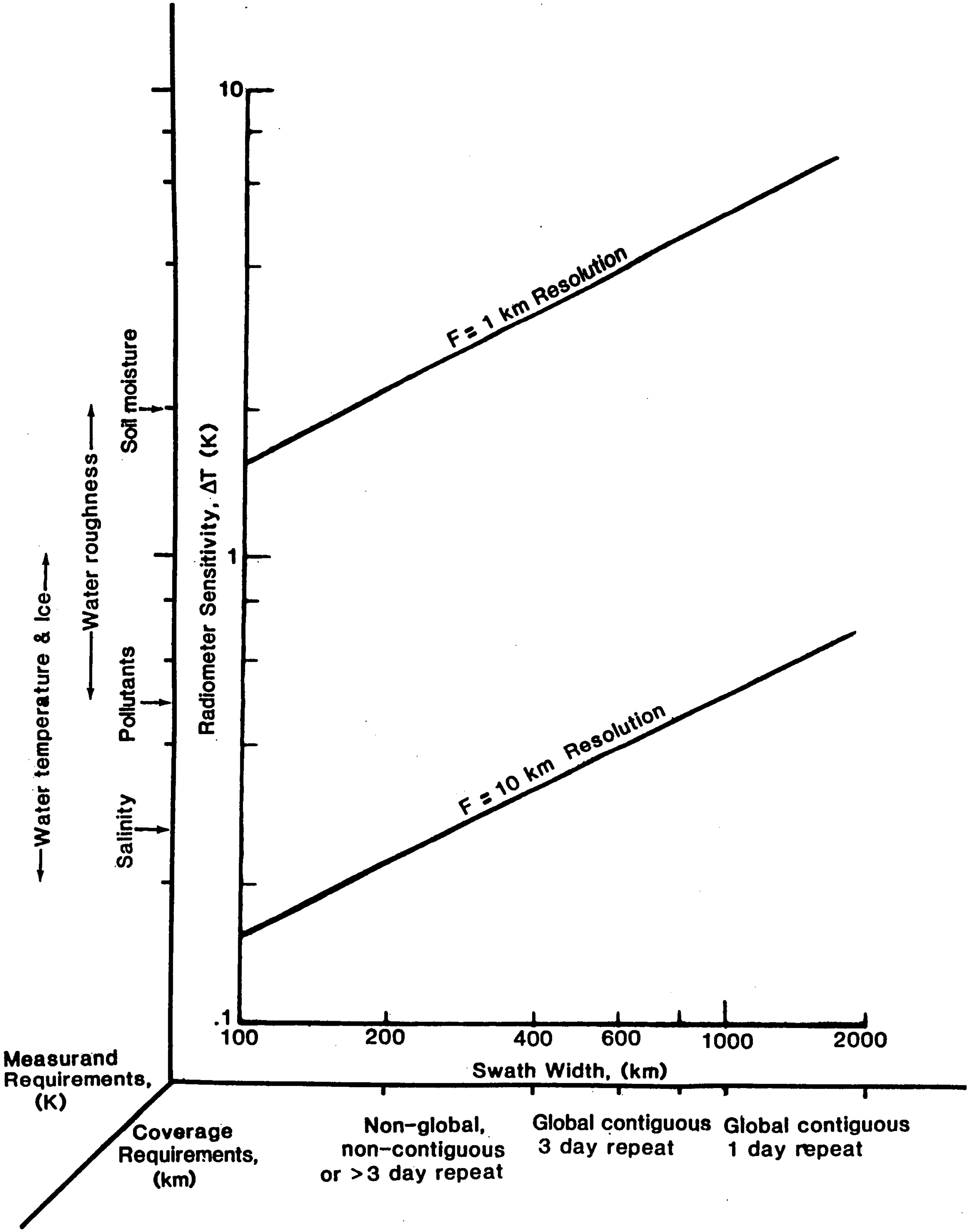

Fig. IV-3 Brightness Temperature Sensitivity vs. Swath Width for Modeled Single-Beam Radiometer Compared to Measurand and Coverage Requirements further no longer reduces variance proportionally. It is reasonable, therefore, to choose a value larger than 0.2 K for the required $\Delta T$. The value chosen as "reasonable" for this requirements definition is $\Delta T < 0.5$ K. This choice represents the approximate break points between (1) the dominance of the C factor and $\Delta T$ in the variance relationship, (2) the stringent salinity water temperature and ice requirements and the other measurand requirements, and (3) the 10-km mandatory and the 1-km desired spatial resolution requirements. To meet the global contiguous coverage, 10-km resolution requirement for salinity, water temperature and ice and to meet the 1-km resolution requirement for any of the measurands, steps must be taken to dramatically reduce $\Delta T$'s (i.e., improve radiometer capability) below the values typical of real single-beam scanned radiometers as represented by the one modeled. Furthermore, for $\Delta T < 0.5$ K, the relationship between measurement variance and $\Delta T$ must be analyzed in detail for generic or particular LSA radiometer designs. Such systems implication are discussed next.

## System Design Implications

This discussion is aided by the use of the sensor system design diagram of figure IV-4. In the figure those items which have been discussed previously are marked by the numbers of the sections in this report in which those discussions occurred. From figure IV-3, it appears that good measurements with spatial resolutions of 10 km to 1 km will be difficult to achieve because (1) measurement uncertainties are related to other antenna and radiometer characteristics besides $\Delta T$, and (2) $\Delta T$ at higher frequencies is larger than the modeled estimate. For example, (1) actual measurement uncertainties for real flight radiometers are often two

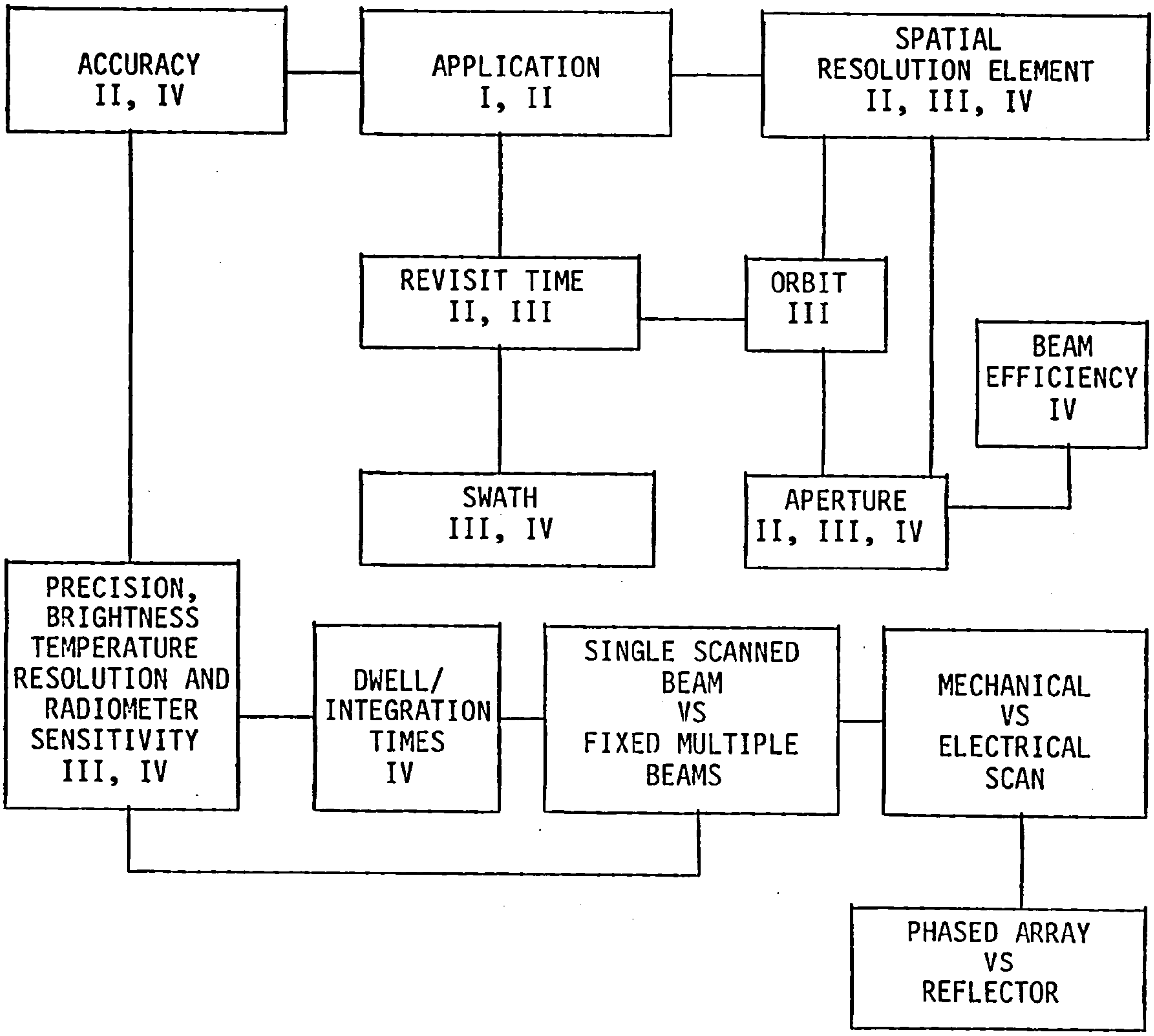

Fig. IV-4 Microwave Radiometer Sensor Design Diagram to three times the pre-experiment estimates, and are caused by various antenna losses, and (2) alternative empirical estimates of system temperature [such as 50 f(GHz) + 200 and 20 f(GHz) + 350] result in $\Delta T$'s that are up to a factor of four larger than modeled. The system design implications, therefore, are strong regarding (1) error analysis and calibration and (2) reducing $\Delta T$'s (after doing all that is practical concerning system noise and bandwidth) by considering integration and dwell times. The latter has a major impact on flight radiometer configurations.

The minimum allowable measurement integration time for a single-beam cross-track scan system with 10-km resolution and 600-km swath is approximately 0.025 seconds. Taking into consideration real radiometric systems, this is generally an insufficient time for measurements with noise-equivalent $\Delta T$ of $< 0.5°C$. It is obvious, therefore, that real LSA radiometric systems will likely have to utilize multiple-beam concepts in order to meet requirements for frequency range of operation, swath width, spatial resolution, and temperature sensitivity.

There are two basic systems for effecting multiple-beam operation: (1) Phased-array systems intercept the whole wavefront impinging on the microwave antenna aperture and adjust signal phases electronically to form beams which may be fixed or scanned to obtain the swath widths required; (2) reflector systems utilize multiple-feed arrays with a single large reflector. Multiple-beam reflector systems can be configured for "push-broom" operation (fixed beams with orbital velocity scan only) or for "whisk-broom" operation (multiple-beams mechanically cross track scanned in conjunction with orbital velocity scan).

For reflector systems large angular fields-of-view necessary for wide swaths can best be obtained with multiple-beam configurations whose feed illumination areas on the reflector do not fully overlap, resulting in the requirement for a reflector whose size may be appreciably larger than the aperture size for a single beam.

Image quality requirements impose a severe beam efficiency requirement on reflector systems which in turn impose reflector surface irregularity and shape distortion limits which are related to the wavelength of operation. The reflector surface material or finish and the structural distortion under thermal cycling are the important considerations. Reflector error tolerances fall somewhere within the $\lambda/30$ to $\lambda/100$ range for random roughness ( $\lambda/55$ is equivalent to 5-percent loss in beam efficiency) and within the $\lambda/16$ to $\lambda/32$ range for large scale shape (thermally or otherwise deterministic) distortion.

Other image quality requirements (adopted from ref 6) are:

- The variations in resolution element, F, sizes for a multiple beam system shall not exceed ±10 percent of the average for all beams.

- Allowable deviations from perfect contiguity and cross-scan alignment of the resolution elements are:

(1) Static cross-scan contiguity - Gaps between individual resolution elements and overlaps of resolution elements shall not exceed F.

(2) Static along scan displacement - Shall not exceed 2F.

(3) Static image distortion of a group resolution elements - Although contiguity may be maintained with some types of image distortion, the cross-scan or along-scan displacement of any single resolution element from its ideal position shall not exceed 2F.

(4) Dynamic deviations - jitter or oscillatory deviations of any kind with equivalent spatial wavelengths of less than 500F shall not exceed a peak amplitude of 0.5F.

- Allowable deviations from perfect registration of resolution elements are defined as follows:

| | Global | Over control points |
|---|---|---|
| Temporal registration offsets between two images over same area | <5F | <0.5F |
| Geodesic accuracy of an image | <5F | <0.5F |
| Uncertainty between two adjacent images from different passes | <5F | <0.5F |
| Rotation between adjacent images from different passes | <3° | <1.0° |

Detailed system requirements for the number of beams, beam alignment, scanning technique, spacecraft pointing accuracy/precision and other configuration or design-dependent parameters can be derived from the basic requirements keeping in mind their interdependence as depicted in fig. IV-3.

# V. CONCLUSIONS

## Program

1. Mission requirements have been defined for Large Space Antenna (LSA) Radiometer systems to enable delineation of corresponding performance and system requirements necessary for focusing the Langley Research Center's Spacecraft Research Program in this area.

2. Based on previous studies and this requirements analysis, the a priori selection of the range of antenna aperture sizes, 50-200 m, is appropriate for Earth radiometry applications.

3. Based on the outlook for LSA technology and Earth observation program maturity, projecting mission requirements to circa 1990 is reasonable for this definition activity.

## Earth Observational Needs

4. Microwave sensing is needed to measure a variety of geophysical phenomena simultaneously to support agricultural, hydrological, meteorological, and other global-scale applications.

5. Potential measurands for LSA radiometers include soil moisture, sea surface temperature, sea surface salinity, sea state (winds), ice, and water pollutants (oil slicks).

6. In addition to value of their own, measurements made with moderate resolution passive microwave systems capable of contiguous mapping of large regions of the Earth with frequent revisits will complement high resolution measurements made over limited areas with optical systems and active microwave systems.

## Key Measurement Requirements

7. Soil moisture and sea surface temperature are key measurands and LSA technology drivers.

8. Many application needs are met with approximately 10 km resolution. A number of applications, however, require resolutions as fine as 1 km. Therefore, the spatial requirement ranges from 10 km mandatory to 1 km desired.

9. Most application needs are met with temporal repeats (sampling or revisit intervals) of approximately once every 3 days. A few applications, however, require repeats as often as once every day. Therefore, 3 days is considered the primary requirement for temporal resolution and 1 day the secondary requirement.

10. Contiguous coverage of large geographic areas is vital to full utilization of the various measurements, e.g., soil moisture measurements over major farm belts.

11. Climate applications have the greatest need for measurements over long periods of time. A precise specification is not needed for technology development purposes, so the requirement lifetime is simply stated as "several years."

## Orbital Requirements

12. Spatial resolution capability of 50-200 meters LSA's means that the spatial resolution requirements can be met only with operation in low Earth orbit (LEO).

13. Within the LEO altitude range of 450-2200 km many design tradeoffs are possible and approximately 640 km is a good choice for initial parametric studies.

14. Geographic coverage requirements generally can be met with orbital inclinations in the range of approximately 60° to 98°.

15. Obtaining contiguous coverage with the stated revisit intervals and orbital inclinations imposes the requirements for swath widths of 300 km or more.

16. Strict orbit maintenance is required to minimize variations in spatial resolution and to insure contiguity and geodetic precision of mapped data products.

## Radiometric Requirements

17. For the complete list of measurements and for the 50-200 meter antenna aperture range, the frequency range to be considered is approximately 1-37 GHz.

18. The key measurements (soil moisture and sea surface temperature) require the lower frequencies, 1-10 GHz, and the larger apertures, approaching 200 meters for 1 km spatial resolution.

19. Dual polarization measurements (or single linear, non-rotating polarization) are required because of inversion errors caused by emissivity effects at large off-normal angles (>30°) of the emitted microwave radiation.

20. Main beam efficiencies of >90 percent are required for Earth radiometry in order to obtain good image quality and avoid smearing of heterogenous scenes.

21. An extremely large angular field-of-view (60° or more) is required to meet the contiguous mapping/wide swath requirements.

22. Dynamic range in terms of brightness temperature is approximately 0-350 K.

23. For the required spatial resolution, the systematic error in derived brightness temperature must be less than approximately 2-3°C.

24. Brightness temperature resolution requirements range from approximately 0.2 to 5 K.

25. Radiometric system noise temperature must be minimized over the frequency range to achieve sensitives dictated by brightness temperature precision and resolution requirements.

26. The predetection bandwidth, B, requirement at the lower frequencies is set at <200 MHz in order to reduce RFI from band-allocated active radiators. Larger bandwidths are possible at the higher frequencies.

27. With the range of system noise and bandwidth of typical radiometers, a brightness temperature sensitivity of approximately 0.5 K is achievable and the mandatory spatial resolution requirement of 10 km can be met for most measurands.

## System Requirements

28. For a typical radiometer, spatial resolution better then 10 km requires longer dwell/integration times than can be provided by a scanning single-beam system.

29. Real LSA radiometer systems will likely have to utilize multiple-beam concepts in order to meet requirements for frequency range of operation, swath width, spatial resolution, and brightness temperature sensitivity.

30. Phased array systems intercept wavefronts and adjust signal phases while reflector systems utilize multiple-feed arrays to effect multiple-beam operation; thus, both types of systems have potential for obtaining high resolution, wide swath measurements over the 1-40 GHz range.

31. Reflector system concepts utilizing multiple-beams with either the "push broom" or "whisk broom" operation are electronically much less complex than phased arrays.

32. Large angular field-of-view requirements can best be met with multiple-beam concepts whose feed illumination areas on the reflector do not fully overlap, resulting in the requirement for a reflector whose size is appreciably larger than the aperture size for a single beam.

33. Beam efficiency requirements impose reflector irregularity and structural distortion limits which are related to the wavelength of operation and the size of the antenna aperture.

34. Reflector error tolerances fall somewhere within the following ranges depending on aperture size, the inherent beam efficiency of the feed and illumination designs, and the side lobe power-loss budget established:

- Random roughness - $\lambda/30$ to $\lambda/100$
- Large scale shape (deterministic) - $\lambda/16$ to $\lambda/32$

35. Detailed system requirements for the number of beams, beam alignment, scanning, spacecraft pointing accuracy/precision, reflector tolerances and related design-dependent parameters can be derived from the measurement, orbital, radiometric and general system requirements delineated herein.

## VI. RECOMMENDATIONS

1. The requirements delineated herein are adequate for deriving the system requirements necessary to initiate LaRC's spacecraft system technology work with the LSA focus', however, continued study of Earth radiometric applications, their measurement needs, and their associated radiometric requirements is recommended.

2. The mission and measurement needs defined herein are not uniquely satisfied by LSA radiometry; furthermore, LSA technology is applicable to other applications such as communications and astronomy. Therefore, it is recommended that future design studies periodically assess competitive and complementary approaches.

3. LSA technology's realistic response to expressed needs is always tempered by cost considerations. It is recommended, therefore, that the next "requirements update" include at least a first order consideration of potential benefits vs. developmental and operational costs.

Langley Research Center
National Aeronautics and Space Administration
Hampton, Virginia 23665
April 1982

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# APPENDIX

## LSA SYSTEM REQUIREMENTS COMMITTEE

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16. Abstract

Requirements are defined for Earth observational microwave radiometry for the decade of the '90's using Large Space Antenna systems with apertures in the 50 to 200 meter range. General Earth observational needs, specific measurement requirements, orbital mission guidelines and constraints, and general radiometric requirements are defined.

General Earth observational needs are derived from NASA's basic space science program. Specific measurands include soil moisture, water surface temperature, water roughness, ice boundaries, salinity, and water pollutants. Measurements with 10 to 1 km spatial resolution and 3 to 1 day temporal resolution are required. The primary orbital altitude and inclination ranges are 450-2200 km and $60^{\circ}-98^{\circ}$, respectively. Contiguous large-scale coverage of several different areas of the globe dictate large (several hundred meter) swaths.

Radiometrically the measurements are made in the 1-37GHZ range preferably with dual polarization radiometers with $\gtrsim$ 90% beam efficiency. Reflector surface r.m.s. deviations in the range from $\lambda/30-\lambda/100$ are required and resolution requirements for brightness temperature are in the order of 2K and 0.5K, respectively, dictating radiometer sensitivity of $\lesssim$ 0.5K. System implications point toward multiple beam configurations used in either "whisk" or "push" broom modes.

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