IN-43
47533
P.62

NASA Contractor Report 4408

The Science Benefits of and the Antenna Requirements for Microwave Remote Sensing From Geostationary Orbit

CONTRACT NAS1-18471
OCTOBER 1991

NASA

NASA Contractor Report 4408

The Science Benefits of and the Antenna Requirements for Microwave Remote Sensing From Geostationary Orbit

Edited by
Warren L. Stutzman and Gary S. Brown
Virginia Polytechnic Institute and State University
Bradley Department of Electrical Engineering
Blacksburg, Virginia

Prepared for
Langley Research Center
under Contract NAS1-18471

National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Program
1991

NASA

Large Space Antenna

Science Benefits Panel

FINAL REPORT

Editors

Warren L. Stutzman
Gary S. Brown

Virginia Tech

EXECUTIVE SUMMARY

The primary objective of the Large Space Antenna (LSA) Science Panel was to evaluate the science benefits that can be realized with a 25-meter class antenna in a microwave/millimeter wave remote sensing system in geostationary orbit. The panel concluded that a 25-meter or larger antenna in geostationary orbit can serve significant passive remote sensing needs in the 19 to 60 GHz frequency range, including measurements of precipitation, water vapor, atmospheric temperature profile, ocean surface wind speed, oceanic cloud liquid water content, and snow cover. In addition, cloud base height, atmospheric wind profile, and ocean currents can potentially be measured using active sensors with the 25-m antenna. Other environmental parameters, particularly those that do not require high temporal resolution, are better served by low earth orbit based sensors.

PANEL MEMBERS

Ghassem Asrar, NASA Headquarters

Gary Brown, Virginia Tech

Walter Flood, Army Research Office

Al Gasiewski, Georgia Tech

Samuel Gasster, The Aerospace Corp.

James Hollinger, Naval Research Laboratory

Ramesh Kakar, NASA Headquarters

Chester Parsons (deceased), NASA Goddard-Wallops Island

Warren Stutzman, Virginia Tech

Calvin Swift, U. Massachusetts

Warren Stutzman

Warren Stutzman, Co-chair

Gary Brown

Gary Brown, Co-chair

TABLE OF CONTENTS

EXECUTIVE SUMMARY iii

PANEL MEMBERS iv

1. INTRODUCTION 1

2. IMPLICATIONS OF REMOTE SENSING FROM GEO WITH A 25-METER CLASS MICROWAVE APERTURE AND THE BENEFITS TO SCIENCE . . 6
   2.1 Ranking of Observables
   2.2 Spatial and Temporal Resolutions
   2.3 Sensor Radiometric Accuracy and Precision
   2.4 Beam Efficiency
   2.5 Summary

3. LARGE SPACE ANTENNA NEEDS OF FUTURE U.S. PROGRAMS . . . 28
   3.1 Overview
   3.2 Defense Meteorological Satellite Program

4. RECOMMENDATIONS FOR TECHNOLOGY DEVELOPMENT 37

5. REFERENCES 41

6. Appendix A: Water Vapor Profiling Using the 22 GHz Radiometer Data 43

7. APPENDIX B: Sidelobe Contributions to Beam Efficiency from GEO 47

8. Appendix C: DMSP Block 5D and Block 6 Systems Descriptions 52

1. INTRODUCTION

The impetus for this effort grew out of the large antenna research program within The Antennas and Microwave Research Branch (AMRB) at NASA Langley Research Center (LaRC). One example of LaRC involvement with large aperture antenna technology is the large deployable antenna (LDA) program which resulted in the construction and thorough ground testing of the 15-meter hoop-column antenna. Since communications and remote sensing needs will place increasing demands on spaceborne antennas, AMRB is exploring both generic large antenna technology as well as mission specific designs. At this point the mission drivers for large spaceborne antennas are the remote sensing capabilities of microwave radiometers in geostationary orbit. This mission is referred to as ESGP (Earth Science Geostationary Platform) which is a part of the NASA Mission to Planet Earth. The microwave radiometer instrument portion dominates the platform architecture because of the large antennas required.

Earth remote sensing can be performed from low earth orbit (LEO) or geostationary earth orbit (GEO). The advantage offered by a few GEO platforms is high temporal resolution. A constellation of many LEO satellites would be required to approach the temporal resolution and near global coverage of a few GEO satellites. The panel did not specifically address the tradeoffs between LEO and GEO based systems because a recent study has addressed this issue [1]. The NASA Langley architecture trade study [1] concluded the following: "The need for full global coverage with repeated daily samplings, augmented by near continuous regional intensive coverage measurements, lead to orbit selections of both sun-synchronous LEO and GEO locations."

The ESGP mission is envisioned to have antennas larger than the current maximum launch envelope dimension of 4.4 m; therefore, deployment or erection in space is essential. To avoid extensive extra vehicular activities, the deployable approach has been identified as an attractive solution.

Virginia Tech is involved in the structural and electromagnetic design elements for LaRC's Large Deployable Antenna program. Summarized below are the findings from Phase I of that effort. Phase II will produce a ground test article design that will be used to validate critical technologies. Prior to Phase II, it will be necessary to ensure the value of the ESGP remote sensing instrumentation and this requires a study of the science benefits that will ultimately result. The Large Space Antenna (LSA) Science Benefits Panel was formed for this purpose.

Examination of potential science benefits is a necessary step because whenever a spacecraft antenna is designed compromises always arise. For example, the antennas should be made large enough to achieve the desired ground resolution but small enough in size to meet launch or cost constraints. The resulting size compromise may lead to data of marginal utility. The panel of experts was formed to examine remote sensing issues and antenna system requirements along with the benefits to science from the data acquired by a GEO LSA.

The dominant sensor is assumed to be a multichannel microwave radiometer operating in the desired range of 6 to 220 GHz. It is unlikely that such operation could be achieved with a single aperture. A concept for a two antenna configuration spacecraft is shown in Fig. 1. JPL has examined the upper portion of this frequency span using a four-meter antenna [2]. The JPL design includes frequencies down to 37 GHz; however, the 4-m antenna would have a spatial resolution of 83 km at that frequency and the panel considered this to be inadequate. The LDA Phase I study considered an antenna for the 6 to 60 GHz band and the design goals for that study are shown in Table 1 (taken from [3]). A 40-m design goal was selected, without regard to its implementation, because of the high spatial resolution.

The Virginia Tech LDA project examined reflector surfaces and support trusses for the reflector. The initial design showed that a deep truss is required in order to meet surface accuracy demands. A truss and solid reflector were designed to stow in current large launch vehicles and to deploy in space. Both 20-m and 28-m diameter main reflectors were designed. However, the part count on the 28-m design was very high and was considered to be impractical.

With this as a background the science benefits panel was formed in July 1990. It met September 27/28 and December 13/14. This report forms the output. The formal charge for the panel follows.

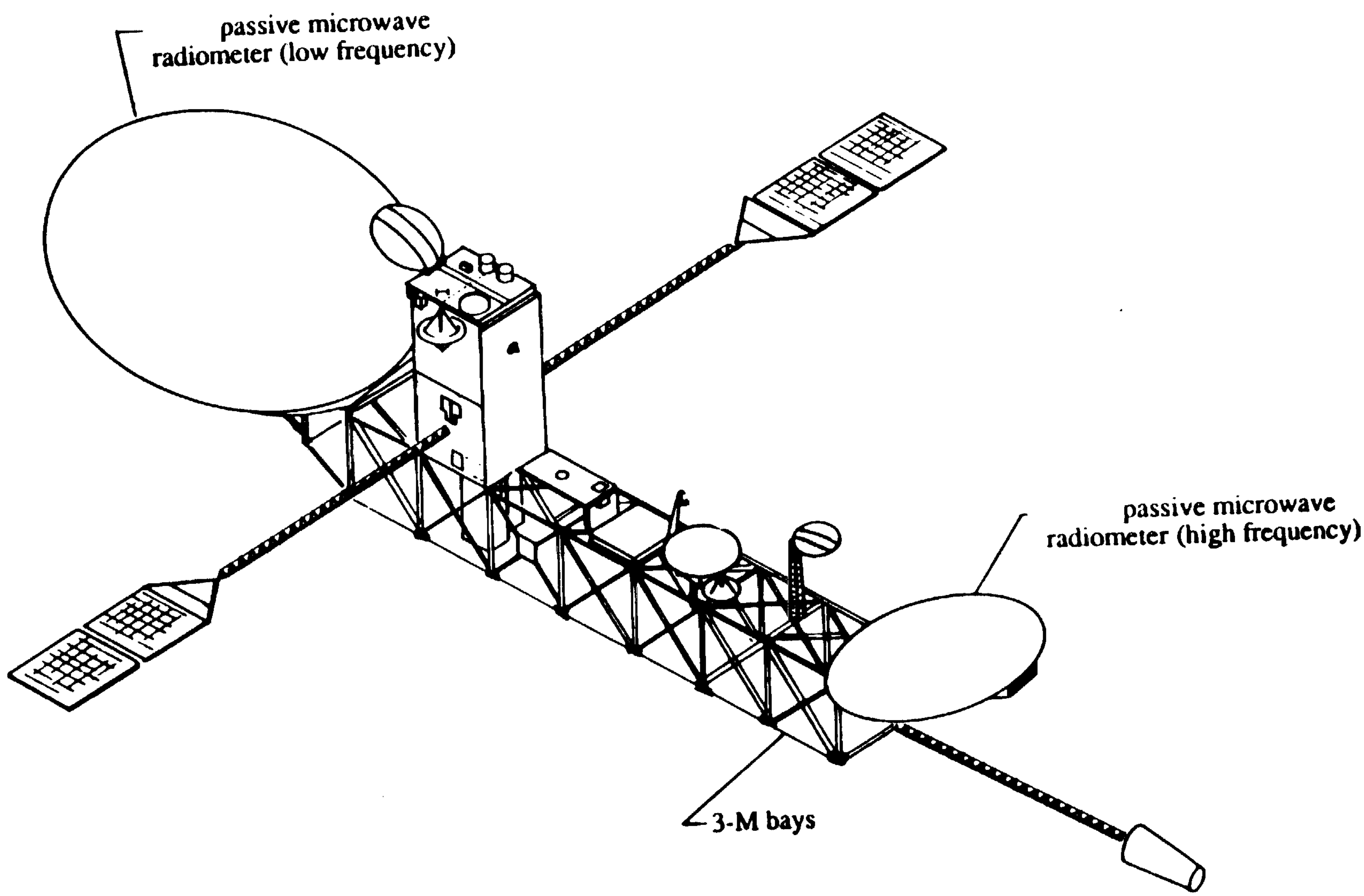

Figure 1. A concept proposed by Ford Aerospace for ESGP using two antennas to cover the radiometer bands.

Table 1

Initial Antenna Design Goals for the LDA Program. From [3]

Parameter	Requirement and/or Specification
1. Frequency	
Range	6-40 GHz, with 60 GHz upper goal
Bands	6, 13, 22, 31, 37, 60 GHz
2. Antenna Sizes	
Main Reflector	40 m
Subreflector	0.5-0.6 x main reflector sizes or approximately 20 m
3. F/D	1.5-2.5 with goal toward 1.5-2.0
4. RMS surface accuracy (main & subreflector)	0.1 mm
5. Portion of full disc to scan	
Mode 1 - full disc	$\pm$ 7.5°
2 - limited scan	$\pm$ 2.4°
3 - stare	dwell on small region(s)
6. Beam efficiency	> 90%
7. Steering requirements	1-3 hrs.
8. Thermal differential	100°

"The primary objective of the LSA Science Panel is to evaluate the science benefits that can be obtained through the use of a 25-meter class antenna in a remote sensing system in geostationary orbit. This must be addressed if the LDA Phase II technology development program can proceed as planned. Also, the panel shall: (1) identify the science needs that will benefit from using an antenna of 25-meter class diameter in the frequency band of 6-60 GHz, (2) prioritize the importance and timeliness of these needs to programs of NASA and other agencies over the next 10-20 years, and (3) provide recommendations for possible improvements in the technology program."

The panel was able to address these issues, agree upon the approach to be followed for the antenna design at the requirement level, and identify the technology needed. This report discusses the panel's deliberations and conclusions.

2. IMPLICATIONS OF REMOTE SENSING FROM GEO WITH A 25-METER CLASS MICROWAVE APERTURE AND THE BENEFITS TO SCIENCE

The panel spent a great deal of time discussing the question of what environmental parameters can be measured from GEO. Obviously, there are some situations where GEO affords a significant advantage over LEO because the globe (approximately a hemisphere) is visible at all times. This makes possible staring at a scene with fixed pointing, as contrasted to a ground tracking beam for a fixed-pointed LEO system. An example of an operational LEO system is the SSM/I (Special Sensor Microwave/ Imager) on the Defense Meteorological Satellite Program (DMSP) Block 5D satellites. The retrieved environmental parameters together with associated measurement accuracies for the SSM/I system are given in Table 2 which is taken from [4].

2.1 Ranking of Observables

The starting point for panel discussions was a reevaluation of Table 3, which resulted from earlier studies of earth remote sensing (not restricted to GEO) [1]. The panel then identified the environmental parameters measured from GEO that would be of scientific value.

One major departure from prior needs is at the low frequencies. Frequency coverage for ESGP radiometric observations have frequently been quoted as beginning at 6 GHz. Measurements from a GEO platform at about 10 GHz and below require an antenna of 50 to 60 m diameter for acceptable resolution. This antenna size is beyond even the 40-m antenna size goal. The panel felt that such a significant upsizing was not justified for the few frequencies involved. The one possible need discussed was that of precipitation measurements at 10 GHz. The 10 GHz measurement would only be useful under conditions of very heavy rain which occurs infrequently. However, high rain rate regions are of small spatial extent and, therefore, demand even higher spatial resolutions.

The lowest channel in the 50-60 GHz band is used to remove surface emissivity which is a contaminant in atmospheric observations data below 55 GHz.

Table 2

SSM/I Environmental Parameters. From [4]

Parameter	Resol.(km)	Range of Msmts.	Absolute Accuracy
Ocean Wind Speed	25	3-25 km/s	± 2 m/s
Ice Area Covered	25	0-100 %	± 12 %
Ice Age	50	1st yr & Mltyr	10 % *
Ice Edge location	25	N/A	± 12.5 km
Precip over Land	25	0-25 mm/hr	± 5 mm/hr
Cloud H_2O	25	0-1 kg/m^2	± 0.1 kg/m^2
Int. H_2O Vapor	25	0-80 kg/m^2	± 2.5 kg/m^2 or 10%
Precip over Water	25	0-25 mm/hr	± 5 mm/hr
Soil Moisture	50	0-60%	TBD
Land Surf. Temp	25	180-340°K	TBD
Snow Water Cont.	25	0-50 cm	TBD
Surface Type	25	12 Types	N/A
Cloud Amount	25	0-100%	± 20%

N/A = not applicable
TBD = to be determined
* = added by panel

Table 3

Observables, Frequencies of Observation, and Resolutions. From [1]

REQUIREMENTS FOR EARTH SCIENCE MEASUREMENTS

Regime/ Category	Measurable	Priority and Diurnal Cycle		Global Change Studies		Regional Process Studies	
				Temporal	Spatial	Temporal	Spatial
Solar	Spectral Radiation	1	NO	1D	Sun disk	1D	Sun disk
Atmosphere	Pressure (Surface)	1	NO	3-12H	10km		
	Temperature Profile	1,2	YES	1-3H	10-50km	15M-1H	5km
	Stratospheric Gases	1,2	NO	3-12H	50km	30M	5-10km
	Aerosols & Part.	2	NO	3-12H	10km	15M-1H	0.1-1km
	Tropospheric H2O	2	NO	3-12H	10km	30M-1H	10km
	Cloud Cover & Height	2	YES	1-3H	1km	15M-1H	1km
	Tropospheric Gases	2,3	YES	1-3H	10km	30M-1h	10-50km
	Wind Fields	2,3	YES	1-3H	10km	30M-1H	
Radiation Budget	Reflected SW & Emitted LW Flux	2	YES	1-3H	10-30km	30M-1H	1-30km
Multi-frequency Radiometer req'd	Surface Temperature	1	YES	1-3H	1-4km	6M-24H	30m-200km
	Precipitation	1	YES	1-3H	1-30km	3M-3H	1-200km
L-band, Large Aperture req'd	Vegetation cover/type	1	NO	7D	1km	1-30D	30m-10km
	Soil Moisture	1	NO	2D	1-10km	12H-7D	30m-10km
	Biomass Inventory	1	NO	7D	1km	1-30D	1-10km
Earth (Land/Ocean)	Ocean Color (Chloro.)	1	NO	2D	1-4km	2D	30m-4km
	Ocean Circulation	1	NO	2D	1-4km	1D	30m-4km
	Sea Level Rise	2	NO	2D	10km	2D	10km
Multi-frequency Radiometer req'd	Sea Ice Cover/depth	2	NO	7D	1-20km	1-3D	1-25km
	Ocean CO2	2	NO	2D	500km		
	Snow Cover/depth	3	NO	7D	1km	12H-3D	1-10km

Dual polarization measurements were not specifically called out in the observables listings. However, linear polarization diversity is essential for incidence angles off nadir because the emission, scattering and reflection properties of the surface are significantly different for the horizontally and vertically linearly polarized components of the radiation. This is particularly true for the ocean where the vertical component is less dependent on surface roughness than the horizontal component thus allowing surface effects to be separated from those of the atmosphere. It is also true for land surfaces where the difference between the two polarizations is dependent upon soil type, roughness, moisture content, vegetation and snow cover. Therefore, orthogonal linear polarized channels can be as important as two different frequencies in the determination of surface properties. Dual polarized operation is recommended at 19 and 37 GHz and one channel in the 50 to 60 GHz band.

The use of a 22 GHz channel to provide the water vapor content is not a standard remote sensing technique, but it is worthy of inclusion as explained in Appendix A. Water vapor was noted by the panel to be of most value when observed over ocean. The rankings were based on temporal resolutions and uniqueness of the GEO orbit for observing short-lived phenomena; high emphasis was placed on observing short-lived events. The environmental parameters and associated frequencies and spatial resolutions listed in Tables 4 to 7 formed the basis for subsequent deliberations by the panel.

The observables in Table 3 were prioritized as to importance for GEO measurements. This prioritization was based in large measure on comparison to LEO platform sensors. That is, high weight was given to measurements that are performed much better from GEO than LEO. The environmental parameters listed in Tables 4 to 7 reflect the result of prioritization consensus by the panel, i.e. the highest priority observable is listed first.

The three categories used in the evaluation process are: 1. Very useful; 2. Acceptable; and 3. Limited use. Environmental parameters in Category 1 were deemed of high utility to the scientific and/or operational communities: all spatial and temporal requirements are satisfied. In Category 2, environmental parameters are somewhat deficient in either spatial or temporal resolution, but are still of value. The environmental parameters in Category 3 are of limited use because of poor spatial resolution of all measurements and construction of an instrument could not be justified on the basis of these environmental parameters alone.

Accuracy estimates are not included in Tables 4 to 7 because such estimates depend on overall system architecture including data reduction algorithms and, therefore, go beyond antenna considerations. The "Overall Merit" column is an evaluation primarily based on spatial resolution, but the panel considered other factors as well in arriving at the merit category. Figure 2 displays the rankings given in Tables 4 to 7 in a tower style plot.

Table 4

ESGP Millimeter Wave Remote Sensing
Environmental Parameters with Frequencies and Resolutions
Using a 20-meter Antenna
(Ordered beginning with highest priority)

Environmental Parameter	Freq (GHz)	Resolution (km) Goal	with 20-m Ant	Overall Merit*
Precipitation over ocean	19	1-30	32	3
	37	1-30	17	2
	50-60	1-30	11	2
Precipitation over land	37	1-30	17	2
	50-60	1-30	11	2
Water vapor Total**	19	5-20	32	3
	22	5-20	28	3
	37	5-20	17	3
Profile	22	5-20	28	3
	37	5-20	17	3
Temperature profile	50-60	5-30	11	1
Surface wind speed	19	10-50	32	1
Cloud base height	35 active	5-25	N/A	1
Cloud water content*** (over ocean)	19	1-30	32	2
	22	1-30	28	2
	37	1-30	17	2
Atmospheric winds profile	37 active	50	N/A	1
Snow cover	19	1-30	32	2
	37	1-30	17	2
Ocean currents	10-30 active	1-30	N/A	1

* 1 = Very useful; 2 = Acceptable; 3 = Limited use
** Requires all three frequencies
*** Requires two of the three frequencies

Table 5

ESGP Millimeter Wave Remote Sensing
Environmental Parameters with Frequencies and Resolutions
Using a 25-meter Antenna
(Ordered beginning with highest priority)

Environmental Parameter	Freq (GHz)	Resolution (km) Goal	Resolution (km) with 25-m Ant	Overall Merit*
Precipitation over ocean	19	1-30	26	2
	37	1-30	14	1
	50-60	1-30	9	1
Precipitation over land	37	1-30	14	1
	50-60	1-30	9	1
Water vapor				
Total**	19	5-20	26	3
	22	5-20	22	3
	37	5-20	14	2
Profile	22	5-20	22	1
	37	5-20	14	1
Temperature profile	50-60	5-30	9	1
Surface wind speed	19	10-50	26	1
Cloud base height	35 active	5-25	N/A	1
Cloud water content*** (over ocean)	19	1-30	26	2
	22	1-30	22	2
	37	1-30	14	1
Atmospheric winds profile	37 active	50	N/A	1
Snow cover	19	1-30	26	2
	37	1-30	14	1
Ocean currents	10-30 active	1-30	N/A	1

* 1 = Very useful; 2 = Acceptable; 3 = Limited use
** Requires all three frequencies
*** Requires two of the three frequencies

Table 6

ESGP Millimeter Wave Remote Sensing
Environmental Parameters with Frequencies and Resolutions
Using a 40-meter Antenna
(Ordered beginning with highest priority)

Environmental Parameter	Freq (GHz)	Resolution (km) Goal	Resolution (km) with 40-m Ant	Overall Merit*
Precipitation over ocean	19	1-30	16	1
	37	1-30	8	1
	50-60	1-30	6	1
Precipitation over land	37	1-30	8	1
	50-60	1-30	6	1
Water vapor				
Total**	19	5-20	16	2
	22	5-20	14	2
	37	5-20	8	1
Profile	22	5-20	14	2
	37	5-20	8	1
Temperature profile	50-60	5-30	6	1
Surface wind speed	19	10-50	16	1
Cloud base height	35 active	5-25	N/A	1
Cloud water content*** (over ocean)	19	1-30	16	1
	22	1-30	14	1
	37	1-30	8	1
Atmospheric winds profile	37 active	50	N/A	1
Snow cover	19	1-30	16	1
	37	1-30	8	1
Ocean currents	10-30 active	1-30	N/A	1

* 1 = Very useful; 2 = Acceptable; 3 = Limited use
** Requires all three frequencies
*** Requires two of the three frequencies

Table 7

ESGP Millimeter Wave Remote Sensing
Environmental Parameters with
Resolutions for Frequencies Above 60 GHz
Using a 20-meter Antenna
(Ordered beginning with highest priority)

Environmental Parameter	Freq (GHz)	Resolution (km) Goal	Resolution (km) with 20-m Ant	Overall Merit*
Precipitation over land	90	1-30	6.8	1
	157	1-30	3.9	1
	220	1-30	2.8	1
Water vapor profile Profile	183	5-20	3.4	1
Temperature profile	118	5-30	5.2	1
Cloud base height	95 active	5-25	N/A	1
Cloud water content** (over ocean)	90	1-30	6.8	1
	157	1-30	3.9	1
	220	1-30	2.8	1
Atmospheric winds profile	90-140 active	50	N/A	1
Cloud water content** (over land)	157	1-30	3.9	1
	270	1-30	2.8	1

* 1 = Very useful; 2 = Acceptable; 3 = Limited use
** Requires all three frequencies

In order to retrieve the environmental parameters one generally requires brightness temperature measurements at multiple frequencies and polarizations. The panel noted that the antenna beams associated with each frequency for an environmental parameter need not be concentric. The antenna beams can be displaced provided the same area is illuminated within the temporal requirements (usually on the order of seconds).

2.2 Spatial and Temporal Resolutions

Ground resolution goals were set by the panel for each of the environmental parameters and are expressed as a range of values. Resolutions equal to the smallest number would yield data with the most applications to the remote sensing community. The resolutions were computed for three reflector diameters (20m in Table 4, 25m in Table 5, 40m in Table 6) and were based on half-power beamwidth, HP, computed as follows [5]:

$$HP = 1.14\ \lambda/D \quad \text{[radians]} \qquad (1)$$

where λ = wavelength and D = diameter. The corresponding ground resolution at nadir from GEO is

$$R = 35{,}865 \tan(HP) \qquad \text{[km]} \qquad (2)$$

The frequency dependence of the spatial resolution at nadir for each antenna size is plotted in Fig. 3. For off-nadir operation the projection of the beam footprint on the spherical earth will elongate, increasing the resolution value. Computed values for this effect are plotted in Fig. 4. In all cases considered, ideal antenna performance is assumed; that is, performance degradation due to antenna surface distortions from thermal

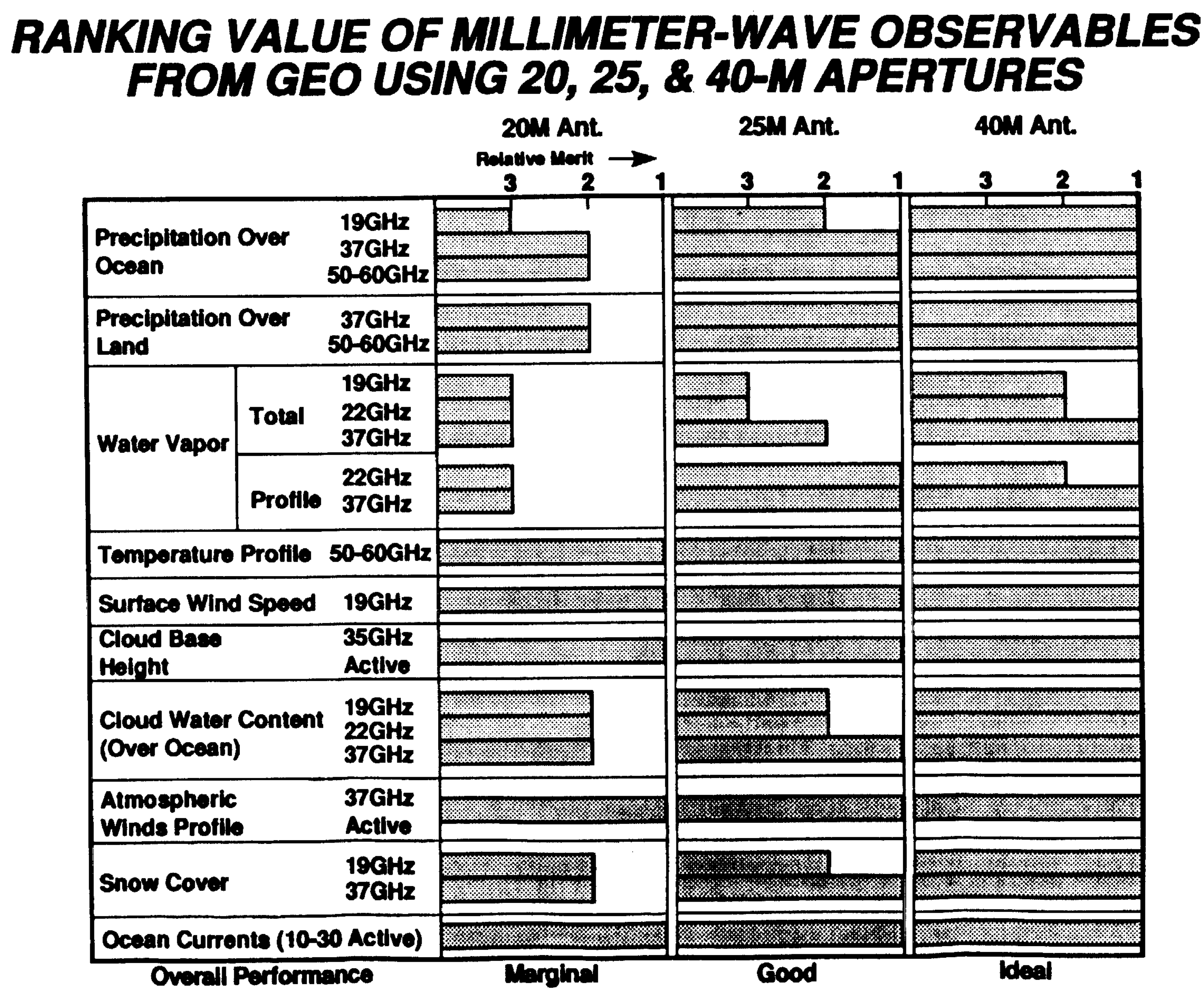

Figure 2. Rankings of usefulness (1-highest) of millimeter-wave observables from GEO using 20, 25, and 40-m apertures. See "Overall Merit" column in Tables 4 to 6.

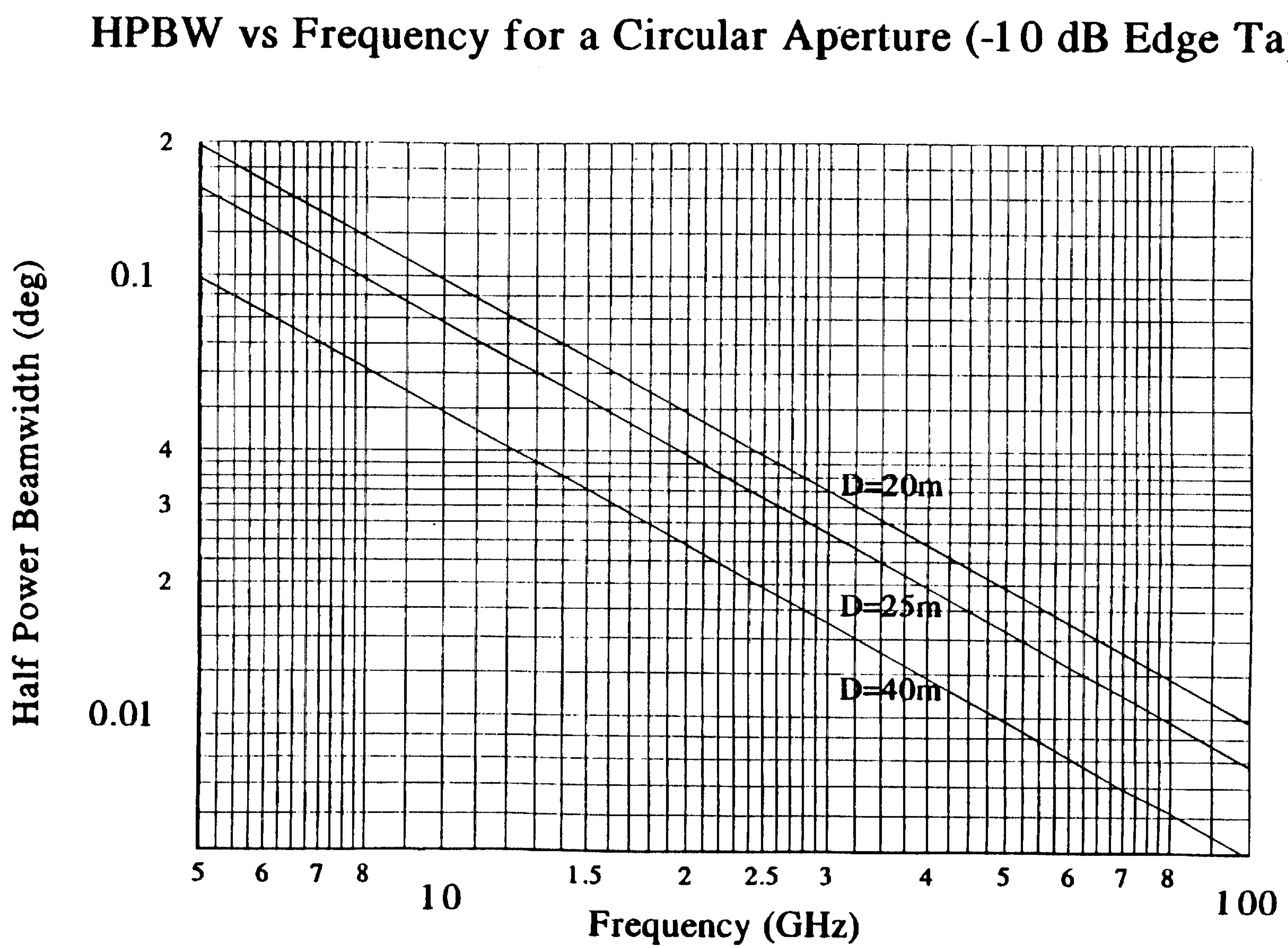

Figure 3. Half-power beamwidth as a function of frequency for various antenna diameter values, D.

gradients, control/pointing movements, etc. are neglected.

Tables 4 through 6 indicate that the lowest frequency proposed for GEO passive microwave remote sensing will be 19 GHz. From Figure 3 this frequency corresponds to a 0.05° half-power beamwidth with a 20-m antenna, 0.04° with a 25-m antenna, and 0.026° with a 40-m antenna. From Figure 4 we see that the 25-m and 40-m antennas will not degrade appreciably in ground resolution for latitudes up to about 40°. Relative to the 40-m antenna the 20-m antenna will suffer an increase in spot size (from 30 km to 50 km) for a scan to 40° latitude. Resolution degrades significantly for latitudes above 60°. However, the main environmental parameter there is sea ice which exhibits slow temporal variations; furthermore, LEO satellites provide good coverage over polar regions.

The spatial resolution requirements are rather challenging and are tied to temporal resolution. As a baseline, the SSM/I radiometer system operating from LEO has a geometric resolution equal to 12.5 to 50 km on a six hour revisit time (see Section 3.2). The advantage from GEO is that significantly better temporal resolution is possible with fewer satellites. This, in turn, requires fine spatial resolution because small time scale phenomena tend to have fine spatial scale behavior; intense rain cells are a good example. The fine spatial resolution from GEO then requires a large antenna.

Mesoscale phenomena require observation of precipitation, temperature, and water vapor and therefore were ranked high on

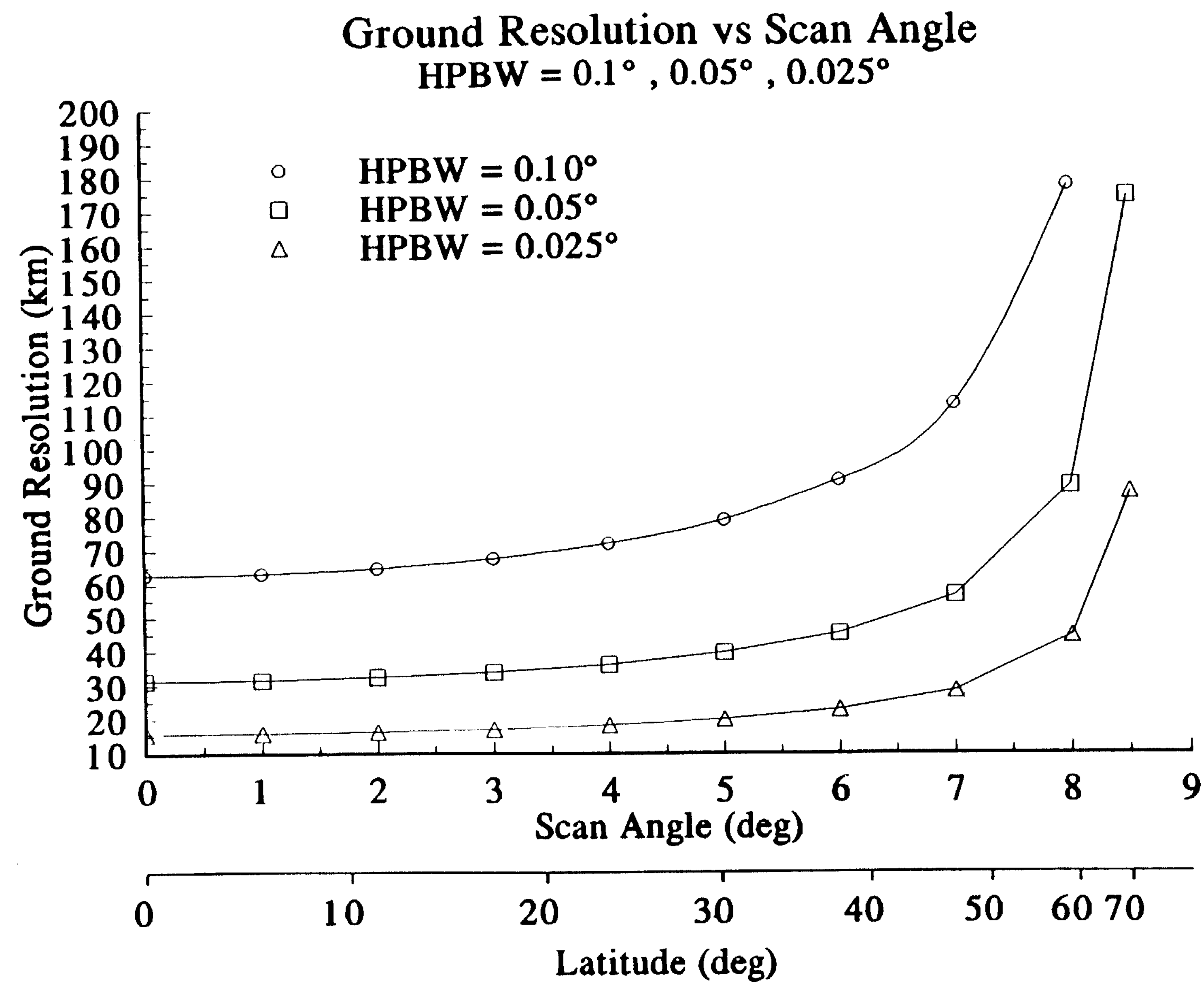

Figure 4. Ground resolution as a function of off-nadir observation angle and half-power beam width. Also shown is latitude angle for the case of scan along a fixed longitude.

the listings. Surface winds and precipitation go hand in hand and are important to the Navy. Surface winds are also very important for hurricanes and are needed on an hourly temporal scale. LEO platforms may not pass over storms during their early stages of development. Cloud water drives precipitation, thus both parameters are important. The relatively short temporal scale of precipitation is better suited to measurements from GEO.

2.3 Sensor Radiometric Accuracy and Precision

In order to provide quantitatively useful data, the LSA system, including all associated radiometers and receivers, must achieve a desired level of absolute radiometric accuracy and precision. The overall utility of an LSA instrument will depend not only on the achievable spatial resolution, but on the absolute accuracy and precision of the data. The accuracy and precision of the sensor data records directly determines, in conjunction with the retrieval algorithms, the final accuracy and precision of the retrieved environmental parameters.

The absolute accuracy of the instrument reflects the calibration requirements and knowledge of and compensation for systematic effects. The precision requirement reflects the instrument noise, quantization level, random and retrieval errors. The precision is related to the instrument sensitivity and signal-to-noise ratio.

While it was not appropriate for the panel to derive detailed requirements for precision and accuracy, the panel did discuss estimates for the precision of the measured environmental parameters. These values were specified in terms of a minimum detectable temperature difference, ΔT, and are listed in Table 8.

The issue of calibration was discussed and considered to be of significant technology issue for the LSA that requires further study. The panel did not arrive at any specific recommendations regarding either the LSA instrument accuracy or retrieved environmental parameter accuracy. However, for comparison, values given in the DMSP Block 6 Statement of Work (SOW) [6] and the paper by Gasiewski and Staelin [7] are given in Table 9. Note that the accuracies and precisions specified by DMSP are on the retrieved environmental parameters, and therefore have the same units as the parameter itself. The accuracies specified by Gasiewski and Staelin are for the radiometric measurement capabilities of the sensor and consequently are expressed in terms of brightness or apparent temperature.

2.4 Beam Efficiency

Beam efficiency (BE) is the fraction of total radiated power contained in the main beam. It is important to maximize BE to reduce stray noise pickup from the side lobes. Although antenna beam efficiency calculations are available, the GEO earth-observing microwave radiometers must be evaluated for their unique parameters. Figure 5 shows BE values computed for a specific case as requested by the panel. The BE calculations are based on the following parameters:

HP = 0.10°

Main beam extent = 2.5 HP

Table 8

ESGP Millimeter Wave Remote Sensing
Environmental Parameters with Required Radiometric Sensitivities

Environmental Parameter	Minimum Radiometric Temperature Resolution, ΔT
Precipitation over ocean	1 K
Precipitation over land	1 K
Water vapor	
Total	0.5 K
Profile	0.25 K
Temperature profile	0.25 K
Surface wind speed	0.5 K
Cloud water	0.5 K
Snow cover	1 K

Table 9

Comparison of Absolute Accuracy Requirement for Microwave Remote Sensing

Environmental Parameter	Absolute Accuracy (DMSP)	Radiometric Accuracy ([7]) (K)
Precipitation (over ocean & land)	5 mm/hr[1,2]	1.5 - 3
Water vapor		
Total	1-3 kg/m^2	
Profile	± 20%, 2 gm/kg over ocean ± 35%, 3.5 gm/kg over land	0.5 - 1.5
Temperature Profile	2 - 7 K	0.5 - 1.5
Surface Wind Speed	2 m/sec	N/S
Cloud Water Content (over ocean)	0.1 kg/m^2	0.5 - 1.5
Atmospheric Wind Profile	5 m/sec ± 20°	N/S
Snow Cover	≤ 0.5(HSR)[3]	N/S
Ocean Currents	N/S	N/S

N/S = not specified
1. Based on three year Block 6 study of current DMSP Block 5D capabilities.
2. Over the range of 0 to 25 mm/hr.
3. Horizontal Spatial Resolution.

Zero side lobes beyond the earth limb (±8.5°)

Two cases of side lobe envelopes:

Constant and FCC-type (25 log θ).

The results are slightly pessimistic in that there are no side lobe nulls; this gives rise to an effective increase of no more than 3 dB in the side lobes over the corresponding case with nulls.

A specification on beam efficiency is difficult to develop. Table 1 lists greater than 90%; the specific value needed may vary with the parameter to be measured. Contributions off of the earth can be of less significance because the sky background is relatively uniform and, as the antenna scans, there will be little change in unwanted noise from the off-earth sidelobes. Appendix B discusses the effects of various off-earth contributions. There it is shown that a BE of 96.3% must be maintained if an off-earth sidelobe noise contribution of 0.1 K is to be achieved. Table 10 lists the beam efficiencies for SSM/I as inferred from measurements; these vary from 91 to 96.5% [9]. The same definition of beam efficiency (i.e. 2.5 HP) was used in determining beam efficiencies in this table.

2.5 Summary

Table 4 indicates that a 20-m antenna provides marginal performance. On the other hand, Table 6 shows that a 40-m antenna affords excellent performance. Since a 40-m antenna is an extremely challenging GEO space structure, the panel took a closer look at more modest structures. Table 5 shows that a 25-m

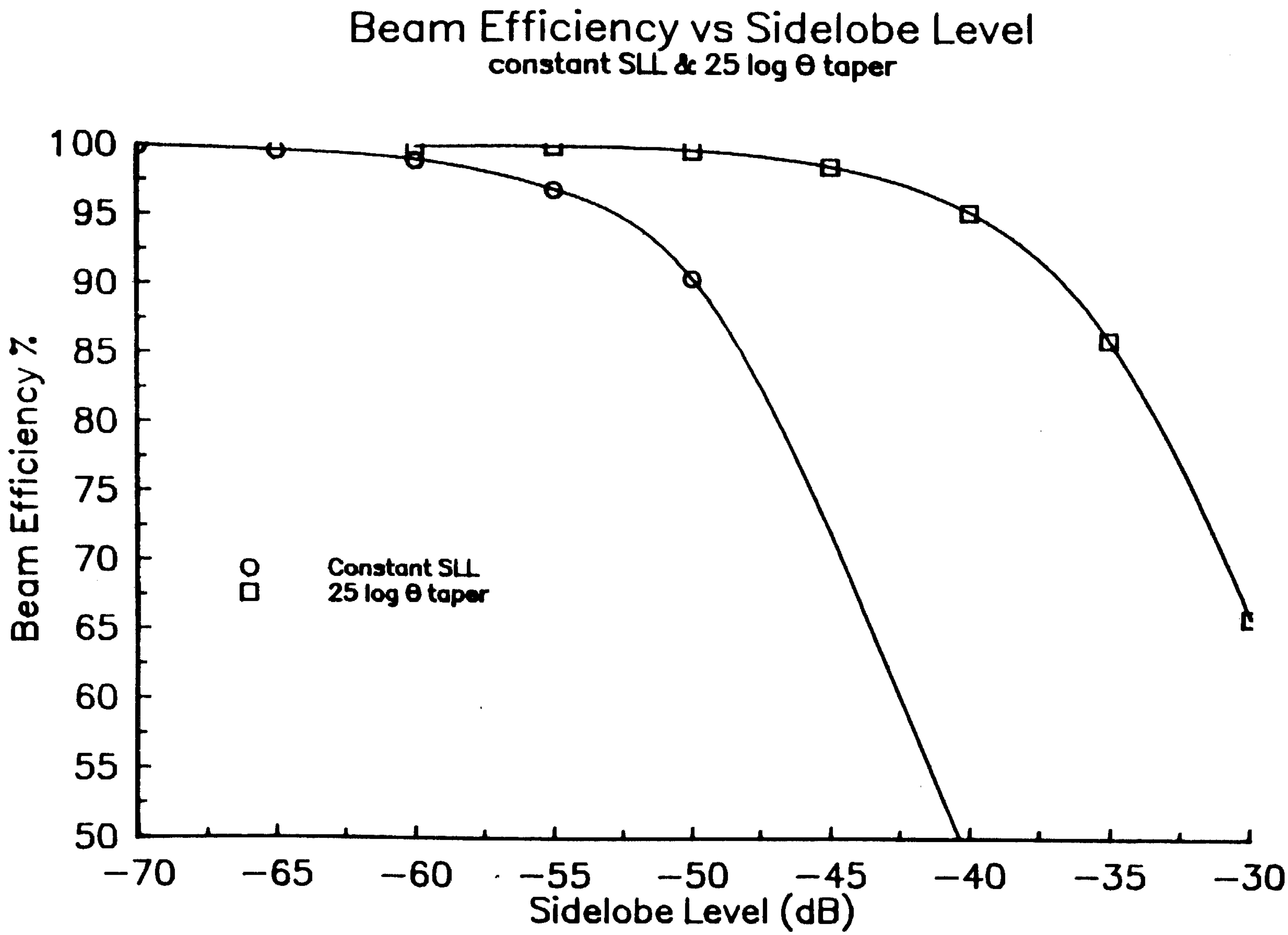

Figure 5. Beam efficiency computed for a 0.1° half-power beamwidth antenna with no sidelobes beyond the earth limb (± 8.5°) and for two cases of sidelobe taper near the main beam.

Table 10

Beam Efficiencies Based on Measured SSM/I (Antenna SN-002) Data. From [9]

Freq	Pol	Beam Eff (%)
19.35	V	96.1
19.35	H	96.5
22.235	V	95.5
37	V	91.4
37	H	94.0
85.5	V	93.2
85.5	H	91.1

antenna has very promising performance. Furthermore, the current LDA Project Phase II design approach could perhaps be stretched to achieve a 25-m design. At higher frequencies the 20-m antenna (see Table 7) is more than adequate; in fact, the JPL study recommended a 4-m antenna [2].

Table 11 summarizes the findings of the panel in quantitative terms. Increasing the aperture size from 20 to 25 m results in a performance improvement from the "marginal" to the "good" category. Although these terms are highly subjective, they reflect the panel's feeling that enough of the high priority remote sensing goals were met by this change to be of value to the scientific and operational communities. It should be noted that it is highly desirable to achieve the remote sensing goals with as small an aperture as possible. In addition to the need to erect and/or deploy this large antenna in space, there are the very difficult electromagnetic design goals of greater than 90% beam efficiency. Also, the scan requirement of 15° (hundreds of beamwidths) with a revisit time of 1 to 3 hours is very difficult to achieve with a large structure such as that being considered here. All of these factors were considered by the panel when deciding the merit of the various antenna sizes.

3. LARGE SPACE ANTENNA NEEDS OF FUTURE U.S. PROGRAMS

3.1 Overview

The ESGP portion of Mission to Planet Earth formed the model application for the panel. Therefore, the results presented in Chapter 2 are directly applicable to future ESGP efforts.

Table 11

Design Goals for a Large Space Antenna for Remote Sensing from GEO

Parameter	Requirement and/or Specification	
1. Frequency		
Range	19-60 GHz	
Channels	19, 22, 37, 50-60* GHz	
2. Aperture Size	20 m	Marginal
	25 m	Good
	40 m	Ideal
3. Radiation Pattern		
Beam efficiency	> 90%	
Side lobes	< -14 dB	
4. RMS surface accuracy (main & subreflector)	0.1 mm	
5. Dual polarization	19,37 and one channel in 50 to 60 GHz	
6. Portion of full disc to scan		Revisit time
Mode 1 - full disc (± 7.5°)		1-3 hrs
2 - limited scan (± 2.4°)		1 hr
3 - stare		dwell on small region(s)

* Multiple channels similar to AMSU and DMSP

In addition to research missions such as ESGP, which include microwave remote sensing instruments, there may well be operational programs in the next century that would use large antennas in GEO if the technology were available. Primary among these are both civilian (NOAA) and military (DMSP) meteorological applications. The military also has needs for large space antennas such as envisioned in space-based radar and/or radiometers.

In addition to radiometry and radar, there are also needs for large space antennas for communications. Original concepts, for example, for the Land Mobile Satellite System reflector antenna at L-band were envisioned up to 50m and larger.

There is also activity in the area of large space antennas in Europe and Japan. Most concept structures are fully deployable.

3.2 Defense Meteorological Satellite Program

The purpose of this section is to provide a bridge between the microwave remote sensing capabilities considered by the LSA panel and the current and future operational capabilities which DMSP provides the US Armed Forces (Air Force, Navy/Marines and Army). This bridge is also intended to provide a comparison of the DMSP requirements with those considered for the LSA, and assess the potential utility of the LSA for DMSP. A detailed status of DMSP systems is given in Appendix C.

The LSA utility to DMSP is assessed in the following terms. Given that such a platform were available with at least the spatial resolutions provided by the 25-m class antenna (see Table 5), would the LSA system provide data of use to DMSP? To answer this question a comparison will be made between the LSA environmental parameters, and the DoD requirements for environmental and meteorological parameters [6,8]. Issues such as how the data from the LSA system would be provided to, and processed by, the central sites (e.g. Air Force Global Weather Central), although important, are not considered at this level of comparison.

An important parameter to consider when comparing DMSP with the LSA is the refresh rate, which is defined as the ". . . average time interval between consecutive measurements of a given parameter for the same geo located element of spatial resolution . . ." [6]. The DMSP requirement is for a 6 hour refresh rate.

Another key issue in the comparison of the DMSP system with the LSA is that of temporal resolution. The Block 6 program has the requirement to maintain at least the refresh rate that Block 5D provided, i.e., 6 hours average and not to exceed 18 hours for the microwave measurements. Of course, significant improvements in the refresh rate for some of the microwave environmental data parameters required by DMSP would be extremely useful. As a general guide to DoD environmental data requirements the MJCS 154-86 document [8] provides a list of environmental parameters desired by each service and specific requirements on these measurements (precision, accuracy, dynamic range, area coverage, refresh rate, . . ., etc.). Some of the environmental parameters listed in the MJCS 154-86, which can be measured with passive microwave sensors, are specified with refresh rates as short as 1 hour, which is significantly less than the maximum of 6 hours.

It should be remembered that the DMSP requirements, while setting the MJCS requirements as a goal, must take into account many constraints, cost being one of the most important. Thus it was considered useful to provide a comparison between the LSA and DMSP in order to assess the potential for such a system to provide improved data to an operational system. However, the high revisit rate possible with the LSA (see Table 11) may have the potential for meeting the DoD environmental monitoring requirements.

The assessment of the utility of the LSA to provide additional data for DMSP (incorporation into AFGWC or FNOC) is based on the potential for significantly improved temporal resolution and the capability to stare. The improved temporal coverage which results in higher refresh rates (much less than the 6 hours for DMSP) could have a significant impact on weather prediction, observations of storm development and storm tracing. The LSA could provide these higher refresh rates over that portion of the earth's disk which was visible, and could additionally provide even higher refresh rates in a stare mode over a much smaller region (e.g., tactical theater) for observing the evolution of severe weather and in general observing the temporal variation of the environmental parameters of interest. The LSA could also provide very good spatial coverage near the equator and lower latitudes, also with a high refresh rate. This could provide data for enhancing the capabilities of DMSP for monitoring the birth and evolution of tropical storms.

In addition to the temporal sampling of the LSA, it is important to consider the requirements on horizontal spatial resolution and measurement precision and accuracy. Table 12 provides a comparison between the spatial resolution requirements specified in the MJCS 154-86, the DMSP Block 6 SOW and the estimated capabilities of the LSA 25-m class antenna (taken from Table 5). Several points need to be made regarding this comparison. The spatial resolutions specified for the LSA are nadir footprints for half power beamwidths, whereas the DMSP requirements are for the retrieved environmental parameter horizontal spatial resolution. In spite of this difference there is some overlap between the various spatial resolution requirements. The DMSP requirements are typically in the range of 10 to 25 km, whereas the LSA covers the range from 10 to 35 km (all of these values are frequency dependent). The small differences in spatial resolution in specific cases do not appear to be large enough to render the LSA data useless to DMSP. Given the potential for high refresh rate, it appears that the LSA data could be quite useful for the applications discussed above.

The DMSP requirements also specify the measurement precision and accuracy for each retrieved parameter. The LSA study did not determine the required precision, and accuracy estimates can be taken from [7] for comparison. These values can be compared with the DMSP Block 6 requirements, and are given in Table 9 and 13. Note that the DMSP requirements for precision and accuracy are on the retrieved environmental parameters. The values specified

Table 12
Comparison of Spatial Resolution Requirements

Observable	f (GHz)	LDA (Goal/25m Ant) (km)	MJCS (km)	DMSP Blk.6 (km)
Precipitation over ocean	19 37 50-60	1-30/26 1-30/14 1-30/9	1-5	12.5-50(goal)
Precipitation over land	37 50-60	1-30/14 1-30/9	1-5	25 (goal)
Water vapor				
Total	18 22 37	5-20/26 5-20/22 5-20/14	10-100	50 (goal)
Profile	22 37	5-20/22 5-20/14	10-25	≤ 50
Temperature profile	50-60	5-30/9	10-25	≤ 50
Surface wind speed	19	10-50/26	1-25	50
Cloud water (CLWC)	19 22 37	1-30/26 1-30/22 1-30/14	10-25	50 (goal)
Atmospheric winds profile	37(A)	50/(n/a)	1-25	50 (Geostrophic)
Snow cover	19 37	1-30/26 1-30/14	10	50 (goal)
Ocean currents	10-30(A)	1-30/(n/a)	10-25	N/R

NOTE: Not all of the environmental parameters specified for the LSA are required by DMSP, in which case these are indicated by N/R.

for the LSA are the sensor radiometric precision and accuracy. The two sets of requirements are related by the specific retrieval algorithms used to obtain the environmental parameters from the sensor data; however, it is not a simple matter to relate these without specifying the retrieval algorithms. Also, many of the retrieval algorithms rely on multiple channels of the microwave radiometer so that the error in the retrieved parameter will depend on the precision and accuracy of each of the channels concerned. The reader should therefore use these tables as a guide in assessing whether a particular retrieval algorithm used with the LSA data (given its accuracy and precision requirements) would meet the DMSP requirements. Using the existing algorithms for retrieval of DMSP environmental parameters from the LEO spacecraft one could estimate the errors in the retrieved parameters using the LSA data, however, this would provide only an approximate sense of the utility of the LSA data (this was not attempted for the LSA panel study). In actuality, one would want to optimize the retrieval algorithms for the specific LSA data sets during a complete validation phase.

To conclude, it appears that many of the environmental parameters of interest to DMSP could be measured by the LSA with a horizontal spatial resolution which is compatible with the DMSP requirements. In terms of the improved temporal sampling resulting in much higher refresh rates than the current DMSP, the LSA offers a significant capability. The issues of measurement precision and accuracy capabilities from such a system, while

Table 13
Comparison of Measurement Precision Requirements

Environmental Parameter	LSA (K)	DMSP [6]
Precipitation over ocean or land	1.	1 mm/hr
Water Vapor		
Total	0.5	0.1 kg/m^2
Profile	0.25	TBD
Temperature Profile	0.25	0.5 K
Surface Wind Speed	0.5	0.1 m/sec (ocean)
Cloud Water Content (over ocean)	0.5	0.05 kg/m^2
Atmospheric Wind Profile	N/S	0.1 m/sec (Geostrophic)
Snow Cover	N/S	TBD
Ocean Currents	N/S	N/R

NOTE: The LSA values are for the sensor radiometric precision and are consequently given in units of brightness or apparent temperature. The DMSP values are for the precision of the retrieved environmental parameter and therefore have the same units as the parameter.

N/S - not specified, N/R - not required, TBD - to be determined.

within the realm of feasibility, require more detailed study to fully assess the compatibility with DMSP.

4. RECOMMENDATIONS FOR TECHNOLOGY DEVELOPMENT

There were a number of areas where the Panel felt that further technology development was required in order to achieve the successful operation of a 25-m class antenna remote sensor in GEO orbit. These are summarized in Table 14. There are three broad categories addressed here - Antenna Technology, Mechanical/Structures, and Sensors.

The table lists the technology items requiring further development, the considerations as to why these items are important to the remote sensing mission, and the particular problems that need to be resolved. For example, the first item is "pursue 25- and 40-m designs". The reasons for doing this are the important science benefits relative to the costs and risks involved with these aperture sizes. The primary problems that still have to be resolved with these large antennas are the size of the launch package and the subsequent deployment in space. It should be noted that nearly all of the antenna technology items pose very difficult problems for the antenna designer and all possible approaches should be considered in solving them.

The mechanical/structures category mostly relates to the spacecraft or the entire mission. Some of these problems are not unique to the large space antennas situation; however, they may be magnified given the degree to which it is necessary to control the deformation of the large antenna.

Table 14

RECOMMENDATIONS FOR TECHNOLOGY DEVELOPMENT

Item	Considerations	Problems
1 Antenna technology Pursue 25-m and 40-m designs	Science benefit vs. cost & risk	Launch package Deployment in space
Surface accuracy	Reduced surface error for high BE	What BE value is required? High accuracy in central portion of antenna for high frequencies On-orbit determination/correction of pattern and surface accuracy
Scanning	Essential for global coverage	Mechanical slewing gives structural design problems and polarization purity crosstalk
Array feeds	Electronic scanning	Hardware readiness Calibration
Pointing	Essential for geophysical event location	Sensing & control of error (bias & random)

	Item	Considerations	Problems
2	Mechanics/Structures		
	Mechanical slewing	Simplified EM design	Bus disturbances and momentum compensation Long duration effects of continual continual slewing (3-5 years for M. to P. Earth)
	Active control of antenna system	Distortion compensation Surface reshaping	Non-space qualified technology Monitoring & control
	Power source	Solar arrays & power loads vs. time	Potentially large power load
	In-orbit life	Mission viability	Material degradation In-orbit repair?
	Thermal effects	Full spacecraft	How to diss. heat?
	Launch	Single launch or multiple Titan IV? Deployable Erectable Hybrid	EM/Mechanical tradeoffs Transport to/from orbit
3	Sensors		
	Calibration	Long-term antenna changes	Antenna distortions and frequency of calibration Mechanical configuration for calibration Use of LEO beacon or earth base Spillover calibration
	Radiometer system	Relationship to antenna design	Calibration Design

The final category comprising "sensor calibration " is extremely important to the large space antenna program because of the importance of knowing the accuracy of the resulting remotely sensed environmental parameters. Without proper calibration, such questions cannot even be addressed. A further point here is the importance of calibration relative to the minimum detectable "signal" being measured by the sensor. Many geophysical features and/or events are very difficult to extract from radiometric data if the minimum detectable temperature change for a sensor is too high. This threshold is highly dependent upon accurate and repeatable calibration.

The panel did not rank or prioritize the technology development items.

5. REFERENCES

1. Garrett, L.B., editor, "Global Change Technology Architecture Trade Study," NASA TM-104128, 1991.

2. "Geostationary Microwave Precipitation Radiometer: Phase A Study Report" JPL Report JPLD-7428, May 1990.

3. Rogers, C.A., W.L. Stutzman, T.G. Campbell, and J.M. Hedgepeth, "Mission to Planet Earth Technology Assessment and Development for Large Deployable Antennas," International Astronautical Federation (Dresden, GDR), Oct. 1990.

4. Hollinger, J.P., "Introduction to Special Issue on DMSP Calibration and Validation of the SSM/I," IEEE Trans. Geoscience & Remote Sensing, Vol. 28, No. 5, pp. 779-80, 1990.

5. Stutzman, W.L., and G.A. Thiele, Antenna Theory and Design, John Wiley and Sons: New York, p. 421, 1981.

6. DMSP Block 6 Draft RFP (Preliminary), F04701-89-R-0029, DMSP Block 6 Risk Reduction (Phase 2), USAF Space Systems Division, Los Angeles, 13 March, 1991. (See note below)

7. Gasiewski, A.J., and D.H. Staelin, Science Requirements for Passive Microwave Sensors on Earth Science Geostationary Platforms, NASA Conference Publication 3040, Proc. of the Workshop on Earth Science Geostationary Platform Technology, NASA Langley, 1988.

8. Memorandum, Joint Chiefs of Staff, DoD, "Military Requirements for Defense Environmental Satellites," MJCS 154-86, 1 Aug., 1986. (See note below)

9. Hollinger, J.P., J.L. Pierce, & G.A. Poe, "SSM/I Instrument Evaluation," IEEE Trans. Geoscience & Remote Sensing, Vol. 28, No. 5, pp. 781-790, 1990.

A-1. Ulaby, F.T., R.K. Moore, and A.K. Fung, Microwave Remote Sensing, Vol. 3, Addison-Wesley, Reading, MA, 1982.

A-2. Waters, J.W., "Absorption and Emission by Atmospheric Gases," in Methods of Experiments Physics, Vol. 12, Part B, (M.L. Meeks, Ed.) Academic Press, New York, 1976.

A-3. Becker, G.E. and S.H. Autler, "Water Vapor Absorption of Electromagnetic Radiation in the Centimeter Wavelength Range," Phys. Rev., Vol. 70, pp. 300-307, 1946.

A-4. Dryagin, Yu. A., A.G. Kislyahov, L.M. Kukin, A.I. Naumou, and L.I. Fedoseer, Sov. Radiophys, Vol. 9, pg. 1078, 1966.

A-5. Askue, J.I.H. and B.G. Skoog, "Atmospheric Water Vapor Profiling by Ground Based Radiometry at 22 and 183 GHz," IEEE Trans. Geoscience & Remote Sensing, Vol. GE-21, pp. 320-323, 1983.

A-6. Ruf, C.S. and C.T. Swift, "Atmospheric Profiling of Water Vapor Density with a 20.5-23.5 GHz Autocorrelation Radiometer," J. Ocean, Atm. Tech., Vol. 5, pp. 539-546, 1988.

B-1. Silver, S., Microwave Antenna Theory and Design, McGraw-Hill, New York, 1949.

Note: References 6 and 8 are available from the Aerospace Corporation or U.S. Air Force Space Systems Division (SSD/MW):

Dept. of the Air Force
Space Systems Division
Headquarters
Los Angeles Air Force Base
POB 92960
Los Angeles, CA 90009-2960

6. Appendix A: Water Vapor Profiling Using the 22 GHz Radiometer Data

The atmospheric emission T_A received by an upward-looking radiometer is described by the following form of the radiative transfer equation:

$$T_A(f) = \int_0^{\infty} T(h)\, K_e(f,h)\, e^{-\int_0^h K_e(f,z)\,dz}\, dh$$

where f is the electromagnetic frequency, $K_e(f, h)$ is the attenuation coefficient of the atmosphere at frequency f and altitude h, and T(h) is the true atmosphere temperature profile. This equation is quite general and adequately describes the emission process over the entire microwave/millimeter wave bands. The attenuation coefficient is a function of several atmospheric parameters, including water vapor density. A great deal of activity has transpired over the past 30 years to extract information such as temperature and, lately, water vapor profiles. Although the algorithms are somewhat involved, the essence of the approach is to collect data at several frequencies about a resonance line and then proceed with inverting the integral equation.

Figure A-1 shows a plot of the water vapor attenuation as a function of frequency. This curve indicates that there is a strong line at 183 GHz, and a much weaker one at 22 GHz. Usually, one is driven towards choosing the stronger emission line. However, there are problems with choosing the stronger line for water vapor profiling. First of all, the attenuation is so great

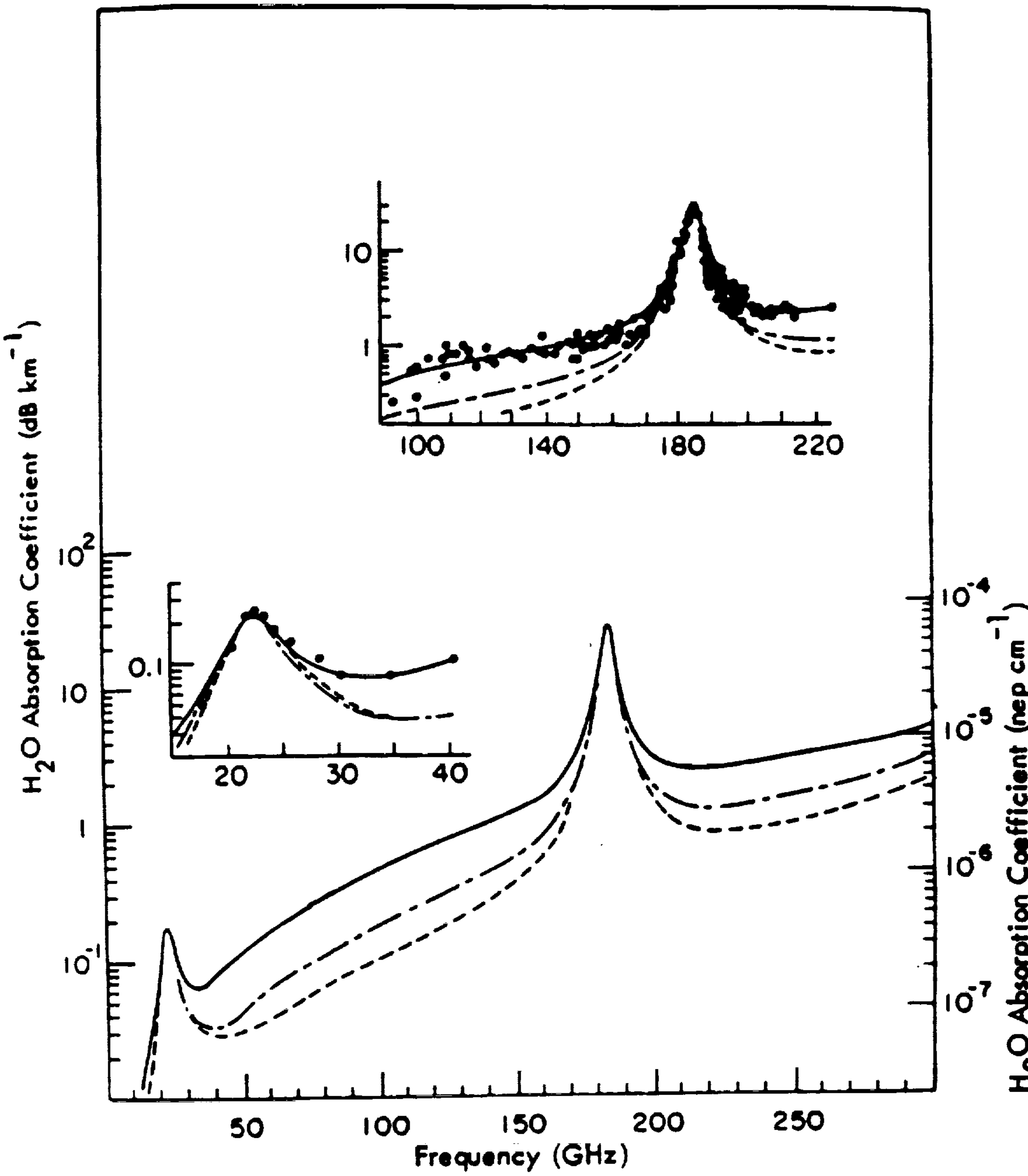

Fig. A-1. Measured and calculated water-vapor absorption (from Waters [A-2]). Calculations are shown for the Van Vleck-Weisskopf line shape (---), the Gross line shape (←--→), and the Gross line shape with the added empirical correction discussed in the text (——), with T=300 K, P=1013 mbar, and ρ_v = 7.5 g m^{-3}. Points in the 20-40 GHz inset are measurements of Becker and Autler [A-3], where T=318 K, P=1013 mbar, and ρ_v=10 g m^{-3}. Points in the 100-200 GHz inset are measurements quoted by Dryagin et al. [A-4], where T=300 K, P=1013 mbar, and ρ_v=7.5 g m^{-3}.

that emission from the upper layer of the troposphere will not be observed. Furthermore, since the value of the weighing functions decrease with increasing altitude as shown in Figure A-2 there is less radiation energy available as we depart from resonance in order to reduce surface attenuation. Also, since the line is strong, retrieval errors may be introduced by unknown values of true air temperature at the various altitudes.

At 22 GHz the water vapor line is weaker, and (as also shown in Figure A-2) frequencies can be selected which will result in increasing values of the weighing function with increasing altitude. As another consequence of the weaker line, the radiative transfer equation can be linearized such that

$$T_A(f) \approx \int_0^\infty T(h)\, K_e(f,h)\, dh$$

Reference to Ulaby, Moore, and Fung [A-1] shows that $K_e(f, h)$ is directly proportional to the water vapor density, so that inversion is nearly a linear process. Finally, deviation from the true air temperature profile from an input test profile will have a relatively small effect because the product $K_eT(h)$ is also small.

In order to assess the capability of water vapor profiling using the 22 GHz line, an autocorrelation radiometer was fabricated at the University of Massachusetts and later tested in the field. A block diagram of the system is shown in Figure A-3, and is actually comprised of two radiometers, differing by addition of a variable time delay $\Delta\tau$ in one of the channels. Data are

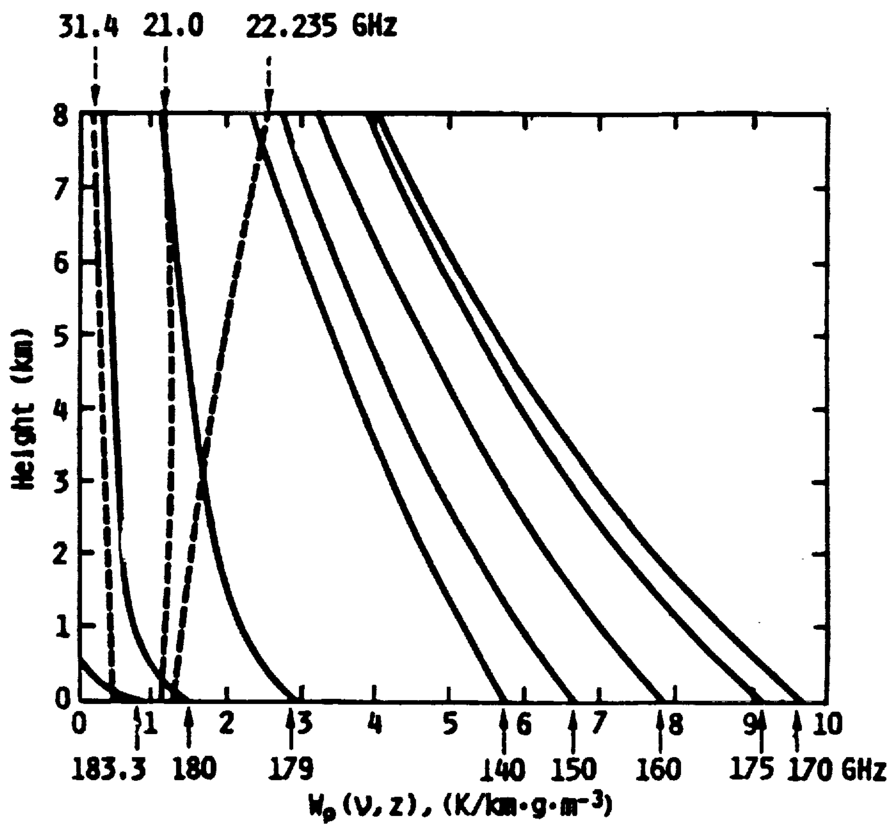

Fig. A-2. Weighting functions for frequencies around the 22.235 GHz line (---) and the 183.31 GHz line (—) (from Askue and Skoog, [A-5]).

collected over a range of 64 time delays and Fourier transformed to obtain 64 values of $T_A(f)$ in the frequency domain. This brightness temperature spectrum is used to generate the water profiles. One example is Figure A-4, where a comparison is made with a radiosonde measurement. Although 64 channels are clearly much more than are needed from the viewpoint of independent measurements, the redundant channels still have value in reducing measurement noise. The noise reduction is a very important consideration in maintaining stability of the inversions.

It should be noted, however, that the actual use of spectral measurements near 22 GHz to infer the water vapor profile has not been extensively demonstrated from space.

7. APPENDIX B: Sidelobe Contributions to Beam Efficiency from GEO

In order to meet the sensitivity requirements for all spots, constraints on the antenna pattern are necessary. These can be discussed by defining five angular regions, as in Fig. B-1:

1) **Main lobe.** The main lobe region includes all angles within the first pattern null, and subtends ~ $3.26\lambda/D$ radians for an aperture of diameter D with linear field illumination taper. In this case, the peak main lobe gain G_M is approximately 0.75 $(\pi D/\lambda)^2$, or G_M = 102.1 - 20 log R dBi, where R is the 3 dB equatorial footprint (in km). An aperture efficiency of 75% has been assumed [B-1]. Thus, for resolutions R of 2 to 20 km, the required main lobe gains are 96 to 76 dB, respectively.

2) **Near-sidelobes.** The near-sidelobe region is defined to be the angular region within approximately 10 to 15 beamwidths of

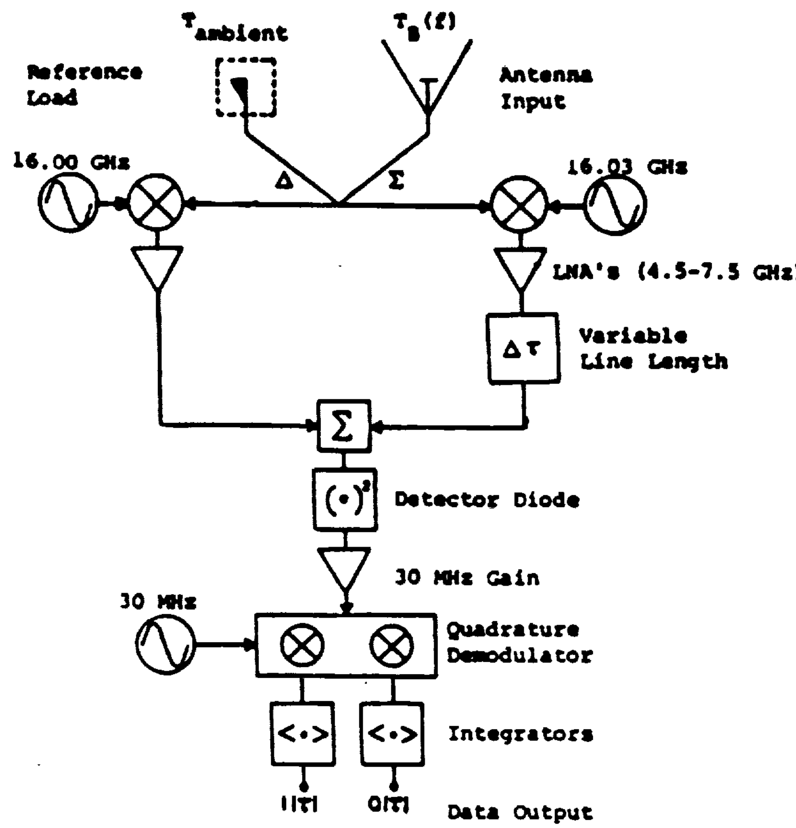

Fig. A-3. CORRAD hardware schematic. The brightness temperature spectrum is determined indirectly, via measurements of the autocorrelation of the thermal noise. The autocorrelation is sampled by cross correlating the voltage time series at the antenna with a time delayed version of itself. From [A-6].

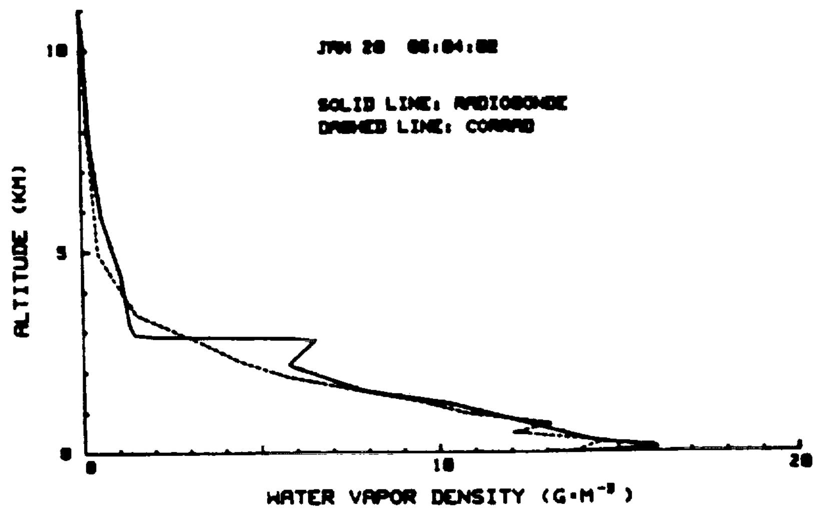

Fig. A-4. Radiosonde profile vs. CORRAD inversion. The radiometer spectrum can be inverted using the integral weighting functions to estimate the vertical profile of the water vapor density which generated that spectrum. Relatively fine vertical structure such as the vapor density inversion at 2.5 km is smoothed in the radiometer estimate because of the correspondingly smooth nature of the integral weighting functions. The initial vertical lapse rate (below 2 km) is, however, tracked with much higher accuracy by the radiometer's profile. From [A-6].

the main lobe, but not including the main lobe. Some enhancement of the raw image might be achieved via deconvolution of the main and near-sidelobe antenna pattern.

3) **Limb sidelobes.** The limb sidelobe region is the angular region (outside of the near sidelobe region) containing all angles which cross the Earth's limb during a full disk scan. The sidelobes in the limb region will alternately view cold space (2.7 K) and the Earth's disk (~ 250 K), depending upon the particular spot being observed. The limb-sidelobe region subtends an angle of 17.4°, or 0.072 steradian.

4) **Ecliptic sidelobes.** The ecliptic region is defined to contain all angles which directly view the sun or moon. Thus, the ecliptic region is a angular strip bounded at the elevation angles $\epsilon = \pm 37.9°$, and symmetric about the ecliptic plane. The solid angle subtended is 2.6 steradians. The sun can be modelled as a blackbody of temperature between 6,000 K (at 220 GHz) and 10,000 K (at 6 GHz), and subtends an angle of 0.53°. (The moon subtends nearly the same angle, but exhibits a brightness temperature less than 400 K, and hence is much less significant.)

5) **Ortho-ecliptic sidelobes.** The ortho-ecliptic region is the complement of the ecliptic region, and contains all angles which never directly view the sun, moon, or Earth. This region subtends 9.9 steradians.

By requiring the maximum antenna temperature contribution from the limb sidelobes to be less than 0.1 K, a constraint is placed on the limb gain G_L. This can be met by requiring that G_L

remain below -11.5 dBi. Under this constraint, the limb region efficiency is less than 0.04%.

Table B-1

Antenna pattern efficiencies for the various angular regions.

Angular Region		Constraint	Efficiency (%)
Main-beam	M		95.8-94.3
Near-sidelobe	N		0.5-2.0
Limb-sidelobe	L	$G_L \leq -11.5$ dBi	0.04
Ecliptic	E	$G_E \leq -14.3$ dBi	0.77
Ortho-ecliptic	$E_\perp$	$G_{E\perp} \leq -14.3$ dBi	2.93

Within the ecliptic region, all radiometric fluctuations due to the passage of the sun through the antenna sidelobes should remain less than 0.1 K. This is satisfied by requiring that all ecliptic sidelobes remain below 3 dB; this is a much less stringent requirement than for the limb sidelobes. However, if the total brightness contribution from cold space is to remain below 0.1 K, then the average ecliptic and ortho-ecliptic gains (G_E and $G_{E\perp}$) must be kept below -14.3 dBi. This requires a combined ecliptic and ortho-ecliptic efficiency of less than 3.7%.

From the constraints on G_L, G_E, and $G_{E\perp}$, the main lobe and near-sidelobe regions will require a combined efficiency greater than ~96.3% (Table B-1). The fraction of this contribution from the near-sidelobe region must be less than 0.5-2%, depending on the particular channel. This will insure that the instrument measures main lobe brightnesses to the required accuracy in the presence of strong brightness gradients due to, for example, glaciated rain cells, land-ocean boundaries, and horizontal temperature or water vapor structure. Deconvolution of the ecliptic, ortho-ecliptic, limb, and near-sidelobe contributions might allow slightly lower main beam efficiencies. However, deconvolution requires that the antenna pattern be known with great precision. Less restrictive constraints on the non-main beam contributions might be proposed, but at a loss in absolute accuracy.

8. Appendix C: DMSP Block 5D and Block 6 Systems Descriptions

The Defense Meteorological Satellite Program (DMSP) is designed to provide meteorological data to support Department of Defense (DoD) worldwide operations. The mission is to collect and disseminate, on a global basis, visible and infrared cloud data as well as various meteorological, oceanographic and solar--geophysical measurements. The data are delivered to Air Force Global Weather Central (AFGWC), Fleet Numerical Oceanography Center (FNOC) and real-time to worldwide tactical receiving terminals. It is expected that Block 5D (satellites S6 through S20) will continue to fulfill this mission to roughly the year 2005. After that time Block 6 will start, and fulfill this mission well into the next century.

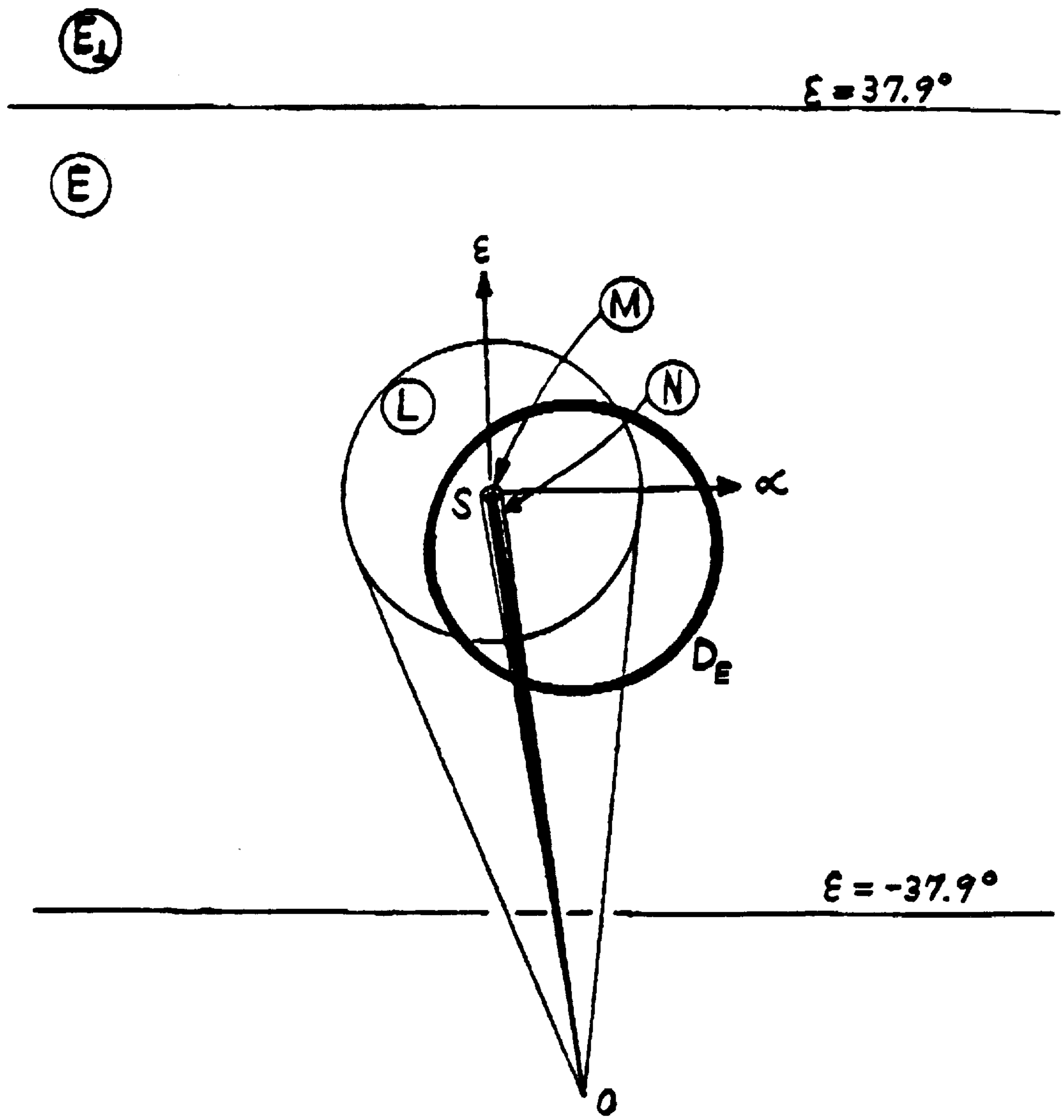

Fig. B-1. Angular regions for the specification of and beam efficiency and sidelobe levels. O is the sensor position, D_E is the outline of the Earth's disk, S is the observed spot, M is the main lobe region, N is the near-sidelobe region, L is the limb-sidelobe region, E is the ecliptic-sidelobe region, $E_\perp$ is the ortho-ecliptic sidelobe region, and ϵ and α define elevation and azimuthal directions relative to the antenna boresight.

Block 5D

The currently operational DMSP constellation (Block 5D-2) consists of 2 LEO spacecraft. Block 5D-2 will cover satellites S6 through S14. The satellites presently on orbit are F8, F9 and F10. The DMSP satellites are in sun-synchronous orbits, with a nominal altitude of 833 km, an inclination angle of 98.7 degrees and a period of roughly 101 minutes. The microwave instruments used on the 5D-2 satellites are: Special Sensor Microwave/Imager (SSM/I) (F8 and F10), Special Sensor Microwave/Temperature (SSM/T-1) (F8, F9 and F10). The SSM/I is a 7 channel, conically scanned microwave radiometer, with a scan angle of 45 degrees and local incidence angle of 53 degrees. The channels cover the frequency range from 19 to 85 GHz with both vertical and horizontal polarizations. The spatial resolution ranges from 12.5 km (85 GHz) to 50 km (19 GHz), with a swath width of 1395 km. The data rate from the SSM/I is 3.3 kbps. The SSM/I has recently undergone a substantial program of calibration and validation [4]. The environmental parameters which can be retrieved or derived from SSM/I data are: ocean surface wind speed, ice age, edge location and coverage, precipitation cloud liquid water, integrated water vapor. soil moisture, land surface temperature, snow water content, surface type and cloud amount [4].

The SSM/T consists of two cross track scanning sounders for determining atmospheric temperature (SSM/T-1) and moisture (SSM/T-2) profiles. There are 12 microwave channels in the frequency range of: 50-60 GHz (7 channels), 91.5 GHz (window channel), 150 GHz (low humidity windows) and 183 GHz (3 channels). The temperature sounder has a 32 second sweep and spatial resolutions in the range 250-480 km. The humidity sounder has an 8 second sweep with spatial resolutions from 60 to 120 km. The SSM/T swath width is 1500 km. The data rate is 468 bps.

The 5D-2 Block is due to undergo an upgrade to Block 5D-3, which will include enhancement to the microwave remote sensing capability. The microwave imaging and sounding capabilities will be combined into a single sensor, the SSM/IS (Special Sensor Microwave/Imager-Sounder). The SSM/IS will provide improved temperature and moisture sounding, extending the temperature profiles to 70 km. The SSM/IS is a conically scanned system (45 degree nadir angle) with 24 channels from 19 to 183 GHz. The spatial resolution is from 12.5 to 50 km with a swath width of 1707 km and a data rate of roughly 14.2 kbps.

Block 6

As previously mentioned, Block 6 will provide the DoD with meteorological data beyond the year 2000. In addition to the basic mission, as stated above, the goals of Block 6 are to increase the capability to meet unfulfilled operational requirements by providing an enhanced DMSP system within the Life Cycle Cost limits of the present system. This includes providing, as a minimum, the Block 5D-3 environmental data capability, incorporation of significant improvements to the environmental data, improvements to user and operator areas and a path for meeting both Army and Navy unique requirements. The Block 6 program completed the Phase 1 Concept Studies in 1990, and will be starting the Phase 2 Risk Reduction in 1991.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA CR-4408	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle The Science Benefits of and the Antenna Requirements for Microwave Remote Sensing from Geostationary Orbit		5. Report Date October 1991
		6. Performing Organization Code
7. Author(s) (Editors) Warren L. Stutzman, Gary S. Brown		8. Performing Organization Report No. EE SATCOM 91-1
		10. Work Unit No. 590-41-14-03
9. Performing Organization Name and Address Virginia Polytechnic Institute and State University, Bradley Department of Electrical Engineering, Blacksburg, Virginia 24061-0111		11. Contract or Grant No. NAS1-18471
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia 23665-5225		13. Type of Report and Period Covered Contractor Report
		14. Sponsoring Agency Code

15. Supplementary Notes

Technical Monitor: Lyle C. Schroeder
NASA Langley Research Center
Hampton, VA 23665-5225

Task 18 Final Report

16. Abstract

The primary objective of the Large Space Antenna (LSA) Science Panel was to evaluate the science benefits that can be realized with a 25-meter class antenna in a microwave/millimeter wave remote sensing system in geostationary orbit. The panel concluded that a 25-meter or larger antenna in geostationary orbit can serve significant passive remote sensing needs in the 19 to 60 GHz frequency range, including measurements of precipitation, water vapor, atmospheric temperature profile, ocean surface wind speed, oceanic cloud liquid water content, and snow cover. In addition, cloud base height, atmospheric wind profile, and ocean currents can potentially be measured using active sensors with the 25-meter antenna. Other environmental parameters, particularly those that do no require high temporal resolution, are better served by low Earth orbit based sensors.

17. Key Words (Suggested by Author(s)) large aperture antenna, geostationary orbit, science benefits	18. Distribution Statement unclassified - unlimited, subject category 43

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
unclassified	unclassified	64	A04

NASA FORM 1626 OCT 86

For sale by the National Technical Information Service, Springfield, Virginia 22161-2171

NASA-Langley, 1991