CONSIDERATIONS FOR HIGH ACCURACY RADIATION EFFICIENCY MEASUREMENTS FOR THE SOLAR POWER SATELLITE (SPS) SUBARRAYS

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INTRODUCTION

The relatively large apertures to be used in SPS [1], small half-power beamwidths, and the desire to accurately quantify antenna performance dictate the requirement for specialized measurements techniques. The subject matter presented herein is under investigation as part of a program at Georgia Tech to address the key issues*.

The objectives of the program include the following:

1) For 10-meter square subarray panels, quantify considerations for measuring power in the transmit beam and radiation efficiency to ± 1% (± 0.04 dB) accuracy .
2) Evaluate measurement performance potential of far-field elevated and ground reflection ranges and near-field techniques.
3) Identify the state-of-the-art of critical components and/or unique facilities required.
4) Perform relative cost, complexity and performance tradeoffs for techniques capable of achieving accuracy objectives.

The precision required by the techniques discussed below are not obtained by current methods which are capable of ± 10% (± 0.4 dB) performance. In virtually every area associated with these planned measurements, advances in state-of-the-art are required.

ERROR SOURCES

In general, the RF and physical environment and the electronic instrumentation all contribute to the overall measurement error. Ideally, the RF source is stable in amplitude and frequency, the transmitted wave arrives at the receiver as a true plane wave free of objectionable reflections, and the atmospheric effects are negligible. The receiver must be ideal and error free, and the gain antenna reference is accurately known. In the real world, one must deal with the errors which occur as the instrumentation departs from the ideal performance listed above.

For SPS subarray antenna pattern measurements, the critical error sources have been quantified into four categories shown in Table 1. The objective of this investigation is controlling these error sources to yield an overall gain uncertainty of ± 0.04 dB. Because of the large size of an SPS subarray (81.67-wavelengths at 2.45 GHz), antenna range effects are given

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the largest allowance in the error budget. The errors allocated to transmitter/receiver sources require advances in state-of-the-art of associated microwave electronics. However, even with currently available equipment, because of single frequency operation, and the fact that receiver and transmitter are phase-locked and thermally stabilized, errors can be accurately controlled. Use of a microcomputer will permit error compensation of such factors as the nonlinearity of receiver and detector.

Controlling the antenna structure for measurement will require developing a cradle assembly that will hold the antenna rigid. Preliminary weight estimates indicate approximately 2.5 tons for a prototype subarray assembly. Ambient temperature, solar energy and wind effects can be controlled somewhat by selecting the measurement time period. However, since several thousand 10-meter apertures may need to be measured during the course of the SPS program, unique test facilities are anticipated. For instance, shielding from the adverse external parameters listed above can be achieved through use of a large dome radome.

Antenna measurements can be made with the test antenna either receiving or transmitting because of the reciprocity theorem. However, in the case where the SPS array is transmitting and the goal is to determine power in the transmit beam via beam integration, unique problems arise. Figure 1 illustrates one measurement concept being considered.

FAR-FIELD MEASUREMENT CONCEPTS

The predominant error contributors for far-field measurements are 1) field nonuniformity due to ground reflection, 2) gain loss due to quadratic phase error (near-field effects), and extraneous reflections. The National Bureau of Standards has investigated error budgets associated with far-field measurements [2]. For SPS, an adopted far-field error subbudget is shown in Table 2. The large size of an SPS subarray dictates a far-field criteria of greater than 6 D^2/λ to maintain quadratic phase error loss below 0.01 dB.

Field nonuniformity can be controlled via an elevated range concept where the receive antenna null is placed at the midpoint reflection point as depicted in Figure 2. Tradeoff calculations indicate the required tower heights for elevated range distances greater than 6 D^2/λ are not practical, however, consideration for a mountain top to mountain top range with an elevation of 600 feet and a measurement range of 7 miles appears very attractive.

Consideration was given to use of a ground reflection range facility. Here, transmit and receive tower heights are selected so that the reflection from the ground adds in phase to the direct ray path. A negative feature is that a relatively large range is required to obtain a sufficiently flat amplitude wavefront over the vicinity of the test antenna. Figure 3 relates the transmit and receive tower heights as a function of range. Under the constraint of a minimum and maximum tower height of 20 and 100 feet, respectively, and minimum range of 3 miles based on near-field criteria; the shaded area indicates regions where satisfactory operation may be obtained. The criteria for a sufficiently flat amplitude wavefront over the test zone is currently under investigation. Initial calculations indicate the performance of a 4-mile ground reflection range with receive and transmit tower heights of 30 and 70 feet, respectively, provided a wavefront within 0.1 dB over a 10-meter zone, but only with use of high efficiency absorber barricades at the midrange point.

POSITIONER CONSIDERATIONS

The large weight handling requirement (2.5 tons minimum)*, and small angular accuracy requirements, indicate that the positioner is a potential problem area based on units currently available. It has been determined that the positioner must be able to resolve a sample within 0.0016 degrees corresponding to a 19 bit encoder to resolve the beam power within a ± 0.04 dB accuracy.

A survey was made of available antenna positioners, and is summarized in Table 3. The positional accuracy of off-the-shelf positioners is on the order of 0.005 degrees. Available positioner data indicate positioning of anything larger than the 10-meter subarray will not be possible based on the weight projections.

The fractional power in the beam based on a uniformly illuminated 10-meter square aperture is plotted in Figure 4. Here, it is seen that the main beam (± 0.312 degrees) encompasses approximately 79 percent of the transmitted energy.

Based on these results, a concept was devised providing desired scan performance as illustrated in Figure 5. Here, a small angle positioner (SMAP) provides very accurate scan capability over a ± 1.5 degree sector for the purpose of beam integration. The larger gimbal arrangement provides coarse positioning over the complete ± 20 degree sector. Positioner hardware providing greater angular scan does not currently exist. From the plot of fractional beam power (Figure 4) approximately 89% of the total radiated power is accounted for within ± 1.5° scan; over 99% of the power is radiated in the ± 20 degree sector.

NEAR-FIELD MEASUREMENTS

Near-field techniques utilize a calibrated probe antenna to measure the amplitude and phase of the field close to the antenna aperture. Two orthogonally-polarized probes, or a single linear-polarized probe oriented in the vertical and horizontal directions are used, together with a probe compensation technique [8, 9] to obtain the complete radiation characteristics of the antenna under test (AUT). This measurement procedure requires an automated facility capable of reading the measured data in digital form for the required computer processing. The planar near-field measurement technique is particularly attractive for SPS since the SPS subarray does not have to be moved during the measurement, i.e. only the probe antenna is moved.

Recent work at Georgia Tech has demonstrated that accurate antenna patterns can be obtained via near-field techniques [4, 5]. The National Bureau of Standards has shown that for planar near-field scanning, the near-field derived patterns are more accurate than far-field measured patterns when considering all error sources involved [6].

Martin Marietta [3] has implemented an indoor planar near-field measurements facility capable of measurement of antennas up to 50-foot diameter. The benefits of this facility include all weather operation, a thermally controlled environment (maintained within 2°F), and an RF anechoic environment. RCA has also implemented an indoor planar near-field facility for acceptance testing of the AN/SPY-1 phased array antenna for the AEGIS system [10].

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[*] This weight estimate is based on using either conventional aluminum waveguide (without klystrons) or ultra-thin aluminum waveguide with klystrons included.

Near-field measurements can also be implemented by employing cylindrical or spherical probe scanning. However, in the spherical technique it is necessary to move the AUT while holding the probe fixed. In the case of SPS, spherical near-field scanning cannot be used because of the difficulty of gimbaling the heavy subarray in order to scan over a full sphere. However, planar and cylindrical scanning concepts are applicable. A planar scan concept is shown in Figure 6 and a cylindrical concept in Figure 7. Either system has potential to be implemented outdoors, however, the effects of thermal changes on scanning mechanism and instrumentation and the fact that an outdoor facility is subject to environmental conditions, makes an indoor near-field facility far more attractive and practical.

Tradeoff studies at Georgia Tech have suggested that the planar near-field concept has potential for array measurements of an SPS mechanical module (30 square meters). Problem areas to be resolved include computer requirements and the complexity of scanning over a much larger surface with acceptable precision. A previous study performed by Georgia Tech for NASA indicated that the cylindrical near-field technique is attractive for the measurement of electrically and physically large ground station antennas [11].

Previous studies at Georgia Tech have considered the cost tradeoffs of far-field measurements versus a near-field measurement [8, 11]. The results of these investigations for both large phased array and large reflector antennas demonstrate that costs are less for the near-field facility, and that the projected measurement accuracy is superior to that which could be obtained on a high quality far-field antenna measurement range.

However, the capital investment and operating costs of the near-field facility are functions of the required measurement accuracy. For example if the on-axis antenna gain is to be determined to within 0.01 dB, the measurement probe axial position accuracy must be within 0.1 wavelength, i.e. 0.048 inches for the SPS. Also, the scan width-to-diameter ratio must be at least 1.5. Thus, this requirement has a direct effect on the mechanical design of the near-field measurement system.

In order to obtain a complete representation of the antenna pattern from a planar or cylindrical near-field scan, the field is normally sampled at 1/2 wavelength intervals along the linear scan dimension. If the AUT is electrically large, the required Fourier transform processing can become burdensome. However, it has been shown that the sample spacing can be increased by almost an order of magnitude if only the main-beam and first sidelobes are to be defined [4, 11].

In order to obtain accurate polarization information on the antenna pattern, the polarization characteristics of the measurement probe must be carefully characterized over the maximum possible dynamic range. Work at RCA [7] has also indicated that careful probe polarization design is necessary too if a very accurate gain determination is required. For instance, assuming an SPS antenna polarization ratio of 30 dB, a probe polarization ratio of 20 dB will result in a gain measurements error of approximately 0.25 dB. Thus, a very stringent requirement is placed on probe polarization ratio; a requirement of 30 dB, or better, is anticipated.

CONCLUSIONS

Because of the large electrical size of the SPS subarray panels and the requirement for high accuracy measurements, specialized measurement facilities are required. Most critical measurement error sources have been identified for both conventional far-field and near-field techniques. Although the adopted error budget requires advances in state-of-the-art of microwave instrumentation, the requirements appear feasible based on extrapolation from today's technology.

Additional performance and cost tradeoffs need to be completed before the choice of the preferred measurement technique is finalized.

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TABLE 1

MEASUREMENTS ERROR BUDGET

ERROR SOURCE	ERROR COMPONENTS	ALLOWABLE VALUE IN ERROR BUDGET	COMMENTS
ANTENNA RANGE	FIELD UNIFORMITY		
	QUADRATIC PHASE ERROR		
	EXTRANEOUS REFLECTIONS	.037 dB	
	STANDARD GAIN ANTENNA UNCERTAINTY		AN ADEQUATE GAIN STANDARD HAS NOT YET BEEN IDENTIFIED
	ATMOSPHERIC EFFECTS		REFERENCE RECEIVER MUST BE USED TO NORMALIZE EFFECTS OF ATMOSPHERE
STRUCTURAL/ ENVIRONMENTAL	SPS ANTENNA REGIDITY/STABILITY		
	POSITIONER ERROR	.01 dB	
	WIND LOADING THERMAL		WIND LOADING/THERMAL CAN BE CONTROLLED BY RADOME OVER TEST ANTENNA
TRANSMITTER	*AMPLITUDE STABILITY*		PHASE LOCKED TECHNIQUES AND TEMPERATURE STABILIZATION MUST YIELD AMPLITUDE STABILITY OF 0.007 dB
	FREQUENCY STABILITY	.01 dB	
RECEIVER	PRECISION ATTENUATOR UNCERTAINTY		ATTENUATOR CALIBRATED TO 0.005 dB
	REFERENCE INPUT PHASE/ AMPLITUDE ERRORS		
	SIGNAL TO NOISE RATIO	.01 dB	S/N RATIO MUST EXCEED 40 dB
	FREQUENCY STABILITY		
	DYNAMIC RANGE		THROUGH ENVIRONMENTAL CONTROL DETECTOR CALIBRATION CAN EXCEED 0.005 dB
	DETECTOR LINEARITY		
	VSWR		VSWR KEPT BELOW 1.05
		TOTAL RSS = .04 dB	

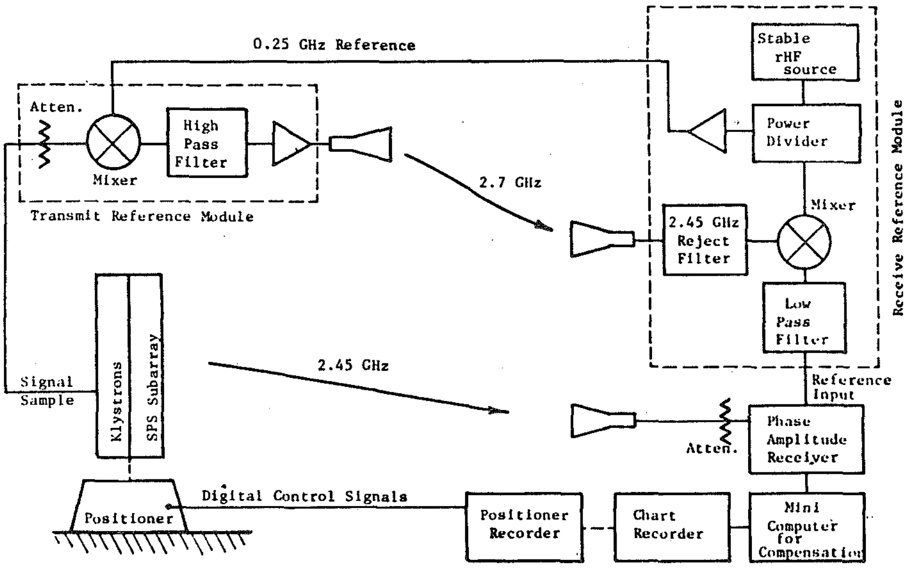


Figure 1. Equipment Configuration for Antenna Measurements.

TABLE 2

ANTENNA RANGE MEASUREMENTS ERROR SUB-BUDGET

ERROR COMPONENT	ALLOWABLE VALUE	COMMENTS
Field Uniformity	0.015 dB	Maximum amplitude taper at edge of SPS subarray approx. 0.04 dB
Quadratic Phase Error	0.010 dB	Requires range greater than 6 D^2/λ
Standard Gain Antenna Uncertainty	0.020 dB	Gain standard needs to be developed
Atmospheric Effects	0.005 dB	Atmospheric effects cancelled by reference
VSWR	0.005 dB	VSWR loss calibrated out
Extraneous Reflections	0.025 dB	Extraneous reflections -57 dB down
RSS Subtotal	0.037 dB	

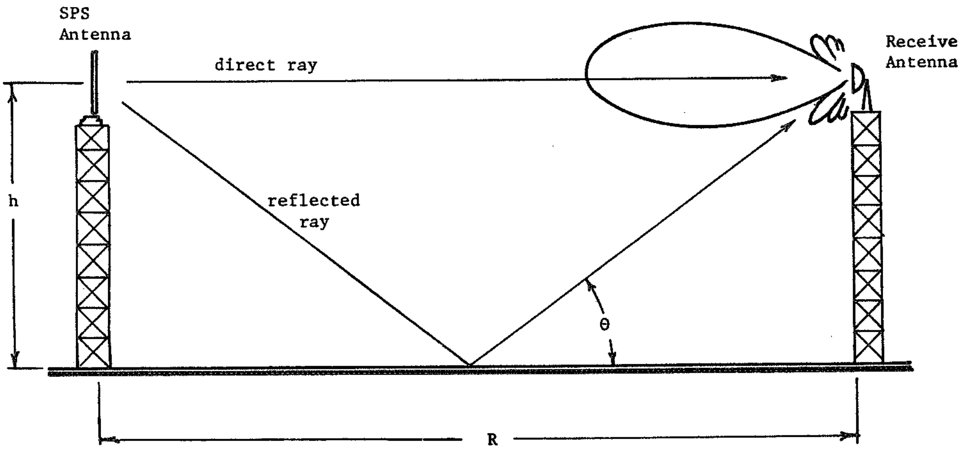
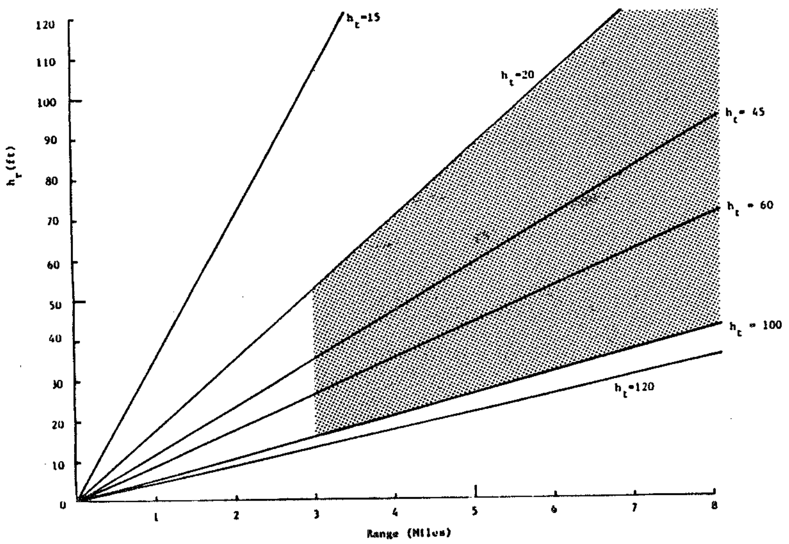


Figure 2. Elevated Antenna Range.



Note: Darkened area is allowable operating region.

Figure 3. Relation Between Receive Antenna Height (h_r), and Transmit Antenna Height (h_t) for a Ground Reflection Antenna Range.

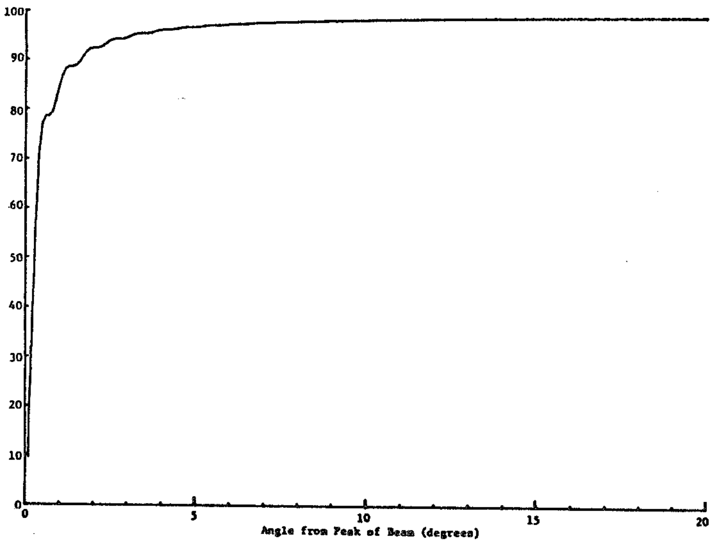


Figure 4. Fractional Beam Power for SPS Subarray Pattern.

Figure 5. Antenna Positioner Mechanism For Far-Field Patterm Measurements

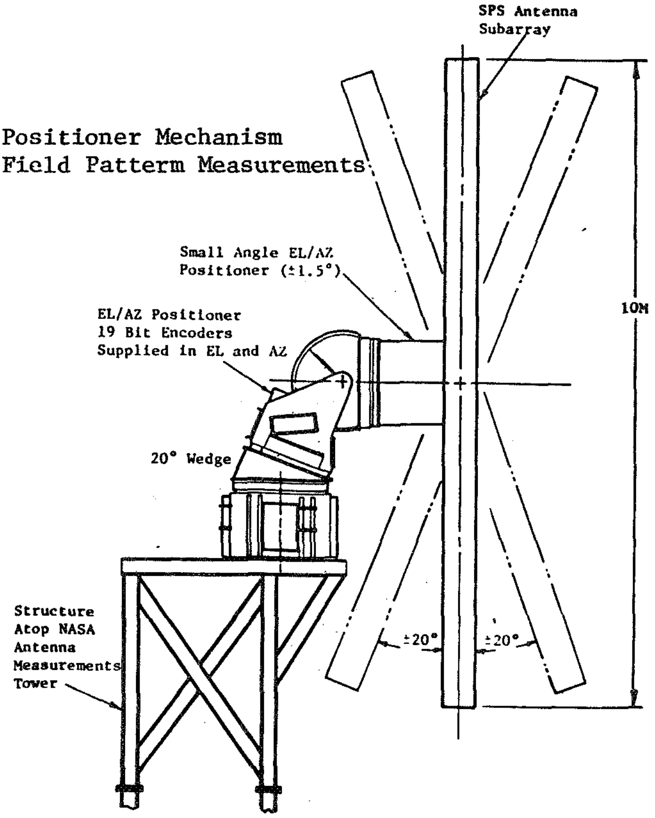


TABLE 3

SUMMARY OF POSITIONER PERFORMANCE

Scientific Atlanta Series**	Maximum Moment (Kft-lb)	Estimated Moment Arm* (ft)	Maximum Subarray Wt.		Cost***		
			Klbs	Tons	Elev./Az.	SMAP	Total
85	150	9.5	15.8	7.9	$ 440K	$400K	$ 840K
45	75	7.5	10	5	$ 111K	$100K	$ 211K

*Elevation over azimuth plus SMAP configuration.

**NOTE: the series 85 has a maximum vertical load limit of 25 tons.

***November 1979 estimates.

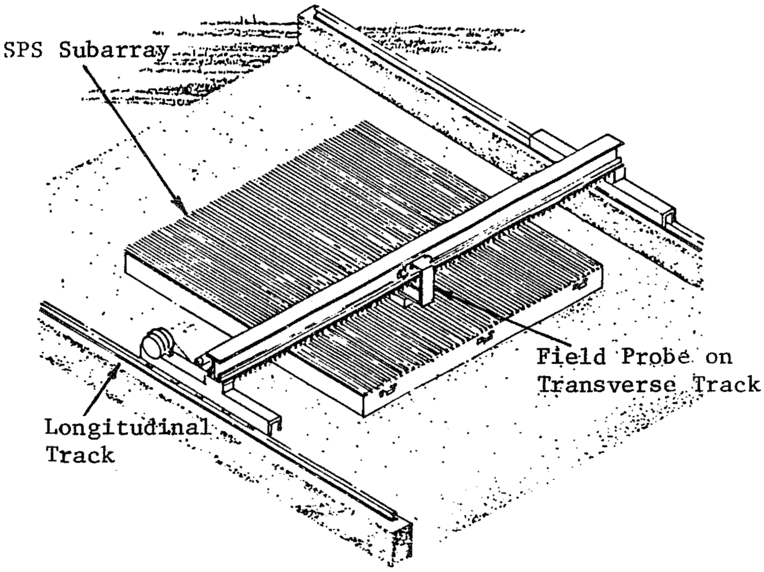


Figure 6. Planar Scanner Concept for Near-Field Measurements.

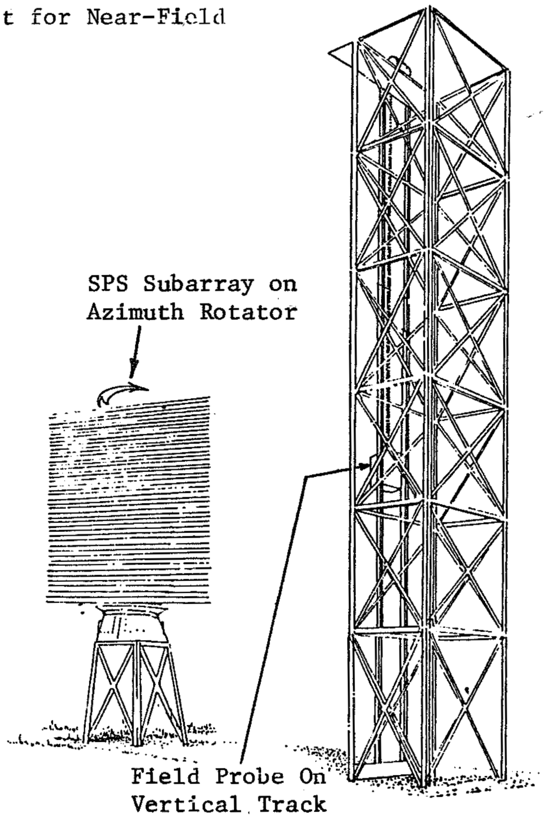


Figure 7. Cylindrical Scanner Concept for Near-Field Measurements.

CONCLUSIONS PRESENTED AT THE RADIATING ELEMENTS SESSION

1. Radiating Element Efficiencies - Low CTE (coefficient of thermal expansion) materials are required in order to obtain the required radiating efficiency of 96%
2. Type of Radiator - For large power blocks the most efficient radiator is a planar slot subarray with waveguide feed techniques.
3. Polarization - Linear polarization is preferred for simplicity and analyses show that Faraday rotation does not produce a significant loss.
4. High Voltage Breakdown - High voltage breakdown is not expected to be a problem at nominal geosynchronous orbital conditions. However, further study is required to determine the extent to which the SPS satellite produces an atmosphere.
5. Performance Measurements - Improved highly accurate measurement techniques and instrumentation will be required to verify system performance.

REMAINING ISSUES - PRESENTED AT THE RADIATING ELEMENTS SESSION

1. Practical efficiency design goal
    a. Mass manufacturing tolerances vs. efficiency
    b. Cost vs. efficiency

2. Suitable low CTE (coefficient of thermal expansion) material
    a. Performance improvements
    b. Effects of power level, multipacting, thermal cycling
    c. Type of CTE material

3. Pilot signal reception
    a. Shared aperture - diplexer: isolation, loss, transmit η loss
    b. Separate aperture - filter: isolation, loss, transmit η loss

4. RF measurement accuracies
    a. High efficiency measurements
    b. Statistical analysis - desirable/feasible