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TRW Space & Technology Group

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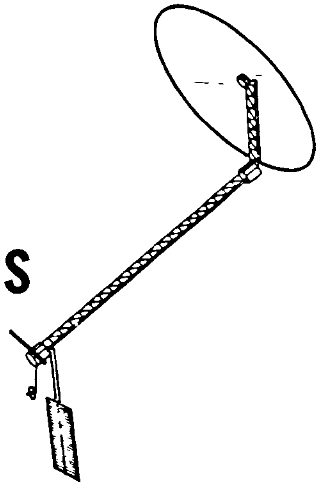
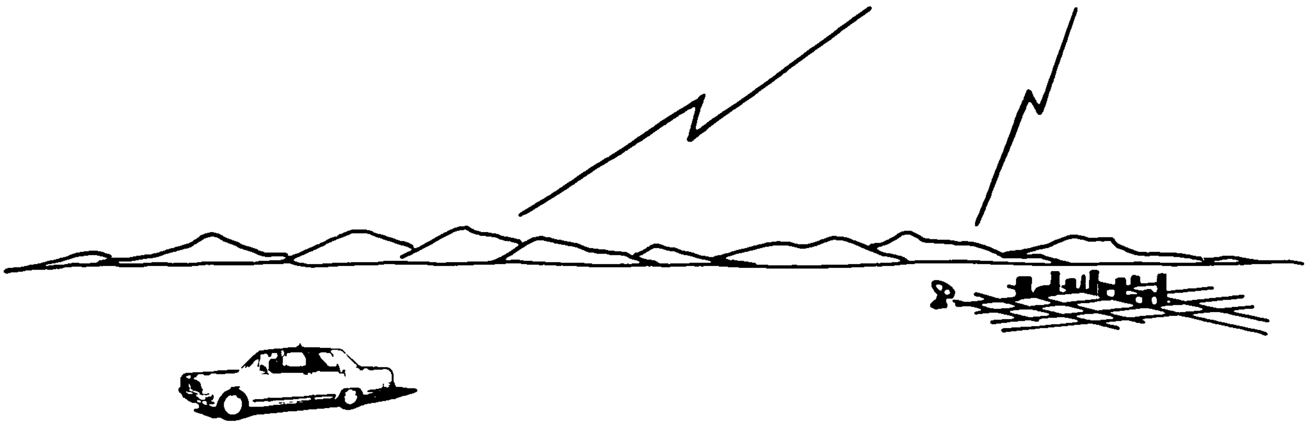
Requirements for a

Mobile Communications Satellite System

Volume 3 — Large Space Structures Measurement Study





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Final Report
Technical Monitor - Charles Provencher, Jr.
NASA/Lewis Research Center

16 Abstract

This study report defines a set of tests and measurements required to characterize the performance of a Large Space System (LSS), and to scale this data to other LSS satellites. Requirements from the Mobile Communication Satellite (MSAT) configurations derived in the parent study, were used. MSAT utilizes a large, mesh deployable antenna, and encompasses a significant range of LSS technology issues in the areas of structural/dynamics, control, and performance predictability.

In this study, performance requirements were developed for the antenna. Special emphasis was placed on antenna surface accuracy, and pointing stability. Instrumentation and measurement systems, applicable to LSS, were selected from existing or on-going technology developments. Laser ranging and angulation systems, presently in breadboard status, form the backbone of the measurements. Following this, a set of ground, STS, and GEO-operational were investigated.

A third scale (15 meter) antenna system was selected for ground characterization followed by STS flight technology development. This selection ensures analytical scaling from ground-to-orbit, and size scaling. Other benefits are cost and ability to perform reasonable ground tests. Detail costing of the various tests and measurement systems were derived and are included in the report.

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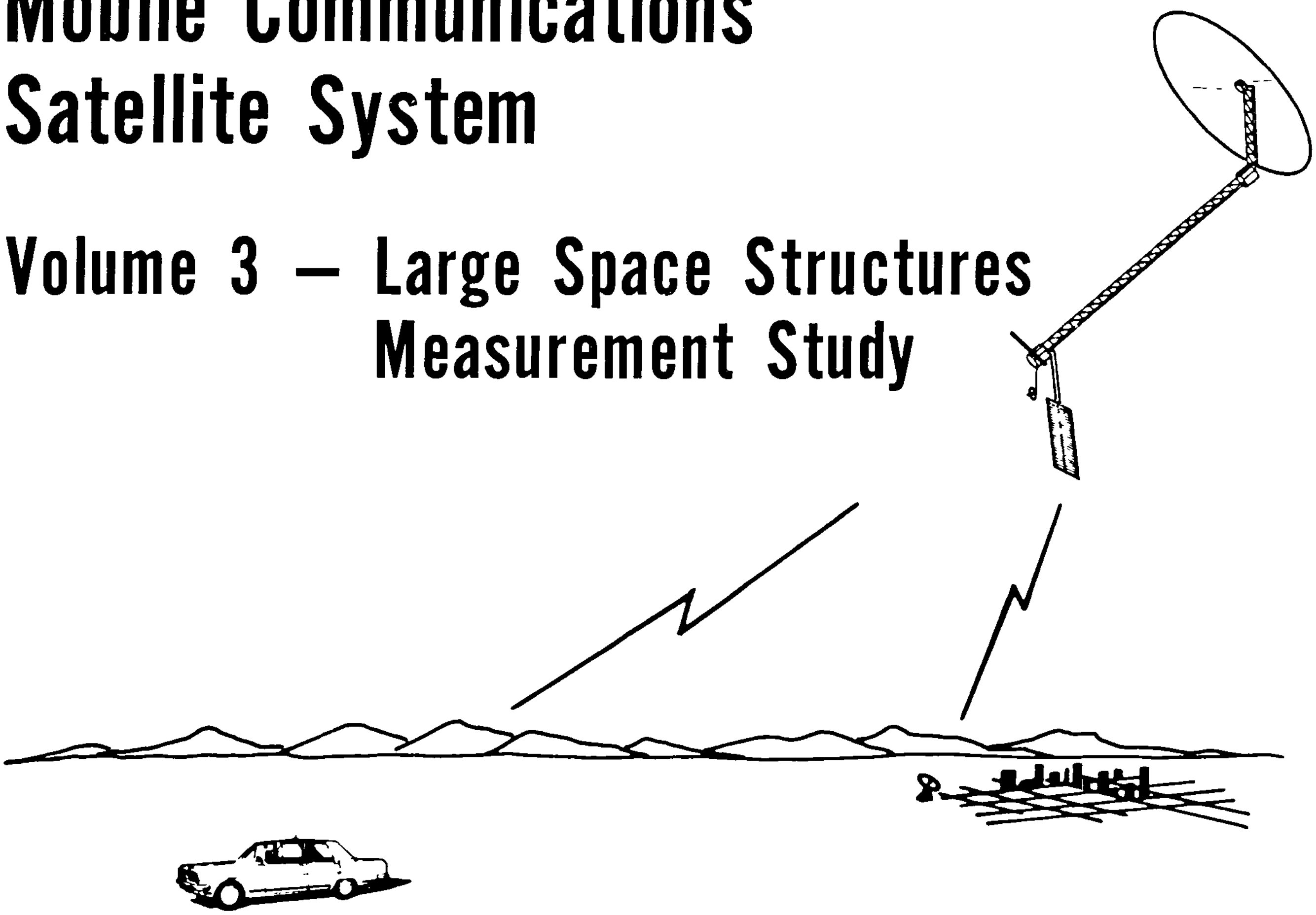

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TRW Space &
Technology Group
One Space Park
Redondo Beach CA 90278

TRW

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Prepared for:
NASA
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Approved:

Wade Akle

W. Akle
Task Manager

M. Horstein

M. Horstein
Project Manager

R H Sparks

R.H. Sparks
Manger, Systems Design and Verification

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The task manager at TRW was Mr. Wade Akle. This study was performed within the Mission and System Engineering division. The contributors to this report are:

Dr. Bob S. Neisswander	Sensors
Dr. Frank C. Tung	Control
Mr. Ed R. Pacheco	Payload
Mr. Don O. Chandler	Structures
Mr. Dave J. Philips	Costing
Mr. George T. Inouye	EMI

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INTRODUCTION

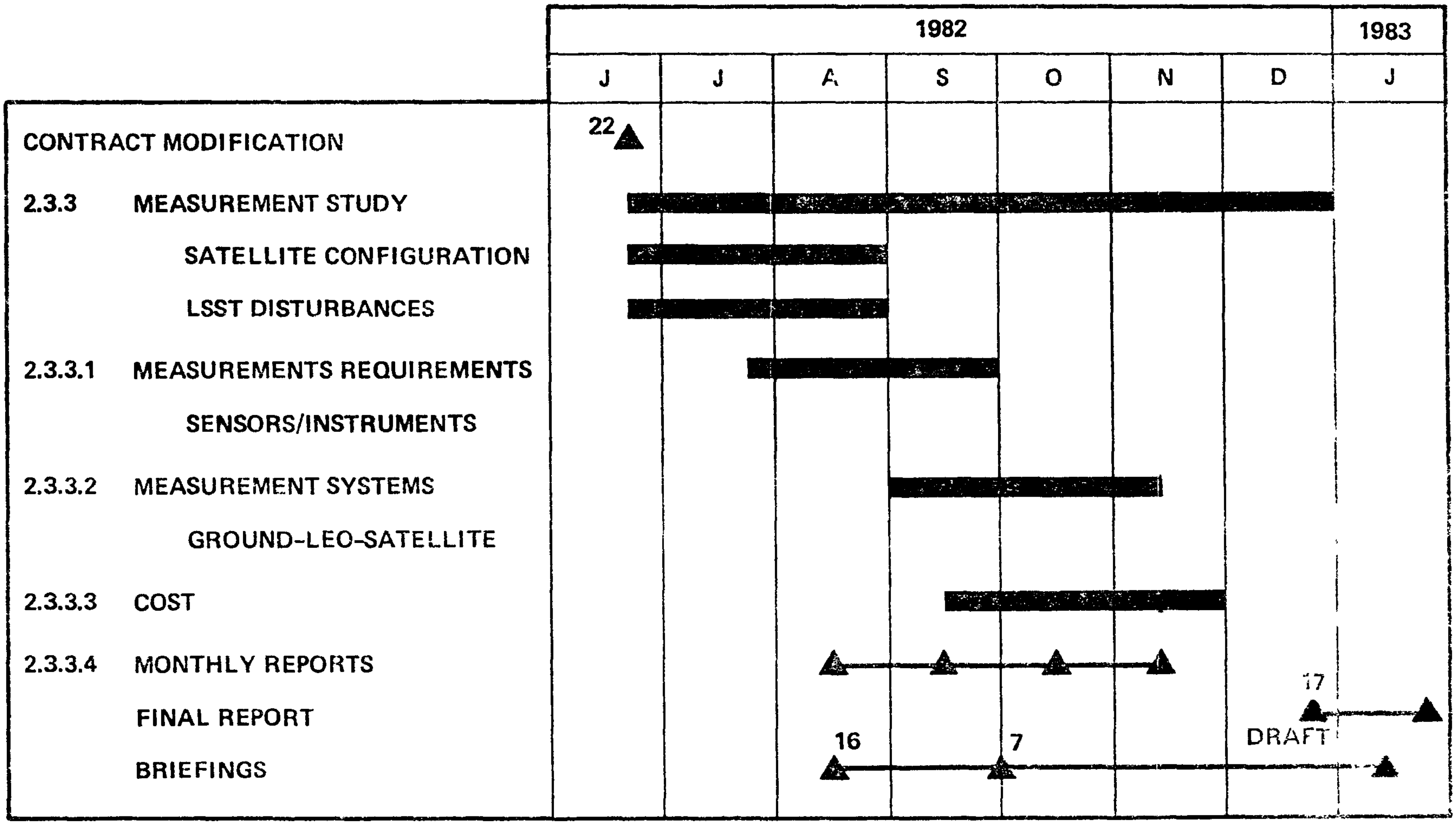
This report documents the Large Space Structure Technology (LSST) measurement study add-on to the Mobile Communication Satellite System Study, for NASA-LeRC, Cleveland, Ohio. The study consisted in developing a set of RF, mechanical, and thermal measurements to be made on the MSAT antenna to obtain scaling paremeters needed for similar large space antenna systems. The measurements data can be used to validate scalability of the analytical tools developed for LSST. This ability to analytically predict the behavior of other large antenna systems is essential since their size may preclude full scale ground or STS-tended testing.

The measurement system is also an integral part of the attitude control subsystem (ACS) position/rate feed-back sensors loop. The sensors provide an assessment of relative motions between feed and reflector, as well as reflector surface motions, to the ACS controller.

As shown by the schedule in Figure 1, the study is divided into three tasks, preceded by a description of the MSAT system.

FIGURE 1.

MEASUREMENT STUDY DEVELOPMENT PLAN



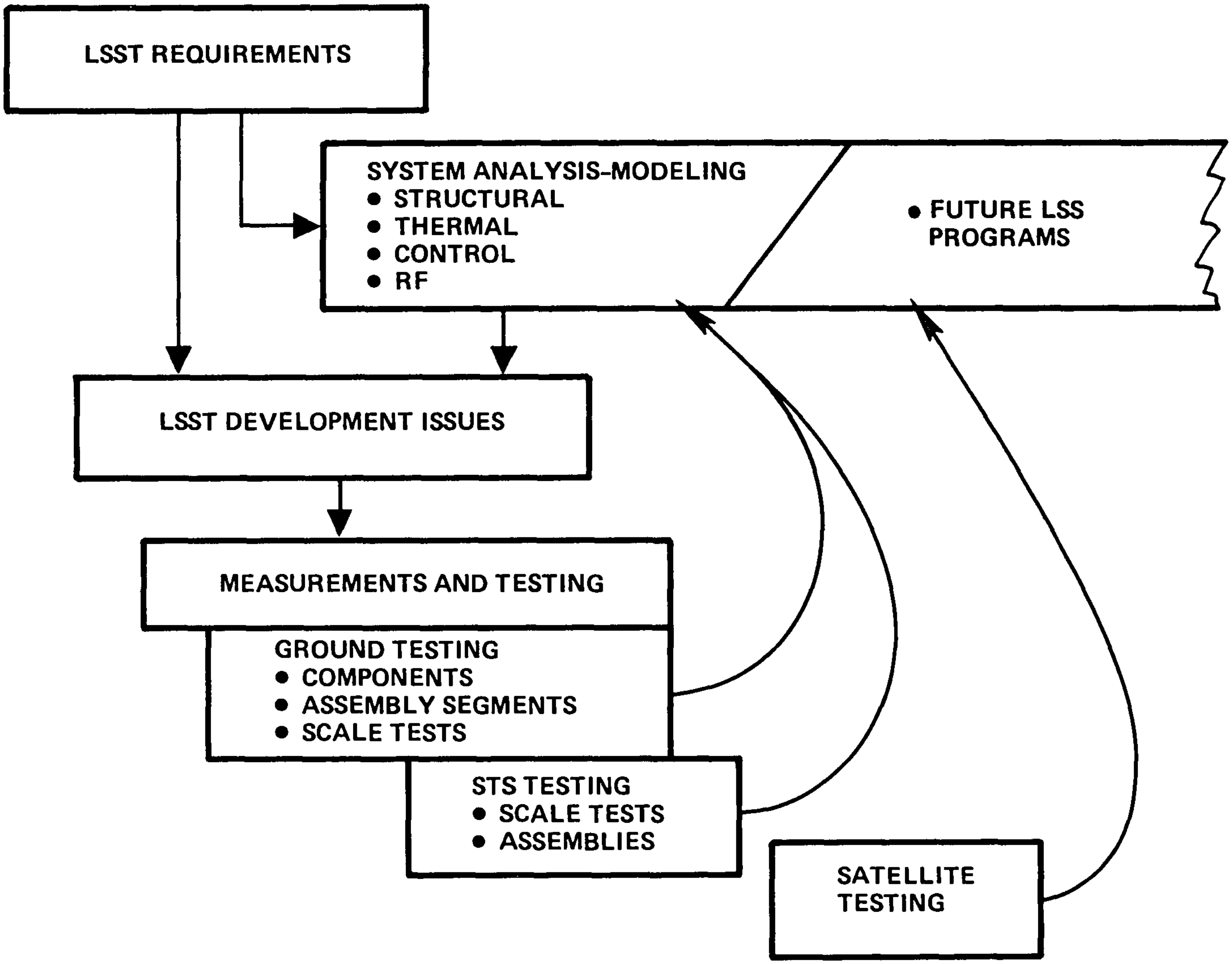
2.3.3 Measurement Study System Baseline

MSAT draws most of its technology from the Large Space Structures Technology (LSST) programs sponsored by NASA, DoD and industry. The measurement study assumes that this technology will mature in the late 80's, allowing an MSAT program start in 1990, for a 1995 launch. For the purposes of the study, LSST technology tests before the MSAT Phase B are not part of MSAT tests, but the LSST development is critical for MSAT, and must precede it.

The usual satellite development relies on predictive analysis coupled with full-scale testing to provide corrective feedback to the analysis. This coupling of analysis and test provides a high degree of confidence in predicting satellite behavior. But because of its size and relatively low structural stiffness, MSAT must rely on constrained or scale testing, thus increasing the importance of the accuracy of the analysis.

As shown in Figure 2, system analytical modeling is central to MSAT development. MSAT requirements ana analytical models provide together a set of development issues relating to test configuration, scalability of results, and test measurements. Ground scale testing is repeated in orbit on an STS-attached flight, providing 1 to 0g correlation in the analytical model. This data is then scaled to the full satellite. Ground tests may also be conducted on full-scale elements such as the short mast, or an individual rib. Once MSAT is deployed in GEO orbit, its performance is characterized by a full set of measurement, coupled with ground data analysis. From this information, MSAT control paremeters are updated and the satellite becomes operational. The analytical models used then provide a solid scaling base for other LSS programs.

FIGURE 2. ANALYSIS IS CORE OF MSAT DEVELOPMENT



Development Plan

The assumed development relationships between MSAT and LSST are shown in Figure 3. Timelines for LSST are derived from NASA plans for technology demonstrations for reflectors and masts in the mid-80's. For the measurement study, costs are charged to MSAT starting with Phase B, in 1988; only those costs that are unique to the LSST aspects of MSAT are included. The schedule uses LSST development to lead into specific MSAT configuration tests and measurement issues. Earliest MSAT activity is development of analytical models, followed by mock-up ground RF tests; these tests are used to define the MSAT reflector performance and to develop the feed. From this work, the feed-reflector selection is made, and scale testing definition begins. Data from this testing will be used to validate the analytical techniques and to fine tune the flight design.

MSAT Satellite Configuration

Two satellite configurations were selected at the start of this study, direct offset-fed wrap-rib at 52 M aperture and tri-aperture hoop-column at 115 M diameter. The wrap-rib offset-fed design, in the parent study, was baselined at 46 M aperture. The 52 M aperture was retained for the measurement study. The hoop-column design was carried through the measurements requirements and ACS sensors phase of this study (2.3.3.1); it was not carried further since there are similar LSST measurement requirements with the offset-fed design.

Figures 4 thru 7 and Tables I thru IV define the characteristics of interest for each of the two satellite systems selected. The data presented are taken from the parent study parametric analysis, published data, particularly from the 1981 LSST conference at NASA-Langley, and contacts with LMSC during this study.

FIGURE 3.

MSAT DEVELOPMENT - MEASUREMENT STUDY

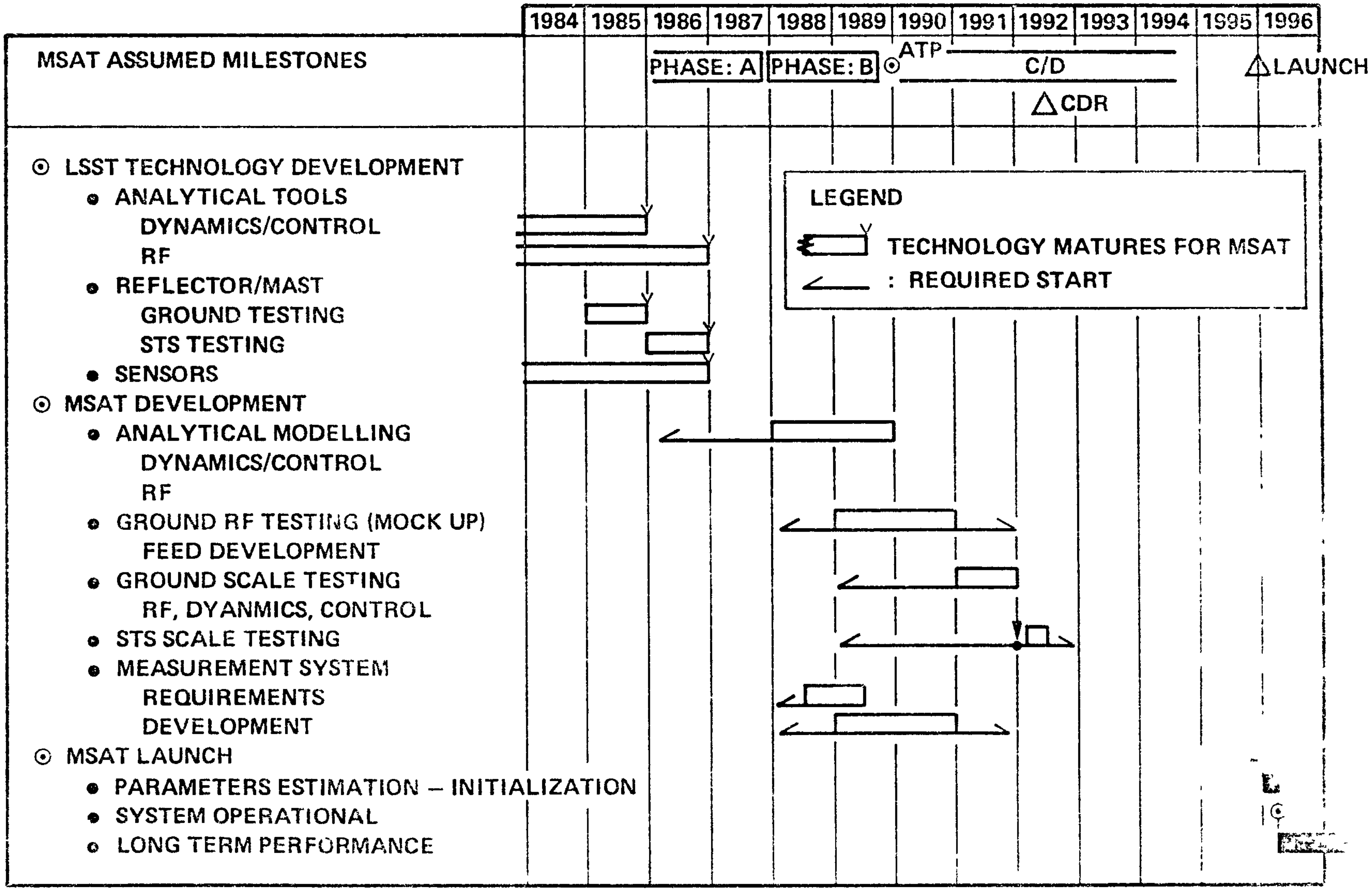


FIGURE 4.

DIRECT OFFSET-FED CONFIGURATION

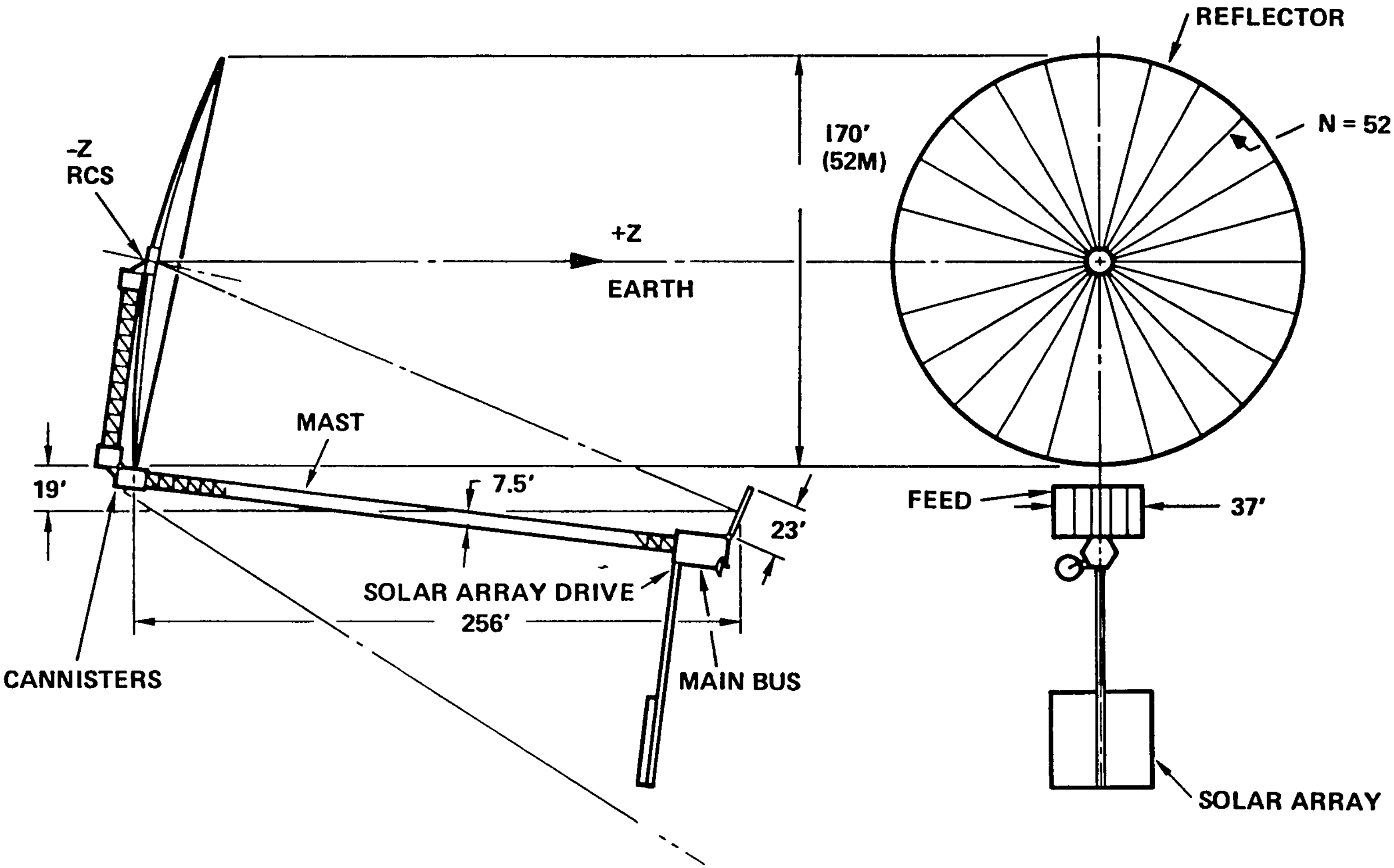


FIGURE 5.

SATELLITE DEPLOYMENT CONCEPT FOR OFFSET-FED CONFIGURATION

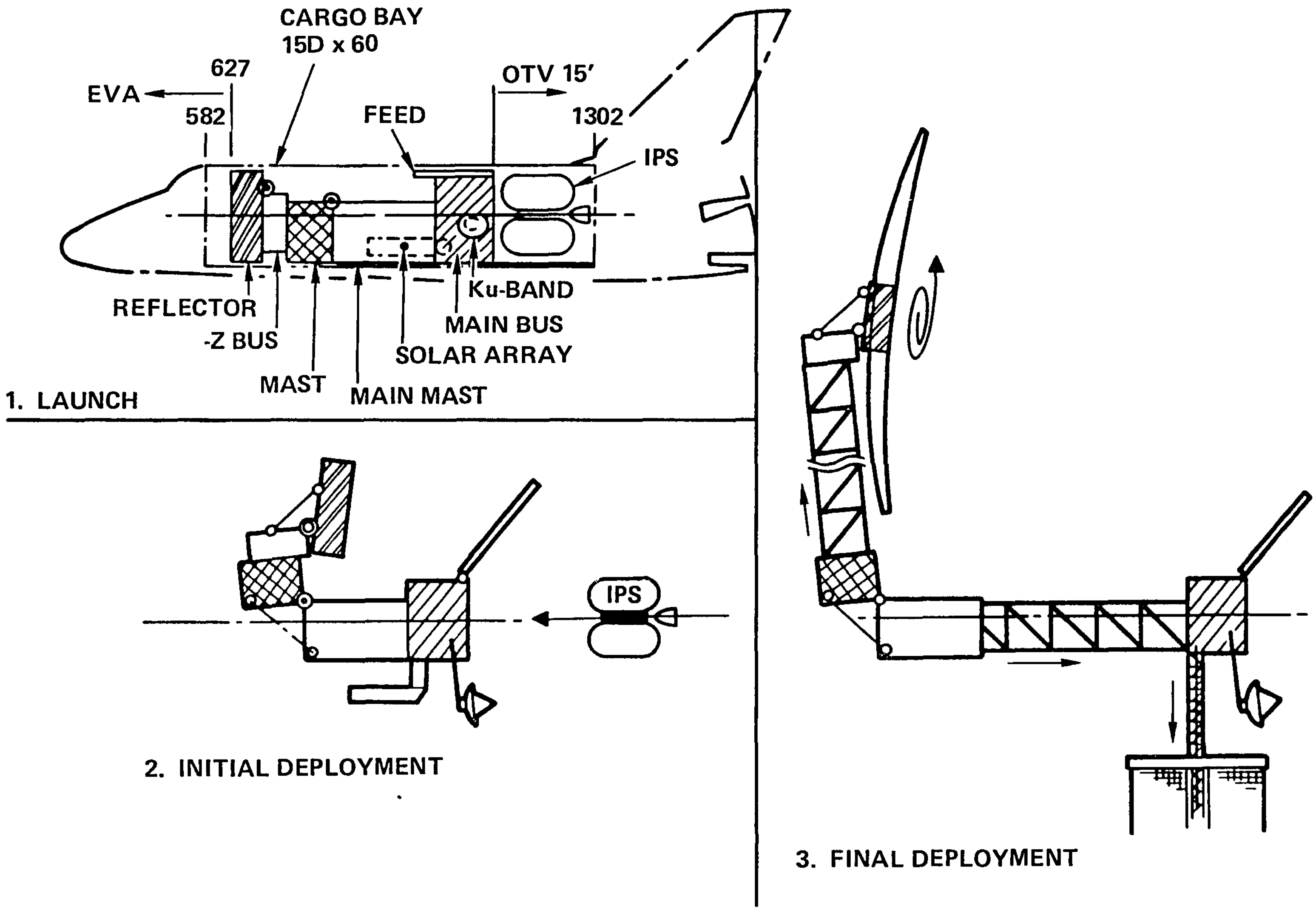


FIGURE 6.

HOOP-COLUMN SYSTEM CONFIGURATION

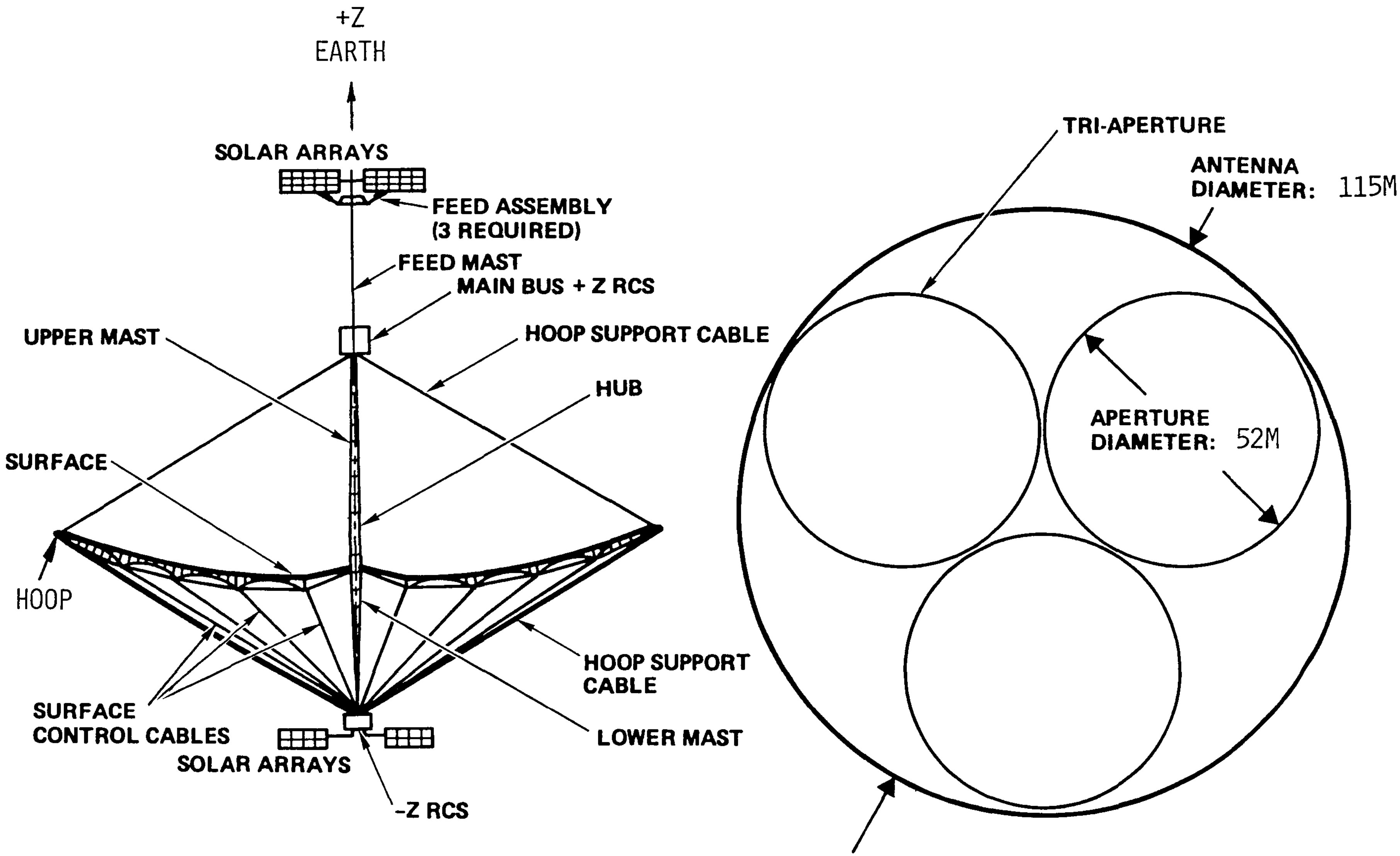


FIGURE 7.

HOOP-COLUMN SATELLITE DEPLOYMENT CONCEPT

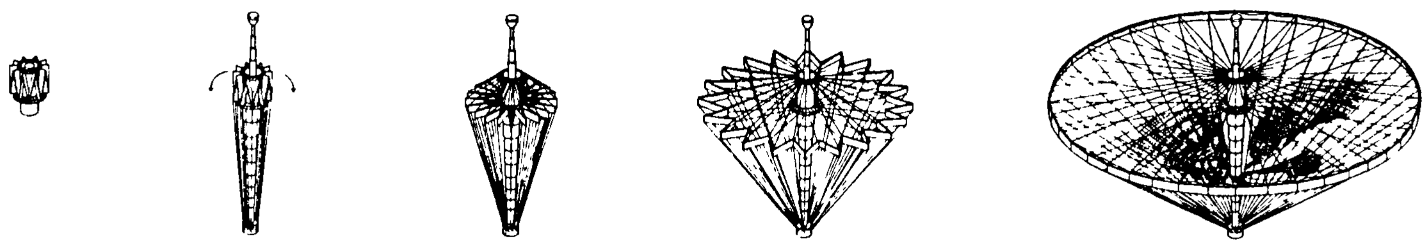


TABLE I.

REFLECTOR RIBS COMPOSITE CONFIGURATION - NOMINAL VALUES (*)

PROPERTY	$[0/90_2/0]$
NO. LAYERS	4
E (LONG) MSI	16.6
E (TRNS) MSI	16.6
(A) G (TORSN) MSI	1.0
LAM. WT. LB/IN^2	0.001206
POISSON (L-T)	0.199
POISSON (T-L)	0.199
THERMAL COND. (LONG) BTU/HR-FT ^oF	13.25
(B) THERMAL COND. (TRNS) BTU/HR-FT ^oF	13.25
(C) CTE (LONG)/^oF	4.4×10^{-7}
CTE (TRNS)/^oF	4.4×10^{-7}

(*) PROPERTIES SCATTER (TBD)

LMSC DATA

TABLE II.

TYPICAL WRAP-RIB DYNAMIC RESPONSE CHARACTERISTICS

FLEX * MODE	FREQ. (HZ)	DESCRIPTION
1	0.0872	SHORT BOOM TORSION
2	0.1473	DISH TORSION, LONG BOOM TWIST
3	0.1965	DISH TORSION, LONG BOOM BENDING
4	0.2062	DISH BENDING
5	0.2201	DISH BENDING, LONG BOOM BENDING
6	0.2906	DISH TORSION
7	0.6644	DISH ROTATION, LONG BOOM BENDING

** REFLECTOR NATURAL FREQUENCIES: ROCKING MODE 0.59 HZ
TORSION MODE 0.07 HZ

* Ref: Yu-Hwan Lin, JPL
LSST 1981 Conference

** Ref: LMSC Data

TABLE III.

HOOP-COLUMN SATELLITE STRUCTURAL/MECHANICAL ERRORS PERFORMANCE

				RMS (IN)	MAX (IN)
CONTOUR	MANUFACTURING			0.18	3.03
	PILLOWING			.12	--
	THERMAL ELASTIC ECLIPSE			.03	.17
	MATERIAL PROPERTIES			.05	--
	UNCERTAINTIES			.03	3.2
	MESH	STIFFNESS	--		(.02)
		PRETENSION	(.01)		(.49)
	GR CORDS	STIFFNESS	(.01)		(.31)
		CTE	--		(.15)
		CREEP	--		(.17)
	GFRP	STIFFNESS	(.01)		--
		CTE	(.01)		(.3)
		MOISTURE	(.01)		--
	TEMPERATURE		(.01)		(.38)
	DEPLOYMENT/HOOP EGGING/ MEASUREMENTS		(.02)		(1.59)
	TOTAL			0.22	6.44

REF. NASA-CR-3558
JUNE, 1982

TABLE IV.

TYPICAL DYNAMIC RESPONSE CHARACTERISTICS -

HOOP-COLUMN

NO.	FREQ. HZ	DESCRIPTIONS
7	0.35	MAST TORSION
8	0.18	ROLL BENDING
9	0.18	PITCH BENDING
10	0.31	MAST TORSION
11	0.56	MAST TORSION
12	0.95	MAST/DISH ROLL BENDING
13	0.99	MAST/DISH PITCH BENDING
14	1.68	DISH WARPING
15	1.71	DISH WARPING
16	1.76	DISH WARPING MAST BENDING
17	1.77	DISH WARPING MAST BENDING
18	2.42	DISH WARPING MAST BENDING

Ref: Yu-Hwan Lin, JPL LSST
1981 Conference

One of the study tasks is to define the expected magnitude of the as-built structural errors. The results of the Harris Corporation LSST study (NASA-CR-3558, June 1982), in conjunction with analysis from this study, are used in section 2.3.3.1 to provide error budgets for MSAT pointing and surface accuracy.

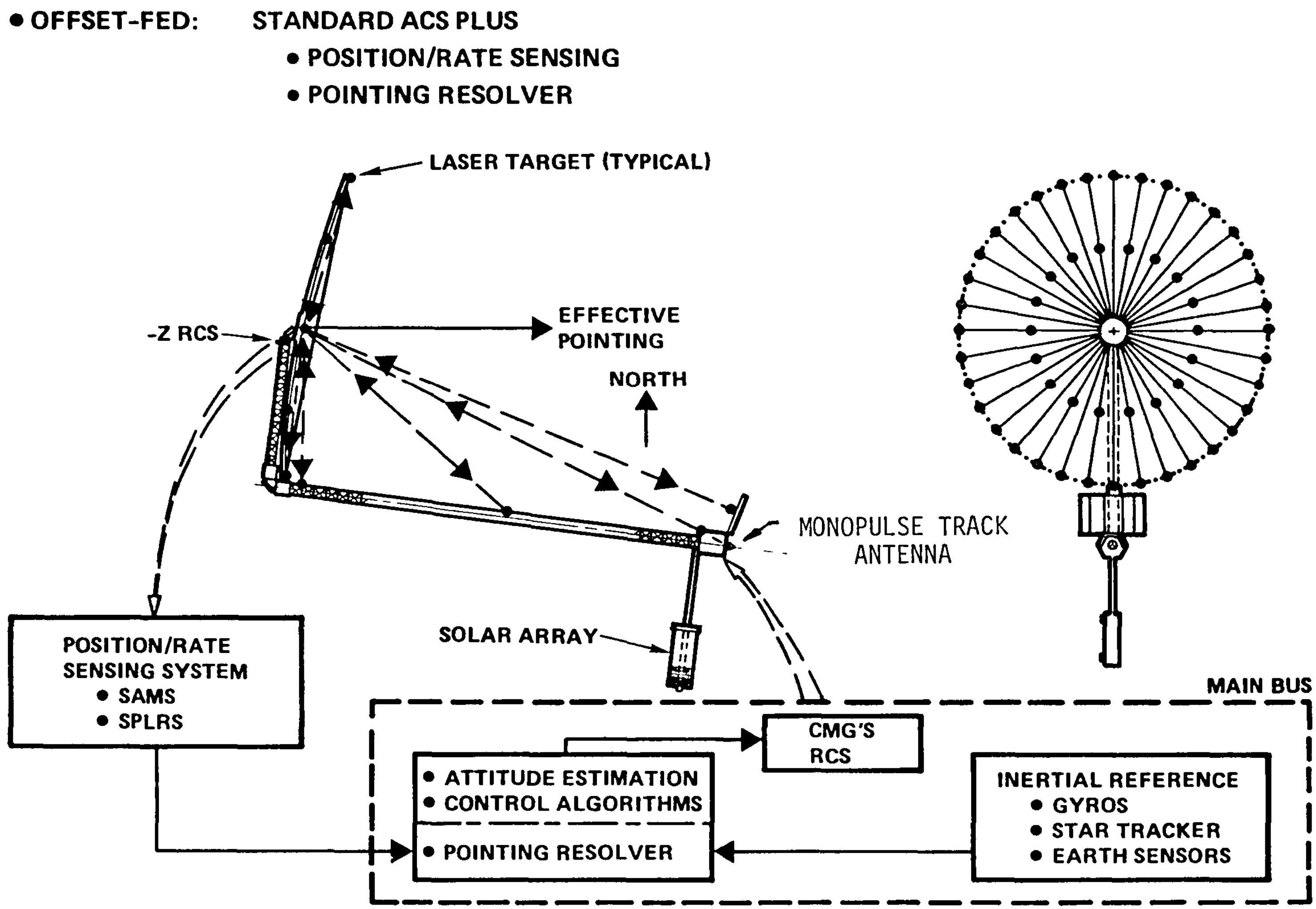
MSAT Attitude Control

The satellite attitude control subsystem (ACS) concept is shown in Figures 8 for wrap-rib and in Figure 9 for hoop-column. A monopulse RF tracking signal, received from a selected ground gateway station, provides pointing reference. A set of sensors provides position and rate data relative to a) position of the feed-to-reflector hub and b) reflector surface with respect to the hub. All measurement data are then referenced to the ACS inertial reference platform. RF beam pointing optimization and control algorithms using this sensor data reside in an ACS pointing resolver to provide the desired pointing direction. For hoop-column, an additional surface resolver is needed to provide active reflector surface control. Control moment gyros (CMG) and the reaction control subsystem (RCS) provide the control authority to steer the satellite to the commanded direction.

When the satellite initially achieves its orbit, uncertainties exist as to its dynamic response. Closely-spaced, low-frequency structural modes may be within the ACS control bandwidth, degrading the pointing performance. The position/rate measurement system will provide a ground station with satellite modal response data. On the ground, a structural parameter estimator, shown in Figure 10, recomputes the ACS control parameters. The ACS is updated and the cycle is repeated until acceptable convergence, and the satellite is declared operational. Table V details the steps.

FIGURE 8.

OFFSET WRAP-RIB SATELLITE ATTITUDE CONTROL SUBSYSTEM (ACS)



SAMS SURFACE ACCURACY MEASUREMENT SYSTEM
SPLRS: SELF-PULSED LASER RANGING SYSTEM

FIGURE 9.

HOOP-COLUMN SATELLITE ACS POINTING AND SURFACE CONTROL LOOPS

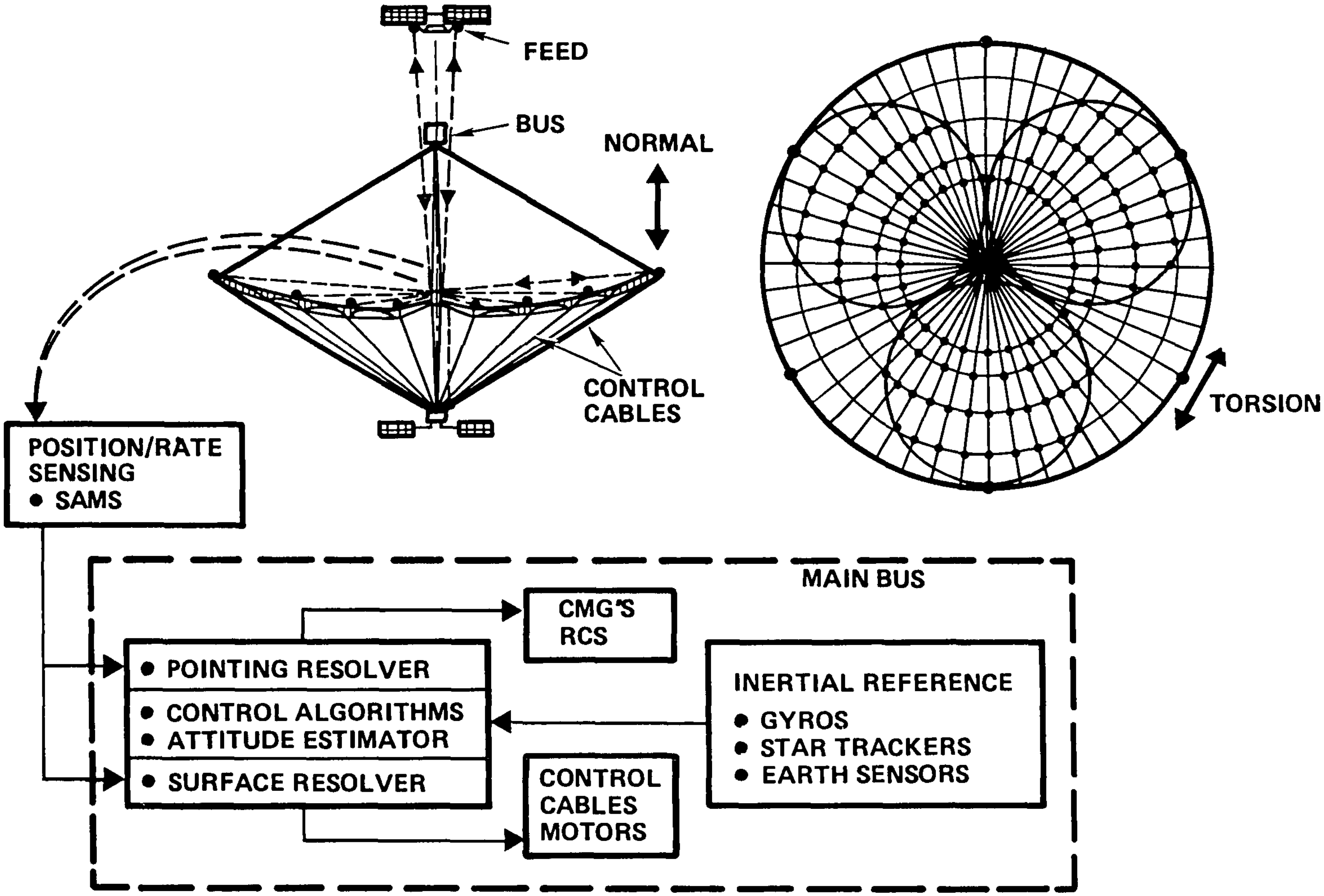


FIGURE 10.

ON-BOARD CONTROLLER TUNING VIA STRUCTURE IDENTIFICATION

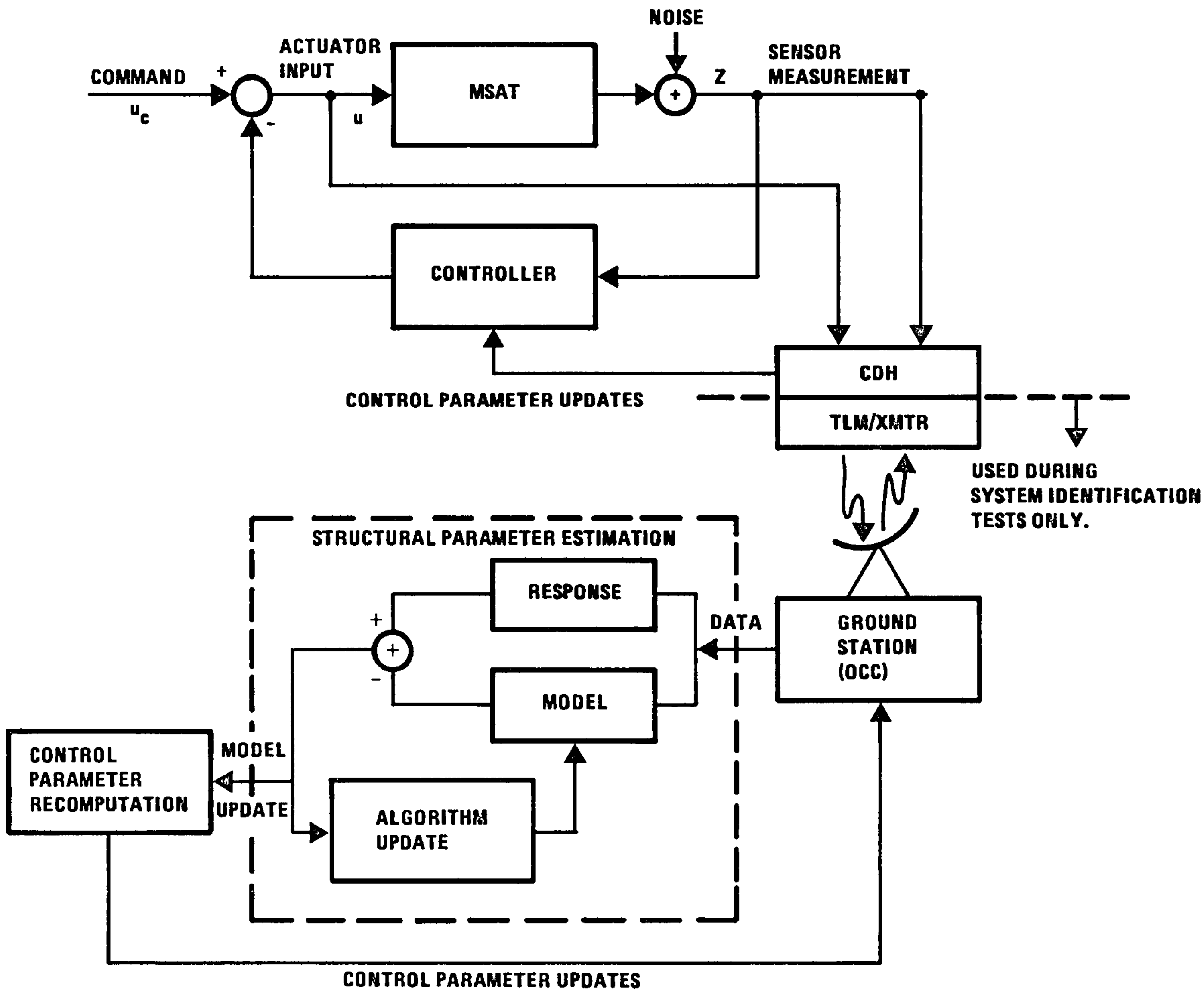


TABLE V.

SATELLITE ACS INITIALIZATION PHASE

DEPLOYMENT AND INITIAL STABILIZATION

- DEPLOYMENT
- HIGH UNCERTAINTIES ON STRUCTURAL PARAMETERS
- POINTING ERROR ALLOCATION LARGER THAN OPERATIONAL REQUIREMENTS
- ROBUST CONTROLLER TO STABILIZE THE SATELLITE

ON-ORBIT STRUCTURE IDENTIFICATION

- RECORD CMG, RCS, AND DISTURBANCE INPUTS AND MEASUREMENT SYSTEM SIGNALS
- TRANSMIT DATA TO GROUND STATION
- PROCESS DATA USING STRUCTURAL PARAMETER ESTIMATION (SPE) PROGRAMS TO OBTAIN ACCURATE STRUCTURAL PARAMETERS

CONTROLLER ADJUSTMENT

- RECOMPUTE CONTROL PARAMETERS USING ACCURATE STRUCTURAL PARAMETERS
- TRANSMIT NEW CONTROL PARAMETER TO SPACECRAFT SO AS TO MEET POINTING REQUIREMENT

OPERATIONAL PHASE

- MONITOR SYSTEM DISTURBANCES PERFORMANCE, AND LONG-TERM EFFECTS

Thus the measurement system has two applications: satellite position/rate sensing for use in ACS controller and initial ACS controller parameters update. Other instrumentation described later is used for gathering data on thermal and RF performance, magnitude of orbital disturbances, materials long term stability, and other LSST issues.

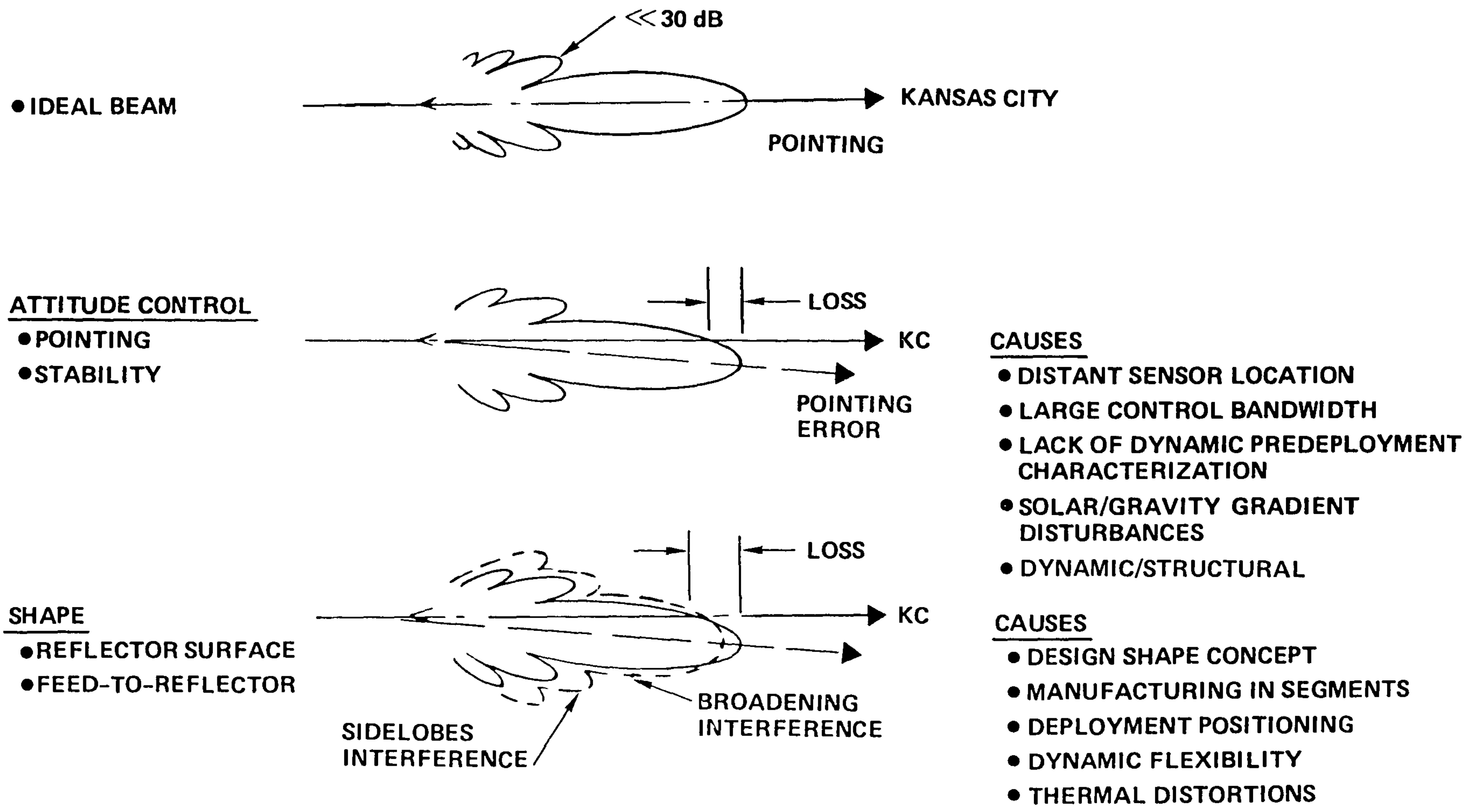
2.3.3.1 Measurement System Requirements. The objective of the measurement system is to relate, in a scalable manner, MSAT LSST configuration and disturbance issues to the antenna RF performance.

LSST disturbances affect RF performance due to 1) the need to have a robust ACS controller (which insures satellite pointing stability) and 2) large deflections affecting reflector shape and position relative to the feed, as shown in Figure 11. The measurement system attempts to determine the magnitude of each error and its contribution to the overall RF performance budget. In addition, as described in the previous section, the measurement system is an integral part of the ACS feedback loop.

Development of the measurement system requires that testing and analysis plans address LSST issues considering structural concepts, materials, blockage contour, and mesh performance. The first step is to develop ground tests at the material, component and sub-assembly levels, which are limited by size and 1g environment. Next, scale testing correlates deployment and dynamics behavior with the analytical tools being developed. The STS gives the opportunity for zero-g, controlled, disturbance testing of major assemblies (or scaled assemblies) of the satellite, giving further confidence in analysis and instrumentation scalability. Operational deployment in GEO provides the final characterization of the systems structural/mechanical, dynamic, thermal, and controls performance.

FIGURE 11.

LARGE SPACE STRUCTURE DISTURBANCES AFFECT RF BEAM QUALITY



The measurement system development follows this program evolution, summarized as follows:

Design Analysis	- Define measurements requirements
Ground Testing	- Limited to 1g, components and sub-assemblies
	- Scale testing - analytical correlation to zero-g and full scale,
LEO-STS Testing	- Limited to scale or sub-assembly testing
	- Deployment mechanics
	- Dynamics/control demonstration
	- Controlled disturbances
GEO System	
Initial Characterization	- Deployment
	- Structural/Mechanical
	- Dynamic
	- Disturbances
	- Control update
Operational	- Control performance
	- Long-term space exposure

The development flow has to be combined with a set of LSST measurements issue. For each issue of concern, a measurement plan, from ground component to full system operation, will be derived.

MSAT/LSST Measurement Issues

As shown in Table VI, the measurements are grouped in nine technology issues:

TABLE VI-1.

SUMMARY - MEASUREMENT STUDY LSST ISSUES

• DESIGN:	BLOCKAGE SURFACE CONTOUR MESH
• MATERIALS.	PROPERTIES SCATTER LONG TERM DEGRADATION EMI
• MANUFACTURING/DEPLOYMENT:	MASTS MATERIALS/JOINTS/PRELOADS REFLECTOR MESH CABLING TENSION DEPLOYMENT RATES/LOADS
• DYNAMICS·	MODELING STIFFNESS, DAMPING JOINTS, PRELOADS
• THERMAL:	CTE TEMPERATURE PROFILES
• ACTIVE CONTROLS	SENSORS, ACTUATORS
• ATTITUDE CONTROL·	CHARACTERIZATION, CONTROL LOOP UPDATE DISTURBANCES SENSORS FEEDBACK
• RF.	LSS EMI, GROUNDING RF PERFORMANCE
• LSS.	1g TO ϕg CORRELATION TEST DATA SCALING

TABLE VI-2.

DETAILED MEASUREMENT STUDY LSST ISSUES

ITEM	MEASUREMENT	VARIABLES	SYSTEM APPLICABILITY	
			WRAP-RIB	HOOP-COLUMN
1. DESIGN				
CABLING BLOCKAGE	• BLOCKAGE	- MATERIALS, SIZE		X
MESH KNIT	• LOSSES	- MATERIALS, SIZE	X	X
MESH PILLOWING	• DIMENSIONAL	- MESH PRELOAD	X	X
SURFACE CONTOUR	• DIMENSIONAL	- RIBS,	X	
		CABLES, PRELOAD		X
		1G TO ØG CORRELATION	X	X
2. MATERIALS				
PROPERTIES UN-CERTAINTIES (INITIAL)	• MODULUS, CTE, DAMPING, CREEP	- STATISTICAL SCATTER, 1G TO ØG CORRELATION, PRELOAD, SPACE ENVIRONMENT MICROCRACKS	X	X

DETAILED MEASUREMENT STUDY LSST ISSUES

(CONTINUED)

ITEM	MEASUREMENT	VARIABLES	SYSTEM APPLICABILITY	
			WRAP-RIB	HOOP-COLUMN
2. PROPERTIES DEGRADATION (LONG TERM)	• MODOLUS, CTE, DAMPING, CREEP	- STATISTICAL SCATTER, 1G TO ØG CORRELATION, PRELOAD, SPACE ENVIRONMENT, MIRCOCRACKS	X	X
3. MANUFACTURING/DEPLOYMENT	• ALL	• 1G TO ØG CORRELATION	X	X
		• SCALING	X	X
MASTS - AS BUILT	• DIMENSIONAL	NUMBER OF ELEMENTS, TOLERANCES	X	X
PINNED JOINTS	• LASH	DIAGONALS PRELOADS, TOLERANCES	X	X
PRELOAD	• DYNAMIC RESPONSE	LOADS	X	X

DETAILED MEASUREMENT STUDY LSST ISSUES

(CONTINUED)

ITEM	MEASUREMENT	VARIABLES	SYSTEM APPLICABILITY WRAP-RIB	SYSTEM APPLICABILITY HOOP-COLUMN
3. REFLECTOR - AS BUILT	• DIMENSIONAL	TOLERANCES, MESH TENSION	X	X
		PRELOADS CABLING		X
HOOP - AS BUILT	• DIMENSIONAL	NUMBER OF SEGMENTS, PRELOAD		X
FEED - STRUCTURAL	• DIMENSIONAL	ASSEMBLY	X	X
ELEMENTS	• DIMENSIONAL	ASSEMBLY	X	X
DEPLOYMENT	• RATE, LOADS	ACTUATION LOADS, DAMPING	X	X
4. DYNAMIC	• ALL	• 1G TO ØG CORRELATION	X	X
		• SCALING, MODELING	X	X
STIFFNESS VALUES	• DEFLECTION/ RATE	• MATERIALS, PRELOADS	X	X
DAMPING	• DECAY RATES	• MATERIALS, PRELOADS,	X	X

DETAILED MEASUREMENT STUDY LSST ISSUES

(CONTINUED)

ITEM	MEASUREMENT	VARIABLES	SYSTEM APPLICABILITY WRAP-RIB	HOOP-COLUMN
4. JOINTS	• STIFFNESS, DAMPING	• TOLERANCES, PRELOADS	X	X
DEPLOYMENT	• STIFFNESS, LOADS	• RATES	X	X
5. THERMAL				
CTE	• DIMENSIONAL	• TEMPERATURE	X	X
		• MATERIALS, LAYUPS	X	X
TEMPERATURE DISTRIBUTIONS	• TEMPERATURE	• LOCATION	X	X
6. ACTIVE CONTROL				
SURFACE CONTOUR	• DIMENSIONAL-SURFACE	• CABLING PRELOAD		X
		• NUMBER OF ACTUATORS		X
		• NUMBER OF SENSORS		X
FEED - REFLECTOR GIMBAL	• DIMENSIONAL-POSITION	• MASTS PRELOAD	X	

DETAILED MEASUREMENT STUDY LSST ISSUES

(CONTINUED)

ITEM	MEASUREMENT	VARIABLES	SYSTEM APPLICABILITY	
			WRAP-RIB	HOOP-COLUMN
7. ATTITUDE CONTROL POINTING, STABILITY	• DIRECTIVITY	• DYNAMIC CHARACTERIZATION • CONTROL LOOP UPDATE • SENSORS ACCURACY, RESPONSE • ACS DISTURBANCES • RCS DISTURBANCES • ORBITAL DISTURBANCES	X	X
8. RF	• NOISE, EMI	• MATERIALS, GROUNDING	X	X

1) As-Designed: cabling blockage, surface contour compliance, and mesh properties. The designer needs data relating each of these elements to RF losses, i.e., number of ribs/cables, cables size/materials, mesh size/preloads, etc. The measurement plan will take these variables into account.

2) Materials Characterization: Extensive use is made of graphite-epoxy minimum gauge materials for ribs and masts. Due to thin composites material used, properties scatter is expected to be within ±10% (3), affecting dynamic and control analysis. A measurement plan to control these variables will be developed. Long term properties in the space environment also need to be defined.

3) Assembly and Deployment: Pinner joints lash, and preloads are critical in this series of tests. Masts have multiple pinned joints that must be preloaded by the mast diagonals to have an acceptable dynamic response. The preload has to exceed the maximum expected tensile loads on the longerons. Mesh preload affects the degree of out-of-contour pillowing and surface accuracy. Deployment rates affect loads on the structure and require instrumentation. Measurements to insure correct deployment of the system are also needed for evaluation.

4) Dynamics: Modeling of the structure requires accurate definition of the structural elements stiffness and damping characteristics. Materials tests provide only partial knowledge of these characteristics, with Øg required for adequate damping tests. Ground scale tests, STS-tended assembly level tests, and operational characterization measurements will be planned to define the satellite dynamic behavior.

5) Thermal: Materials properties tests will include measurement of coefficients of thermal expansion. The expected materials data scatter and effects of thermal gradients will be taken into account. Prediction for LSST is made difficult by the complex shadowing of the structure and conductivity across joints and within components. The measurement system will address these issues.

6) Active Controls: Number and positioning of sensors and feedback errors are critical to the active control loops proposed. Definition of these sensor systems is a key objective of the measurement plan. Inertially referenced measurements will also be proposed to characterize the active control system performance.

7) Attitude Control: Key elements of the attitude control subsystem are the accuracy of the structural dynamic model, disturbances predictions, and sensors feedback. This data is used to stabilize and point the satellite, and to provide active controls feedback for surface or position corrections. Proposed measurements will provide attitude control feedback with a minimum number of rate and position sensors.

8) RF: The large satellite size, and its use of composite or dielectric (cabling) materials, with large insulated surfaces, may interfere with the RF signal or produce electromagnetic interferences. Measurements will be specified to evaluate EMI and blockage of the LSST satellite.

9) LSST relates all of the above issues into a satellite measurement system. Measurements of disturbances and satellite response are input to analytical models to predict and qualify system performance.

MSAT Error Budgets

Having defined measurements system development, and LSST issues, the next step is to define the satellite error budget to give a range for the required measurements. This budget is given in Figure 12.

The basis for this figure is 1) published Harris Corporation data presented in Table III and 2) evaluation of the design configurations and disturbances. The allowable error was obtained by performing an RF analysis for surface errors and defocus, as shown in Figure 13; a directivity loss of 0.1 dB was used to determine the desired error.

The data in Figure 12 takes into account the assumed active controls for each of the two systems.

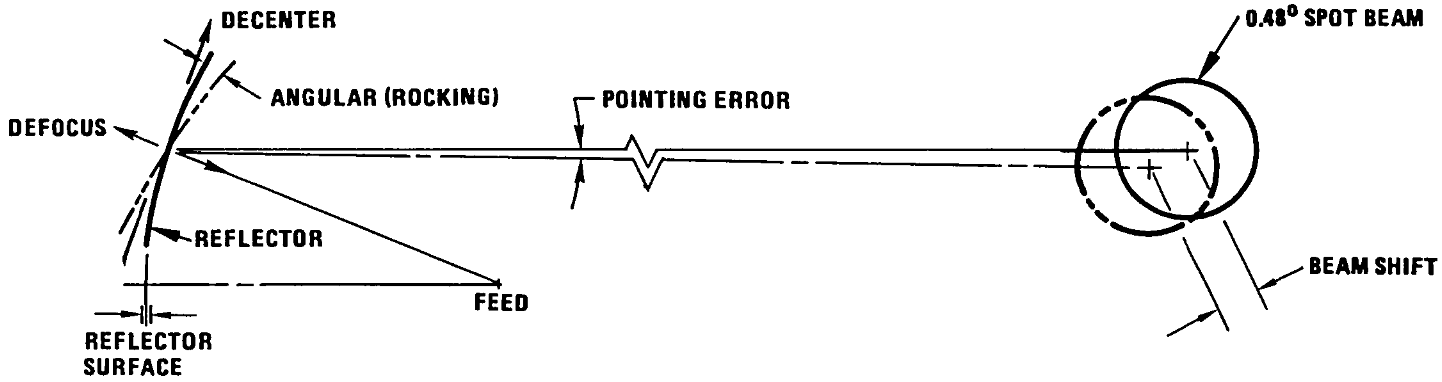
The effect of feed-to-reflector decentering on the RF performance is evaluated in Figure 14. Decentering error was based on allowing a one-quarter shift of the 0.48° spot beams; a larger allowance would require a re-evaluation of the number of beams required for CONUS coverage, specifically at the map periphery. This analysis shows a small drop of peak performance with lateral displacement of feed-to-reflector, but a pointing error in excess of the 0.12° allocation occurs. The baselined ACS actively controls satellite pointing to maintain beam shift within the allowable error.

Measurement Instrument and Sensors

The applicable instruments and sensor used in MSAT are listed here. Measurements are grouped as to function, and matching instrument/sensor types are identified. The sensors can be applied for ground, STS, and free-flyer measurements except where noted in parantheses.

FIGURE 12.

ERROR BUDGET - STRUCTURAL AND CONTROL



	RMS ERROR ESTIMATES (IN., IN DEGREES)							
	POINTING (BEAM SHIFT)		SURFACE		DEFOCUS		DECENTER	
	WRAP-RIB	HOOP-COLUMN	WRAP-RIB	HOOP-COLUMN	WRAP-RIB	HOOP-COLUMN	WRAP-RIB	HOOP-COLUMN
1 DESIGN	NA	NA	* λ/10	* λ/16	NA	NA	NA	NA
2 MATERIALS	(0 03°)	(0 01°)	0 3	(0 5)	1 0	2.0	(1.0)	(1.0)
3 MANUFACTURING/ DEPLOYMENT	(0 12°)	(0 04°)	1 0	(3 0)	4 0	4 0	(6 0)	(3.0)
4 DYNAMIC	(0 22°)	(0 12°)	3 0	(3 0)	4.5	3 0	(6.0)	(4 0)
5 THERMAL	0 03°	(0 03°)	1 0	(1 0)	1 0	2 0	(2.0)	(1 0)
6 ACTIVE CONTROL	0 08°	0 03°	NA	λ/12	NA	NA	NA	NA
7 ATTITUDE CONTROL	0 09°	0 09°	NA	NA	NA	NA	NA	NA
ESTIMATED ERROR (RMS)	0 12°	0 12°	λ/10	λ/10	λ/2	λ/2	INCLUDED IN POINTING	

NA NOT APPLICABLE
* SYSTEMATIC (NON-RMS) ERROR
(XX) CORRECTED BY ACTIVE CONTROL

FIGURE 13.

PEAK DIRECTIVITY LOSS DUE TO SURFACE AND DEFOCUS ERRORS

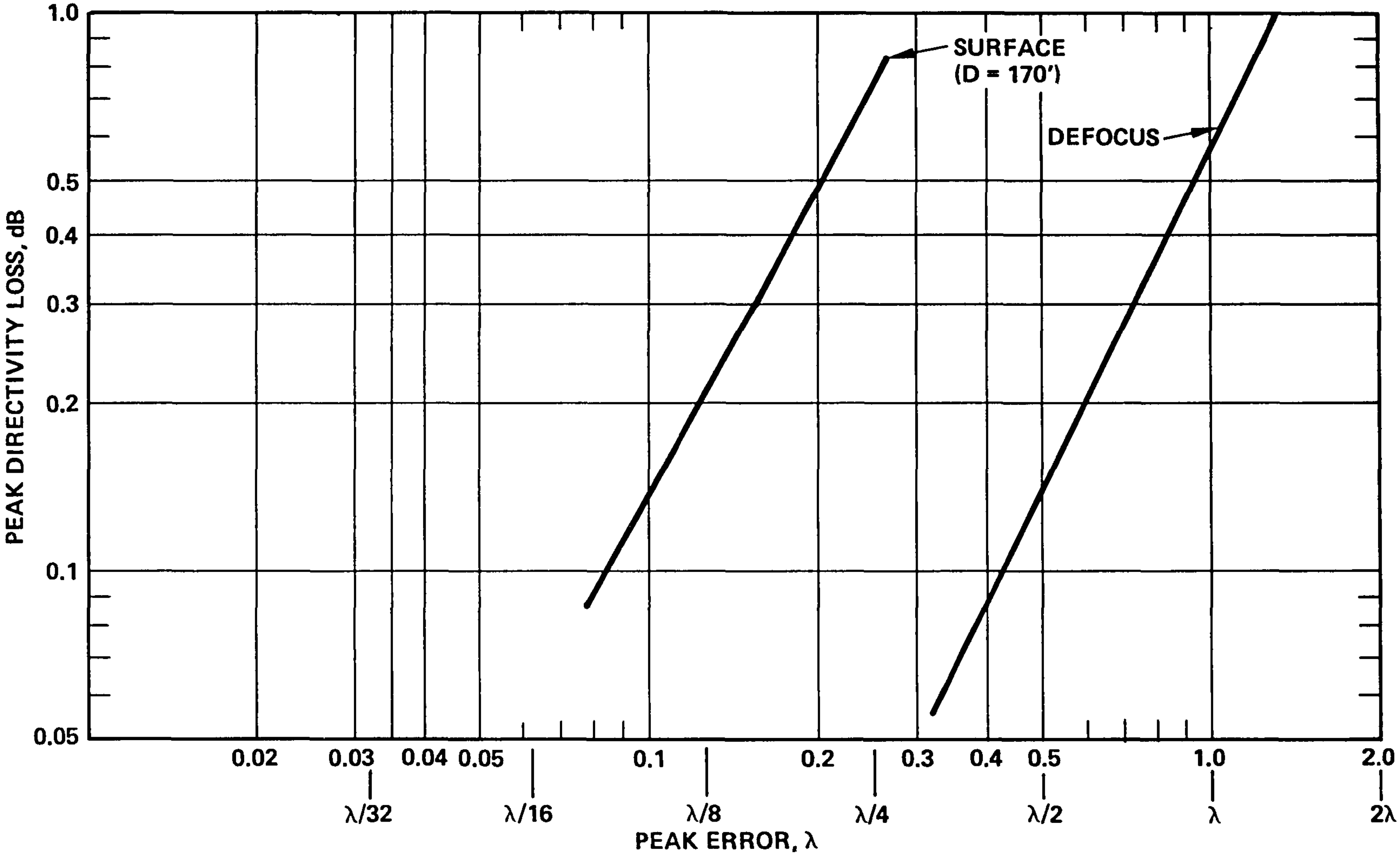
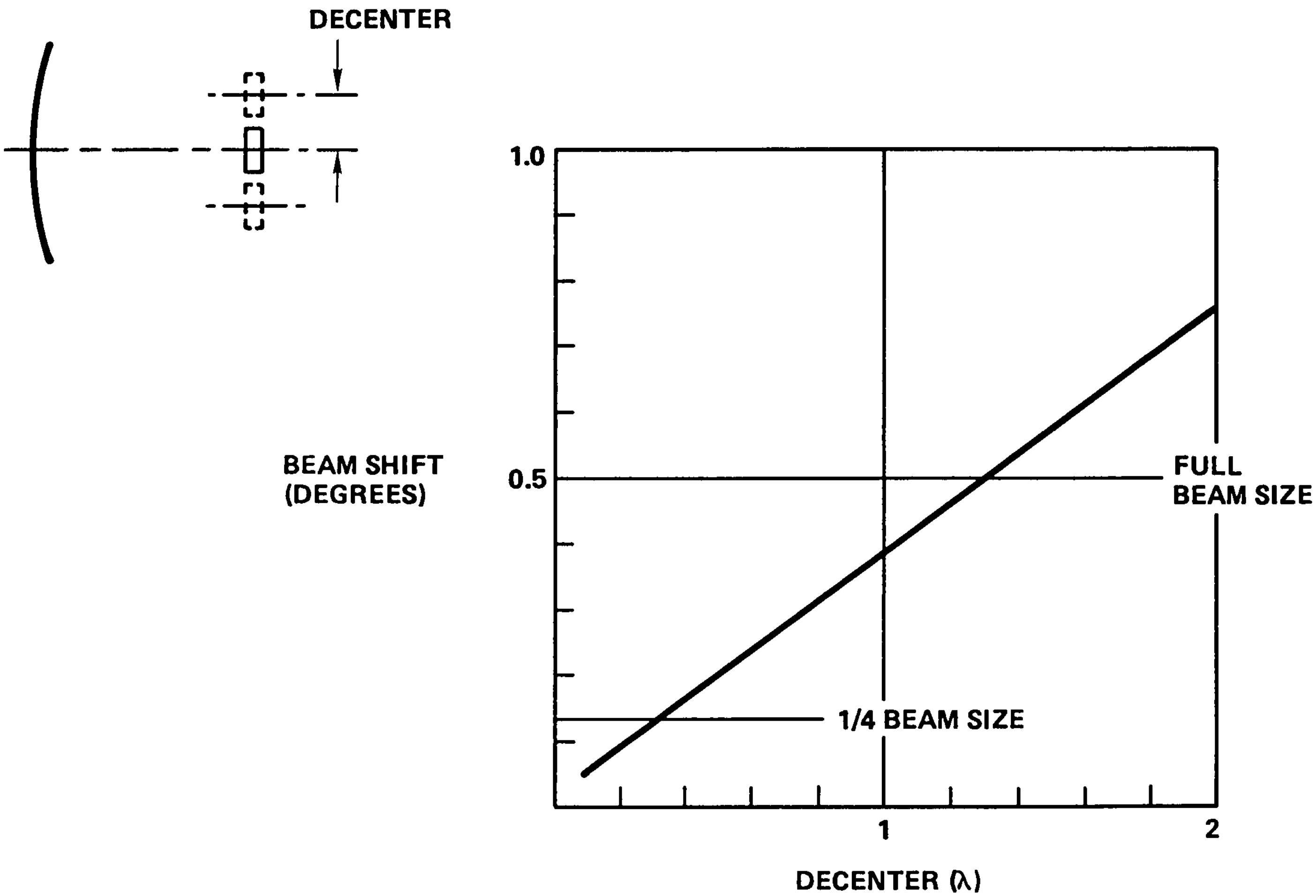


FIGURE 14.

BEAM SHIFT DUE TO LATERAL FEED-TO-REFLECTOR DISPLACEMENTS (DECENTER)



Measurement Grouping

Measurement	Sensor/Instrument
Materials Properties	Strain Gauges Quartz Tube or Rod Dilatometer (CTE) Interferometry (Ground)
Displacement - Near Distance	Linear/Rotary Potentiometers Capacitive Probes Eddy Current Probes (Non-Contacting)
- Far Distance	Laser Interferometers Cameras (Ground, STS) Photogrammetry (Ground, STS) Theodolite (Ground, STS)
Forces Acting on Elements	Piezzoelectric Transducers, Axial and Linear Moment Sensing Strain Gauges/Load Cells
Inertial Position	Gyros Rate Gyros Star, Earth Sensors
Velocity	Velocity Transducers
Acceleration	Inertial Accelerometers Piezzoresistive Accelerometers
Temperatures	Resistance Temperature Detectors
RF	Near or Far Field Scan Ground Performance Scan at GEO

Table VII provides the characteristics of LSST critical sensors. Table VII-1 shows the four laser ranging systems considered; TRW's SAMS, and JPL's SPLRS were selected for the measurement system, and their characteristics will be discussed in more detail. Table VII-2 provides data on other proven state-of-the-art instruments. Measurement accuracy, range, and rates are given for typical sensors.

TABLE VII-1.

SURFACE ACCURACY MEASUREMENT SYSTEMS

MANUFACTURER AND CATALOG NUMBER	BAND-WIDTH (Hz)	OPERATING RANGE	RESOLUTION	MASS	SHAPE	DIMENSIONS (CM)	POWER REQUIREMENT (W)	COMMENTS
TRW SAMS	0-8	± 29 7 CM EXCURSIONS AT 45 m DISTANCE	0 2 m (3) AT 45 m DISTANCE	–	BOX	12 x 15 x 40	0 3	RELIABLE PROTOTYPE, DOES NOT MEASURE RANGE CHANGES
JPL SHAPES	0 1-10	± 10 CM	0 2 mm	15 kg	–	–	20	IN DEVELOPMENT
JPL SPLRS (SELF-PULSED LASER RANGING SYSTEM)	2	30 m	0 5 mm	–	–	–	–	IN DEVELOPMENT
BARNES ENGINEERING CO	2-10	4-100 m	0 5 mm AT 100 m DISTANCE	7 kg	–	23 x 28 x 13 + 23 x 23 x 10	35	IN DEVELOPMENT

	MEASUREMENT RANGE	ACCURACY	POWER	DATA RATE	OUTPUT
1 UNIVERSAL TESTING MACHINE	0 TO 160K LBS	±0 5%	NA	NA	DIGITAL + CHARTS
2. QUARTZ TUBE/ROD DILATOMETER	-300°F TO +350°F	±0 2%	NA	NA	(*)
3 PIEZORESISTIVE ACCELEROMETER	0 TO 50 g	±0 2%	250 mW	50/SEC	(*)
4. STRAIN GAGE	0 TO 0 04 IN /IN	±0 015%	250 mW	NA	(*)
5. THEODOLITE	UNLIMITED	±0 0005 DEGREES	NA	NA	VISUAL
6 SAMS	±29 7 CM @ 45 M DISTANCE	±0 00025 DEGREES	0.3W	NA	
7. PIEZOELECTRIC FORCE TRANSDUCER	0 TO 560 LBS	±0 015%	250 mW	NA	(*)
8 ROTARY POTENTIOMETER	0 TO 3 TURNS	±0 15%	250 mW	ONCE PER SECOND	(*)
9 LINEAR POTENTIOMETER	0 TO 1 0 IN	±0 008%	250 mW	ONCE PER SECOND	(*)
10 RESISTANCE TEMPERATURE DETECTOR	-250°F TO +200°F	±5°F	250 mW	NA	(*)

(*) TYPICAL CIRCUITRY

SENSOR → BRIDGE CONDITIONING EQUIPMENT → AMPLIFIER → DATA HANDLING SUBSYSTEM

The SAMS block diagram shown in Figure 9 of Appendix A, developed by TRW under contract to NASA-Langley, was proven earlier this year at Harris Corporation, in a brass-board testing of a segment of hoop-column reflector. The expected performance shown is derived from the Harris-NASA tests. The physical characteristics of SAMS are shown in Figure 15. The size and weight of the target are small enough to allow their placement on the reflector ribs or on surface control cables. SAMS is an angular measurement sensor, i.e., it measures lateral displacement of the target with respect to the receiver. SPLRS (Figure 16) under development at JPL is a ranging measurement sensor; it measures distance from the target to the receiver. Combination of range (SPLRS) and angular data (SAMS) provides knowledge of feed-to-reflector motions. SPLRS is not as developed as SAMS but its feasibility was demonstrated in 1981.

All instrumentation and sensors selected are immune to the test environment, either on the ground or in the free-flying MSAT. In actual use, they will be calibrated to the environment by other sensors; for example, strain gauges which are sensitive to large temperature variations will be complemented with temperature detectors, thus allowing analytical correction of temperature effects. On the other hand, the test environment has a large effect on dynamic response; this issue is discussed in section 2.3.3.2.

2.3.3.2 Measurement System and Test Planning. In this section, measurement requirements and sensors/instruments described in the preceding section, are integrated into an MSAT test plan. The test plan attempts to answer the LSST issues raised.

2.3.3.2.1 Test Options and Limitations

Structural Testing

FIGURE 15.

SURFACE ACCURACY MEASUREMENT SENSOR TARGET AND RECEIVER

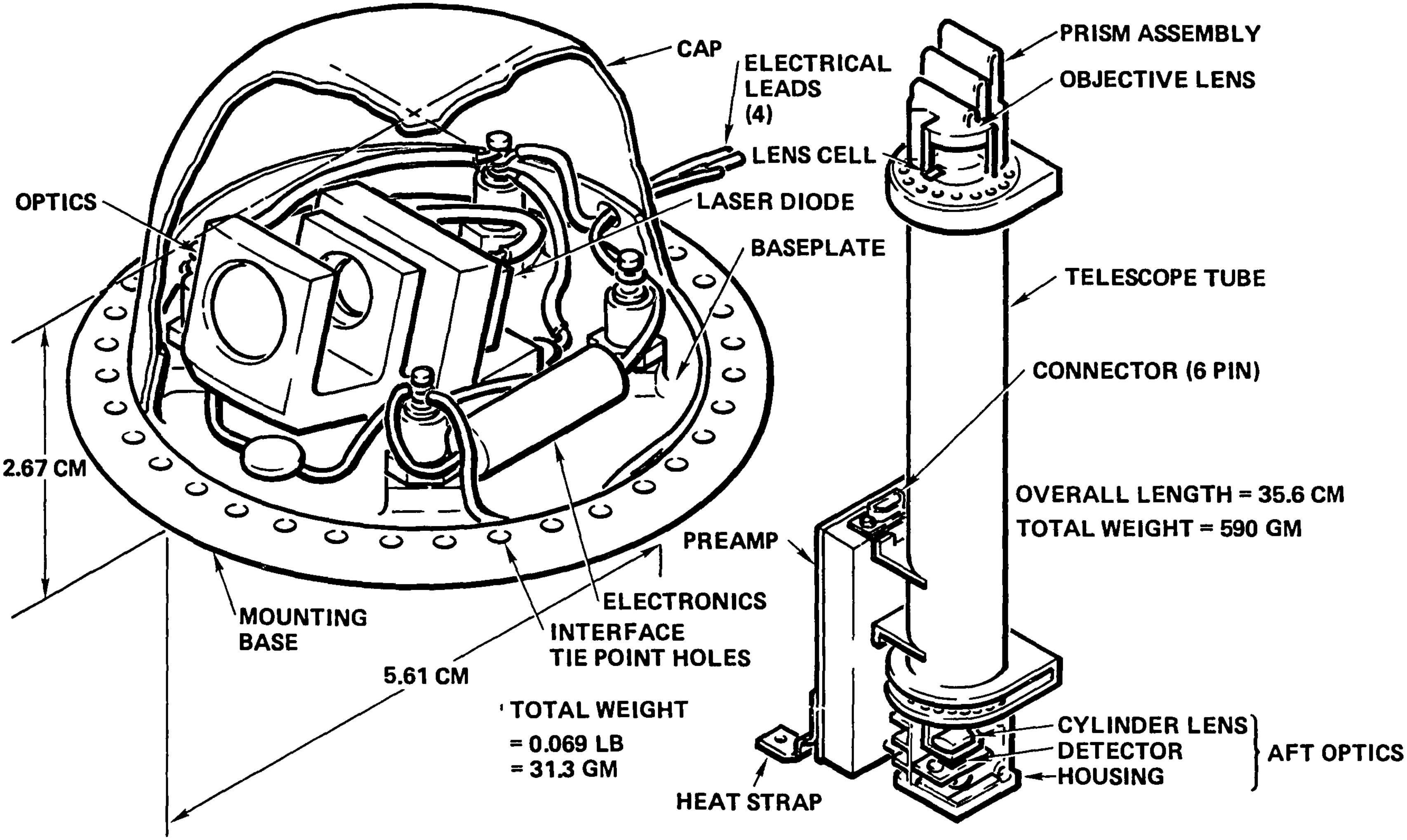
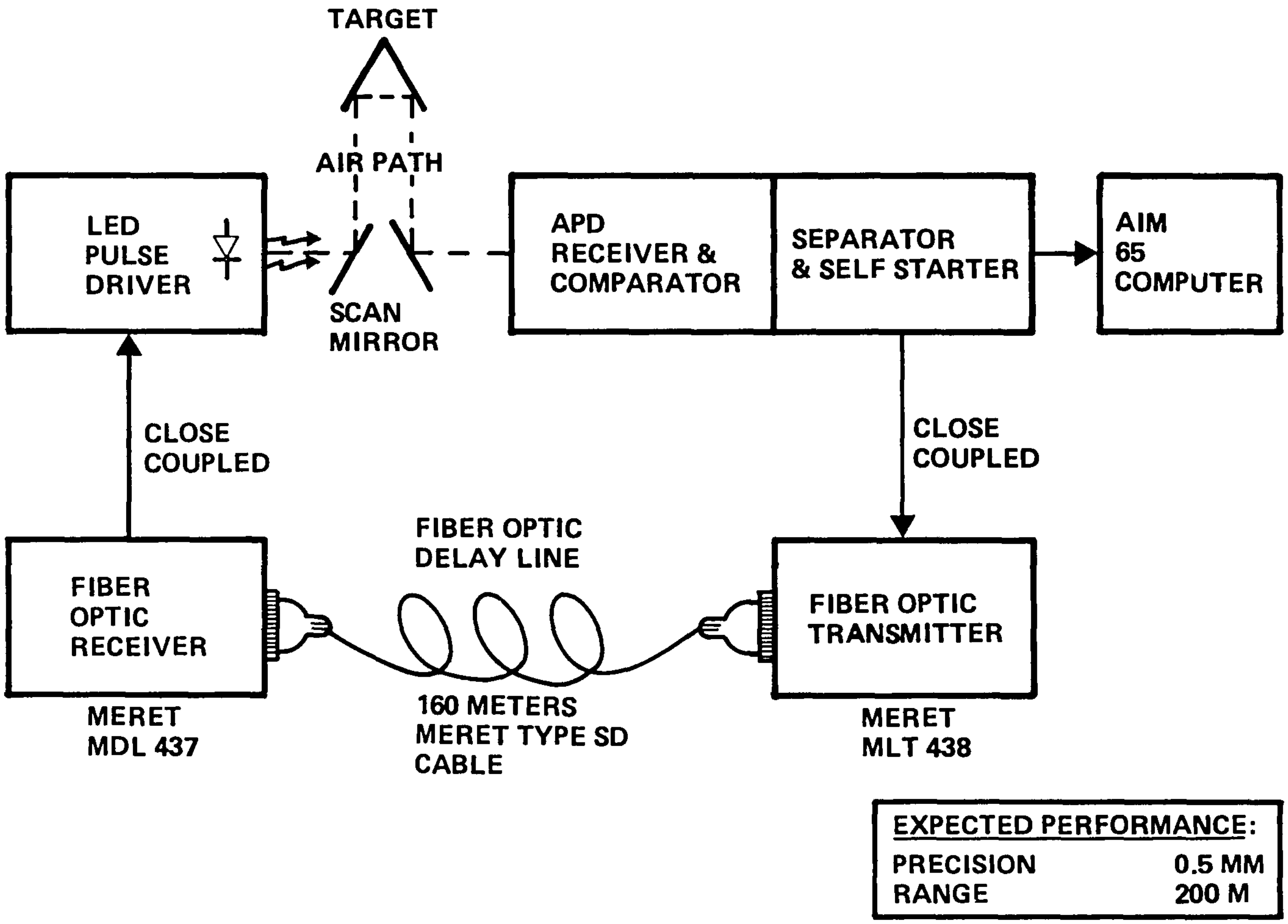


FIGURE 16.

JPL SELF-PULSED LONG RANGE SENSOR (SPLRS) BLOCK DIAGRAM



MSAT full scale structural ground testing is not practical. The structure is designed for Øg operation, and must be lightweight. In a ground 1g environment, it may not support its own weight. Testing of MSAT on the ground requires one (or a combination) of the following:

- <u>Tethering of the Structure</u> to relieve gravity loading. This can be done by a) bungee cords to elastically support the structure at various points, b) neutral buoyancy using tethered balloons (in air, or water), or c) by low friction (air bearings, long wires, etc., ...) restraint in one or more degrees of freedom. These methods inhibit some of the structural response characteristics, and require a reliable analytical model, which may be difficult to achieve for LSS structures. Also such testing requires a very large test facility, beyond any available.

- <u>Scaling of the Structure</u> to make the test specimen size more manageable. Again the key to success in scale testing is a reliable analytical model. The scale test must retain LSS features (lightweight, low-stiffness) since modal response simulation is critical. The scaling parameters are a) mass distribution, b) extensional, torsional, and flexural stiffness, and c) preloads and joints damping characteristics. For a structure that is already using minimum gauge materials, and lightweight assembly methods, scaling is not trivial.

- <u>Separate Testing of Structural Elements</u>, i.e., test mast or reflector separately. Separate testing may answer some of the questions raised by tethering or scale testing, but it introduces additional uncertainties at the interface response between the elements.

- <u>Truncating Elements of the Structure</u> such as testing only 3 or 4 bays of the mast or a few full scale ribs on the reflector. These tests are useful for mechanical development and to acquire data points on structural response.

The proposed test plan will make use of scale testing, element (in place of full system) full scale tests, and truncated structures for mechanical development tests.

Ground testing by itself will not provide an adequate resolution of the structural response, and must be combined with orbital, Øg, tests. The STS is the natural vehicle for Øg tests. Ideally, following ground testing, the same test specimen is flown and tested in orbit. Confidence can be established in the analytical model to predict orbital behavior from relatively inexpensive ground tests.

Both ground and STS impose limitations on MSAT tests, summarized in Table VIII. Ground test limitations will be addressed first:

- Pendulum effect acts to damp or excite the response of a vertically oriented structure. If the mass is below the support, damping occurs; if the mass is above the support, added momentum is introduced into the test.

- Air resistance due to drag on structural motions or air currents in the test building will damp or excite the structure. Drag must be removed (vacuum) in the test, or taken into account analytically.

- The structurel response of present satellites is linear, and structural damping can usually be specified globally as a constant because of the relatively high structural stiffness compared to less than 1% damping. The final damping constant used in analysis of present systems is derived from ground tests. This technique cannot be used for MSAT where multiple pinned joints (mast, reflector rib, ...) and preloaded cabling are extensively used; structural response may not be linear, and

TABLE VIII.

LSS TESTING LIMITATIONS

• GROUND TESTING LIMITATIONS	REQUIRES
• PENDULUM EFFECT ALTERS DEFLECTION RESPONSE	ϕ g
• AIR RESISTANCE PROVIDES UNWANTED DAMPING	VACUUM
• 1g GRAVITY LOAD ON JOINTS AND STRUCTURE AFFECTS DAMPING	ϕ g
• LSS SIZE WILL NOT FIT TEST FACILITIES	SCALING
• LSS IS NOT ABLE TO SUPPORT 1g GRAVITY	ϕ g
• STS TESTING LIMITATIONS	
• STS DISTURBANCE LEVELS	DRIFT FLIGHT
• STS LIMIT CYCLING	DRIFT FLIGHT
• COST	SIZE LIMITATION
• TIMELINES	TEST PREDICTABILITY
• SAFETY	PROVEN CONCEPT
• TEST SPECIMEN RETRIEVAL	RESTOW CAPABILITY

joints/cabling damping may be a major factor in dynamic analysis. This problem is probably the single most critical item in obtaining useful data from ground testing.

- Lack of adequately sized facilities and the inability of the structure to support its own weight, previously mentioned, are other limitations on ground testing.

STS testing limitations (Table VIII) are discussed next:

- STS orbiter is an active vehicle with men aboard and its operational disturbance levels may be excessive for MSAT testing. Crew motions/reactions, fuel cells, radiator, and water system operations provide significant inputs to MSAT dynamic response. The test specimen support must isolate these effects, or quiescent flight of the STS for a period of 1 to 2 hours must be specified. Alternately, these disturbances can be measured real-time and corrected for analytically. This adds complexity to the already complicated analytical tool.

- Limit cycling of the RCS to maintain STS attitude is the major STS-induced disturbance. Inhibiting of the RCS will be required for the test duration.

- An MSAT test will occupy from 1/3 to 1/2 the orbiter cargo bay. Assuming a compatible payload to share the flight, cost is still high (over $50 million). Added to this is the cost to design the MSAT/STS interface, and STS integration.

- STS testing timelines are critical since the flight is limited to a few days, and disturbance controls discussed above limit test time. STS testing must be planned to occur on time, within available time windows. Measurement systems must be reliable.

- STS imposes manned system safety requirements on its payloads. Deployment reliability, ability to resist disturbance loads, and contingency ejection will add weight and cost to the specimen.

- Test specimen retrieval is desirable due to its cost and possible reuse. MSAT does not require retrieval capability operationally. Ability to restow (in order to retrieve) will add weight, complexity, and cost to the test specimen.

RF Performance Testing

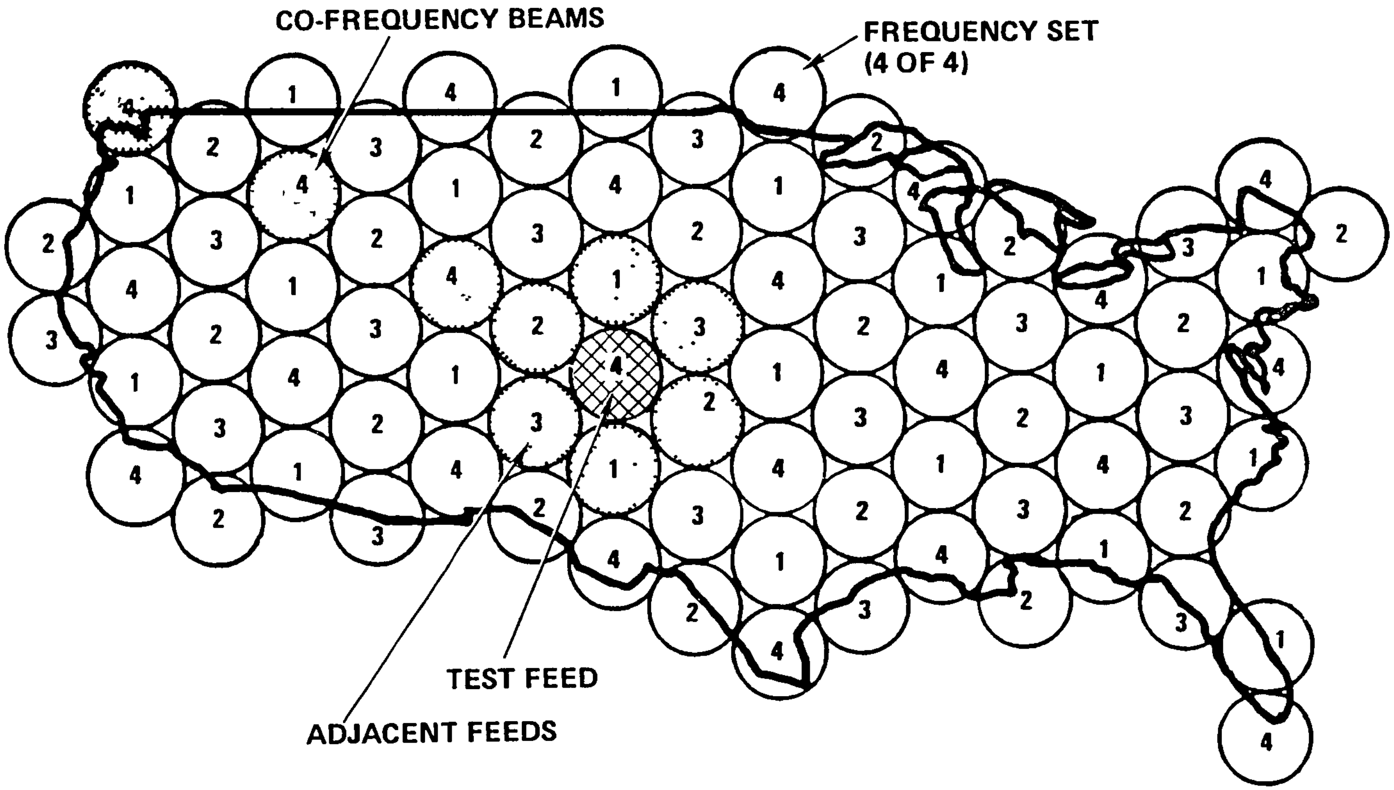
RF performance testing of MSAT is required to develop the feed system and the reflector mesh/ribs assembly. Full scale tests are costly, because of the need to enclose the large satellite in a facility to protect it from wind loads. This facility has to be RF transparent (radome structure). The reflector can be scaled, but scaling down of the feed system is not recommended; the feed development is size critical since wavelength-to-feed dimensional relationships are important for interference evaluations. In the test plan the feed is maintained full size, while the reflector is scaled to 1/2 to 1/3 its size.

Frequency reuse, and close feed spacing, lead to interference between feeds. It is not practical, or required, to test all 83 feeds. Development can start with one or more feeds; once a concept shows promise, feeds that may interfere will be added to the test. In general the feed system will include feeds adjacent to the main test feed, plus all feeds using the same frequency that are in line with it. This is shown in Figure 17; 10 feeds (out of 83) are required to test the four frequency set feed system of the offset-fed antenna.

RF performance testing can be done in near-field or in far-field measurements. Near-field measurement require added facilities to measure

FIGURE 17.

FEED TEST CONFIGURATION



the RF field and analytical tools to predict the far-field performance. These techniques are being developed for LSST. For MSAT, far-field testing is recommended due to cost and data applicability.

Far field is defined as distance exceeding $(2D^2/\lambda)$. At λ (wavelength) = 1.13 feet, and D (diameter) = 60 feet, the far field is approximately at 1.25 miles. This suggests that the test transmitter be located on an overflying aircraft. This will keep the reflector in a horizontal position. In an inclined position the reflector ribs and mesh will sag unsymmetrically. It is preferable to keep the reflector horizontal (pointing up). In this position, rib supports and mesh preload bias should bring the mesh surface within tolerance.

Other testing of MSAT includes thermal and ACS performance, EMI levels, and disturbance spectrum evaluation.

Thermal measurements will include thermal loads (inputs), structural shadowing and structural thermal constants (thermal loads into the structure), and structural response to the thermal loadings (distortions, materials properties). Instrumentation consists of temperature detectors, with the laser measurement system providing distortion data. Analysis will evaluate the long term material properties.

ACS performance measurements will not require additional instrumentation since the ACS is fully instrumented.

MSAT's large size and possible need for RF-transparent (dielectric) materials require careful design techniques to prevent surface charging and resultant EMI. Measurements will include instrumentation to evaluate EMI.

Environmental and ACS operational disturbances will be evaluated during MSAT test. Ground disturbances include air currents and gravity.

STS disturbances include manned motions, orbiter RCS and other active systems, and LEO environment. Operational disturbances include all the GEO orbital environments, as well as active ACS and RCS satellite subsystems. Instrumentation will be the same as for structural dynamic characterization (e.g., strain-gauges, accelerometers, laser sensors) and will use analysis to isolate the disturbance levels.

2.3.3.2-2 Position and Rate Sensing System. The SAMS and SPLRS laser sensors, described in Section 2.3.3.1, have been integrated into a position rate sensing system. This system is at the heart of structural dynamics and control measurements of MSAT. It provides real-time position/rate data to the ACS controller, as well as measurements on the dimensional status of the structure. It is later coupled with complementary strain-gauges and accelerometers to give a complete status of MSAT.

The detailed analysis, leading to selection of the position/rate sensing system, is given in Appendix A. For the offset-fed antenna, triangulation and trilateration (ranging) techniques were compared; system configurations for each are shown in Figures 5 and 6 (App.A). Based on reduced complexity the angular system was baselined.

For the hoop-column configuration, only SAMS (angular displacement) sensor is used. Since mast and reflector are centered, and their distance (range) can be accurately predicted. Figure 8 (App.A) shows the sensing system and target locations. Hoop-column measurements, testing and cost were not carried further due to similarities of issues with wrap-rib.

Table 2 (App.A) details the specifications and capabilities of the selected position and rate sensing system.

2.3.3.2-3 Test Plans. Test planning follows the MSAT development plan (Figure 3). It is assumed that generic LSST development tests were accomplished thru 1986, prior to MSAT full scale development commitment. This section provides MSAT specific test planning starting in a 1988 Phase B effort, leading to program authority to proceed by 1990, and, finally, a satellite launch data of 1995.

Testing outline summarized in Table IX, is detailed in this section. Test numbering, for convenience only, is divided into mast testing (1.0), reflector testing (2.0), antenna system scale tests (3.0), and satellite tests (4.0). Some of these tests share the same elements. For example, the full scale mast dynamic test specimen (1.3) will also be used for the STS orbital test (3.3); the reflector dynamic and thermal test specimen (2.3) is used in ground RF testing (3.2), and then on the STS test (3.3).

The major development test flow is shown in Figure 18. It is assumed that a ground RF test facility will be available to MSAT by 1988. The first RF test (3.1) consists of the reflector mesh, supported by simulated ribs. This will allow testing of various mesh configuration, mesh support and preloads, as well as varying number of ribs. Scale of the reflector is the largest that can be accommodated by the test facility, assumed to be 1/3 scale for this study. Coupled with this reflector, full size feed development is planned. From 1 to 10 feeds are used in various phases of this test. The purpose of the test is to provide RF data to be used in antenna system design selection.

The other tests shown in Figure 18 are all keyed to an STS orbital flight test (3.3), which is planned for eacly '92 (Figure 3). Schedule for this test allows for Critical Design Review (CDR) and full scale MSAT development to meet a 1995 launch. The mast selected is the short leg of the offset-fed antenna L-shaped mast. Both short mast (1.3), and 1/3 scale reflector (2.3) undergo deployment, structural, dynamic and

TEST	MEASUREMENT: PROPERTIES	DEPLOYMENT	CONFORMANCE	DYNAMIC	THERMAL VAC	CONTROL	RF	EMI	LOCATION: GROUND	STS-TENDED	GEO: INITIAL	OPERATIONAL	LONG TERM
1. MAST TESTING													
1.1 MATERIAL COUPONS LONGERONS	X							X	X				
MATERIAL COUPONS DIAGONALS	X							X	X				
1.2 FULL SCALE – 3 BAYS		X	X	X	X				X				
1.3 FULL SCALE SHORT MAST		X	X	X	X			X	X				
2. REFLECTOR TESTING													
2.1 MATERIALS RIBS	X							X	X				
MATERIALS MESH	X						X	X	X				
2.2 FULL SCALE – 4 RIBS/MESH		X	X	X					X				
2.3 1/3 SCALE		X	X	X	X				X				
3. ANTENNA – SCALE TESTS													
3.1 MOCKUP DEVELOPMENT							X		X				
3.2 GROUND TEST			X				X	X	X				
3.3 STS FLIGHT TEST	X	X	X	X	X	X	X	X		X			
4. SATELLITE TESTING													
4.1 ELEMENTS	X								X				
4.2 ALL-UP		X	X	X	X	X	X				X	X	X

Table IX – Tests Outline – Offset-Rod Satellite System

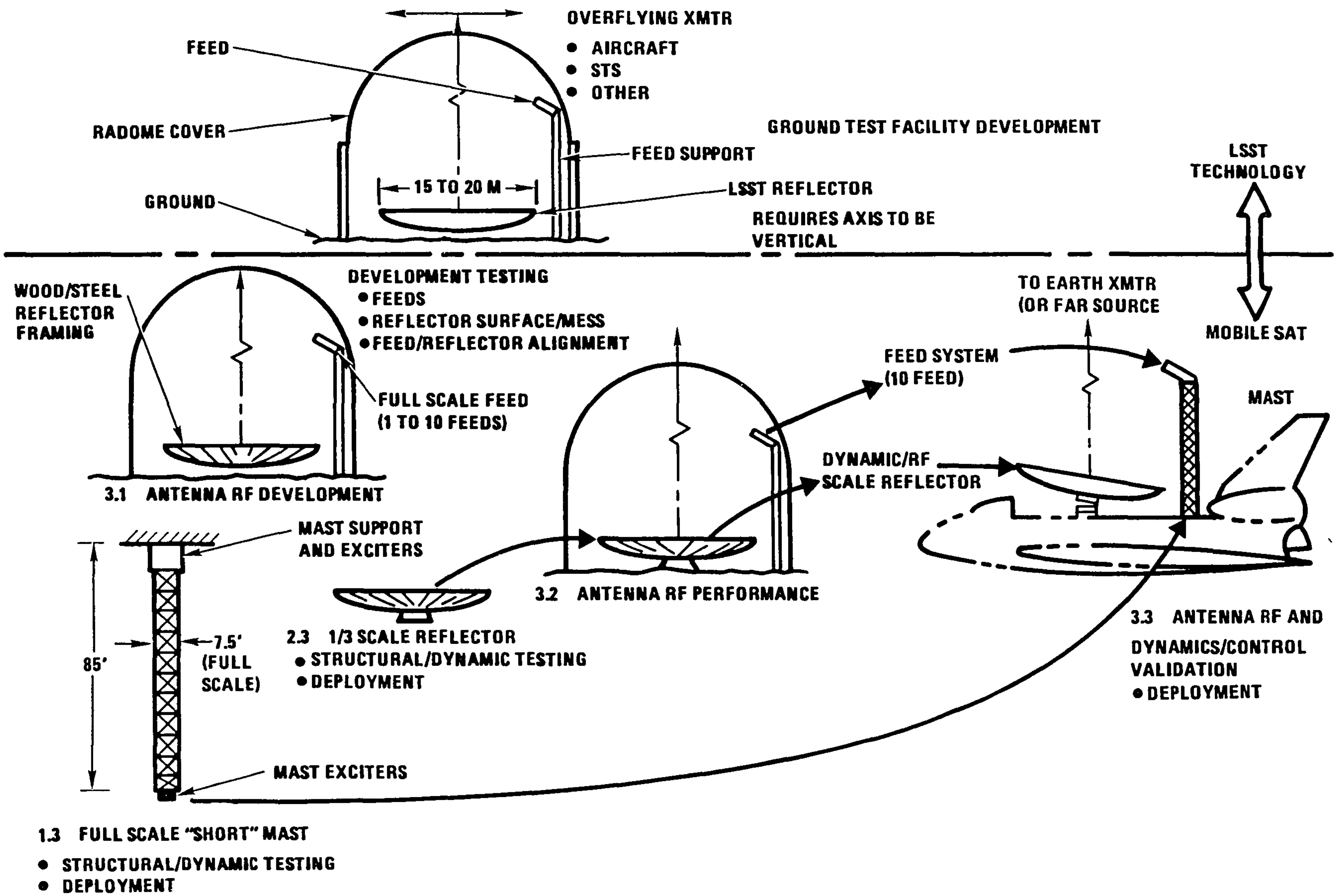


Figure 18 – Antenna System Development Test Plan

thermal characterization testing. The reflector is then used in (3.2) for antenna RF performance testing. All test elements are then integrated into an STS orbital test. This test flow allows maximum data scaling for analytical tools validation.

Other tests of MSAT components, shown in Figure 19, consist of the following:

- Materials Characterization Tests (1.1, 2.1, 3.1). These are mostly material coupon tests to obtain definitive properties inputs for structural and thermal analysis. The test coupons are obtained simultaneously from actual parts used in ground and orbital testing. For the reflector mesh, additional RF performance tests are planned.

- Mast Mechanical Development may involve as few as three bays, as shown in 1.3. This test develops canister deployment, longerons locking features, and diagonals preload and stowage/deployment. Its size allows this mast to be tested dynamically using standard test facilities.

- Reflector Mechanical Development (2.2) requires a facility that allows tethering of the ribs during deployment tests. This test develops ribs deployment and mesh management (stowage, preload, support, etc.). Existing facilities (LMSC) may be able to accomplish this test.

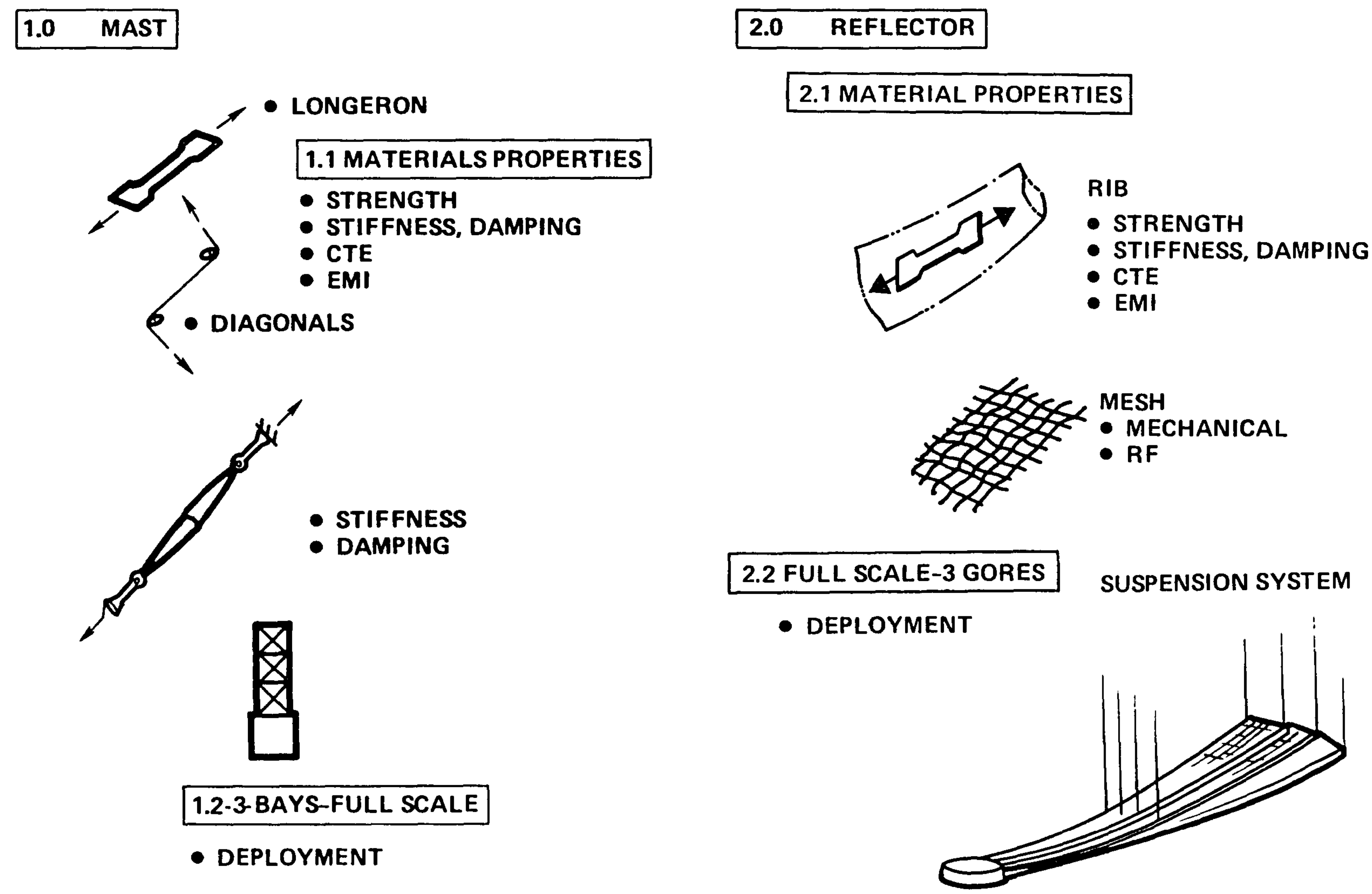
2.3.3.2-4 Test and Measurements Description. This section details the tests configuration and the measurement system proposed for each test. In all cases, only those measurements related to LSST aspects of the test are detailed; other measurements are assumed to be required for any test of this kind. Test and measurements descriptions are then used for costing analysis in Section 2.3.3.3.

Test 1.1, 2.1, 3.1 - Materials Properties Testing.

Three types of materials are of concern: 1) cabling used in mast diagonals, hoop-column surface control, and hoop supports, 2) RF reflective

FIGURE 19.

COMPONENT TESTS OUTLINE



mesh, and 3) thin gauge composites. In addition, longeron joints properties are of concern because of their contribution to system damping.

Critical LSST issues that must be resolved by Long-term In-space exposure are 1) for cabling, creep stability during long term storage and under constant preload in space environment, 2) for mesh, shape conformance versus preload to avoid underdeterminate saddling and RF performance verification, and 3) for thin gauge composite, material properties scatter and long term stability. Accelerated-aging ground test will be corelated with long-term exposure in space to evaluate effect of moisture loss, space radiation, and temperature cycling on the materials.

Table X details data requirements and proposed testing.

Test 1.2 Mast Development - Full Scale, 3-Bays

The purpose of this test is to develop mast mechanical stowage and deployment. Utilizing 3-bays will eliminate major LSST issues associated with gravity loads on a multiple bay mast.

The remaining LSST issues for this test concerns development of longeron joints tolerances, and cabling preload system to, achieve reliable deployment/stowage, and mast deployed stiffness.

This mast is installed on a shaker and taken through sinusoidal and random vibration to characterize its response at varying combinations of diagonals preload and pin-joints tolerances.

Test measurments are visual, dimensional, strain-gauges, and accelerometers; no measurement technology issues exist.

Test 1.3 - Full Scale Short Mast

The short leg of the offset-fed mast is used for this test. It is long enough to qualify as an LSST assembly while remaining manageable on the ground.

Table X. Materials Properties Testing					
Test	Cabling	Mesh	Composites	Longeron	LSST Issue
Material Properties					Statistical Scatter
Tension	6/spool	--	4/rib	3 each	Statistical Scatter
Bending	---	--	4/rib	3 each	Statistical Scatter
Shear	---	--	4/rib	3 each	Statistical Scatter
Thermal (CTE)	4/spool	4/roll	2/rib	2 each	Scatter
Moisture	3/spool	4/roll	2/rib	2 each	Stability
Longeron Assembly	---	--	---	Each	Dimensional
Creep (Microcracking)	3/spool	--	3/rib	--	Long Term Stowage, Preload
Long Term Environment	3/spool	--	3/rib	--	7 Year, Accelerated
Saddling (Preload)	---	4/roll	---	--	Preload Control
RF Reflectivity	---	4/roll	---	--	Reflectivity

Note:
Above tests are for 1/3 scale tests (1.1, 2.1) and are repeated for satellite (3.1)

This mast will undergo ground tests followed by an STS test flight (3.3).

LSST issues to be answered by this test are:

- Cabling tension versus dynamic response and damping
- Longeron joints versus dynamic damping
- Deployment mechanics
- Stowage mechanics if required
- Longeron dimensional length variations versus mast alignment and select longerons location
- Thermal response (distortions)

Proposed test is shown in Figure 20. The mast can be deployed and dynamically tested both horizontally and vertically. Correlation of the two-axis test results provides data of the 1g effect on its response.

The mast test makes use of SAMS laser angular (displacement) measurements to define its real-time deflections. As seen in Figure 3, measurements development occurs in the 1989-1990 period, in time to support this test.

Test 2.2 Full Scale - 3-Gores Reflector Test

Feasibility of tethering 4 ribs, to produce a three-gores test specimen, has been proven by LMSC on the wrap-rib reflector. This test makes use of this technology to develop MSAT specific mechanical deployment techniques.

LSST issues to be answered by this test are:

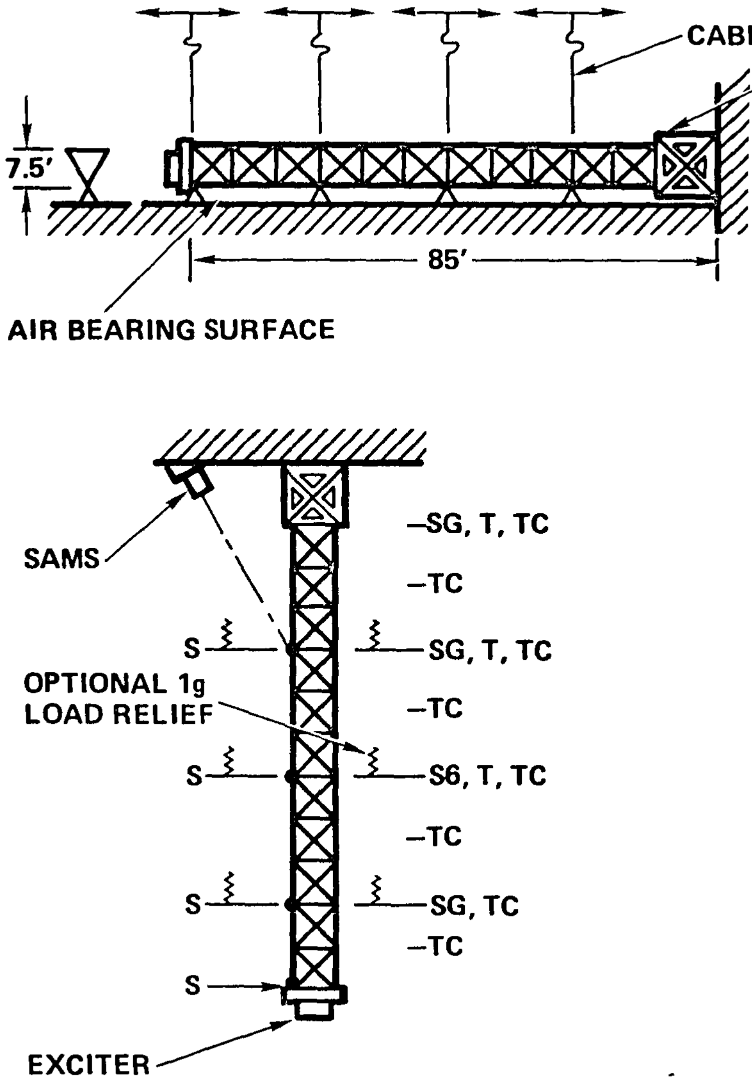
- Ribs stowed configuration to minimize strains on the wrapped and stacked ribs
- Long term stowage, composites creep
- Long term stowage, composites micro-cracking and properties degradation
- Mesh management:
    - Stowage and deployment
    - Automated restowage for retrieval
    - Controlled mesh preload after deployment for accurate shape repeatability
- Integration of SAMS receivers into hub and targets on ribs

Measurements include the following:

- SAMS will measure deployed alignment
- Strain-gauges on ribs to measure stowed stress levels (3 strain-gauges at 3 rib locations x 4 ribs = 12)

FIGURE 20.

MAST GROUND TEST #1.3



HORIZONTAL TESTING

- OPTIONAL: AIR BEARING OR TETHERED (CABLING) SUPPORT
- DEPLOYMENT AND RETRACTION DEVELOPMENT
- MODAL RESPONSE VIBRATION
  LIMITATIONS: 2 DoF (MAY BE 3)
  DRAG (AIR, SUPPORTS)

VERTICAL TESTING

- OPTIONAL: 1g LOAD RELIEF
- DEPLOYMENT AND RETRACTION DEVELOPMENT
- MODAL RESPONSE VIBRATION
  LIMITATIONS: 1g EFFECT ON JOINTS DAMPING
  AIR DRAG
- THERMAL LOADING AND RESPONSE (DEFLECTIONS)

MEASUREMENTS:

S – SAMS ANGULAR SENSORS: (4 TARGETS)
SG – STRAIN-GAUGES: 6/LOCATION X 4 LOCATIONS (24)
T – TENSIOMETERS ON CABLING: 6 CABLES/LOCATION X4 LOCATIONS (24)
TC – THERMOCOUPLES: 3/LOCATIONS X8 LOCATIONS (24)
– ENVIRONMENTAL CONDITIONS: (AS REQUIRED)
  – TEMPERATURE STABILITY
  – AIR CURRENTS (MINIMIZE)

TEST VARIABLES:

- TEST AXIS (VERTICAL, HORIZONTAL)
- CABLING PRELOADS
- LONGERON JOINTS TOLERANCES
- HEAT LOADING

- Thermocouples to measure temperature gradients
  (2 thermocouples at 6 rib locations x 4 ribs = 24)
- Environmental temperature and air currents
- Theodolite to measure mesh saddling
- Visual deployment

Test 2.3 - 1/3 Scale Reflector Ground Testing

At 1/3 scale this reflector measures 17 feet in diameter. It is assumed that ground facilities will exist in the late 1980's for RF and thermal vacuum/dynamic testing.

LSST issues to be resolved by this test are:

- Deployment and restowage mechanics, and mesh management
- Dimensional Characterization
- Dynamic response (in 1g, but in vacuum)
- Long term stowage effect on ribs mechanical properties
- Thermal vacuum dimensional stability

Test flow is shown in Figure 21.

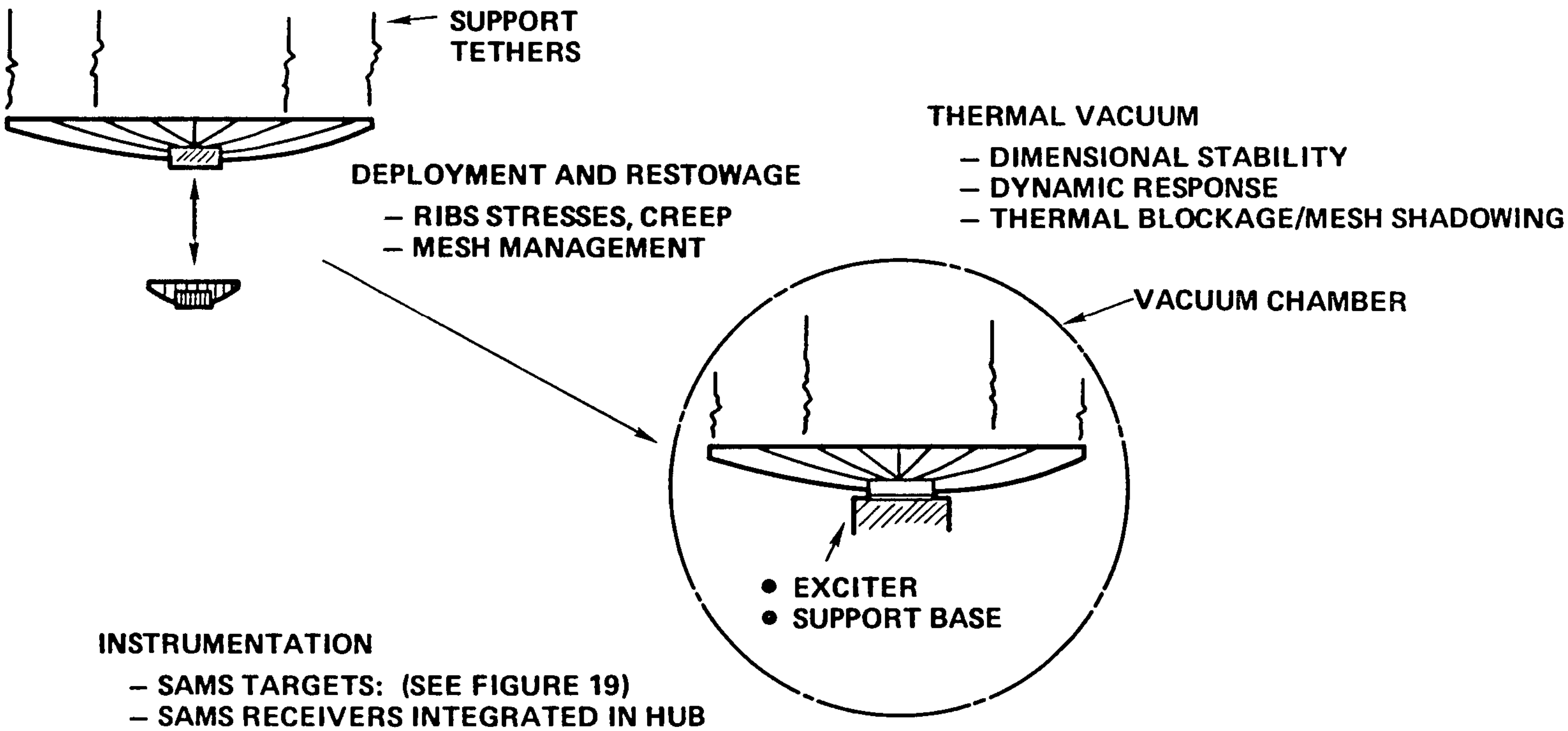
At the completion of this test, the reflector is used for RF ground development testing (3.1 and 3.2) and finally will fly on STS (3.3) to correlate test data obtained in 1g, and thus qualify the analytical scaleability.

Measurement technology issues concern SAMS integration into the reflector structure. All other measurements are standard. The same test instrumentation will be carried through the 3.0 series of tests.

Data acquisition and reduction is well within state-of-art. Accurate dynamic response analysis of this data is an LSST issue that must be resolved.

FIGURE 21.

1/3 SCALE REFLECTOR GROUND TESTING - TEST #2.3



INSTRUMENTATION

- SAMS TARGETS: (SEE FIGURE 19)
- SAMS RECEIVERS INTEGRATED IN HUB
- THERMOCOUPLES 4/RIB
- STRAIN-GAUGES 6/RIB
- MESH PRELOAD – THEODOLITE OR EQUIVALENT SHAPE MEASUREMENT
- ACCELEROMETERS ON 6 RIBS, 3 EACH
- VISUALLY (AUGMENTED) INSPECTION OF RIBS AND MESH PRE-POST TESTING

Test 3.1 - Antenna Parametric RF Development

This test is depicted in Figure 18. The reflector ribs are simulated. Reflector test variables include number of ribs, mesh selection, and mesh support and preload. Purpose of these reflector tests is to provide system engineering with parametric data used in selecting satellite and scale tests reflectors. A 1/3 scale reflector will allow use of existing (late 1980's) facilities.

This test will also develop the feed concept. Several full-scale feed configurations can be evaluated, as well as evaluating shared frequency interferences between feeds. An overflying aircraft will provide the transmit input. The aircraft position will be measured, and it will sweep the antenna field to provide performance data.

LSST issues to be resolved by this test are:

- Reflector design parametrics: Number of ribs, mesh selection, and mesh preload
- Feed development and selection

There is no critical measurement issues. The transmitter on the aircraft, aircraft position sensing, and calibrated standard gain antenna (signal strength) technology is state-of-art.

Test 3.2 - Antenna RF Development

This test (Figure 18) provides ground evaluation and qualification of the reflector and feed configurations selected in 3.1 The reflector is initially tested in test number 2.3 for structural and thermal response. The feed will also be structurally evaluated, but does not pause LSST structural issues.

Same facilities as previous test (3.1) will be used. It will fully characterize the antenna performance. One critical correlation factor between ground and STS testing is sagging of the mesh in 1g environment. Mesh dimensional characteristics will be measured and monitored in this test.

SAMS is an integral part of this test measurement.

Test 3.3 - STS Flight Testing

For this test (Figure 18) the full scale, 10 feeds, assembly from test 3.2, will be supported from the "short" full scale mast (Test 1.3). The reflector is from tests 2.3 and 3.2. All these elements are designed to the STS requirements discussed in section 2.3.3.2-1.

Due to physical necessity, the feed/mast is supported in the STS cargo bay on a different pallet than the reflector. This increases cargo bay length used, thus adding to STS charged costs.

LSST issues to be resolved are:

- Mast and reflector deployment (and restowage)
- Mast response dynamics (variable diagonals preload)
- Reflector response dynamics
- Thermal dimensional stability, shadowing effect
- Mesh management: Preload, shape, restowage
- Feed-reflector RF performance

Measurements systems are identical to those specified in the leading ground tests (1.3, 2.3, 3.2).

Input disturbances to excite the structures are as follows:

- Thermal: STS orbit, plus STS orientation control
- Dynamic:
  - Monitor STS induced disturbances
  - Exciters (gyros, shakers, ...) at feed for mast, and hub for reflector

A typical STS flight test timeline is shown in Figure 22. Measurements and test equipment must be reliable to meet the narrow test window. STS disturbances cannot be inhibited for the whole test duration; they will be measured by accelerometers at the support base. Data handling support for the measurement system is estimated at less than 20 Kbits, well within STS capability.

Test 4.0 - Satellite Measurements

The preceding tests provide the data base from which MSAT satellite is developed and flight qualified. By CDR (Figure 3), the analytical tools are fully developed and previous test data measurements are used to validate the analysis. This reliance of MSAT on test data scaleability is critical to mission success, since MSAT's size and lightweight structure, precludes its testing on the ground prior to committing to flight.

Measurement system LSST issues of concern are broken down in operational phases as shown:

A) Launch

- STS launch environment on the flexible mesh, and stowed ribs

B) Deployment and Initialization

- Mechanical and control stability during deployment
- Satellite (masts, reflector, ...) dynamic response characterization and ACS controller parameters updating
- RCS and ACS disturbances characterization and decoupling from satellite response
- Orbital disturbances (thermal, solar, gravity, ...) characterization and MSAT response

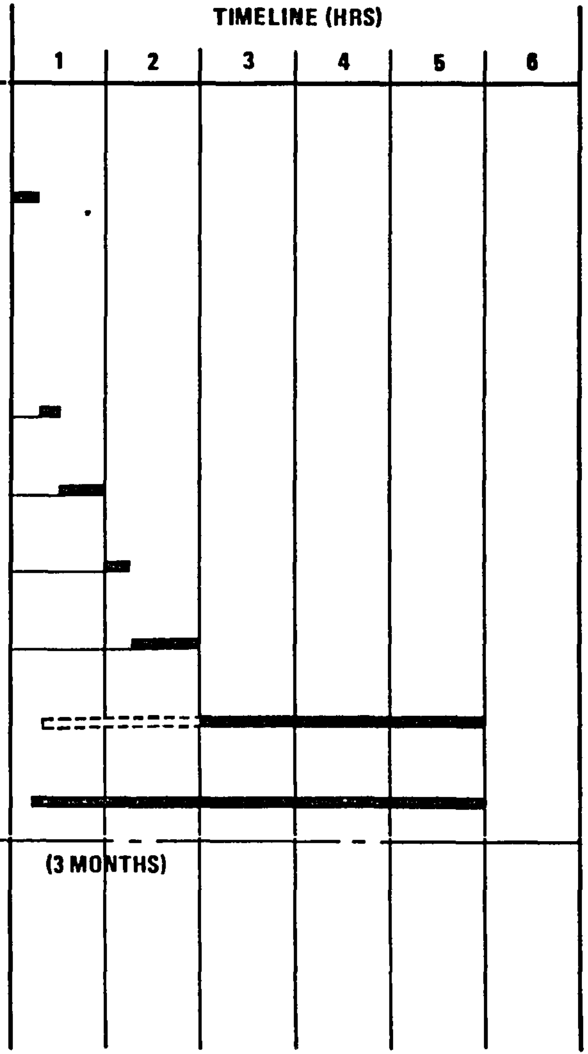
c) Operational phase and long term effects

FIGURE 22.

STS FLIGHT TEST PHASING - TEST #3.3

TEST 1.4 – FULL SCALE MAST TEST – STS

SEQUENCE	MEASUREMENTS
1. DEPLOYMENT IN ϕ_g a) MAST b) REFLECTOR	• STS CCTV CREW AUTOPILOT • ACCLERATIONS • LOADS • TEMPERATURES • DEFLECTIONS
2. ACTIVATE SAMS/SPLRS	• SAME AS 1+ • SAMS/SPLRS
3. RESPONSE TO PULSE LOAD (10 VARIOUS PULSE RATES)	• SAME AS 2+ • VIBRATION DECAY
4. SINUSOIDAL SWEEP	• SAME AS 3+ • CRITICAL FREQUENCIES
5. SINUSOIDAL DWELL AT CRITICAL FREQUENCIES (15 MODES)	• SAME AS 4
6. THERMAL DISTORTIONS	• TEMPERATURE • DEFLECTIONS
7. RF PERFORMANCE	• GROUND XMITTER
8. GROUND ANALYSIS – SPE ANALYSIS – CORRELATION TO 1g TEST – CROSS-CHECK FREE-VIBRATION DELAY AND PHYSICAL VALUES – RF PERFORMANCE	NONE



- MSAT control performance
- MSAT RF performance
- Structural long-term stability (materials degradation)

Measurements sensors and instruments are detailed in Figure 23. They are derived from ground and STS flight measurements previously described. MSAT activation phasing and measurements time spans are shown in Figure 24.

Data acquisition and telemetry will make use of existing satellite command and data handling subsystem (CDH) capability. None of the measurements described requires high data rates; assuming 160 sensors at 10 Hz, and 200 at 1 Hz sampling rate, and 16 bit data, results in less than 20 Kbits data stream; a relatively small increase in CDH capacity should handle MSAT measurement requirements.

SPACECRAFT CHARGING AND MAGNETIC EFFECTS INVESTIGATIONS

There are a number of plasma and magnetic field effects related to large space structures in geosynchronous orbit which need to be investigated in-situ to supplement studies which can be performed analytically and in ground based laboratories. Table XI summarizes these effects, and lists some of the diagnostics which will provide information to quantify the effects of the phenomena involved.

The rationale for performing these studies in the real in-orbit environment is the prohibitive cost of properly simulating all of the significant elements of the environment, especially for the effects which are expected to be revealed only after a long exposure period. Another obvious reason for on-orbit testing is the cost of test facilities large enough to eliminate effects of nearby test facility walls and other equipment.

Magnetic torques and $\vec{v} \times \vec{B}$ induced electric fields are usually not of concern for smaller spacecraft, but may have to be taken into account for larger structures even though the geomagnetic field, about 200 gammas in magnitude, is much smaller than for lower altitude orbits. Since the field is percentage-wise much more variable at geosynchronous altitudes, the on-board magnetometer will provide continuous accurate data to sort out magnetic effects from other effects such as solar pressure and gravitational torques. The local magnetic field also is an essential parameter in characterizing the electron and ion particle environment.

Spacecraft charging effects will be influenced by the large size of the spacecraft in that the debye shielding distance and plasma sheath thicknesses are no longer much larger than the spacecraft dimensions. The effects listed in Table XI may be affected in ways which are not predicted by current technology. Radiation effects due to MeV particles will be enhanced on large space structures because of their inherent light weight and resultant decreased shielding. Degradation of the mechanical and electrical properties of materials because of the light weight configuration superimposed on the charging and radiation environments, and also the solar UV irradiation, is an area of concern because the mission lifetime of large structures must be increased to permit longer term amortization of their increased cost.

TABLE XI

Large Space Structure Environmental Effects

A. Plasma Interactions

1. Torques due to remnant magnetic materials and current-area products- long dimensions: attitude control.

2. Impulsive torques due to large arc discharge currents: pointing transient errors.

3. $\vec{V} \times \vec{B} \cdot L$ induced voltages: affects spacecraft equilibration potentials.

4. Spacecraft Charging:
   - Arc discharge electromagnetic interference (EMI)
   - Corona discharge EMI noise background
   - Enhanced contamination by affecting ion trajectories
   - Enhanced degradation of materials by arc discharges and coronaing
   - Unknown effects due to properties of materials peculiar to large space structures e.g. plastics and carbon fibers

5. Radiation damage of semi-conductor components due to poor shielding. Cosmic ray effects.

6. Breakdown of high voltage components and power supplies.

TABLE XI (Cont.)

B. Diagnostics

1. Magnetometer - provides in-situ measure of magnetic fields to evaluate torque effects as well as the properties of the plasma environment.

2. Plasma detectors to provide number density, energy and direction of the plasma flux. Energy range should be from 1 eV to 10 MeV for electrons and ions. Also provides a measure of spacecraft potential.

3. Arc discharge detector to characterize and localize the EMI emanation sources. Multiple locations and multiple sensors (E-field, B-field, currents, voltages) should be provided.

4. High energy radiation effects sensor - arc discharges caused on internal components.

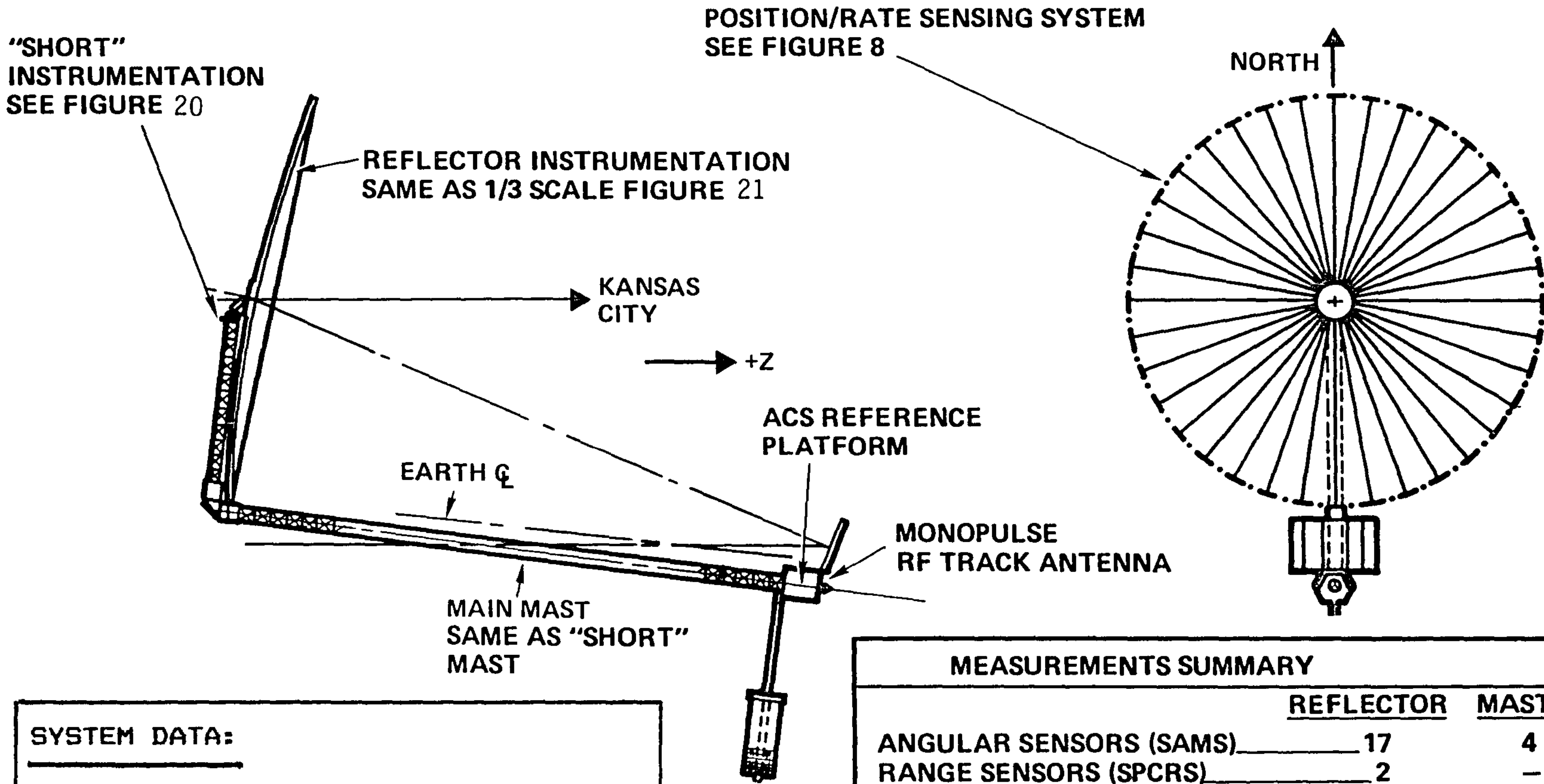
5. Temperatures, quartz crystal microbalances (QCMs), electrical continuity and resistance measurements and other associated diagnostics which will provide additional information.

2.3.3.2-5 Measurement Requirements and Testing Cross Index. Measurement study requirements were detailed in Table VI. In order to insure that the recommended tests provide data applicable to these requirements, a cross-index was prepared as shown in Table XII. Both hoop-column and offset-fed configurations are shown, but as stated previously, detail test numbering was not provided for the hoop-column.

2.3.3.2-6 Measurement Scaleability, Accuracy, and Test Environment Considerations. There is nothing inherent in any of the proposed sensors and instruments that is affected by scale testing, or test environment (ground versus space). The measurements data quality is practically independent of test environments.

When compared to the range of expected errors (Figure 12), the proposed measurements accuracy (Table VII) is satisfactory.

Scaleability of test data, i.e., response prediction by analysis, from either 1) 1/3 scale to full scale testing, or 2) ground to orbital testing, is another matter. As discussed in several sections of this report, and specifically 2.3.3.2-1, structural/control analytical tool development is at the core of a successful MSAT launch by mid-1990's. The proposed measurements provide a comprehensive and timely set of data to be used to validate these analytical tools.



SYSTEM DATA:

-WEIGHT MEASUREMENTS	75	
INTEGRATION	60	
TOTAL (Lb) -----		135
-VOLUME (SAMS CORE) (CuFt) --		9
-AVERAGE POWER (W) ----------		10
-AVERAGE DATA RATES (KBPS) --		20

MEASUREMENTS SUMMARY

	REFLECTOR	MASTS
ANGULAR SENSORS (SAMS)	17	4
RANGE SENSORS (SPCRS)	2	–
STRAIN-GAUGES	120	24
THERMOCOUPLES	120	24
ACCELEROMETERS	18	12
TENSIOMETERS	–	12

Figure 23 — Satellite Measurement System

FIGURE 24.

SATELLITE MEASUREMENTS PHASING PLAN

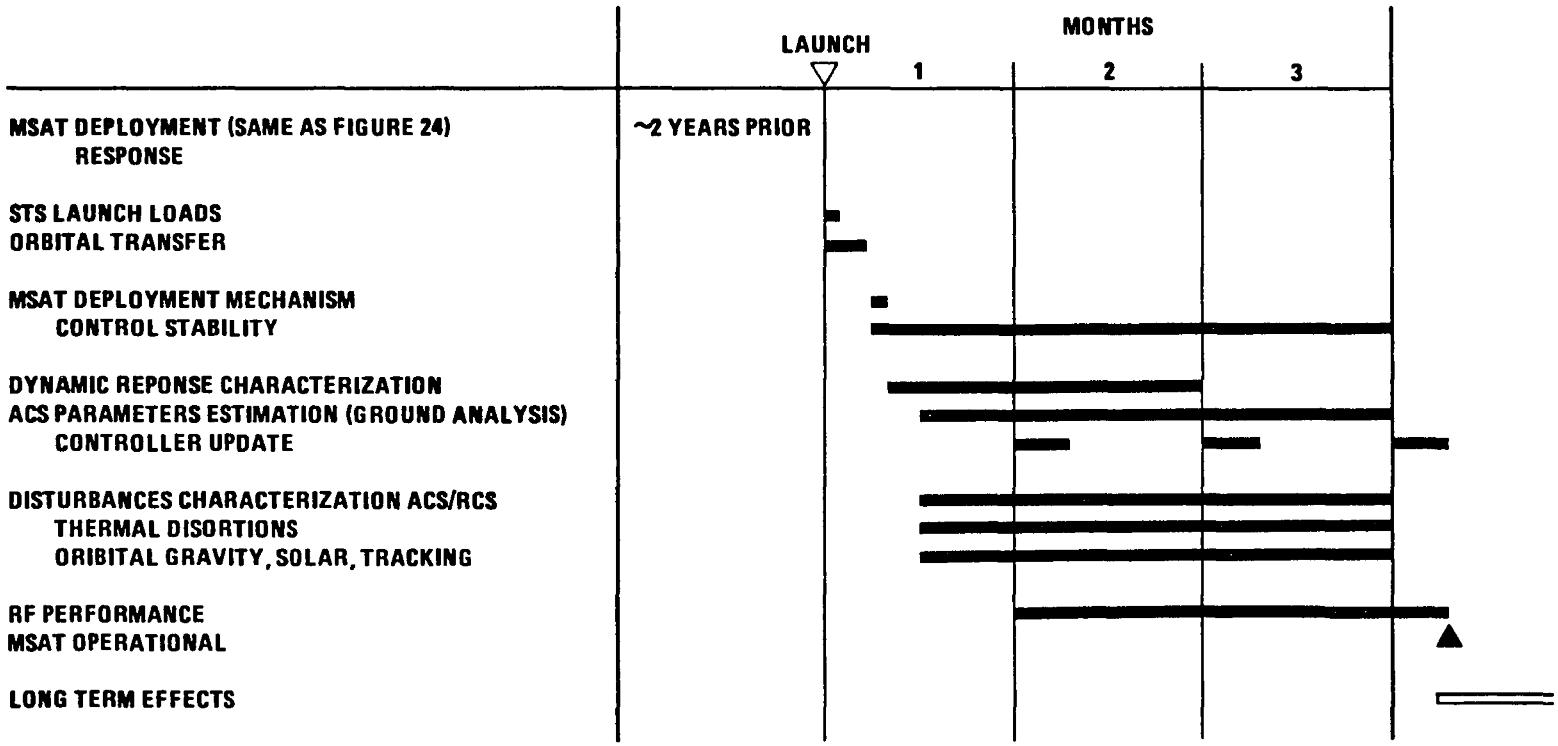


TABLE XII.

MEASUREMENT REQUIREMENTS AND TESTING CROSS-INDEX

ITEM	MEASUREMENT	VARIABLES	SYSTEM APPLICABILITY: OFFSET-FED	SYSTEM APPLICABILITY: HOOP-COLUMN	TEST NO
1. DESIGN					
• CABLING BLOCKAGE	RF PERFORMANCE	MATERIAL		X	
		NUMBER OF CABLES			
		SIZE			
• MESH KNIT	RF PERFORMANCE	MATERIALS	X	X	
		MESH SIZE			
• MESH PILLOWING	RF PERFORMANCE	MESH PRELOAD	X	X	2,3
	DIMENSIONAL				
• SURFACE CONTOUR	DIMENSIONAL	CABLES/MESH PRELOAD		X	
		RIBS ASSY, MESH PRELOAD	X	X	2,3
		ϕ TO 1g CORRELATION	X	X	
		SCALING			
2 MATERIALS	FOR EACH ITEM DETERMINE				
CABLING	STRENGTH	STATISTICAL SCATTER	X	X	1 1,2 1,4 1 SPECIFIC
RIBS	STIFFNESS	PRELOAD			(ALL OTHERS
MESH	DAMPING	1g TO ϕ CORRELATION			INDIRECT)
HOOP-COLUMN	CTE				
LONGERONS	CREEP				
DIAGONALS	LONG TERM				
	EMI				

MEASUREMENT REQUIREMENTS AND TESTING CROSS-INDEX

(CONTINUED)

ITEM	MEASUREMENT	VARIABLES	SYSTEM APPLICABILITY		TEST NO
			OFFSET-FED	HOOP-COLUMN	
3. MANUFACTURING • MAST	DIMENSIONAL	NO OF ELEMENTS JOINTS TOLERANCES ELEMENTS TOLERANCES DIAGONALS PRELOAD CREEP, LONG TERM	X	X	1.2,1 3,3 3
	DYNAMIC RESPONSE	MODELING STIFFNESS, DAMPING PRELOADS	X	X	1.2,1 3,3 3
	EMI	MATERIALS, COATING, . . .	X	X	3 3
	ϕg TO 1g CORRELATION SCALING	ALL OF ABOVE	X	X	3.3
• REFLECTOR	DIMENSIONAL	• NO OF GORES RIGGING MESH, MESH PRELOAD CREEP (PRELOAD)	X		2 2,2 3,3.2,3 3
		• SAME AS ABOVE + HOOP CABLES PRELOAD SURFACE CABLES PRELOAD		X	
	DYNAMIC RESPONSE	MODELING STIFFNESS, DAMPING PRELOADS	X	X	2 3,3 3
	RF PERFORMANCE	DIMENSIONAL MESH	X	X	2 3,3 2,3.3
	EMI	MATERIALS COATINGS	X	X	2 3,3 3
	ϕ TO 1g CORRELATION SCALING	ALL OF ABOVE	X	X	3 3

MEASUREMENT REQUIREMENTS AND TESTING CROSS-INDEX

(CONTINUED)

ITEM	MEASUREMENT	VARIABLES	SYSTEM APPLICABILITY		TEST NO
			OFFSET-FED	HOOP-COLUMN	
4 DYNAMIC RESPONSE • STIFFNESS DAMPING	• TIME PHASING DEFLECTION MODE DISPLACEMENTS ACCELERATIONS DELAY RATES	DISTURBANCES MATERIALS PROPERTIES ASSEMBLY, RIGGING JOINTS TOLERANCES CABLING, DIAGONALS PRELOAD ϕ TO 1g CORRELATION SCALING	X	X	1.3,2.3,3 3
• DEPLOYMENT	STABILITY	RATE PRELOADS ϕ TO 1g CORRELATION SCALING	X	X	1.3,2 3,3 3 3.3
5. THERMAL • CTE (ALL ELEMENTS)	DIMENSIONAL	TEMPERATURE GRADIENTS MATERIALS LAYUP METHODS PRELOAD MOISTURE	X	X	1,2,3
• DISTRIBUTION PROFILE	TEMPERATURE	LOCATION/SHADOWING HEAT LOADING MATERIALS, JOINTS	X	X	1 3,2 3,3 3
• DISTORTIONS	DIMENSIONAL	CTE TEMPERATURE DISTRIBUTION	X	X	1.3,2 3,3 3

MEASUREMENT REQUIREMENTS AND TESTING CROSS-INDEX

(CONTINUED)

ITEM	MEASUREMENT	VARIABLES	SYSTEM APPLICABILITY		TEST NO
			OFFSET-FED	HOOP-COLUMN	
6 ACTIVE CONTROLS • SURFACE CONTOUR	DIMENSIONAL RF	CABLING PRELOADS ϕ TO 1g CORRELATION SCALING		X	
• POINTING	STABILITY ACS RESOLUTION SAMS/SPLRS RF FIELD	SYSTEM DISTORTIONS DISTURBANCES ACS RESOLVERS	X	X	3 3
7 ATTITUDE CONTROL	STABILITY ACCURACY	CONTROL ALGORITHMS SURFACE RESOLVER POINTING RESOLVER ACS AUTHORITY DISTURBANCES ACS, RCS, ORBITAL DYNAMIC MODEL	X	X	3.3
8. RF	FAR FIELD PERFORMING	POINTING SURFACE ACCURACY FEED-REFLECTOR POSITION	X	X	3
	NEAR-FIELD SURVEY	SURFACE ACCURACY FEED-REFLECTOR			
EMI	NOISE LEVEL FREQUENCY	MATERIALS ENVIRONMENT GROUNDING	X	X	3
9 LSST MEASUREMENTS	SENSORS, ACCELEROMETERS, THERMOCOUPLES, STRAIN GAUGES LOADS	ACCURACY, PRECISION RELIABILITY	X	X	1,2,3

testing, is another matter. As discussed in several sections of this report, and specifically 2.3.3.2-1, structural/control analytical tool development is at the core of a successful MSAT launch by mid-1990's. The proposed measurements provide a comprehensive and timely set of data to be used to validate these analytical tools.

2.3.3.3 Measurement System Cost

2.3.3.3-1 Ground Rules and Assumptions

1) Rough Order of Magnitude (ROM) costs are limited to testing, measurement, test analysis and to scale model or hardware to run tests. Operational hardware is not included.

2) Cost estimating relationships (CER) were derived from non-recurring data on past TRW programs for top down estimates. Where applicable bottom up estimates were made.

3) Estimates are all based on a wrap-rib antenna design

4) All costs are in 1982 dollars

5) No fee included in the costs

6) No costs have been included for the basic ground facility which is assumed to be available from other LSST activities in the mid-80's.

7) Shuttle and Shuttle pallet costs not included

2.3.3.3-2 Cost Summary

		COST ($82-M)	
TEST	DESCRIPTION	TEST	MEASUREMENT
1.0	MAST	3.1	0.5
	1.1, 1.2 CHARACTERIZATION	0.1	0.1
	1.3 GROUND-FULL SCALE	(*) 3.0	0 4
	(*) INCLUDES 85' MAST		
2 0	REFLECTOR	8 3	1.0
	2.1, 2.2 CHARACTERIZATION	0.3	0.2
	2.3 GROUND-SCALE	(**)8.0	0.8
	(**)INCLUDES 15M REFLECTOR		
3.0	ANTENNA	18.0	13.9
	3.1 DEVELOPMENT	2.9	1.5
	3.2 GROUND INTEGRATED TEST	9.0	8.3
	3.3 STS FLIGHT TEST	6.1	4.1
4.0	MSAT INITIALIZATION	-	9.0
	MEASUREMENT SYSTEM	-	8.0
	DATA REDUCTION, SCALING, REPORT	-	1.0
	SUB-TOTAL	29.4	24.4
	PROGRAM LEVEL	14.6	
	TOTAL	68.4	

APPENDIX A

A GLOBAL SENSOR SYSTEM

FOR

MOBILE LINK ANTENNA EXPERIMENTS,

MOBILE COMMUNICATIONS SATELLITE SYSTEM

PREPARED BY: R. S. Neiswander
TRW SPACE AND TECHNOLOGY GROUP
ONE SPACE PARK
REDONDO BEACH, CALIFORNIA

1. REQUIREMENTS

One of the primary functions of the MSAT experimental satellite system is to characterize the behavior of the mobile link antenna by a sequence of testing from ground models through geosynchronous orbit experiments. In part, this characterization can be accomplished by local thermal and strain sensors at critical sampling points within the antenna structure and by microwave sensors (far-field, and near-field if available) establishing the beam shape. The local sensors however, cannot provide a composite description of the structure, antenna surface and feed and their reference to inertial space; and the microwave measurements give only the collective result[1] of the many factors influencing beam shape. What is demanded in addition to these sensors is a Global sensor subsystem that can define the absolute dynamic geometry of the antenna elements. This Global subsystem provides a direct capability of determining beam shape from surface aberrations and defocus, of establishing instantaneous beam pointing, and of correcting both beam quality and pointing by active control. Moreover, the global subsystem offers a diagnostic tool for examining detailed behavior of structural components.

---

[1] In theory, it is possible to use a dither-adaptive approach analogous, to that proposed for large optics. This approach is useful only where relatively few degrees of freedom (error sources) exist, and the couplings between these freedoms are well defined. Since the antenna may embrace a hundred or more degrees of freedom and their couplings are imprecisely known, dither techniques are not eligible.

The general requirements on the global sensor subsystem are:

- A coordinate reference frame common to all measurements is defined.
- In the coordinate frame, the geometry of the antenna reflecting surface is measured with sufficient sampling density to establish its figure and structural response.
- In this coordinate frame, the attitude and position of the antenna feed and the inertial space attitude reference (typically at the main bus) are determined.
- Measurements are made continuously, in real-time, with outputs compatible with microprocessing and active control.
- Measurements are immune to spurious background effects such as sunlight glints and earthshine.
- The sensor subsystem does not degrade nor interfere with the microwave properties of the antenna and its feed.

Depending upon the test phase, the specific configuration of the global sensor subsystem may take slightly different forms. General requirements as noted above apply to the mobile link antenna at geosynchronous altitude with the capability for active control available. Diagnostic structural analysis may need additional targets at additional structural sampling points; and tests with the antenna attached to the STS may require additional coordinate transfer functions.

By assignment, the operating frequency of the antenna is 871 MegaHertz - a wavelength of 34.4 centimeters. If an accuracy of $\lambda/200$, or 1.5 millimeters (rms) is required of all measurements related to antenna figure, then the sensor injects negligible error into the reconstruction of the surface geometry. A similar accuracy is invoked upon lateral positioning of the feed and of the main bus. Since the depth of focus of the antenna is about ± 1 meter, axial spacing (ie. feed to reflector) need be measured to about 1 centimeter.

Beamwidth of the main lobe from the antenna is about 16 milliradians at its first minimum. Therefore, attitude transfers that factor into pointing accuracy are required to be made to an accuracy of Beamwidth/75, or .2 milliradians. The required number and function of the sampling points at the antenna surface and other sites is largely dependent upon the antenna configuration. Behavior of the Harris antenna, both as a relector and as a large structure, is determined by the two rigid elements--the hoop and the column, and the shaping tie lines. The surface figure can be established by 30 distributed samples in each subaperture (each sample a surface normal displacement measurement), plus 6 samples around the hoop to determine its position relative to the column. Torsion, or twist, behavior of the antenna is dominated by the hoop action, and is measured by 6 samples at the hoop. Radial spacing of hoop from the column can also be determined from these 6 measurements.

The Wrap-Rib antenna behavior is largely determined by the rib geometry. In that these ribs are quite stiff in the surface normal direction, measurement of rib tip position is sufficient to establish the surface normal coordinates of the reflector. Torsionally, however, the ribs are flexible; and the lateral action of the ribs both as components of a large structure and for their influence upon surface figure is important. We propose here to sample the torsional motion of every other rib at its mid-point and at its tip, with the proviso that if higher rib bending modes are of interest, the sampling density is increased. These requirements are summarized in Table 1. Note that in the Lockheed configuration, the feed and the main bus are at a common site. Attitude transfer between the two is assumed unnecessary. For the Harris configuration, axial spacings between the feed and the antenna apex and the main bus are all defined by the straight rigid column. It is assumed here that these spacings are controlled and known.

TABLE 1

MOBILE LINK ANTENNA

SENSOR REQUIREMENTS

	ANTENNA CONFIGURATION		
PARAMETER	LOCKHEED WRAP-RIB	HARRIS HOOP-COLUMN	COMMENTS
ANTENNA TYPE	WRAP-RIB & MESH REFL. OFFSET FEED	TRIPLE SUBAPERTURE MESH REFL., CENTRAL COLUMN FEED	SEE FIGURES 5 AND 7
ANTENNA DIAMETER	52 M	52M- SUBAPERTURE (115M-OVERALL)	
FREQUENCY	871 MHz	871 MHz	
REFL. SURFACE SAMPLING			
NO. SAMPLES			
SURFACE NORMAL	52	96	
SURFACE TWIST	52	6	
FEED MEASUREMENT			
POSITION	3 DOF	2 DOF	FOR THE HARRIS, COLUMN LENGTH IS ASSUMED TO BE KNOWN
ATTITUDE	3 DOF	3 DOF	
MAIN BUS AND INERTIAL REFERENCE			
POSITION	SAME AS FEED	2 DOF	FOR THE HARRIS, THE BUS IS ATTACHED TO THE COLUMN
ATTITUDE	SAME AS FEED	3 DOF	
MEASUREMENT ACCURACY			
DISPLACEMENT			
LATERAL & NORMAL	$\lambda/200$ = 1.5 MM, RMS	$\lambda/200$ = 1.5 MM, RMS	
AXIAL	1 CM RMS	1 CM RMS	
ATTITUDE	.2 MRAD, RMS	.2 MRAD, RMS	

2. APPROACH

The most promising candidates for global measurements are optical. As previously noted, in theory, the antenna surface can be measured and optimized by dither adaptive RF techniques, by intentionally oscillating each degree of freedom and centering this dither at maximum beam power or best beam quality. While this technique has had limited success with some simple optical telescopes, it is not applicable to complex antennas.

2.1. METHODS OF OPTICAL MEASUREMENTS

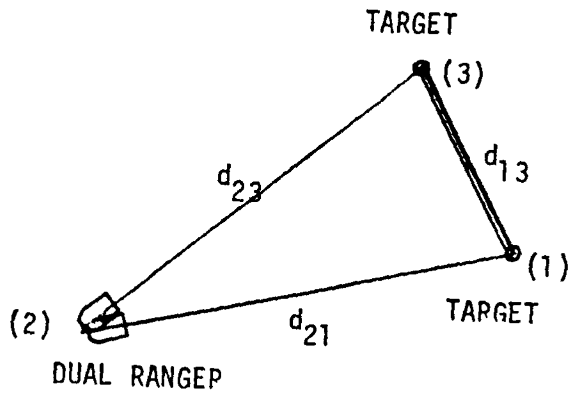
Within the general class of optical sensors, approaches relying upon holography or photogrammetry are disqualified for either unacceptable complexity or lack of real-time response. The three useful methods that can offer global measurements are:

> Trilateration: The geometry of the antenna and structure are established by distance measurements.
> Triangulation: The geometry is defined by angle measurements.
> Hybrid: Both distance and angle measurements are used to determine antenna and structure geometry.

These methods are described briefly, and then applied to the two antenna measurement applications.

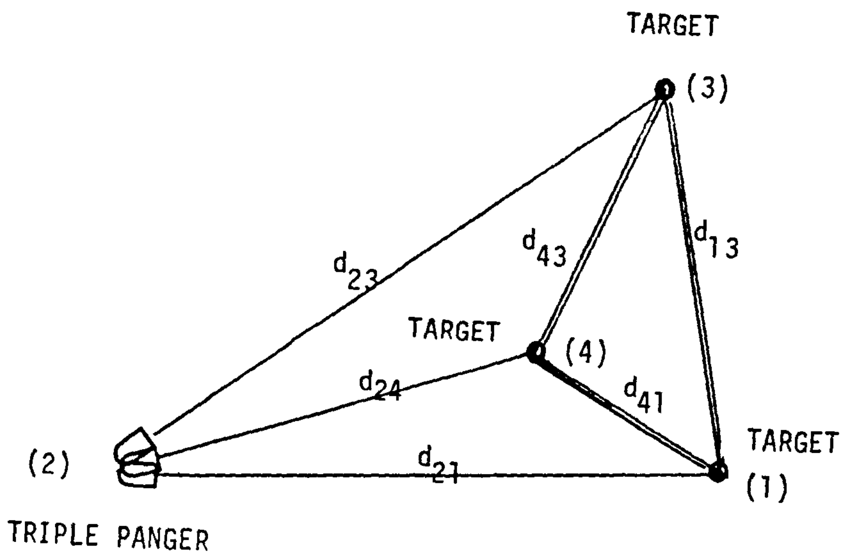
TRILATERATION

The optical ranger measures one dimension,distance to the target along the optical line-of-sight (LOS). For a simple two-dimensional triangle geometry (Figure 1), the measurement of deformations at target (3) for example, requires two rangers and a known spacer (d_{13}).



TWO-DIMENSIONAL GEOMETRY

FIGURE 1



THREE-DIMENSIONAL GEOMETRY

FIGURE 2

These determine the three legs of the triangle and thereby its apex positions.

For the three-dimensional case, the geometry becomes more complicated, as shown in Figure 2. To determine the position or the motion of the apex at target 4, three rangers and three known spacers are required. These establish the legs of the tetrahedron.

The absolute rangers currently developed are primarily for surveying (EODM or Electro-Optical Distance Measuring devices). Additionally, two developments in rangers specifically for space application are noted.

EODM DEVICES TYPICAL EODM INSTRUMENT PERFORMANCE

Instrument	Manufacturer	Maximum Range	Accuracy
Geodimeter 710	AGA	5 km	5 mm
Reg Elta 14	Carl Zeiss	2 km	5 mm
Mekometer 3000	Kern	3 km	.2 mm
TellurometerM-100	Tellurometer Ltd.	2 km	1.5 mm

The two most significant development programs for space instruments are:

Lockheed multi-color distance measuring instrument: This system uses a hierarchy of modulations and wavelengths from a CO_2 laser to establish absolute distance. The system is extremely complex, and in an early development stage. The system can, in principal, accommodate excursions of centimeters with measurement accuracy of .1 micrometers.

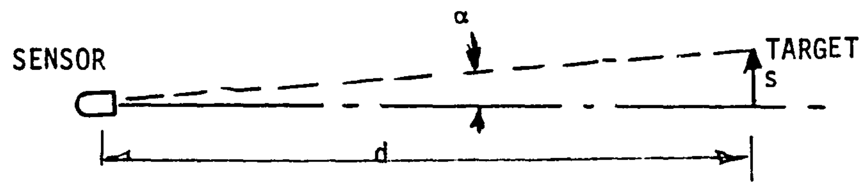
Jet Propulsion Laboratory Self Pulsed Ranging System: This is a simple time of flight ranger in which the return pulse stimulates the next emitted pulse. Range is measured by the resultant repetition rate. Development through the brassboard has been completed. General characteristics are rangers up to 200 or so meters with a measurement accuracy of about .2 millimeters.

TRIANGULATION

The basic sensor in the triangulation approach is a target angle sensor. As shown in Figure 3, the sensor measures the angular deflection of a sample point at the antenna or the structure.

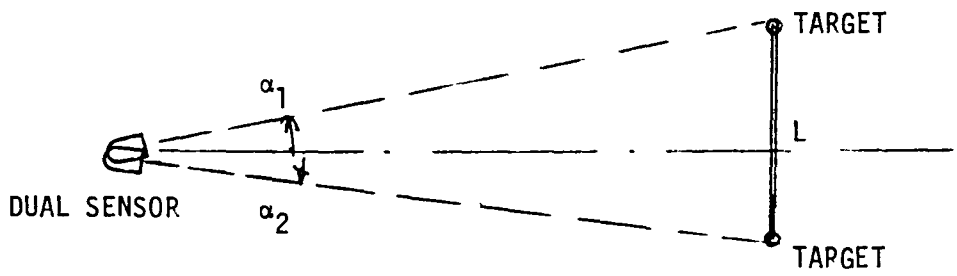
The sensor measures angle α, as shown in Figure 3. If the target range, d, is known, then the displacement of the target normal to the line-of-sight (LOS) is: $s = d\alpha$. If the target range is unknown, then dual targets at the ends of a spacer are required (see Figure 4). Here, L is a stiff and known length. Its perturbed displacements, including range, can be determined from the angle coordinates at its tips. With three targets spaced laterally and in depth, the six angle measurements reduce to six degrees of freedom transfer from the target frame to the sensor frame.

Representative sensors are imaging devices in which line-of-sight angle is converted to image position at the detector. Performance is determined by the detector measurement capability. A comparison of potentially useful detectors is give in Table 2, and includes the return beam vidicon, the image dissection, a typical ccd array, and the lateral effect silicon photodiode. As can be seen, the photodiode provides the highest accuracy.



LATERAL DISPLACEMENT SENSING

FIGURE 3



LATERAL DISPLACEMENT AND RANGE

FIGURE 4

TABLE 2

A COMPARISON OF ANGLE SENSORS

SENSING DEVICE	TARGET		ACCURACY (FRACTION FULL SCALE)			COMMENTS
	TYPE	MODULATION	UNCORR.	FIXED COR.	CALIB. COR.	
RBV VIDICON	RETRO OR ACTIVE	NONE	10^{-2}	$5x10^{-3}$	$5x10^{-4}$	TYPICAL OF LANDSAT VIDICON
IMAGE DISSECTOR	RETRO OR ACTIVE	NONE	10^{-2}	10^{-3}	$3x10^{-4}$	
CCD ARRAY	RETRO OR ACTIVE	NONE	$2x10^{-3}$	10^{-4}	$<10^{-4}$	512x512 ARRAY; FIXED CORRECTION WITH 20/1 INTERPOLATION
LATERAL EFFECT PHOTODIODE	ACTIVE	UP TO 5 KHZ	$5x10^{-5}$	$<5x10^{-5}$	$<5x10^{-5}$	ACCURACY IMPROVEMENT WITH NONLINEARITY CORRECTION HAS NOT BEEN ESTABLISHED

For each angular degree of freedom, a silicon photodiode produces two signal current, I_1 and I_2. Image position is found by the simple algorithm, $X_{image} = (I_1 - I_2)/(I_1 + I_2)$.

Additionally, the targets can be modulated shifting the signal frequency band well out of the background effects caused by sunlight glints, etc. The primary disadvantages of the silicon photodiode are:

1) Relatively low sensitivity
2) Target centroid measurement

The sensitivity limit disqualifies the detectors for low level applications such as star trackers. The detector measures the centroid of identifiable targets, and thereby can accept multiple targets by frequency identification, but not by spatial position within its field. The practical limit in multiplexing targets at a single detector is thus about ten targets.

HYBRID SENSOR

The hybrid sensor system measures both angles and ranges. It can consist of somewhat independent angle and range sensors, such as those described above, or of combined functions (ie. a fully automatic, ranging theodolite) sensors. Specialized capabilities such as attitude transfer by means of autocollimation or by retro-reflecting Porro prisms can be included. As will be shown, all requirements can be met with mixes of simple angle sensors and rangers, providing high commonality redundancy within the system. For the conceptual design considerations, we will assume the modular approach in which the sensor elements are much as those described in the prior two subsections.

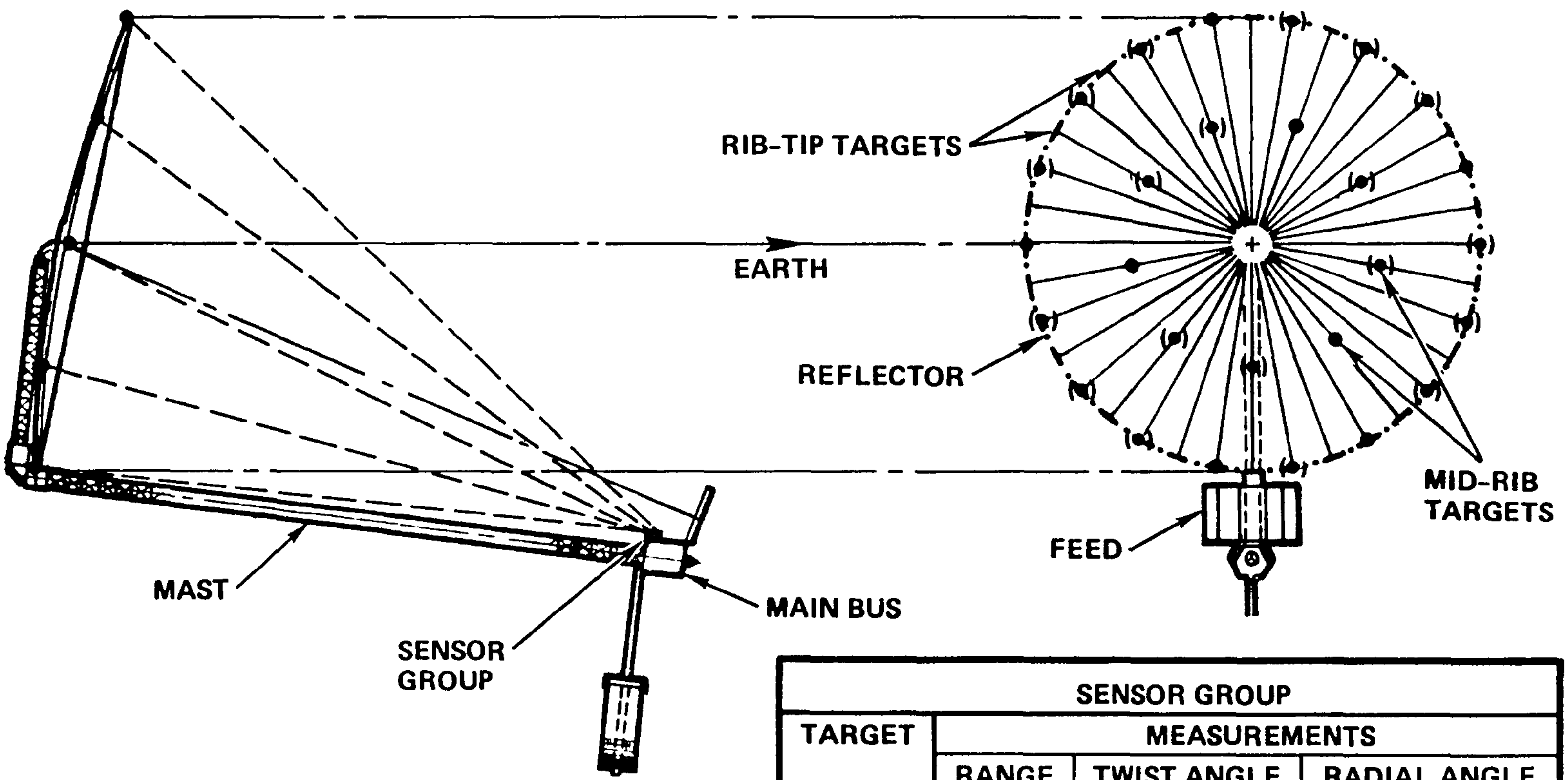
2.2. GLOBAL SENSORS FOR LOCKHEED WRAP-RIB ANTENNA

In the Lockheed configuration, the feed and main bus are essentially common; no coordinate inter-transfer is required. Two global sensor system approaches are examined--one that emphasizes ranging, and the other predominantly angle measurements.

The trilateration or ranging configuration for the Wrap-Rib antenna is shown in Figure 5. At the main bus is a cluster of sensors establishing the bus as the basic coordinate frame. Antenna surface normal excursions are measured by ranging against the rib tip targets and the hub. Torsional effects however, cannot be measured by the ranging sensors; an additional set of angle sensors are required to determine the lateral excursions of the rib mid-points and the rib tips. Two angles and range are needed to provide a vector location of the antenna hub. Structural deformations (eg. at the cannister end of the mast) will demand angle measurements as well as range to determine lateral deflections.

Thus, in reviewing the sensor group listed on Figure 5, we see that despite the intent of utilizing ranging for measurements, over half the sensor functions are angular measurements.

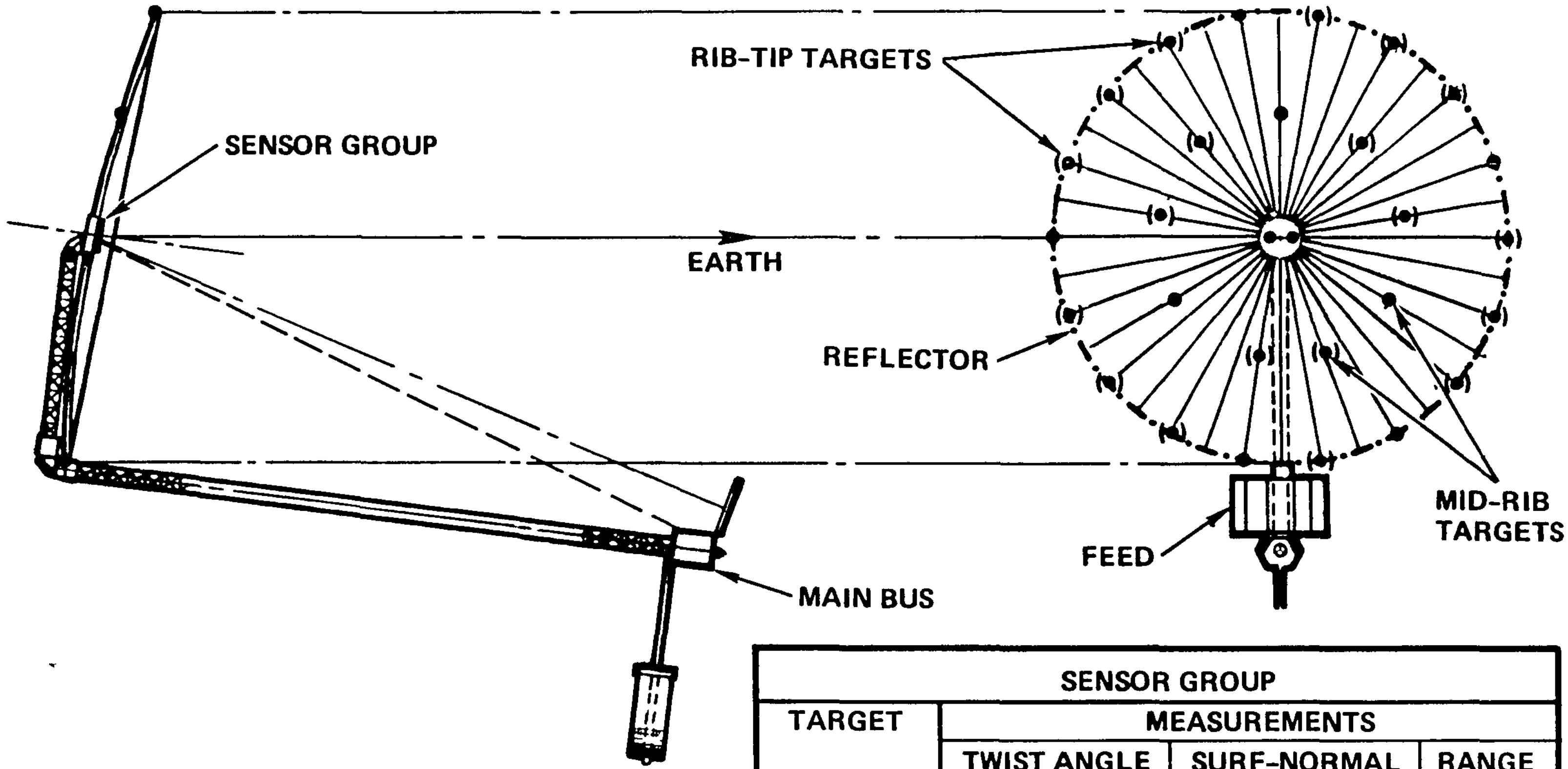
In the alternative triangulation approach (Figure 6), the sensor cluster is at the hub of the antenna with a six degree-of-freedom transfer to the feed and bus. This sensor group measures both surface normal and torsion motions of the ribs by angle sensing. Ranging between the hub and bus, and between the hub and structural sampling points can either be accomplished stadiametrically (see Section 2.1) with angular measurements, or by ranging instruments.



TARGET	SENSOR GROUP MEASUREMENTS		
	RANGE (SPLRS)	TWIST ANGLE (SAMS)	RADIAL ANGLE (SAMS)
MID-RIB	–	3 (9)	–
RIB TIP	9 (18)	–	–
HUB	2 (2)	2 (2)	2 (2)

(XX) USED FOR INITIAL CHARACTERIZATION
XX USED FOR OPERATIONAL CONTROL

Figure 5 – Global Sensor Arrangement Using Trilateration (Ranging) As Basic Method



TARGET	SENSOR GROUP MEASUREMENTS		
	TWIST ANGLE (SAMS)	SURF-NORMAL ANGLE (SAMS)	RANGE (SPLRS)
MID-RIB	3 (9)	–	–
RIB TIP	5 (9)	5 (18)	–
HUB	2 (2)	2 (2)	(2) (2)

(XX) USED FOR INITIAL CHARACTERIZATION
XX USED FOR OPERATIONAL CONTROL

Figure 6 – Global Sensor Arrangement Using Triangulation As Basic Method

2.3. GLOBAL SENSORS FOR THE HARRIS HOOP-AND-COLUMN ANTENNA

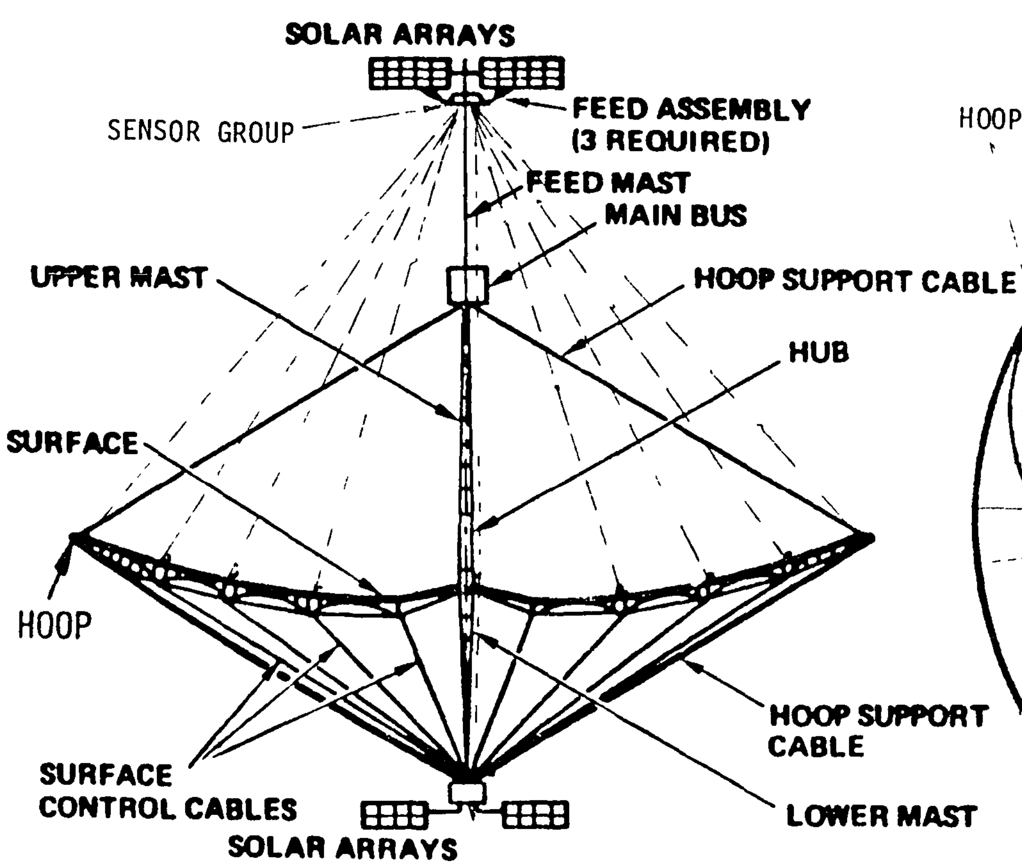
In the Harris Hoop-and-Column configuration, the antenna feed is at the extreme tip of the column, and the bus (see Figure 7) is optionally placed at the feed, at the lower column extreme, or at an intermediate position. In general, attitude transfer between the bus and the sensor group is required. Again, we compare two sensor approaches--one stressing ranging instruments, and the other angular measurements.

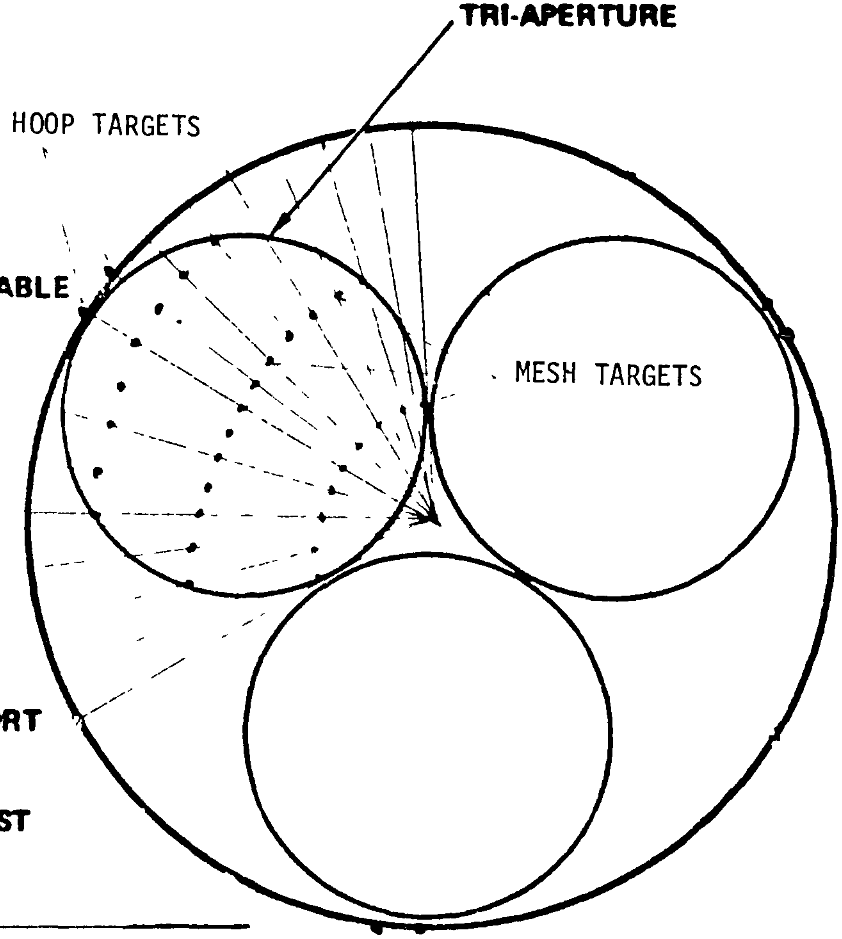
With trilateration, the configuration is as shown in Figure 7. The instrument group is at the feed, viewing the reflecting surface somewhat normally. Surface normal measurements at the mesh and at the hoop are made by ranging. Torsional and axial geometry of the surface is controlled by the hoop; this requires six targets at the hoop, measured in lateral angle. While range to the main bus is assumed to be determined by the stiff column length, lateral bus/position and attitude demand a set of angular measurements. Similar requirements apply to measurement of structure behavior (eg. bending modes of the column).

With the Harris antenna (as compared to the Wrap-Rib), the trilateration approach is a purer system using about a hundred ranging measurements, and only twenty or so angular measurements.

For the triangulation configuration, the sensor group is mounted as a ring at the apex of the antenna (see Figure 8). With the assumption that range to the bus and to structural sample points along the column are determined by column length, the total set of measurements are angular. Axial displacement of the hoop is derived stadiametrically from the separated pair of hoop targets at each subaperture.

GLOBAL SENSOR CONFIGURATION
USING TRILATERATION
AGAINST THE HOOP-COLUMN ANTENNA





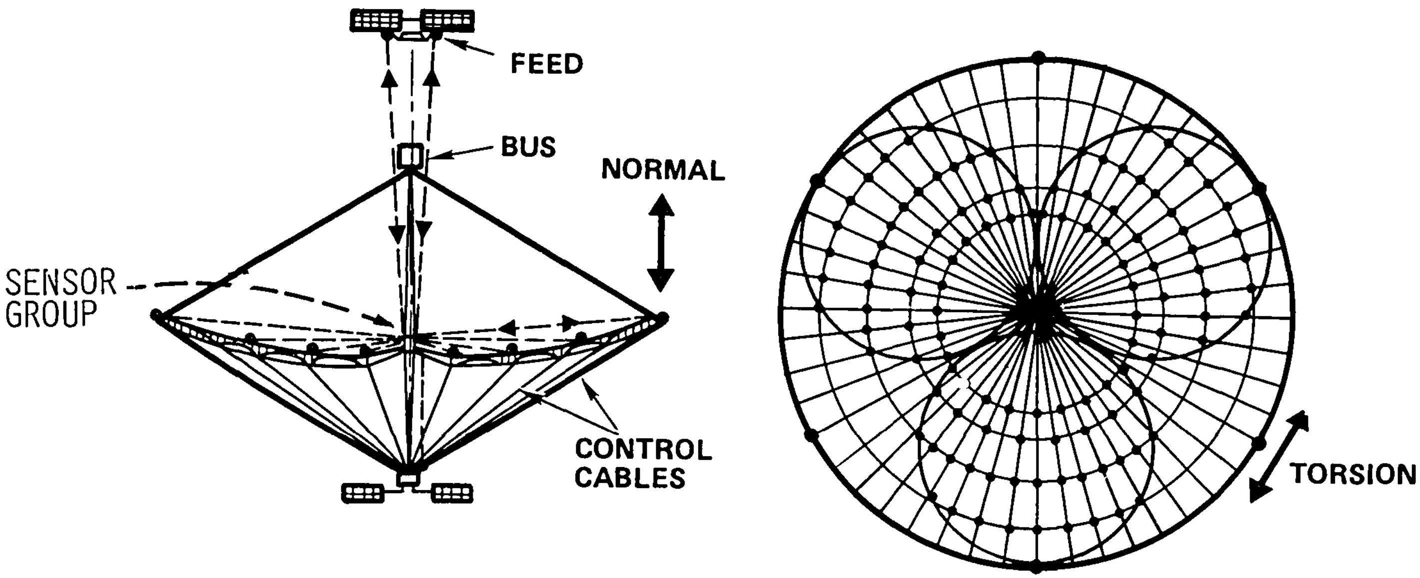
SENSOR GROUP

TARGET	MEASUREMENTS			
	RANGE SURF. NORM.	TWIST	ANGULAR AXIAL	ATTITUDE
MESH	90	-	-	-
HOOP	6	6	6	-
BUS/FEED	1	1	1	3
STRUCTURE	1	1	1	3

FIGURE 7

FIGURE 8.

GLOBAL SENSOR CONFIGURATION USING TRIANGULATION AGAINST THE HOOP-COLUMN ANTENNA



Sensor Group

Target	Surf. Norm.	Measurements Angular Twist	Axial	Attitude
Mesh	46	---	-----	---
Hoop	6	6	6 (1)	---
Bus/Feed	1 (2)	1	1	3
Structure	1	1	1	3

(1) Axial derived from twist measurement (2) Range along rigid column

2.4. APPROACH SELECTION

The Wrap-Rib antenna, as noted in Section 2.2, demands a substantial complement of angle sensors even if the approach emphasizes ranging. For the Harris antenna, the ranging approach demands that the sensor group be mounted at the feed. This is an undesirable location in that the feed is at the tip of a thin column extension; to minimize whip and twist at the feed, weights and inertias must be kept to an absolute minimum.

In comparing sensors, the rangers are substantially more complicated. Incentives of the commercial market have brought optical rangers to a high level of development; but, an instrument that can measure target excursions over a range of half a meter to an accuracy of a millimeter is still relatively large and complex. It is inappropriate to consider dedicated staring sensors, each assigned to a single target. In the alternative approach, precision scanning of a reduced set of rangers is required. If, for example, four ranging instruments are used, then these must be two-angle indexed programmed to sequentially point at 15 to 25 targets.

The angle measuring sensor is typically a small (1" diameter, 6" length) telescope containing a single element objective, a cylinder anamorphic lens and a detector. As previously noted, up to ten targets can be accommodated if the targets have identifiable modulations. With this simplicity, the configurational approach is to use a cluster of staring sensors, each assigned to a target set. Measurements are made in parallel without scanning. Data processing to derive angular coordinates, as discussed in Section 2.1, is of the form Angle = (A-B)/(A+B).

Targets for the rangers are passive corner cube reflectors. These are simple, relatively easy to install, and introduce minor effects upon the microwave and structural properties of the antenna. Considerable precautions however, must be taken to insure that stray reflections from adjacent surfaces do not cause interfering return glints.

Targets for the angle measurements can be illuminated retro-reflectors but best performance is obtained if the targets are miniature active sources. Typically, the target capsule is 1.4 inches in diameter, 1 inch high, and weighs 17 grams. Power feed lines* are either bonded to the ribs (for the Wrap-Rib) or laced to the gore edge cables (for the Harris antenna). The feed line and the target introduce negligible effects upon the microwave and structural properties of the antennas.

For either the Lockheed Wrap-Rib or the Harris Hoop-and-Column antenna, the most effective sensor system approach is triangulation. The sensor group is substantially simpler, with corresponding higher reliability. For flight experiments, the recommended targets are active, providing high performance at the expense of adding feed lines during antenna assembly. For operational antenna, however, the targets would be passive.

3. DESCRIPTION OF THE SENSOR SUBSYSTEM

The principal elements of the sensor system based upon the tri-angulation approach are:

- An array of active targets at the reflecting surface and targets at the feed and bus
- A cluster of angle sensors at the antenna hub or apex
- A ranging sensor, if required
- Support processing and supply electronics

* A representative target feed line is four wire, each No. 28 stranded.

If active control of the antenna is effected, then additionally, actuators, actuator drives, and more sophisticated data processing are required.

3.1. FUNCTIONING OF THE SENSOR SYSTEM

With the triangulation approach, the function of the sensor system is essentially angle sensing. For the Harris antenna, no ranging is needed unless the behavior of the extended column demands length checks. For the Lockheed antenna, range is needed only to determine separation between the antenna hub and the feed, and optionally to find spacings to structural sampling points.

The angle sensing system functions are shown in Figure 9. Three of the sensor channels are shown, each containing three targets observed simultaneously by its assigned receiver. Synchronously controlled by the master clock, the targets are turned on in sequence so the only one target is active within a sub-frame interval. As each target is imaged at the sensor detector, its actual angular position relative to an expected or ideal position, is evidenced by image offset at the sensor detector.

This image offset is transduced at the detector to differential current signals that are amplified, multiplexed to common analog-to-digital converters, and fed to the central microprocessor. At the processor, the image coordinate is computed, from which the target angular dislocation and its surface normal deformation are calculated.

If this system is part of an actively controlled antenna, the resultant set of deformations are then entered into a dynamic model of the antenna that computes the corrective actions to be taken by the network of surface adjustment actuators. For passive antennas, the measurement set can be either recorded or directly transmitted to a

SENSOR SYSTEM FUNCTIONS

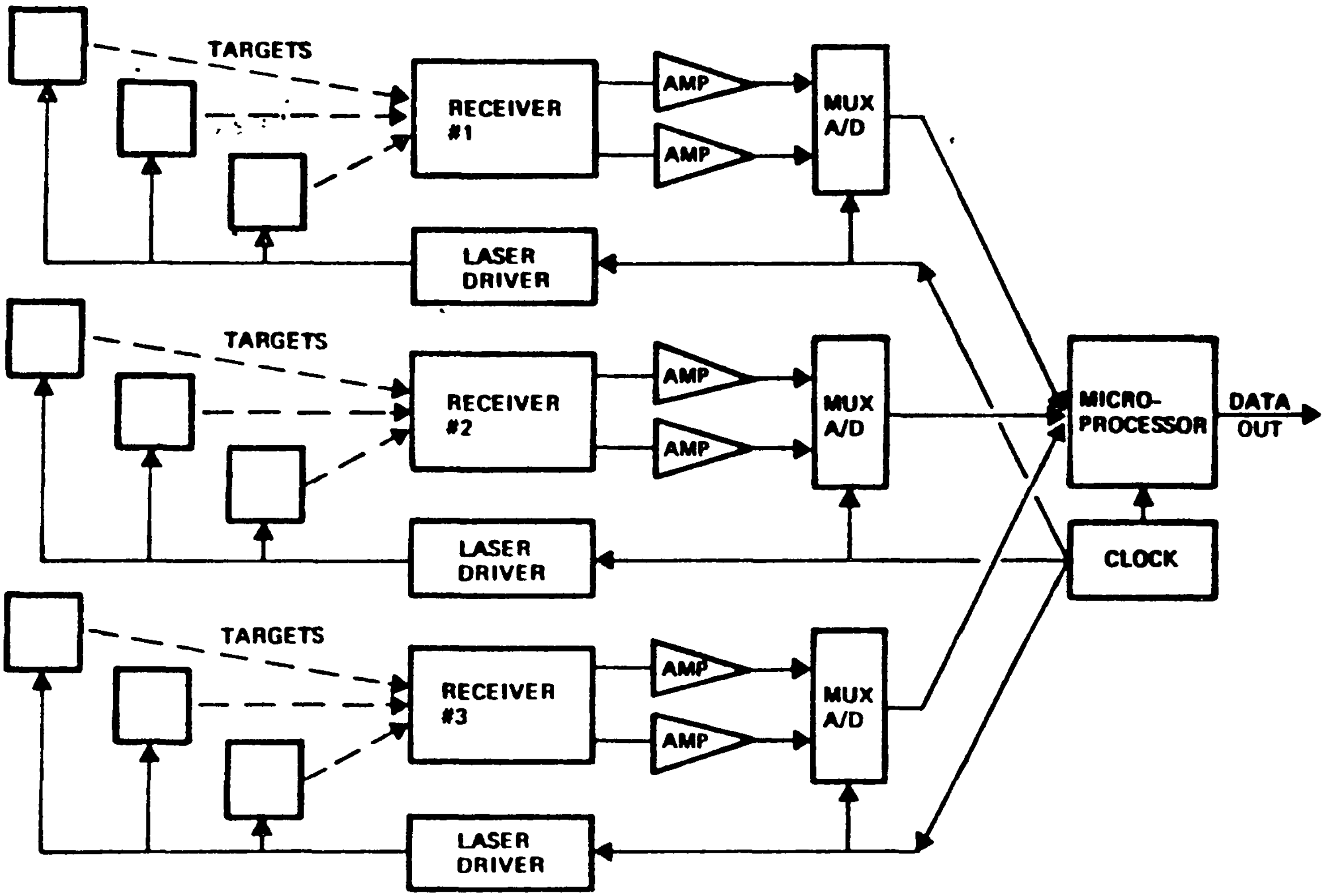


FIGURE 9

manned station. For either passive or active type of operation, a complete deformation data frame is available up to forty times a second.

To impose a minimal processing burden upon the central computer, the required calculations are exceedingly simple. After digitization, the detector signal currents are converted to image position,

$$\Delta y_D = \frac{I_1 - I_2}{I_1 + I_2}$$

That immediately transforms to target angle:

$$\Delta\phi_T = k_0 \Delta y_D$$

where k_0 relates to the focal length of the receiver telescope.

With a knowledge of range from the sensor to the target, the lineal displacement of the target normal to the line of sight is:

$$\Delta y_T = z_T \, \Delta \, \phi_T$$

where:

Δy_T = is the deformation normal to the LOS
z_T = target sensor range
$\Delta\phi_T$ = angular motion measured by the sensor

Since the Lockheed antenna ribs are stiff radially, radial separation distances between the hub and the rib tips need not be measured. The "L" structure supporting the antenna at one end and the feed-bus at the other can flex, changing the hub-to-feed spacing. This spacing can be measured stadiametrically (the angular separation of two targets at the hub), or by a ranging instrument.

For the Harris antenna, Column-to-Hoop spacing is determined by the tensioning cords and can vary slightly without severely affecting the overall surface figure. For example, if the uncertainty in Hoop location were as much as $\pm$ 2 centimeters, the resultant contribution to surface normal error would be about .1 millimeters. Therefore, it can be assumed that the radial distance can be estimated, a priori, to an accuracy of few centimeters, eliminating the need for ranging measurements. For the flight experiment however, the capability for continuous range measurements to the hoop is included.

3.2. ACTIVE TARGETS

A closeup view of the target is shown in Figure 10. Each target is a miniature source consisting of a laser diode, beam shaping optics, and passive/active thermal control. At the mesh sites, the targets are mounted upon pads or bases integrally fabricated with the antenna and connected to small supply lines laced to the gore tensioning cords. At the rib or hoop sites, the targets are attached to similar bases fixed to the rigid segments.

Selected primarily for lifetime and optical efficiency, the source is a gallium aluminum arsenide solid state laser diode. For maximum power transfer to the target position detector, the centrally located receiver, the source beam is narrowed by beam shaping optics; and thus moderately accurate beam pointing means are provided at the target.

Target parameters are:

Wavelength:	.78 to .85 micrometers (selectable)
Total power:	5 milliwatts
Modulation:	Up to 5 KHz
Beamwidth:	2° x 6°
Radiant intensity:	1.2 Watts/steradian

ACTIVE TARGET

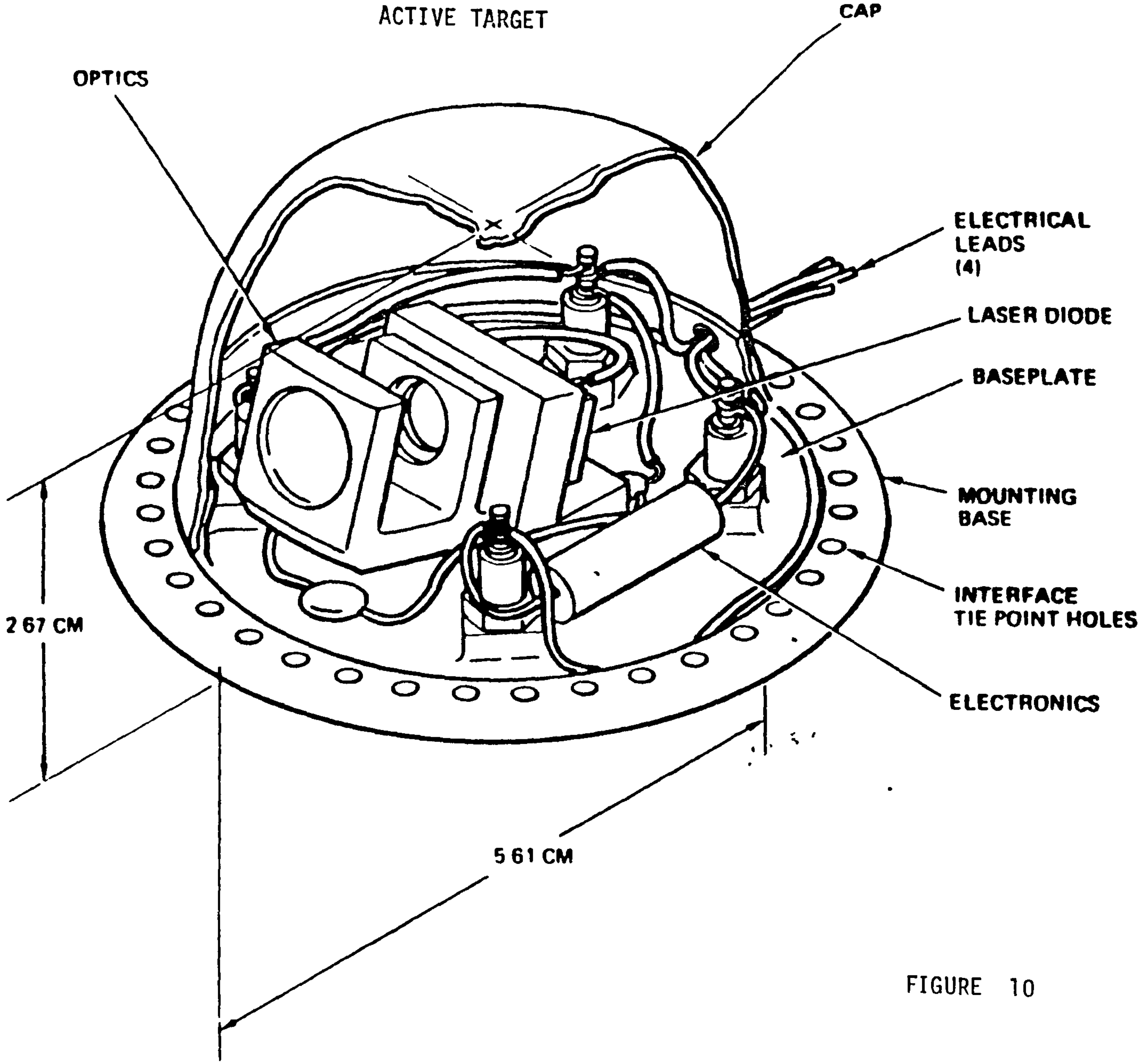


FIGURE 10

3.3. THE SENSOR GROUP

The heart of the sensor system is the cluster of sensors that continuously observe the dislocations of the antenna surface at selected sample or target points. The sensor group is imbedded in a hexagonal support ring (Figure 11).

The required number of angle sensors in the cluster are:

LOCKHEED WRAP-RIB:

Antenna surface normal:	52 targets 2 targets/sensor no. sensors	26
Antenna torsion:	52 targets 2 targets/sensor no. sensors	26
Feed-Bus:	3 targets (6 DOF) 3 targets/sensor no. sensors	1
Structure:	3 targets (6 DOF) 3 targets/sensor no. sensors	1
	TOTAL NO. SENSORS	54

HARRIS HOOP-and_COLUMN

Antenna surface normal:	90 targets 2 targets/sensor (aver) no. sensors	45
Antenna torsion: (and radial spacing)	6 targets 2 targets/sensor no. sensors	3
Feed:	3 targets (6 DOF) 3 targets/sensor no. sensors	1
Bus:	3 targets (6 DOF) 3 targets/sensor no. sensors	1
Structure:	3 targets (6 DOF) 3 targets/sensor no. sensors	1
	TOTAL NO. SENSORS	51

SENSOR GROUP

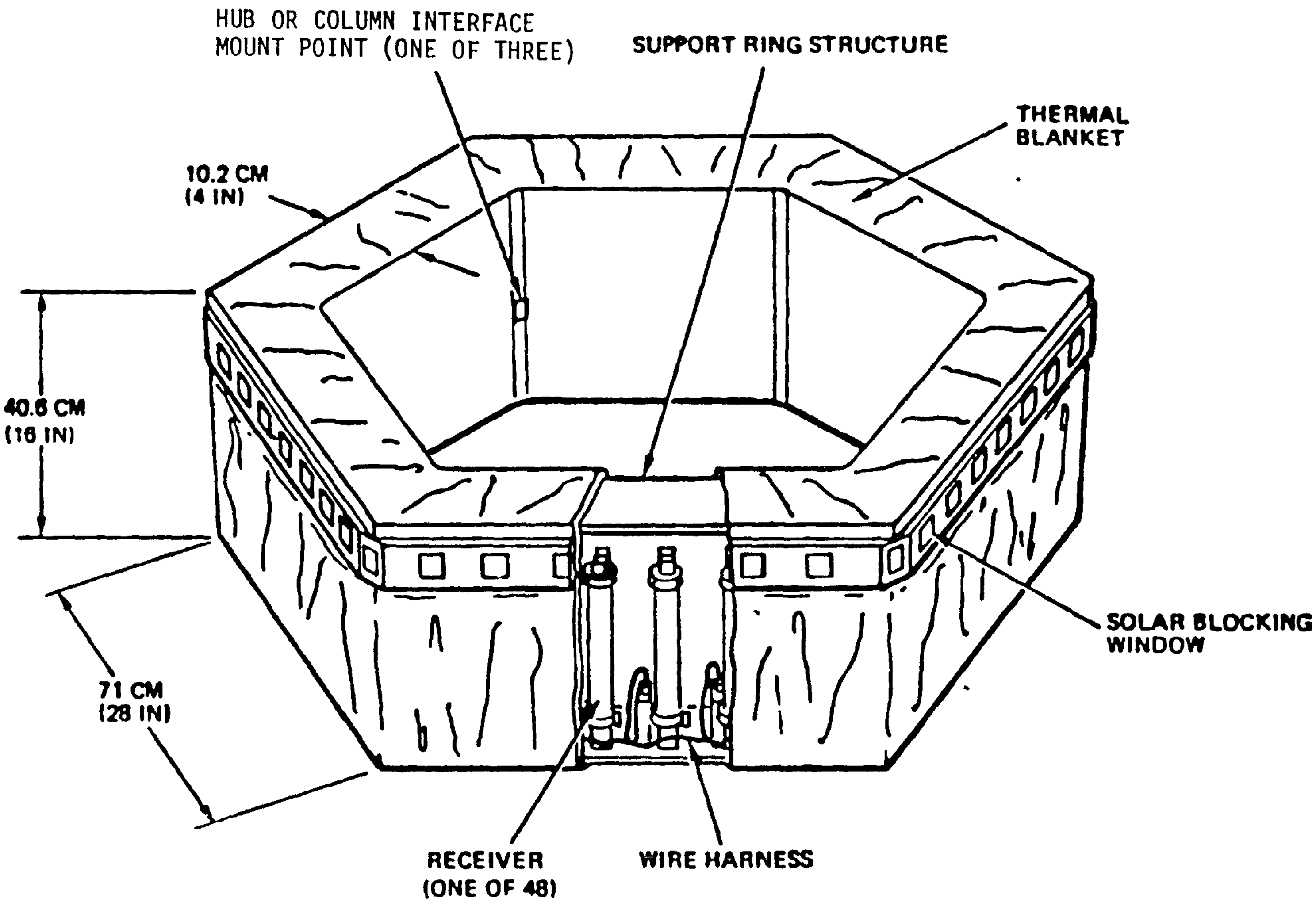


FIGURE 11

These sensors are positioned in a hexagonal support ring kinematically mounted to the antenna hub or column. Preliminary designs show that a composite material ring will produce the high intrinsic rigidity and stability required for maintaining sensor coalignment through boost environment, antenna deployment, and a ten year operational lifetime.

3.4. PERFORMANCE ESTIMATES

Capabilities for the triangulation approach to the global measurement sensor system are listed in Table 3. In general, the estimated performances are conservative. For an example, the accuracy in measuring lateral displacements is .5 millimeters. Field tests on a brassboard sensor against a half scale Harris antenna model demonstrated about ten times this accuracy, or .05 MM (scaled to maximum range).

As assumed throughout this review, the column of the Harris configuration is of determined length, and requires no additional distance measuring instrumentation. For the flight experiments, range is measured stadiametrically, however, as a check on this assumption, ranging accuracy is 1.5 CM.

For the Lockheed configuration, the feed and bus are common. A 6-DOF (Degree of Freedom) transfer from the feed-bus to the antenna hub is required to fully describe the global geometry. Since the bus and the feed are both at the column of the Harris configuration, accuracies in performing 6-DOF transfers to the reference (sensor group) are similar.

Measurement response, or frame time, is listed as 10 frames per second. This allows resolution of structural frequencies up to 2 Hertz. Should higher frequency responses be desired, these are available simply by changing the processing integration time, at the sacrifice of measurement accuracy. Doubling the frequency response roughly increases measurement error by the square root of two.

TABLE 2.

GLOBAL TRIANGULATION SENSOR SYSTEM PARAMETERS AND CAPABILITIES

Parameter	Lockheed Wrap-Rib	Harris Hoop-Column
Antenna Size	52 M Diameter	52 M Diameter Triaperture 115 M Diameter Overall
Operating Frequency	--------------- 871 MHz ---------------	
Configuration	Mesh Reflector Rib Support Offset Feed	Mesh Reflector Hoop Column Support Offset Feed (At Column)
Measurements-Antenna		
Surface Normal		
No. Sample Points	18 (3)	45
Max. Excursion	±52 CM	±50 CM
Meas. Accuracy (3σ)	.5 MM	.5 MM
Torsion (Twist)		
No. Sample Points	9 (3)	6
Max. Excursion	±50 CM	±50 CM
Meas. Accuracy (3σ)	.5 MM	.5 MM
Radial Displacement		
No. Sample Points	Not Required	3 pair
Max. Excursion		±50 CM
Meas. Accuracy (3σ)		3 MM
Measurements-Feed (and Bus)		
Feed-Antenna Spacing		
Max. Excursion	± 1 M	± 1 CM[1]
Meas. Accuracy (3σ)	1 CM	Not Required
Feed Lateral Displacement		
Max. Excursion	± 1 M	± 1 M
Meas. Accuracy (3σ)	1 MM	1 MM

GLOBAL TRIANGULATION SENSOR SYSTEM PARAMETERS AND CAPABILITIES

(CONTINUED)

Parameter	Lockheed Wrap-Rib	Harris Hoop-Column
Feed Attitude		
Max. Excursion	±3°	±3°
Meas. Accuracy (3σ)	.5 Min	.5 Min
Measurements-Structure		
Spacing to Reference		
Max. Excursion	±1 M	±1 CM[1]
Meas. Accuracy (3σ)	1 MM	Not Required
Lateral Displacement		
Max. Excursion	±1 M	±1 M
Meas. Accuracy (3σ)	1 MM	1 MM
Attitude		
Max. Excursion	±3°	±3°
Meas. Accuracy (3σ)	.5 Min	.5 Min
Measurement Rate	10 Frames/Sec[2]	10 Frames/Sec[2]

Note (1): It is assumed that after deployment, the column extends to a known length (established by the column segments and the latching mechanisms).

Note (2): This is a complete frame, providing the full set of measurements listed above.

Note (3): In Appendix A, this table shows 52 measurements. This was reduced to 26 since wrap-rib reflector does not require active surface control.

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