NASA Contractor Report 181703

Development of a Verification Program for Deployable Truss Advanced Technology

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SEPTEMBER 1988

Contract NAS1-18274

National Aeronautics and
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LIST OF ACRONYMS

ACS	Attitude Control System
AFD	Aft Flight Deck
AOA	Abort Once Around
ASAT	Anti-Satellite
ASE	Airborne Support Equipment
ATO	Abort to Orbit
ATU	Accelerometer Triad Unit
BFS	Back-up Flight Software
BIU	Bus Interface Unit
CAP	Crew Activity Plan
CCD	Charge Coupled Device
CCTV	Closed Circuit Television
CDA	Carriage Drive Assembly
CDMS	Control and Data Management Subsystem
CDR	Critical Design Review
CER	Cost Estimating Relationship
CIMG	Cargo Integration Management Group
CIR	Cargo Integration Review
COFR	Certificate of Flight Readiness
COFS	Control of Flexible Structures
COWG	Cargo Operations Working Group
CPB	Constant Power Bus
CPCB	Crew Procedures Change Board
CPOCC	Centaur Payload Operations Control Center
CRT	Cathode Ray Tube
CTE	Coefficient of Thermal Expansion
DCS	Deployment Control Subsystem
DDA	Dual Drive Assembly
DDCU	Data Display and Control unit
DDS	Dedicated Support System
DDT&E	Design Development Test and Evaluation
DN	Discrepancy Notice
DOD	Department of Defense
DRL	Design Requirements List

DSAT	Defensive Satellite
DTO	Detailed Tests Objectives
EDS	Excitation and Damping Subsystem
EIMG	Experiment Integration Management Group
EMI	Electromagnetic Interference
ERD	Experiment Requirements Document
ESP	Experiment System Procession
EVA	Extra Vehicular Activity
F/D	Focal Length/Diameter
FCA	Figure Control Actuation
FCOH	Flight Control Operations Handbook
FCS	Figure Control Subsystem
FDF	Flight Data File
FFT	Fast Fourier Transforms
FOR	Flight Operations Review
FOSA	Flight Operations Support Annex
FOSP	Flight Operations Support Personnel
FRR	Flight Readiness Review
G&A	General and Administrative
GAS CAN	Get Away Special Canister
GBL	Ground-Based Laser
GD	General Dynamics
GDA	Gimbal Drive Assembly
GDSSD	General Dynamics Space Systems Division
GDTTSP	General Dynamics Tetrahedral Truss Synthesis Program
GFE	Government Furnished Equipment
GOR	Ground Operations Review
GPC	General-Purpose Computer
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
GSTDN	Ground Satellite Tracking and Data Network
GTD	Geometric Theory of Diffraction
HOL	Higher Order Language
I&T	Integration and Testing
ICD	Interface Control Document
IHSR	Integrated Hardware and Software Review

IIA	Instrumentation Interface Agreement
IR	Infrared
JIS	Joint Integrated Simulation
JISWG	Joint Integrated Working Group
JOIP	Joint Operations Interface Procedures
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
JSS	Jettison Separation Subsystem
KSC	Kennedy Space Center
LaRC	Langley Research Center
LDR	Large Deployable Reflector
LeRC	Lewis Research Center
LOS	Line of Sight
LSA	Laser Scan Assembly
LSS	Laser Scan Subsystem
LSSM	Launch Site Support Manager
LSSP	Launch Site Support Plan
LST	Laser Scan Target
LVDT	Linear Variable Differential Transformer
LWIR	Long-Wave Infrared
MBPS	Megabytes Per Second
MCC	Mission Control Center
MDIS	Modular Distributed Instrumentation Subsystem
MDM	Multiplexor/Demultiplexor
MDP	Mission Design Panel
MET	Mission Elapsed Time
MIP	Mission Integration Panel
MMC	Martin Marietta Company
MMS	Motion Measurement Subsystem
MPESS	Mission-Peculiar Experiment Support Structure
MSFC	Marshall Space Flight Center
MSSTM	Military Space Systems Technology Model
NASA	National Aeronautics and Space Administration
NSSTM	NASA Space Systems Technology Model
NSTSPO	National Space Transportation System Program
O&IA	Operations and Integration Agreement

OMS	Orbital Maneuvering System
OST	Operations Support Timeline
PAA	Primary Actuator Assembly
PC&D	Power Conditioning and Distribution
PCB	Power Control Bus
PCS	Photogrammetric Camera Subsystem
PDR	Preliminary Design Review
PDRS	Payload Deployment and Retrieval System
PDU	Power Distribution Unit
PIP	Payload Integration Plan
PMM	Payload Mission Manager
PO	Program Office
POCC	Payload Operations Control Center
POWG	Payload Operations Working Group
PPB	Pulse Power Bus
PRCS	Primary Reactions Control Center
PRT	Platinum Resistance Thermocouple
R/B	Reflector/Beam
RAM	Random Access Memory
RCS	Reaction Control System
RF	Radio Frequency
RFT	Retro-reflector Field Tracker
RGU	Rate Gyro Unit
RMS	Remote Manipulator System
ROM	Read Only Memory
RTS	Remote Tracking Station
SAFE	Solar Array Flight Experiment
SBL	Space-Based Laser
SBR	Space-Based Radar
SDR	Systems Design Review
SDSS	Step Dedicated Support System
SG	String Gauge
SHAPES	Spatial High Accuracy Position Encoding Sensor
SMS	Strain Measuring Subsystem
SPIDPO	Shuttle Payload Integration Development Project Office
SSP	Standard Switch Panel

SSPO	Space Shuttle Project Office
SSR	Systems Requirements Review
SSV	Space Shuttle Vehicle
STEP	Shuttle Test Experiment Platform
STS	Space Transportation System
T/R	Transmit/Receive
TDRSS	Tracking and Data Relay Satellite System
TMS	Thermal Measuring Subsystem
UHF	Ultra High Frequency
UV	Ultraviolet
V-IMS	Voltage-Current Measuring Subsystem
WBS	Work Breakdown Structure
WDE	Wheel Drive Electronics

SECTION 1
INTRODUCTION AND SUMMARY

Use of a large deployable space structure to satisfy the growth demands of space systems is contingent upon reducing the associated risks that pervade many related technical disciplines, including structural dynamics, control dynamics thermal control, materials, and mechanization. NASA has recognized this issue and has sponsored significant research aimed at developing the needed large space structures technologies.

The overall objective of this program, which uses the products of these research efforts, is to develop and verify deployable truss advanced technology applicable to future large space structures, with primary emphasis on large high-performance antenna reflectors.

Specific program objectives include:

• Develop a detailed plan for a comprehensive analysis, ground test, and flight test program that will provide practical usable insight into large deployable truss structures technology issues. The plan addresses validation of analytical methods, the degree to which ground testing adequately simulates flight testing, and the in-space testing requirements for large deployable antenna design validation.

• Integrate into the plan deployable truss structure development issues and technology requirements to support future NASA and DOD missions.

• Develop a preliminary design of a deployable truss reflector/ beam structure for use as a technology demonstration test article. Preliminary design and planning is based on a test program using an existing General Dynamics 5-meter aperture deployable tetrahedral truss reflector and a new 15-meter deployable tetrahedral truss antenna design.

To address critical deployment, dynamics, controls and interface issues for large antenna structures, the test articles include a deployable truss beam element that represents a typical antenna support structure. An overview of the ground test and flight experiment programs is shown in Figure 1-1.

The technical effort on this program was conducted over a total period of 13 months (May 1986 thru June 1987). The detailed program plan was developed during the first nine months. Preliminary design and analysis of the experiment was initiated at the end of the sixth month and was completed at the end of the technical effort.

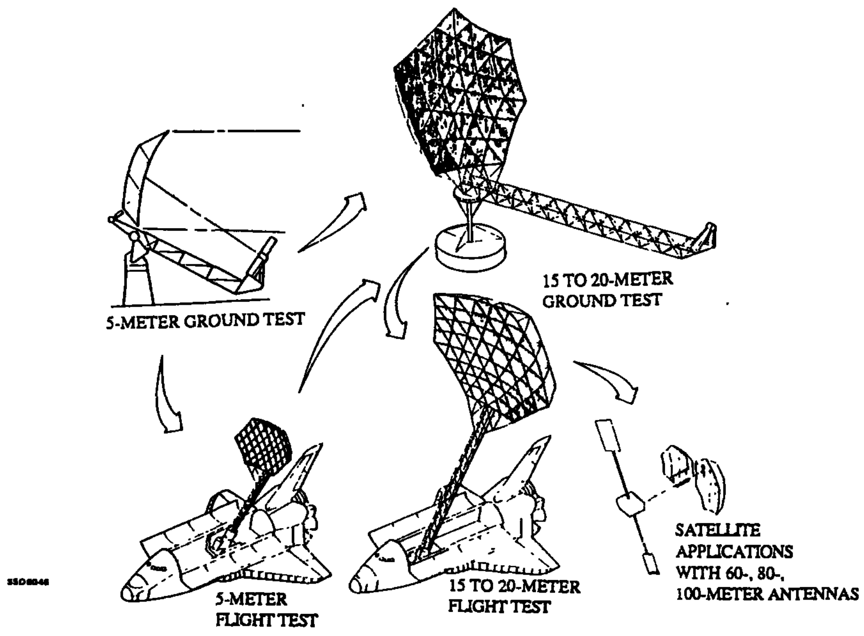


Figure 1-1. Ground Test and Flight Experiment Overview

The program was managed by J.E. Dyer of General Dynamics Space Systems Division. Major contributions were made to the program by Dr. A. L. Hale, Structural Dynamics and Controls; R. H. Riecken, Structural and Mechanisms Design; R. L. Pleasant, Thermal Analysis; G. S. Davis, Flight Experiment and Shuttle Integration; R. E. Bailey, Ground Test Planning; J. M. Youngs, Cost Analysis; S. C. Maki, Avionics and Instrumentation; E. T. Lipscomb, R. F. Systems. R. Quarteraro of SPARTA, Inc.provided major inputs to the study in the areas or requirements, surface measurement and control.

SECTION 2
PROGRAM PLAN

The primary output of this study is a detailed program plan that includes the definition of a comprehensive analysis, ground test, and flight test program that provides insight into large deployable truss structures technology issues. The plan addresses analytical methods validation, ground testing approaches, and in-space testing requirements. The plan is divided into nine elements:

- Performance and Design Requirements identifies deployable truss structure technology requirements for future space systems.
- Design and Development includes evaluation analyses, experiment options definition and experiment design.
- Analysis Plan addresses the analysis component of the integrated analysis, ground test and flight test technology verification program.
- Test Plan defines both the ground and flight test elements.
- Payload Integration covers the requirements for integrating the flight test program with the STS.
- Post-flight Evaluation provides a plan to evaluate and correlate test and analysis data.
- Program Schedule defines the overall program master schedule.
- Facility Requirements identifies facilities required for the development, manufacture, test, and analysis efforts.
- Cost Analysis develops a cost model for the total verification program including hardware, fabrication and testing.

Each of these nine elements of the program plan is discussed in the following sections.

2.1 PERFORMANCE AND DESIGN REQUIREMENTS

The program objective, planning for the development and verification of deployable truss structure technology for future space systems, suggests that performance and design requirements must be based upon the structural needs of anticipated large space systems. Accordingly, the approach outlined in Figure 2-1 was used to determine deployable truss requirements. These requirements and technology issues were established by reviewing the "NASA Space Systems Technology Model" (NSSTM) (Ref. 1); the "Military Space Systems Technology Plan," (MSSTP) (Ref. 2); NASA/LaRC briefings on the "Control of Flexible Spacecraft" program; documentation on the Air Force Weapons Laboratory's "Large Optical Structures" program; and private communications with NASA and DOD personnel. Data from these sources are divided into four classes:

- NASA and commercial antennas
- NASA optical systems

• Military space-based radar antennas

• Military laser optics

The first class is of most interest, serving to establish baseline technology issues, because of its primary relevance to NASA research objectives and compatibility with deployable structure capabilities. The other classes are examined to determine if technology developed for antenna truss structures would be applicable, or if optical or radar issues could be addressed on an antenna test article. The final output of this process is a set of preliminary, needs-driven technology development issues.

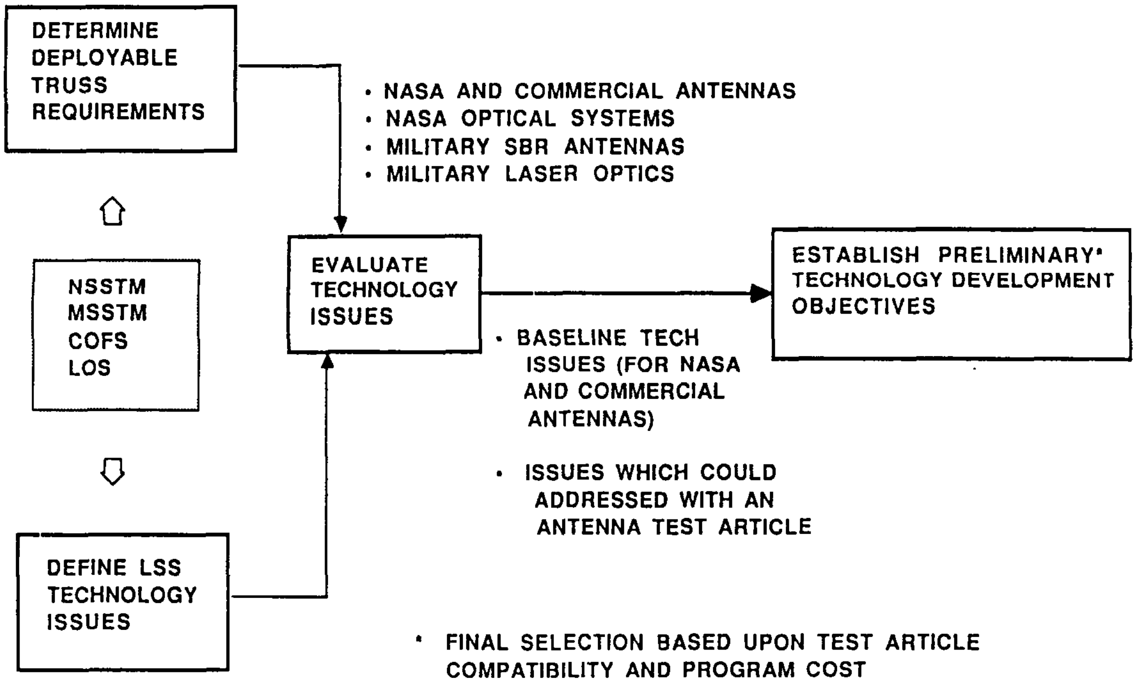


Figure 2-1. Approach for Determining Deployable Truss Requirements and Technology Development Issues

2.1.1 <u>NASA AND COMMERCIAL ANTENNAS.</u> A review of the NSSTM indicates that the most demanding future NASA and commercial space antennas are characterized by:

• Benign disturbances (operation of attitude and velocity control components, solar array tracking, and interaction with the earth orbital space environment)

• Accurate staring-mode body pointing towards earth and stellar targets

• Precision shape and alignment requirements.

A summary of future NASA missions and a representative commercial system, Intelsat IV, is presented in Table 2-1. Wide ranges of sizes (5-300 meters) are projected, and operating

Table 2-1. Summary of Mission Requirements for Future NASA and Commercial Antennas

NSSTM DESIGNATION	MISSION	DIAMETER (M)	OPERATING FREQUENCY	START DATE	LAUNCH DATE
C-3	MOBILE COMMUNICATIONS				
	PHASE I	5-7	UHF	ONGOING	1989
	PHASE II	20	UHF	1989	1993
	PHASE III	≤ 55	UHF	1994	1998
C-4	ADVANCED COMMUNICATION	1-3, 1-2	20,30GHz	ONGOING	1990
C-7	HIGH FREQUENCY DIRECT BROADCAST	65-100+	15-26GHz	≥1990	ND
L-5	SEARCH FOR EXTRATERRESTRIAL LIFE	300	RF-RADAR	1988	ND
LM-5	ADVANCED COMMERCIAL COMMUNICATIONS	160-230	L-BAND	ND	ND
E-17	SOIL, SNOW MOISTURE AND PRECIPITATION RESEARCH AND ASSESSMENT MISSION	10	MICRO-WAVE	1990-2000	ND
E-18	FREE-FLYING IMAGING RADAR	10	L-,C-,X-BAND	1990-2000	ND
A-20	ORBITING VERY LONG INTERFEROMETRY OBSERVATORY	15-20	X-BAND	1990-1995	ND
	INTELSAT VII	5	C-,K -BAND	1990	ND

wavelengths range from less than 1cm (K-band) to 1 meter (UHF). For the most part, these are standard reflector-type antennas that must maintain reflector surface figure and reflector/feed alignment accurate to a fraction of one wavelength. The technology addressed in this program is applicable to virtually all of these missions.

2.1.2 <u>NASA OPTICAL SYSTEMS.</u> Future NASA optical systems are summarized in Table 2-2. These systems have two classes of structures: 1) primary reflector backup structures with secondary mirror support (e.g., LDR); and, 2) booms to maintain precision alignment (e.g., Pinhole Occultor and Infrared Interferometer). Some are free-flyers with benign disturbances, and others are subjected to potentially troublesome disturbances because they are Shuttle-attached (Pinhole Occultor) or may contain mechanical cryo coolers (Infrared Interferometer). All are required to point very accurately towards stellar or solar targets. Structural dimensions range from 20-100 meters, while operating wavelengths range from 0.4μM (visible) to 1 millimeter (LWIR).

2.1.3 <u>MILITARY SPACE-BASED RADAR</u>. SBR studies have generally favored phased array configurations over reflector-type antennas in order to effect agile, electronic beam steering. These

Table 2-2. Summary of Mission Requirements for NASA Optical Systems

NSSTM DESIGNATION	MISSION	SIZE (M)	OPERATING FREQUENCY	START DATE	LAUNCH DATE
A-23	LARGE DEPLOYABLE REFLECTOR	20M DIA	30 μM -1MM	1993	1997
A-29	100-M THINNED APERATURE TELESCOPE	100M DIA	VISIBLE	>1995	ND
A-12	PINHOLE OCCULATOR FACILITY	32M BEAM		1988	1992
A-26	INFRARED INTERFEROMETER	100M BEAM	IR	>1995	ND
A-28	COHERENT OPTICAL SYSTEM OF MODULAR IMAGING COLLECTORS	34M BEAM	VISIBLE	>1995	ND

designs avoid the need to point the structure accurately or to slew rapidly. However, the phased array antenna surface must be kept planar to within a fraction of a wavelength. This task is complicated by heating from transmit/receive modules on the array. Furthermore, there is a desire to perform rapid orbit change maneuvers in order to avoid threats, and the attendant antenna surface errors must be suppressed quickly.

Typical SBR design characteristics and requirements are listed in Table 2-3. Operating wavelengths typically range from 3-30 centimeters, and a typical flat array antenna has an area on the order of 300 meters^2.

2.1.4 MILITARY LASER OPTICS. Large optical structures for laser weapon systems include orbiting "relay" and "mission" mirrors to reflect laser light from ground-based sources and beam expanders for space-based lasers that contain their own laser generators. These systems are characterized by 10-meter-class optics, precise body pointing, and rapid retargeting maneuvers. All are subjected to severe disturbances, with space-based laser device vibration the most intense.

Typical laser system requirements and characteristics are summarized in Table 2-4. Operating wavelengths range from 0.01µM(UV) to 3µM(IR), and optical tolerances are fractions of a wavelength.

Table 2-3. SBR Antenna Mission Requirements

PARAMETER	TYPICAL VALUES
MISSION	AIRCRAFT AND CRUISE MISSILE DETECTION AND TRACK; STRATEGIC SURVEILLANCE; SHIP DETECTION AND IDENTIFICATION; MID-COURSE DISCRIMINATION
RADAR TYPE	CORPORATE-FED PHASED ARRAY (ELECTRIC STEERING); SPACE-FED LENS (ELECTRONIC STEERING); REFLECTOR (BODY POINTING); REFLECTOR AND PHASED FEED (BODY + ELECTRONIC)
SIZE	ARRAY AREA > $300M^2$ (30M X 10M);
OPERATING FREQ.	$1\text{-}10.9^{+}$GHz
POINTING MODE	EARTH POINTING (ELECTRONIC STEERING)
DISTURBANCES	THREAT AVOIDANCE MANEUVERS; T/R MODULE HEAT; ACS; SOLAR ARRAYS; ENVIRONMENT
SURFACE ACCURACY	$\lambda/20$ - $\lambda/80$

Table 2-4. Laser Weapon System Requirements

PARAMETERS	TYPICAL VALUES
MISSION	STRATEGIC DEFENSE ASAT ASAT
OPTICAL SYSTEM TYPE	GBL RELAY MIRROR: MONOCLE AND BIFOCAL SBL BEAM EXPANDER
SIZE	ASAT/DSAT = $\geq$ 5M STRATEGIC DEFENSE = $\geq$ 10M
OPERATING FREQUENCY	UV - IR
POINTING MODE	SLEW AND SETTLE; TRACK
DISTURBANCES	ON-BOARD LASER; MIRROR COOLANT FLOW;ACS
SURFACE ACCURACY	$\lambda/15$ - $\lambda/40$

2.1.5 BASELINE REQUIREMENTS. Characteristics and requirements for the four space structure classes discussed above are summarized in Table 2-5. The "Baseline" column lists ranges of values that should be addressed in developing and validating deployable truss technology. They are selected to be the NASA and commercial antenna parameter values, because that class is the primary focus of this technology development program. Comparing the columns of values, indicates that truss structures developed for the Baseline applications will have characteristics suitable for SBR antennas, but which are not applicable to NASA and military optical structures. However, the following discussion will show that all of the structural classes have some common technology issues, and addressing those issues on an antenna structure should be of some help in developing solutions for optical structures.

Table 2-5. Baseline Requirements

PARAMETERS	NASA AND COMMERCIAL ANTENNAS	NASA OPTICAL SYSTEMS	MILITARY SBR ANTENNAS	MILITARY LASER OPTICS	BASELINE
SIZE	5-300M DIA.	20-100M DIA	>300M^2 (30M X 10M)	≥ 5M DIA	5-300M
WAVELENGTH, λ	1CM$^-$- 1M$^+$	.4μM-1MM	3 -30CM	.01-3 μM	1CM-1M
TOLERANCES					
SURFACE	λ/20- λ/40	λ/20	λ/20- λ/80	λ/20	λ/40
DEFOCUS	2λ	2λ	2λ	2λ	2λ
LATERAL	0.1λ	0.1λ	0.1λ	0.1λ	.1λ
DISTURBANCES	ACS SOLAR ARRAY ENVIRONMENT	ACS SOLAR ARRAY ENVIRONMENT SHUTTLE	MANEUVERS T/R MODULE HEAT ACS SOLAR ARRAY ENVIRONMENT	LASER FLUIDS ACS	ACS SOLAR ARRAY ENVIRONMENT
POINTING MODE	EARTH INERTIAL	STELLAR SOLAR	EARTH	RETARGET TARGET TRACK	EARTH INERTIAL

2.1.6 TECHNOLOGY ISSUES. Four categories of technology issues have been identified: 1) deployment, 2) shape accuracy, 3) pointing and alignment, and 4) articulation and maneuvers.

2.1.6.1 Deployment. Deployment issues are of greatest concern for very large NASA and commercial antennas and some NASA optical systems. Antenna deployment is an issue because it has not been demonstrated for 50-300 meter structures. Large optical systems operating at relatively long wavelengths or containing long precision beams for alignment may employ deployable trusses that have not been demonstrated and must be very accurate. The specific deployment technology needs applicable to both antenna and optical trusses are:

- Accurate computer simulation of deployment dynamics
- Ground test methods for very large structures
- Deployment motion control mechanisms and deployable optical trusses with zero-play joints

Military space-based radar structures do not pose as critical a problem because structures of this smaller size have been deployed on the ground and in space. Military laser optical structures do not share common deployment issues with NASA and commercial antennas, because their sizes are more limited and shape/alignment tolerances are so critical that standard deployment techniques are not applicable. It is likely that these structures will be partially or totally erectable.

2.1.6.2 Shape Accuracy. A standard measure of the technical challenge posed by a reflector surface is diameter divided by the rms surface roughness requirement (D/ε), where the surface roughness requirement is a fraction of the operating wavelength. Figure 2-2 plots the values of these parameters for the future NASA/commercial systems listed in Tables 2-1 and 2-2. The plot also shows that the threshold of capability for a typical passive reflector, with a faceted mesh reflector attached to a deployed backup structure, is between $D/\varepsilon = 10^4$ and $D/\varepsilon = 10^5$. Systems such as C-3 and C-4 that are to the right of the "Passive Truss/Mesh Capability" line could be accommodated by this passive reflector.

The capability of the truss/mesh configuration could be improved by adding active shape control. If the control system were perfect, it could correct all errors except a 10^{-2} to 10^{-3} meter geometric error resulting from approximating a continuous reflector surface by many flat facets. Thus, the limit of control capability is indicated in Figure 2-2 by the vertical line labeled "Active Truss/Mesh Potential." The plot shows that all the future NASA/commercial antennas considered here and the space-based radar requirements could be accommodated by active shape control. Clearly, the development of active reflector shape control would be beneficial, especially for very large antennas.

At least these three shape accuracy issues should be addressed:

- Development of figure measurement sensors
- Development of actuators and algorithms for adjusting mesh surface shape
- Development of accurate analytical models for predicting thermal distortions

Addressing these topics specially for truss/mesh antenna reflectors will result in designs that will not be directly applicable to optical and military radar systems. However, these same issues are relevant to all four system classes, and there should be at least some technology transfer.

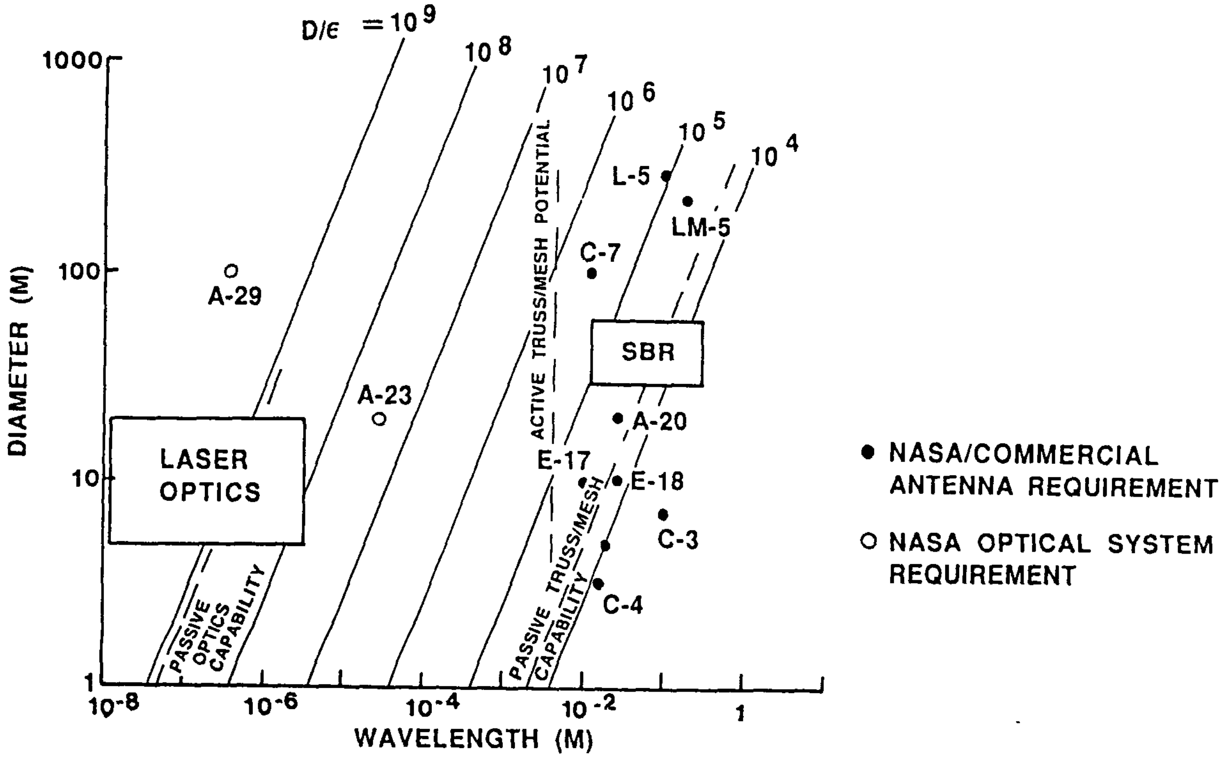
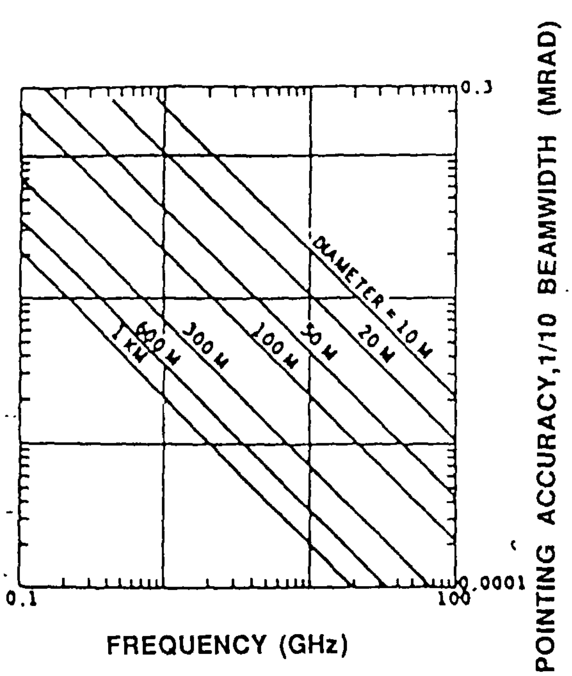


Figure 2-2. Assessment of Reflector Shape Accuracy Requirements

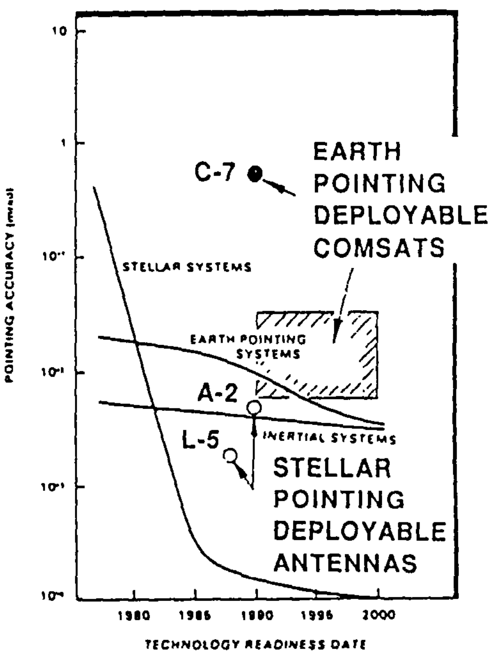
2.1.6.3 Pointing and Alignment. Alignment is considered along with pointing, because the major impact of misalignment of an antenna feed or secondary mirror relative to its reflector is to introduce pointing errors. Figure 2-3 addresses the body pointing issue only. It shows that although pointing accuracy requirements become more severe as operating frequency and diameter are increased (left side of Figure 2-3), the range of requirements is within the pointing control state-of-the-art (right side).

Alignment issues, on the other hand, are similar to shape accuracy issues, in that requirements are a fraction of the operating wavelength and errors tend to increase with size for uncontrolled structures. For this reason, the specific shape accuracy issues mentioned above probably apply to feed and secondary alignment, too.

Another closely related issue is control/structure interaction. As antenna diameter (D) increases and operating wavelength (λ) decreases, the bandwidth of the pointing control system tends to increase to achieve more accurate pointing. Increasing antenna diameter lowers the fundamental structural frequency (f), thereby increasing the likelihood of unstable control/structure interactions.



LARGE ANTENNA POINTING ACCURACY REQUIREMENTS



POINTING ACCURACY REQUIREMENTS

Figure 2-3. Assessment of Body Pointing Issues

Reference 3 indicates that unstable interactions tend to occur for values of D/ f greater than approximately 10^4. Using this criteria to evaluate the NASA antenna and optical systems (Figure 2-4), most of the antennas are in the "no interaction" region, and the largest antennas may experience unstable interactive. All of the NASA optical systems are well within the "interaction" region. Thus, the development of techniques to avoid interactions will be useful for the largest antennas, and techniques developed for antennas should be applicable to optical systems. These techniques will include developing accurate structural dynamic modeling and verification methods.

In summary, the pointing and alignment issues for future NASA/commercial antennas are:

- Feed or secondary mirror alignment
- Control/structure interaction
- Structural dynamic modeling and verification

All of these issues are applicable to both NASA and military optical systems, and alignment control may be applicable to military space-based radar.

2.1.6.4 Articulation and Maneuvers. These two topics are combined into one issue because the most stressing maneuver is the rapid retargeting of articulated optical telescopes. This issue is applicable to military space-based lasers and, to a lesser extent, military radar. The class of primary interest, NASA/commercial antennas, generally does not have stressing articulation or

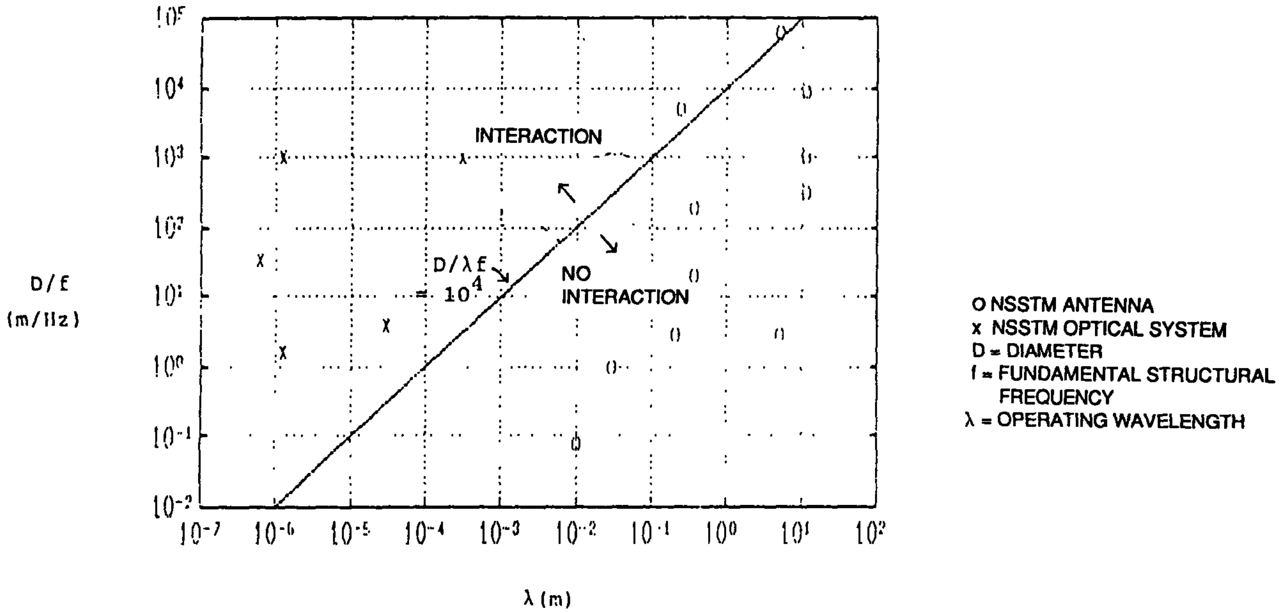


Figure 2-4. Assessment of Control/Structure Interaction

maneuver requirements. Therefore, this issue will not be included in the development plan.

2.1.6.5 Summary of Technology Issues. These technology issues are summarized in Table 2-6.

Table 2-6. Summary of Baseline Antenna Technology Issues

Area	Technology Development Need
Deployment	• Accurate computer simulation of deployment dynamics • Ground test methods for very large structures • Deployment motion control mechanisms
Shape Accuracy	• Figure measurement sensors • Actuators and sensors for adjusting mesh surface shape • Accurate analytical models for predicting thermal distortions
Pointing and Alignment	• Methods to suppress control/structure interactions • Structural dynamic modeling and verification methods

2.1.7 SPACE TESTING. In-space testing is required to verify technology developed for large deployable trusses that must maintain precise shape and alignment. This requirement results from the inadequacy of current ground test methods in simulating the free-fall and thermal loading environments experienced in space. Ground testing with gravity off-loading supports introduces nonoperational loads, constraints and disturbances that affect deployment dynamics, vibration characteristics and shape/alignment accuracy. Furthermore, it is difficult to simulate realistic, transient solar-thermal heating and shadowing in a thermal/vacuum chamber; and the measurement of thermally induced distortions is complicated by gravity loading. The space testing portion of the program should verify new truss technology and validate ground test methods for future large deployable antenna structures.

2.2 DESIGN AND DEVELOPMENT

Based on the design requirements and large deployable truss technology issues discussed in Section 2.1, evaluation analysis, experiment options definition, and experiment designs were developed. Previous work on the deployable geo-truss antenna reflector and the deployable truss beam strongly influenced the experiment concept definition, which includes both 5-meter and 15-meter diameter reflector/beam test articles.

2.2.1 <u>STRUCTURAL DYNAMICS AND CONTROLS EVALUATION</u>. This section describes preliminary structural dynamics and controls analyses of candidate reflector-beam flight-experiment configurations. The analyses have three main objectives: to determine inherent characteristics of the candidate flight configurations, to define sequences of flight experiments that validate the appropriate structural dynamics and controls technologies identified in Section 2.1, and to define instrumentation requirements for the flight experiments.

Many previous studies have considered possible flight experiments for validating structural dynamics and controls technologies of large, flexible space structures (e.g., Refs. 4-15, inclusive). The present study is distinct in that it focuses on the technology issues appropriate for deployable large truss-antenna structures. Since truss-antennas are inherently stiffer than other types of antenna structures, structural dynamics and controls requirements for them are less demanding. This is reinforced by the analyses reported below.

The individual analyses were designed to: 1) determine the dynamic behavior of 5- and 15-meter reflector-beam flight experiment configurations; 2) evaluate the effects of Space Transportation System (STS) primary RCS firings on loads in the flight structures; 3) locate candidate flight instrumentation, both sensors and actuators, for on-orbit structural and control dynamics experiments; 4) evaluate STS vernier RCS and internally mounted torque-wheels as disturbance sources for on-orbit dynamics experiments; 5) evaluate candidate structural configurations for on-orbit vibration control experiments; 6) evaluate candidate configurations for on-orbit articulation and pointing control experiments; 7) determine candidate ground- and flight-test scenarios for structural dynamics and controls experiments; and, 8) compare the technology issues being addressed herein with those addressed by NASA's proposed Control of Flexible Structures (COFS) II program.

2.2.1.1 Reflector-Beam Configurations. The three structural configurations are (Figure 2-5):

- A 5-meter (radio frequency diameter) reflector mounted on a 6.5-meter beam
- A 5-meter reflector mounted on a 20-meter beam
- A 15-meter reflector mounted on a 20-meter beam.

The reflectors and beams are deployable truss structures. Each reflector is edge-mounted to one end of the beam, and the opposite end of the beam is attached to the Space Transportation System's (STS) cargo bay at a 45-degree angle to the bay. The reflectors face forward (towards the STS crew compartment) and down (towards the cargo bay).

Actual designs for the reflectors, truss-beams, reflector-beam interface structures, and STS-beam mount are discussed in Section 2.2.5. The beam lengths of 6.5 and 20 meters allow mounting an RF feed near the STS for a focal length-to-diameter ratio of unity for the 5- and 15-meter reflectors, respectively.

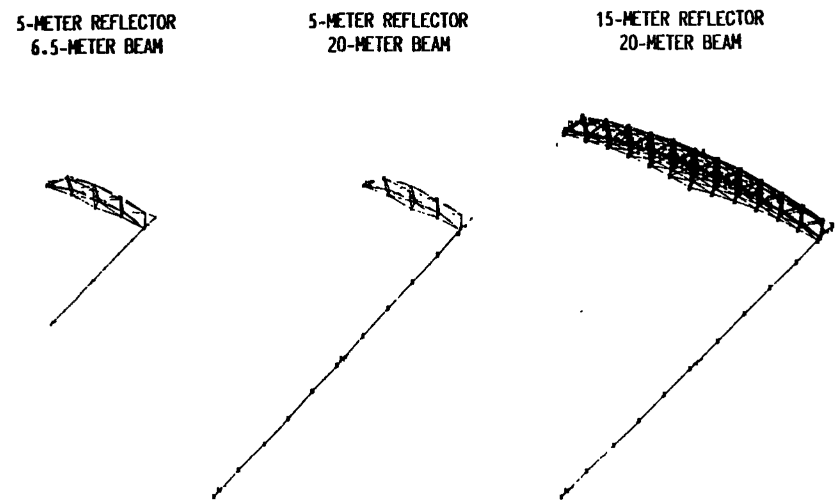


Figure 2-5. Both 5-and 15-Meter Antenna Structures Were Evaluated

2.2.1.2 Structural Finite-Element-Model Assumptions. The reflectors are modeled as truss structures using NASTRAN CROD elements with three translation degrees of freedom at each node. The beams, on the other hand, are modeled with NASTRAN CBAR elements (axial, transverse bending, and torsion elements) using effective axial, bending, and torsional mass and stiffness properties. There are six degrees of freedom, three translations, and three rotations at each beam node. Beam cross-sections are assumed symmetric.

Reflector-beam interface structures are also modeled using CBAR elements. The interface structures have six degrees of freedom per beam-connection node and three degrees of freedom per reflector-connection node. Element stiffnesses are commensurate with those of reflector elements.

The STS is modeled as a rigid body (NASTRAN CONM2 element) with the STS mass connected to a beam mount by a rigid massless element (NASTRAN RBAR element). The mass moments of inertia of the STS about its center of mass are taken as: Ixx=2.03E6, Iyy=9.26E6, Izz=9.72E6, Ixy=4.1E4, Ixz=1.9E4, and Iyz=1.01E3 (N-s2-m) where x, y, and z refer to the roll, pitch, and yaw axes, respectively, of the STS.

2.2.1.3 Reflector Properties. The 5-meter reflector has four bays and a strut angle of 45 degrees. The modules of elasticity of each strut is 1.38E11 N/m2 and the weight density is 1.52E3 Kg/m3. Upper and lower surface struts are 2.22 cm diameter tubes with a wall thickness of 0.7 mm. Diagonal struts are 2.22 cm -diameter tubes with a wall thickness of 0.48 mm. Strut lengths vary from approximately 118 cm for the diagonals to approximately 150 (cm) for the upper and lower surface struts. Total mass of the 5-meter reflector structure is 39.3 Kg. The fundamental natural frequency of the reflector cantilevered from its mounting points is 9.29 Hz. The fundamental free-free reflector natural frequency is 41.7 Hz. The lowest pinned-pinned local natural frequency of an individual strut is approximately 110 Hz.

The 15-meter reflector has 12 bays. The 5-meter reflector's truss structure is a four-bay section of the 15-meter reflector. Therefore, the strut sizes, strut angle, and material properties for the 15-meter reflector are the same as those given above for the 5-meter reflector. The total mass of the 15-meter reflector structure is 250 Kg, its fundamental cantilevered natural frequency is 1.44 Hz, and its fundamental free-free natural frequency is 12.0 Hz. Note that the 5-meter reflector is significantly stiffer than the 15-meter reflector with the same bay size and truss depth.

2.2.1.4 Truss-Beam Effective Properties. Effective mass and stiffness properties of truss beams are found from detailed finite element models of several deployed bays. Stiffness properties are found by applying unit longitudinal forces, unit transverse forces, and a unit couple to each end of a section model and computing the axial, bending, and torsional stiffnesses, respectively, of a Bernoulli-Euler beam that would yield equal static deflections under equivalent applied loads. Effective masses per unit length are found by uniformly distributing total masses of the various truss-beams.

Both "square" and "diamond" truss-beam designs are candidates. While the designs have equal axial stiffnesses, a diamond truss-beam provides approximately 2.4 times more torsional stiffness but approximately 2.1 times less bending stiffness than a square truss-beam of comparable dimension and mass per unit of length. The diamond beam design is preferred over the square beam design because it yields reflector-beam system natural modes with the frequency of the fundamental torsion mode commensurate with the frequency of the fundamental bending mode. Using a square beam design yields system modes dominated by a beam-torsion mode at a frequency approximately 0.65 of that for a comparable diagonal beam.
The choice of particular bay and strut sizes for a truss-beam is based on stiffness rather than strength criteria. Three beam configurations (six total) referred to as "flexible," "nominal," and "stiff" were considered for this study. Properties of the three beams are based on their effects on system characteristics.

Effective masses per length (Kg/m), axial stiffnesses (N), bending stiffnesses (N-m2), and torsional stiffnesses (N-m2) for the 6.5-meter beams are, respectively: 1.34, 7.21E6, 1.38E11, and 6.51E10 for the flexible beam; 2.69, 4.63E7, 3.51E12, and 1.23E12 for the nominal beam; and 5.39, 9.25E7, 2.11E11, and 7.37E12 for the stiff beam. The first cantilevered bending frequencies of the three beams are 2.5, 8.8, and 15.2 (Hz), respectively.

Effective masses per length (Kg/m), axial stiffnesses (N), bending stiffnesses (N-m2), and torsional stiffnesses (N-m2) for the 20-meter beams are, respectively: 2.69, 4.63E7, 3.51E12, and 1.23E14 for the flexible beam; 8.95, 3.02E8, 7.03E13, and 2.45E13 for the nominal beam; and 13.4, 6.05E8, 4.22E14, and 1.47E14 for the stiff beam. The first cantilevered bending frequencies of the three beams are 0.93, 2.3, and 4.6 Hz, respectively. Note that the flexible 20-meter beam has the same properties as the nominal 6.5-meter beam.

2.2.1.5 Deployed System Dynamic Characteristics. Nine deployed reflector-beam systems are considered, consisting of flexible, nominal, and stiff beams in each of the three combinations of reflectors and beam lengths. The frequencies for each of the nine systems of the two lowest elastic natural modes of vibration are given in Table 2-7.

The dynamic characteristics of each configuration are dominated by beam bending and torsional flexibility. The STS is so massive and stiff relative to the reflector-beam structure that its participation is quite small in any dynamic response and/or in the lower natural modes of vibration. Both reflectors are also quite massive and stiff relative to the beam, so that in the lower natural modes of the system they participate as nearly rigid bodies. This is seen, for the second and third

Table 2-7. Summary of System Lowest Natural Frequencies (Hz)

Beam	Configuration 1 5-m Refl/6.5-m Beam		Configuration 2 5-m Refl/20-m Beam		Configuration 3 15-m Refl/20-m Beam	
Description	1st Tors.	1st Bnd.	1st Tors.	1st Bnd.	1st Tors.	1st Bnd.
Flexible	0.460	0.592	1.52	0.40	0.157	0.218
Nominal	2.05	2.89	6.18	1.52	0.668	0.892
Stiff	4.87	6.41	8.81	3.39	1.33	1.37

configurations with a flexible beam, by examining the mode shapes of Figures 2-6a thru 2-6d and 2-7a through 2-7d, respectively.

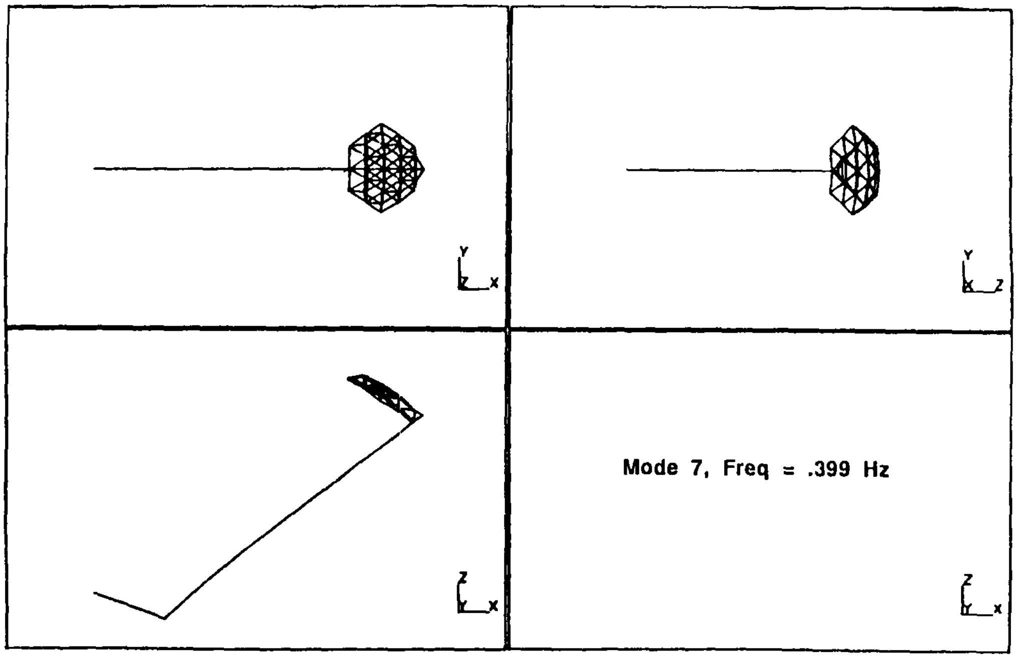


Figure 2-6a. First Elastic Natural Mode: 5-Meter Reflector on 20-Meter Flexible Beam

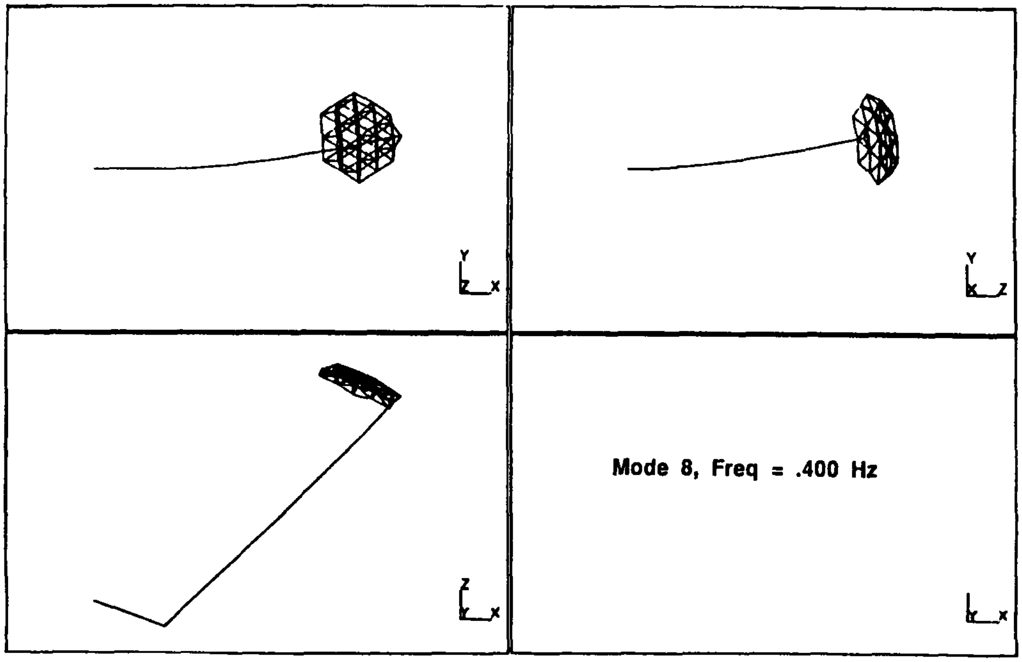


Figure 2-6b. Second Elastic Natural Mode: 5-Meter Reflector on 20-Meter Flexible Beam

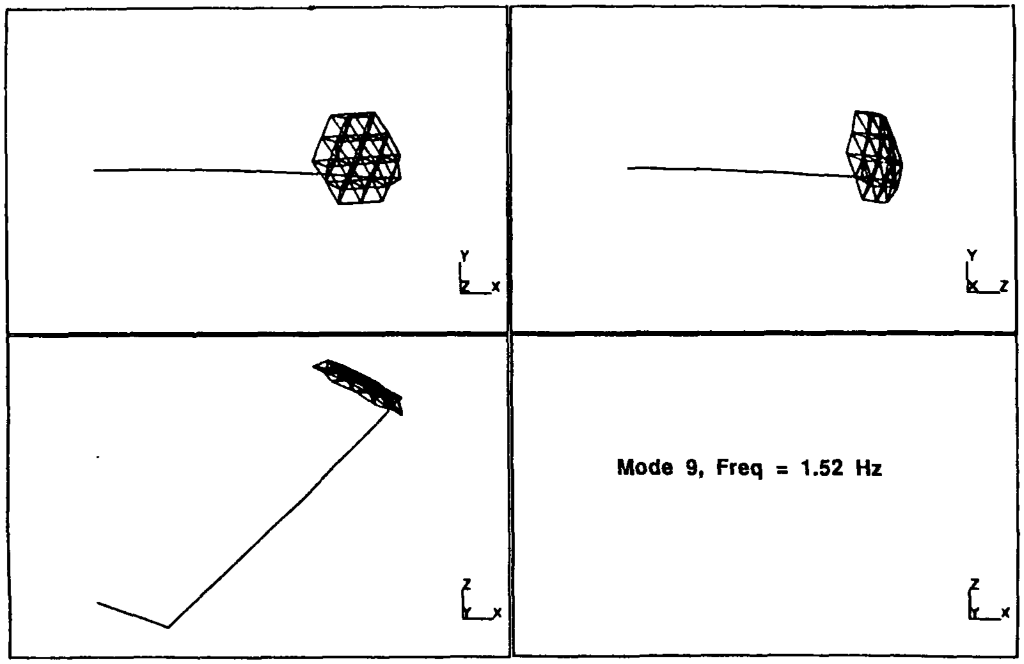


Figure 2-6c. Third Elastic Natural Mode: 5-Meter Reflector on 20-Meter Flexible Beam

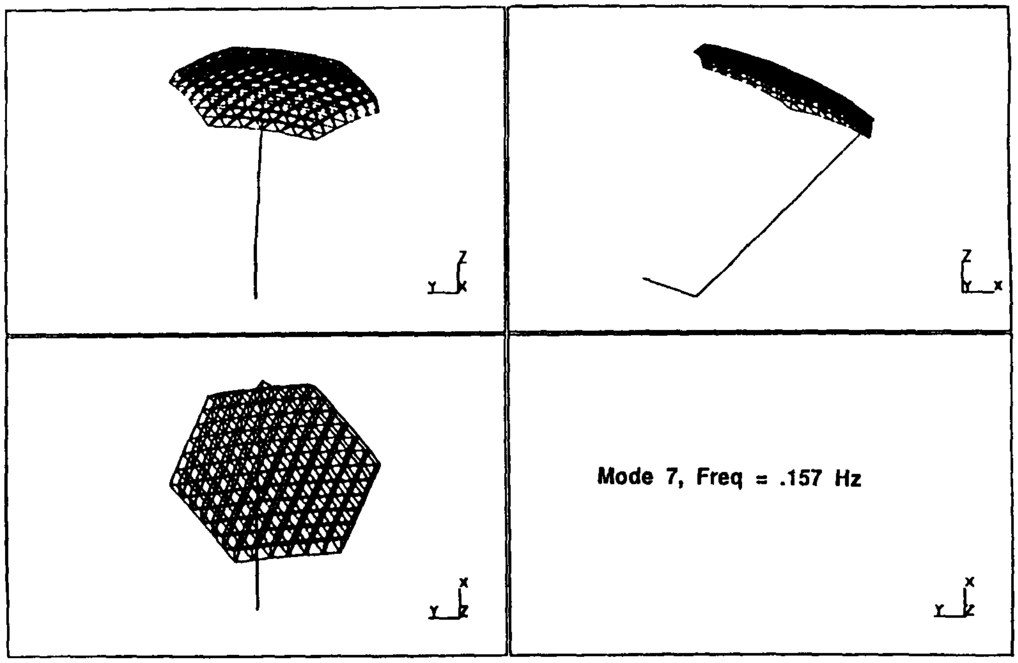


Figure 2-6d. Fourth Elastic Natural Mode: 5-Meter Reflector on 20-Meter Flexible Beam

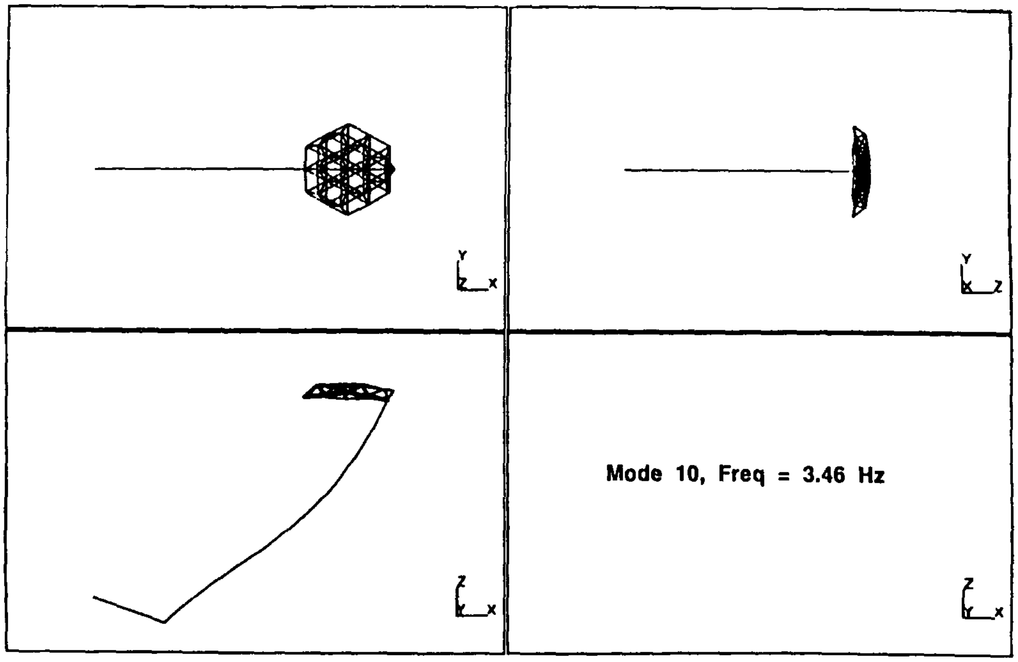


Figure 2-7a. First Elastic Natural Mode: 15-Meter Reflector on 20-Meter Flexible Beam

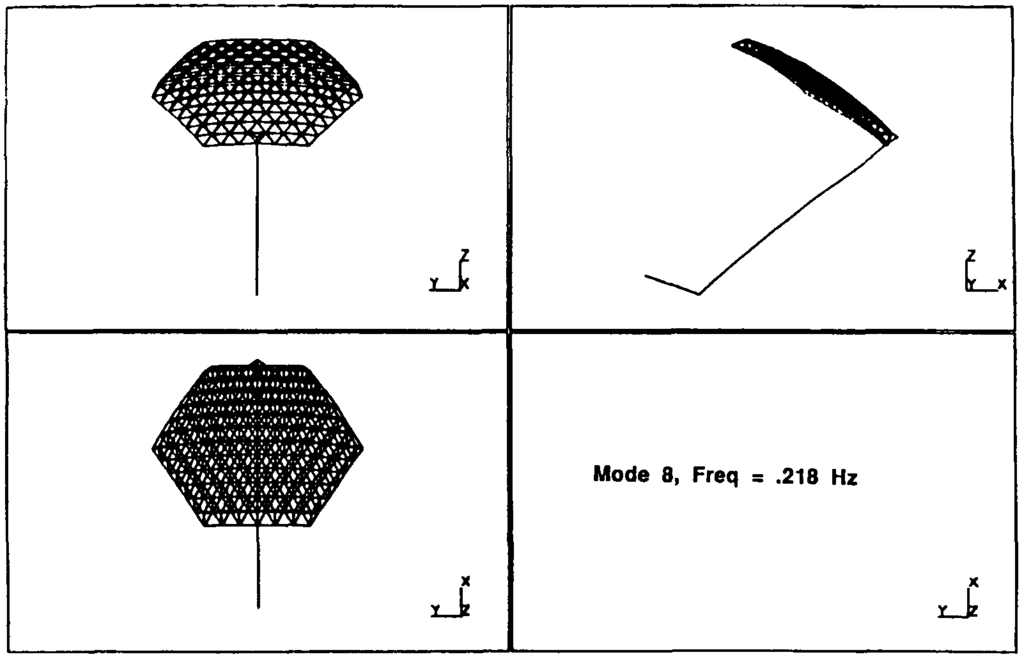


Figure 2-7b. Second Elastic Natural Mode: 15-Meter Reflector on 20-Meter Flexible Beam

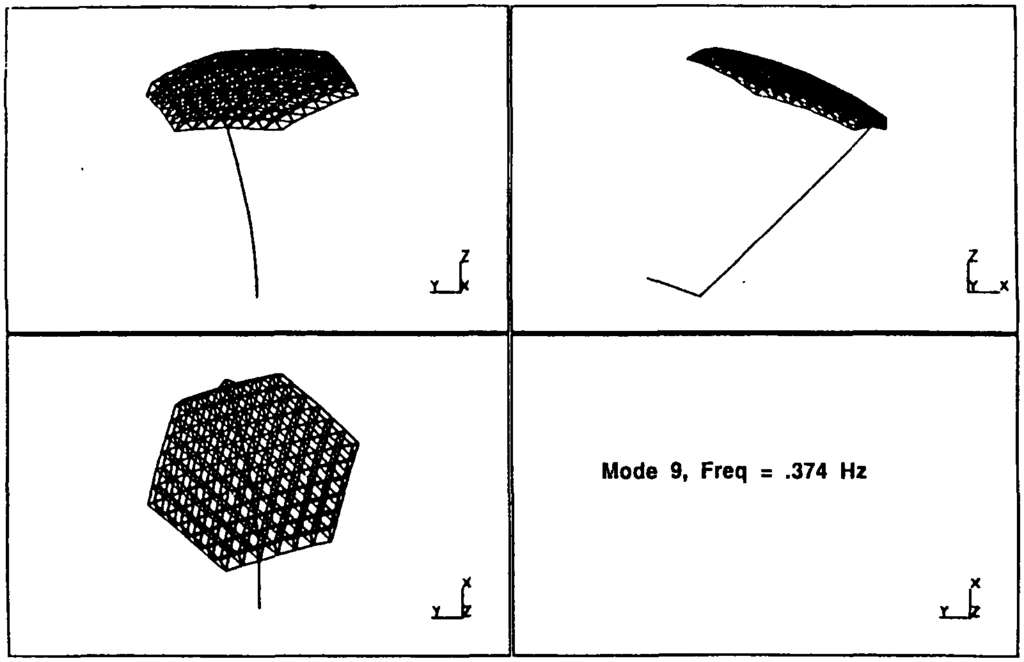


Figure 2-7c. Third Elastic Natural Mode: 15-Meter Reflector on 20-Meter Flexible Beam

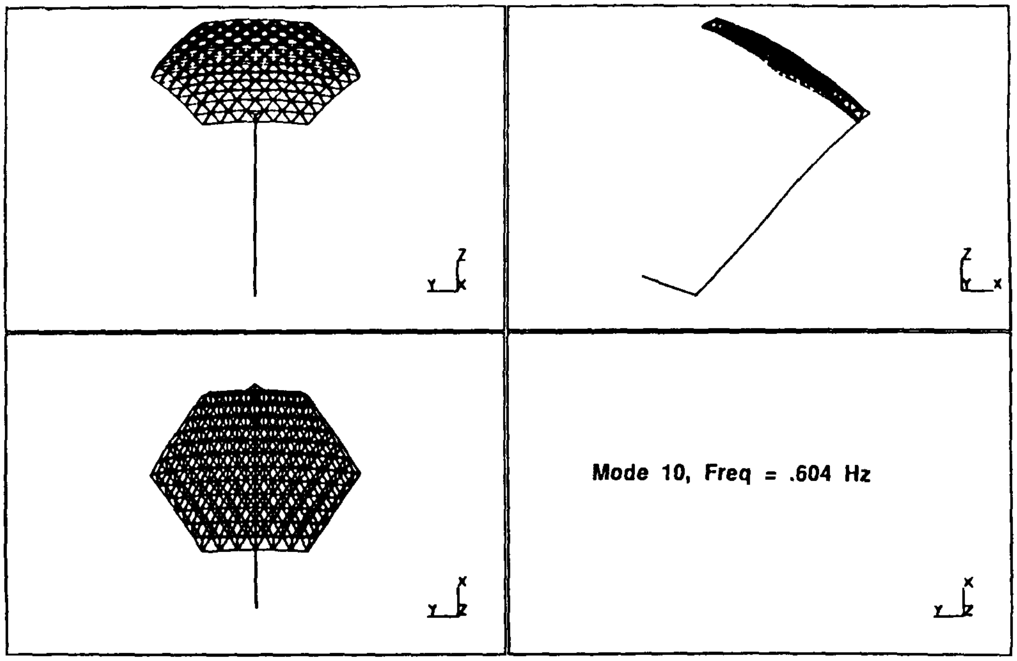


Figure 2-7d. Fourth Elastic Natural Mode: 15-Meter Reflector on 20-Meter Flexible Beam

Table 2-7 shows that a range of system dynamic characteristics is obtained by varying truss-beam stiffness properties. When the beam stiffness is closer to that of the reflector (the stiff case), the system natural frequencies are relatively high. This situation is preferable from the view of accomplishing a specific mission. However, from the view of verifying structural dynamics technologies required for future missions, i.e., for systems that perhaps are so large that they cannot be satisfactorily tested on Earth, the more flexible beams are preferred.

The study of Reference 7 considered the interaction effects of large STS payloads with the STS autopilot. It was determined that combined STS-payload elastic modes with natural frequencies greater than 0.15 Hz do not significantly interact with the autopilot. Therefore, 0.15 Hz is a lower bound on the lowest natural frequency of the selected reflector-beam-STS systems. Note that the flexible beam case of the third configuration has lower frequencies that are close to this lower bound.

2.2.1.6 Preliminary Loads Analysis. Primary reaction control system (PRCS) operation by the STS will induce significant dynamic loads in the deployed reflector-beam systems. Should PRCS operation be necessary once the experiment is deployed, it is desirable, particularly since the reflectors cannot be retracted, for the system to be able to survive.

For a preliminary analysis, PRCS thruster combinations are formed to give predominantly roll, pitch, and yaw attitude torques. Then for each of roll, pitch, and yaw, the appropriate combination of thrusters is pulsed (selected thrusters fire simultaneously) and the dynamic response is computed. For roll and yaw, the pulse duration is tuned to be equal to one half of the period of the lowest torsional mode. For pitch, the pulse duration is tuned to be equal to one half of the period of the lowest xz-plane bending mode. From the computed dynamic responses, one obtains the maximum effective bending moment, axial load, and shear load in the truss beam. The maximum effective moment and loads are then applied simultaneously to a detailed finite element model of the appropriate truss-beam, and member stresses are computed.

Table 2-8 summarizes the internal loads due to pitch, roll, and yaw tuned PRCS torques for two configurations, the 5-meter reflector on a flexible 6.5-meter beam and the 15-meter reflector on a flexible 20-meter beam. Note that, as one would expect, the 15-meter reflector/20-meter beam configuration has the highest internal loads. However, even this configuration survives our tuned PRCS pulses with a factor of safety of two.

Table 2-8. Summary of Internal Loads to PRCS Attitude Torques

	5M Reflector/6.5M Beam			15M Reflector/20MBeam		
	Torque Direction			Torque Direction		
Description	Roll	Pitch	Yaw	Roll	Pitch	Yaw
% Allowable Stress	13	15	7	36	43	25
% Allowable Buckling Load	13	14	7	48	58	34

2.2.1.7 STS Vernier RCS Excitation for Dynamics Experiments. On-orbit experiments are required to verify structural dynamic modeling of deployable truss structures. In this section, we evaluate the STS vernier RCS as a possible disturbance source for on-orbit structural dynamics experiments (Figure 2-8).

The STS vernier thrusters F5R, F5L, R5D, and L5D identified in Figure 2-8 are selected since plumes from their firing will not impinge on the deployed reflector-beam. A simple sequence of firing these four thrusters is used to excite each deployed structure. Measuring time from 0.0 at the start of the sequence, we consider the following firings: thruster F5L from 0.0 to 2.0 seconds, thruster L5D from 0.0 to 4.4 seconds, thruster F5R from 7.52 to 9.52 seconds, thruster R5D from 7.52 to 11.92 seconds, thruster F5L from 14.96 to 16.96 seconds, thruster L5D from 14.96 to 19.36 seconds, thruster F5R from 22.48 to 24.48 seconds, and thruster R5D from 22.48 to 26.88

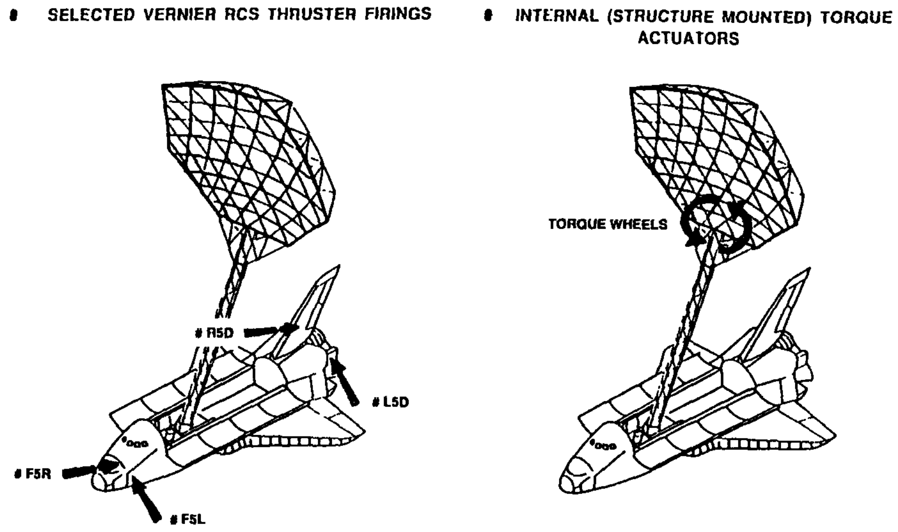


Figure 2-8. Two Approaches to Exciting the Reflector/Beam Were Examined

seconds. This sequence produces two cycles of x- and z-axis torques with net magnitudes varying from approximately -472 to +237 and -1294 to +1305 (N-m), respectively; and it produces four cycles of y-axis torque with net magnitudes varying from approximately +901 to -673 (N-m). The sequence is the same as that in Table 1 (Files 28 and 29) of Reference 15, which was determined by C. S. Draper Laboratories in conjunction with Rockwell International to excite in-plane, out-of-plane, and multi-modal responses of the Solar Array Flight Experiment (SAFE) wing, while minimizing the net angular accelerations of the STS.

The structural vibrations excited in each reflector-beam configuration are small. Two measures of the vibration magnitude are relative line of sight (LOS) and reflector tip motion (Figure 2-9). Each measure has three components, one along each of the x,y,z axes. Table 2-9 shows the maximum magnitude of each component of each measure for the three reflector/flexible beam configurations. Note that while the torques transmitted to the structure at the beam's base are relatively large, the accelerations induced are small, producing small excitation in all configurations.

The magnitudes of the responses produced by the vernier RCS sequence are not large enough for good experimental identification of the structural dynamic characteristics. Consequently, structure-mounted actuators will be required for on-orbit structural dynamics experiments.

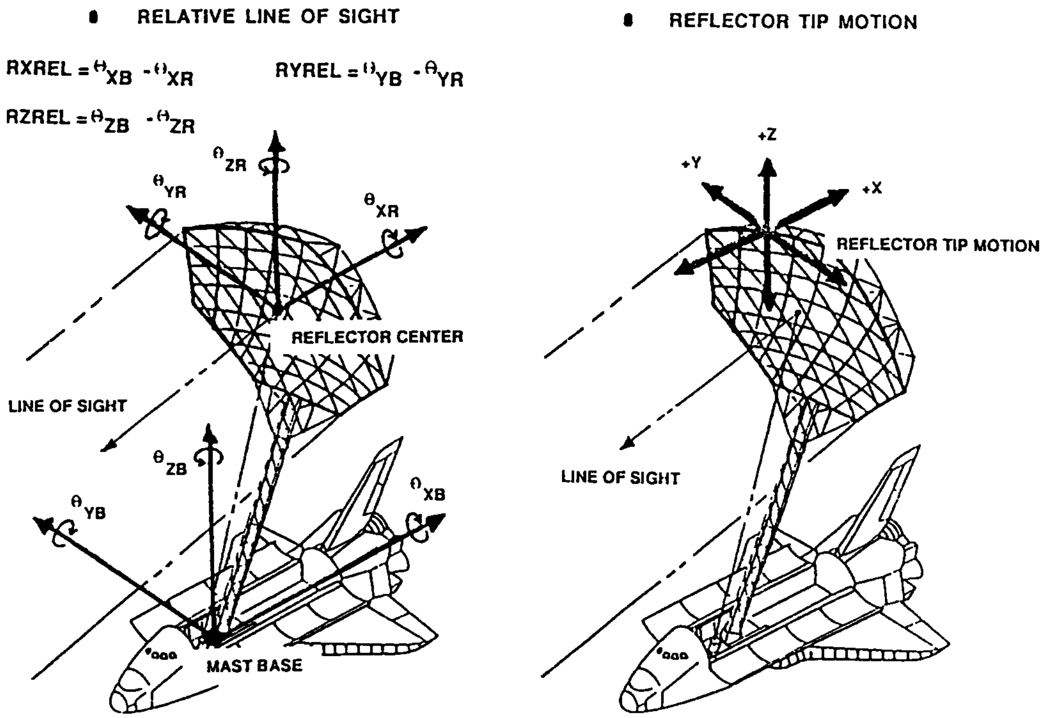


Figure 2-9. Two Primary Performance Measures Were Used to Evaluate Open- and Closed-Loop Dynamic Response

Table 2-9. Maximum Performance Measures Response Summary

Performance Measure	5M Reflector 6.5M Beam	5M Reflector 20M Beam	15M Reflector 20M Beam
Relative LOS, x-axis (Arc Sec)	14.0	22.0	180.0
Relative LOS, y-axis (Arc Sec)	5.4	25.0	54.0
Relative LOS, z-axis (Arc Sec)	9.0	11.0	110.0
Tip Deflection, x-axis (mm)	0.13	1.4	3.9
Tip Deflection, y-axis (mm)	0.42	1.5	15.0
Tip Deflection, z-axis (mm)	0.05	0.63	1.5

2.2.1.8 Structure-Mounted Torque Wheels for Dynamics Experiments. To be most effective, actuators should be at locations of high modal disturbance. Only torque-type actuators were considered because of their ability to operate easily at the low frequencies associated with the lower modes of the deployed flight experiment structures. For torque-type actuators, the modal slopes are indices of disturbance magnitude.

Upon examining the slopes as a function of location in each of the lowest six elastic modes for each configuration, it was clear that the reflector/beam interface structure and the reflector truss itself are both effective locations for actuators. The x-axis slopes in the first and fifth elastic modes, the y-axis slopes in the second and fourth modes, and the z-axis slopes in the first, third, and fifth modes are all high at these locations. The sixth elastic mode has high y-axis slope at the interface structure but not in the reflector structure.

The reflector/beam interface structure was selected as the location of internal torque actuators based on effectiveness as well as the ease of packaging the hardware when the structure is stowed. Two or more skewed torque wheels mounted at the interface are required for multi-mode excitation. Three skewed torque wheels capable of generating individual torques about each of the x, y, and z axes were selected.

The torque wheels were sized to be able to produce experimentally significant response amplitudes in 30 seconds of sinusoidal excitation at the lowest deployed natural frequency. Wheels capable of 5 N-m torques are sufficient to produce tip deflections greater than 8 cm and relative line of sight rotations greater than 0.85 deg for the 5-meter reflector/6.5-meter flexible beam configuration. Wheels capable of 10 N-m torques are sufficient to produce tip deflections greater than 3.5 cm and relative line-of-sight rotations greater than 0.12 deg for the 15-meter reflector/20-meter flexible beam configuration.

A torque wheel actuator capable of 10 N-m already exists and is applicable to the 5- and 15-meter reflector/20-meter beam experiments herein. It has a total mass of 22.7 Kg including its electronics, a bandwidth of 125 Hz, a breakout resolution of 3.5E-3 N-m, a wheel diameter of 38.4 cm, and a maximum wheel speed of 400 RPM. For the 5-meter reflector/6.5-meter beam experiments, torque wheels capable of 5 N-m are appropriate. Such an actuator does not exist off-the-shelf although it can be produced by down-sizing the larger actuator. Such an actuator would have a total mass of approximately 11.3 Kg.

Using three of the existing 10 N-m torque wheel actuators at the reflector/beam interface adds a total mass of 68 kg at this location. This mass is significant when compared to the 39.3 Kg mass of the 5-meter reflector and the 250 Kg mass of the 15-meter reflector. Such a large mass significantly affects the structural dynamic characteristics. In fact, the natural frequencies given in Table 2-7 for the 5-meter reflector/20-meter beam configuration and the natural modes of Figures 2-8 include an actuator mass at the reflector/beam interface.

However, the natural frequencies in Table 2-7 for the other two configurations do not include actuator mass, although it is significant. Indeed, adding a 68-Kg mass at the interface of the 15-meter reflector/20-meter beam configuration decreases the system natural frequencies of Table 2-7;

e.g., for the flexible beam case, the lowest two natural frequencies decrease from 0.157 and 0.218 Hz to 0.155 and 0.198 Hz, respectively. For the 5-meter reflector/6.5-meter beam configuration and the flexible beam case, adding a 34 Kg mass at the interface decreases the lowest two natural frequencies from 0.46 and 0.59 Hz as given in Table 2-7 to 0.325 and 0.440 (Hz), respectively.

2.2.1.9 Sensors for Structural Dynamics Experiments. Sections 2.2.1.7 and 2.2.1.8 above considered excitation sources for on-orbit structural dynamics experiments. It remains to determine sensors for these experiments. The complement of sensors must be able to observe motion in all of the lower modes of vibration and also to observe the quasi-static straightness of the beam as well as the alignment of the reflector relative to the beam.

To observe the dynamic motion, three skewed-rate integrating gyros mounted at the reflector/beam interface structure and seven triads (a triad consists of three mutually orthogonal accelerometers), 21 in all, of force-rebalance accelerometers distributed throughout the structure were considered. Four of the accelerometer triads are distributed along each beam structure, one triad each at 10%, 40%, 70%, and 100% of the length as measured outward from the STS.

In addition, one accelerometer triad is located at the reflector tip, and one triad is located at each of two of the reflector edges. In all, the accelerometers are distributed so as to allow accurate identification of the lowest six natural mode shapes. The rate gyros have a natural frequency of 20Hz, a minimum sensed rate of less than 2 degrees per second, and a mass of approximately 0.75 Kg. Each accelerometer has a natural frequency of 300 Hz, an overall accuracy of 0.020 milli-G's, a threshold accuracy of 0.001 milli-G, and a total mass of 0.10 Kg.

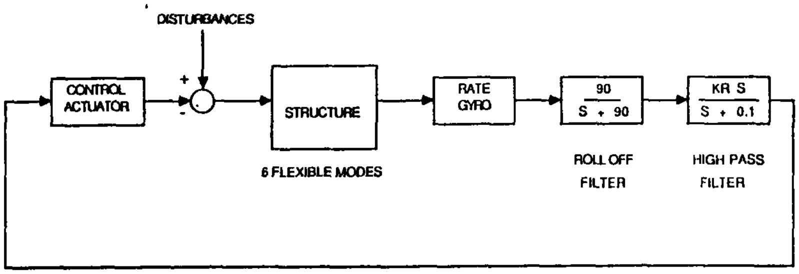
Retro-reflector field trackers are used to observe the quasi-static alignment of the beam and the reflector to the beam. Five 30-mW laser diodes are mounted at the base of the beam in the beam/STS support structure. Laser targets are distributed along the beam and across the reflector. Four laser targets are located along the beam, one each at 10%, 40%, 70%, and 100% of the length as measured outward from the STS. In addition, laser targets are located on the reflector at the tip, each of two edges, and at the center.

2.2.1.10 Active Vibration Control Experiments. The primary interest in the dynamics flight experiments is to verify structural dynamic modeling technology. Indeed, uncertainty in the accuracy of structural dynamic models is a major contributor to the issues of control/structure interaction. However, the instrumentation required for structural dynamics experiments can also be used in active vibration control experiments.

In this section, the design and simulated performance of a simple rate-feedback control system for the 15-meter reflector/20-meter flexible beam configuration is presented.

The control system consists of three simultaneous loops, one for each of roll, pitch, and yaw (Figure 2-10). Each rate gyro output is filtered by a first-order roll-off filter at 90 (rad) and a first-order high-pass filter at 0.1 rad. The filtered output of each gyro, times a gain, is fed to the torque wheels to produce a control torque about the appropriate axis. The roll, pitch, and yaw loop gains are 6.5E4, 2.0E5, and 4.0E4, respectively.

Closed-loop natural frequencies and damping ratios are tabulated in Figure 2-10 for the lowest six elastic modes. Figure 2-11 compares the frequency response of a typical transfer function, the y



CONTROL GAINS ROLL . KR = 6 5E4
PITCH: KR = 2 0E5
YAW KR = 4 0E4
IN LB SEC

CLOSED LOOP PERFORMANCE
15M REFLECTOR - 20M MAST (FLEXIBLE 15)

MODE NUMBER	FREQUENCY (RAD/SEC)	ROTATIONAL AXIS	DAMPING RATIO	SECONDS TO 95%
7	0 9791	ROLL/YAW	0 0991	30 90
8	1 3681	PITCH	0 1890	11 60
9	2 3411	YAW	0 0973	13 10
10	3 7677	PITCH	0.5970	13 30
11	7 5188	ROLL/YAW	0.0692	5 80
12	37 8429	PITCH	0 0671	1 20

Figure 2-10. Closed-Loop Vibration Control Evaluation Model

axis disturbance torque to the y-axis rate gyro output, for the uncontrolled system to that of the closed-loop system. The comparison shows the significant increase in damping of the system due to the simple controller. Note that the three peaks in Figure 2-11 are associated with the second,

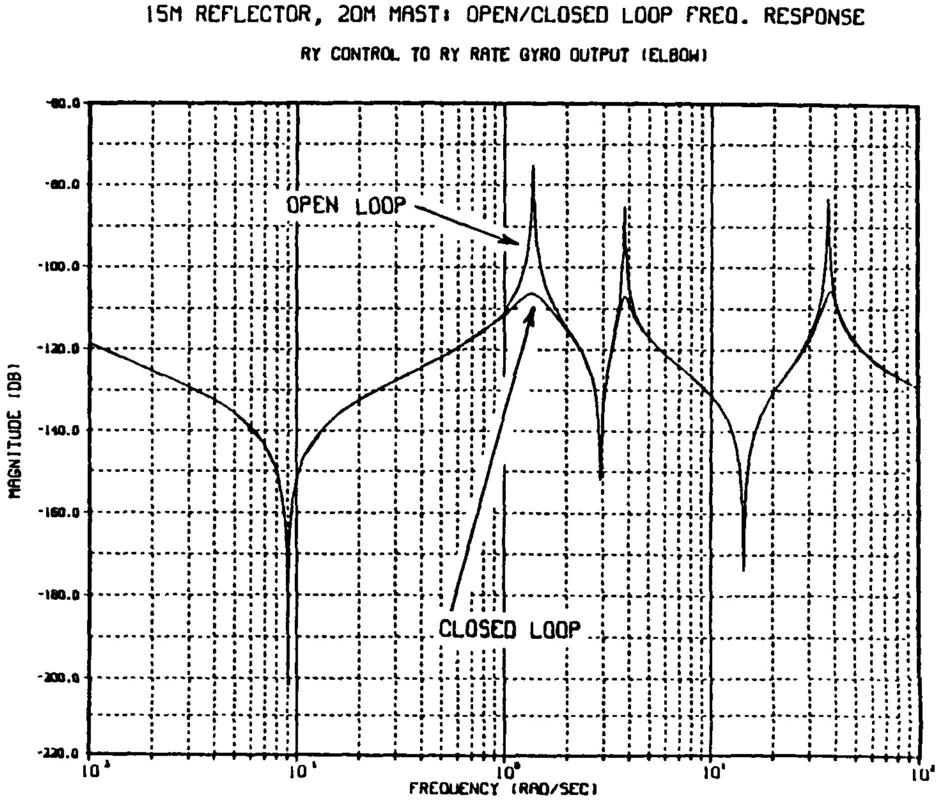


Figure 2-11. Active Damping Augmentation Significantly Reduces Modal Peaks in the Frequency Response

fourth, and sixth elastic modes. The simple rate feedback provides significant active damping of the lowest six modes of vibration.

The active damping system is useful in conducting the structural dynamics experiments. It provides a mechanism for decreasing the time to structural quiescence between excitation/data-collection cycles. While the simple system is sufficient for damping, more complex control algorithms can also be verified using the same flight-experiment hardware.

2.2.1.11 Articulation and Pointing Control Evaluation. Articulation and pointing control are not included in the flight experiments for the following eight reasons:

1. Articulation and pointing control is not identified in Section 2.1 as a technology development issue for large NASA and commercial antennas. It is felt that the technology required is within the current state of the art.

2. Actuators for precision pointing are relatively expensive.
3. Pointing sensors are not generic; the best is probably to use the operating antenna itself to produce an attitude error signal, but this depends on the operation mode of the antenna.
4. Since truss antennas are relatively stiff, controller sensitivity to model errors is reduced. Indeed, the lowest elastic-mode frequencies are relatively high compared to other antenna concepts, and the lowest modes are distinct up to frequencies commensurate with member local modes.
5. The main control/structure interaction "problem" is due to uncertainty in the dynamic characteristics of the structure, a technology that is included in our program. The uncertainty will be reduced through the analysis, ground- test, flight-test sequence.
6. Demonstrating precision pointing on a flight experiment does not provide generic knowledge. Instead, it is a feat of knowing the sensor(s), actuator(s), and mathematical model for the particular configuration.
7. Actuators and sensors can be characterized on the ground, in many cases, making orbital verification unnecessary.
8. Line-of-sight settling after a transient event, such as a retargeting or other maneuver, depends on vibration suppression, which is included in the baseline experiment.

The alignment technology identified in Section 2.1 as an issue for NASA and commercial antennas is addressed in Section 2.2.2 under reflector surface measurement and adjustment.

2.2.1.12 Ground- and Flight-Test Scenarios. Verifying structural dynamic modeling methodology requires a sequence of analysis, ground-test, and flight- test. The same is true for verifying flexible structure control technology. In this section, ground- and flight-test scenarios for verifying these technologies are outlined.

First, consider the structural dynamics ground-tests. Since future larger structures will not be fully testable on the ground, accurate verification models must be created with only development and substructure testing. Development tests include static stiffness tests of the deployer/repacker (STS/beam interface structure), of a typical beam section (approximately five bays), and of the reflector/beam interface structure. Substructure tests include static and vibration tests of the beam alone and of the reflector alone. The vibration tests include random excitation in three directions, and sine-dwell tests for the lowest six modes at three different excitation levels. Both beam and reflector substructure tests are performed with the structure suspended horizontally.

To avoid coupling of the suspension system with the 20-meter flexible beam cantilevered modes (fundamental frequency equals 0.93 Hz), a suspension length of approximately 7 meters gives a factor of 5 frequency separation between the fundamental structural frequency and the pendulum frequency. The objective of the tests is to build a database of information on the measured and modeled properties of the deployable truss structures. Appropriate analyses must be performed to correlate test data with prior analyses and to update analytical models as necessary after each test. Finally, for the verification flight experiment structures, the assembled system is ground tested.

Both static and vibration tests will be conducted for final pre-flight tuning of the structural dynamic models and to understand any additional modeling problems. The suspension system for the assembled system will couple strongly with the structure (a factor of 5 frequency separation would require a pendulum length of approximately 150 meters) so that the suspension system must be modeled and its effects adjusted analytically.

Next, consider control dynamics and instrumentation ground tests. A hybrid test approach is used once development tests have been performed. Development tests are performed on breadboard electronics units for the excitation and damping subsystem, the motion measurement subsystem, the modular distributed instrumentation subsystem, and the figure control subsystem. They are also performed on a proof-of-concept figure adjustment actuator and a slow deployment mechanism. Hybrid tests of the excitation and damping actuators and sensors verify their integrated function, but with the beam's motion simulated by computer. Hybrid tests of the reflector structure integrated with the figure control actuators use simulated sensing and verify the actual figure with photogrammetry. In addition, assembled system hybrid tests are performed to verify integrated operation of all actuators and sensors and to verify control algorithms, with system motion simulated by computer. Finally, for the flight experiment article, ground vibration and figure control tests of the deployed, suspended system using actual system motion are performed.

Lastly, consider flight tests for both structural dynamic identification and for vibration control performance. A full set of structural dynamics tests is performed after the beam is deployed, before deploying the reflector, and again after the reflector is deployed. The torque wheel actuators are used to produce random excitations in roll, pitch, and yaw both individually and simultaneously. The wheels are also used to produce sinusoidal torques at near resonant frequencies of each of the lower five modes.

Once the amplitude of motion has built up, the excitation is removed and data is collected during the free decay. This is followed by a period of operation with active damping to bring the structure back to quiescence. After the structural dynamics tests, control tests are performed for various control algorithms. The torque wheels are used both to excite and to control the system. The closed-loop performance is measured for later correlation with predicted performance.

2.2.1.13 Comparison With NASA's Control of Flexible Structures (COFS) II Program. At the time this study was conducted, the Control of Flexible Structures (COFS) I program was in development. COFS I consisted of mainly structural dynamics and some limited controls experiments on a 60-meter truss- beam deployed from the STS. At the time, there was additional simultaneous activity to define a COFS II technology verification flight experiment directed primarily at advanced controls technology issues. As mentioned earlier, this study is distinct in that it addresses technologies associated with deployable truss structures; it does not specifically address technologies associated with control of flexible structures. Nevertheless, there are similarities between the present flight experiment and the one envisioned at the time for COFS II.

The COFS II program was intended to verify all the following technology issues: maneuver control, articulation and slewing, pointing (line-of-sight stabilization), shape control, alignment control, system identification, structural concept evaluation, deployment characterization, vibration suppression, adaptive control, and fault detection, identification and reorganization. This study found (Section 2.1) that NASA and commercial antenna missions required development of only shape control, alignment control, structural modeling, and deployment characterization technology issues. The present flight experiment, therefore, addresses all of these identified technology issues. It also addresses, at least partially, vibration suppression technology. The remaining technology issues of COFS II can be included as options, although their development is not identified as needed for future NASA and commercial antenna missions.

2.2.2 SURFACE MEASUREMENT AND ADJUSTMENT. The development of an active, on-orbit reflector-surface control system would enable a number of future space antennas (see Section 2.1.6.2). A major objective of the deployable truss technology program is to design and demonstrate surface control techniques that allow truss/mesh reflectors to function adequately over the full range of baseline design parameters (Table 2-5). The most critical needs are for sensors to measure surface figure errors, actuators to make precise adjustments, and a control strategy that minimizes complexity.

2.2.2.1 Requirements. Reflector surface errors are measured by first finding the Best Fit Paraboloid (assuming that the ideal surface is a paraboloid) for the actual surface, as illustrated in Figure 2-12a. The surface roughness, Δ, is then defined to be the difference between the Actual and Best Fit surfaces, and Δ_{RMS} is the root mean square value over the entire surface area. Defocus is equal to the displacement of the Best Fit paraboloid's focal point from the Ideal paraboloid's focal point measured along the common centerline.

Allowable surface roughness and defocus errors vary with antenna operating frequency, as depicted in Figures 2-12b and c. The bands of values range from "typical" to "most stressing"errors. Representative values are called out in the plots for an operating frequency of 30 GHz, which is at the upper end of the baseline design range. They are $\Delta_{RMS} \leq 10$ mils and Defocus $\leq$ 50 mils.

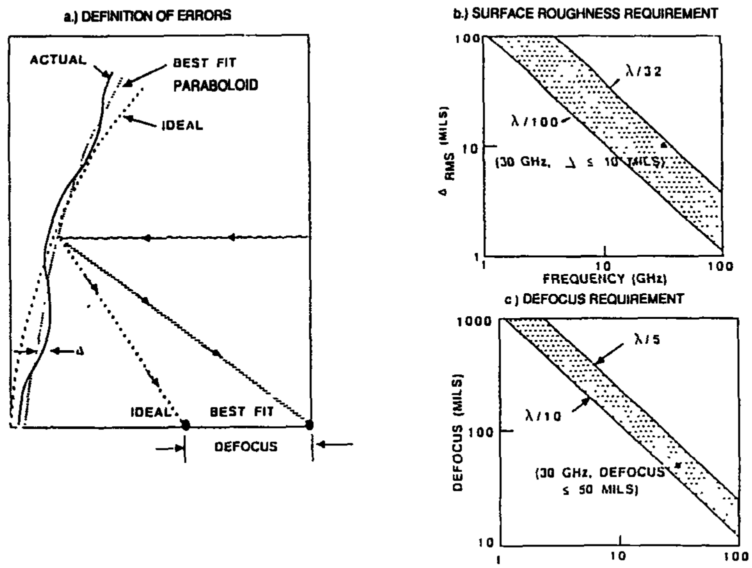


Figure 2-12. Reflector Surface Accuracy Requirements

2.2.2.2 Performance Capability. Analytical predictions of surface roughness have been verified by laboratory tests on small antennas at General Dynamics. The individual error sources are scaled with size and combined to obtain a total surface error prediction in Figure 2-13 for systems without on-orbit surface control. The values shown are for an eight-bay truss supporting a mesh reflector surface that uses many flat surface segments ("facets") to approximate the ideal shape. Thus, if perfect on-orbit adjustments were made, all of the error components except the "facet" term could

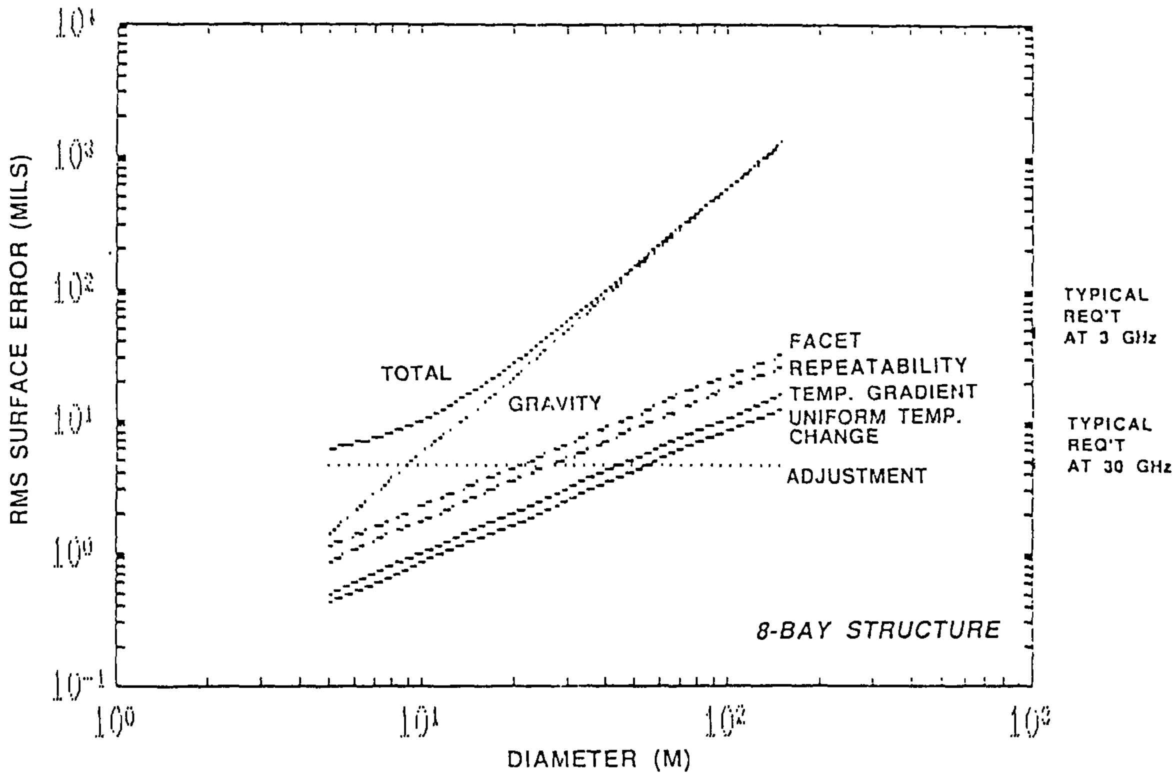


Figure 2-13. Predicted Surface Error Without On-Orbit Surface Control

be eliminated. This means, for example, that the uncontrolled reflector in this example could not satisfy the 50 mils roughness requirement for a 30 GHz antenna. However, adding on-orbit surface control would enable 30 GHz antennas up to 21-meter diameter.

The same approach could extend the range of 3 GHz antennas from the 26-meter diameter limit for passive antennas to 210 meters by adding active shape control.

2.2.2.3 Actuation. There are three general approaches for adjusting surface shape with minimal impact on the current passive design: changing the shape of the supporting truss, adjusting the location of the control line/truss interface points, and changing the length of individual control lines connecting the mesh to the truss. Figure 2-14 illustrates specific design approaches for each of the general approaches. Detailed design trades and analyses are needed to select the best overall approach, which might involve a combination of actuator types

One analysis was performed to help define the issues. A structural/thermal model of a 6.4-meter diameter reflector with four truss bays and 19 spiders was developed. It included truss, control line and mesh elements that were disturbed by uniform temperature changes and gradients caused by eight sun illumination conditions. Typical error contour plots for two conditions are shown in

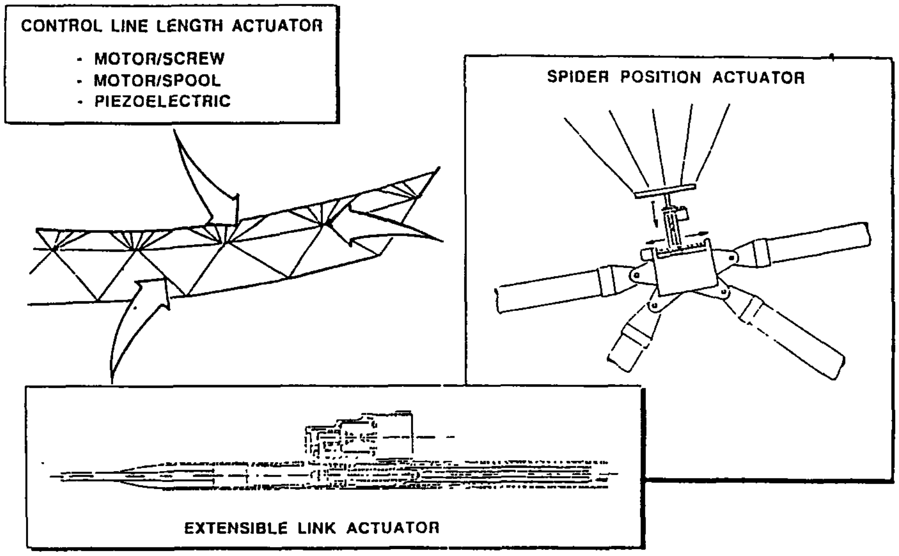


Figure 2-14. Surface Adjustment Approaches

Figure 2-15, and all results are summarized in Table 2-10. Surface roughness and defocus errors are listed for both uncontrolled and controlled mesh. The "controlled" values were obtained by moving each control line bundle attach point normal to the mesh surface. The adjustment strategy was to compute the movement needed to minimize the rms error of the mesh directly attached to the bundle lines, and then to make all adjustments at once. This adjustment scheme had the same general result in all eight illumination cases -- the surface error was significantly decreased and the defocus error was significantly increased.

These results suggest that:

- A strategy that simultaneously minimizes both errors is needed.
- Additional actuator degrees of freedom (e.g., spider motion parallel to the mesh surface) may be needed.

Furthermore, it is worth noting that the existing mesh/control line/truss configuration was not specifically optimized for on-orbit adjustment. A better design may be achievable.

2.2.2.4 Surface Measurement. Surface measurement issues are driven by both surface accuracy and measurement speed. For a typical space antenna, surface measurement accuracy is approximately 2.5 parts per million (ppm). During manufacture and initial adjustment checkout, one second per measurement is acceptable. For on-orbit thermal compensation measurements must

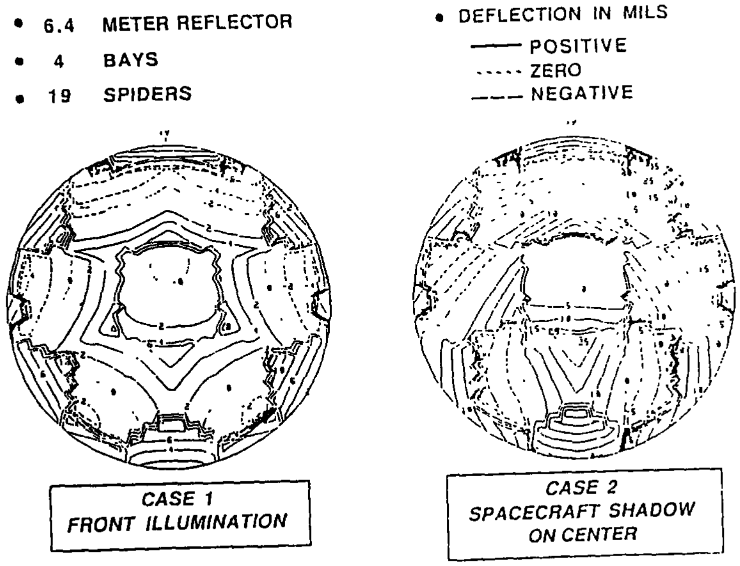


Figure 2-15. Mesh Thermal Distortion

Table 2-10. Residual Surface Error Summary

SUN ILLUMINATION CONDITION	RMS SURFACE ERROR (MILS)		FOCAL LENGTH CHANGE (MILS)	
	UNCONTROLLED	CONTROLLED	UNCONTROLLED	CONTROLLED
• BACK	5.3	3.8	-22.6	156.2
• SIDE	5.9	4.2	-38.3	93.9
• FRONT (CASE 1)	3.7	2.3	-27.1	112.3
• ECLIPSE	19.6	13.1	-141.9	638.7
• SPACECRAFT SHADOW NEAR INBOARD EDGE	9.0	7.7	224.5	290.6
• SPACECRAFT SHADOW ON CENTER (CASE 2)	11.7	9.7	270.0	445.0
• SPACECRAFT SHADOW NEAR OUTBOARD EDGE	8.6	6.6	58.9	286.4
• AUX. REFLECTOR AND FEED MAST SHADOW	6.6	4.8	24.7	186.2
REQUIREMENT	10		50	

be made an order of magnitude faster (0.1 sec per point). To satisfy active dynamic control, measurements must be made at least another order of magnitude faster (0.01 sec per point).

There are a number of concepts that could be used to measure surface position. Some measure motion transverse to the line-of-sight direction. Examples are:

- Imaging systems
- One- and two- dimensional detectors

Other techniques make measurements along the line-of-sight direction:

- Geometric techniques (triangulation)
- Time-of-flight techniques
- Interferometric techniques
- Diffraction techniques (e.g., speckle sensor)

Several development efforts have been started to adapt these proven techniques for flight spacecraft applications. A significant example is JPL's Spatial High Accuracy Position Encoding Sensor (SHAPES). In a typical application, SHAPES would be attached to the feed of a space antenna and measure motion of a number of retroreflector targets on the reflector (Figure 2-16). A time-of-flight technique is used to measure motion along the line-of-sight, and motion-of-target images on a two-dimensional CCD focal plane are used to measure displacements transverse to the line-of-sight direction. Laboratory experiments at JPL have demonstrated a measurement speed of 0.1 sec per target, which is adequate to control on-orbit thermal distortions, and an accuracy of 0.025 millimeter (1 mil), which is adequate for a 30-GHz antenna.

While the SHAPES sensor satisfies the baseline requirements, there could be significant advantages from simpler approaches. One potential concept is shown in Figure 2-17. It features a rotating low-power beam mounted at the center of the antenna. The beam sweeps out a plane near the surface of the reflector; and a number of one-dimensional CCD detectors mounted to intercept the beam measure motion perpendicular to the antenna surface by detecting the laser crossing position. This concept offers potential benefits: low cost, rapid measurements, and long life.

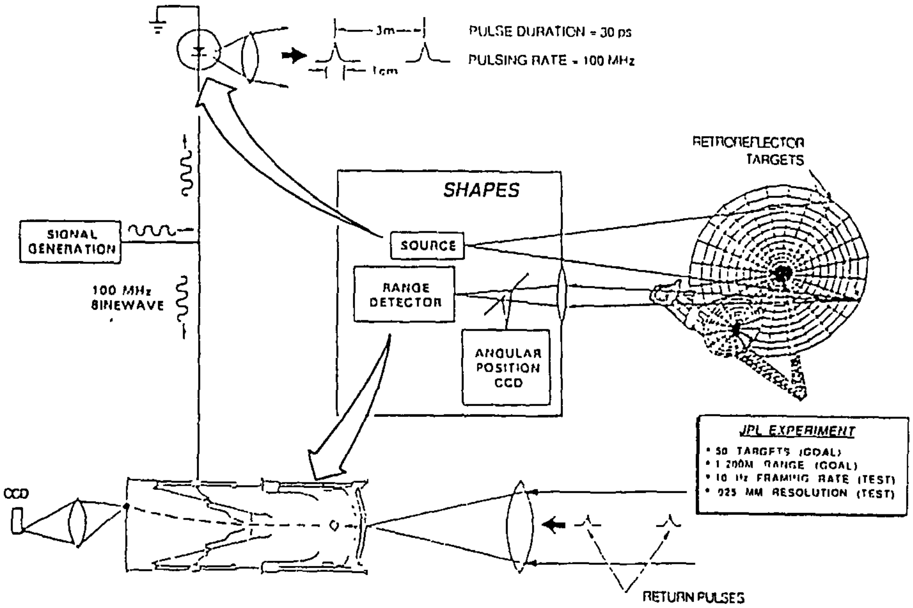


Figure 2-16. Shapes Sensor

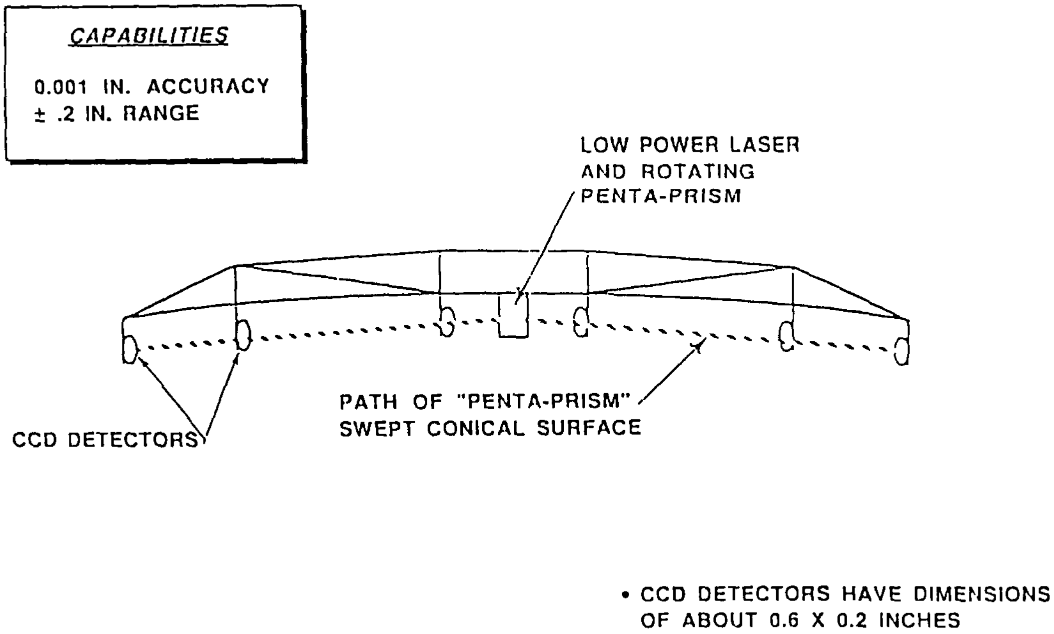


Figure 2-17. Scanning Laser/CCD Sensor

2.2.2.5 Development Recommendations. Development should address actuators, sensors, control algorithms, and optimization of the integrated control system/ structure design to minimize the number of actuators and sensors. A control system capable of satisfying baseline requirements for a quiescent antenna should be developed and demonstrated. A laboratory demonstration will be adequate for proof-of-concept testing. However, tests in space would provide additional benefits: The measurement system could determine changes in surface accuracy under different orbital conditions, and the technology readiness level of the control system could be improved.

2.2.3 ELECTROMAGNETIC (RF) EVALUATION. One of the issues typically addressed for experimentally evaluating RF system performance on orbit is whether direct or indirect performance measurements should be made for comparison with analytical predictions and ground test results. Indirect measurements on orbit (surface distortions and deflections) are an integral part of the planned flight test program. These measurements are used to assess the capability to predict on-orbit distortions and resulting performance degradation using analysis and ground testing. As an option, a program to make direct RF measurements on orbit has also been defined. The objective of the electromagnetic evaluation task was to identify RF measurement issues and define recommended approaches for directly measuring RF performance on orbit

2.2.3.1 RF Measurement Issues. Measurement issues that must be addressed to develop a suitable RF measurement test plan include:

• Sun orientation with respect to antenna/ Shuttle test configuration for thermal distortion testing. This requires detailed a detailed Shuttle maneuvering study as impacted to the selected test approach, i.e., far-field or near-field measurements.

• Stability required of test elements during measurements. Measurement uncertainty in the orbital environment as a function of pointing stability and vibration is critical for accurate data.Co-orbital signal source or receiver specifications. Critical parameters include power available, beamwidth, range, control and time available for measurements.

• Use of the Shuttle RMS to support RF measurements. Issues include attachment of RF absorber to the boom, positioning accuracy of the boom, installation of a field probe assembly and auxiliary test reference antennas.

• Multipath errors due to RF reflections from earth or Shuttle.

• Blockage of test signals due to orbital configuration. This issue drives antenna test orientation requirements and gimbal design.

• Auxiliary test antenna requirements for gain and phase reference. Primary requirements include pointing accuracy, RF power level, equipment mounting and gimbal design.

• Auxiliary position measurement and control requirements. Issues include number and location of photogrammetic targets, accuracy required of optical/RF ranging systems, accuracy and precision required of field probes or reference antenna and speed bandwidth of the control system.
• Selection of antenna measurement points to optimize their sensitivity to surface and alignment variations.
• Selection of generic antenna design parameters to satisfy different and possible conflicting applications requirements.

The basic measurement technique used to characterize the reflector antenna system is also one of the issues. Figure 2-18 illustrates measurement categories that were considered. A combination of analytic and direct or indirect measurements is required to adequately characterize the on-orbit performance of a large reflector. Cost and schedule programmatic issues become primary constraints in defining the scope of a test program to measure the performance of a large reflector antenna in space.

2.2.3.2 RF Measurement Techniques and Category Trades. Accurate knowledge of the antenna system far-field performance is necessary to determine the operational capability in terms of gain and pattern characteristics. Measurement techniques that were considered and the trade results are summarized in Table 2-11. A critical aspect of performing measurements in space is the

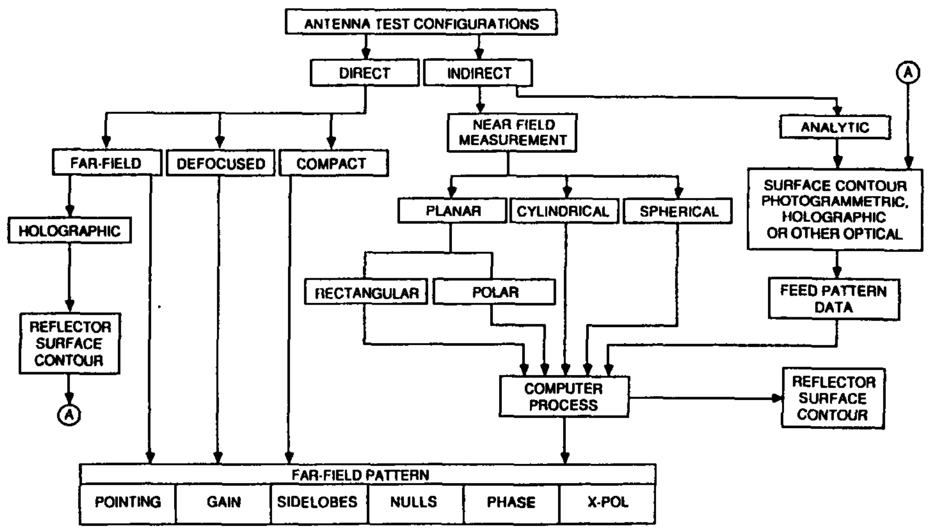


Figure 2-18. Measurement Categories for Obtaining Far-field Patterns in Space Environment

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Table 2-11. RF Measurement Techniques and Measurement Category Trades

MEASUREMENT TECHNIQUE	ADVANTAGES	DISADVANTAGES / CONCERNS
FAR FIELD DIRECT	- LONG DISTANCE RANGE AVAILABLE, MEASUREMENT RANGE REQUIREMENT FOR RANGE LENGTH $\geq 2D^2/\lambda$ READILY SATISFIED - DIRECT ACCESS TO TEST ANTENNA FROM SHUTTLE - USES STANDARD, WELL DEVELOPED MEASUREMENT PROCEDURES - MINIMAL DATA PROCESSING REQUIRED IN COMPARISON TO OTHER TECHNIQUES	- POTENTIAL MULTIPATH PROBLEM DUE TO EARTH REFLECTION OF TEST SIGNAL - REQUIRES USE OF STABLE CO ORBITAL SOURCE ATTITUDE CONTROL OF SOURCE - CHANGE OF SUN ORIENTATION DURING MEASUREMENT - GIMBAL REQUIREMENTS FOR TEST AND REFERENCE ANTENNAS - LENGTH OF TIME REQUIRED TO ADEQUATELY CHARACTERIZE ANTENNA - REFERENCE ANTENNA MUST TRACK SPARTAN CARRIER CONTINUOUSLY DURING MEASUREMENTS
HOLOGRAPHIC	- MAY BE COMBINED WITH FAR-FIELD DIRECT	- REQUIRES PHASE REFERENCE ANTENNA MOUNTED ADJACENT TO TEST ANTENNA - GIMBALING/POINTING OF REFERENCE AND TEST ANTENNAS - MAINTAINING CONTROL OF RANGE DISTANCE TO EXTREMELY TIGHT TOLERANCE
COMPACT	- GREATLY REDUCES RANGE DISTANCE	- REQUIRES SOURCE ANTENNA MUCH LARGER THAN TEST ANTENNA
INDIRECT-NEAR-FIELD • PLANAR SCAN	• PLANAR RECTANGULAR OR PLANAR POLAR SCAN IS SUITABLE FOR OFFSET REFLECTOR CHARACTERIZATION • PROVIDES DIAGNOSTIC AND SETUP INFORMATION • MEASUREMENT SYSTEM CAN BE SETUP IN A CONTROLLED LABORATORY ENVIRONMENT WITH TEST ANTENNA TO ESTABLISH PERFORMANCE BASE PRIOR TO IN SPACE TESTING • COMPLETE FAR FIELD INFORMATION IS DERIVED FROM A SINGLE SET OF NEAR FIELD MEASUREMENTS • ANTENNA CAN BE TESTED WITHOUT BEING MOVED – NO GIMBAL REQUIRED ON TEST ANTENNA • PROVIDES HIGH DENSITY PHASE CONTOUR MEASUREMENT FOR SURFACE CONTOUR CHARACTERIZATION • PROVEN MEASUREMENT TECHNIQUE • WELL DEVELOPED AND PROVEN PROCESSING ALGORITHMS AVAILABLE	• WIDE ANGLE PATTERN DATA REQUIRES USE OF AUXILIARY MEASUREMENT SYSTEM • RMS USE - POSITIONING ACCURACY OF RMS - INSTALLATION OR RF ABSORBER ON RMS BOOM AND TEST PROBE ASSEMBLY - AVAILABILITY OF SPACE QUALIFIED RF ABSORBER - DESIGN, MANUFACTURE, AND INSTALLATION OF FIELD PROBE ASSEMBLY • MANEUVERING OF SHUTTLE TO MAINTAIN CONSTANT SUN ANGLE DURING MEASUREMENT • MODIFICATION OF RMS OR DEVELOPMENT OF FIELD PROBE ASSEMBLY FOR APERTURES >5 METER DIAMETER • MEASUREMENT UNCERTAINTY IN ORBITAL ENVIRONMENT • TIME REQUIRED FOR AQUIRING DATA • MINIMUM FIELD PROBE SCAN RANGE IS APPROXIMATELY 1 25 TIMES APERTURE DIAMETER
• SPHERICAL SCAN	• REQUIRES USE OF CLOSELY CONTROLLED CO ORBITAL SIGNAL SOURCE	• SHUTTLE MANEUVERING • TIME REQUIRED FOR FULL DATA SET AQUISITION

requirement that a specific sun orientation with respect to the antenna reference coordinated be maintained to minimize thermal distortion changes during data acquisition periods. The effect of the space environment on the measurement system also is a concern that must be addressed in developing the test system.

To make direct far-field measurements, a change in sun orientation will occur unless the measurements are made under full shadow conditions. Thus an indirect-near-field approach is optimum when rigorous characterization of the antenna system is necessary. Also, this approach provides a full set of near-field probe data for post -measurement analysis of antenna performance for a more complete set of antenna gain, polarization, and pattern data. A functional diagram of the proposed near-field test system is shown in Figure 2-19. This diagram is applicable to either a planar rectangular or polar scanning approach.

2.2.4 <u>EXPERIMENT DEFINITION.</u> Experiment hardware configuration options center around the requirements to be representative of large-scale flight hardware, to address the deployable truss technology issues, and to satisfy the two basic configuration groundrules:

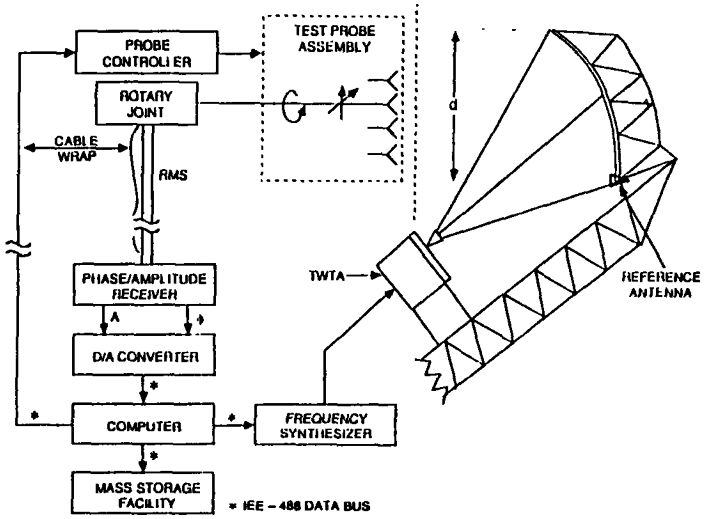

Figure 2-19. Near-Field Test Diagram

- Experiments use a deployable geotruss antenna reflector combined with a deployable truss beam.
- All flight experiments use the STS

Primary experiment configuration drivers include number of flights, hardware size, and hardware reuse. Because of the complexity of the experiments and the large quantity of experimental data, two flights are planned with the first flight functioning as a prototype or pathfinder to check out and validate the systems and procedures. Both flights are used to gather experimental data.
The primary experiment hardware configuration issue is clearly size. The system performance requirements are driven by future large, precision antenna systems up to 150 meters in diameter. Because of scaling issues, it is desirable to have experimental hardware as close to full-scale as possible. This goal is obviously constrained by considerations of STS compatibility, ground test facilities, and program cost and schedule. To select the experiment hardware size two questions must be answered. What is the smallest size that will demonstrate the deployable truss structure technology issues? Does that size meet the program constraints?

Starting with an existing 5-meter deployable geotruss antenna reflector, a performance evaluation was performed on reflectors 5, 15, and 20 meters in diameter. For the 5-meter reflector three options were examined: use the existing hardware, refurbish and flight -qualify the existing hardware, and fabricate new hardware tailored to meet experiment requirements. The 15- and 20-meter reflectors were assumed to be new designs incorporating all experiment provisions. For each reflector ground test flight and scaling issues were addressed. The evaluation results are shown in Table 2-12.

Table 2-12. Reflector Configuration Performance Evaluation

PARAMETER	EXISTING 5 METER	EXISTING 5 METER (REFURB. & FLT. QUAL.)	NEW 5 METER	NEW 15 METER	NEW 20 METER
GROUND TEST					
CONTOUR	5	7	7	10	10
DEPLOYMENT (FREE)	3	6	9	10	10
DEPLOYMENT (CONTROLLED)	0	0	6	10	10
RF PERFORMANCE (NEAR-FIELD)	4	7	7	10	2
VIBRATION	4	5	6	8	10
PASSIVE VIB. CONTROL	3	3	6	9	10
ACTIVE VIB CONTROL	0	2	6	9	10
SHAPE CONTROL	0	1	6	10	10
THERMAL (THERM/VAC)	2	2	6	10	3
FLIGHT TEST					
CONTOUR	0	7	7	9	10
DEPLOYMENT (FREE)	0	6	8	10	10
DEPLOYMENT (CONTROLLED)	0	0	6	10	10
RF PERFORMANCE	0	5	7	9	10
VIBRATION	0	5	6	9	10
PASSIVE VIB. CONTROL	0	3	6	9	10
ACTIVE VIB CONTROL	0	2	6	9	10
SHAPE CONTROL	0	1	6	10	10
THERMAL	0	2	6	10	10
REPACKAGE/REUSE	0	0	10	9	7
SCALING					
CONFIGURATION	2	4	7	9	10
DYNAMIC	2	3	5	9	10
THERMAL	2	3	5	9	10
RF	2	5	8	10	10
OVERALL	1.3	3.4	6.6	9.4	9.2

Because the 20-meter reflector would not fit in existing RF and thermal/vacuum ground test facilities, the 15-meter reflector had the best overall performance rating. Based on a preliminary cost analysis, the 20-meter reflector costs approximately 63% more than a 15-meter article. Because of this cost difference and the performance evaluation results, the 15-meter reflector was selected as the baseline size for the experiment.

The next issue is reusability. Reuse was not selected for the geotruss reflector for the following reasons:

The next issue is reusability. Reuse was not selected for the geotruss reflector for the following reasons:

- For operational systems reflector retraction and reuse is not a requirement.
- The basic geotruss reflector concept is not designed for automated retraction and restow.
- Cost and risk is high to add automated retraction and restow to the geotruss reflector experiment hardware.

Without reuse, two geotruss reflectors must be built. Thus a new 5-meter reflector was selected for use on the first flight to reduce hardware costs. The 5-meter reflector can satisfactorily demonstrate and check out the flight experiments at a major cost reduction. To further reduce cost, the 5-meter and 15-meter reflectors share common geometry and structural element designs.

Based on the system performance requirements and technology issues discussed in Section 2.1 as well as the structural dynamics and controls, surface measurement and adjustment and RF issues discussed in Sections 2.2.1, 2.2.2, and 2.2.3, a baseline experiment configuration was defined. This baseline is summarized in Table 2-13. The detailed experiment designs discussed in Sections 2.2.5 and 2.2.6 use this baseline experiment definition.

2.2.5 <u>EXPERIMENT STRUCTURAL DESIGN DEFINITION</u>. This section presents the overall design approach for the ground and flight structural test articles. The basic approach to the experiment structures design was to evaluate program objectives and establish requirements, criteria, and methodology using existing design database for deployable geotruss reflectors and linear truss beams. Selection of the experiment baseline configurations for ground- and flight-test hardware was established by performing trade studies in all respective areas, as follows:

- Experiment hardware requirements
- Deployable geotruss reflectors
- Deployable linear truss beams
- Deployable reflector/beam interface
- Materials
- Deployment mechanisms
- Stowed experiment configuration
- Deployment sequence
- Utilities integration
- STEP/MPESS interface
- STS cargo bay interface
- Overall experiment configuration

Table 2-13. Baseline Experiment Configuration Definition

PARAMETER	PROTOTYPE TEST ARTICLE	FULL TEST ARTICLE	COMMENTS
REFLECTOR DIAMETER	5 M	15 M	BASELINE COMMON BAY SIZE
REFLECTOR F/D	1.3	1.3	
REFLECTOR MOUNTING	OFFSET/EDGE	OFFSET/EDGE	
REFLECTOR HARDWARE	NEW	NEW	REFURB EXISTING 5-METER IS OTIONAL
OPERATING RF FREQUENCY	14-30 GHz	14-30 GHz	K BAND
SURFACE ACCURACY	0.2 MM	0.2 MM	40-13 PPM
POINTING ACCURACY	0.01 DEG	0.01 DEG	
BEAM LENGTH	20 M	20 M	BASELINE COMMON DESIGN
REFLECTOR 1ST MODAL FREQ.	9.29 Hz	1.44 Hz	EDGE CANTILEVER
SYSTEM 1ST MODAL FREQ.	0.40 Hz	0.157 Hz	BEAM DOMINATED
SHUTTLE INTERFACE	STEP PALLET	STEP PALLET	
REFLECTOR REUSE	NO	NO	RETRACTION NOT DEVELOPED, NOT REQUIRED FOR OPERATIONAL SYSTEM
BEAM REUSE	YES	YES	
CONTROLLED DEPLOYMENT			
REFLECTOR	YES	YES	
BEAM	YES	YES	
GIMBAL - REFLECTOR/BEAM	NO	NO	OPTIONAL
GIMBAL - BEAM/STEP (1-AXIS)	YES	YES	PRECISION 2-AXIS GIMBAL OPTIONAL
EXCITATION AND DAMPING SYSTEM	YES	YES	REQUIRED FOR STRUCTURAL DYNAMICS TESTS
PASSIVE DAMPING TREATMENTS	NO	NO	OPTIONAL
ACTIVE VIBRATION CONTROL	YES	YES	SYSTEM ALREADY AVAILABLE
REAL-TIME SURFACE MEASUREMENT & CONTROL	YES	YES	LASER SCAN SYSTEM, ADJUST SPIDER POSITIONS
RF-FEED ALIGNMENT	YES	YES	
ACTIVE PRECISION POINTING CONTROL	NO	NO	OPTIONAL
ACTIVE RF SYSTEM	YES	YES	BASELINE INCLUDES RF TESTING
PHOTOGRAMMETRY	YES	YES	FOR VERIFICATION

The detailed hardware objectives for this experiment were to develop, evaluate and select a generic deployable reflector/beam configuration representative of systems-level concepts applicable to near-term space missions. The hardware design should be adaptable to a wide range of experiment applications yet use a building-block approach for growth and retest capabilities for both ground and flight testing. Systematic trade studies were performed in selecting the generic configuration.

In addition, a total systems package, not just a structures experiment, was sought using proven hardware concepts. Controlled automatic deployment of the structure, with possible total retraction, was examined with the major criteria of being compatible with STS safety and interface requirements. Use of existing material database for the deployable truss structures and support systems hardware with relation to STS and space environment compatibilities was included as part of the design evaluation.

A primary goal of this study is to identify new structures technology issues required to meet the objectives of the planned ground and flight experiments.

2.2.5.1 Truss Structures Design Requirements. To achieve a better understanding of the design and analysis trade study tasks, we established the following truss structure design requirements.

- High reliability (single/double failure tolerant)
- Meets operational performance requirements
- Zero free-play joints
- Low number of parts/commonality
- Easily automated process of fabrication and assembly
- Low weight
- No special tools required to construct or repair
- Low rotational forces-friction
- Reflyable (beam only)
- Remotely deployed/no EVA or RMS assist.
- Low stowage volume and low packaging ratio
- Interchangeable subassemblies/detailed parts
- Sequentially deployed and retracted
- Easily inspectable/repairable
- Redundant load paths
- Accurate/repeatable positioning
- Ground testing capability
- Dynamically and thermally stable
- Compatible with STS requirements

These requirements were applied to the three structural elements: reflector, beam and reflector/beam interface, which make up the ground and flight experiment.

2.2.5.2 Reflector Truss Structure Selection. The geotruss structures accommodate two basic mounting options: center attachment and edge attachment. Variations of these concepts include the number of attachment points required to satisfy mission performance requirements and the mating spacecraft interfaces.

The geotruss reflector is unique because it can be edge-mounted for offset configurations while providing a relatively high structural frequency. The edge-mounted configuration was selected because it requires fewer structural elements (less weight), simplified interface mounting, and allows for simplified offset reflector design. Several geotruss reflectors were developed, fabricated and tested, which provides an excellent design database. The beam truss, when attached to the reflector, provides additional structural complexity in the experiment.

2.2.5.3 Beam Truss Structure Selection. The function of the beam is to deploy the attached geotruss reflector into the proper position with respect to the orbiter and associated experiment systems. The prescribed orientation of the reflector shall be maintained during subsequent pointing and dynamic excitation testing. Possible retraction of the beam and the reflector is the most demanding criteria identified in the program.

An initial study was conducted to identify deployable truss beam concepts suitable for the ground and flight experiment applications. A survey of existing and proposed mission applications was conducted to identify design criteria. These criteria were arranged into groupings based upon what aspect of the truss beam mission they are critical for and what parts of the design process they affect. Based upon these considerations, the design criteria for deployable truss beams were arranged into six categories as follows:

- Space Environment Compatibility
- Operational Performance Requirements
- Launch Performance Requirements
- Material and Manufacturing Considerations
- Deployment Mechanism Interface
- Payload/Utilities Integration

This list was provided as an initial starting point for determining design considerations.

Truss structure construction methods were identified as falling within two basic groups: solid-strut construction and prestressed construction. Solid-strut construction uses fixed length strut members with mechanical hinge points that provide desired structure folding. Basic construction members include hinged struts, telescoping struts and fixed-length struts. Prestressed construction uses a combination of solid-strut members and tension members that stabilize the structure. Basic construction members include tension wires, straps and rods, in addition to any of the solid-strut members listed previously.

The initial evaluation of construction options identified many fabrication concerns and operating issues with concepts using the prestressed methods. Solid-strut construction provides greater confidence that structural properties will remain as modeled throughout ground and flight testing. Concepts incorporating prestressed construction were eliminated for the remaining studies.

The truss beam configurations suitable for this experiment are shown in Figure 2-20, which consist of three- and four-longeron construction. In this figure we also illustrate the methods considered for deployment and retraction.

Each remaining candidate was evaluated as to the different types of retraction methods that could be applied. Obvious limitations were identified that did not allow specific truss beam geometries to comply with all methods of retraction studied. Some of these limitations are:

- Joint design complications
- Inefficient packaging ratios
- Physical geometric limitations
- Difficulties of integrating deployment mechanisms, reflector, and utilities
- Excessive weight

In selecting among these configurations, the initial choice was based upon high reliability and functional concerns. Three longeron beams are statically determinate. They are thus single-failure intolerant. The redundant four longeron beams, which are more likely to be used in an operational scenario, were selected for the baseline beam configuration.

Of the four longeron beams, the box truss beam configurations require many more structural elements (more weight) to interface to the geotruss reflector. A more complex interface design would be required to accommodate this configuration. In past studies the diamond truss beam has been verified by analysis to provide higher torsional capabilities than the box truss beam. Due to less complex interfaces, the diamond truss beam was selected for this specific experiment application.

The deployed geometry of the diamond truss beam fully exploits the benefits of triangulation, which gives the structure a high degree of stiffness and structural efficiency. There is a degree of

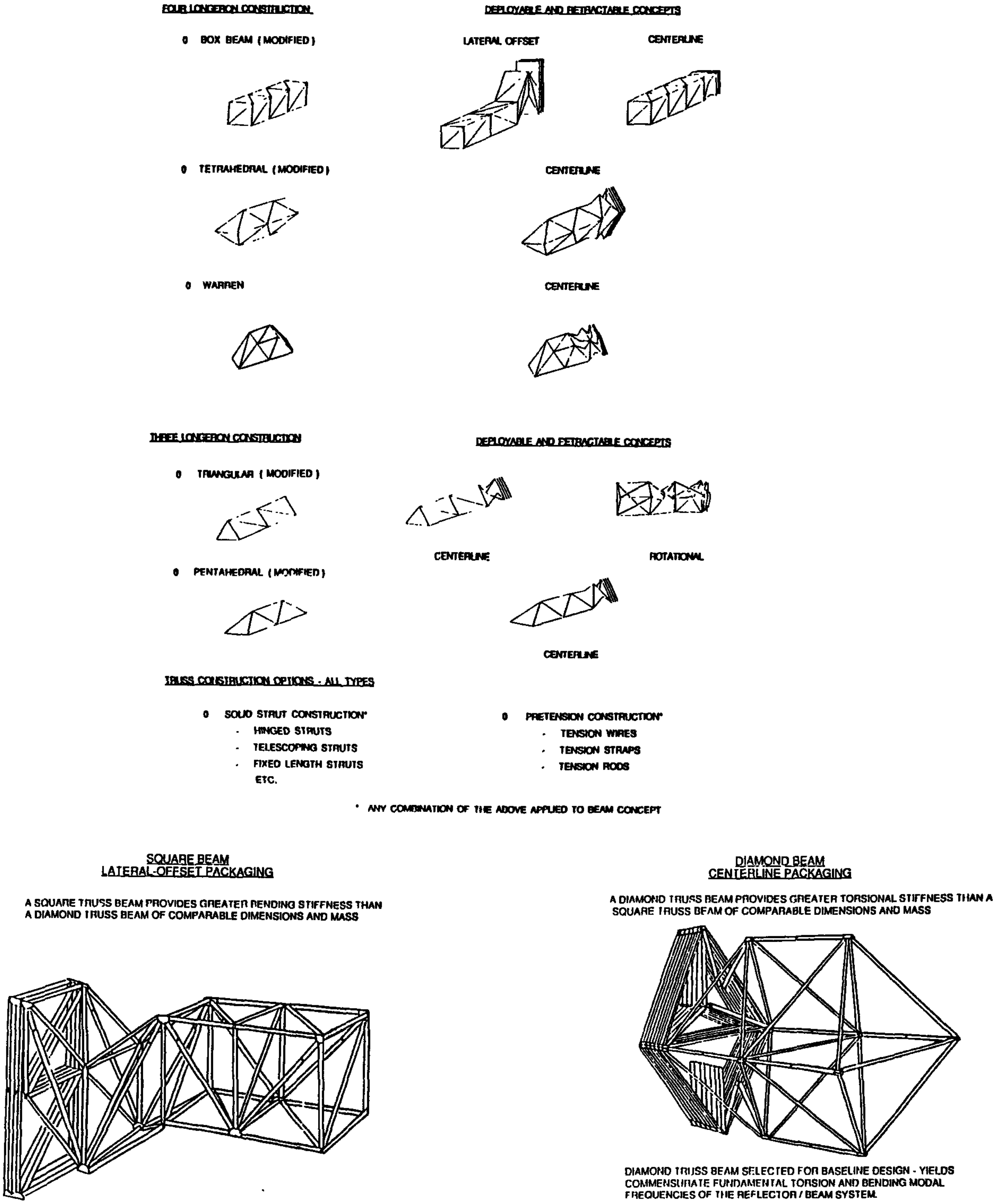

Figure 2-20. Selected Truss Beam Configurations

structural redundancy because any member can be removed from each bay without loss of structural integrity of the remaining structure. The selected diamond truss beam is constructed with equal strut lengths. Preliminary sizing of the bay lengths were based on the loading conditions identified in Section 2.2.5.8, loading conditions-deployed. Initial analysis indicated that a 914.40 mm-long strut by 25.40 mm outside diameter by 1.53 mm wall thickness fabricated from intermediate modules graphite/epoxy was a sufficient starting point to begin the design effort.

One basic of deployment concept can be easily applied to the diamond truss beam due to its geometric configuration. This method consisted of stowing the truss beam by packaging it directly along the centerline, commonly referred to as centerline deployment. The four longerons are hinged in the middle to give each bay the capability to fold directly along its own centerline.

2.2.5.4 Reflector/Beam Interface Truss Structure. In the two previous sections we have identified the edge-mounted, offset, geotruss reflector and the diamond truss beam as the two major structural elements requiring integration.The reflector/beam interface structure evaluation and development flow is shown in Figure 2-21. This flow chart shows the various steps and decision points in the design process and the design requirements that must be considered at each step.

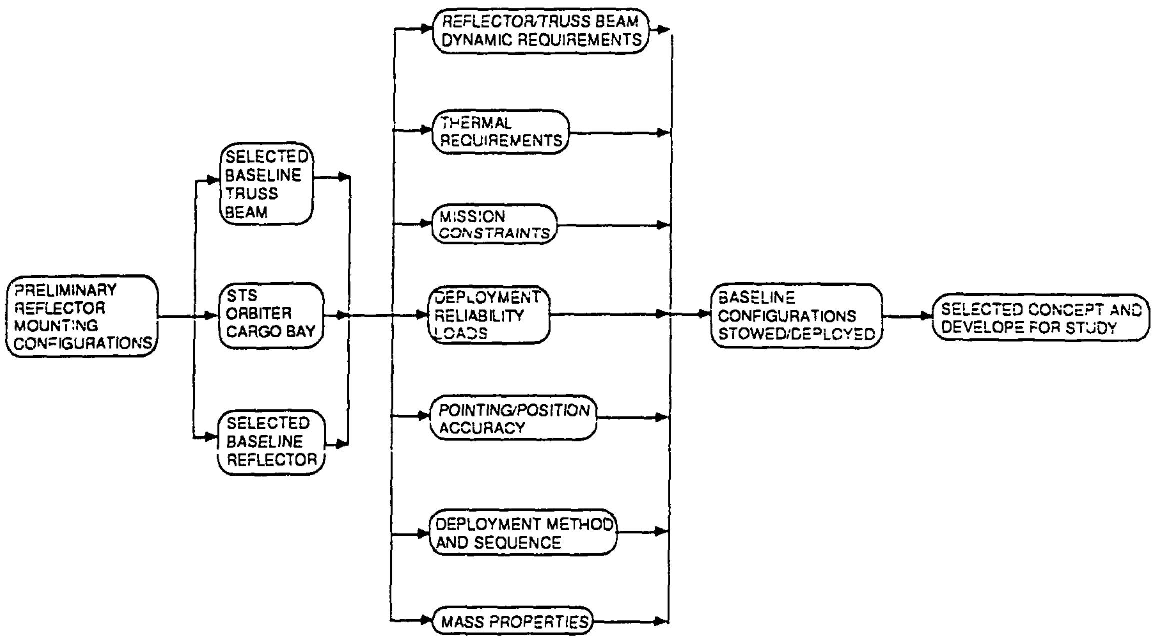

Figure 2-21. Reflector/Beam Interface Structure Evaluation and Development

Evaluation of past reflector support structures developed for the geotruss helped identify edge mounting interface concepts. The number of attach points to the geotruss reflector nodes is dictated by the multiple tetrahedral bays that can accommodate either three-point or five-point, edge-mounted structural systems. A three-point, edge-mounting interface to the geotruss structure was selected over the five-point, edge-mounting system because the three-point system provides adequate support for loading conditions identified, has fewer structural members, and allows easier structural integration to the diamond truss beam and geotruss structure.

Determining the method of construction was the remaining design issue. Three general methods of construction for edge-mounted reflector systems were identified:

- Total truss structures interface
- Hinged-fixed frame interface (A-arm concepts)
- Combination of truss and pretensioned structures interface

Hinged-fixed frame concepts have been \successfully developed in the past. Figure 2-22 shows hinged fixed-frame concepts for both three- and five-point edge mounting that have been fabricated and tested. Although they provide excellent deployment control and stiffners, the hinged-fixed frame concepts are difficult to integrate with a deployable beam.

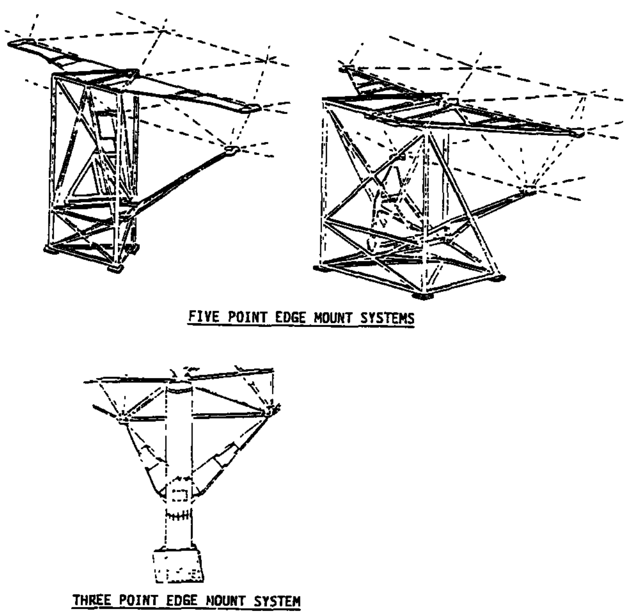

Figure 2-22. Hinged Fixed-Frame, Edge-Mounted Systems

Total truss structures interface use fixed-length strut members with mechanical hinge points that provide desired structures breakdown. Basic construction members included hinged struts, telescoping struts, and fixed-length struts.

A combination of truss and pretensioned structures interface use solid-strut members that are stabilized by tension members within the structure. Basic construction members included tension wires, straps, and rods in addition to the solid-strut members.

The evaluation of construction options identified many fabrication concerns and operating issues with concepts using the pretensioning methods. Total truss structure interface construction provides greater confidence that structural properties will remain as modeled throughout ground and flight testing. Thus our analyses ruled out the use of concepts incorporating pretensioning construction. A total truss structure interface between the diamond beam and geotruss reflector was selected as the baseline.

2.2.5.5 Geo Truss Analysis Code. The geo truss structural geometry, mass properties, parts count, package size, graphics, and NASTRAN model generated with the General Dynamics Tetrahedral Truss Synthesis Program (GDTTSP). Through the use of this program, numerous geotruss configurations were created and analyzed to arrive at the final configuration.

Figure 2-23 illustrates the process through which a geotruss configuration is derived in the early design phases. Design parameters such as RF diameter, F/D ratio, percent offset, strut tube thicknesses, etc. are fed into the GDTTSP program. GDTTSP performs the geometry definition, preliminary strut sizing, mass properties analysis, package size analysis, and part-count analysis. GDTTSP also outputs graphic displays of the configuration geometry, and outputs NASTRAN data sets for both static deflection and modal analysis.

Figure 2-24 illustrates structural, thermal, and RF analysis programs that interface with the GDTTSP program to provide a broad-based antenna analysis capability. In particular, GDTTSP geometry files were used to interface the MESH surface RMS analysis program for RF performance analysis, and GDTTSP NASTRAN interface files were used with NASTRAN for structural analysis.

2.2.5.6 Deployable Truss Structures Baseline Configuration. At this task level the objective was to evaluate different structural configurations for deploying and supporting a reflector/beam experiment from the STS cargo bay. Having selected the type truss construction, the next step was to establish the size and mass of the reflector for sizing of the beam and interface structure.

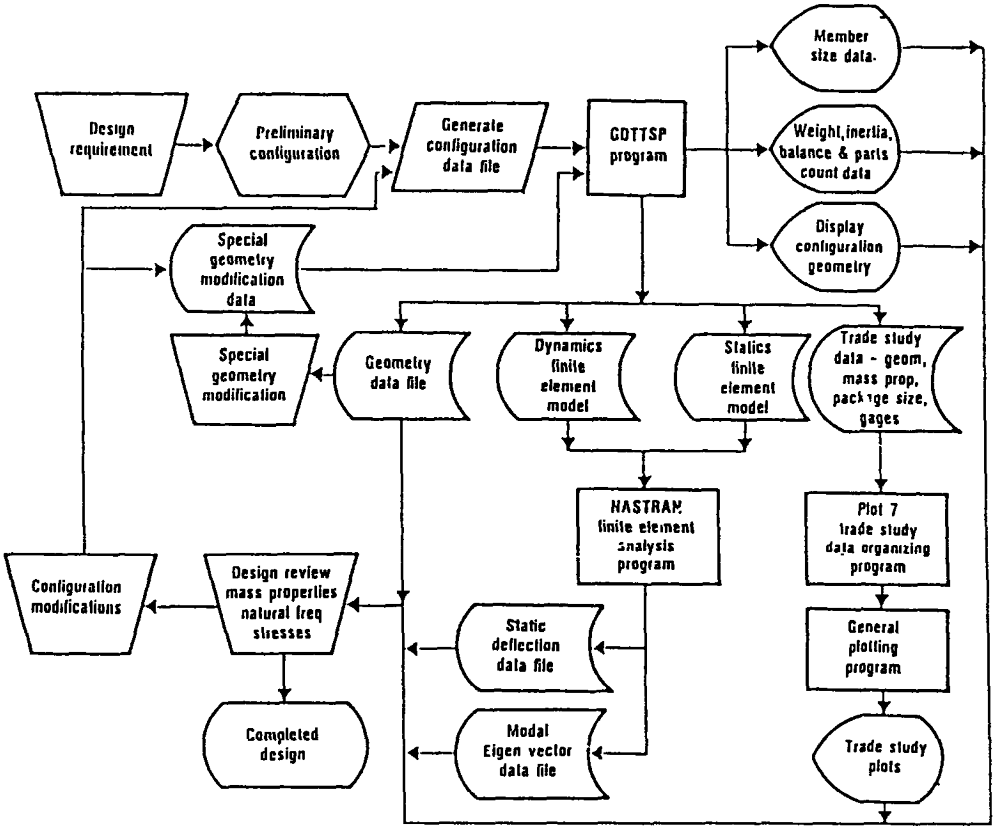

Figure 2-23. Geotruss Design with GDTTSP Program

A major design goal was to establish structural commonality between test articles that would lower overall experiment costs. First, designing, analyzing, and fabricating just one common diamond truss beam for all tests would significantly reduce hardware cost. The common diamond truss beam is sized for the largest reflector. This ensures adequate structural performance and safety for all experiment testing.

Secondly, by sizing the two proposed reflectors to use common structural elements, an additional savings in tooling and assembly fixturing can be achieved. For this experiment a five-meter diameter, four-bay geotruss reflector, shown in Figure 2-25, and a 15-meter diameter, 12-bay geotruss reflector shown in Figure 2-26 were selected.

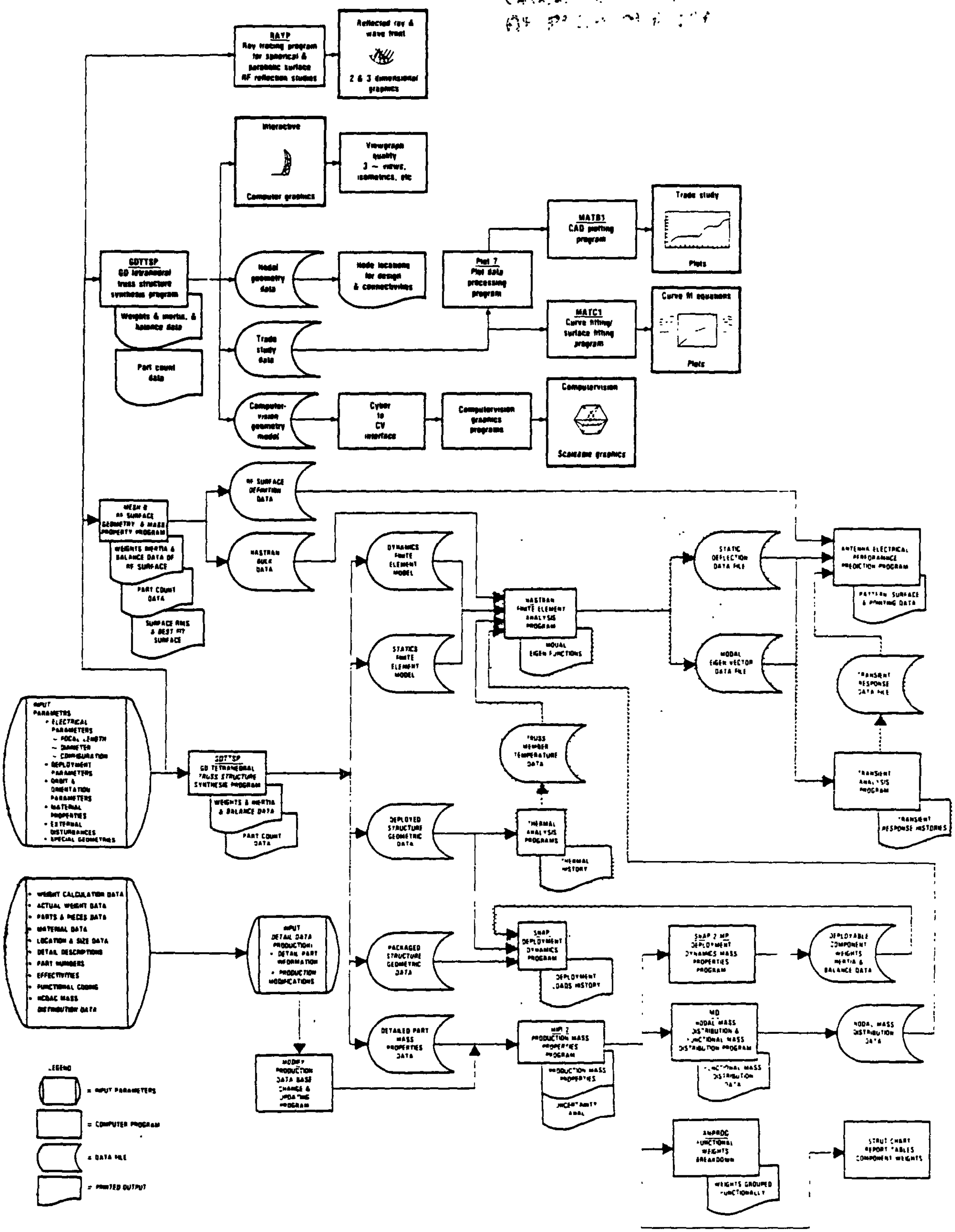

Figure 2-24. Computer Programs and Data Interfaces Used in Geotruss Design

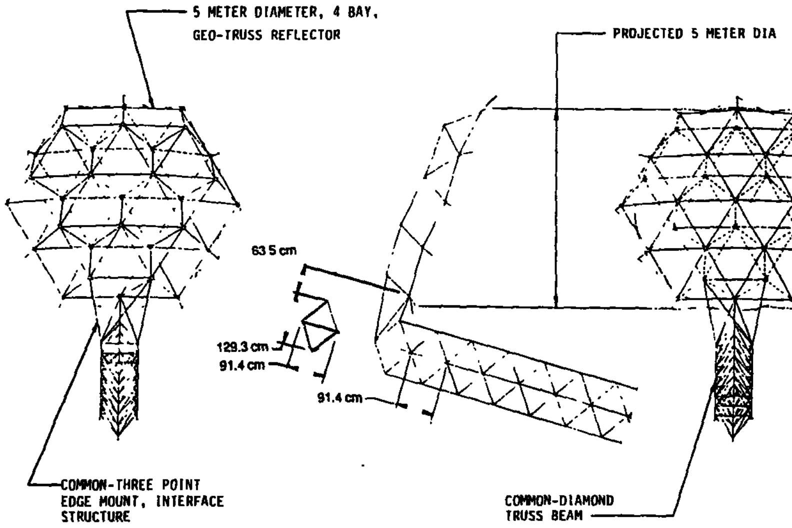

Figure 2-25. 5-Meter Reflector Configuration

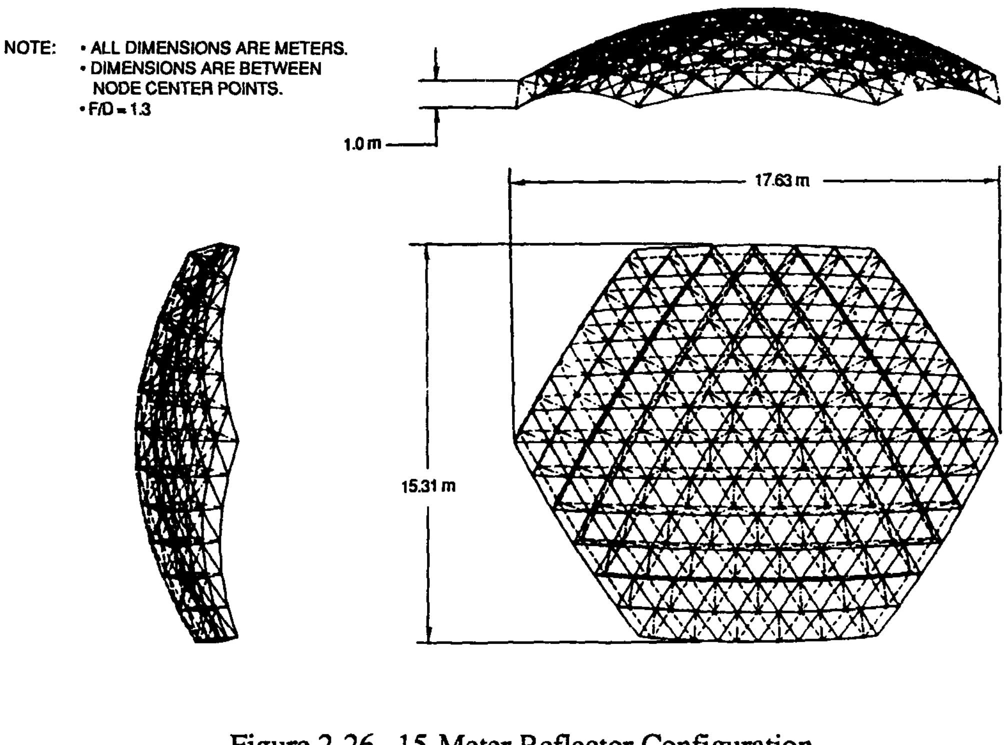

Figure 2-26. 15-Meter Reflector Configuration

A preliminary design was developed for an edge-mounted deployable truss interface between the geotruss reflector and the diamond truss beam, shown in Figure 2-27. This interface structure acts as a two-dimensional torque frame that provides the support between the diamond truss beam and the geotruss reflector. The torque frame provides interfaces that were optimized during the preliminary design to accommodate the structural configuration of the two mating structures The frame also provides a rigid interface that can react all ground, launch, deployment, and operational loads. This is accomplished by joining the reflector support nodes to the truss beam node fittings with fixed-length, hinged, and telescoping struts.

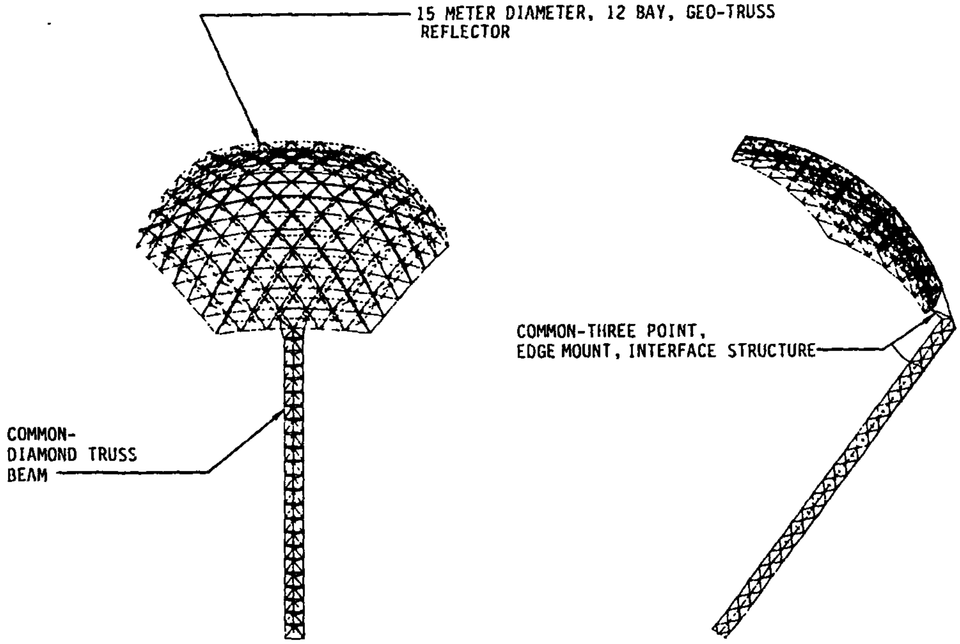

Figure 2-27. Beam Reflector Interface

During the preliminary design phase, final dimensions for the interface structure were established and a basic approach was taken as to the positioning/orientation of the reflector to the truss beam. The reflector was placed symmetrically to the centerline of the truss beam and perpendicular to the truss beam longitudinal axis. The spacing of the reflector to the truss beam was based on sufficient clearances to package and deploy the reflector's outriggers and mesh system.

The perpendicular positioning of the reflector to the beam's longitudinal axis is variable by changing the length of the telescoping strut. This may be used to accommodate desired R/F feed positioning requirements or fine-tuning angular adjustments between the truss beam and reflector.

2.2.5.7 Reflector/Beam Stowed Configuration. The packaged configuration was driven by the payload diameter envelope of the Shuttle cargo bay. The reflector and interface structure are retracted onto the end of the stowed diamond truss beam. This is accomplished by hinging three interconnecting struts and retracting one telescoping strut. Figure 2-28 shows the retracted configurations of each structural element.

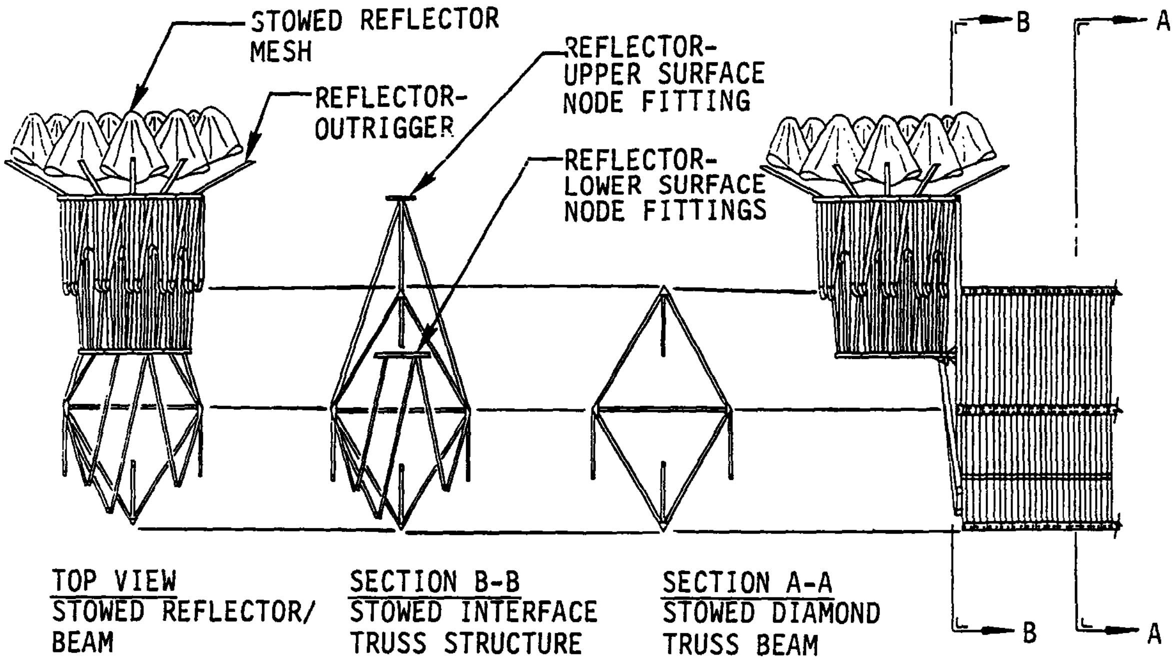

Figure 2-28. Reflector/Beam Stowed Configuration

2.2.5.8 Loading Conditions Deployed. The fully deployed truss structures were assumed to be under translational and rotational accelerations of the Space Shuttle Primary RCS thrusters. The translational accelerations used were 0.18, 0.21, 8.4, 0.39 m/sec 2 in the X, Y, and Z directions, respectively. The rotational accelerations used were 0.021, 0.026, and 0.014 rad/sec2 about the X, Y, and Z axes, respectively.

2.2.5.9 Structural Analysis. A preliminary structural analysis was conducted on the reference configurations for the deployable, four-longeron, diamond truss beam. This analysis was intended to determine the behavior of the structure under operating loads and to verify the strength capability of the truss structure components. The primary method used in this analysis was the creation of a detailed finite element model of the structures. A model was created of a 16-bay configuration to determine the effect of reflector sizes on truss beam behavior.

The model included elements representing the components of the tubular truss structure of the selected diamond beam configurations. The longerons were represented by bar elements that contained bending and axial stiffness. The diagonals and battens were represented by rod elements that incorporated axial stiffnesses only. Separate mass elements were included at each node point to represent the node and hinge fittings of the truss beam. The effects of the antenna mass on truss beam behavior were represented by a mass element at the center of gravity of the antenna, which was connected to the main truss beam with rigid bar elements.

The design load conditions resulted from operation of the Orbiter Primary RCS thrusters. These conditions were represented in the finite element model by applying translational and rotational acceleration factors. The resulting inertial loads, deflections, and internal loads on the truss beams were calculated by the finite element program.

The critical design points were for maximum deflection at the tip of the truss beam and maximum axial loads in the longerons at the base of the truss beam. The maximum deflection at the tip of the truss beam for this loading condition is 2.94 cm.

The minimum margins of safety were calculated for the longerons at the base of the truss beam. These members consist of tubes of ultra-high modulus graphite epoxy connected to the nodes by hinged connections. The critical-failure mode is Euler buckling of the member acting as a pinned ended column. The minimum margin of safety was determined to be +0.45 for the worst-case compression loading using a 1.40 safety factor.Strut diameter was 25.40 mm (outside diameter) with a 1.53 mm wall thickness.

2.2.5.10 Experiment Support Structure Design Requirements. The selected interface between the flight experiment and the STS cargo bay is the STEP Dedicated Support System. The structural interface between the experiment and the STEP pallet is a frame that reacts all pitch, roll, and yaw loads during all flight phases.

The following general requirements were identified for the experiment support structure:
- Compatible with STEP interfaces

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- High stiffness
- Contained within dynamic envelope of orbiter cargo bay
- Allow for avionics and experiment subsystems integration
- Statically determinant hardpoint mounting
- Use standard STSS hardpoint interfaces
- Supports deployment systems
- Compatible with orbiter and experiment operations environments
- Provides experiment rotation capability at STEP interface
- Provides for beam retraction and stowage after reflector jettison

Figure 2-29 illustrates the overall support structures network with relation to the stowed 15-meter reflector/beam experiment. The primary interface surface is located on the underside of the support structure frame. The frame interface with the STEP pallet incorporates the standard hardpoint ball and socket fittings. This combination of hardpoint locations on the support structure provides a statically determinant interface to the STS STEP pallet. Load transfer into the STEP pallet was analyzed to verify compliance with the Structural Interface Document for the pallet (Spacelab Payload Accommodations Handbook, SLP/2104, Appendix B-1).

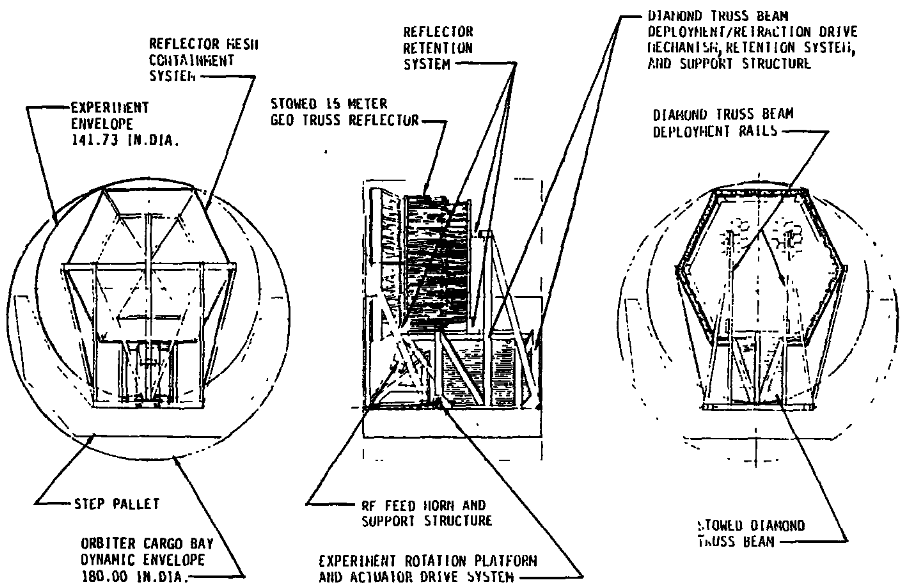


Figure 2-29. Packaged Experiment to Step Interface

2.2.5.11 Materials Considerations. The selection of materials and processes for this experiment were important factors in achieving desired performance levels. They also are major factors in the producibility and cost of the overall system. As with all flight hardware, low mass is important to reduce overall launch costs especially when experiment reflight is a consideration..

The space environment imposes severe constraints on the choice of materials. Materials were selected that have low moisture absorption, can withstand hard vacuum without outgassing, and withstand the eroding flux of charged particles and atomic oxygen without degradation. To prevent electrical arcing and associated RF noise, electrical charges cannot be permitted to build up on surfaces. The materials of the assembly hardware must withstand repeated thermal cycling without buildup of micro-defects and the associated losses in strength and stiffness.

Truss structures dimensional stability through low CTE, high specific strength, and stiffness is required. The experiment structure will experience a wide range of operating temperatures and the effects of localized shadowing. Due to the stringent requirement for positioning and pointing accuracies, the structure uses graphite/epoxy struts to achieve near-zero overall CTE to minimize the thermal induced distortion.

2.2.5.12 Utilities Integration Design Requirements. Provisions for utility subsystems are required at several locations throughout the experiment package. Installation points consist of STEP pallet - mounted, orbiter-mounted, and truss-structures-mounted utility subsystems, consisting of the following;

- Dynamic controls and actuators (pitch, roll, and yaw)
- Avionics
- Instrumentation
- Power amplifiers
- Ordnance initiation systems (pyrotechnic separation devices)
- RF equipment
- Safety equipment
- RMS grapple fixture and target
- Bus interface units
- Utility lines, cable trays, source connections and interconnections
- Equipment mounting platforms and standoffs

The main requirements for utilities integration are reliability, high performance, and low cost. Reliability includes elimination of cable straining during deployment and retraction, and minimal number of connections or joints that will not degrade operations of deployment/retraction cycles or truss structures lock-up.

Performance includes protection from adverse environments (thermal, radiation, vibration) and elimination of electrical interference by separation of power and data/signal equipment, without affecting experiment packaging efficiencies.

Cost considerations include: accessibility for end-to-end checkout for ground and flight tests in both the retracted and deployed configurations, ease of installation, maintenance, and replacement using standard tools.

2.2.5.13 Control Systems Installation. Excitation and damping of the experiment is provided by flight-proven torque actuation wheels (rate gyro units). The reaction wheels, including power amplifiers, ordnance hardware, instrumentation, and avionics components are located at the tip of the diamond truss beam. Three of these units are used to provide pitch, roll, and yaw (X,Y, and Z) forces.

The structural interface for these units includes mounting provisions for all associated equipment in both the stowed and deployed configurations, as shown in Figure 2-30. This mounting structure

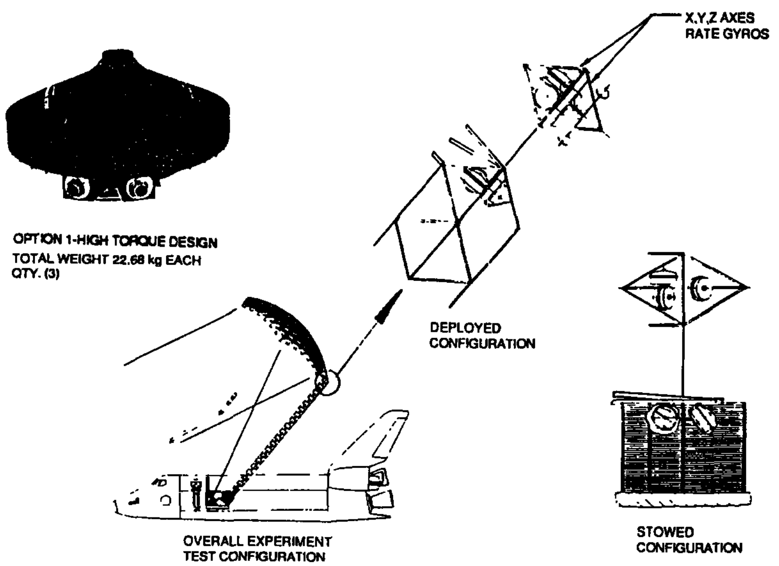


Figure 2-30. Mounting of Rate Gyro System

must match the CTE of the truss beam in all radial directions to ensure no adverse effects on the diamond beam and the interface structure.

Accessibility to all units and associated equipment in both the deployed and the stowed positions was required so that maintenance such as removal and replacement, checkout tests, and repair can be performed with using standard hand tools.

2.2.5.14 Pyrotechnic Separation System Installation. If the beam fails to restow, an emergency separation and jettison is provided to restore the orbiter to a safe operating condition. Figure 2-31 shows the two pyrotechnically activated separation points within the experiment. These separation points are part of the baseline experiment hardware configuration. The failure modes and operational test sequences identified have been satisfied with two pyrotechnic separation methods

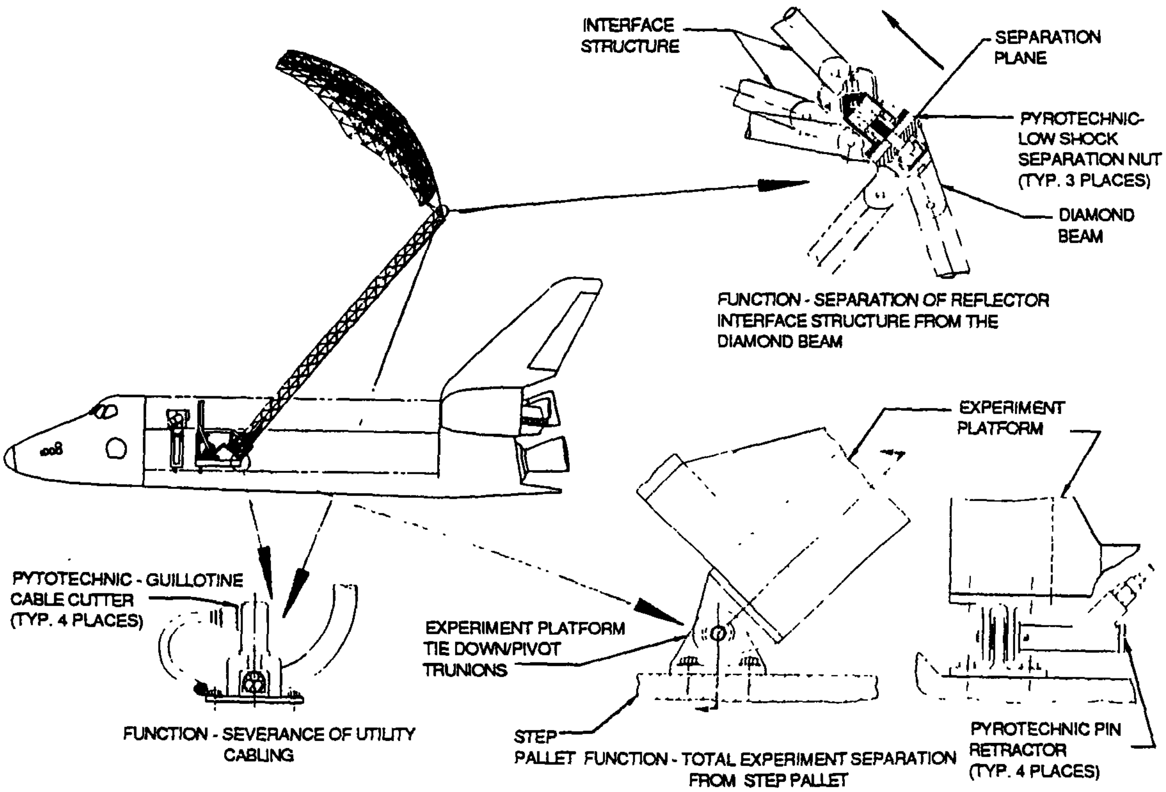


Figure 2-31. Experiment Pyrotechnic Separation System

For flight experiments the geotruss reflector and the interface structure will not be retracted and restowed into the STS cargo bay for return to Earth. The geotruss reflector separation point is at the end of the diamond truss beam. The separation occurs by activating three pyrotechnic, low-shock separation nuts and a cable cutter for utility line separation. Structure separation fittings are located on one apex node fitting and two base node fittings of the diamond truss beam. This separation system location provides reflector and interface structure separation from the beam at the completion of the on-orbit testing or at any other time during the experiment.

The entire truss structure experiment is jettisoned by activating the pyrotechnic system at the base of the truss beam support structure platform. This separation plane has been established as the interface points to the STEP pallet. Total experiment separation from the STEP pallet is achieved by pyrotechnic pin retractor located at all structural interface points. Utility lines from the STEP pallet to the experiment platform are severed by a pyrotechnic cable cutter.

Experiment removal from the STS cargo bay is accomplished by RMS support. This approach was selected for the experiment due to cost, safety, and reliability. RMS interface provisions for the entire experiment (experiment platform, beam, interface and reflector), and the tipmass (interface and reflector) are provided by attaching RMS grippling fixtures and targets to the beam and reflector structures.

2.2.5.15 Experiment/STS Cargo Bay Layout Options. The required interfaces between the reflector/beam experiment and the STS include power, data, control, and mechanical. This study concentrated on the STS structural and mechanical capabilities to support the flight experiment using existing support hardware (i.e., STEP pallet and MPESS pallet).

During the experiment the crew members must work in the Aft Flight Deck (AFT) to initiate and monitor test operations and to operate the RMS. The physical location of the experiment within the cargo bay in relationship to the aft control station and the associated cargo bay support equipment have been considered. Failures during the experiment need to be assessed by the crew by using both actual line-of-sight verification and remote camera detection. Therefore, placement of the experiment is an important consideration for operational testing and safety concerns.

Crew EVA egress requires a minimum clearance of 1.22 meters between the experiment, and on the experiment require EVA clearance of 1.22 meters from the crew compartment hatch of the cargo bay. This limits the experiment location within the cargo bay.

A major driver in identifying and selecting the optimum cargo bay layout for the experiment is the capability to deliver additional payloads as part of the launch manifest . Figure 2-32 illustrates three-cargo-bay layout options in both the stowed and deployed configurations.

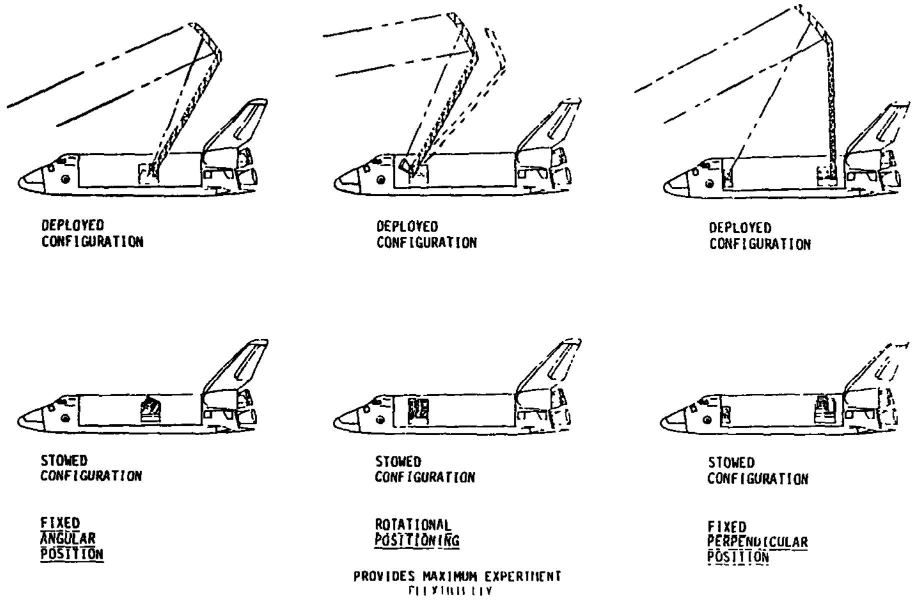


Figure 2-32. Experiment Position Options Within STS Cargo Bay

The fixed angular position and the fixed perpendicular position experiment configurations do not comply with the criteria identified. The loss of cargo bay volume due to required experiment configuration hamper additional payload possibilities.

The deployed and stowed configuration of the fixed angular position requires the experiment to protrude into forward and aft adjacent spaces. In order to maintain adequate safety margins, forward and aft payloads would require large separations from the STEP pallet and the experiment.

The fixed perpendicular position of the experiment requires separation of the experiment package. The actual truss structures experiment mounted on the STEP pallet is placed aft in the cargo bay. The associated test equipment is mounted forward creating a large separation for all interface systems. Line-of-sight of the experiment from the AFT becomes impossible once a payload(s) container is located in the mid-cargo bay section. Any failure mode of the truss structure would impose great danger to the orbiter's tail section.

The rotational positioning experiment configuration was selected because it best suits the criteria identified for this flight experiment. Consolidation of all experiment hardware and STS interfaces simplifies cargo bay processing and installations. Obstruction of other payloads are minimized by forward placement of the experiment in the cargo bay. Crew egress and EVA clearances are maintained. Line-of-sight from the AFT is possible during all phases of on-orbit tests.

2.2.5.16 Experiment Deployment Methods and Sequence. Deployment methods and sequencing are primarily driven by safety issues, mission requirements, and launch vehicle constraints. Various deployment sequences can be implemented for the structural configurations identified for the 5- and the 15-meter reflector/beam experiment.

Deployment mechanisms are required for experiment retention, release, deployment drive, truss structures lock-up and beam retraction. Mechanism concepts were evaluated in the areas of function, weight, reliability, and simplicity. A common goal of all deployment functions is slow, controlled, and reliable methods to achieve the desired levels of experiment configurations. All truss structures and support structures must work integrally with all deployment control systems.

Operational deployment issues and how they should relate to the on-orbit testing were addressed first. Consideration was then given to orbiter compatibilities such as safety, payload interfaces, and the manned environment. High reliability drove the requirements for fail-safe, dual-failure tolerant, and redundant design approaches. Deployment mechanism design requirements as they applied to the ground/flight experiment are as follows:

- Automatic deployment in space and automatic or manual deployment on ground
- Automatic retraction (beam only)
- Controlled deployment/(retraction)
- Strength of truss maintained at all stages of deployment
- Suitable for use with add-on structures and utilities
- Efficient packaged volume (compact)
- Low power consumption
- High reliability (single/double failure tolerant)
- Suitable and safe for EVA operations in the event of malfunction
- Able to generate extra force in the event of a hang-up or jam
- EVA/RMS back-up capabilities
- Compatible with reflector/interface structure jettison

The selected deployment method for the diamond truss beam is a continuous electromechanical drive system. The drive source is integrated with a track and belt drive system that contains the beam during stowage, deployment, and retraction. This mechanism is integral with the support structure. Controlled sequential deployment is provided for the truss beam. The beam unlock and retraction capability is provided within the same system that operates in reverse of the deployment sequence. Strut folding is achieved by tripping the lock mechanism on each folding strut.

The reflector/beam interface structure is deployed integrally with the diamond truss beam and the geotruss reflector. In this concept, the deployment motions for the interface structure is established by the deploying geotruss structure. Final lock-up of three interfacing hinged struts are provided by the locking hinge mechanism. A linear actuator operates the telescoping strut . The deployment stroke required from the retracted to the deployed position is approximately 6.09 cm.

Controlled deployment methods for the geotruss reflector has been studied in depth. The optimum approach is to deploy in a controlled synchronous manner using continuous electromechanical drives in conjunction with linkage or gear interfaces with the deploying struts. These deployment drives are locked at selective node fittings. The geotruss reflector deployment energy is provided by carpenter-tape hinges in the center of all surface struts. The hinges act as basic folding element and the drive mechanism. Once released it deploys into a positive locked configuration.

A step-by-step deployment sequence of the reflector/beam experiment is shown in Figure 2-33. The steps are as follows:

Step 1: The total experiment is retained for launch on the step pallet. The diamond truss beam is retracted along its longitudinal axis in a single-fold (stowed position). The interfacing structure is collapsed and nested between the geotruss and the diamond truss beam.

Step 2 : The release of the mesh containment deuce is activated by the first motions in the experiment platform rotation. As the distance increases from the reflector mesh and the mesh containment device in separation forces become higher until mesh release, (i.e., velcro peel effect) rotation of experiment platform is activated by a redundant actuator drive system.

Step 3 : Release of the retention devices that secure the diamond truss beam are actuated. Truss beam deployment begins.

Step 4 : Diamond truss beam deployment is complete. Release of the retension devices that secure the interface structure to the truss beam are activated. Partial interface structure deployment is achieved. The interface structure telescoping strut is fully deployed and locked in conjunction with the two fixed struts that establish a fixed upper surface node point on the geotruss reflector.

Step 5: The geotruss containment systems is actuated. The geotruss reflector is allowed to deploy in conjunction with the remaining three hinge struts of the interface structure.

Step 6: Deployment of the geotruss reflector is complete as well as the entire interface structure and the diamond truss beam.

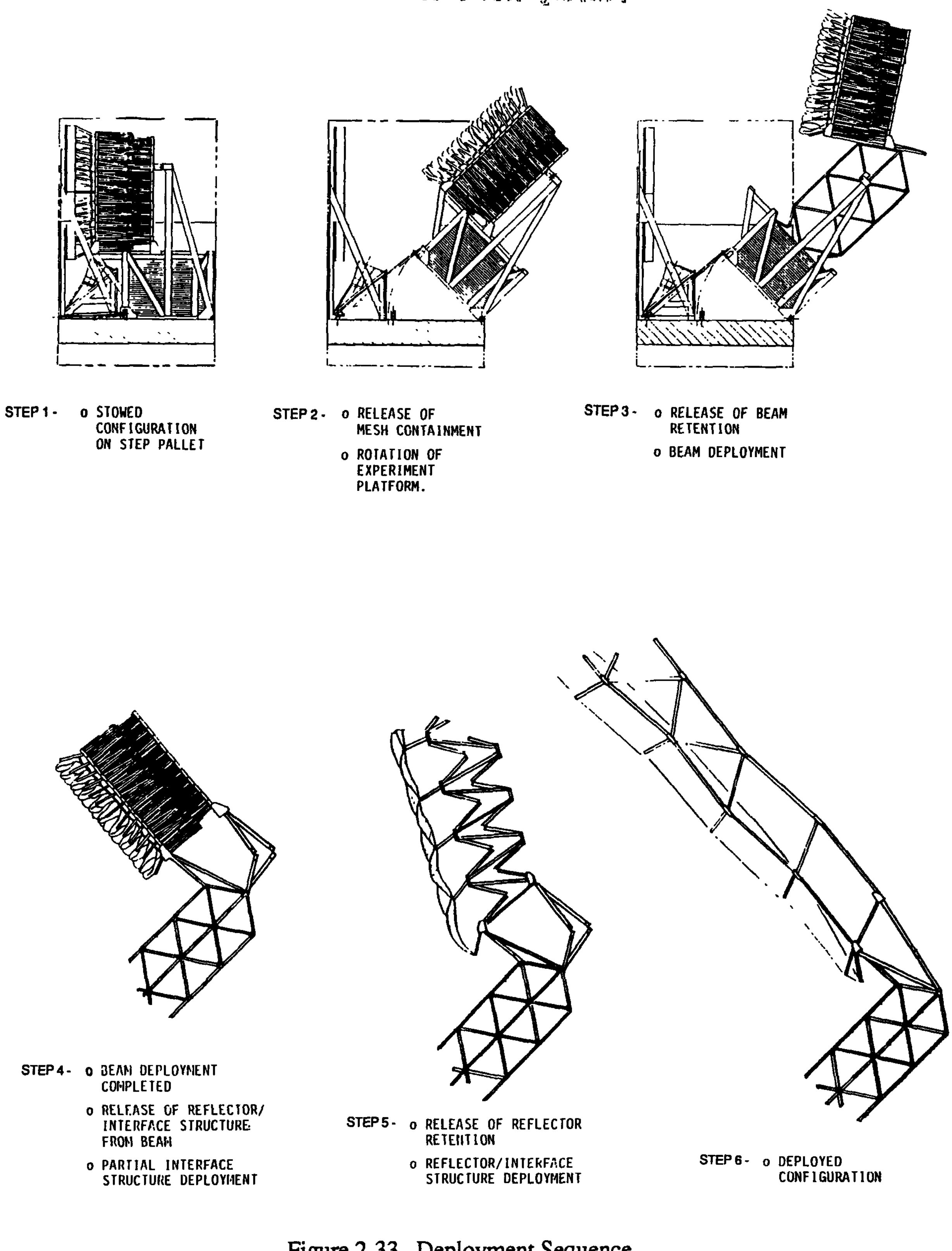


Figure 2-33. Deployment Sequence

2.2.5.17 Selected Baseline Experiment/STS Cargo Bay Configuration. The baseline for the reflector/beam.flight experiment .hardware is characteristic of generic large deployable truss structures with unique capabilities to support a comprehensive research program. The design approach is suitably configured to meet all experiment requirements.

The proposed two flight experiment uses two different-sized reflectors: a 5-meter (four-bay) for the first flight, and a 15-meter (12-bay) for the second flight. Reflector design commonality was selected to reduce the costs over a two-flight program.

Both flight experiments use a common diamond truss beam and the associated mechanisms, retention system, and support structure. The beam deploys from the STS cargo bay with the reflector mounted at the tip. Once the flight test program is complete, the reflector is jettisoned and the beam is retracted and restowed for return and reuse.

The reflector/beam interface structure is the same configuration for both flights. Jettison of both reflectors occurs at a separation plane between the diamond truss beam and the interface structure. A simple three-point, edge-mounted truss structure interface was selected to mate the reflector and beam.

The diamond truss beam is sized to support the larger 15-meter reflector under the worst -case loading conditions. Figure 2-34 shows the experiment in the deployed configuration. Figure 2-35 shows the experiment in the stowed position within the orbiter cargo bay. With this configuration experiment processing and testing can be performed on a non-interference basis with other payloads.

The selected flight experiment approach is adaptable to a wide variation of payload manifests and growth options and makes use of existing orbiter support equipment to minimize experiment costs.

2.2.5.18 Mass Properties. Preliminary estimates of the mass properties of all experiment system elements for the 5-meter and 15-meter reflector flight test hardware.is summarized in Table 2-14. The estimates do not include STS support hardware. Mass properties have been updated as alternative and modified designs were developed that lead to the baseline configuration. This data has been used in the computer simulations to establish overall systems dynamics. Total weight of the 5-meter reflector experiment is 928 kg, and the 15-meter reflector experiment is 1173 kg

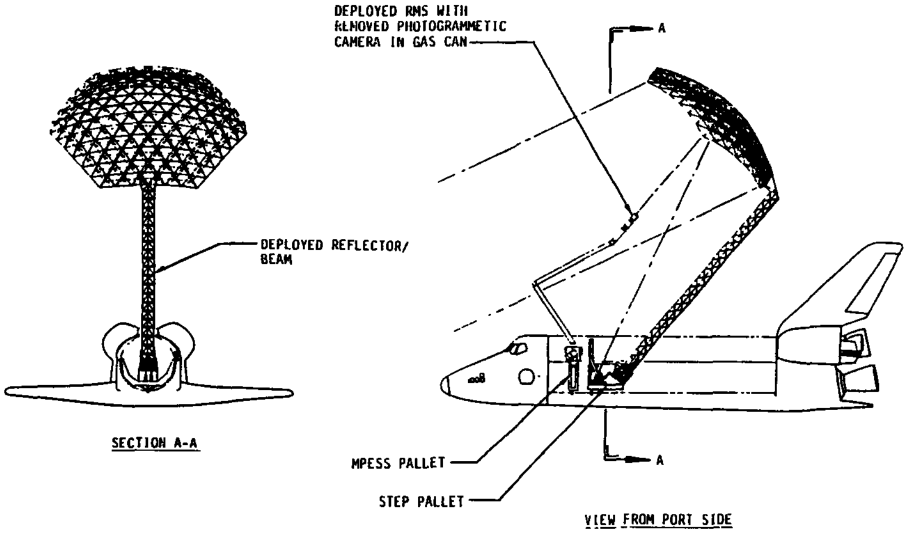


Figure 2-34. Flight Experiment in Deployed Configuration

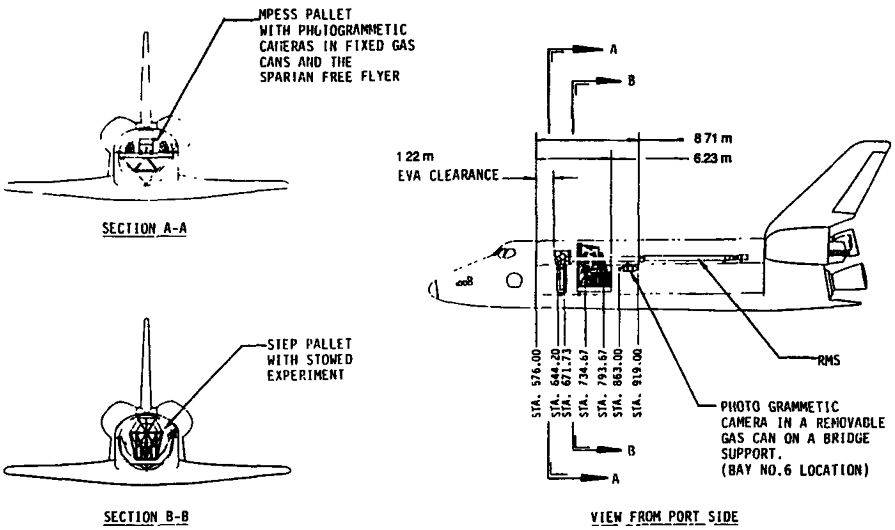


Figure 2-35. Flight Experiment in Stowed Configuration

Table 2-14. Experiment Mass Properties

	5 METER GEOTRUSS REFLECTOR	15 METER GEOTRUSS REFLECTOR
GEOTRUSS REFLECTOR	39 kg (87 lbs)	250 kg (552 lbs)
GEOTRUSS REFLECTOR MESH CONTAINMENT SYSTEM	132 kg (290 lbs)	166 kg (365 lbs)
GEOTRUSS REFLECTOR RETENTION/SUPPORT	59 kg (130 lbs)	59 kg (130 lbs)
DIAMOND TRUSS BEAM	74 kg (163 lbs)	74 kg (163 lbs)
DIAMOND TRUSS BEAM DEPLOYMENT/ RETRACTION DRIVE MECHANISM	268 kg (590 lbs)	268 kg (590 lbs)
DIAMOND TRUSS BEAM RETENTION/ SUPPORT STRUCTURE	67 kg (147 lbs)	67 kg (147 lbs)
RF FEED HORN	5 kg (11 lbs)	5 kg (11 lbs)
RF FEED HORN SUPPORT	34 kg (74 lbs)	34 kg (74 lbs)
EXPERIMENT ROTATION PLATFORM AND ACTUATOR DRIVE SYSTEM	239 kg (528 lbs)	239 kg (528 lbs)
INTERFACE STRUCTURE	11 kg (25 lbs)	11 kg (25 lbs)
TOTAL (DOES NOT INCLUDE STS SUPPORT HARDWARE)	928 kg (2045 lbs)	1173 kg (2585 lbs)

2.2.6 AVIONICS/ INSTRUMENTATION DEFINITION. The flight experiment avionics/instrumentation definition is predicated on a 1992 flight date for the 5-meter geotruss reflector. This early flight date mandates the use of mostly proven avionics/instrumentation technology.

2.2.6.1 Avionics/Instrumentation Requirements. The basic experiment measurement/control requirements fall in the areas of contour measument, shape control, defocus measurement, and pointing measurement. These requirements, which establish the basic radiated RF field wavefront accuracy, are summarized in Table 2-15.

Table 2-15. Experiment Measurement/Control Requirements

Contour Measurement

- RMS error of 0.6 mm at 10 GHz results in 1.2dB gain loss and 10 dB side lobe increase.
- 1.5 mm RMS error gives 6.8 dB gain loss and higher side lobes.
- Higher frequency operation (14-30 GHz) requires smaller RMS error (0.02λ).
- Measurement sample rate to provide bandwidth adequate to sense contour dynamic deflections.

Shape Control

- Utilize contour measurement displacement data for shape control effectiveness.

Defocus

- Defocus tolerance of 3.0 mm (0.2λ) at 20 GHz.

Pointing

- Pointing tolerance in the order of 0.01 degrees for 20 GHz and 15 m reflector diameter.

These basic experiment measurement/control requirements are the basis for desired requirements in the areas of operational constraints, operational implementation, operational hardware, and operational hardware implementation. These requirements are summarized in Tables 2-16 - 2-19.

Table 2-16. Measurement/Control Operational Requirements

Structural Dynamics
- Even passive damping requires instrumentation to evaluate behavior.
- Passive damping needs excitation actuators.
- Both passive and active damping shall be demonstrated and assessed.
- Strain measurements shall be provided at locations given in Figure 2-36 (SG - Strain Gauge).

Shape Control and Measurement
- Thermal differential temperature measurements are more critical than absolute temperature accuracy.
- Thermal data may be used to compensate for temperature effects.
- Temperature sensor locations identified in Figure 2-36 (T-temperature sensor).
- Number of shape control actuators are reduced with structure spider design.

Gimbal Pointing
- Use RF field measurements to calibrate antenna pattern versus gimbal angle.
- Provide gimbal angle position sensor.

Beam/Reflector Deployment
- Open loop deployment sequencing. No closed loop automatic control required. Time duration not critical.
- Actuation position and limits monitoring by observer instumentation. Observer initiation and over-ride capability.
- Reversible operation to apply only to beam element.
- Provide failure detection (temp, volt, etc).
- Jettison capability for beam retraction failure.

Table 2-17. Operational Implementation Requirements

Shape Control

- Shape control actuator position instrumentation data will be useful for test result analysis.

Thermal/Strain Measurement

- Minimize low level signal run lengths with appropriately placed Bus Interface Units (BIU - Figure 2-36).
- Provide equipment temperature sensing.

Recording

- Deployment data recorded.
- Pointing commands and pointing position sensor data recorded.
- Contour measurement data recorded.
- Thermal data recorded.
- Shape control actuator commands and position data recorded.
- Passive/active damping actuator commands, measurement data, actuator performance recorded.
- Strain data recorded.

General

- Use single string hardware (except where redundancy insures safety).
- Use data acquisition response and protocol, which insures adequate sensor sampling rates and time correlation.
- Provide flexibility for modifications.
- Use ADA as the Higher Order Language (HOL)
- Provide interface compatibility testing prior to STEP and experiment mating.
- Follow NASA procedures for Orbiter experiments.

Table 2-18. Operational Hardware Requirements

General

- Use off-the-shelf or modified hardware wherever feasible.
- Use serial data bus to minimize copper, weight, and bending deployment stresses.
- Use STEP hardware to maximum advantage (recording, power control, etc.).
- Use GFE STEP hardware for ground tests also.
- Provide EMI and transient protection features.
- Comply with all STEP, Orbiter, and TDRSS interface requirements (electrical, thermal, mechanical, structural).

Table 2-19. Operational Hardware/Implementation

Contour Measurement

- Use Photogrammetric Camera Subsystem (PCS) for primary contour data.
- Provide a low cost, alternative, real time, experimental Laser Scan Subsystem (LSS) as test of alternative method.
- Measure from focal point for photogrammetry and from reflector center for LSS (LSA - Laser Scan Assembly, LST - Laser Scan Target, Figure 2-36).
- LSS contour data recorded on STEP recorder, and photogrammetry data on camera film.

Shape Control

- Use micro-motion actuators for shape control.
- Use STEP recorder for all pertinent data for later data correlation.
- In general use platinum wire thermal sensors with common switch current injection.

Structural Dynamics

- Active damping will employ rate gyro sensing and rotating inertial torque actuators (RGU - Rate Gyro Unit, PAA - Primary Actuator Assembly, Figure 2-36).
- Use beam and reflector inertial acceleration sensing (ATU - Accelerometer Triad Unit, Figure 2-36).
- Use the Retro-Reflector Field Tracker (RFT) to measure beam lateral motions (Figure 2-36).
- Use the LSS beam deflection measurements for performance monitor and as an eventual low cost replacement for the RFT (LSA, LST, Figure 2-36).

Gimbal Pointing

- Use a Gimbal Drive Assembly with Direct Drive Actuator (GDA, DDA, Figure 2-36).

Deployment

- Use a Carriage Drive Assembly with 3 Direct Drive Actuators (CDA, DDA, Figure 2-36).

Processing

- Provide 1750A processor, and memory for control sequencing, data processing and transfer, and control algorithm computation (ESP - Experiment System Processor, Figure 2-36).

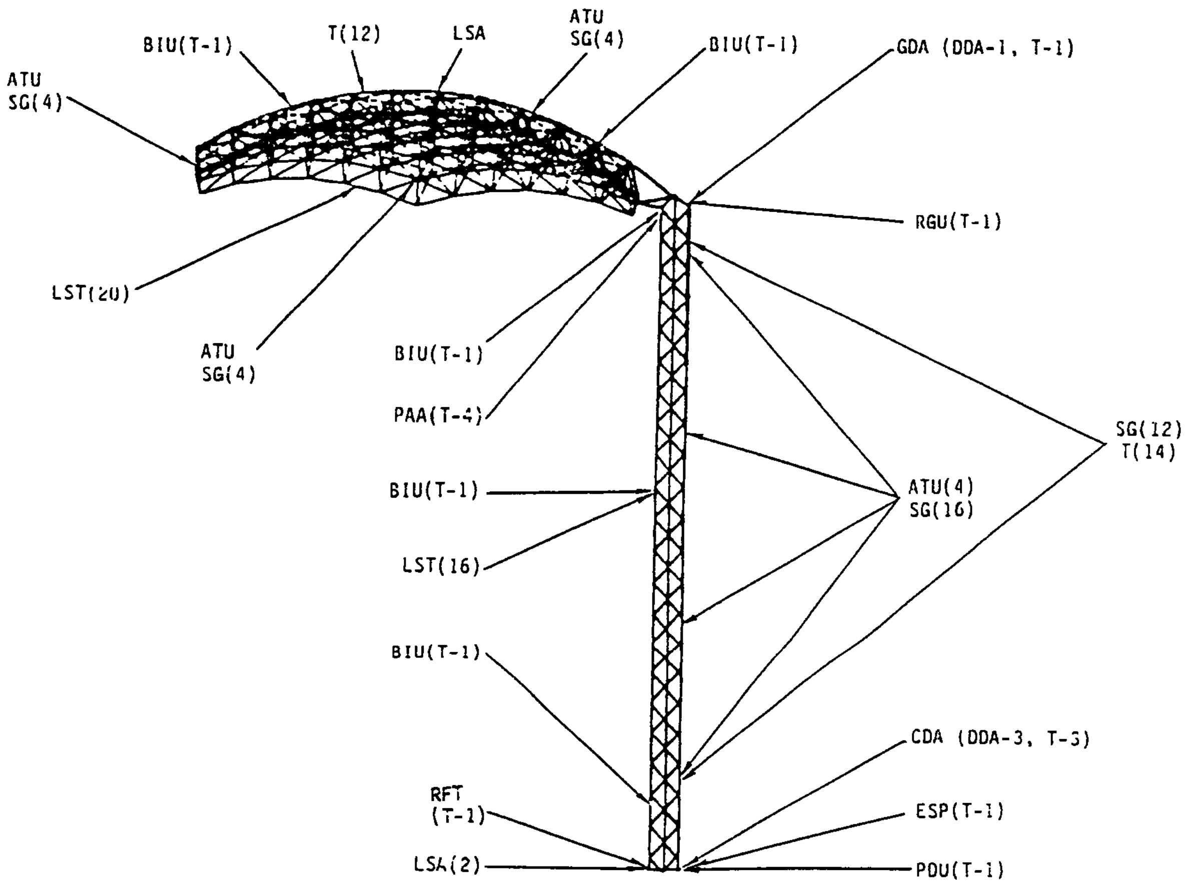


Figure 2-36. Control/Instrumentation/Measurement Identification and Locations

The major functional subsystems and elements and their interfaces are shown in Figure 2-37. A hardware-oriented block diagram is given in Figure 2-38. In addition to more detail on electrical interfaces, Figure 2-38 gives the thermal interfaces to the SDSS cold plate. Functions and descriptions of the various subsystem and hardware elements are described in Tables 2-20 through 2-24. Further detailed hardware component descriptions are supplied in Table 2-25.

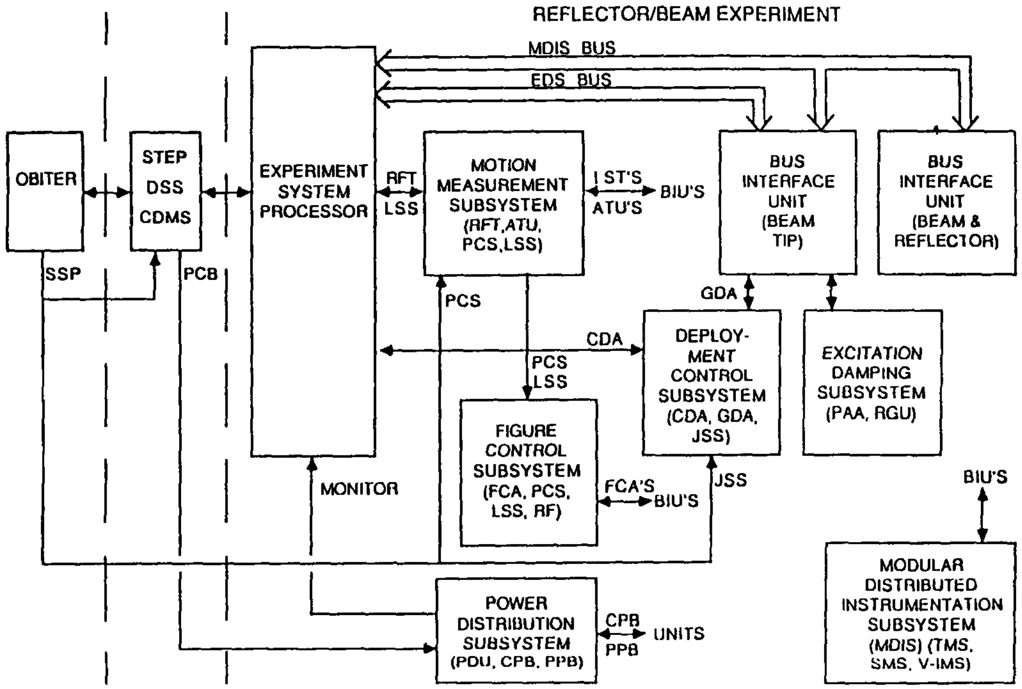


Figure 2-37. Experiment Major Avionics Subsystems and Subsystem Elements

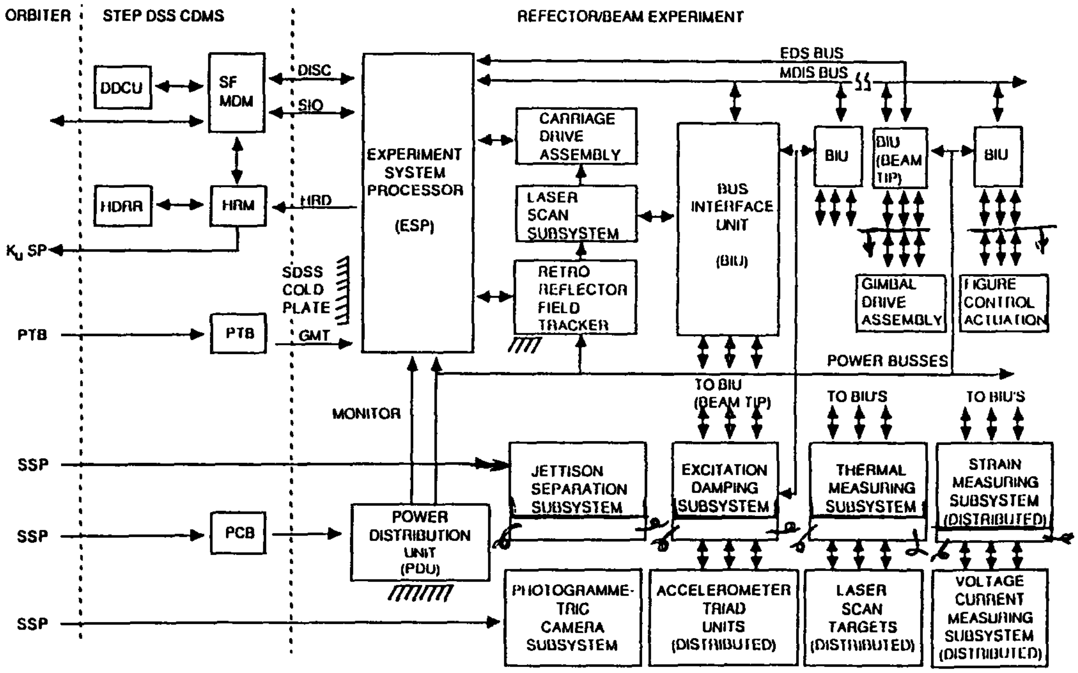


Figure 2-38. Experiment and STEP DSS CDMS/Orbiter Interfaces

Table 2-20. Motion Measurement System Avionics

ATU - Accelerometer Triad Unit; triad of accelerometers; located at reflector tip, 2 units at reflector edges, beam tip, 3 units distributed along beam, 7 units total; analog outputs to nearest BIU; could be applied to real time control.

RFT - Retro-reflector Field Tracker; star field sensor based optical system with a base mounted Main Electronics Box (MEB) and Sensor Head (SH) and 8 beam mounted reflective Scotch type Laser Targets (LT); data, control, and monitor interfaces to ESP; after flight data analysis; for beam measurements.

PCS - Photogrammetric Camera Subsystem; multiple cameras in gas cans mounted on RMS; simultaneous stereoscopic film imaging of photo targets; after flight data analysis; for reflector measurements.

LSS - Laser Scan Subsystem; a low cost experimental displacement measurement system for both beam and reflector measurements; real time data available, could be applied to an active control system, could replace both the RFT and PCS in subsequent structural control tests; one Laser Scan Assembly (LSA) at the reflector center; two LSA's at the base, one x-axis, one y-axis; 20 Laser Scan Targets (LST) on the reflector, 16 LST's on the beam.

Table 2-21. Modular Distributed Instrumentation Subsystem Avionics

MDIS Bus - Serial 1 MBPS bus using modified protocol 1553B for all data collection other than EDS and MMS data; interfaces BIU's and ESP.

TMS - Thermal Measuring Subsystem; a mix of thermistor and PRT temperature sensors; thermistors, 1 in each BIU (7), RGU (1), GDA 1), PAA 1 per wheel and 1 electronics (4), RFT (1), ESP (1), PDU (1), CDA 1 per DDA (3), total 19; PRT, 12 on the reflector, 14 in two locations on beam, total 26; all PRT's interface to a nearby BIU; most thermistors interface to a BIU.

SMS - Strain Measuring Subsystem; a set of structural strain gauges (SG) located as 4 at each ATU location (28), 2 on 3 structural elements at 2 beam locations (12), total 40; all SG's interface with a nearby BIU.

V-IMS - Voltage/Current Measuring Subsystem; measures all critical power supplies voltages and currents, actuation drive currents, and prime power voltages and currents; interfaces thru BIU's.

ESP - Shared 1750A processor and shared memory used for collecting and formatting data, and passing data on to SDSS; shared BIU controller for MDIS Bus Interface.

Table 2-22. Development Control Subsystem Avionics

CDA - Carriage Drive Assembly; consists of 3 Dual Drive Actuators (DDA) driven mechanisms, 3 discrete switch sensors, a carriage absolute position sensor, and a carriage incremental sensor; these all interface directly with the ESP.

GDA - Gimbal Drive Assembly; consists of 1 DDA driven gimbal, 2 discrete switch sensors, and 1 rotary position sensor; these all interface with the beam tip BIU.

JSS - Jettison Separation Subsystem; pyrotechnic devices for jettison of the reflector and beam; this is hardwired from the SDSS for both monitor and activation.

Table 2-23. Figure Control Subsystem Avionics

FCA - Figure Control Actuator; a low power slow micro-inch control actuator at multiple spider locations in the reflector back structure; interfaces directly with the reflector BIU's; includes position sensor inputs to BIU's.

PCS - Used to monitor reflector shape; requires film and computer processing for feedback to FCA.

LSS - A low cost experimental displacement measurement system that can provide real time feedback for FCA.

Table 2-24. Power Distribution Subsystem Avionics

PDU - Power Distribution Unit; 2 buses instead of 3 as in MAST proposal.

CPB - Constant Power Bus

PPB - Pulse Power Bus

Table 2-25. Avionics Hardware Description

Experiment System Processor (ESP) - 1 unit

The ESP is the main processor for the experiment.

In the processor modules, a 1750A processor will be utilized. No co-processor is required at this time, however a spare module slot shall be provided for future insertion of a co-processor. The 1750A processor module shall have on-card cache ROM/RAM.

There will be at least 512K bytes in memory module(s). In addition, a spare memory module(s) slot(s) shall be provided.

Primary Actuator Assembly (PAA) - 1 unit

The PAA consists of three inertia wheels and the associated drive electronics. The wheel size has not been established (either a 90 or a 45 in-lb size).

Dual Drive Actuator (DDA) - 4 units

The redundant dual motor electric actuator is utilized in 4 mechanisms, 3 for the Carriage Drive Assembly and 1 in the Gimbal Drive Assembly.

Rate Gyro Unit (RGU) - 1 unit

This includes a triad of rate integrating gyros and associated analog output circuitry, and a power supply operating off 28 Vdc.

Accelerometer Triad Unit (ATU) - 7 units

As the name implies, this is a triad of Sundstrand QA 2000 class accelerometers.

Retro-Reflector Field Tracker (RFT) - 1 unit

This is a modification of the SAFE Dynamic Augmentation tracker and is available from Ball Brothers.

Photo-grammetric Camera Subsystem (PCS) -

The PCS has not been designed but is expected to consist of at least two cameras, with some means of photo-image synchronization, mounted in gas cans for vacuum operation. The cameras are film type because the available digital imaging type are not yet high enough resolution.

Table 2-25. Avionics Hardware Description (contd)

Laser Scan Subsystem (LSS) - 3 Laser Scan Assembly (LSA) units & 36 Laser Scan Target (LST) units

The LSS is a low cost experimental real time deflection measuring system which would replace the PCS and the RFT in future tests and operating systems. Each LSA would consist of laser diode (2 for redundancy) and the associated circuitry and power supply, and a rotating penta-prism with drive motor and power supply. Power requirements are low. The LST consists of a linear multiple element CCD line scan array integrated circuit sensor, a threshold circuit, a scan clock circuit, and a binary counter circuit for scan element identification.

Bus Interface Unit (BIU) - 5 units

The BIU interfaces with the EDS Bus and the MDIS Bus, both of which are modified 1553B protocol busses. On the actuator command side of the interface, the appropriate BIU provides command signals to the PAA WDE, to the GDA DDA, and to the FCA's.

On the sensor side of the interface, the appropriate BIU interfaces with wheel speed sensing from PAA WDE, RGU rate sensing, ATU acceleration sensing, GDS angular position sensing, FCA's displacement sensing, 26 structural PRT sensors, 13 unit thermistor sensors, 40 structural strain sensors, 36 LST deflection sensors, and various unit voltage-current sensing.

Power Distribution Unit (PDU) - 1 unit

The PDU has the function of filtering and current limiting the SDSS supplied 28 Vdc, and distributing it on two buses, a pulse load bus and a constant load bus, each with filtering. The pulse load bus can accept regenerative power from the PAA. In addition the JSS pyro signals are processed thru the PDU.

Figure Control Actuator (FCA) - 5 units

Each FCA drives a spider node in the reflector support structure for adjustment of the reflector shape. These are low power micro-adjustment actuators using a stepper motor drive. The actuator can be operated open loop where a given number of pulses is a specified incremental displacement. If necessary, a LVDR position sensor could be added for a closed loop position control. The FCA requirements have not been determined. Since it is a static figure control device, bandwidth and dynamic force output are not critical.

Miscellaneous Components -

These include the CDA absolute and incremental position transducers, the CDA travel limit switches, and GDA rotary position transducer, the GDA travel limit switches.

2.3 ANALYSIS PLAN

Verifying reflector/beam truss-structure technology requires an integrated analysis, ground-test, flight-test effort. This section addresses the analysis component of the effort, and describes the primary analyses required to support ground and flight tests along these disciplinary lines: structural dynamics, control dynamics, thermal, and electromagnetic analyses.

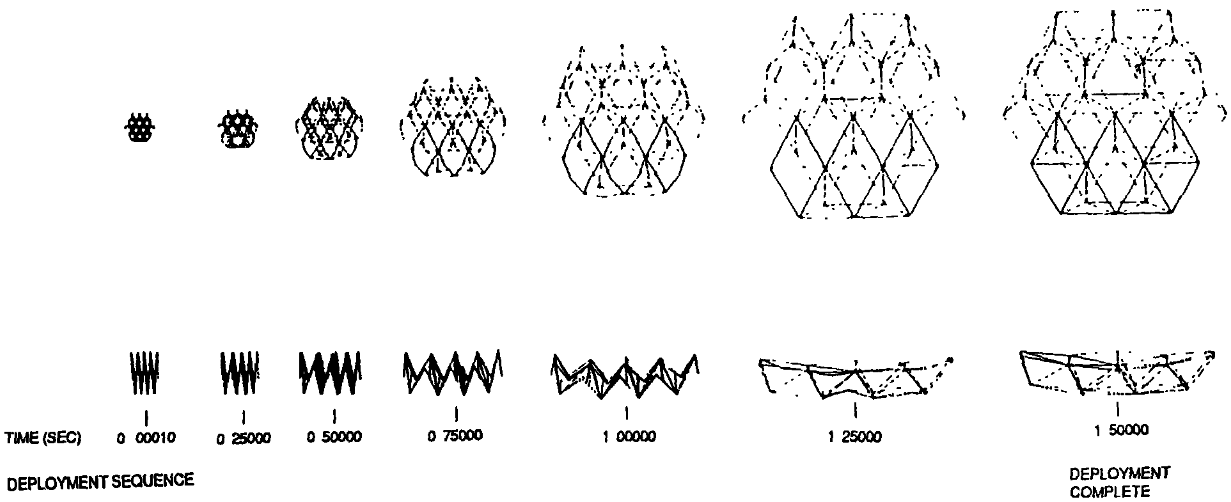
In addition to the disciplinary division of analyses, they can also be divided by objective. For example, one distinguishes among analyses for design development, design validation (or verification), ground-test support, flight-test support, ground and flight operations, post-flight evaluation, safety, and damage tolerance. Design development considers trade studies to finalize system and subsystem design requirements. Design validation considers performance of the flight hardware during all phases of flight, including orbiter ascent, orbiter descent, beam deployment, reflector deployment, reflector jettison, beam retraction, system emergency jettison, vernier RCS maneuvers, and primary RCS maneuvers when partially and fully deployed.

Ground- and flight-test support considers simulating specific tests, correlating simulated and measured ground-test data, and improving analytical models as required. Post-flight evaluation considers reducing flight data, comparing simulated flight responses with actual flight data, improving analytical models as required, and documenting all conclusions. Safety analyses include the effects of premature extension, premature jettison, structural failure, orbiter digital autopilot interactions, support structure safety, beam deployer/repacker function, hazards, and control and power reliability. Damage tolerance analysis includes the effects of debris collision, meteoroid collision, remote manipulator system collision, inadvertent vernier or primary RCS operation during deployments, and EVA.

2.3.1 STRUCTURAL DYNAMICS ANALYSIS PLAN. There are two basic requirements of structural dynamics analyses: the capability to analytically predict in- flight deployment sequence and loads; and the capability to analytically predict the in-flight dynamic characteristics, including natural frequencies, mode shapes, and damping. The accuracy and the number of accurate modes required depends on the overall stiffness requirements and on mission and control system requirements.

Refinement and validation of existing techniques to predict deployment sequences and loads is needed to ensure accurate deployment modeling and accurate dynamic simulation.
Existing deployment dynamics methods, both procedures and computer codes (e.g., Figure 2-39), are validated. The validation approach begins by modeling the deployment mechanisms of

the reflector and of the beam. Using the models, the ground deployment of the reflector and the beam are simulated, both separately and as parts of the assembled flight article. The simulated ground deployment sequences and loads are compared to ground-test results and model improvements are made as required. Then, as part of the pre-flight analyses, on-orbit deployment sequences and loads are simulated. Finally, as part of the post-flight evaluation, actual flight data are correlated with the pre-flight analyses.



- SNAP computes both the kinematics of deployment, and the elastic response of the structure.
- The deployment sequence is propagated through hinge lock-up and continued until dynamic axial loads are dissipated.
- SNAP-computed deployment times and dynamic loads compare well to measured data.

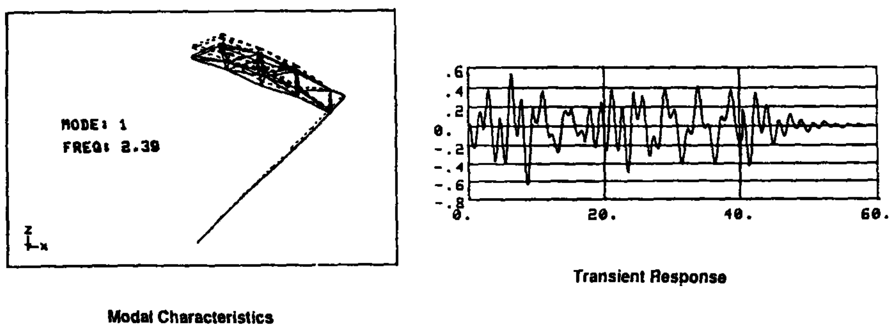
Figure 2-39. Structural Dynamics Analysis of Free Deployment Using SNAP

Technology issues associated with predicting structural dynamic characteristics are:
- Accurate structural dynamic modeling of complex truss structures with many joints.
- Structural dynamic model validation from individual substructure ground tests.
- Passive damping modeling and prediction.
- Model improvement based on substructure ground-test data to the accuracy required by control dynamics.

The following analysis objectives address these issues:
- Validate dynamics analysis modeling methods (finite-element modeling) for complex many-jointed truss structures with possibly discrete damping treatments

• Validate methods for improving structural dynamic models from substructure full-scale ground tests
• Validate the accuracy of analytical substructure synthesis methods (e.g., component modal synthesis) when individual substructure models are verified by substructure ground tests.
• Provide analysis support for structural design and control system design, specifically structural dynamic loads and characteristics.

The associated analysis approach (Figure 2-40) begins by modeling and computing the dynamic characteristics of suspended major structural components (reflector and beam) as well as the fully assembled structure. A full set of ground tests on the separate substructures provides test data for improving the substructure models. The substructure models are then analytically synthesized to form an assembled system model and correlate the dynamic characteristics of the assembled model with ground test data for the assembled article. The on-orbit dynamic characteristics of partially (after beam but before reflector deployment) and fully deployed configurations are computed from the analytical models. The on-orbit response for each structural dynamic flight-test case is simulated before flight and correlated with flight-test data after the flight. Structural models are then adjusted as indicated by the flight test data.



• Linear analysis of truss structure is standard.
• Must also do nonlinear static and dynamic analyses to include effects of joint free-play.

Figure 2-40. Structural Dynamics Analysis of Deployed Structure

2.3.2 CONTROLS ANALYSIS PLAN. The requirements of control dynamics analyses are: the capability to analytically predict closed-loop pointing performance (stability and accuracy) to the level required for future NASA space-antenna missions; the capability to predict control-structure interaction and its adverse effects, including vibration suppression techniques and control system robustness; and the capability to analytically predict reflector surface errors and to reduce the errors to the level required using an active adjustment system.

Technology issues associated with controls are:

- Verified accurate structural dynamic analytical models
- Control-structure interaction: the level depends on controller requirements
- Stability and performance robustness of controllers to modeling errors and uncertainties
- Figure measurement and actuation concepts and devices
- Ground testing methods for design verification, specifically the hybrid test approach
- Fault tolerance

The following analysis objectives address these technology issues:

- Validate controller design methodology, including system modeling and model order reduction
- Validate the hybrid test approach for on-ground design verification
- Validate figure adjustment methodology, including the ability to measure figure errors (figure sensing) and actuation concepts (figure actuation) for reducing surface errors
- Provide analysis support for design and safety reviews

The associated analysis approach (Figure 2-41) begins by developing the following controls models for simulations of the system on-orbit: deployed beam dynamic model, deployed reflector/beam system dynamic model, and reflector and mesh actuator influence model. Forming the models requires coupling with structural and thermal analyses and with ground tests, including vibration suppression and figure adjustment ground tests. Then, ground-test analyses are performed simulating the ground-test support conditions and configurations. A full set of tests and analyses considers excitation and damping subsystem tests, reflector figure distortion tests, and reflector figure adjustment tests.

Finally, flight-test analyses associated with on- orbit controls experiments are performed. This includes analysis of the vibration suppression system and prediction of damping levels, analysis and prediction of closed-loop stability robustness, and analysis and prediction of closed-loop antenna performance under all orbital conditions.

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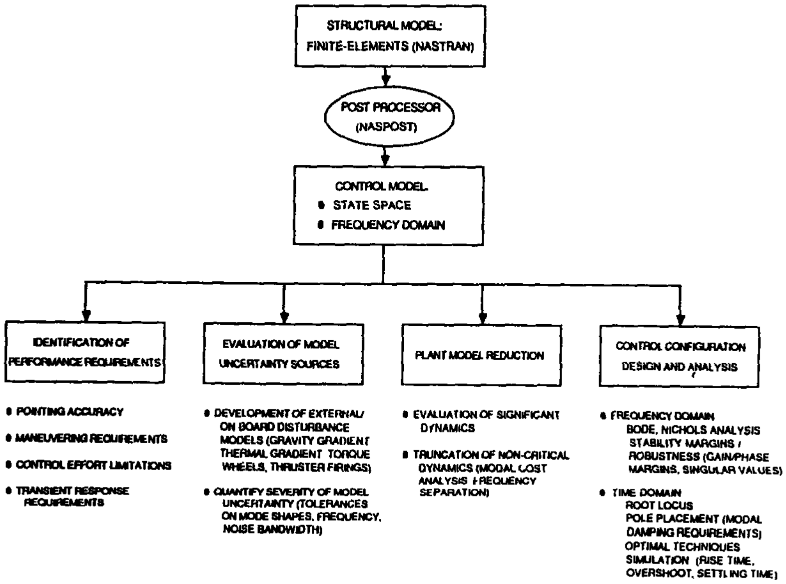
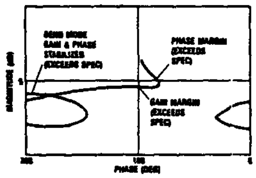
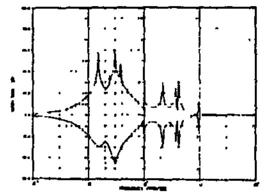


- ALL CONTROL DESIGNS MUST ACCOUNT FOR UNCERTAINTY IN THE FLIGHT VEHICLE MODEL
  THESE UNCERTAINTIES INCLUDE UNKNOWN OR POORLY MODELED STRUCTURAL PROPERTIES, HARDWARE NOISE AND NONLINEARITIES, AND UNCERTAIN ENVIRONMENTAL INFLUENCES
- ACTIVE FEEDBACK CONTROL IS USED TO CONTINUALLY CHANGE THE CONTROL ACTION UNTIL SYSTEM PERFORMANCE REQUIREMENTS ARE MET, DESPITE UNCERTAINTIES
- MOST CONTROL DESIGNS FOR FLIGHT VEHICLE APPLICATIONS MAKE USE OF STANDARD ANALYSIS TECHNIQUES
  FREQUENCY DOMAIN TECHNIQUES: PERFORMANCE MUST BE MET OVER THE FREQUENCY RANGE OF INTEREST

OPEN-LOOP NICHOLS PLOT



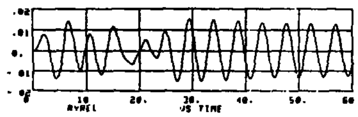
MAX/MIN SINGULAR VALUES



TIME DOMAIN TECHNIQUES: PERFORMANCE MUST BE MET OVER THE TIME RANGE OF INTEREST

TRANSIENT SIMULATION

OPEN-LOOP



CLOSED-LOOP

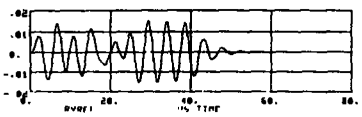


Figure 2-41. Control Dynamics Analysis Methodology

2.3.3 THERMAL ANALYSIS PLAN

2.3.3.1 Thermal Analyses Issues and Objective. On-orbit deployable truss reflector/beam performance is sensitive to small thermal distortions. Accurate simulation of transient temperature response to the changing thermal environment is therefore required. However, thermal modeling and analysis of this complex truss structure is difficult. Use of ground and flight test data is required to develop and validate analytical predictions.

The overall thermal analysis objective is to correlate analytical predictions with measured temperatures and distortions, thereby validating analysis methods for operational thermal conditions. The thermal analysis will also support thermal design of large deployable truss structures to satisfy operational distortion requirements.

2.3.3.2 Overall Thermal Analysis Approach. The first step in the overall thermal analysis is to develop a thermal model of the structure. To adequately simulate the thermal transients and shadowing for these sparse structural systems, the models typically are very complex.

The second step is to perform a pre-ground test analysis simulating ground test environmental conditions. Ground thermal tests are then conducted in a solar vacuum chamber. In these tests temperatures at selected locations on the structure are measured, and photogrammetric measurements establish the corresponding structural distortion. The thermal analysis is then rerun with measured chamber boundary temperatures. Structural member temperatures and length changes are predicted. At the temperature sensor locations, detailed member peripheral temperature distributions are predicted. These predicted structure temperatures are correlated with measured temperatures, the model is adjusted and the analysis is rerun. Resulting analytically predicted member length changes are then used as input to a separate distortion analyses for eventual correlation with measured distortion.

The third major step is to perform pre-flight test analysis simulating on-orbit flight test environmental conditions. On-orbit testing is then performed.with Shuttle attitude, orbit and Earth eclipse times selected to give desired space-environmental heating conditions. Temperatures at selected locations on the structure are measured and corresponding distortions measured by photogrammetry. A post-flight test thermal analysis is then performed using actual flight experiment thermal/environmental conditions. Predicted structure temperatures are correlated with measured temperatures and the thermal model is adjusted and rerun if required. Analytically predicted individual member length changes are input to a distortion analysis for eventual correlation with measured distortion data..

2.3.3.3 Individual Member Thermal Analysis Methodology. Folding and non-folding truss members, and the mesh reflector surface elements for the deployable truss reflector/beam are individually modeled. A folding member may require up to 13 thermal model sections of uniform thermal characteristics, as shown in Figure 2-42. Temperatures are computed for each of the sections including conductive coupling between sections. Member length change is determined by computing the average temperature change from a reference temperature for each section and employing the coefficient of thermal expansion (CTE) for that section. Total member length change is then computed as the sum of the length changes for the individual sections.based on the above modeling.

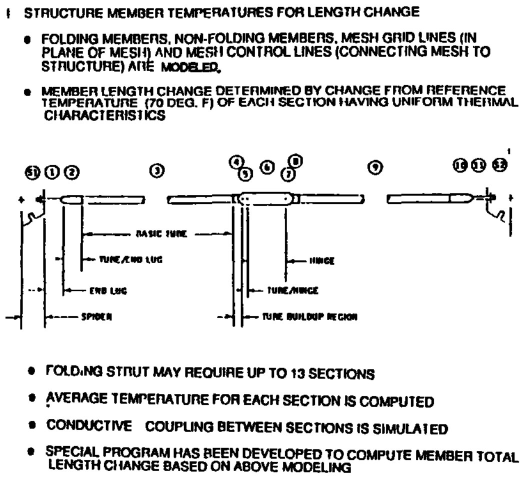
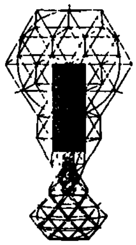


Figure 2-42. Folding Member Thermal Modeling

2.3.3.4 Opaque Solar Shadowing on Modeled Members. An example of spacecraft solar shadowing on modeled members is shown in Figure 2-43. Solar shadowers may include the Shuttle or spacecraft, other truss members, or node fittings used to interconnect ends of the members. Each truss and mesh reflector structural element is sub-divided into 1000 lengthwise divisions for computation of full or no shadowing on each 1/1000 sub-element. Shadowed and non-shadowed sub-elements within each thermally uniform section are counted and space heating incident to that section is reduced by the ratio of shadowed to total sub-elements.

II. OPAQUE SOLAR SHADOWING ON MODELED MEMBERS



EXAMPLE. SPACECRAFT SOLAR SHADOWING ON MODELED REFLECTORS

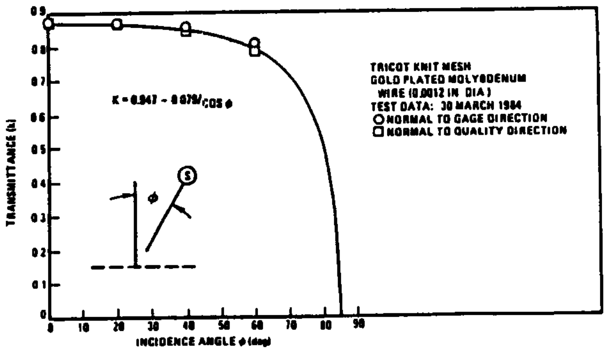
- SOLAR SHADOWERS MAY INCLUDE:

  SHUTTLE OR SPACEACRAFT
  OTHER STRUCTURAL MEMBERS
  STRUCTURE AT ENDS OF MEMBERS (SPIDERS)

- EACH MEMBER/MESH LINE SECTION IS SUB-DIVIDED INTO 1,000 LENGTHWISE DIVISIONS FOR COMPUTATION OF FULL OR NO SHADOWING ON EACH 1/1,000 SUB-ELEMENT
- SHADOWED AND NON-SHADOWED SUB-ELEMENTS WITHIN EACH THERMALLY UNIFORM SECTION ARE COUNTED TO DETERMINE HEATING REDUCTION FACTOR FOR THAT ELEMENT

Figure 2-43. Solar Shadowing on Reflector Members

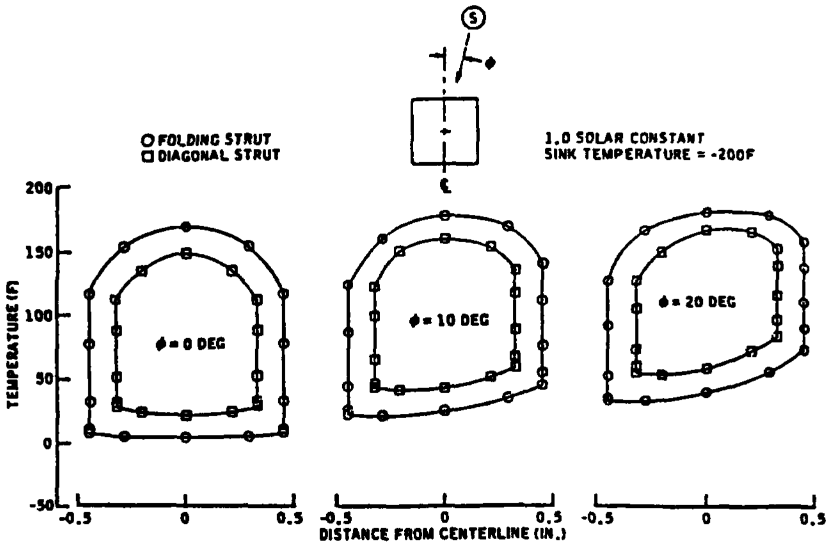
2.3.3.5 Semi-Transparent Mesh Shadowing. The mesh acts as an angle-dependent shadower of solar, albedo and Earth thermal heating. Typical transmittance (transparency) of the mesh as a function of incidence angle is shown in Figure 2-44. The mesh becomes opaque at shallow angles. Solar transmittance vs. incidence angle is measured using solar cell output voltage as an indicator of percent of energy passing through the mesh. A transmittance equation (shown in Figure 2-44) is developed from the measured data and is used in the thermal analysis. At certain attitudes solar heating can pass through the mesh twice before reaching reflector/beam structure, and this condition is simulated in the analysis as it occurs.



- MESH SOLAR TRANSMITTANCE VS. INCIDENCE ANGLE IS MEASURED
- TRANSMITTANCE EQUATION IS DEVELOPED FROM MEASURED DATA
- MESH SHADOWING IS SIMULATED FOR SOLAR, EARTH THERMAL AND ALBEDO HEATING
- SINGLE AND DOUBLE MESH SHADOWING ARE SIMULATED AS APPROPRIATE
- MESH BECOMES OPAQUE AT SHALLOW ANGLES

Figure 2-44. Mesh Semi-Transparent Shadowing is Angle-Dependent

2.3.3.6 Detailed Modeling in the Area of Temperature Sensors. Thermal analysis methods described above predict member cross-section average temperature but do not consider the temperature spread around the cross-section periphery. Typical cross-section temperature distributions are shown in Figure 2-45 for folding and non-folding (diagonal) members. Since peripheral temperature variation can exceed 75C, it is clear that peripheral modeling is required for local temperature prediction at sensor locations. Internal radiation is included because of the low conductivity in the peripheral direction. Sun angle with respect to a cross-section flat is seen in Figure 2-45 to have the effect of skewing the temperature distribution, and is therefore included in the analysis.



- MEMBER CROSS-SECTION PERIPHERAL MODELING IS REQUIRED FOR LOCAL TEMPERATURE PREDICTION AT SENSOR LOCATIONS (LOCAL TEMPERATURE = AVERAGE ± 75 DEG. F)
- INTERNAL RADIATION IS INCLUDED BECAUSE OF LOW CONDUCTIVITY IN PERIPHERAL DIRECTION
- SUN ANGLE WITH SURFACE NORMAL MUST BE CONSIDERED

Figure 2-45. Detailed Temperature Prediction at Sensor Locations

2.3.3.7 Thermal Analysis Capability. The thermal analysis tools/programs described above are all developed and operational. A transient distortion analysis of complex orbiting structures, including more than 300 structural truss members and 4100 reflector mesh elements, has been conducted. Modeled structural member thermal characteristics include cross-section geometry, material thermophysical properties, wall thickness and coefficient of thermal expansion. Any number of discrete time intervals throughout the orbit may be selected for temperature distributions predictions. With this approach, all significant changes in transient heating throughout the orbit are simulated for each member. The key to operational use of these analysis tools is a comprehensive validation and correlation with flight experiment test results.

2.3.4 ELECTROMAGNETIC (RF) ANALYSIS. A communication or radar antenna is generally required to provide a specified level of RF performance in the space environment throughout its design life. The antenna is manufactured and adjusted to near ideal dimensions and tested under controlled laboratory conditions to demonstrate performance compliance. On orbit, the antenna reflector is subjected to continuous variations in temperature distribution due to diurnal change in sun angle. Parts of the reflector will also be shadowed by the spacecraft or the reflector itself. In this varying orbital thermal environment the reflector surface will distort from the ideal shape. On-orbit dynamic disturbances will also affect RF performance characteristics through surface distortion and alignment errors. Due to these distortions, the antenna RF performance can vary significantly from the ideal.

The purpose of the electromagnetic analysis is to predict the on-orbit RF performance of the experiment reflector when subjected to the ground-test and flight-test environments. This includes the calculation of performance degradation due to predicted thermal distortion and alignment errors for correlation with measured test results. Figure 2-46 shows the process required to achieve an

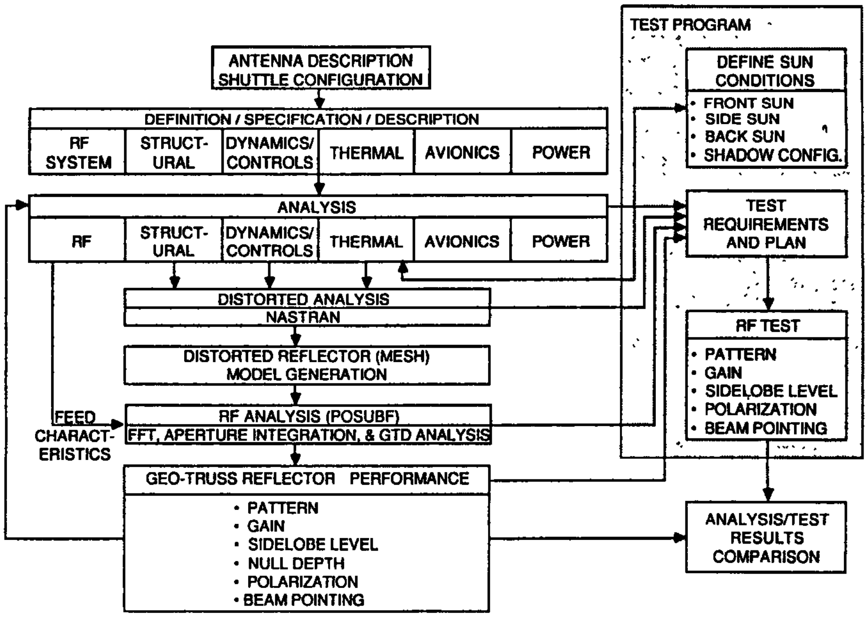


Figure 2-46. Electromagnetic Analysis Flow

accurate prediction of the reflector performance when subjected to a non-ideal test. The key to the prediction process is the computation of thermal and dynamic distortions of the reflector surface. A computer code called MESH has been developed to compute the shape of the distorted reflector surface when subjected to thermal and loading disturbances. The distorted surface data from MESH is input to a program called POSUBF, which is a physical optics electromagnetic analysis program used to analyze the gain and pattern performance of the antenna. A hierarchy chart for POSUBF, which uses FFT, aperture integration and GTD analyses, is shown in Figure 2-47.

Features of the program include:

• Arbitrary rim shapes may be analyzed, including the GEOTRUSS hexagonal configuration.

• Applied Kirchoff-Huygens-Silver integral using the induced-current method (positioned and oriented).

• Accuracy is determined by the physical optics integration and number of analytic facets used to approximate the reflector surface.

• The MESH program is used to provide node and connectivity data for the distorted reflector to the POSUBF program.

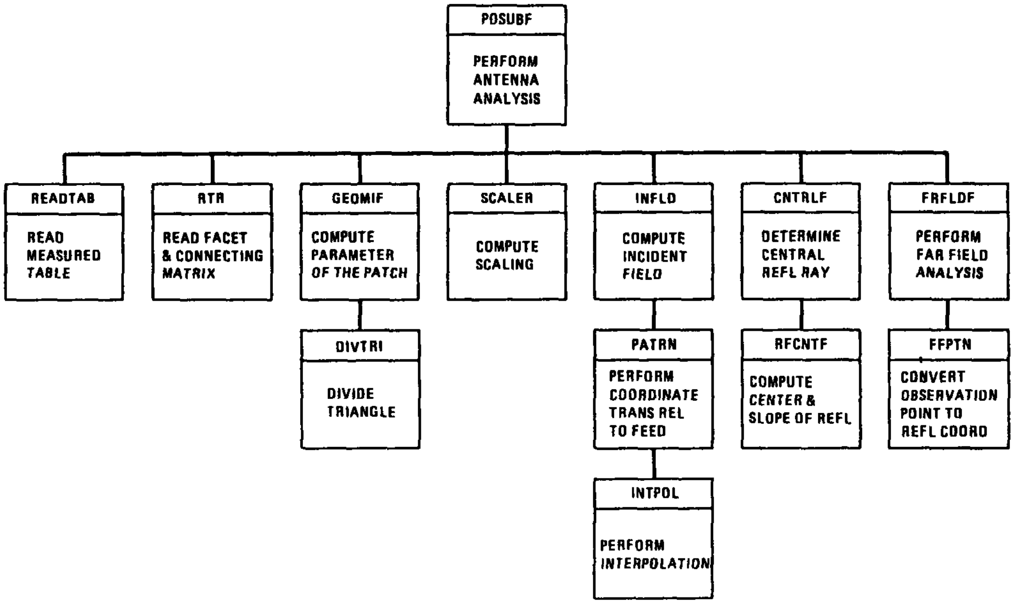


Figure 2-47. Hierarchy Chart for POSUBF

Other computer codes that may be used include an FFT program and an aperture integration/geometric theory of diffraction (GTD) program, both of which may be used to provide a quick, low-cost analysis of an ideal reflector using analytic or measured feed pattern data. A key feature of the aperture integration/GTD program is the capability of calculating a complete 360 degree pattern for a general rim shape.

Output of the electromagnetic analysis include predicted pattern, gain, sidelobe level, null depth, polarization and beam pointing performance of the reflector when subjected to the test environments. These predictions are compared to measured test results for validation of the analysis methods.

2.4 TEST PLAN

The integrated test plan for the Deployable Truss Advanced Technology Program defines all testing to be performed during the design, development, fabrication, and flight testing of the 5-meter and 15-meter reflector beam test articles. Tests include development, qualification, acceptance, ground experiments and flight experiments for both reflector/beam test articles. The test plan also provides for verification of the initial technical risk assessment of the ability of each hardware element and system to accomplish the required performance goals.

The overall objective of the test program is to provide NASA with a comprehensive series of ground and flight tests designed to answer development and operational issues for the deployable truss advanced technologies and to validate analytical methods and ground-test approaches proposed for future large deployable truss structures.

The program encompasses all levels of testing to be performed on the test articles and uses MIL-STD-1540B, Test Requirements for Space Vehicles, as a guide to define the test program. In that context, most testing is considered to be developmental in nature. However, specific test requirements relating to Shuttle integration and Shuttle flight safety issues will be at the qualification testing level. The test plan is divided into Ground Testing, discussed in Section 2.4.1, and Flight Testing, discussed in Section 2.4.2.

2.4.1 GROUND TESTING. The ground-test program is divided into four elements: development tests, acceptance tests, qualification tests, and ground experiments. The test program flow is shown in Figure 2-48.

2.4.1.1. Development Tests. Development testing is intended to answer specific design concerns during the initial design and early hardware development stages. As such, they are typically performed at the component and subsystem level. A summary of the development test matrix is shown in Figure 2-49.

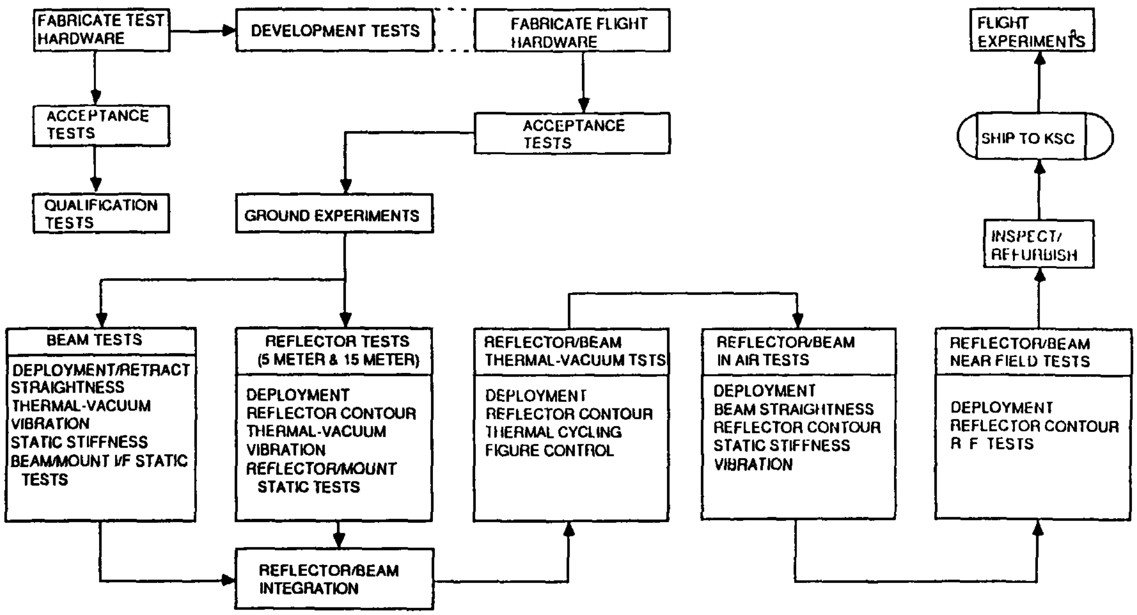


Figure 2-48. Ground Test Program Flow

2.4.1.2. Qualification Tests. The qualification test program is intended to qualify components and subsystems for flight in the STS orbiter cargo bay. These tests require quality assurance and DCAS suveillance along with documentation of compliance with the system requirements. The qualification test matrix is shown in Figure 2-50.

TEST ARTICLE OR SYSTEM \ TEST ACTIVITY	BREADBOARD	STRUCTURAL	FUNCTIONAL	THERMAL-VACUUM.	VIBRATION	THERMAL CYC.	
REFLECTOR (5 AND 15 M.)							
- STRUTS		X				X	
- SPIDERS (*)		X				X	
- MESH (*)						X	
- DEPLOYMENT MECH. (*)			X	X	X		
- VIBRATION ACTUATORS (*)			X	X	X	X	
- VIBRATION SENSORS (*)			X		X	X	
- FIGURE ACTUATORS (*)	X		X	X		X	
- FIGURE SENSORS (*)	X		X	X		X	
- TEMPERATURE SENSORS (*)			X		X	X	
BEAM							
- STRUTS		X			X	X	
- JOINT FITTINGS		X	X	X	X	X	
- DEPLOYMENT MECH.	X		X		X	X	
- JETTISON MECH.	X		X		X	X	
- VIBRATION ACTUATORS			X				
- VIBRATION SENSORS			X		X		
REFLECTOR/BEAM							
SDSS I/F HARDWARE	X		X		X	X	
SYSTEM GIMBAL MECH.			X	X	X	X	
R. F. SYSTEM			X	X	X		
PHOTOGRAMMETRY SYS.			X	X	X	X	
P/L BAY SUPPORT STRUCTURE		X	X		X		
DATA RECORDERS			X		X	X	

NOTE: X - PERFORM TEST
NOTE: (*) 5 AND 15 METER ANTENNA COMMON ITEMS TO BE TESTED ONCE

Figure 2-49. Development Test Matrix

TEST ARTICLE OR SYSTEM \ TEST ACTIVITY	ACOUSTIC	VIBRATION	THERMAL CYCLING	THERMAL VACUUM	FUNCTIONAL	E.M.C. TESTS	STRUCTURAL
REFLECTOR (5 AND 15 M.)	X	X			X		
- STRUTS (1)	X	X	X				X
- SPIDERS (1)	X	X	X	X	X		X
- MESH (1)			X		X		
- DEPLOYMENT MECH. (1)							
- VIBRATION ACTUATORS (1)	X		X	X	X	X	
- VIBRATION SENSORS	*		*	*	*	*	
- FIGURE ACTUATORS (1)	X	X	X	X	X	X	
- FIGURE SENSORS (1)	X	X	X	X	X	X	
- TEMPERATURE SENSORS	*	*	*	*	*	*	
BEAM	X						
- STRUTS	X	X	X	X	X	X	
- JOINT FITTINGS	X	X			X		
- DEPLOYMENT MECH.	X	X	X	X	X	X	
- JETTISON MECH.	X	X	X	X	X	X	
- VIBRATION ACTUATORS	X	X	X	X	X	X	
- VIBRATION SENSORS	*	*	*	*	*	*	
REFLECTOR/BEAM							
SDSS I/F HARDWARE	X	X	X		X	X	X
SYSTEM GIMBAL MECH.	*	*	*	*	*	*	
R. F. SYSTEM	X	X	X	X	X	X	X
PHOTOGRAMMETRY SYS.	X	X	X		X	X	
P/L BAY SUPPORT STRUCTURE	X	X	X	X	X		X
DATA RECORDERS	*	*	*	*	*	*	

(*) ASSUMES USE OF QUAL. COMP. OR SUBSYSTEMS
NOTE: X - PERFORM TEST
NOTE: (1) - 5 AND 15 METER COMMON ITEMS TO BE QUALIFIED ONCE

Figure 2-50. Qualification Test Matrix

2.4.1.3 Acceptance Tests. This category covers those tests performed on production hardware to prove compliance with the manufacturing specifications. They include both functional and environmental tests and require quality assurance and DCAS surveillance. The acceptance test matrix is shown in Figure 2-51.

TEST ARTICLE OR SYSTEM \ TEST ACTIVITY	PROOF LOAD	THERMAL CYCLE	FUNCTIONAL	THERMAL/ VACUUM	FLT. LEVEL VIB. & ACOU.	
REFLECTOR (5 AND 15 M.)		X			X	
- STRUTS	X					
- SPIDERS	X					
- MESH						
- DEPLOYMENT MECH.			X		X	
- VIBRATION ACTUATORS		X	X		X	
- VIBRATION SENSORS		X	X		X	
- FIGURE ACTUATORS		X	X		X	
- FIGURE SENSORS		X	X		X	
- TEMPERATURE SENSORS		X	X		X	
BEAM	X	X				
- STRUTS	X					
- JOINT FITTINGS	X		X			
- DEPLOYMENT MECH.		X	X	X	X	
- JETTISON MECH.		X	X	X	X	
- VIBRATION ACTUATORS		X		X	X	
- VIBRATION SENSORS		X		X	X	
REFLECTOR/BEAM					X	
SDSS I/F HARDWARE			X	X		
SYSTEM GIMBAL MECH.		X	X	X	X	
R. F. SYSTEM		X	X	X	X	
PHOTOGRAMMETRY SYS.		X	X	X	X	
P/L BAY SUPPORT STRUCTURE	X	X			X	
DATA RECORDERS			X		X	

NOTE: X - PERFORM TEST

Figure 2-51. Acceptance Test Matrix

2.4.1.4. Ground Experiments. Ground experiments are performed at the system level and are redesigned to validate analysis methods and demonstrate key flight experiment parameters. The ground experiment test program includes deployment testing,thermal testing, dynamic/control testing and near-field RF testing. The ground experiments are defined in Figure 2-52. The matrix of hardware and system elements involved in the ground experiment test program is shown in Figure 2-53.

TEST ARTICLE OR SYSTEM \ TEST ACTIVITY	THERMAL-VACUUM SUB-SYSTEM TSTS.	VIBRATION	ZERO-G DEPLOY	REFLEC. CONTOUR	REFLEC./MOUNT I/F STATIC TESTS	BEAM STRAIGHT	BEAM STATIC STIFF	BEAM/MOUNT I/F STATIC TESTS	MODAL SURVEY	REFLEC SHAPE TESTS	NEAR FIELD TEST
REFLECTOR (5 AND 15 M.)	X	X	X	X	X			X	X	X	
- STRUTS											
- SPIDERS											
- MESH											
- DEPLOYMENT MECH.	X	X	X								
- VIBRATION ACTUATORS									X		
- VIBRATION SENSORS									X		
- FIGURE ACTUATORS										X	
- FIGURE SENSORS										X	
- TEMPERATURE SENSORS	X										
BEAM	X	X	X			X	X	X	X		
- STRUTS											
- JOINT FITTINGS											
- DEPLOYMENT MECH.	X	X	X								
- JETTISON MECH.		X									
- VIBRATION ACTUATORS									X		
- VIBRATION SENSORS									X		
REFLECTOR/BEAM	X		X	X						X	X
SDSS I/F HARDWARE											
SYSTEM GIMBAL MECH.	X	X									
R. F. SYSTEM	X	X									X
PHOTOGRAMMETRY SYS.	X			X		X				X	
P/L BAY SUPPORT STRUCTURE	X	X									
DATA RECORDERS	X	X									

NOTE. X - PERFORM TEST

Figure 2-52. Ground Experiment Definition

2.4.2. FLIGHT TEST. The objective of the flight test program is to provide a comprehensive series of on-orbit tests designed to demonstrate advanced truss structure technologies and validate analysis and ground test methods and performance prediction capabilities. Specifically, the program addresses deployment, structural dynamics, control and thermal distortion issues. To achieve the flight test objectives, extensive coordination of many flight and flight support elements is required. This coordination effort, which is discussed in detail in Section 2.5, includes: Shuttle orbiter and crew, SPARTAN payload for RF experiments, MCC-Houston, TDRSS and Nascom networks and the experiment POCC.

2.4.2.1 Approach. The flight crew is responsible for execution of experiment and orbiter support during the mission. The majority of experiment activity to be performed by the flight crew can be categorized as:

- Orbiter configuration and support operations
- SPARTAN operations
- Experiment operations

The orbiter will provide various modes of support to the Reflector/Beam experiment. Mission specialists using the RMS will deploy and retrieve the SPARTAN payload for the RF experiments. Once the SPARTAN is deployed, the orbiter will be required to fly in station-keeping modes to establish and maintain a suitable RF test range, and will also provide the pointing and attitude platform for reflector experiments. The pilot and commander will be responsible for orbiter control including SPARTAN proximity maneuvers for range orientation, attitude maneuvers, and pointing control for reflector RF and thermal tests. The orbiter RCS may also be used as a low-frequency excitation source for dynamics experiments.

The SPARTAN free-flyer payload will carry the signal source for the RF experiments. While the SPARTAN can provide a space-based RF test range, operational limitations will require extensive analysis and pre-flight planning. The current SPARTAN configuration does not include a transponder or other means of remote, real-time command capability. Once deployed, all operations and functions (power switching, attitude maneuvers, etc.) are controlled by pre-programmed memory. Events and operations sequences are initiated by timers or onboard sensors (star scanners, sun sensors, etc.).

Because of this, an elaborate program scheme could be required to accomplish the experiment objectives of the flight test program. This dependence on a fixed, inflexible program also increases the flight-test sensitivity to unforseen problems and schedule deviations. If an in-flight anomaly should occur that required real-time analysis or replanning, a block of experiments would probably be eliminated in order to "catch up" with the SPARTAN operating sequence that could not be delayed and that continued to function during the unscheduled delay. To avoid this scenario, the SPARTAN program should be kept as simple as possible, such as operating in an attitude hold mode requiring orbiter maneuvers for pointing or range requirements.Additionally, timelines for experiments should be liberally estimated to avoid test sequence time sensitivity.

An additional concern for SPARTAN capability is battery life. Depending on power requirements, battery life with the standard configuration could be low. Add-on battery kits are available and should be included because of the SPARTAN power operation mode. If the onboard computer senses low battery power output, the SPARTAN "auto-modes" to a low-power configuration where all systems are powered down in an orderly fashion, except for the attitude control package. To avoid "early" termination of SPARTAN support operations, battery loads should be sized with considerable margins.

Real-time operations decisions affecting the STS and flight crew will be controlled by the Houston Mission Control Center (MCC-H). The MCC-H flight control team is responsible for flight crew and SSV safety, and for the execution of the flight to accomplish mission objectives. All mission support operations are coordinated with and controlled by this team. The Houston Payload Officer is the primary interface between the MCC-H and the experiment POCC, and is responsible for ensuring that proper STS support and facilities are provided.

The Reflector/Beam POCC will provide technical support and recommendations to the STS on decisions affecting experiment operations. POCC activities will be accomplished by a team of NASA and contractor scientists, engineers, and management personnel. Specific tasks and responsibilities of the POCC team include:

- Provide the MCC-H Payload Officer with recommendations concerning normal and contingency operations involving the experiment and STEP Pallet.
- Monitor the experiment and STEP operational status and safety-related data during experiment operations.
- Record real-time data and recorder dumps for in-process and post-mission analysis.
- Monitor and verify all crew-initiated experiment operations.
- Authorize continuation and/or provide revisions to experiment sequence execution, or direct termination of the experiment at specified points in the experiment plan.

2.4.2.2 <u>Flight -Test Definition.</u> To ensure completion of essential flight-test objectives, the flight-test plan is designed for flexibility to compensate for unanticipated time deviations from nominal plans, and to allow for the resolution of possible anomalies in experiment operations. A preliminary set of the experiment events and major test block sequences needed to meet the flight test objectives were identified. Preliminary time estimates indicate that four crew work periods of eight hours each will be adequate for experiment flight objectives, as shown in Figures 2-53 and 2-54. Time scales for these figures show hours (even hours numbered), and orbital period. One orbit period represents 90 minutes total with 50 minutes of sunlight and 40 minutes in darkness. Note that the start of each flight day is timed to provide sunlight during critical or "light-required" operations such as deployment operations or thermal effect tests.

Flight test day 1 consists of beam deployment and beam dynamics investigation with the reflector in the stowed configuration. Test objectives for deployment include the evaluation of deployment mechanisms performance, and the structural dynamics of the beam during this process. Once deployed, a series of low- and high-frequency surveys will be performed to provide data for dynamic characterization of the beam.

R/B flight day 2 involves the deployment of the reflector, and the investigation of combined Reflector/Beam dynamic behavior. Deployment objectives include measurement of deployment performance, reflector dynamics, beam behavior, and the resulting surface quality of the deployed reflector. After the reflector has been successfully deployed, dynamic surveys on the combined structure will be performed.

Flight day 3 addresses the RF performance of the reflector. To accomplish this, SPARTAN operations for checkout, deployment, and RF range setup are scheduled before any R/B activity. Once SPARTAN support has been established, a series of experiments on environmental influences on reflector shape and resultant RF performance will be conducted. Various attitude maneuvers will be performed by the orbiter to produce suitable conditions of shade and sun exposure on the reflector surface. Effects of solar exposure on reflector shape and the resulting changes in RF performance will be measured.

Flight day 4 involves the active manipulation of the reflector surface. Both surface contour control and reflector pointing capabilities will be investigated for effects on RF performance and dynamic behavior. Because the reflector is not designed for re-stow, it will be jettisoned at the completion of reflector testing. Following reflector jettison, the beam will then be re-stowed in the orbiter cargo bay at the end of R/B flight day 4.

Since recovery of the SPARTAN will require several orbital maneuvers for rendezvous and RMS grappling, those operations are intended to be performed on subsequent flight days (not shown), after the experiment tests are completed and the beam hardware has been secured in the cargo bay for return.

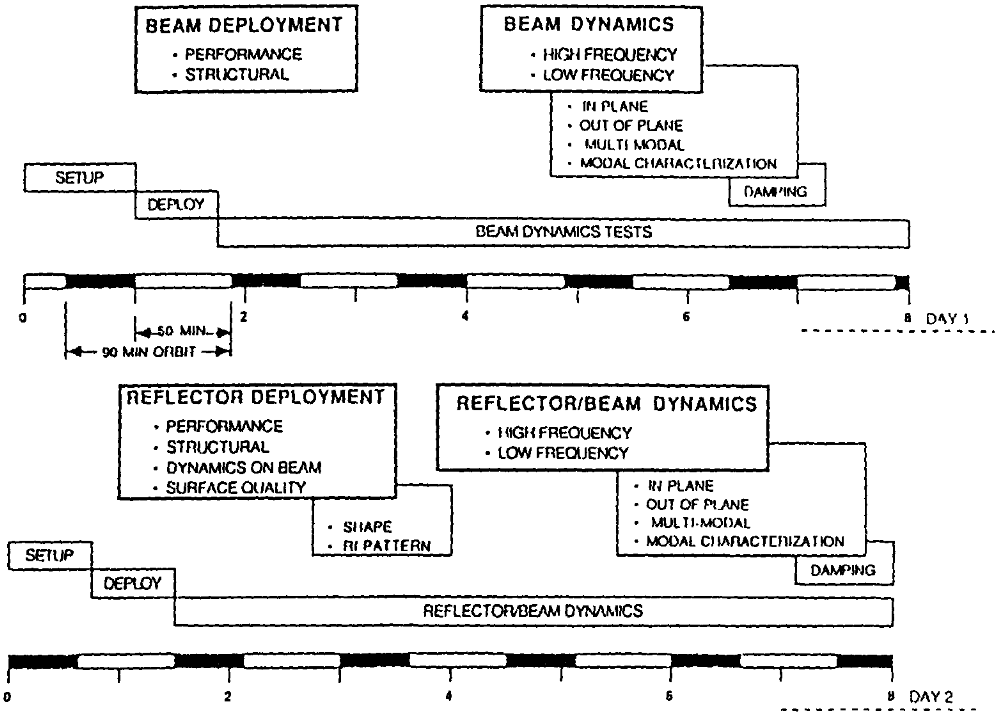


Figure 2-53. Timelines for Flight Days 1 and 2

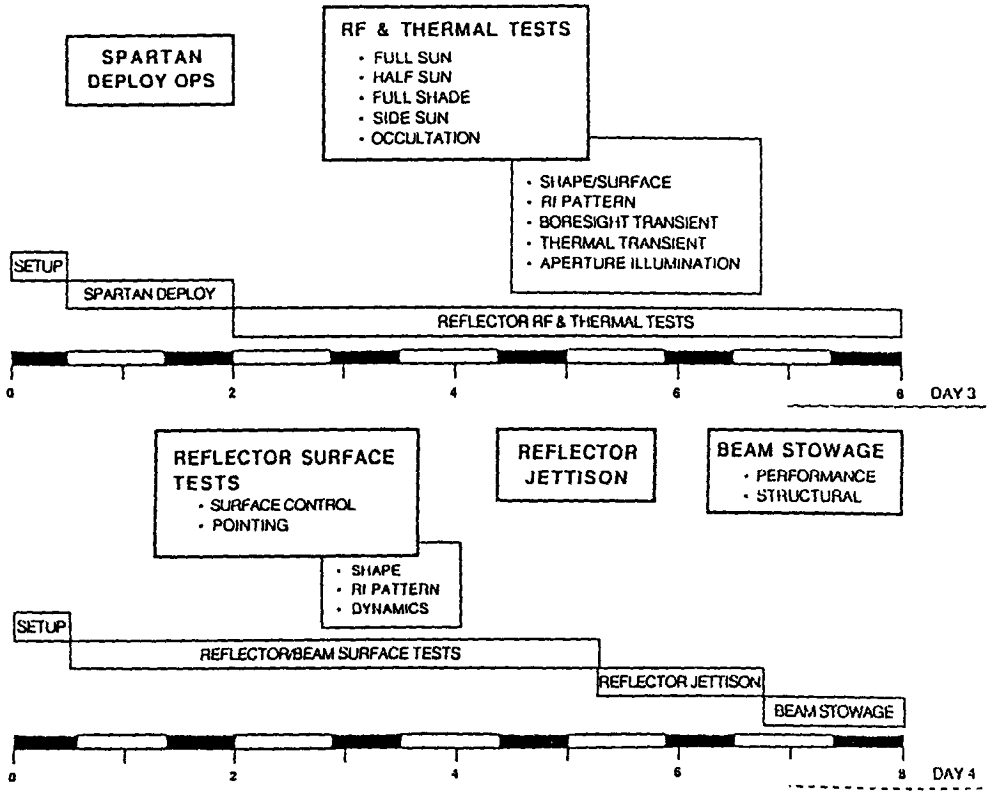


Figure 2-54. Timelines for Flight Days 3 and 4

2.4.2.3 Risk Assessment. Figure 2-55 is a functional flow diagram for the reflector/beam flight experiment. This flow was used to develop the risk assessments summarized in Table 2-26. These risk assessments were developed to drive out the verification requirements that could be reasonably satisfied by test. Other requirements are verified by analysis. These initial risk assessments are based on prior experience with similar hardware and projections of the capabilities of existing hardware. Ultimate traceability of the reflector/beam test program to the system requirements, including performance verification, is shown in Figure 2-56.

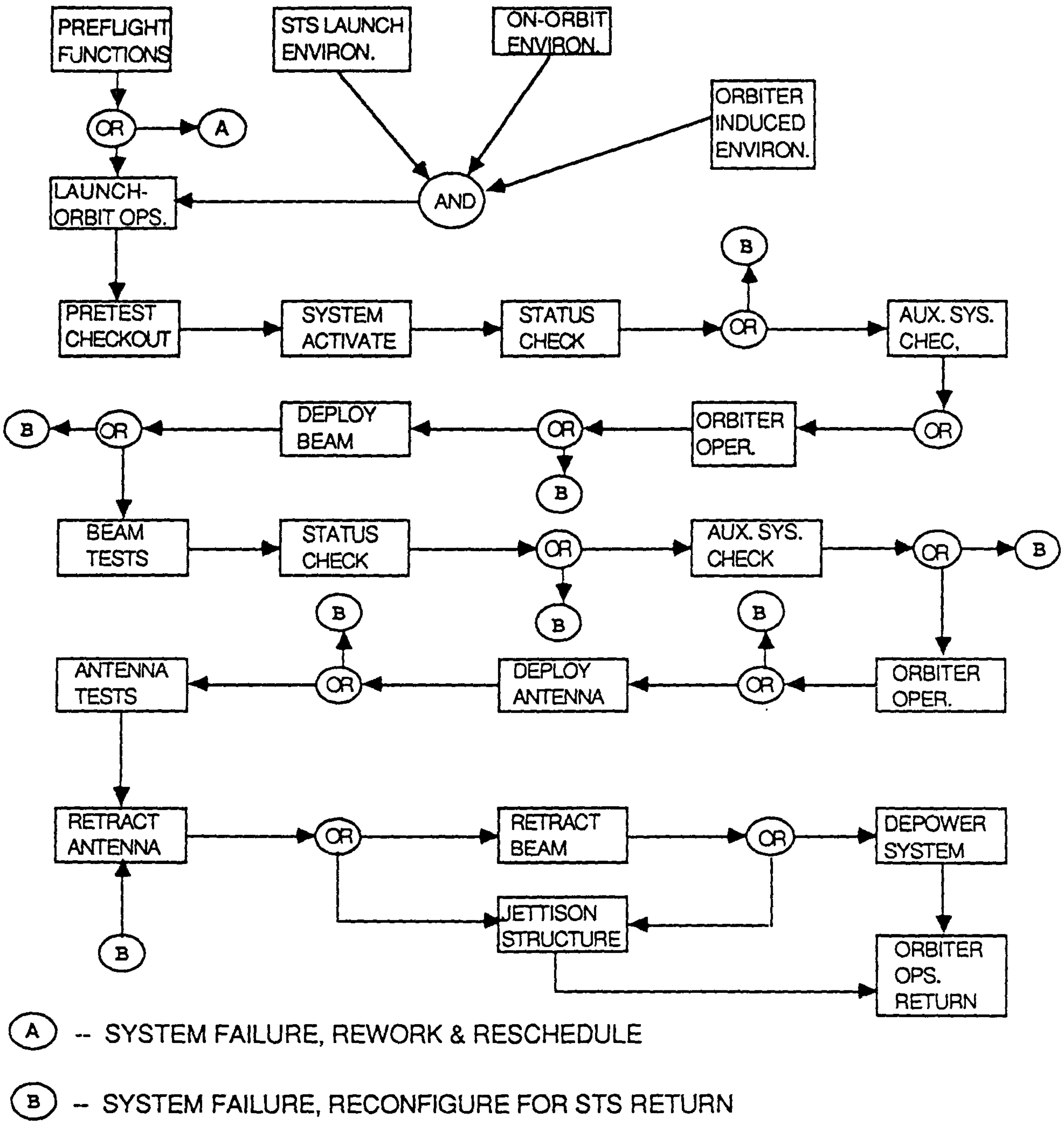


Figure 2-55. Beam/Reflector Flight Experiment Functional Flow

Table 2-26. Preliminary Risk Assessment

CRITICAL FUNCTION	SUBSYSTEM/ COMPONENT	REQUIREMENTS	RISK	VALIDATION METHOD
PREFLIGHT CHECKOUT	EXPERIMENT PACKAGE	SUCCESSFUL CHECKOUT	LOW	DEVELOP., QUAL. TESTS
LAUNCH	EXPERIMENT PACKAGE	SURVIVE LAUNCH ENVIRONMENTS	MEDIUM	DEVELOP., QUAL. TESTS; ANALYSIS
ON-ORBIT CHECKOUT	DEPLOY. & FUNC. COMPONENTS	SUCCESSFUL CHECKOUT	LOW	JSC PRECURSON THERMAL-VACUUM TST
DEPLOY BEAM	DEPLOY. MECH. & BEAM	SUCCESSFUL DEPLOY.	LOW	GROUND TESTS, ANALYSIS
DYNAMIC EXCITATION OF BEAM	EXCITATION MECH. AND SENSORS	ACQUIRE MODAL DATA	LOW	GROUND ZERO-G TESTS, ANALYSIS
THERMAL EXPOSURE OF BEAM	BEAM, SENSORS, PHOTOGRAM. SYSTEM	ACQUIRE PHOTOGRAMMETRIC STRUCT. DEFLEC. DATA	HIGH (*)	PHOTOGRAM. SYS. DEVELOP, GROUND TESTS, ANALYSIS
DEPLOY ANTENNA.	DEPLOY. MECH. & ANTENNA	SUCCESSFUL DEPLOYMENT	MEDIUM	GROUND ZERO-G TESTS ANALYSIS
DYNAMIC EXCIT. OF ANTENNA	EXCITATION MECH. & SENSORS	ACQUIRE MODAL & VIBR. DATA	LOW	GROUND ZERO-G TESTS ANALYSIS
THERMAL EXPOS OF ANTENNA	PHOTOGRAMMETRIC SENSORS & SYSTEM	ACQUIRE PHOTOGRAM-METRIC & THERMAL DATA	HIGH (*)	ANALYSIS, GROUND TESTS
ANTENNA R.F. PERFORMANCE	R.F. SUBSYSTEM & BEAM + ANTENNA	VERIFY ANTENNA R.F. PERFORMANCE	MEDIUM	GROUND TESTS, ANALYSIS
RETRACT ANTENNA & BEAM, OR JETTISON	DEPLOYMENT OR JETTISON MECH.	PERMIT ORBITER TO DE-ORBIT SAFELY (FLIGHT SAFETY ITEM)	MEDIUM	GROUND TESTS, MANNED INTERVENTION BACKUP

(*) HIGH UNCERTAINITY IN ANALYTICALLY PREDICTING THERMAL DISTORTIONS.

2.4.3 <u>POST-FLIGHT EVALUATION.</u> Post-flight evaluation includes correlation of analysis and ground testing with the reduced flight test data, post-flight testing of the returned hardware, and modifying and updating the flight experiments.

2.4.3.1 <u>Analysis and Ground-Test Correlation</u>. The primary post-flight evaluation task is to reduce the extensive deployment dynamics, thermal surface accuracy, shape control and RF flight test data and to correlate it with preflight analysis and ground-test experiment performance predictions. This evaluation is designed to verify the analytical and ground-test techniques used to predict flight behavior and to identify areas where analysis and ground-test methods improvement are needed. The primary test correlation activity is shown in Table 2-27.

2.4.3.2 Post-Flight Testing. Since the reflector is jettisoned at the end of each flight, post-flight testing is directed primarily at the deployable truss beam which is retracted, restowed, and returned after each flight. The truss structure will be inspected for damage, repaired and refurbished as required, and then tested to verify performance. These tests will include functional deployment tests, a dynamic modal survey, and static tests to verify structural integrity. Results will be correlated with similar tests performed prior to each flight to identify any changes in the system.

2.4.3.3 Experiment Update. A major advantage of having two flights is the ability to modify the second flight experiment based on an evaluation of the first flight data. Of particular interest are instrumentation and data acquisition and updated and hard/software changes due to experiment difficulties. To remit these changes within the limited time between flights (19 months), a highly automated data-reduction system is required.

2.5 PAYLOAD INTEGRATION

The payload STS integration and operations support activities occur over many months. Figure 2-57 shows the progression of these activities by major functions. The integration process includes: 1) integration of the experiment; 2) integration of the various payloads into a cargo; 3) integration of the cargo with the STS; and 4) identification and development of ground and flight capabilities required to support the mission. These activities provide an assessment of payload design, assurance of cargo physical and functional compatibility with the space shuttle vehicle (SSV), a definition of requirements for flight design, assurance of feasibility for ground and flight operations support, and preparation for flight.

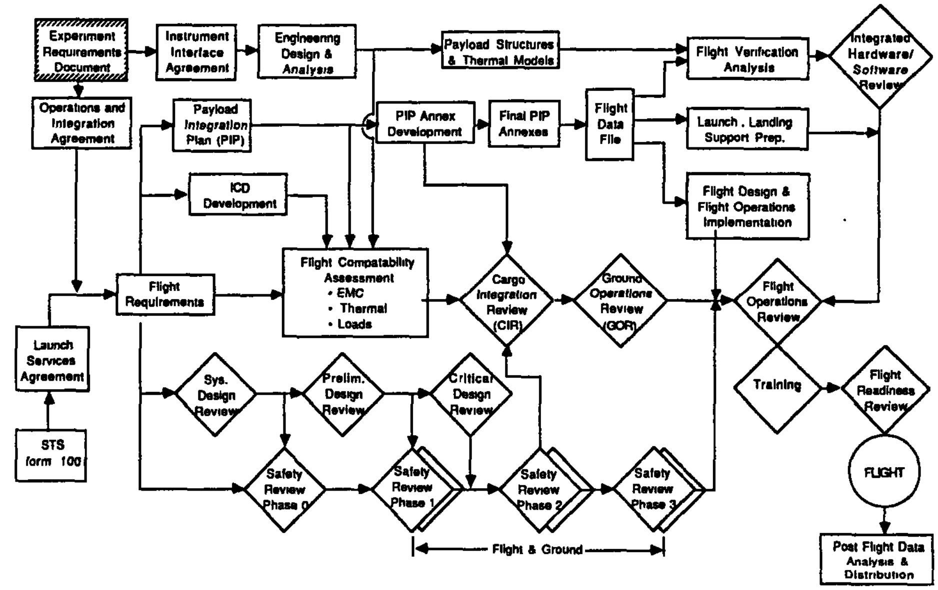


Figure 2-57. STS Cargo Integration Process

2.5.1 MISSION MANAGEMENT. The integration process for the Reflector/Beam flight experiment is directed by the Payload Mission Manager (PMM) assigned to the project by NASA Headquarters. The PMM is ultimately responsible for integrated payload definition and design, verification of STS compatibility and safety compliance, and for coordinating requirements with supporting organizations. The PMM interfaces are shown in Figure 2-58.

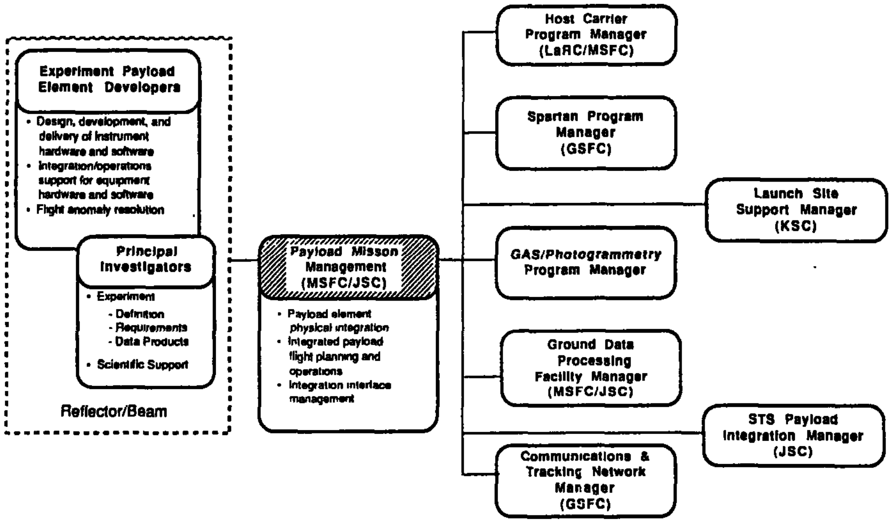


Figure 2-58. STS Mission Management Structure

The PMM will be assigned from either JSC or MSFC and the selection could have a significant impact on the overall integration process. The MSFC integration process is designed primarily for Spacelab-hosted experiments and hardware. Under this arrangement, the integration functions are performed at MSFC and all documentation is then submitted to JSC for review, approval, and integration into the STS operations plans. This would require the Reflector/Beam organization to support the total process through two NASA levels: first through the MSFC organizations, and then through the JSC organizations, essentially doubling the number of technical and managerial interfaces that the Reflector/Beam program must deal with.

The JSC integration process addresses the experiment as an attached STS payload, thus eliminating a significant amount of the intermediate "Spacelab-to-STS" integration activities. Another consideration is the fact that JSC Mission Management is colocated with the STS Operations elements, allowing simpler and more cost-efficient representation to those elements ultimately responsible for the integration, planning, and execution of the experiment mission.

Since the Reflector/Beam will require integration with a Spacelab-derived hardware element, (i.e., the Step Pallet), it is not clear which center will be assigned the PMM responsibility. Precedents have been set for both cases by previous experiments.

2.5.2 INTEGRATION MANAGEMENT. This section addresses the approach to planning and supporting the Reflector/Beam experiment development, integration, and operations activities. Primary focus is on manned interfaces and interactions between the STS and the cargo element, and developmental application of full capabilities to support a payload system. The integration management discipline comprises six major elements:

- **Program Conceptual and Integration Planning**—Defines program tools, personnel, and other resources required to support the integration and operations process.
- **Integration and Operations Management System**—Defines management involvement, roles, and responsiblities.
- **Milestone Program Reviews**—Describes how to prepare and conduct major incremental program reviews.
- **Interface Requirements and Verification Management**—Defines how interface requirements are collected, documented, controlled, and verified.
- **Mission Readiness Certification**—Describes how to prepare mission interface certification packages to support NASA readiness reviews.
- **Mission Support**—Provides guidelines for making real-time decisions and postflight reports.

2.5.2.1 Conceptual Integration and Management. Conceptual planning should begin before formally initiating the STS integration process, with the Space Flight Operations group participating in payload system definition, development, and definition of essential ground and crew interfaces required for experiment command and control. STS related experience has demonstrated that the early introduction of operations philosophy provides assurance of STS/payload compatibility and reduces the possibility of adverse program redirection and costly hardware redesign.

The Space Flight Operations group provides shuttle data and integration experience to new payload program offices, along with trade study and analysis support, to help define shuttle compatible payload configurations, mission planning, and operations concepts. This process is detailed in Figure 2-59.

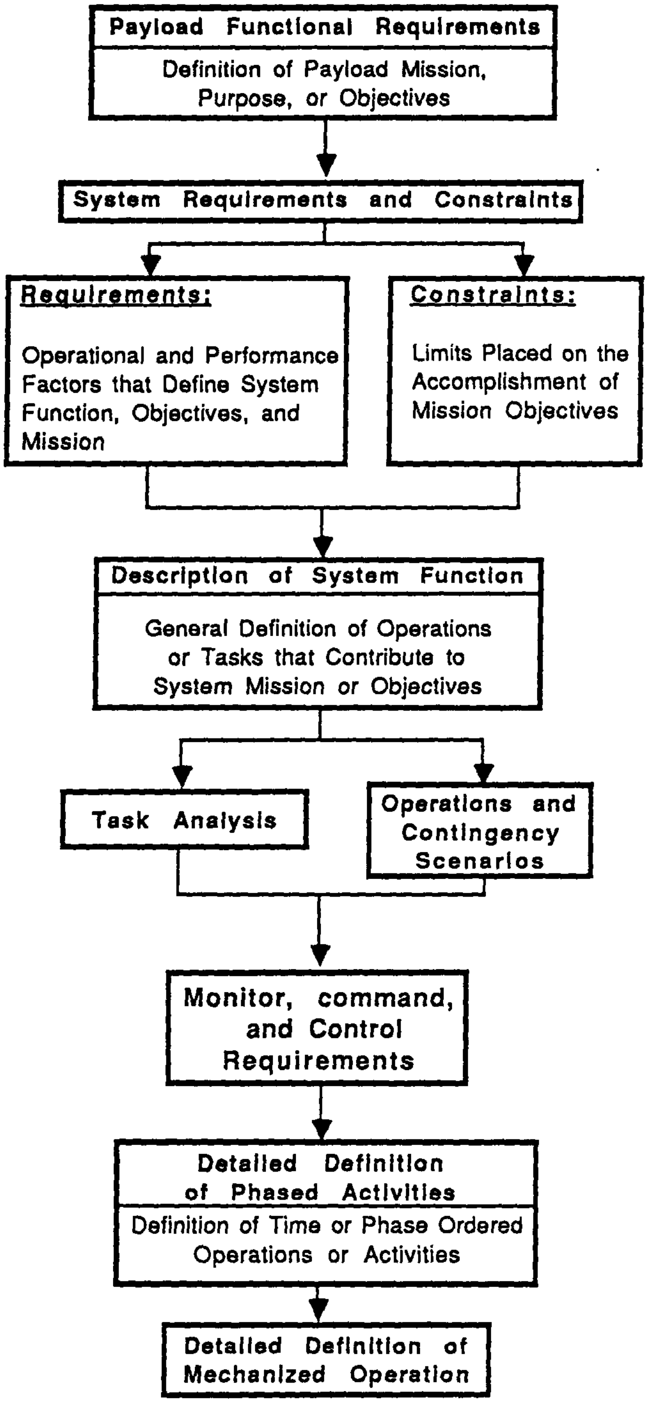


Figure 2-59. Conceptual Integration Process

2.5.2.2 Integration Operations Management. Organizational participation in the integration effort for an experiment program is normally controlled by two integration management groups. The plan includes an Experiment Integration Management Group (EIMG) co-chaired by NASA LeRC and the experiment contractor, and a joint Cargo Integration Management Group (CIMG) co-chaired by the participating NASA field centers. The relationship between the management groups, working groups, and supporting discliplines is shown in Figure 2-60.

The Integration Management Group plans and schedules working group activities, monitors progress and action item status, resolves problems, and ensures that interface documentation is completed in accordance with master schedules. The EIMG has five primary functions:

- Ensures the adequacy and accuracy of all requirements and verification documentation
- Resolves technical and management interface issues
- Prepares the integration flight certification data packages
- Facilitates spacecraft design and design trades
- Prepares for joint CIMG activities

The CIMG convenes when joint NASA integration activities begin, and functional participation is essentially the same as for the EIMG. The NASA integration team is led by a Space Shuttle Program Office (SSPO) project engineer who serves as JSC's representative for the experiment program.

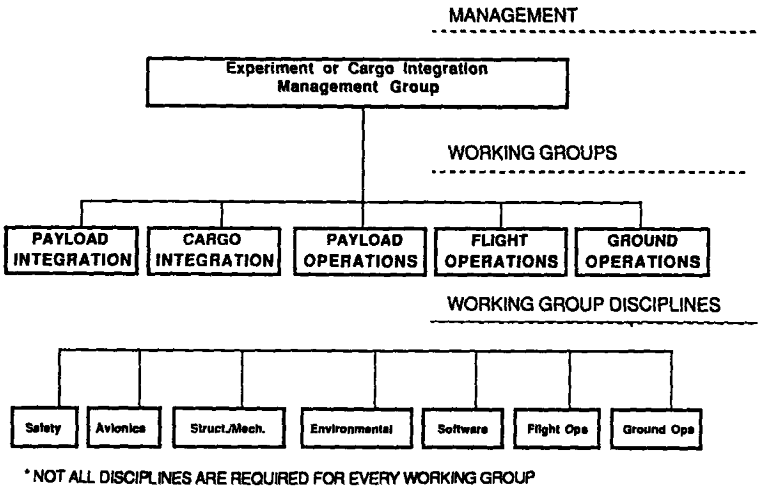


Figure 2-60. Integration Working Group Structure

2.5.2.3 Interface Requirements and Verification Management. The interfaces that may exist between a cargo element and the STS are: 1) physical (including structural elements, mating connectors, and mechanical envelopes); 2) functional (including electrical power and signal data, software, RF communications, and fluid); 3) environmental (including dynamic and static loads, thermal, electromagnetic, and vibroacoustic); and 4) operational (including flight crew, ground crew, and control center interactions).

Verification requirements for the Reflector/Beam will be drawn from those defined for STEP hosted payloads. Each requirement will be defined by identification number, description,verification method, and source of design requirement. A formal verification plan complete with schedules will be developed.

2.5.2.4 Mission Readiness Certification. A certificate of safety compliance is prepared to support program readiness reviews. This certificate states that all interfaces and elements are compatible, have been verified, and are ready for flight. NASA elements are similarly certified. A certificate of flight readiness (COFR) is signed by NASA at the FRR to certify compliance.

2.5.2.5 Mission Support. The objectives of this area are to monitor prelaunch, mission, and post-landing operations and to make decisions regarding aborts, contingency operations, and early termination of mission. General Dynamics has maintained an active role in mission support for Atlas and Atlas/Centaur launch vehicles at the Eastern Test Range and Vandenberg Air Force Base, and was extensively trained in space shuttle operations and mission support in the Centaur Payload Operations Control Center (CPOCC) at Cape Canaveral Air Force Station.

2.5.3 INTEGRATION REVIEWS. Significant activities in the Reflector/Beam experiment integration process are the periodic reviews conducted to allow Program and STS management to properly assess that the planning efforts have adequately scoped and directed implementation activities. These milestone reviews are conducted anywhere from L-48 to L-1 months depending on the integration complexity and schedule adherence.

2.5.3.1 Program-Level Reviews.

Systems Requirements Review. The SRR is normally conducted within the first few months after contractor award(s). The review verifies management's understanding and completeness of the operational requirements to be satisfied by the experiment system. It also assesses the effects of those requirements on the proposed system design and STS integration effort. The Reflector/Beam organization is responsible for and chairs this review.

Systems Design Review. The SDR is the final formal review of all system requirements, production planning, system characteristics, and systems engineering progress before developing preliminary configuration items. The Reflector/Beam Program and General Dynamics will cochair the review, but GD is responsible for establishing the time, location, agenda, and conducting the review. Working group inputs will be incorporated into the SDR data package distributed prior to the review.

Preliminary Design Review. The PDR evaluates the progress, technical adequacy, and risk resolution of the configuration item design approach prior to initiating the detailed design. The main differences between the SDR and the PDR are: 1) the SDR addresses the total system while the PDR reviews each system component; and 2) the SDR evaluates the total system development methodology and the PDR examines the design approach for each configuration item in more detail.

Critical Design Review. The CDR determines: 1) design adequacy in meeting the performance and engineering requirements; 2) design compatibility between configuration items and other interfaces; 3) areas and degree of risks; and 4) completeness of preliminary product specifications for each configuration item under review.

2.5.3.2 NASA Reviews.

Safety Reviews. The STS payload safety review process is established to assist the JSC Shuttle Payload Integration Development Program Office (SPIDPO) and the KSC Director of Safety in their responsibility for safety assurance. The safety panels, chaired by JSC and KSC, are responsible for conducting the phased reviews during which all safety aspects of payload design, flight operations, GSE design, and ground operations are reviewed.

Phased safety reviews will be conducted at four levels of Reflector/Beam development-phase 0 through III. The phase 0 review will be an informal review. Phase I through III reviews will be conducted by review panels according to specific agendas and topics as outlined in Table 2-28.

All appropriate data to be presented at each safety review will be submitted 30 days in advance by the Reflector/Beam organization to the JSC SPIDPO and the KSC Director of Safety.

Flight Readiness Review. The STS FRR is conducted to verify completion of all STS/cargo integration activities, and certify the readiness of all flight elements to support the mission. Prior to the FRR, the Reflector/Beam experiment, other cargo elements, and the STS will be internally statused to verify readiness to support the flight. The FRR is conducted by NASA Headquarters and is supported by the following elements:

- Space Shuttle Vehicle
- Cargo Integration
- Payloads
- Carriers (STEP Pallet, etc.)
- Mission Control Center
- POCCs
- Communication Network and Range Safety
- Launch and Landing Site

As a result of the FRR, all flight and flight support elements are committed to launch on a specific date and time of day.

2.5.4 DOCUMENTATION. The process of documenting requirements begins by defining the initial mission/experiment objectives, design constraints, and STS constraints. These initial requirements are continually assessed in the flight planning activity. They evolve into detailed support documents developed by various STS agencies. The matrix in Figure 2-61 cross-references the products and functions of the integration process with the applicable facilities and organizations involved.

JSC SYSTEMS ORGANIZATIONS & FACILITIES \ INTEGRATION FUNCTIONS & PRODUCTS	SCHEDULES	ERD	Q & IA	IIA	POMG	MOMG	PIP	ANNEX 1	ANNEX 2	ANNEX 3	ANNEX 4	ANNEX 5	ANNEX 6	ANNEX 7	ANNEX 8	ANNEX 9	ANNEX 11
PRODUCTION INTEGRATION	X																
FLIGHT DIRECTOR OFFICE	U								I	I							
ENGINEERING & MAINT.DIV.	U											X					
SYSTEMS DIVISION	U				P			I	I	I	I	I	X	I	I	X	X
OPERATIONS DIVISION	U				X	I	U	X	X	X	X	U	•	I	I	•	•
FLIGHT DESIGN & DYNAMICS	U				P		U		X								
TRAINING DIVISION	U				P		U	U	U	U	U	U	U	X	U	U	U
FLIGHT CREW	U				◊				I					I			
VEHICLE INTEGRATION TEAM	U																
RESEARCH & ENGINEERING																	◊
OTHER ORGANIZATIONS & FACILITIES																	
NSTS PROGRAM OFFICE	I						X		◊	◊				◊			
MISSION MANAGEMENT	•	U	•	•	P	◊	•	•	•	•	•	•	•	•	•	•	•
STEP PROJECT OFFICE	•	U	X	X	P		•	•	•	•	•	•	•	•	•	•	•
KSC	U				◊										X		
MSFC		U	U	U	P				◊	◊	◊	◊					
GSFC						X			U	U		U					
LaRC-REFLECTOR/BEAM	U	X	U	U	P	I	I	I	I	I	I	I	I	I	I	I	I
REMOTE POCC	U	I	U	U	P	U						◊					
CONTRACTOR (GDSSD)	U	I	P	P	P	I	I	I	I	I	I	I	I	I	I	I	I

JSC SYSTEMS ORGANIZATIONS & FACILITIES \ INTEGRATION FUNCTIONS & PRODUCTS	FOMG	GOMG	CIR	FOR	FRR	CPCB	IHSR	FLIGHT DESIGN	FLIGHT TECHs	FLIGHT RULES	FLT DATA FILE	CAP	EVA PROCEDURES	EVA TIMELINE	CREW TRAINING	FOSP TRAINING	SIMULATIONS
PRODUCTION INTEGRATION				I													
FLIGHT DIRECTOR OFFICE	P		P	P	P	P			X	X	•	•				P	P
ENGINEERING & MAINT.DIV.			P	P												P	P
SYSTEMS DIVISION	P	P	P	P		P	X		I	•	•	U	X	X	I	P	P
OPERATIONS DIVISION	X	P	X	P	P	X	P	•	•	•	X	X	•	•	I	P	P
FLIGHT DESIGN & DYNAMICS	P	P		P		P	P	X	U	U	•	U			I	P	P
TRAINING DIVISION	P			P		P	P		I	I	U	U	•	•	X	X	X
FLIGHT CREW	P	P		P		P	P		•	•	•	•	•	•	P		P
VEHICLE INTEGRATION TEAM		P	P						I		I	I			P		
RESEARCH & ENGINEERING		◊					◊	◊	◊	◊			◊				
OTHER ORGANIZATIONS & FACILITIES																	
NSTS PROGRAM OFFICE	◊	◊		◊	X		◊	◊		◊	◊						
MISSION MANAGEMENT	P	P	P	P	P	◊	P	◊	◊	•	•	U			I	•	P
STEP PROJECT OFFICE	P	P	P	P	P		P			•	•	U			I	•	P
KSC	◊	X		◊						◊	◊	◊					◊
MSFC		P		◊		◊	◊	◊	◊	◊	◊	◊					
GSFC		P		P			P				•						
LaRC-REFLECTOR/BEAM	P	P	P	P			P	I	I	•	I	I	I	I	I	P	P
REMOTE POCC	P		P						U	U	U	U			P	P	
CONTRACTOR (GDSSD)	P	P	P	P			P	I	I	•	I	I	I	I	I	P	P

X: PRIME   P: PARTICIPANT   U: USER   I: INPUTS   •: I & U   ◊: INTERFACE

Figure 2-61. Integration Document Matrix

2.5.4.1 Experiment Requirements Document. The ERD is one of the first and most significant integration documents to be developed by the Reflector/Beam organization. Submitted to the Payload Mission Manager (PMM), the ERD addresses the experiment-to-carrier interface requirements for:

- Experiment Operations and Configuration
- Flight Operations and Environments
- Electrical Requirements
- Thermal Control Requirements
- Command and Data Management
- Software
- Physical Integration Requirements
- POCC Requirements
- Post-flight Data Requirements

The ERD will become the baseline for engineering and mission analyses to be performed by the PMM organization. Development of subsequent integration and operations documents will also depend on the data contained in the ERD. Because of this, it is extremely important that all Reflector/Beam requirements be documented here. The ERD is phased by level of detail to accommodate the concurrent development of the experiment hardware and the definition, design, and evaluation of the payload. Updates are submitted at key points during the integration process to provide additional detail on the experiment design as they develop.

2.5.4.2 Instrument Interface Agreement. The IIA is the document used jointly by the PMM and the experiment developer to define in detail the physical aspects of electrical, mechanical, and thermal interfaces between the Reflector/Beam and the Step Pallet. Environmental, electromagnetic, mass property, and schedule requirements are included. An envelope drawing indicating maximum size, limits of motion, connector locations, and mounting arrangement is also part of the document. The IIAs are prepared by payload mission management and reviewed in detail with the Reflector/Beam developers. Once agreed to by the R/B organization, the IIA becomes the controlling interface document.

2.5.4.3 Operations and Integration Agreement.(O&IA). The O&IA formalizes the operational and software interfaces between the experiment and the carrier. All flight requirements, including operation sequence, command loading, telemetry formats, timelines, data to be recorded and transferred to the Reflector/Beam investigators, contingency plans, and on-orbit constraints are contained in the flight operations section. The ground operations section contains all requirements pertaining to integration operations at PMM facilities, the launch site, transportation data, and the launch pad.

A formalized configuration management procedure is in effect at the time the interface agreements are baselined and any changes are processed and incorporated according to these procedures. The relationship between the ERD, and the interface agreements is shown in Figure 2-62.

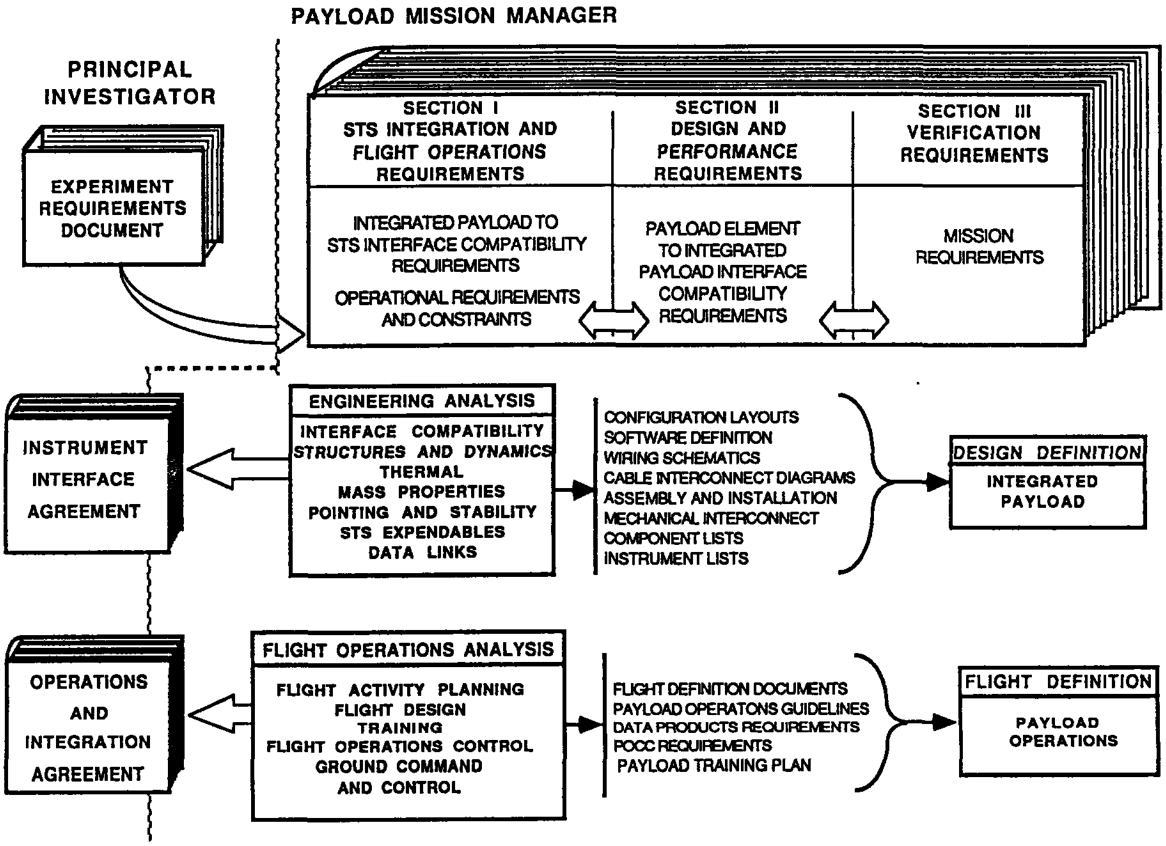


Figure 2-62. Experiment Requirements and Interface Agreement Interaction

2.5.4.4 Payload Integration Plan. The Payload Integration Plan (PIP) is the agreement between the Reflector/Beam Program and NASA that defines agency responsibilities, program requirements, and tasks required to integrate the payload into the STS. The signed PIP constitutes technical agreement on the tasks to be performed, and includes identification of tasks that NASA considers as standard or optional services. The PIP is a dynamic document that must be updated or revised as mission requirements are modified. All aspects of the mission must be documented in the PIP. If a summary of a requirement is not in the PIP, NASA does not consider the requirement as valid. Requirements are detailed in the various PIP annexes.

Development of the PIP is shown in Figure 2-63. The process begins with the preparation of a draft document that scopes the payload/STS requirements. It will provide the format and general level of detail required for the Reflector/Beam integration effort. The draft PIP is distributed to the STS and Reflector/Beam organizations prior to the initial integration meeting.

The purpose of the initial integration meeting is to mutually review the draft PIP and to familiarize the Reflector/Beam personnel with the payload integration requirements flow and review process.

The STS and Reflector/Beam organizations ensure, as a result of this meeting, that the resultant PIP has properly identified the payload's orbital requirements and constraints, required STS interfaces, ground flow at the launch and landing sites, and the engineering and operational analyses required to further define the STS/payload interfaces and services. Additionally, the development of integration activity schedules should be initiated at this meeting.

As a result of this initial meeting, the preliminary PIP will be prepared by JSC and distributed to the Reflector/Beam organization for review, and to the STS organizations for information. Review comments are distributed to the applicable organizations and a meeting is scheduled to resolve any issues. The basic PIP is then approved and signed by the NSTSPO manager and the appropriate Reflector/Beam program manager. The basic PIP is then distributed to STS organizations, NASA Headquarters, and to the Reflector Beam organization for information and implementation.

Annexes to the basic PIP are then established for the Reflector/Beam organization to provide detailed data necessary for STS elements to implement the integration functions provided for in the PIP. Some of the data directly supports crew and ground activities and will become part of the flight data file (FDF).

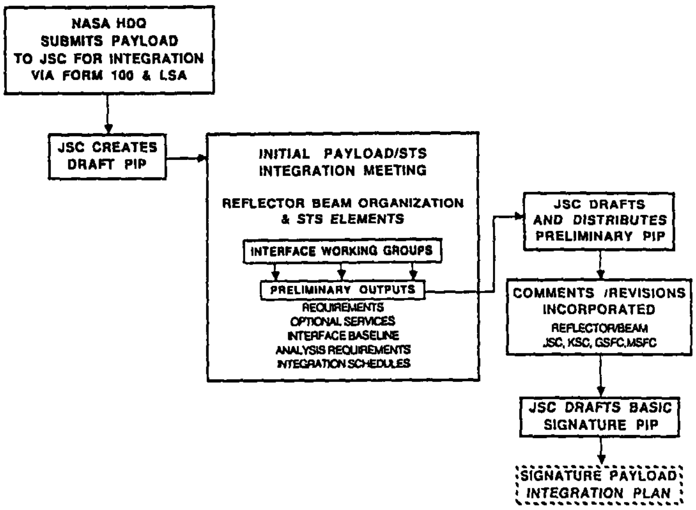


Figure 2-63. PIP Development Process

<u>Annex 1: Payload Data Package</u>. This annex describes the physical and mechanical properties of the Reflector/Beam, airborne support equipment, and ancillary equipment (including that located in the

crew compartment). This description includes payload weight, mass, and RF radiation data, and provides configuration drawings and functional data. Information on elevation and separation mechanisms, special payload deployment and retrieval system requirements, payload attitude and attitude reference data, and thrust characteristics. Annex 1 is not a contractual document, but does provide JSC with payload information needed to satisfy requirements and perform the mission.

Annex 2: Flight Planning. This annex documents the requirements for flight design and crew activity planning. The three major annex sections are: 1) detailed trajectory and launch window requirements; 2) required payload/crew functions; and 3) power, thermal, and attitude requirements. Two formats exist for preparing PIP Annex 2. The applicable format for Reflector/Beam is JSC No.14099 Annex 2 for Attached Payloads. The requirements levied on the STS by PIP Annex 2 drive the post-CIR development of the crew FDF and crew activity plan (CAP).

Annex 3: Flight Operations Support. The flight operations support annex (FOSA) defines how flight control personnel will work and interface during the flight. Included are the operations decisions, alternate plans, or courses of action that need pre-flight consideration.
Nominal, malfunction, and emergency payload procedures that require action by crewmen or flight control personnel are also addressed.

Annex 4: Command and Data. This annex defines the specific requirements for payload command and instrumentation data to be processed by the NASA STS data systems. Included are:

- Data telemetered to the ground
- Data processed by JSC
- Data displayed onboard the orbiter
- Uplinked commands
- Onboard command and control
- Fault detection and annunciation
- Data channelization

The data in this annex is used by JSC to design the orbiter avionics software for the mission.

Annex 5: Payload Operations Control Center Interface Requirements. The payload operations control center (POCC) annex contains Reflector/Beam information required to support command and data monitoring from the POCC. Part 1 is applicable to POCCs resident within the Mission Control Center at JSC (MCC-H), and part 2 defines the requirements necessary for shipment of data to remote locations. The functional interface requirements in this annex include:

- Telemetry support/processing services

- STS communication and command support
- Trajectory related services
- Voice communication services
- Video services
- Text and graphics uplink requirements
- Taped data transfer services
- Testing

Annex 5 constitutes a formal interface agreement between MCC-H and the remote POCC. Because of the importance of this agreement, and the amount of detail required, the preliminary POCC requirements must be developed early in the integration process.

Annex 6: Orbiter Crew Compartment. The orbiter crew compartment stowage annex provides detailed descriptions of the Reflector/Beam items to be stowed in the crew compartment. Descriptions will include size, weight, and use requirements that affect location, access, and handling of the equipment. This annex also defines the nomenclature of payload-assigned controls and displays in the aft flight deck (AFD) stations. Functional interfaces for equipment located in the AFD are documented in the STS/Reflector/Beam ICD.

Annex 7: Training. This annex is a description and schedule of Reflector/Beam-unique training activities required to support the mission. The information required to schedule training includes facilities to be used, and amount and location of training to be accomplished. The following items will be covered:

- Personnel to be trained
- Nominal mission events to be simulated
- Contingency events to be simulated
- Types of simulations to be conducted (joint, integrated, etc.)
- Facilities and locations
- Hours of training required
- Schedule of training activities

These activities ensure familiarization of the Reflector/Beam by flight crew and mission support personnel, and are integrated with STS training activities for scheduling when STS crewmen are available.

Annex 8: Launch Site Support Plan. The launch site support plan (LSSP) annex provides information for planning launch site processing that occurs in parallel with the planning for payload and cargo integration activities conducted by JSC. KSC assigns a Launch Site Support Manager (LSSM) at approximately the same time that the SPIDPO Engineer is assigned by JSC. The LSSM serves as the key point of contact between the Reflector/Beam Program and the STS organization for launch site processing. The LSSP is prepared as a joint STS/Reflector/Beam agreement like the other annexes. The plan constitutes a commitment of launch site facilities, support equipment, and services to the Reflector/Beam Program for a specified period of time.

Annex 9: Payload Verification Requirements. This annex defines the requirements for Reflector/Beam verification and submission of certificates of compliance at key points in the verification program. This annex consists of four parts: 1) verification requirements; 2) launch site service requirements; 3) end-to-end testing requirements; and 4) avionics services for special payload requirements. Part 1 is not required for document submittal purposes while Part 2 is mandatory for all payloads. Requirements for Parts 3 and 4 shall be established in the PIP.

Annex 11: Extra-Vehicular Activity Requirements. Annex 11 defines the specific design configuration for each hardware interface associated with EVA activities required to support the Reflector/Beam experiment. Even if no planned EVA is identified, contingency EVA requirements must be documented. Crew training, flight planning, and flight operations support related to the EVA will be included in their respective annexes. Items covered in Annex 11 include:

- Description of the EVA scenario(s)
- Specific tasks to be undertaken
- Definition of physical worksite characteristics
- Orbiter orientation constraints
- EVA task time estimates
- STS-supplied support equipment
- Stowage location for EVA equipment stowed in the payload bay

2.5.4.5 Safety Report Documentation. The NASA Headquarters document, "Safety Policy and Requirements for Payloads Using the Space Transportation System," NHB 1700.7B, establishes both technical and system safety requirements applicable to all STS payloads. The launch and landing site safety requirements are specified in the Space Transportation System Payload Ground Safety Handbook, KHB 1700.7. These documents are applicable to all payload hardware, including new design, existing design (reflown hardware), and GSE. The implementation procedure for STS payload system safety is documented in JSC 13830A.

The development of safety compliance data is a significant element in the documentation effort. These data provide the basis for certifying that the experiment equipment complies with NHB 1700.7a requirements. In general, safety data packages must incorporate sufficient information to enable assessment of operations, hazards, causes, controls, and verification of the adequacy of hazard controls. Specific data requirements are detailed in the implementation guideline STS Payload Safety Guidelines Handbook, JSC11123, and the Spacelab Payload Project Office Payload Safety Implementation Plan JA-012.

2.5.4.6 Interface Control Documentation. The Reflector/Beam hardware interface design must be verified to determine if all the requirements have been met. Most detailed interface requirements for the Reflector/Beam will be detailed in a dedicated STEP ICD. The Reflector/Beam organization will receive some guidance in defining these interfaces; physically in the IIA, and functionally in the O&IA.

STEP interfaces to the orbiter will be defined in a separate ICD, as will any ancillary hardware unique to the Reflector/Beam experiment that is carried in the crew compartment of the orbiter. The ICD hierarchy and relationship to other integration documents is shown in Figure 2-64.

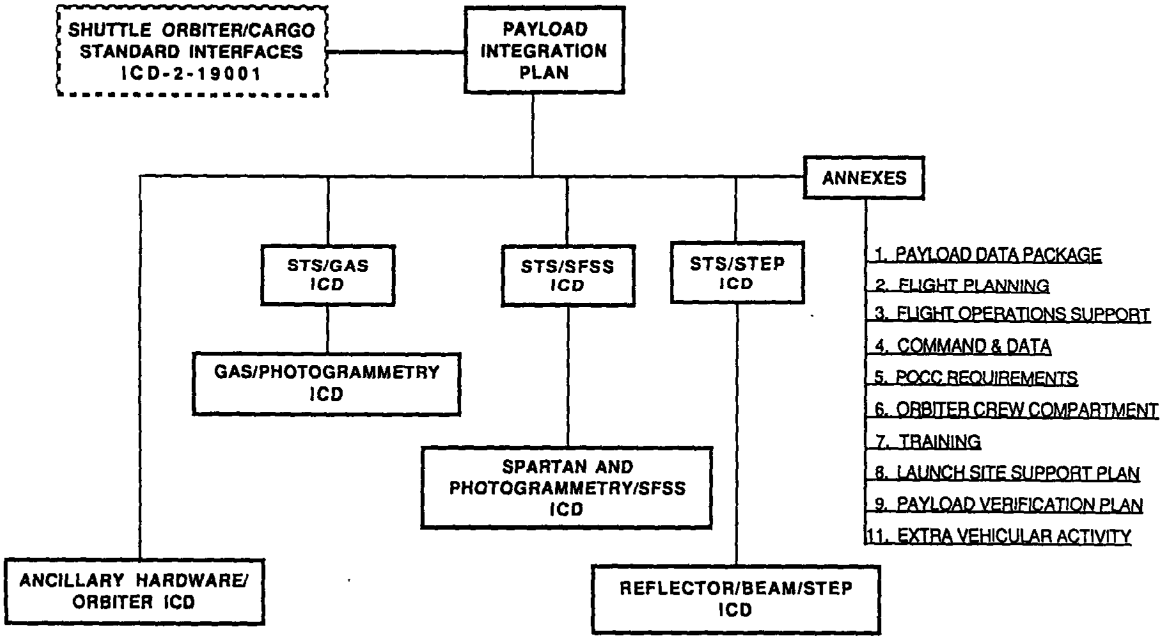


Figure 2-64. PIP/Annex/ICD Structure

2.5.4.7 Flight Data File. The Flight Data File (FDF) is the total onboard complement of documentation and related items available to the crew for flight execution. The FDF includes procedural checklists, integrated timelines, malfunction procedures, reference data books, crew activity plans, decals, cue cards, and miscellaneous hardware such as book tethers and clips.

Data for the development of the preliminary FDF is drawn from the PIP and PIP annexes, and should be published for review in the L-13 to L-11 month range. At approximately L-5 months, the preliminary FDF will be released as the basic issue containing the preliminary version plus any additions or changes that occur after the preliminary release. The FDF basic version will be placed under change control following the Flight Operations Review (FOR), meaning that all changes must be reviewed and approved in writing by the Crew Procedures Change Board (CPCB) representative, Flight Director's Office, and the FDF book manager.

It is the basic version of the FDF that is given extensive use by flight crew and flight operations support personnel (FOSP) during various reviews and training activities. As a result, the basic FDF is subject to many change requests. These requests can originate with anyone involved in the flight, including NASA or contractor FOSP, flight crew, simulator personnel, etc. The critical task is to follow change requests (submitted on NASA form 482), independently evaluate the request , and respond through the appropriate FDF book manager or CPCB representative.

The FDF final version should be released at the L-3 month range, and will incorporate revisions and changes approved since the release of the basic issue. Change requests can still be submitted via the 482 process, and the request review/evaluate/respond process must continue until the FDF is "frozen" at approximately L-3 days.

While JSC is responsible for developing the overall STS FDF, GD Space Systems Division will be working closely with NASA JSC counterparts who publish the FDF, and LaRC Reflector/Beam opeations staff during the FDF development process. This interface ensures that the integration of payload FDF data with SSV data does not adversely affect Reflector/Beam operations and completion of mission objectives. Table 2-29 lists the FDF articles by title, organizational control, and content.

Table 2-29. Flight Data File Articles

DOCUMENT TITLE	ORGANIZATION	CONTENTS
Ascent Checklist	JSC-DH3	• NOMINAL PROCEDURES FOR PRELAUNCH, POST OMS 1 BURN, DELAYED OMS 1 BURN, POST DELAYED OMS 1 BURN, POST OMS 2 BURN • AOA AND AOA POST DEORBIT PROCEDURES • POWERED FLIGHT AND ABORT CUE CARDS • PRELAUNCH SWITCH CONFIGURATION LIST
Post Insertion Checklist	JSC-DH4	• SUMMARY AND DETAILED TIMELINES AND PROCEDURES TO PREPARE ORBITER, CREW, AND PAYLOAD FOR ON-ORBIT OPS • ON-ORBIT SWITCH PICTORIALS • ATO POST INSERTION INSTRUCTIONS
Crew Activity Plan	JSC-DH4	• INTEGRATED SUMMARY TIMELINES • DETAILED ON-ORBIT NOMINAL AND CONTINGENCY TIMELINES. INCLUDES KEY GROUND SUPPORT, ORBITER SYSTEMS, CREW SYSTEMS, AND PAYLOAD SYSTEM OPERATIONS • CONSUMABLES CURVES
Deorbit Prep Checklist	JSC-DH4	• NOMINAL DEORBIT PREP AND DEORBIT PREP BACKOUT PROCEDURES • ENTRY SWITCH LIST PICTORIALS • LAUNCH DAY (ORBITS 2 AND 3) AND EMERGENCY DEORBIT PROCEDURES • BFS/SHORT TIME DEORBIT PREP NOTES • CONTINGENCY DELTAS TO NOMINAL DEORBIT PREP PROCEDURES • NOMINAL AND CONTINGENCY DEORBIT

Table 2-29 Flight Data File Articles (contd)

DOCUMENT TITLE	ORGANIZATION	CONTENTS
		PREP PAYLOAD BAY CLOSURE
Entry Checklist	JSC-DH3	• PRE-DEORBIT BURN, POST BURN DEORBIT AND POST LANDING PROCEDURES OMS PROPELLANT DELTA PADS DEORBIT BURN AND ENTRY CUE CARDS • 1-ORBIT LATE AND LOSS OF FLASH EVAPORATOR PROCEDURES • SWITCH LIST AT WHEEL STOP
EVA Checklist	JSC-DG3	• EVA EQUIPMENT, AIRLOCK & CREW PREP PROCEDURES • EVA PREP AND FAILED LEAK CHECK PROCEDURES • EVA CUFF CHECKLIST WITH EVA CREWMAN PROCEDURES • POST EVA AND ENTRY PREP PROCEDURES • EMU MAINTENANCE AND PROCEDURES • EMERGENCY AIRLOCK REPRESSURIZATION • EVA CUE CARDS
Orbit Operations Checklist	JSC-DH4	• ORBITER SYSTEMS PROCEDURES FOR ON-ORBIT OPERATIONS • PRE- AND POST-SLEEP PROCEDURES • FLIGHT-SPECIFIC DETAILED TEST OBJECTIVE (DTO) PROCEDURES
Payload Ops Checklist	JSC-DH6	• PAYLOAD SYSTEMS PROCEDURES FOR ON-ORBIT OPERATIONS • NOMINAL, BACKUP, AND TIME-CRITICAL CONTINGENCY PROCEDURES
PDRS Ops Checklist	JSC-DH4	• RMS AND PAYLOAD NOMINAL BACKUP, AND CONTINGENCY PROCEDURES/DATA FOR POWERUP/POWERDOWN

Table 2-29 Flight Data File Articles (contd)

DOCUMENT TITLE	ORGANIZATION	CONTENTS
		- CHECKOUT - DEPLOY/RETRIEVAL OPS • PROCEDURES FOR CCTV/RMS INSPECTION • RMS EVA RELATED PROCEDURES
Photo/TV Checklist	JSC-DG3	• TELEVISION SETUP, ACTIVATION, AND DEACTIVATION PROCEDURES • 16mm AND 70mm CAMERA OPERATIONS • 35mm CAMERA OPERATION, PHOTO LIST, AND PHOTO LOG • 16mm, 35mm, AND 70mm CAMERA DISPLAYS AND CONTROLS
<u>OFF-NOMINAL:</u>		
Payload Systems Data and Malfunction Procedures	JSC-DH6	• CRT DISPLAYS • SYSTEMS SCHEMATICS • MALFUNCTION DIAGNOSTIC PROCEDURES • SYSTEMS REFERENCE DATA: - FAULT DETECTION AND ANNUNCIATION - SOFTWARE IDENTIFICATION - CRITICAL EQUIPMENT/ BUSS/MDM LOSS LISTS • PAYLOAD BAY CLOSEOUT PHOTOGRAPHS
Systems Malfunction Procedures	JSC-DF4	• ORBITER SYSTEMS DIAGNOSTIC PROCEDURES • FAILURE RECOVERY PROCEDURES—INTEGRATED PROCEDURES TO RECONFIGURE SYSTEMS AS A RESULT OF ELEMENT FAILURE
<u>REFERENCE:</u> Data Processing Systems Dictionary	JSC-DH4	• LIST OF ALL CRT

Table 2-29. Flight Data File Articles (contd)

DOCUMENT TITLE	ORGANIZATION	CONTENTS
		DISPLAYS AVAILABLE ON-BOARD THE ORBITER • PROGRAM NOTES EXPLAINING SOFTWARE LIMITATIONS AND CORRECTIVE ACTIONS
Reference Data Book	JSC-DH4	• LISTS OF CRITICAL EQUIPMENT LOST WHEN BUS OR SUB BUS IS LOST • LISTS OF I/O GPC PARAMETERS LOST WHEN MDM IS LOST • LIST OF ALL FAULT MESSAGES • GPC MEMORY DATA LOCATIONS

2.5.4.8 Flight Control Documents. JSC will develop the many flight-specific handbooks and manuals required by flight controllers to execute the mission. As with the FDF, the data for these documents will be drawn from various integration activities including the PIP and annexes, trade studies and analyses, working group results, and the milestone reviews previously discussed. General Dynamics will monitor the development of flight control documents to ensure the mission requirements continue to be satisfied.

Flight Rules Annex. The flight rules comprise the formal flight-specific document that defines flight policies considering crew safety and mission objectives for various flight and system contingencies. Preplanned decisions are outlined to minimize the amount of real-time rationalization required when off-nominal situations occur. The associated rationale defines reasons, considerations, and tradeoffs considered in establishing recommended action. The flight rules are developed by a Flight Techniques panel chaired by the Flight Director Office and supported by the General Dynamics Space Flight Operations group. The preliminary flight rules are published at six months before the beginning of integrated simulations. The basic rules are published one month before simulations, and the final at L-1 month.

Operations Support Timeline. The OST is an integrated summary timeline identifying key activities of the major mission-support elements. Referenced to mission elapsed time (MET), the OST provides information on orbiter tracking and acquisition through to TDRSS, RTS, and GSTDN networks, orbit

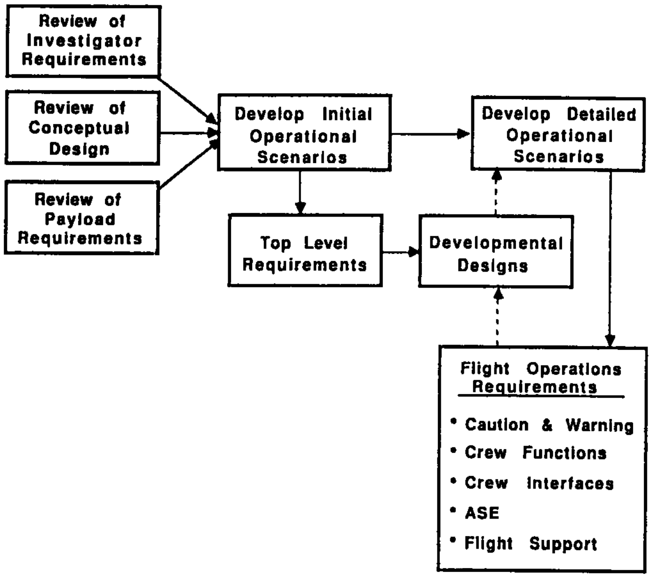


Figure 2-66. Flight Operations Requirements Development

When the operational requirements have been adequately defined, flight planning activities will identify technical analyses and flight designs necessary to implement Reflector/Beam objectives within the capabilities of the STS. This process examines the support necessary for flight, defines event sequences and procedures, and culminates in the documentation required to achieve Reflector/Beam mission objectives. The result is an established baseline for flight operations with an assessment of STS capabilities for implementation. The planning function is detailed in Figure 2-67.

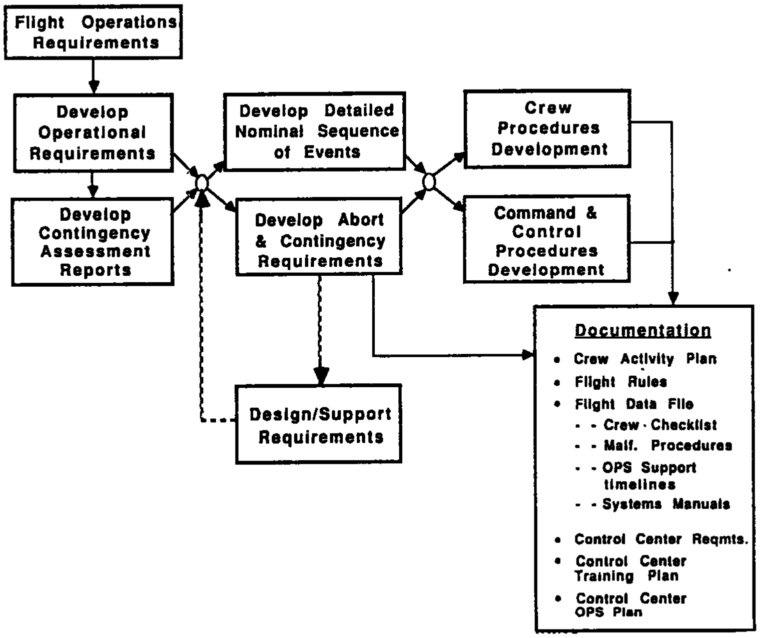


Figure 2-67. Flight Operations Support Planning

2.5.5.2 Flight Readiness Preparation. Flight readiness activities assess ground testing and pre-flight activities as well as the results of flight operations planning. The intent is to validate the FDF and refine the operational procedures used by the flight crew and ground controllers. Validation is accomplished through a planned series of simulations.

The activities needed to develop and implement requirements for NASA training and simulation support are documented in PIP Annex 7. Implementation of training and simulation requirements is the responsibility of the NASA/JSC training manager, and control and implementation of the requirements are accomplished by the POWG.

A Reflector/Beam training plan will be developed to address all aspects of training, including personnel to be trained (FOSP and flight crew), and where, how, and when training will be accomplished. This plan will be the basis for preparing PIP Annex 7. The program defined by this plan will be based on the building-block technique with progressive advances in complexity of subject material and training aids, as shown in Figure 2-68.

Joint integrated simulations (JIS) are the final phase of training, and will be performed with participation of all personnel designated to support the real mission. Each JIS provides the final demonstration of flight readiness for the flight crew and FOSP, and provides a realistic environment in which the flight controllers and flight crew can interact in real-time to prepare for the mission.

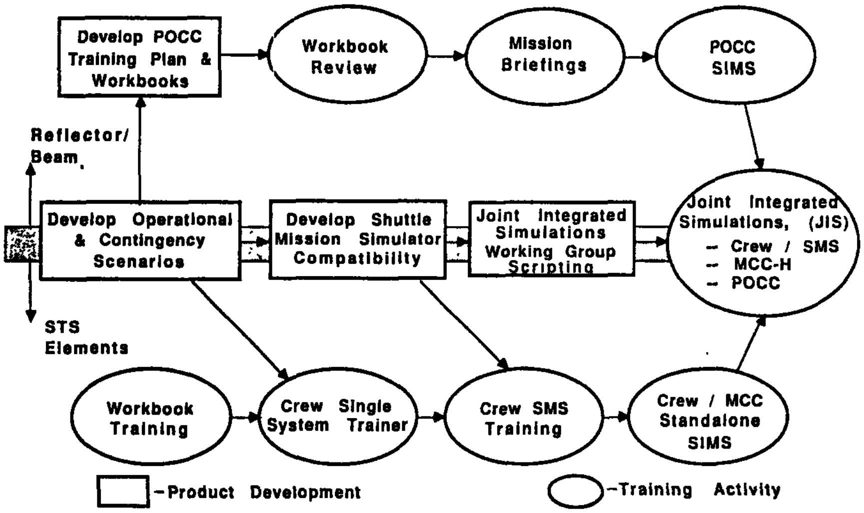


Figure 2-68. Mission Preparation Training Concept

2.5.5.3 Flight Control. Flight control analyses are performed during the integration process to interpret requirements for command, control, communications, and real-time mission support, and to allocate the requirements to the appropriate implementation agencies. Flight control support requirements are derived from operations planning analyses performed with the requirements for mission support at NASA/JSC and GSFC, and prelaunch support at KSC. The implementation approach is documented in the mission-specific flight rules, flight control operations handbook (FCOH), and the FDF. General Dynamics will represent the Reflector/Beam program to JSC and KSC, and will respond to crew and operations support activities to ensure that the implementation agencies understand and continue to satisfy the experiment requirements in the cargo-level flight control documentation. The integration process culminates in real-time flight operations. Shortly before launch, the Reflector/Beam control team will be responsible for manning consoles to provide launch operations configuration status to the KSC test conductor and/or the flight director at JSC. At launch, flight-specific operations will be conducted and monitored by the Reflector/Beam team based on four sets of documents:

- Final FDF
- Mission flight rules
- Console procedures
- Final CAP

This team will be responsible for monitoring on-orbit experiment checkout and operations, and relaying status to MCC-H payload operations personnel from launch until Reflector/Beam safing operations are completed.

2.6 PROGRAM SCHEDULE

A work breakdown structure (WBS) and master schedule for the reflector/beam verification program are given in Figures 2-69 and 2-72, respectively. The baseline program lasts 7.5 years (90 months) and contains two flights, one with a 5-meter reflector and the other with a 15-meter reflector. Both flights use the same instrumented 20-meter truss-beam. The first flight occurs at the end of the fifth year (month 60), and the second flight occurs midway in the seventh year (month 79).

The program schedule is ambitious. It tightly integrates development testing, design and fabrication of one truss-beam and two reflectors, substructure ground testing of the beam and each reflector, final assembly and assembled-system ground testing of the two flight configurations, STS safety reviews of both flight configurations, integration of both flight configurations into the STS, both STS flights, and a full complement of pre- and post-flight analyses. A major challenge in the schedule is overlaying all the integration and ground-testing tasks on flight-hardware fabrication and assembly. Another challenge is overlaying the STS integration (operations WBS element) and safety tasks on the rest of the program.

The schedule contains three critical design reviews (CDRs), one in month 14 for the beam, one in month 18 for the 5-meter reflector and the assembled flight-one configuration, and one in month 24 for the 15-meter reflector and the assembled flight-two configuration. Holding the beam CDR separately and before that for the entire flight-one configuration allows starting beam fabrication earlier and, thereby, starting integration and testing earlier. This reduces the program span from nearly 8 years to 7.5 years. All development testing is completed before the flight-one CDR.

Beam fabrication starts immediately after the beam CDR, month 14, and final assembly is completed in month 27. At the conclusion of beam final assembly, the beam is moved to an integration facility for installation of its instrumentation and then to the ground-testing facilities for substructure static and vibration testing. Beam integration and testing starts in the month 28 and lasts into month 40. The beam is sent back to the final assembly area to await assembly with the 5-meter reflector. Integration and testing of the 5-meter reflector begins in month 31 and is completed in month 42. Two months are allowed for final assembly of the reflector with the beam and deployer/repacker, and integration and testing of the flight-one configuration begins in month 45. Finally, all flight-one configuration testing is completed during month 54, the flight article is shipped to KSC for STS integration and flight during month 60. Meanwhile, the 15-meter reflector assembly is completed in month 52. Integration and substructure testing is performed between months 53 and 64. The beam is returned from the first flight and integrated with the 15-meter reflector during months 65 and 66. Then, integration and testing of the assembled 15-meter flight-two configuration is performed in months 67 through 75. The flight-two article is shipped to KSC in month 75 and flown in month 79.

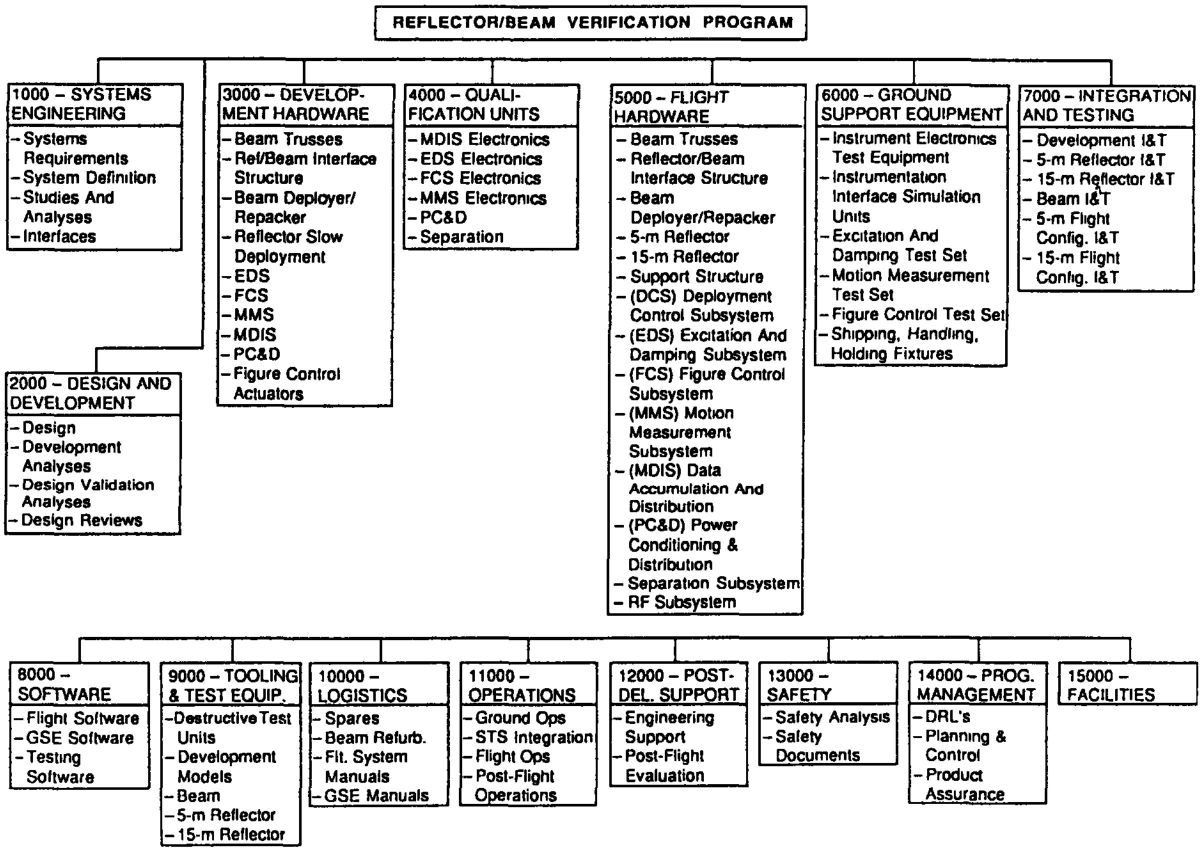


Figure 2-69. Program Work Breakdown Structure

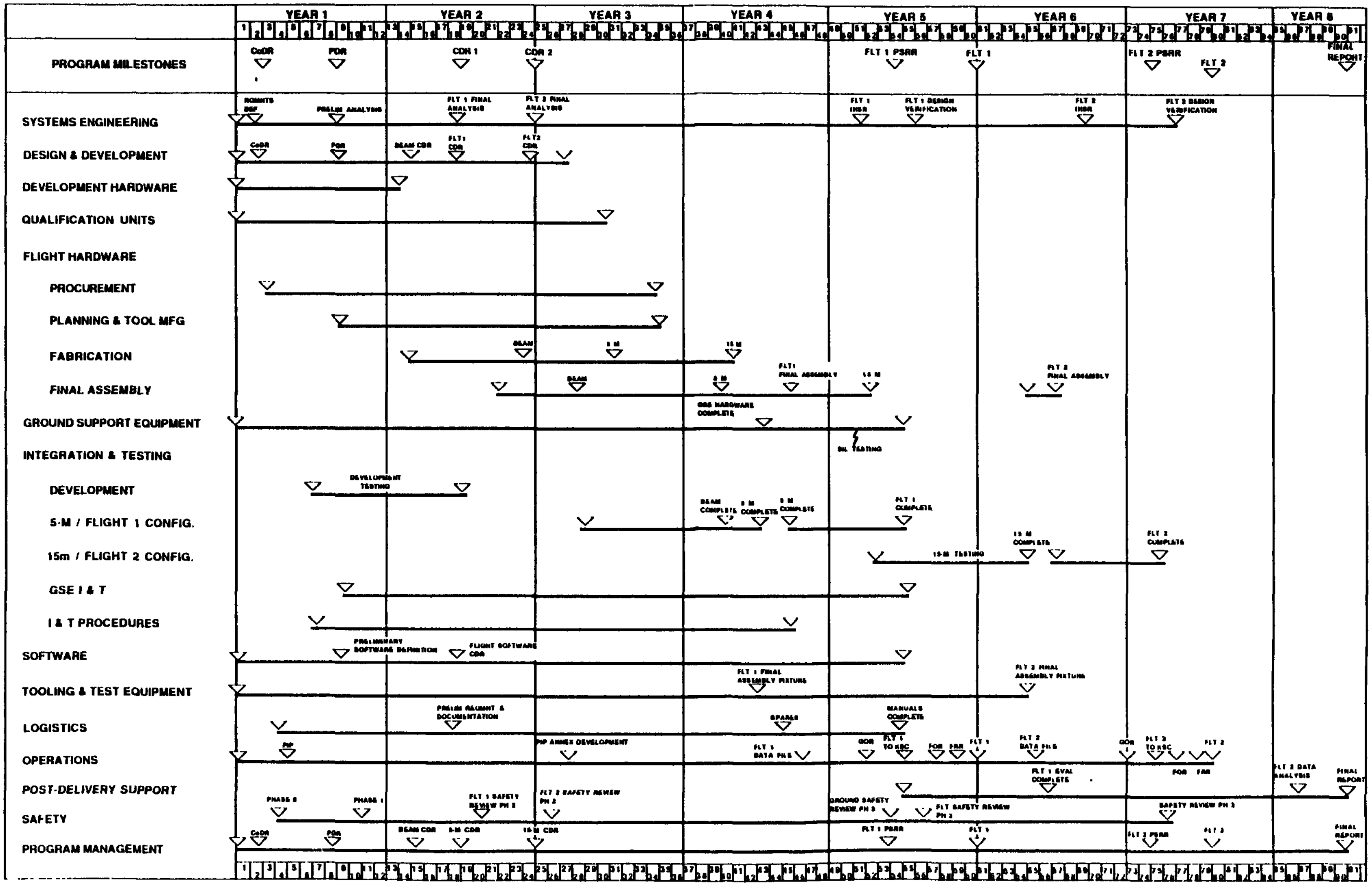


Figure 2-70. Program Master Schedule

2.7 FACILITY REQUIREMENTS

A major consideration in the program definition was facility requirements. To reduce program costs and schedule, the goal was to use only existing government and industry facilities. As discussed in Section 2.2.4, use of existing ground-test facilities, specifically, thermal vacuum chamber and near-field facilities, limited the maximum diameter of the deployable geotruss reflector to 15 meters. However, this is not a severe limitation in achieving the overall program goals.

Facility requirements for hardware fabrication, ground testing, and shuttle integration are shown in Table 2-30. The period during which these facilities are needed is shown on the program master schedule in Section 2.6. With the hardware and tests as defined, all program operations can be done with existing facilities.

Table 2-30. Facilities

OPERATION	FACILITY REQUIREMENT	AVAILABLE FACILITES
HARDWARE FAB/ASSY/INSPECT.	COMPOSITES FABRICATION FACILITY ASSEMBLY FACILITY (CONTROLLED ENVIRONMENT) MEASUREMENT FACILITY (CONTROLLED ENVIRONMENT)	GDSS
DEPLOYMENT TESTS (VACUUM)	65 FT DIA VACUUM CHAMBER	JSC (CHAMBER B)
VIBRATION/ DYNAMIC TESTS	65 FT DIA VIBRATION TEST FACILITY	GDSS VIBRATION LAB
THERMAL/VACUUM TESTS	65 FT DIA THERMAL/VACUUM CHAMBER	JSC (CHAMBER B)
NEAR FIELD RF MEASUREMENT	50 FT DIA NEAR-FIELD FACILITY	MMC., DENVER
SHUTTLE INTEGRATION	PAYLOAD INTEGRATION FACILITY	KSC

ALL PROGRAM OPERATIONS CAN BE ACCOMPLISHED WITH EXISTING FACILITIES

2.8 PROGRAM COST ANALYSIS

Program cost analysis consisted of developing side-by-side cost data for six different antenna system configurations. Costs were developed at the major subsystem level and include the design, development, test and evaluation of prototype hardware and the production of one unit of operational hardware.

Program costs were developed for 5-meter and 15-meter antenna systems both with and without on-orbit RF testing capability. These program costs are shown in Figure 2-71.as these six different program options: 15 meter, 5 meter, combined 15 meter and 5 meter, 15 meter without RF test capability, 5 meter without RF test capability and combined 15 meter and 5 meter without RF test capability. The singular 15-meter and 5-meter antenna systems represent standalone systems that would be developed for only one size antenna, i.e., 15 meter or 5 meter. The antenna systems that combine.both a 15-meter and 5-meter antenna, both with and without RF test capability, assume initial development and production of a 5-meter antenna system. This system is subsequently upgraded by development and production of hardware that will convert the initial 5-meter design to a 15-meter system. The cost difference between a single experiment using the 5-meter reflector and two experiments using both a 5-meter and 15-meter reflector is only $31.7 million (with RF testing) and $30.2 million (without RF testing). This low cost difference is due to the extensive use of common designs and the reuse of all experiment hardware except the reflector.

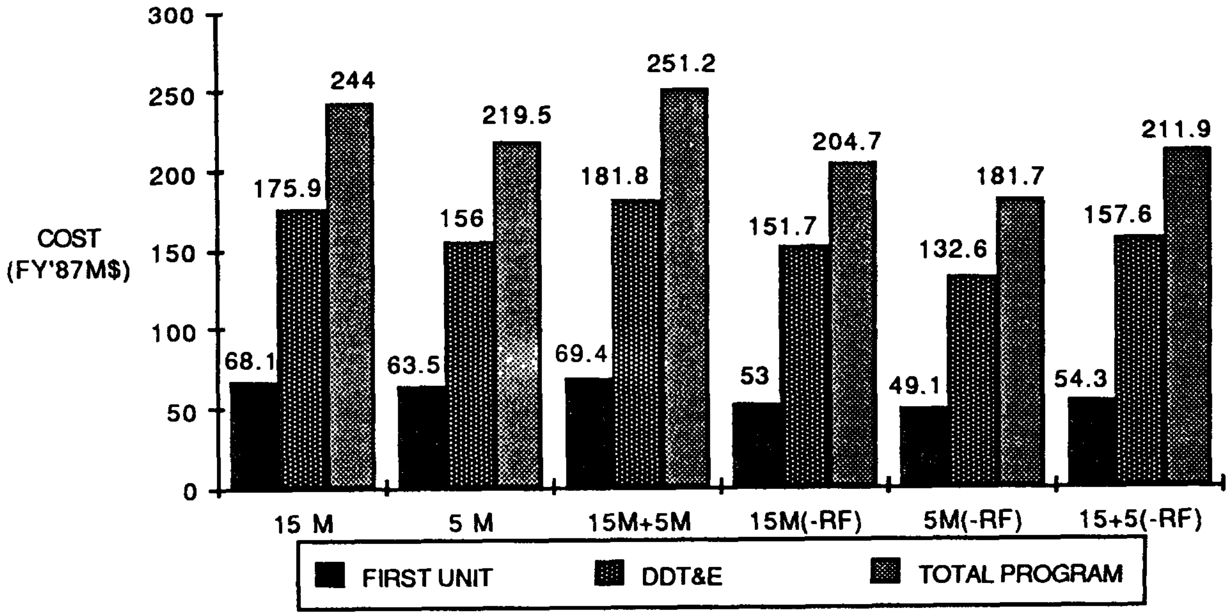


Figure 2-71. Program Cost Summary

2.8.1 COST RESULTS. Total program costs, which represent the sum of design, development, test and evaluation (DDT&E) and one production article, vary from $181.7 million for a standalone 5-meter antenna system without RF capability to $251.2 million for a combined 15-meter and 5-meter antenna system with near-field RF testing capability.

Development costs, which include design, development, test and evaluation , vary from $132.6 million for the standalone 5-meter antenna system without near-field RF capability to $181.8 million for the combined 15-meter and 5-meter antenna system with RF testing capability. First-unit cost for the 5-meter antenna system without RF is $49.1 million compared with $69.4 million for the combined 5- and 15-meter system with on-orbit RF testing ability. Program costs, broken down to the major functional subsystem level, are shown for the 5-meter and 15-meter antenna systems with RF capability in Table 2-31. Similar functional subsystem-level cost data is shown in Table 2-32 for those antenna systems without RF testing ability.

2.8.2 COST DEVELOPMENT AND ANALYSIS. Development costs, unit production costs, and program costs for the various antenna system options were developed using the general methodology outlined in Figure 2-72. The input data, which includes cost of ground rules, a cost database within a functional subsystem work breakdown structure and design, development, and operations definition data for a given system are used to develop and drive a cost model. This cost model develops first-unit production costs and program costs for selected system configurations. Ground rules and assumptions that apply to this study are as follows:

- All costs in FY 1987 millions of dollars.
- Program costs are for 15-meter and 5-meter antenna systems both with and without on-orbit testing capability.
- Includes reflector, support beam, deployment structure, mechanism, power distribution, antenna measurement, control and instrumentation systems, ground support equipment, software, program integration, and RF avionics where appropriate.
- Excludes STEP dedicated support pallet and Space Shuttle associated costs.
- Costs are identified for DDT&E and a single unit production article (first unit) for each of four independent program options. In addition, program delta costs are identified for growth to 15-meter capability from initial 5-meter system development.
- Ground support equipment includes both general-purpose and special support equipment. It consists of electrical, electronic, and mechanical hardware and software.
- All cost data includes direct and indirect costs including general and administrative (G&A) costs and a contractor fee of 12%.

Cost estimates for first-unit production cost and DDT&E were developed at the major subsystem level. The basis for these costs is statistically derived cost estimating relationships (CERs) that were developed at the major functional subsystem level. Each subsystem element represents a specific type of hardware with a level of cost determined by a combination of subsystem size and complexity. The database for these CERs is composed of unmanned spacecraft subsystems and orbital antenna hardware elements. In addition, reasonability checks based on top-level parametric relationships and ratios were made to ensure comparability and consistency among the subsystem elements.

Table 2-31. Program Cost Elements (Including RF Testing)

SPACE ANTENNA (FY'87M$)	15 METER FIRST UNIT	15 METER DDT&E	5 METER FIRST UNIT	5 METER DDT&E
1 REFLECTOR	4	17.7	1.3	5.9
2 EXCIT. DAMP. (EDS)	13.3	16.6	13.3	16.6
3 DEPLOY. MECHANISM	4.7	25.8	4.7	25.8
4 MOTION MEAS. (MMS)	11.9	15.3	11.9	15.3
5 MOD.DIST.INSTRU.(MDIS)	1.4	3.4	1.4	3.4
6 BEAM STRUCTURE	1	6.9	1	6.9
7 RF AVIONICS	11.3	14.8	10.8	14.4
8 FIGURE CONTROL (FCS)	2.2	4.8	2.2	4.8
9 POWER DISTRIB. (PDS)	1.4	3.4	1.1	2.9
10 PROGRAM INTEG.	16.9	38.9	15.8	34.2
11 GSE		24.8		22.3
12 SOFTWARE		3.5		3.5
TOTALS	68.1	175.9	63.5	156
TOTAL PROGRAM		244		219.5

The major structural subsystems are the reflector and supporting beam. The major difference between the 15-meter and 5-meter system is the reflector. The beam structure can be used to deploy either antenna and is considered common to either system in terms of cost. The deployment mechanism also is common from a cost point of view with the ability to deploy both the 15- and 5-meter antenna.

The high production cost subsystems are the excitation damping system (EDS), motion measurement system (MMS), and RF avionics where applicable. From a development point of view, the deployment mechanism, EDS, MMS, RF avionics, and ground support equipment represent significant cost areas. Program integration is a significant cost element for both the development and first-unit cost of all the configurations. Program integration includes program management, systems engineering, systems test and evaluation, acceptance test, quality assurance, data management, and integration and assembly.

Table 2-32. Program Cost Elements (Without RF Testing)

SPACE ANTENNA (FY'87M$)	15 METER-RF FIRST UNIT	15 METER-RF DDT&E	5 METER-RF FIRST UNIT	5 METER-RF DDT&E
1 REFLECTOR	4	17.7	1.3	5.9
2 EXCIT. DAMP. (EDS)	13.3	16.6	13.3	16.6
3 DEPLOY. MECHANISM	4.7	25.8	4.7	25.8
4 MOTION MEAS. (MMS)	11.9	15.3	11.9	15.3
5 MOD.DIST.INSTRU.(MDIS)	1.4	3.4	1.4	3.4
6 BEAM STRUCTURE	1	6.9	1	6.9
7 RF AVIONICS				
8 FIGURE CONTROL (FCS)	2.2	4.8	2.2	4.8
9 POWER.DISTRIB. (PDS)	1.4	3.4	1.1	2.9
10 PROGRAM INTEG.	13.1	33.5	12.2	29.1
11 GSE		20.8		18.4
12 SOFTWARE		3.5		3.5
TOTALS	53	151.7	49.1	132.6
TOTAL PROGRAM		204.7		181.7

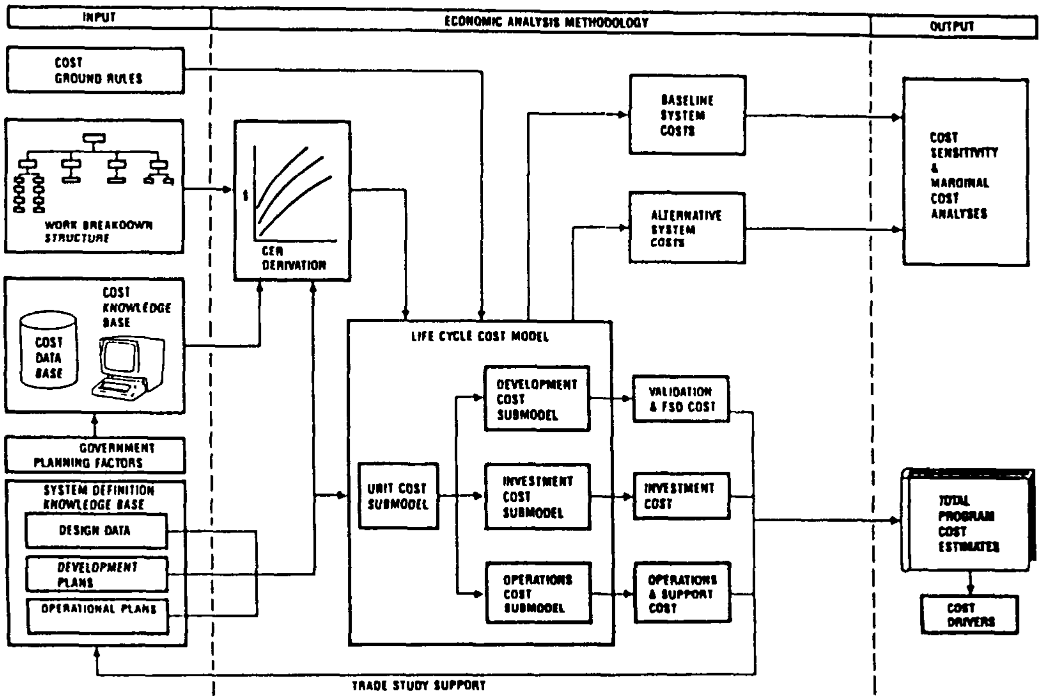


Figure 2-72. Cost Analysis Procedure

SECTION 3
CONCLUSIONS AND RECOMMENDATIONS

This section presents the major conclusions and recommendations.

3.1 CONCLUSIONS

- Future advanced space structures will be large and have high performance.
- Deployment, shape accuracy, and control/structure interaction are critical advanced technologies for deployable truss structures.
- The planned precision deployable truss beam and truss reflector test structures and analysis/ground test/flight experiment program are designed to verify these advanced technologies.
- Critical technologies requiring further development are shape control and truss reflector deployment mechanization.
- The flight experiment objectives can be met using two shuttle flights with the total experiment integration on a single step and MPESS.
- First flight of the experiment can be achieved 60 months after program go-ahead with a total program of 90 months.
- Total baseline program can be accomplished for an estimated $251 million with RF experiments, and $212 million without RF experiments.

3.2 RECOMMENDATIONS

- Initiate immediate technology development programs for :
  - -- Shape control (sending, actuation, system integration)
  - -- Truss reflector controlled deployment (mechanisms, system demonstration)
- Initiate an early thermal distortion analysis/ground test program:
  - -- Use existing deployable truss hardware
  - -- Thermal distortion analysis (truss and reflector)
  - -- Ground test verification
- Initiate a study of flight experiment operations
- Continue overall program planning
  - -- Cost
  - -- Schedule
  - -- Program participation
- Initiate overall program by FY 1989
  - -- Technology development compatibility
  - -- Funding availability
  - -- User need dates

SECTION 4
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16. Abstract

Use of large deployable space structures to satisfy the growth demands of space systems is contingent upon reducing the associated risks that pervade many related technical diciplines. NASA has recognized this issue and has sponsored significant research aimed at developing the needed large space structures technology.

The overall objectives of this program, which uses the products of these research efforts, was to develop a detailed plan to verify deployable truss advanced technology applicable to future large space structures and to develop a preliminary design of a deployable truss reflector/beam structure for use as a technology demonstration test article. The planning is based on a Shuttle flight experiment program using deployable 5 meter and 15 meter aperture tatrahedral truss reflections and a 20 meter long deployable truss beam structure.

The plan addresses validation of analytical methods, the degree to which ground testing adequately simulates flight testing and the in-space testing requirements for large precision antenna designs

Based on an assessment of future NASA and DOD space system requirements, the program was designed to verify four critical technology areas: 1) deployment, 2) shape accuracy and control, 3) pointing and alignment, and 4) articulation and maneuvers. The flight experiment technology verification objectives can be met using two shuttle flights with the total experiment integrated on a single Shuttle Test Experiment Platform (STEP) and a Mission Peculiar Experiment Support Structure (MPESS). First flight of the experiment can be achieved 60 months after go-ahead with a total program duration of 90 months.

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