



Large Deployable Reflector (LDR) System Concept and Technology Definition Study Volume II - Technology Assessment and Technology Development Plan

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Prepared for
Ames Research Center
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FOREWORD

This volume is the second of two that comprise the Final Technical Report. It includes technology assessments and plans prepared by Kodak and its two study team members, McDonnell Douglas Astronautics Company-Huntington Beach (MDAC) and Fairchild Space Company (FSC). Portions of the document primarily prepared by these team members are identified by their company initials (MDAC or FSC) following a section or paragraph heading.

Volume I contains the executive summary for the total study and a report of the systems analysis phase. Topics covered are: study approach and methodology; reports of thirteen system analysis and trade tasks; and descriptions of three selected LDR system concepts. Supporting information is contained in appendices to Volume I.

This Technology Assessment and Technology Development Plan is submitted in response to Article II, Section C, Paragraph 1, Item g of Contract NAS2-11861, Large Deployable Reflector System Concept and Technology Definition Study. The plan format corresponds to the draft outline provided by the NASA Technical Monitor.

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1.0 OVERVIEW

1.1 OBJECTIVE AND BACKGROUND

This Technology Assessment and Technology Development Plan defines a plan aimed at achieving requisite levels of technological capability prior to start of Phase C development of the Large Deployable Reflector (LDR) in the early 1990's. Prepared by Eastman Kodak Company and its subcontractors, McDonnell Douglas Astronautics Company-Huntington Beach and Fairchild Space Company, the plan comprises 22 individual technology development projects, whose sponsorship as technology initiatives by NASA is recommended during the time period 1986-1991.

This plan was developed as part of the LDR System Concept and Technology Definition Study under NASA-Ames Research Center Contract NAS2-11861. It addresses technology concerns derived from review of three system concepts of the LDR observatory synthesized by the Kodak team that are described in Section 2.0. Envisioned as a 20-meter diameter aperture astronomical telescope facility, primarily for observations in the range of 30 micrometers to 1 millimeter, LDR presents technology challenges in many areas. Implementation of the technology augmentation plans recommended herein can beneficially support an LDR schedule requiring technology readiness by year-end 1991.

The 22 proposed augmentation projects selected from more than 30 candidates are designed to accelerate the progress of technology growth essential to LDR, where the rate of growth over the next six years is projected to fall short of LDR needs, based on assessments by the Kodak team. A description of the assessment and plan development is presented in Paragraph 1.2 below.

The five LDR technology areas most in need of supplementary support, (rated "high" based on a high, medium, low, or not-rated prioritization of the candidates) are:

- Cryogenic cooling - demonstration of a hybrid (stored cryogenics and closed cycle mechanical cooler) system for the LDR science instruments.
- Human factors - demonstration of astronaut capability to assemble the optical precision LDR in space and to perform other roles.
- Active primary mirror - demonstration of an LDR unique, segmented, mirror design having tilt, piston, and figure control for each panel.
- Dynamic structural control - development of a dynamic simulation model of the LDR that links dispersed structural design and analysis techniques.
- Primary mirror contamination protection - development of means (such as strippable coatings) to protect the reflector on-orbit during deployment assembly, servicing revisits.

Seventeen other technology areas are adjudged to be of medium concern and augmentation support is also recommended. Assessments of these areas and descriptions of proposed development plans are presented in Section 3.0. Table 1.1-1 lists the 22 high and medium areas by title and provides a cross-reference to their location in Section 3.0, where they are arranged by Office of Aeronautics and Space Technology (OAST) categories.

TABLE 1.1-1

INDIVIDUAL TECHNOLOGY AUGMENTATION PROJECTS CROSS REFERENCE

OAST CATEGORY	TECHNOLOGY PROJECT TITLE	KODAK PROGRAM GROUP	PARAGRAPH LOCATION SECTION 3.0
HIGH PRIORITY (5 PROJECTS)			
B	DYNAMIC STRUCTURAL CONTROL	POINTING & STABILITY	3.2.1
D	HUMAN FACTORS	POINTING & STABILITY	3.4.1
E	HYBRID CRYOGENIC SYSTEM FOR SCIENCE INSTRUMENTS	DETECTABILITY	3.5.1
G	ACTIVE PRIMARY MIRROR	REFLECTOR QUALITY	3.7.1
G	PRIMARY MIRROR CONTAMINATION PROTECTION	DETECTABILITY	3.7.2
MEDIUM PRIORITY (17 PROJECTS)			
A	PRIMARY MIRROR SEGMENT SENSING AND CONTROL APPROACH	REFLECTOR QUALITY	3.1.1
A	FOLD MIRROR CHOPPING	DETECTABILITY	3.1.2
A	SECONDARY MIRROR CHOPPING	DETECTABILITY	3.1.3
A	FINE GUIDANCE SENSING AND CONTROL	POINTING & STABILITY	3.1.4
B	DYNAMIC DIMENSION STABILITY	POINTING & STABILITY	3.2.2
B	DYNAMIC RESPONSE PREDICTION PRECISION	POINTING & STABILITY	3.2.3
B	STRUCTURAL NONLINEARITY	POINTING & STABILITY	3.2.4
B	LOW JITTER AND RAPID SETTLING	POINTING & STABILITY	3.2.5
B	VERIFICATION/ACCEPTANCE GROUND TESTING	POINTING & STABILITY	3.2.6
B	MECHANICAL STABILITY - DAMAGE TOLERANCE	POINTING & STABILITY	3.2.7
B	STEP SUNSHIELD	DETECTABILITY	3.2.8
B	SECONDARY MIRROR TEMPERATURE CONTROL	DETECTABILITY	3.2.9
B	PRIMARY MIRROR TEMPERATURE CONTROL	DETECTABILITY	3.2.10
E	CRYOGENIC SYSTEMS FOR DETECTOR TEMPERATURE LESS THAN 0.3 DEGREES KELVIN	DETECTABILITY	3.5.2
E	ROBOTIC ON-ORBIT CRYOGENIC REPLENISHMENT	DETECTABILITY	3.5.3
G	GLASS MATERIAL FOR PRIMARY MIRROR	REFLECTOR QUALITY	3.7.3
G	COMPOSITE MATERIAL FOR THE PRIMARY MIRROR	REFLECTOR QUALITY	3.7.4

Kodak has synthesized three broad, time-phased, five-year programs from the 22 individual technology projects. This was done to better understand the interrelationships of the projects, so as to identify intermediate decision points where alternatives existed, and to consider the overall funding implications. The three programs are:

- Reflector Quality Program
- Pointing and Stability Program
- Detectability Program

The Reflector Quality Program comprises four interrelated projects concerned with primary mirror (reflector) materials development, selection of a mirror design, and mirror demonstration to meet LDR requirements.

The Pointing and Stability Program combines nine projects. Six are interrelated structural materials, structural design, and test developments. The Dynamic Structural Control simulation modeling is also in this group, as are the Human Factors and Fine Guidance projects.

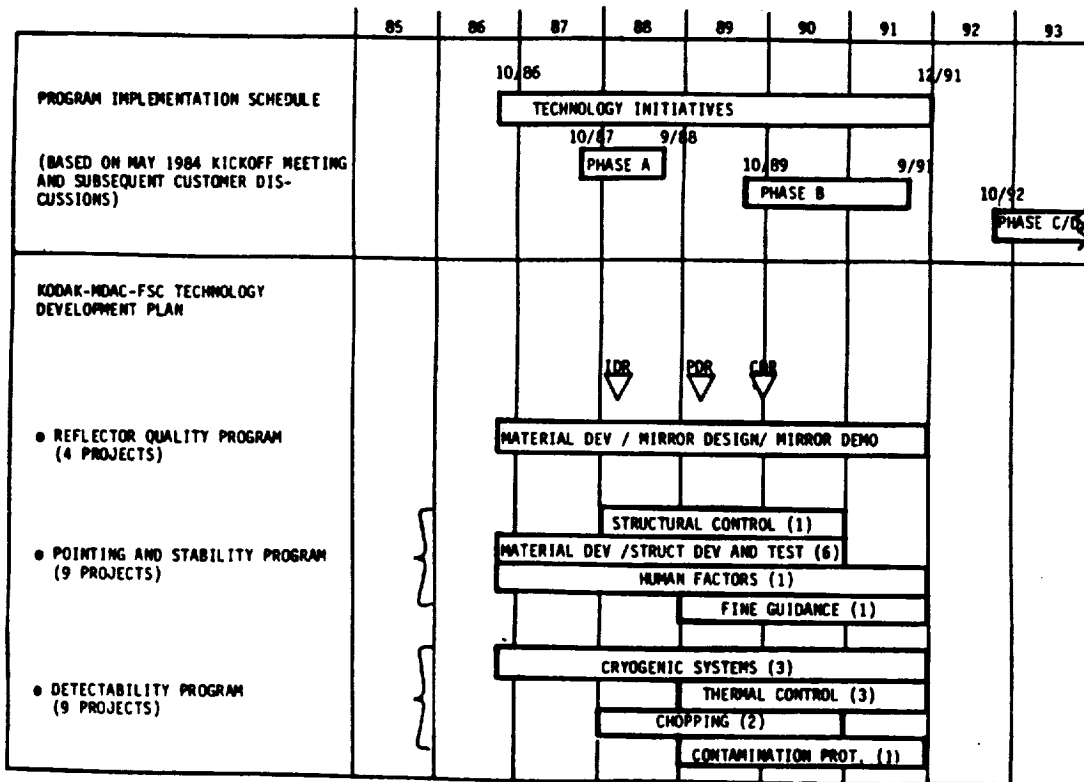
The Detectability Program also comprises nine projects. It deals with technologies that principally determine the ability of LDR to achieve its background-limited NEP sensitivity goals. Three projects are concerned with cryogenics, three with thermal control, two with chopping, and one is the Primary Mirror Contamination Protection Project, mentioned above.

A summary schedule of the Kodak-MDAC-FSC technology development plan is presented in Figure 1.1-1 along with milestones of the NASA LDR master schedule. Separate, more detailed time-phased plans for each of the three programs are included in Section 4.0.

The recommended funding for the technology development projects totals \$70.425 million (rough order of magnitude based on 1985 dollars not forward priced). The three component program funding levels are:

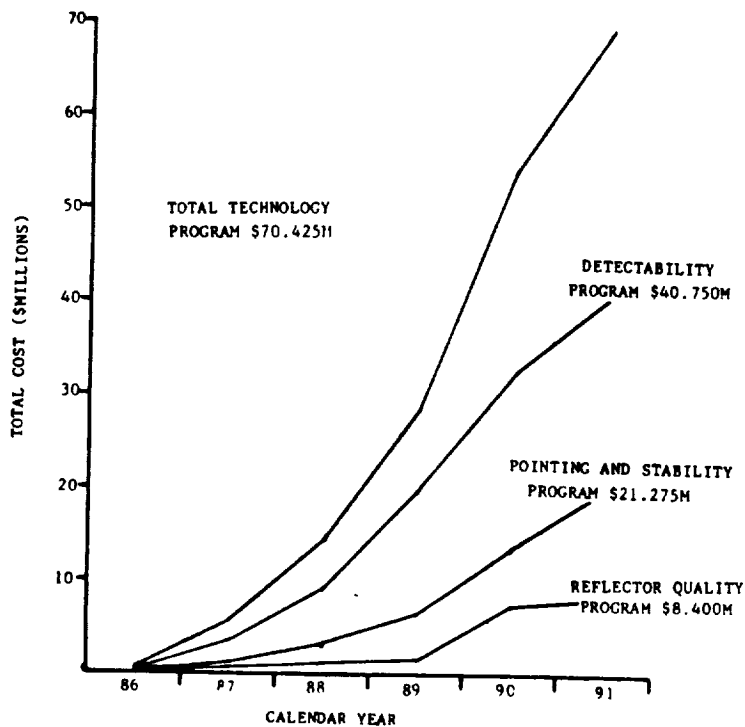
Detectability Program	\$40.750M
Pointing and Stability Program	21.275M
Reflector Quality Program	8.400M

Time-phased funding details by project and program are contained in Section 4.0. The cumulative funding profile is shown in Figure 1.1-2.



SUMMARY LDR TECHNOLOGY DEVELOPMENT SCHEDULE

Figure 1.1-1



TECHNOLOGY DEVELOPMENT PROJECTED FUNDING PROFILE (REVISED 25 FEBRUARY 1985)

Figure 1.1-2

1.2 SYSTEM CONCEPT AND TECHNOLOGY DEFINITION STUDY

This technology assessment and technology development plan is the principal output of an approximately one-year duration study effort, conducted for NASA-Ames Research Center.

This section briefly summarizes the baseline LDR requirements established for the study and their major implications, and describes the study rationale and tasks.

1.2.1 LDR Requirements and Implications

Requirements imposed for the study are reproduced in Figure 1.2-1. Implications with respect to design and technology concerns are highlighted in the following paragraphs, for the more significant requirements.

DIAMETER

The 20-meter aperture, eight times that of the Hubble Space Telescope, immediately infers that the LDR observatory must be mechanically designed to permit its assembly on orbit (automated or manually-assisted). Neither the payload bay of the Shuttle Orbiter nor the proposed Aft Cargo Compartment (on the aft end of the External Tank) can accommodate the packaging of LDR for transportation to orbit without complex folding, modularization, reliable deployment techniques, or astronaut-assisted construction. The 20-meter desired aperture, however, represents a "break-point" in potential LDR science return. The primary mirror, of necessity, is segmented, and requires means for initial establishment and maintenance of its ideal optical figure. Consequently, subsystems must be provided for measuring figure (wave front) and correcting segment tilt and piston errors, matching radius of curvature of the different segments, and, possibly for correcting the figure of the individual segments. (These are obviously driven by zero-g, thermal, and dynamic factors).

The sheer size of LDR forces lightweighting considerations in all designs. The primary mirror, support structure, and sunshield are significant contributors to the weight budget.

F/RATIO

The combination of the system and primary mirror f/ratios constitute a 20-fold magnification. This sets a very tight tolerance on secondary mirror alignment. Precision metering (perhaps by placing glass-matrix rods inside the secondary mirror support struts) of the secondary is required. A secondary mirror sensing and control system will be needed that can sense secondary mirror despace, tilt, and decenter errors and correct them, most likely by utilizing high-precision tilt and piston actuators behind the secondary mirror.

SHORTEST WAVELENGTH OF DIFFRACTION-LIMITED PERFORMANCE

This requirement establishes fundamental requirements on the total system wave front error and the budget allocated to each contributor. As written, the "diffraction-limited" modifier implies that approximately 84% of the energy collected from a point source be contained in the innermost bright spot of the Airy disk formed at the image plane, for the shortest wave length of best attainable performance. This criterion is a standard used in design of optical and infrared telescopes and instruments. The

Parameters	Requirements
Diameter	20 m primary, 1 m secondary
Field of view	≥ 3 arcmin
F/Ratio ^b	System F/10, primary F/0.5
Shortest wavelength of diffraction-limited performance	30-50 μm (aperture efficiency $> 30\%$ at 30 μm)
Light bucket blur circle ^a	2.0 arcsec (at 1-4 μm)
Optics temperature	Primary $\leq 200\text{K}$ (± 1 K uniformity), secondary ≤ 125 K (± 1 K uniformity)
Emissivity (system)	0.05
Absolute pointing	0.05 arcsec
Jitter	0.02 arcsec - within 1 min after slew
Slew	20 - 50°/min
Scan	1° x 1° - linear scan at 1°/min
Track	0.2°/hr (for comets $\geq 25^\circ$ from Sun)
Chopping ^b	Yes, 2 Hz, 1 arcmin (reactionless)
Sidelobes	Low near sidelobes
Other	Limited cross polarization
Sky exclusion	60°-90° from Sun, $\geq 45^\circ$ from Earth
Cryo system	Various temperatures in the range 0.1 K to 50K, 1.5 kW total power required
Lifetime	> 10 yr, approximately 3 yr revisit

^a The tolerances (e.g., rms surface accuracy) needed to achieve a value of 2 arcsec for the light bucket blur are more severe than the tolerances associated with a diffraction limit of 50 μm . This requirement will be studied further.

^b Approximate.

SELECTED LDR SYSTEM PARAMETERS AND PERFORMANCE REQUIREMENTS

Figure 1.2-1

bracketed requirement (that aperture efficiency exceed 30% at 30 μ m) is based on antenna gain definitions and is equivalent to a much less stringent requirement than the Airy disk criterion.

The literal interpretation of this requirement places tighter tolerance on RMS surface quality and budgeted optical alignment than does the interpretation that aperture efficiency of 30% is to be substituted for "diffraction-limited performance".

Figuring of optical surfaces to the more stringent Airy criterion is routinely performed successfully at much shorter wavelengths. Relaxation to the aperture efficiency criterion does suggest that the mirror processing time could be reduced (since the allowable surface error could be relaxed). The benefit, in terms of large tool processing applied to primary mirror glass substrates, does not appear significant, however.

This requirement, from a telescope design point-of-view, has major impact on the design of the LDR optical support structures. The array of segmented mirrors and optical system components must all be kept within budgeted alignment tolerances, in order to maintain the diffraction-limited performance goal. Maintenance of the stability of the primary mirror support structure for an observatory as large as LDR implies consideration of detailed modeling of the dynamics involved, thermal influences on design, interrelationship of the spacecraft control system and the mirror segment control system (including the degree of figure control and rigid body control required), properties of materials, and others.

OPTICS TEMPERATURE

The mirror temperature requirements are of profound importance to the design of LDR.

The need for uniformity of temperature on both these mirrors derives from the basic LDR concept that the local background noise sources be removed by chopping the received signal. (The relatively warm telescope mirrors emit energy in the same wavelength regions as the sources being observed). The effective elimination of background imposes the requirement for the $\pm 1^\circ\text{K}$ uniformity across the mirrors at a given instant, and suggests that the time-varying bulk mirror temperatures can be allowed to change only very slowly during a typical (30 minutes) observation (since the chopping rate is 2 hertz).

The bulk mirror temperature requirements force the utilization of a sunshield or shade and an overall telescope thermal design approach that considers the energy incident from the back of the primary mirror and support structure, the exclusion angles about the sun and earth, and the selected orbit, among many factors.

Since the secondary mirror bulk temperature (125°K) requirement is lower than the primary, thermal design of the secondary will probably require an active cooling concept. Maintenance of LDR image quality is strongly dependent on thermal designs that reduce temperature variability. The use of low coefficient-of-thermal-expansion materials is important in the reflector segments and its structural support. The thermal uniformity requirement on the mirrors implies that high conductivity paths may be required on mirror substrates to assure fast equilibration of varying heat loads. Isotropic CTE of mirror substrates is also essential.

ABSOLUTE POINTING, JITTER, SLEW, SCAN, AND TRACK

This set of requirements places severe requirements on the LDR structural design and pointing and control system, when considered in light of the size of LDR and its assembly mode on orbit.

The absolute pointing requirement implies the need for an optical fine guidance sensing system using a visible star catalog. Direct use of the primary mirror and secondary mirror are thus not acceptable since they are not finished to the quality necessary. A separate sensing system using an optical quality telescope will need to be carefully boresighted to the LDR telescope line of sight.

The jitter, slew, scan, and track requirements all influence the structural design, particularly the primary mirror support structure. The integrated structure of LDR must consider dynamic dimensional stability needs; structural nonlinearities; incorporation of passive techniques to limit jitter and promote rapid decay of dynamic deflections from both vibratory and attitude maneuver responses; one-g to zero-g effects; and the influence of astronaut assembly on the structure.

The control system for pointing the LDR must be adequate to achieve the ranges and accuracies imposed by these requirements (within the duty cycle set by the observation sequence). Its interaction with the fine guidance sensor must be fully defined.

The secondary mirror chopping design must provide for essentially reactionless response to satisfy jitter requirements.

CHOPPING

The chopping requirement calls for a very effective means for eliminating the background (telescope) noise from the signal.

Achievement by oscillating the secondary mirror impacts the secondary mirror support structure and assembly greatly. Combined with the need to cool the secondary, provide for tilt, decenter, and despace adjustments, reactionless chopping adds additional complexity to an already difficult design problem.

Fold mirror chopping (within the S/I compartment) is inherently less effective, adds complexity to the fold mirror assembly which is enclosed in a cryogenically cooled chamber, and has little heritage in ground-based telescope designs. Chopping demands extremely high reliability because it is absolutely critical to the performance of LDR, as it is currently conceived.

SIDELOBES

The requirement for low sidelobes influences the selection of the basic optical designs for LDR. Unfilled apertures, such as a "ring" interferometer, and slot configurations can not satisfy this requirement without special design or operational considerations. The Cassegrain optical configuration easily satisfies this requirement when the mirror segments are aligned and shaped to meet the optical figure tolerances.

SKY EXCLUSION

These requirements have great influence on the thermal control and sunshield design, and place operational restrictions on observations and pointing.

Cylindrical sunshield designs must consider the energy striking the interior when the line of sight is less than 90 degrees from the sun or earth's limb. Thus, a flare (cone or scoop) at the top of the cylinder or equivalent means, such as a step sunshield, must be utilized to meet the 60-degree sun exclusion and 45-degree earth exclusion angles.

CRYO SYSTEM

These extremely low temperature requirements for the science instruments imply very advanced cryogenic cooling systems must be developed for LDR.

Achievement of LDR detection goals is absolutely dependent upon providing adequately sized, reliable cooling. Initial cool down, parasitic losses, space/weight budgets and revisit intervals are factors that indicate a hybrid - - stored cryogen plus a mechanical refrigerator - - system is needed for the generic cooling of the S/I's.

To achieve 0.1°K, adiabatic demagnetization and/or the helium dilution technique will be needed to be developed.

A shutter (plug) may be necessary to isolate the S/I compartment for thermal control.

Contaminants, which have a proclivity to settle at the coldest portion of a system, must be considered in all areas of the cryogenically cooled S/I compartment, including the fold mirror that directs the telescope beam to the individual S/I's.

LIFETIME

Ten year life places basic design goals on all LDR elements, but many items may potentially be designed to be serviced, replaced, repaired, upgraded, or refurbished on-orbit.

The replenishment of cryogenics and propellants on a regular basis throughout the LDR life is considered absolutely essential. Robotic means (using an orbit maneuvering vehicle with smart front end servicer, for example) should be developed.

The lifetime and revisit interval establish basic orbit altitude requirements for LDR and consequent propellant needs for achieving operating altitude and returning to rendezvous with the shuttle or space station. The orbit environment will influence LDR design. Potential impact with space debris and micrometeoroids may call for damage tolerant materials or structurally redundant concepts.

Particulate contamination over the operational life of LDR could degrade primary mirror performance. Attention must be given to use of materials/designs that will minimize outgassing or release of particles.

1.2.2 Study Rationale and Tasks

In developing the design for an advanced space system, such as LDR, it is essential to carefully consider the level of technology readiness of each of the key elements of the proposed system. The probability of successful implementation of the system concept increases the more closely the levels of technology readiness of each of the key elements match the needed operational capability. This principle of program development is the basis for the LDR System Concept and Technology Definition Studies, contracted by NASA-Ames Research Center to two separate industry teams (headed by Eastman Kodak Company and Lockheed Palo Alto Research Laboratories). Each contractor team was tasked to perform LDR system analyses and trades, synthesize two or more concepts, assess the key technology issues, and lay out technology development plans to bring technology levels to the level considered necessary for an LDR development, assuming a technology cutoff date at year end 1991.

This plan was presented at the LDR Technology Planning Workshop, held March 17-22, 1985 at the Asilomar Conference Center in California. It is NASA's goal to subsequently establish a technology development initiatives program for LDR.

Figure 1.2.2-1 presents the overall Kodak study plan. It comprises six major tasks. Approximately 70% of the effort, as established by the contract statement of work (SOW), was performed in the study of systems analysis issues and development of system concepts (blocks above SOW Task 3.1 and 3.2 in Figure 1.2.2-1). During the system analysis task, some 13 issues were analyzed, a review of baseline requirements was performed, and science instrument considerations were surveyed. Based on these analyses, three LDR systems concepts were formulated and reported at Technical Progress Review No. 2 (see Section 2.0).

The final four tasks (SOW 3.3 thru 3.6) concern the Technology definition phase of the study. The activities involved in this phase are summarized in Figure 1.2.2-2.

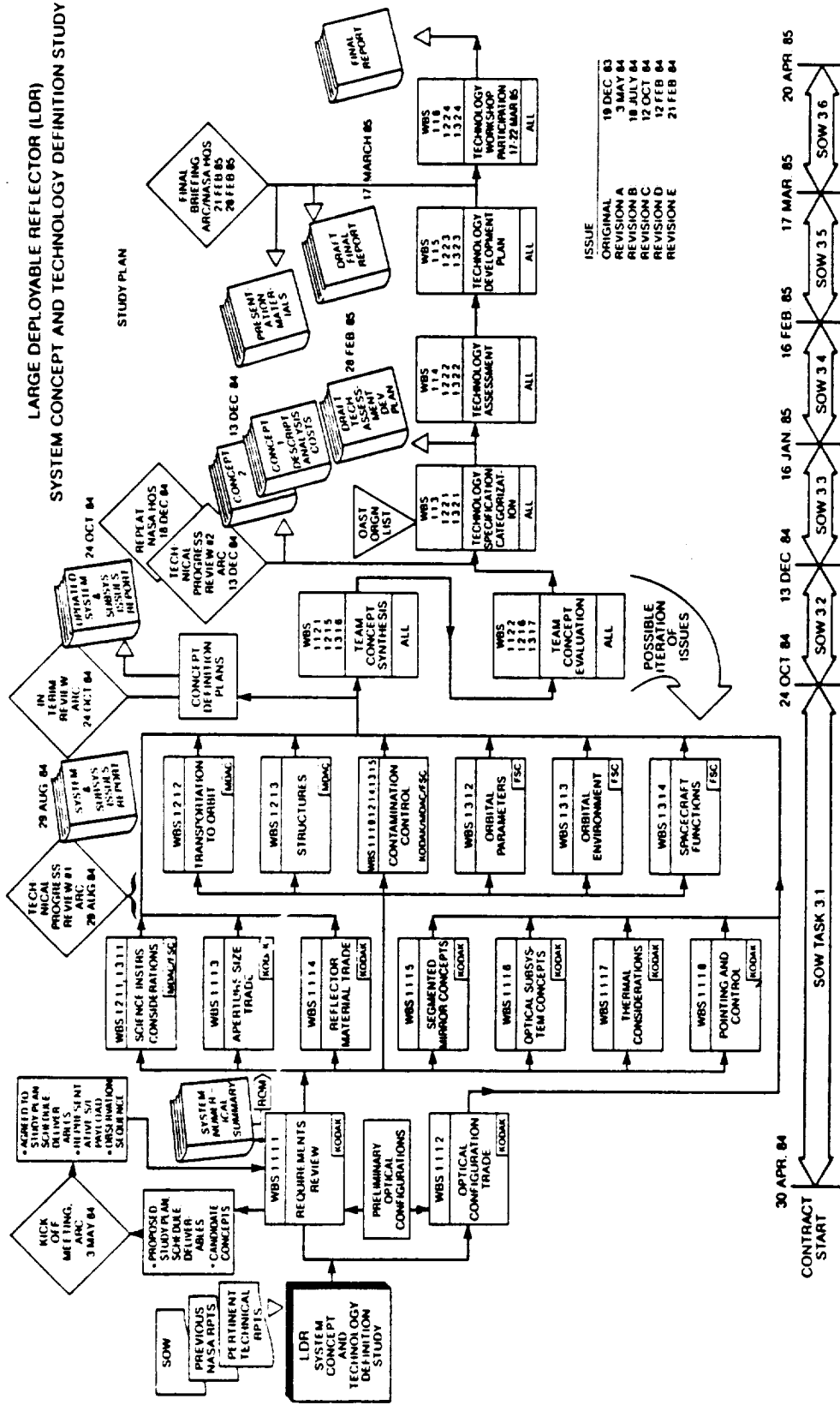
Conduct of these tasks proceeded as follows: In Step 1 (Figure 1.2.2-3) the three system concepts output from the early phase of the study were reviewed by the contractor team members with respect to their functional areas of concern assigned in the system analysis phase. The performance levels of technology issues were established and an initial candidate list of technology issues generated. This was reviewed by the team and a consolidated final list prepared. Each technology issue was then assigned to one of eight categories provided by NASA.

The 31 consolidated technology issues are listed in Table 1.2.2-1 below by the Office of Aeronautics and Space (OAST) categories.

In Step 2 (Figure 1.2.2-4), issues from the categorized technology list were investigated by the assigned contractor, and a technology assessment developed. This assessment included an evaluation of today's level of technology, a forecast of what it may be by the end of 1991 (without any LDR technology development support), and a goal for the level of readiness for LDR by 1991. This approach enabled technology shortfalls to be identified.

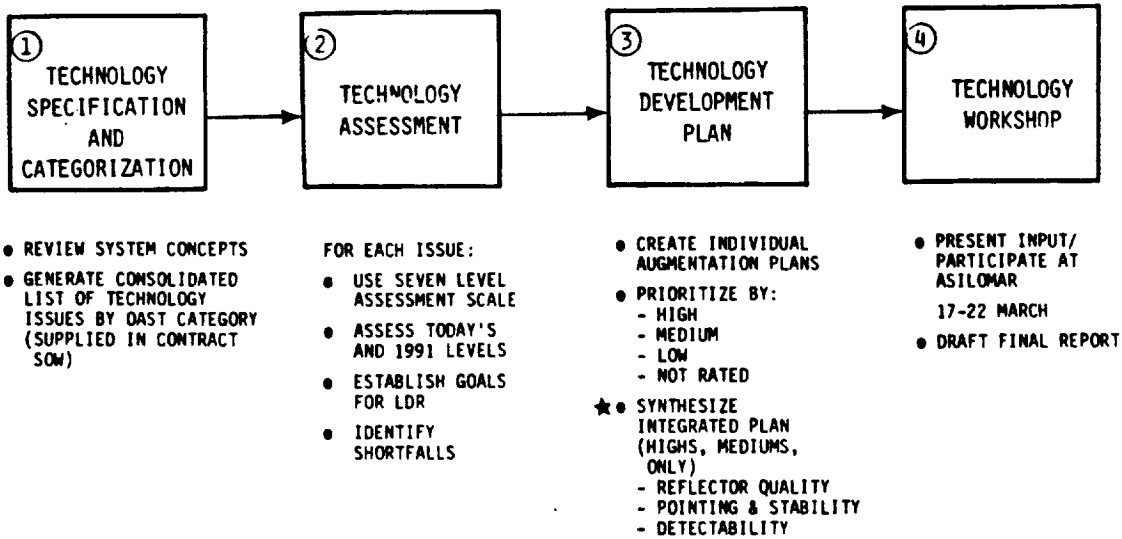
A schematic of the standardized assessment format is presented in Figure 1.2.2-5.

LARGE DEPLOYABLE REFLECTOR (LDR)
SYSTEM CONCEPT AND TECHNOLOGY DEFINITION STUDY



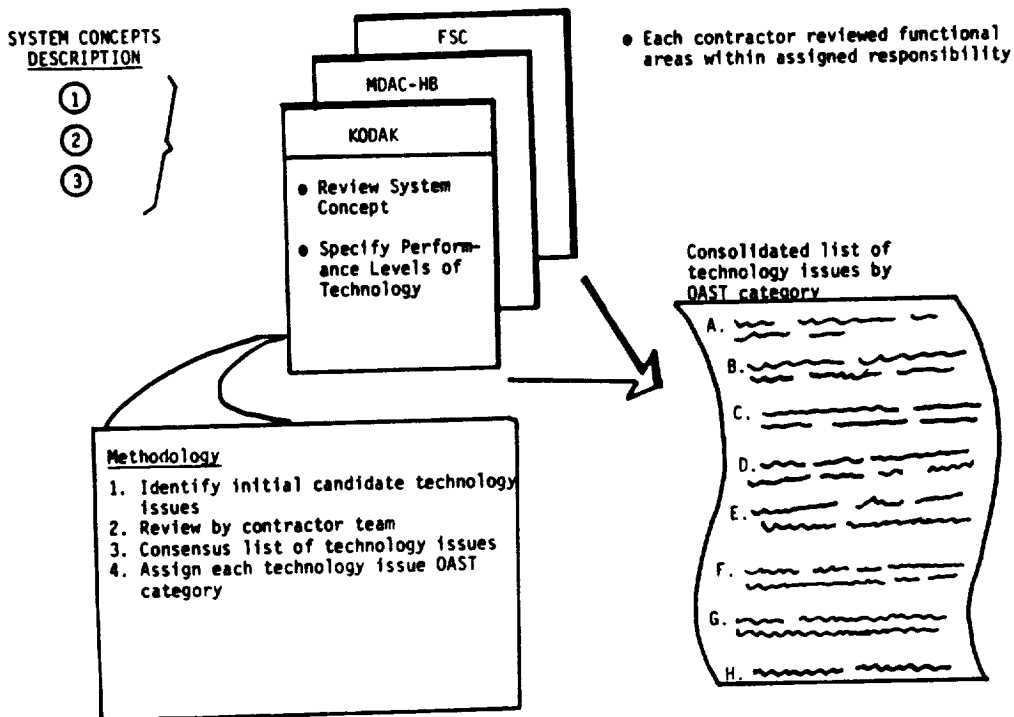
LARGE DEPLOYABLE REFLECTOR (LDR)
SYSTEM CONCEPT AND TECHNOLOGY DEFINITION STUDY

Figure 1.2.2-1



TECHNOLOGY DEFINITION PHASE OF STUDY

Figure 1.2.2-2



TASK ① TECHNOLOGY SPECIFICATION/CATEGORIZATION

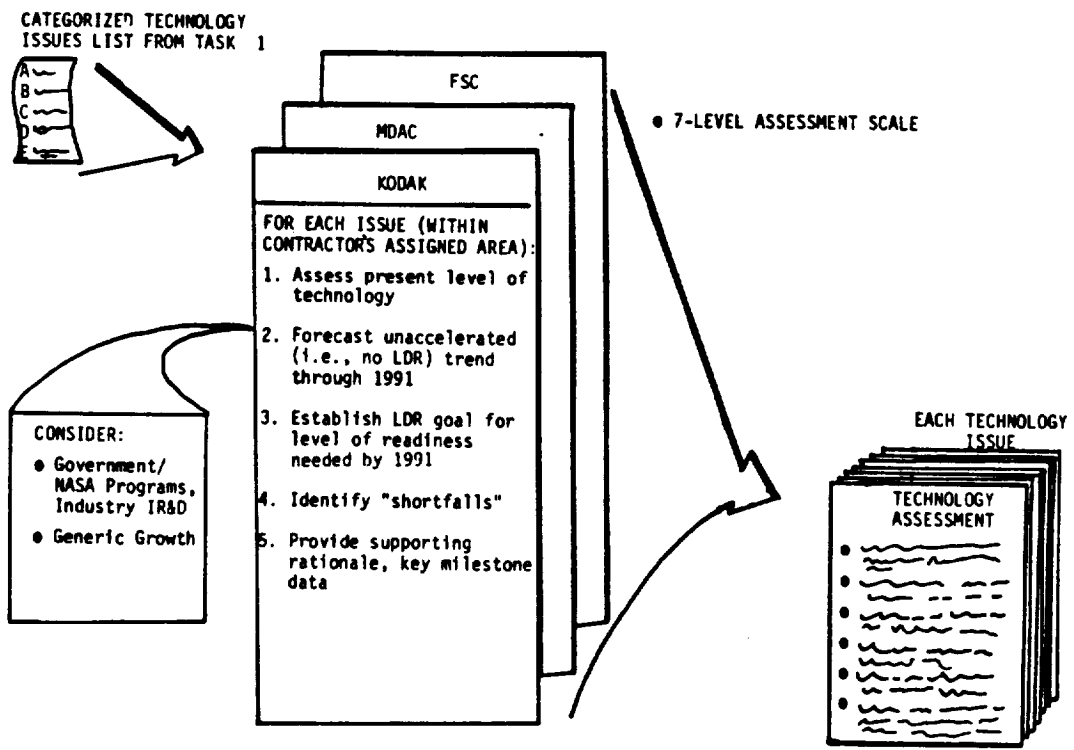
Figure 1.2.2-3

TABLE 1.2.2-1

CANDIDATE TECHNOLOGY ISSUES BY OAST CATEGORY

OAST CATEGORY/TITLE

- A. SENSING, CONTROLS, AND CONTROL ELECTRONICS
 - PRIMARY MIRROR SEGMENT SENSING AND CONTROL APPROACH
 - FOLD MIRROR CHOPPING
 - SECONDARY MIRROR CHOPPING
 - FINE GUIDANCE SENSING AND CONTROL
 - SECONDARY MIRROR SENSING AND CONTROL APPROACH
 - NOISE REDUCTION IN CONTROL MOMENT GYROS
- B. MATERIALS, STRUCTURES, THERMAL, AND DYNAMICS
 - DYNAMIC STRUCTURAL CONTROL
 - DYNAMIC DIMENSIONAL STABILITY
 - DYNAMIC RESPONSE PREDICTION PRECISION
 - STRUCTURAL NONLINEARITY
 - LOW JITTER AND RAPID SETTling
 - VERIFICATION/ACCEPTANCE GROUND TESTING
 - MECHANICAL STABILITY - DAMAGE TOLERANCE
 - STEP SUNSHIELD
 - SECONDARY MIRROR TEMPERATURE CONTROL
 - PRIMARY MIRROR TEMPERATURE CONTROL
 - COLLAPSIBLE SUNSHIELD
 - SPACECRAFT BUILDUP ON ORBIT
- C. PROPULSION AND POWER
 - STRUCTURAL DYNAMICS: ADVANCED POWER SYSTEM
 - MONOPROPELLANT REFUELING
- D. HUMAN FACTORS
 - HUMAN FACTORS
- E. CRYOGENICS AND SENSORS
 - HYBRID CRYOGENIC SYSTEM FOR SCIENCE INSTRUMENTS
 - CRYOGENIC SYSTEMS FOR DETECTOR TEMPERATURES LESS THAN 0.3°K
 - ROBOTIC ON-ORBIT CRYOGENIC REPLENISHMENT
- F. COMMUNICATIONS AND DATA HANDLING
 - NONE
- G. OPTICS MATERIALS AND FABRICATION
 - ACTIVE PRIMARY MIRROR
 - PRIMARY MIRROR CONTAMINATION PROTECTION
 - GLASS MATERIAL FOR THE PRIMARY MIRROR
 - COMPOSITE MATERIAL FOR THE PRIMARY MIRROR
 - OFF-AXIS MIRROR SEGMENT PROCESSING
- H. OTHER
 - ACC CONTAMINATION PROTECTION/REMOTE MANEUVERING ARM
 - SHUTTLE BAY CONTAMINATION PROTECTION

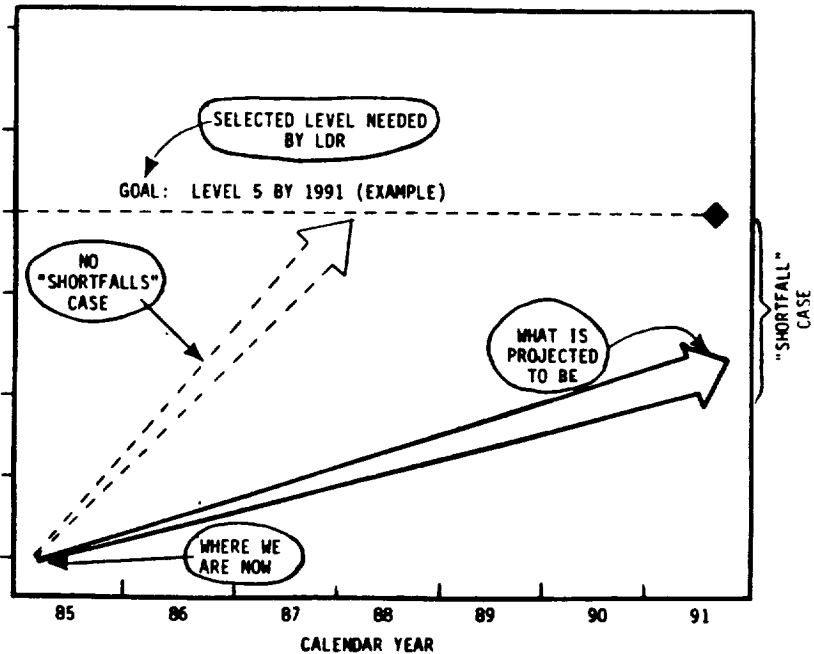


TASK 2 TECHNOLOGY ASSESSMENT

Figure 1.2.2-4

Technology Readiness Level

- 7 - ENGINEERING MODEL TESTED IN SPACE
- 6 - PROTOTYPE ENGINEERING MODEL TESTED IN RELEVANT ENVIRONMENT
- 5 - COMPONENT/BRASSBOARD TESTED IN RELEVANT ENVIRONMENT
- 4 - CRITICAL FUNCTION/CHARACTERISTIC DEMONSTRATION
- 3 - CONCEPTUAL DESIGN TESTED ANALYTICALLY OR EXPERIMENTALLY
- 2 - CONCEPTUAL DESIGN FORMULATED
- 1 - BASIC PRINCIPLES OBSERVED/ REPORTED



TECHNOLOGY ASSESSMENT SUMMARY FORMAT
Figure 1.2.2-5

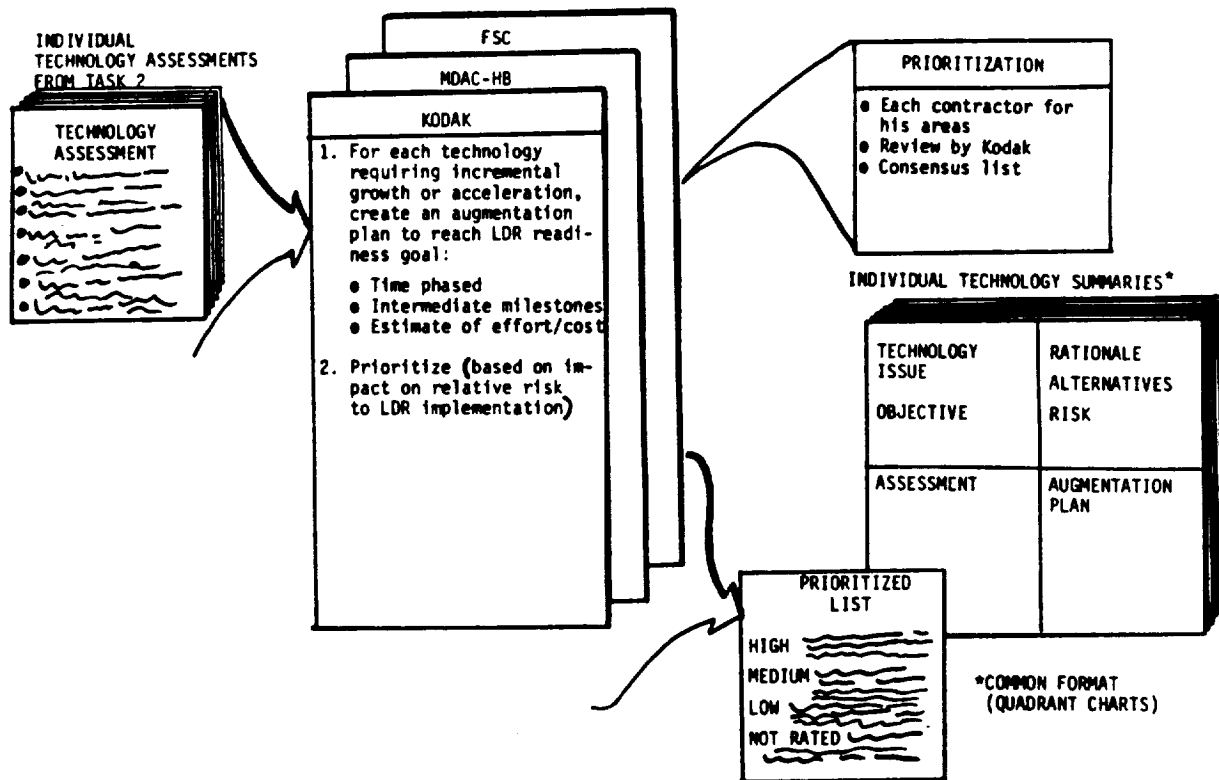
Note that the assessment uses the seven-level technology readiness scale of the NASA System Technology Model.

In Step 3 (Figure 1.2.2-6), individual technology development plans were generated where shortfalls had been identified in the assessments prepared in Step 2. These were formatted into "quadrant" charts, standardized by the LDR contract Technical Monitor.

Prioritization of the plans was accomplished in an iterative process that rated each plan as to its impact on relative risk to LDR implementation.

Ratings of high, medium, low, or not-rated were assigned using the criteria listed in Figure 1.2.2-7.

The final rankings tallied to 5 highs, 17 mediums, 4 lows, and 5 not-rated. These plans are listed in Table 1.2.2-2 by rank and OAST category.



TASK ③ TECHNOLOGY DEVELOPMENT
Figure 1.2.2-6

RANK	CRITERIA
HIGH	<ul style="list-style-type: none"> ● LDR UNIQUE AND REQUIRES MAJOR ADVANCE IN STATE-OF-THE-ART ● NO REASONABLE ALTERNATIVES IF NEED UNSATISFIED ● CRITICAL TO PERFORMANCE OF LDR ● HIGH PAYOFF POTENTIAL IF SUCCESSFUL ● LONG DEVELOPMENT EFFORT FORESEEN
MEDIUM	<ul style="list-style-type: none"> ● LDR UNIQUE AND SOME IMPROVEMENT EXCEEDING PROJECTED STATE-OF-THE-ART IS REQUIRED ● ALTERNATIVE APPROACH IDENTIFIED ● MINOR PERFORMANCE IMPACT IF UNSUCCESSFUL IN SATISFYING NEED
LOW	<ul style="list-style-type: none"> ● SIMILAR ACTIVITIES IN PROGRESS IN NASA, DOD, OR INDUSTRY IR&D WITH HIGH CONFIDENCE OF SUCCESS ● SMALL IMPROVEMENT IN STATE-OF-THE-ART REQUIRED ● SEVERAL ALTERNATIVES ARE POSSIBLE
NOT RANKED	<ul style="list-style-type: none"> ● INTERRELATED WITH EXTERNAL FACTORS ● CONSTRAINED BY STUDY SCOPE/TIME

TECHNOLOGY DEVELOPMENT PRIORITIZATION CRITERIA
Figure 1.2.2-7

TABLE 1.2.2-2
PRIORITIZED TECHNOLOGY AUGMENTATION PROGRAMS

HIGH - 5

<u>OAST CATEGORY</u>	<u>TECHNOLOGY</u>
B	DYNAMIC STRUCTURAL CONTROL
D	HUMAN FACTORS
E	HYBRID CRYOGENIC SYSTEM FOR SCIENCE INSTRUMENTS
G	ACTIVE PRIMARY MIRROR
G	PRIMARY MIRROR CONTAMINATION PROTECTION

MEDIUM - 17

<u>OAST CATEGORY</u>	<u>TECHNOLOGY</u>
A	PRIMARY MIRROR SEGMENT SENSING AND CONTROL APPROACH
A	FOLD MIRROR CHOPPING
A	SECONDARY MIRROR CHOPPING
A	FINE GUIDANCE SENSING AND CONTROL
B	DYNAMIC DIMENSIONAL STABILITY
B	DYNAMIC RESPONSE PREDICTION PRECISION
B	STRUCTURAL NONLINEARITY
B	LOW JITTER AND RAPID SETTLING
B	VERIFICATION/ACCEPTANCE GROUND TESTING
B	MECHANICAL STABILITY - DAMAGE TOLERANCE
B	STEP SUNSHIELD
B	SECONDARY MIRROR TEMPERATURE CONTROL
B	PRIMARY MIRROR TEMPERATURE CONTROL
E	CRYOGENIC SYSTEMS FOR DETECTOR TEMPERATURES LESS THAN 0.3°K
E	ROBOTIC ON-ORBIT CRYOGENIC REPLENISHMENT
G	GLASS MATERIAL FOR THE PRIMARY MIRROR
G	COMPOSITE MATERIAL FOR THE PRIMARY MIRROR

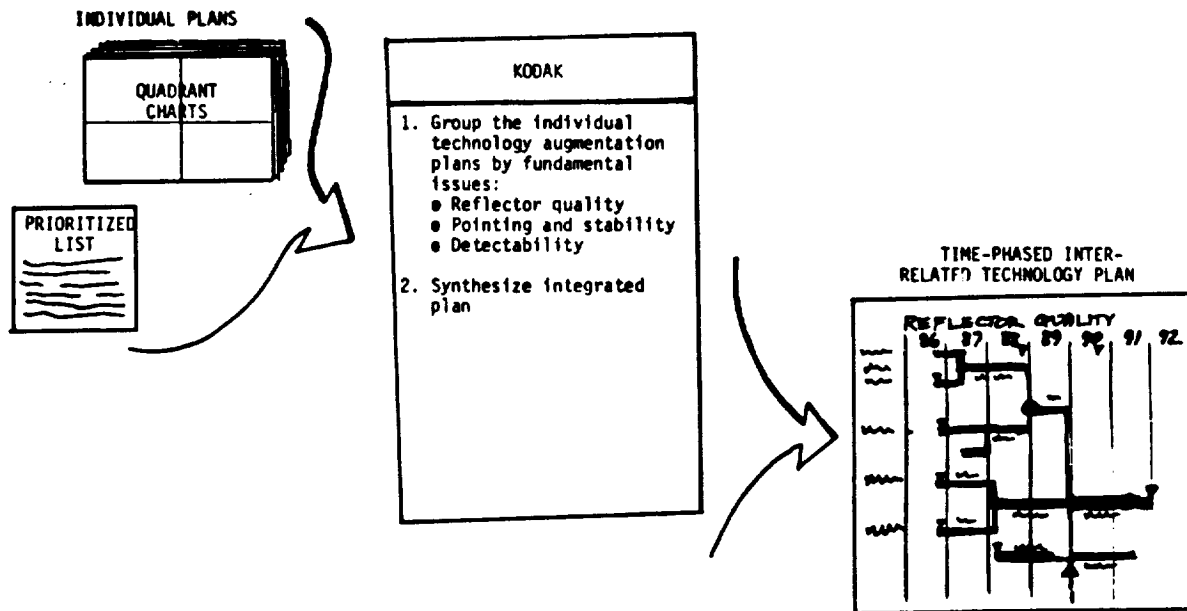
LOW - 4

<u>OAST CATEGORY</u>	<u>TECHNOLOGY</u>
A	SECONDARY MIRROR SENSING AND CONTROL APPROACH
B	COLLAPSIBLE SUNSHIELD
B	SPACECRAFT BUILDUP ON ORBIT
G	OFF-AXIS MIRROR SEGMENT PROCESSING

NOT RATED - 5

A	NOISE REDUCTION IN CONTROL MOMENT GYROS
C	STRUCTURAL DYNAMICS: ADVANCED POWER SYSTEM
C	MONOPROPELLANT REFUELING
H	ALC CONTAMINATION PROTECTION/REMOTE MANEUVERING ARM
H	SHUTTLE BAY CONTAMINATION PROTECTION

Kodak then proceeded to synthesize an integrated technology development plan by grouping individual augmentation plans rated high or medium under one of three fundamental issues as shown in Figure 1.2.2-8.



TASK ③ INTEGRATED TECHNOLOGY DEVELOPMENT PLAN
Figure 1.2.2-8

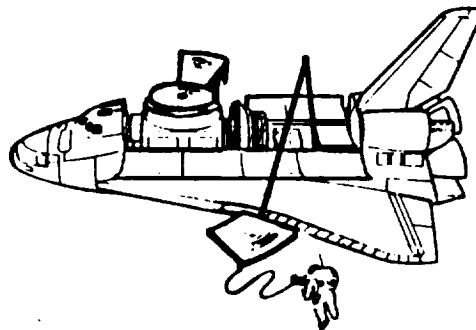
"Quadrant charts" for all of the high/medium rated technologies are included in the technology assessments of Section 3.0.

2.0 SYSTEM CONCEPTS

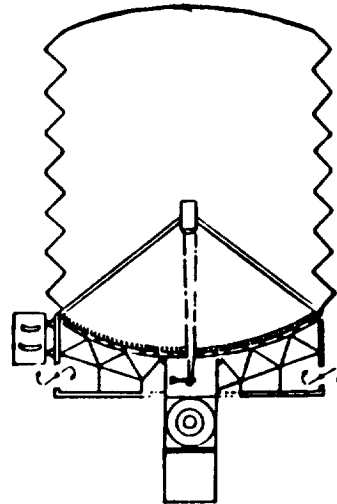
The Kodak team has synthesized three LDR system concepts. These concepts served as aids in defining technology development needs for LDR. Conclusions of the trades performed in the system analysis phase have been incorporated. Different subsystem approaches have been included to insure alternative choices are given visibility. Therefore, the system concepts presented are non-optimized (but representative) and arbitrarily configured to encompass technology candidates. It must be emphasized that the orbital deployment mode has a major system impact.

2.1 CONCEPT 1: MULTIPLE SHUTTLE ASSEMBLY

Concept 1 incorporates an assembly concept utilizing the Shuttle orbiter only (Figure 2.1-1). The goal is to get the LDR up in three Shuttle loads. However, as many as three additional Shuttles for astronaut assembly may be required. In this concept, EVA time must be minimized. This could be accomplished by: (1) maximizing manufacturing and testing on the ground, (2) complete LDR observatory checkout on the ground (i.e., disassembly and reassemble in-orbit), (3) transporting to orbit finished assemblies where possible, (4) utilizing RMS device(s) with EVA assist and (5) utilizing "simple" latching mechanisms. The LDR observatory concept (Figure 2.1-2) is a "true" Cassegrain telescope with trapezoidal primary mirror segments. Chopping would be performed with the secondary mirror. A summary of Concept 1 features is given in Table 2.1-1. The system highlights are shown in Table 2.1-2.



CONCEPT 1: MULTIPLE SHUTTLE ASSEMBLY
Figure 2.1-1



- CASSEGRAIN
- 8 S/I's IN ONE MODULE
- TRAPEZOID SEGMENTS
- SM CHOPPING
- 20 METERS

LDR OBSERVATORY
Figure 2.1-2

TABLE 2.1-1
CONCEPT 1: SUMMARY

OPTICAL CONFIGURATION

- "TRUE" CASSEGRAIN
- PARABOLIC PRIMARY MIRROR
- 1.3 M HYPERBOLIC SECONDARY MIRROR
- PM AND SM BAFFLE MAY BE REQUIRED

APERTURE SIZE

- 20-METER FILLED APERTURE
- <3 SHUTTLE LOADS

REFLECTOR MATERIAL

- GLASS (SELECTED FOR EXCELLENT CTE AND CTE VARIABILITY)

SEGMENTED MIRROR CONCEPT

- TRAPEZOIDAL SEGMENTS
- RIGID BODY MOTION CONTROL ONLY (TILT AND PISTON)

OPTICAL SUBSYSTEM CONCEPTS

- GLASS SECONDARY MIRROR
- TRIPLE BIPOD GRAPHITE/EPOXY METERING
- RIGID BODY MOTION CONTROL (TILT, DECENTER, DESPACE)

THERMAL CONSIDERATIONS

- PASSIVE PM WITH TRIM HEATERS
- THERMAL SHROUD ("STEP SHIELD")
- CRYO-FLUID STORAGE AND ACTIVE REFRIGERATION SYSTEM FOR SCIENTIFIC INSTRUMENTS AND SECONDARY MIRROR

POINTING AND CONTROL

- BODY POINTING ABOUT SYSTEM CENTER OF MASS
- FINE GUIDANCE SENSING WITH SEPARATE VISIBLE TELESCOPE
- CHOPPING WITH SECONDARY MIRROR

TRANSPORTATION TO ORBIT

- 3 SHUTTLE LOADS
- RMS DEVICE(S) WITH EVA ASSIST
- "SIMPLE" LATCHING MECHANISMS

STRUCTURES

- GRAPHITE/EPOXY TRIPLE BIPOD SECONDARY MIRROR SUPPORT
- GRAPHITE/EPOXY TETRAHEDRAL TRUSS PM REACTION STRUCTURE
- REFERENCE PLATFORM UNDER CENTER PM CORE
- THERMAL SHROUD ("STEP SHIELD")

CONTAMINATION CONTROL

- PRIMARY MIRROR PROTECTION (STRIPPABLE COATING)
- POSSIBLE COLLAPSABLE THERMAL SHROUD FOR SHUTTLE REVISIT

SPACECRAFT FUNCTIONS

- PROVIDE SPACE PLATFORM CAPABILITY THROUGH LDR OBSERVATORY ASSEMBLY
- ORBITAL PARAMETERS ($i = 28.5^\circ$; $h > 600$ KM)

TABLE 2.1-2
CONCEPT 1. SYSTEM HIGHLIGHTS

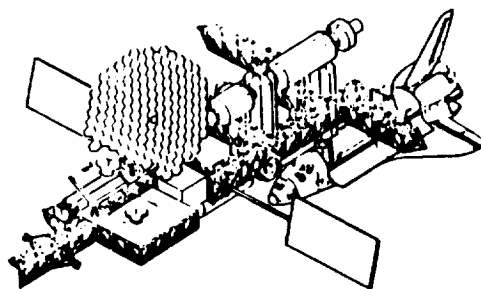
LAUNCH VEHICLE(S)	≤3 SHUTTLES FOR OBSERVATORY COMPONENTS (DEDICATED) ~3 SHUTTLES FOR ASTRONAUT ASSEMBLY, CHECKOUT (SHARED)
ASSEMBLY PLATFORM (28.5° INCLINATION, SHUTTLE/SS ALTITUDE)	SPACECRAFT INTEGRAL TO LDR (ACCOMMODATES VARYING MASS PROPERTIES)
INSERTION INTO OPERATIONAL ALTITUDE (>600 KM)	PROPULSION SYSTEM IN INTEGRAL SPACECRAFT
PRIMARY MODE FOR SERVICE/CHANGEOUT (3 YEAR INTERVALS)	OMV FROM SHUTTLE (SMART FRONT END SERVICER)
ASSUMPTIONS	SHUTTLE ONLY AVAILABLE (NO SPACE STATION, ACC)

2.2 CONCEPT 2. SPACE STATION ASSEMBLY

Concept 2 is a Space Station assembled concept utilizing three Shuttles to transport the observatory components and the support equipment (Figure 2.2-1). The first load will consist of the LDR spacecraft, the science instrument unit and the core mirror segments pre-assembled as a set into their flight configuration. Individual mirror segments will be transported to orbit in a special storage rack in the orbiter cargo bay, and shrouded in some fashion to prevent contamination. EVA support will probably be required for (1) the interim truss deployment/rigidization function as well as (2) the truss to mirror set attachment. Erection of the sunshield and secondary mirror will occur after assembly of the primary mirror segments. The LDR mirrors are sensitive to particulate and gas-film deposition; therefore, there may be a requirement for some sort of environmental shielding enclosing the LDR during Space Station assembly. The LDR observatory concept (Figure 2.2-2) is a "true" Cassegrain telescope with hexagonal primary mirror segments. Chopping would be performed with the secondary mirror. A summary of Concept 2 features is given in Table 2.2-1. The system highlights are shown in Table 2.2-2.

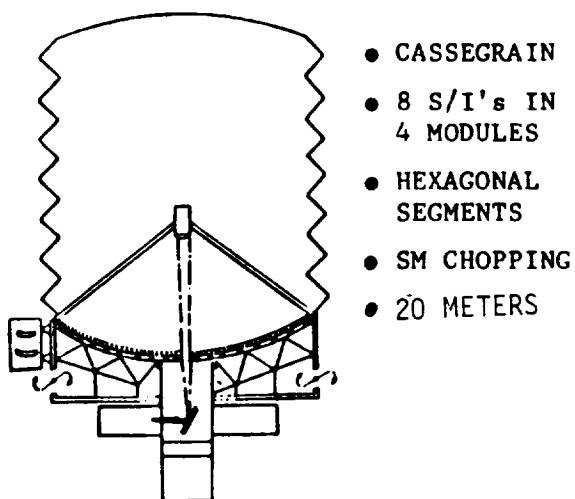
2.3 CONCEPT 3. SINGLE SHUTTLE/ACC ASSEMBLY

The general purpose External Tank Aft Cargo Carrier (ACC) has been suggested as a potential means to transport LDR to orbit. The ACC has a usable volume of 266 cubic meters (9,000 cubic feet) or 60% of the orbiter by volume. Concept 3 utilizes this increased volume capability (Figure 2.3-1). Without a free-flying platform or Space Station, this LDR concept will require total buildup in one Shuttle launch. The LDR primary mirror segments would be stowed as sets in the ACC. The rest of the LDR



CONCEPT 2: SPACE STATION ASSEMBLY

Figure 2.2-1



LDR OBSERVATORY

Figure 2.2-2

TABLE 2.2-1
CONCEPT 2: SUMMARY

OPTICAL CONFIGURATION

- 2-MIRROR TELESCOPE
- PARABOLIC PRIMARY MIRROR
- 1.3-METER HYPERBOLIC SECONDARY MIRROR
- PM AND SM BAFFLE MAY BE REQUIRED

APERTURE SIZE

- 20-METER FILLED APERTURE

REFLECTOR MATERIAL

- GLASS (SELECTED FOR EXCELLENT CTE AND CTE VARIABILITY)

SEGMENTED MIRROR CONCEPT

- HEXAGONAL SEGMENTS
- RIGID BODY MOTION CONTROL (PISTON AND TILT)

OPTICAL SUBSYSTEM CONCEPTS

- GLASS SECONDARY MIRROR
- TRIPLE BIPOD GRAPHITE/EPOXY METERING OF SECONDARY MIRROR
- RIGID BODY MOTION CONTROL (TILT, DECENTER, DESPACE)

THERMAL CONSIDERATIONS

- PASSIVE PM WITH TRIM HEATERS
- THERMAL SHROUD ("STEP SHIELD")
- CRYO-FLUID STORAGE AND ACTIVE REFRIGERATION SYSTEM FOR SCIENTIFIC INSTRUMENTS AND SECONDARY MIRROR

POINTING AND CONTROL

- BODY POINTING ABOUT SYSTEM CENTER OF MASS
- FINE GUIDANCE SENSING WITH SEPARATE VISIBLE TELESCOPE
- CHOPPING WITH SECONDARY MIRROR

TRANSPORTATION TO ORBIT

- THREE SHUTTLE LOADS

STRUCTURES

- GRAPHITE/EPOXY TRIPLE BIPOD SECONDARY MIRROR SUPPORT
- GRAPHITE/EPOXY TETRAHEDRAL TRUSS PM REACTION STRUCTURE
- REFERENCE PLATFORM UNDER PM CORE
- THERMAL SHROUD ("STEP SHIELD")

CONTAMINATION CONTROL

- PRIMARY MIRROR PROTECTION (STRIPPABLE COATING)
- CONTAMINATION SHROUD ON SPACE STATION POSSIBLY NEEDED

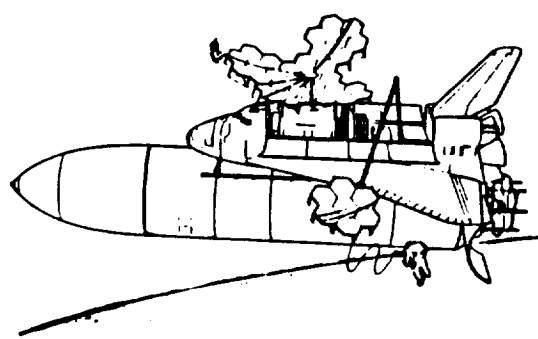
SPACECRAFT FUNCTIONS

- ORBITAL PARAMETERS ($i = 28.5^\circ$; $h \geq 600$ KM)

TABLE 2.2-2
CONCEPT 2: SYSTEM HIGHLIGHTS

LAUNCH VEHICLE(S)	≤3 SHUTTLES FOR OBSERVATORY COMPONENTS, ASSY/CHECKOUT SUPPORT EQUIPMENT
ASSEMBLY PLATFORM (28.5° INCLINATION, SHUTTLE/SS ALTITUDE)	SPACE STATION AND SPACECRAFT INTEGRAL TO LDR
INSERTION INTO OPERATIONAL ALTITUDE (≥600 KM)	PROPULSION SYSTEM IN INTEGRAL SPACECRAFT
PRIMARY MODE FOR SERVICE/CHANGEOUT (3 YEAR INTERVALS)	OMV FROM SPACE STATION (SMART FRONT END SERVICER)
ASSUMPTIONS	MANNED SPACE STATION AVAILABLE (NO ACC)

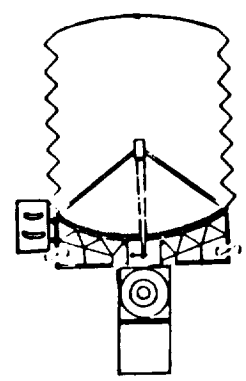
observatory (spacecraft, scientific instruments, secondary mirror assembly, shroud, etc.) and support equipment would be stowed in the Orbiter Bay. Packing density will limit the size of LDR below the 20 meter requirement. The LDR observatory concept (Figure 2.3-2) is a "true" Cassegrain telescope with hexagonal segments. Chopping would be performed by a fold mirror. A summary of Concept 3 features is given in Table 2.3-1. The system highlights are shown in Table 2.3-2.



CONCEPT 3: SINGLE SHUTTLE/ACC ASSEMBLY

Figure 2.3-1

- CASSEGRAIN
- 4 S/I's IN ONE MODULE
- HEXAGONAL SEGMENTS
- FOLD MIRROR CHOPPING
- 13 METERS



LDR OBSERVATORY

Figure 2.3-2

TABLE 2.3-1
CONCEPT 3: SUMMARY

OPTICAL CONFIGURATION

- "TRUE" CASSEGRAIN
- PARABOLIC PRIMARY MIRROR
- 0.85-METER HYPERBOLIC SECONDARY MIRROR

APERTURE SIZE

- 13-METER FILLED APERTURE
- 1 SHUTTLE WITH ACC

REFLECTOR MATERIAL

- GLASS (SELECTED FOR EXCELLENT CTE AND CTE VARIABILITY)

SEGMENTED MIRROR CONCEPT

- HEXAGONAL SEGMENTS IN 7 SEGMENT SETS
- RIGID BODY MOTION CONTROL ONLY (TILT AND PISTON)

OPTICAL SUBSYSTEM CONCEPTS

- GLASS SECONDARY MIRROR
- TRIPPLE BIPOD GRAPHITE/EPOXY METERING OF SECONDARY
- RIGID BODY MOTION CONTROL (TILT, DECENTER, DESPACE)

THERMAL CONSIDERATIONS

- PASSIVE PM WITH TRIM HEATERS
- THERMAL SHROUD ("STEP SHIELD")
- CRYO-FLUID STORAGE AND ACTIVE REFRIGERATION SYSTEM FOR SCIENTIFIC INSTRUMENTS AND SECONDARY MIRROR

POINTING AND CONTROL

- BODY POINTING ABOUT SYSTEM CENTER OF MASS
- FINE GUIDANCE SENSING WITH SEPARATE VISIBLE TELESCOPE
- CHOPPING WITH PLANO FOLD MIRROR

TRANSPORTATION TO ORBIT

- PM SEGMENT MODULES IN ACC
- REST OF LDR OBSERVATORY STORED IN ORBITER BAY
- RMS DEVICE(S) WITH EVA ASSIST
- "SIMPLE" LATCHING MECHANISMS

STRUCTURES

- GRAPHITE/EPOXY TRIPLE BIPOD SECONDARY MIRROR SUPPORT
- GRAPHITE/EPOXY TETRAHEDRAL TRUSS PM REACTION STRUCTURE
- THERMAL SHROUD ("STEP SHIELD")
- REFERENCE PLATFORM UNDER CENTER PM CORE

CONTAMINATION CONTROL

- PRIMARY MIRROR PROTECTION (STRIPPABLE COATING)

SPACECRAFT FUNCTIONS

- PROVIDE SPACE PLATFORM CAPABILITY THROUGH LDR OBSERVATORY ASSEMBLY
- ORBITAL PARAMETERS ($i = 28.5^\circ$; $h \geq 600$ KM)

TABLE 2.3-2
CONCEPT 3: SYSTEM HIGHLIGHTS

LAUNCH VEHICLE(S)	1 SHUTTLE/ACC
ASSEMBLY PLATFORM (28.5° INCLINATION, SHUTTLE/SS ALTITUDE)	SPACECRAFT INTEGRAL TO LDR (SUPPORTED FROM SHUTTLE PAYLOAD BAY)
INSERTION INTO OPERATIONAL ALTITUDE (≥ 600 KM)	PROPULSION SYSTEM IN INTEGRAL SPACECRAFT
PRIMARY MODE FOR SERVICE/ CHANGEOUT (3 YEAR INTERVALS)	OMV FROM SHUTTLE/ACC (SMART FRONT END SERVICER)
ASSUMPTIONS	SHUTTLE/ACC AVAILABLE (NO SPACE STATION)

3.0 TECHNOLOGY ASSESSMENT

3.1 SENSING, CONTROLS, AND CONTROL ELECTRONICS (OAST CATEGORY A)

3.1.1 Primary Mirror Segment Sensing and Control Approach

The primary mirror will be a coherently phased segmented mirror requiring tilt and piston actuation and possibly figure control. A companion sensing concept will be required for any actuation. Figure 3.1.1-1 represents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

KEY ISSUES

- Develop a shroud which meets the solar and energy exclusion angle requirements and maintains the primary mirror at 200°K ±1K. This shroud will also provide contamination protection during observatory assembly, operation and revisiting; therefore, the shroud cannot be made from material(s) which either outgas or emit loose particles.

OBJECTIVES

- Develop a step sun shield using coatings, materials, geometry to minimize overall sun shield size.
- Space qualification program (coatings and materials) if required.
- Proof-of-concept demonstration
- Engineering model test on-ground
- Engineering model test in space (?)

RATIONALE

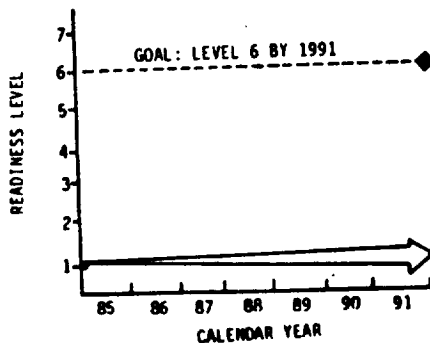
- 10 year life space qualified coatings (high c low a's; low c high a's; low c low a's) for optical baffles are required.
- 10 year life space qualified reflective/transmittive coatings for optics are required.
- Non-contaminating lightweight structural materials and deployment hardware are required.

ALTERNATIVES

- Simple cylinder or tapered cylinder (overall size will be "much larger" for tapered cylinder; heat load will be "much higher" for simple cylinder).

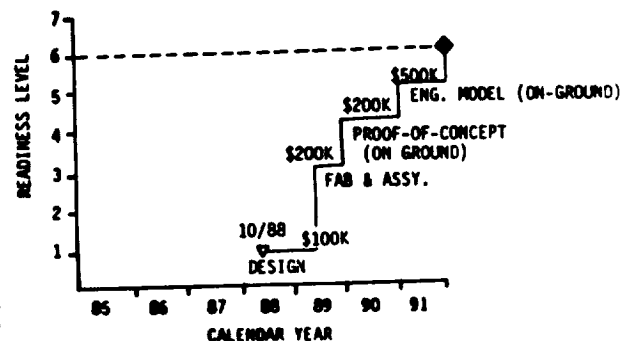
TECHNOLOGY ASSESSMENT

No other programs to develop step sunshield identified



SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

3 1/2 year, \$1M program to reach engineering model demonstration (on-ground) by January 1992.



CATEGORY B. MATERIALS, STRUCTURES, THERMAL, AND DYNAMICS STEP SUNSHIELD Figure 3.1.1-1

3.1.1.1 Requirements Derived from Concepts - A decision should be made in 1989 to proceed with one of two versions of a segmented mirror. The first version is called a passive segmented mirror in which each segment maintains its shape in space after polishing on the ground. The segments are coherently phased by rigid body motion control of the unconstrained degrees of freedom (1 translation called piston and 2 rotations called tilt). The requirements established by the study for maximum

allowable tilt error is 0.6 microradian and for maximum allowable piston error is 1.3 micrometers. The second version is called an active segmented mirror in which each segment maintains its shape in space after polishing on the ground by active figure control using actuators. The segment surface quality, as set by the study, which must be maintained for either an active segment or a passive segment, is 0.5 micrometer rms. In addition to these requirements, a radius matching requirement is imposed on a segmented mirror. This study established a radius mismatch requirement of 50 parts per million.

3.1.1.2 Required Technology Maturity Level - There are currently related DoD segmented mirror activities with "similar" requirements. However, the operational wavelength range and the operating level are unique to LDR. For this reason an LDR segment phasing test (demonstration of cophasing between two outer segments) has been proposed. A set of actuators and sensors is needed for this test. Consequently, the LDR technology program has been configured at OAST Level 5 (component tested) and time phased with the mirror demonstration program.

3.1.1.3 On-going Technology Developments and Estimation of Where the Technology Will Be in 1991 - The actuator and sensor technology is a straight forward extension of current techniques demonstrated in DARPA and industry IR&D programs. Actuators and sensors with similar requirements have been demonstrated for use with future large ground-based telescope programs (Keck Telescope and National New Technology Telescope).

3.1.1.4 Technology Shortfall and Augmentation Plan - A set of actuators and sensors is needed for the segment phasing demonstration. The technology plan activities are:

- 1989 - Design of actuators and sensors (\$200K)
- 1989 - Fabrication and assembly of actuators and sensors (\$2.8M)
- 1990 - Component testing of actuators and sensors (\$650K)

3.1.2 Fold Mirror Chopping

The key issue is the development of a fold mirror control subsystem incorporating "chopping" capability and incremental positioning capability. The former is used to subtract the background level from the star signal. The latter is used to fold the beam to a single scientific instrument (Note: As many as eight scientific instruments are planned). Figure 3.1.2-1 represents an overview of the technology program required to assure appropriate schedule readiness for LDR system development initiation.

3.1.2.1 Requirements Derived from Concepts - The fold mirror must have the capability to rotate in 45 degree increments. The accuracy of mirror location is determined by the location of the detector surface. An accuracy of ± 1 arcsecond was used in the study. In order to have a throw of 1 arcminute for chopping and utilizing a push/pull chopper, the push/pull step will be approximately ± 6 millimeters. In addition to these requirements, the chopping mechanism should provide a two (2) hertz square wave (reactionless).

The Science Working Group would like a selectable chopping axis for use with extended sources. It should be emphasized that any control concept must be compatible with maintaining the fold mirror temperature (Note: probably lower than 125 degrees K for background noise considerations).

KEY ISSUE

- Develop a plano mirror control subsystem incorporating "chopping" capability and incremental positioning capability (Note: As many as eight scientific instruments are planned)

OBJECTIVE

- Design, fabricate, assemble, and test proof-of-concept fold mirror assembly (mirror with controls)

RATIONALE

- Background subtraction (chopping) techniques have been incorporated into several ground based IR telescopes. Two alternative concepts (push/pull and rotating) have been suggested

ALTERNATIVES

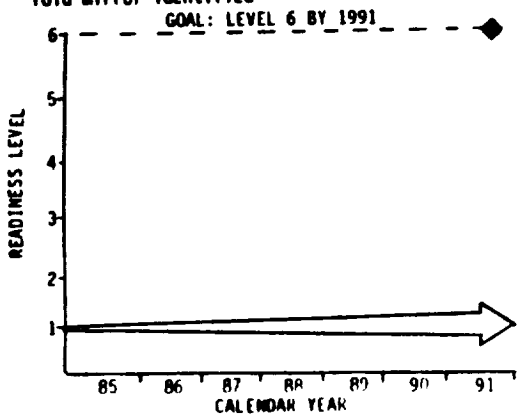
- Secondary mirror chopping

RISK

- Inadequate information for chopping technique selection
- Cost, performance

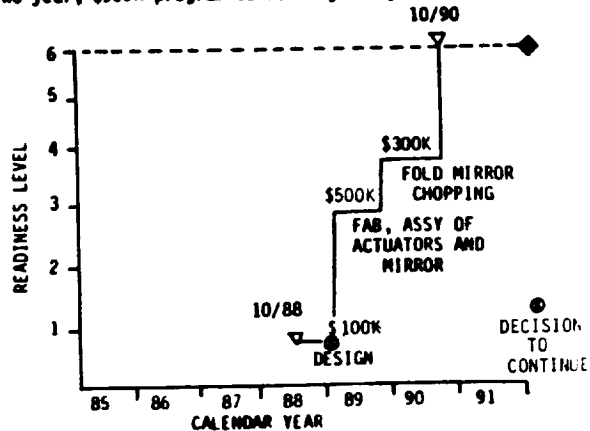
TECHNOLOGY ASSESSMENT

No other programs utilizing chopping with a plano fold mirror identified



SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

Two year, \$900K program to reach goal by October 1990



CATEGORY A: SENSING, CONTROLS, AND CONTROL ELECTRONICS
FOLD MIRROR CHOPPING
Figure 3.1.2-1

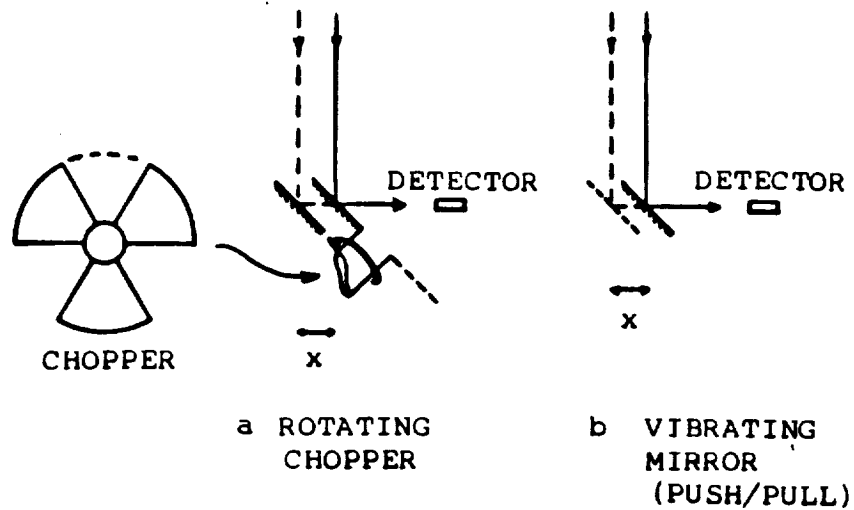
3.1.2.2 Required Technology Maturity Level - In 1989 a decision should be made to proceed with one of two chopping concepts (fold mirror chopping or secondary mirror chopping). No other programs have been identified utilizing chopping with a plano fold mirror. Consequently, the LDR technology program has been configured for a proof-of-concept fold mirror assembly (mirror with controls), i.e., OAST Level 6 (engineering model tested on the ground) by 1990.

3.1.2.3 On-going Technology Development and Estimation of Where the Technology Will Be in 1991 - Shown in Figure 3.1.2-2 are two alternate approaches to fold mirror chopping (rotating and push/pull). The concepts have been "tried" on ground based telescopes. Very little quantitative data exists on the results.

A comparison of the two concepts is shown in Table 3.1.2-1. Since no other programs have been identified utilizing fold mirror chopping, the technology will probably remain at OAST Level 1 (basic principles observed/reported) without LDR sponsorship.

3.1.2.4 Technology Shortfall and Augmentation Plan - Development of a plano mirror control system incorporating both incremental positioning capability and "chopping" capability is needed. The objective of the LDR technology program is a fold mirror assembly (mirror with controls) demonstration. The technology plan involves the following activities:

- 1988 - Conceptual design of fold mirror assembly (\$100K)
- 1989 - Detailed design of fold mirror assembly; fabrication and assembly of actuators and mirror (\$500K)
- 1990 - Chopping Demonstration (\$300K)



FOLD MIRROR CHOPPING CONCEPTS
Figure 3.1.2-2

TABLE 3.1.2-1
ROTATING VERSUS PUSH/PULL TERTIARY CHOPPERS

	<u>DISADVANTAGES</u>	<u>ADVANTAGES</u>
ROTATING	<p>TWO MIRRORS MAY BE AT DIFFERENT TEMPERATURES</p> <p>EDGES MAY REFLECT WARM OBJECTS</p> <p>HARD TO CHANGE PLANE OF ROTATION</p> <p>BEAMS MAY NOT FOLLOW EQUIVALENT PATHS</p>	<p>UNIFORM MOTION EASIER TO SYNCHRONIZE AND CONTROL</p> <p>LESS WASTED TIME BETWEEN POSITIONS</p>
✓ PUSH-PULL	<p>MORE TIME REQUIRED BETWEEN POSITIONS</p> <p>MECHANICAL VIBRATION</p>	<p>SINGLE MIRROR-NO TEMPERATURE DIFFERENTIAL</p> <p>MINIMIZE EDGE EFFECTS</p> <p>LOWER OFFSET</p> <p>SMALLER MODULATION NOISE</p> <p>EASIER TO ROTATE MIRROR PLANE</p>

3.1.3 Secondary Mirror Chopping

The key issue is the development of a secondary mirror control subsystem incorporating both rigid body motion control capability and chopping capability. The former is used to maintain the optical performance of the telescope and the latter is used to subtract the background level from the star signal. Figure 3.1.3-1 represents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

KEY ISSUE

Develop a secondary mirror control subsystem incorporating both rigid body motion control capability and "chopping" capability.

OBJECTIVE

Design, fabricate, assemble, and test proof-of-concept secondary mirror assembly (mirror with controls)

RATIONALE

Direct extension of rigid body motion control techniques used in NASA, DoD, and industry. Background subtraction (chopping) techniques have been incorporated into several ground based IR telescopes.

ALTERNATIVES

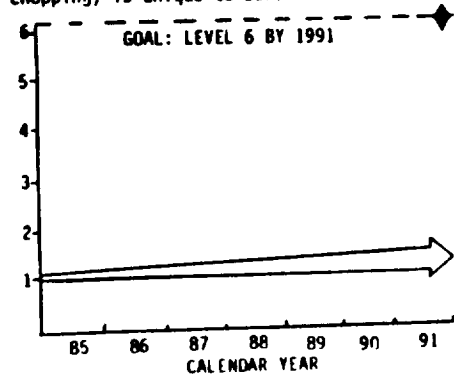
Fold mirror chopping

RISK

- Inadequate information to select chopping method
- Cost, performance

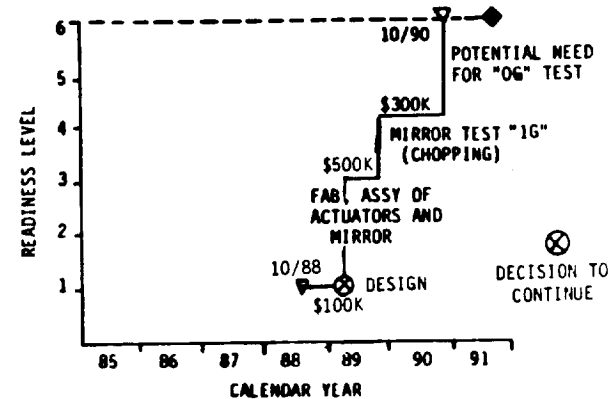
TECHNOLOGY ASSESSMENT

Combination control approach (rigid body motion with chopping) is unique to LDR.



SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

Two year, \$900K program to reach goal by October 1990

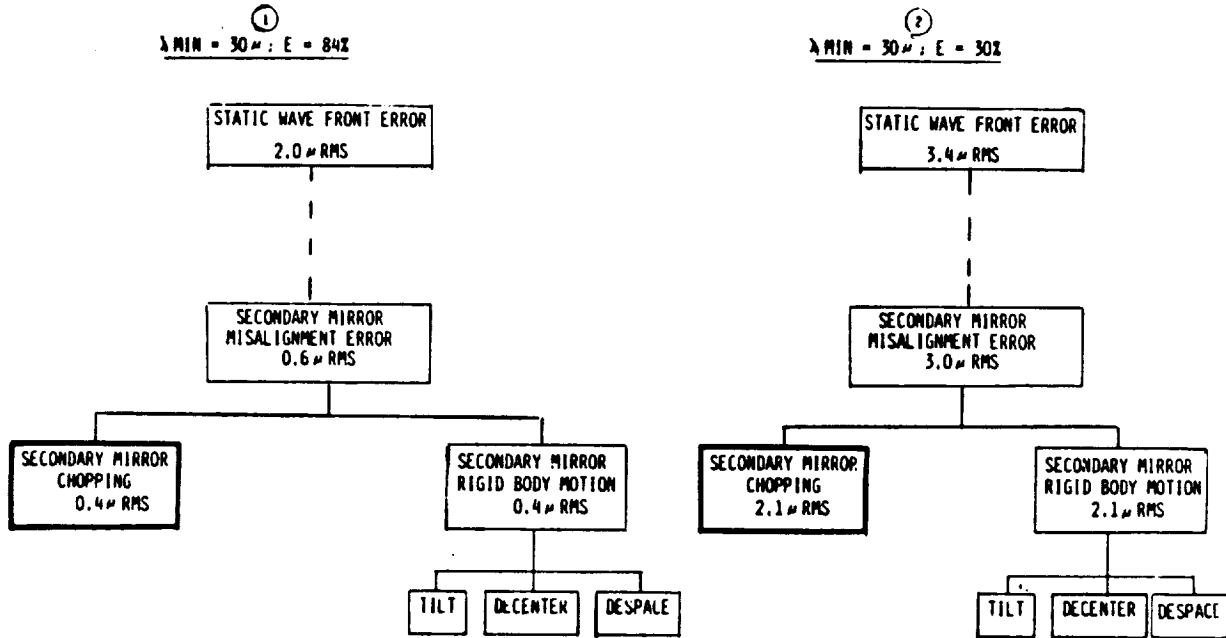


CATEGORY A: SENSING, CONTROLS, AND CONTROL ELECTRONICS SECONDARY MIRROR CHOPPING

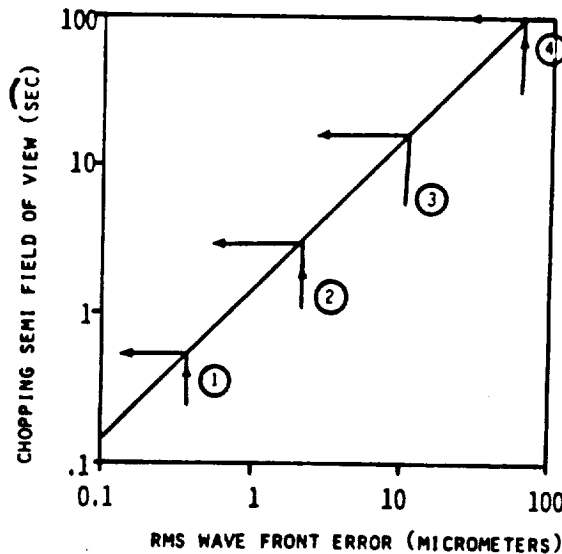
Figure 3.1.3-1

3.1.3.1 Requirements Derived from Concepts - The secondary mirror must be properly aligned (tilt, decenter and despace) to the primary mirror. The requirement set by the study for the despace error (allowable change in primary mirror to secondary mirror spacing) is 4.0 micrometers for λ_{min} of 30 micrometers and an encircled energy of 84% and 35.0 micrometers for λ_{min} of 50 micrometers and an encircled energy of 30%. The allocation for "chopping" for these two cases is shown in Figure 3.1.3-2. This corresponds to a maximum allowable chopping field of view (Figure 3.1.3-3) for vertex chopping. An alternative is to use neutral point chopping. A comparison of the maximum allowable chopping field of views for vertex chopping and neutral point chopping is shown in Figure 3.1.3-4. It should be emphasized that the study goal for a 1 arcminute throw cannot be met over the entire spectral range using secondary mirror vertex chopping. The alternative is a variable throw (versus wavelength) optimized for the selected science instrument. In addition to these

requirements the chopping mechanism should provide a 2 hertz square wave (reactionless). The Science Working Group would like a selectable chopping axis for use with extended sources. It should be emphasized that any control concept must be compatible with maintaining the secondary mirror at 125 degrees \pm 1 degree K.



OPERATIONAL PERFORMANCE PREDICTION
Figure 3.1.3-2



- (1) $\lambda_{MIN} = 30 \mu M, E = 84\%$
- (2) $\lambda_{MIN} = 30 \mu M, E = 30\%$
- (3) $\lambda_{MAX} = 1000 \mu M, E = 84\%$
- (4) $\lambda_{MAX} = 1000 \mu M, E = 30\%$

MAXIMUM ALLOWABLE CHOPPING FIELD OF VIEW
Figure 3.1.3-3

OPERATIONAL WAVELENGTH (μM)	ENCIRCLED ENERGY (%)	AIRY DISK DIA. (SEC)	VERTEX * CHOPPING FOV (SEC)	NEUTRAL ** POINT CHOPPING FOV (SEC)
30	84	1	\pm 0.5	\pm 2
30	30	1	\pm 2.8	\pm 12
1000	84	33	\pm 16	\pm 64
1000	30	33	\pm 100	\pm 400

- THE \pm 30 SEC CHOPPING REQUIREMENTS CANNOT BE MET OVER THE ENTIRE SPECTRAL RANGE, BASED ON EITHER 84% OR 30% ENCIRCLED ENERGY ALLOCATION.
- RELIEF TO 30% ENCIRCLED ENERGY ALLOCATION WILL ALLOW VERTEX CHOPPING FOV OF \pm 3 AIRY DISK DIAMETERS.
- HOW SMALL A CHOPPING FIELD OF VIEW IS ACCEPTABLE (I. E., HOW MANY AIRY DISK DIAMETERS) AND STILL DO NECESSARY BACKGROUND SUBTRACTION?

- ALLOWABLE THROW LIMITED BY COMA
- ** ALLOWABLE THROW LIMITED BY ASTIGMATISM (APPROXIMATE CALCULATION)

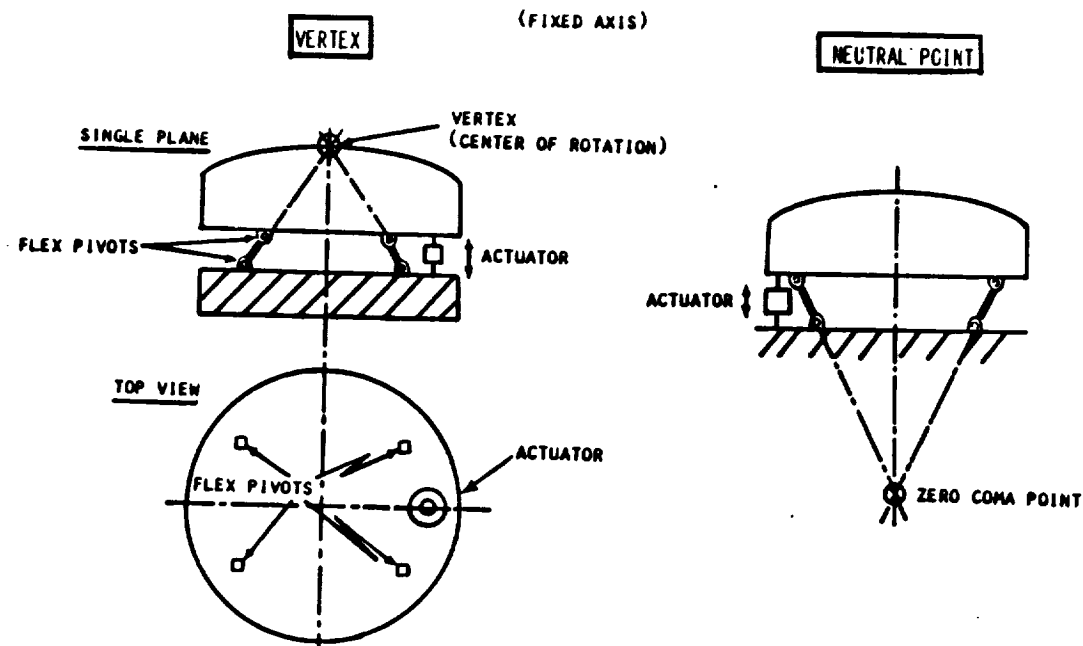
SECONDARY MIRROR CHOPPING

Figure 3.1.3-4

3.1.3.2 Required Technology Maturity Level - In 1989 a decision should be made to proceed with one of two chopping concepts (fold mirror chopping or secondary mirror chopping). If the secondary mirror concept is chosen the resultant control approach (rigid body motion with chopping) is unique to LDR. Consequently, the LDR technology program has been configured for a proof-of-concept secondary mirror assembly (mirror with controls), i.e., OAST Level 6 (engineering model tested on the ground) by 1990. However, the precision requirements and the need to prove space compatibility may mandate a later space demonstration, i.e., OAST Level 7.

3.1.3.3 On-going Technology Developments and Estimation of Where the Technology Will Be in 1991 - The concept of realigning the secondary mirror to the primary mirror using rigid body actuators is a straight forward extension of current techniques demonstrated in DARPA and industry IR&D programs. The NASA Space Telescope utilizes this concept.

Background subtraction techniques using the secondary mirror have been incorporated into several ground-based IR telescopes. Shown in Figure 3.1.3-5 are two secondary mirror chopping concepts investigated in this study. The first involves chopping about the vertex of the secondary mirror. The allowable throw is limited by coma. The second involves chopping about the coma neutral point. The allowable throw is limited by astigmatism. Difficult engineering mechanisms will be required for either secondary mirror vertex or neutral point chopping.



SM CHOPPING MECHANISM CONCEPTS
Figure 3.1.3-5

The only space program identified with secondary mirror chopping is SIRTF. However, the combination control approach (rigid body motion with chopping) is unique to LDR. Therefore the technology will probably remain at OAST Level 1 (basic principles observed/reported) or improve only "slightly" without LDR sponsorship.

3.1.3.4 Technology Shortfall and Augmentation Plan - Development of a secondary mirror control subsystem incorporating both rigid body motion control capability and "chopping" capability is needed. The objective of the LDR technology program is a secondary mirror assembly (mirror with controls) demonstration. The technology plan involves the following activities:

- 1988 - Conceptual design of secondary mirror assembly (\$100K)
- 1989 - Detailed design of secondary mirror assembly, fabrication and assembly of actuators and mirror (\$500K)
- 1990 - Chopping demonstration (\$300K)

3.1.4 Fine Guidance Sensing and Control

The use of a separate visible telescope for fine guidance sensing was selected in this study. This telescope must be co-boresighted to LDR and provide the control system (spacecraft and telescope) the information necessary to meet the pointing stability requirement. Figure 3.1.4-1 presents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

KEY ISSUE

Interrater relationship of telescope control system and spacecraft control system using a separate visible optical system for Fine Guidance Sensor System.

OBJECTIVES

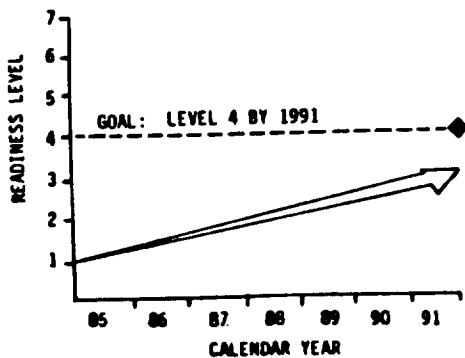
- Conceptual design of Fine Guidance Sensor.
- Conceptual design of co-boresighting approach.
- Critical function demonstration.

RATIONALE

- The use of a separate visible telescope for Fine Guidance Sensing was selected in this study.
- This telescope must be co-boresighted to the main telescope and provide the control system (spacecraft and telescope) the information necessary to meet the pointing stability requirement. Establishing the primary mirror reaction structure as the stable platform for reference of the Fine Guidance sensor is of concern.

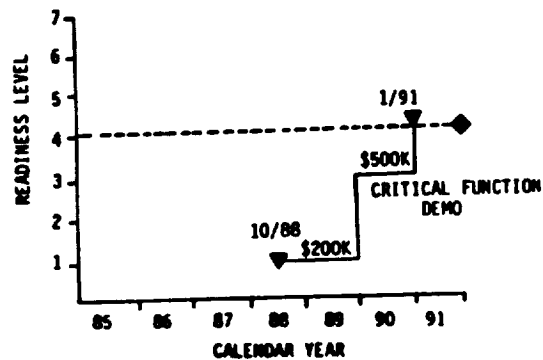
TECHNOLOGY ASSESSMENT

Closely related DoD and NASA Star Tracker and Fine Guidance Sensing Technology.



SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

2 1/2-year, \$700K program to reach goal by January 1991.



CATEGORY A: SENSING, CONTROLS AND CONTROL ELECTRONICS
FINE GUIDANCE SENSING AND CONTROL
Figure 3.1.4-1

3.1.4.1 Requirements Derived from Concepts - The function of the LDR fine guidance sensor is to measure misalignment of the LDR line of sight vector by measuring the position of auxiliary guide images (Note: Space telescope utilizes a visual star catalog with visual star magnitude as low as 14.5). The measurement is transferred to the "pointing control system" to correct the line of sight error. Line of sight errors as small as a few percent of a star image diameter must be measured and corrected to prevent the resulting image motion from significantly degrading image quality (Note: In this study 0.02 arcsecond was used as the maximum allowable pointing stability error). One option would be to utilize the LDR telescope for fine guidance sensing (i.e., the Space Telescope approach). However, visible fine guidance sensing is not compatible with the LDR operational wavelength region from the far I/R to the submillimeter region. Two alternate approaches were evaluated in this study. The first approach utilizes a section(s) of the LDR optical subsystem for fine guidance sensing. The visible quality section(s) could be an inner annulus, an outer annulus, or patches. The concept has the advantages of (1) utilizing the same line of sight and (2) the focal length of the fine guidance sensor is the same as the focal length of LDR allowing relatively small pointing errors to be sensed. It has the disadvantages of requiring (1) fabrication and maintenance of visible quality sections on a large segmented mirror and (2) maintaining visible quality on section(s) of the secondary mirror.

The selected concept was to utilize a separate visible telescope for fine guidance sensing. The optical subsystem would be a set of CCD solid state sensors filling the field of view to meet the threshold magnitude requirements. The line of sight of the fine guidance sensor would be co-boresighted to the LDR line of sight (Note: In this study the maximum allowable co-boresighting error was set at the absolute pointing error, 0.05 arcsecond).

3.1.4.2 Required Technology Maturity Level - There is an interrelationship of the telescope control system and spacecraft control system using a separate visible optical system for fine guidance sensing. This telescope must be co-boresighted to the main telescope and provide the control system (spacecraft and telescope) the information necessary to meet the pointing stability requirement. Establishing the primary mirror reaction structure as the stable platform for reference of the fine guidance sensor is of concern. With respect to the fine guidance telescope itself the catadioptric telescope is state-of-the-art technology. Solid state sensors (CCD's, CID's, PDA's) have become increasingly attractive for astronomical imaging. This is due to low readout noise, high quantum efficiency, high dynamic range, linearity, and stability. The predominance of red stars near the galactic pole (poorest star density region) when combined with a solid state sensor leads to more available stars for a given threshold magnitude than either the eye or a photomultiplier tube as a detector. Technical improvements and availability (yield) make solid state sensors ready for serious consideration in a 1980's fine guidance sensor. The co-boresighting approach is the technology shortfall. Consequently, the LDR technology program is configured at OAST Level 4 (critical function demonstrated). Completion is 1991 to coincide with activities on-going in the structural control area establishing the interrelationship between the LDR structural control philosophy and fine guidance sensing.

3.1.4.3 On-going Technology Developments and Estimation of Where the Technology Will Be in 1991 - The Space Telescope must be able to track an object within a pointing stability error of 0.007 arcseconds with a time constant of much less than 1 second. The only way to reach this level is to use images formed by the Space Telescope itself (2.4 meter aperture). The fine guidance sensor investigated in this study would utilize a similar approach with a 1 meter aperture and an integration time of 500 milliseconds. The Space Telescope fine guidance sensor is based on a concept of star tracking using wave front interferometry. The collimated beam is fed to Koester's prisms which provide a set of interferometric fringes to pairs of detecting photomultipliers. These detectors do not scan the fringes but interrogate the total intensity of signal which varies as the star moves.

Kodak recently completed a one year study for NASA/MSFC. The purpose of that study was to investigate new approaches to fine guidance sensing and furnish a conceptual design for an advanced fine guidance sensor with no moving parts. The resulting concepts utilize solid state sensors. Technical improvements and availability (yield) make these solid state sensors (CCD's and CID's) ready for a 1980's fine guidance sensor. In the area of co-boresighting there are closely related DoD programs in communications and directed energy.

3.1.4.4 Technology Shortfall and Augmentation Plan - The technology shortfall is in the area of co-boresighting relative to the dynamic LDR. The technology plan involves the following activities:

- 1988 - Conceptual design of fine guidance sensor and co-boresighting approach (\$200K)
- 1989 - Critical function demonstration of co-boresighting (\$500K)

3.1.5 Secondary Mirror Sensing and Control Approach

Because of the high asphericity of the LDR primary mirror (f/0.5), the misalignments of the secondary mirror must be controlled to accuracy levels consistent with the allocated tolerances using rigid body actuators with a "true" metering structure. Figure 3.1.5-1, presents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

3.1.5.1 Requirements Derived From Concepts - The alignment of the secondary mirror optical axis to the primary mirror optical axis must be maintained within allocated tolerances.

There are five secondary mirror vertex motions of concern (2 tilts, 2 decenters, and 1 despace). Shown in Figure 3.1.5-2 is a preliminary LDR operational performance prediction. Highlighted is the total RSS of the secondary mirror misalignment error. Shown in Figure 3.1.5-3 is a second performance prediction which loosens the minimum operational wavelength and encircled energy requirements.

KEY ISSUE

- The secondary mirror must be properly aligned (tilt, decenter and despace) to the primary mirror

REQUIREMENTS (SET BY STUDY)

λ min = 30μ E = 84%	DESSPACE ERROR	4.0 MICROMETERS
λ min = 50μ E = 30%	DESSPACE ERROR	35 MICROMETERS

OBJECTIVES

- Develop a control approach (actuation and sensing)
- Component verification program (mirror, sensing, and control, support structure)
- Proof-of-concept demonstration

ALTERNATIVES

CONTROL MECHANISMS

- Linear actuators for rigid body motion control (tilt, decenter, despace)

SENSING

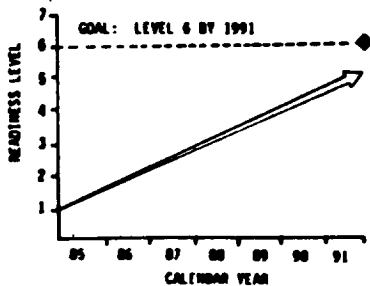
- Internal: tilt, decenter, and despace sensors (direct measurement of misalignment)
- External: star sensing (wavefront) (indirect measurement of misalignment)

SUPPORT STRUCTURE

- The study defined the need for a "true" metering structure. A triple bipod approach was selected over either a shell or truss approach. The secondary mirror would be realigned between observations using the secondary mirror rigid body motion actuators.
- The alternative is a compensation support structure-- the secondary mirror would be realigned during observations using the secondary mirror rigid body motion actuators

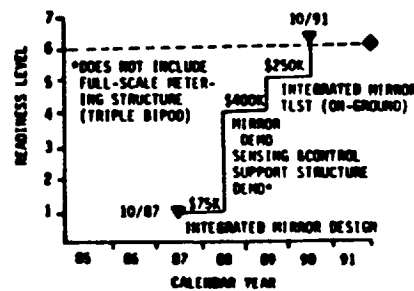
TECHNOLOGY ASSESSMENT

Appears to be straight forward extension of current techniques demonstrated in DARPA and industry IRBD programs. Closely related technology used on NASA Space Telescope.

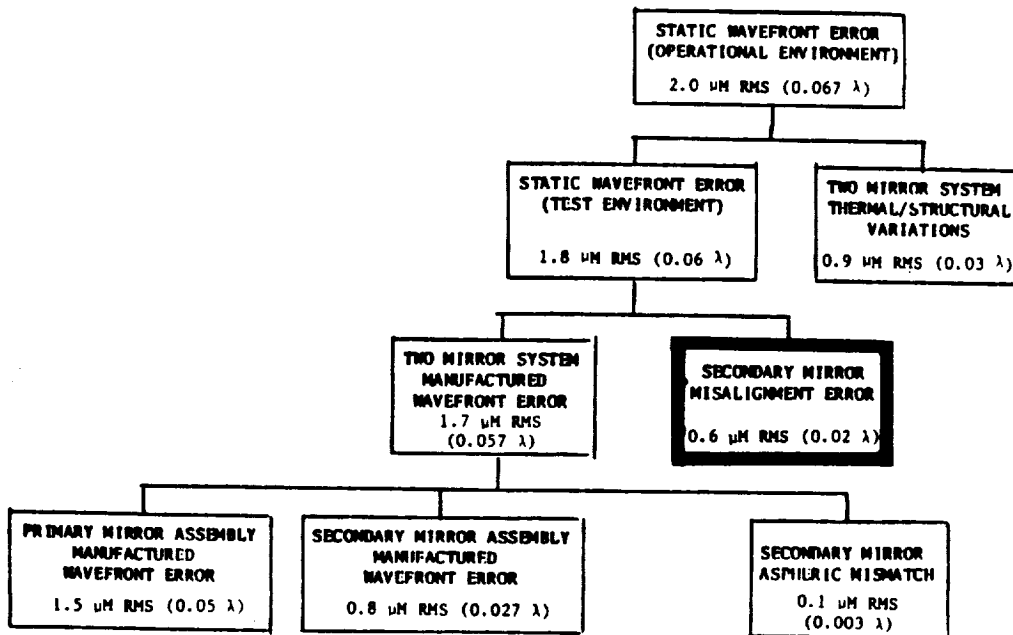


SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

Three year, \$725K program to reach engineering model (on-ground) goal by October 1990.

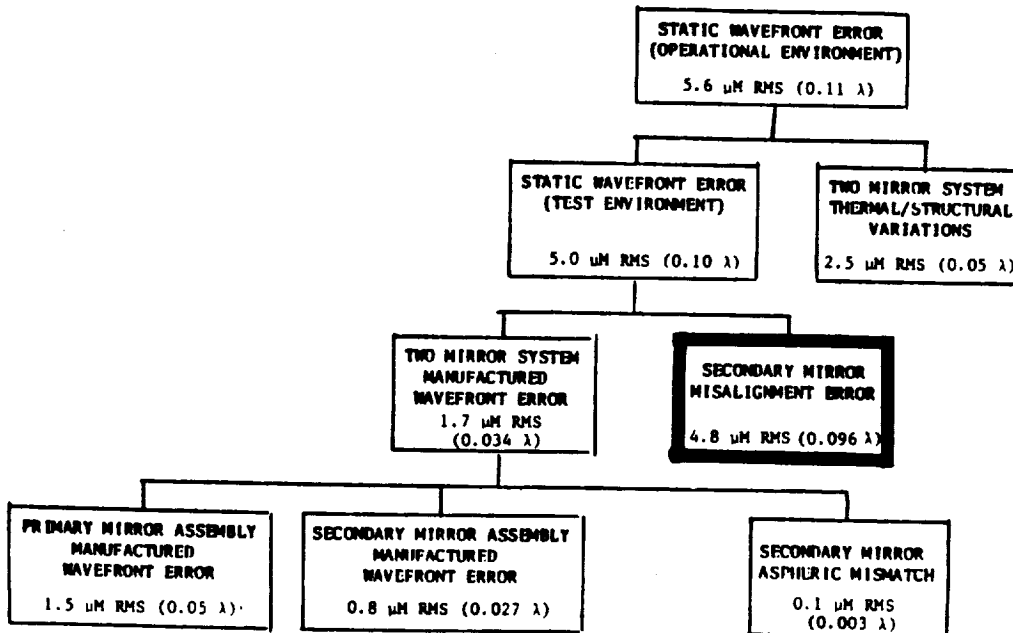


CATEGORY A: SENSING, CONTROLS, AND CONTROL ELECTRONICS
 SECONDARY MIRROR SENSING AND CONTROL APPROACH
 Figure 3.1.5-1



LDR OPTICAL SUBSYSTEM
 OPERATIONAL PERFORMANCE PREDICTION
 $(\lambda_{\min} = 30\mu\text{m}; E = 84\%; D = 20 \text{ m})$

Figure 3.1.5-2

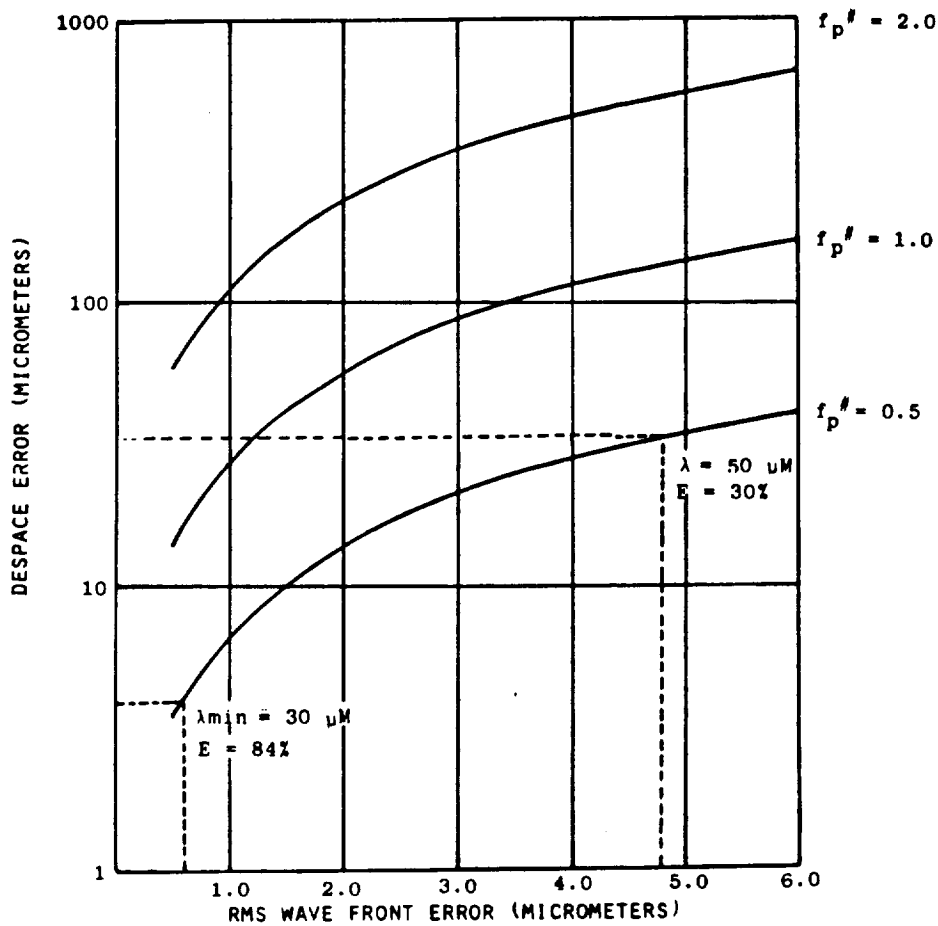


LDR OPTICAL SUBSYSTEM
 OPERATIONAL PERFORMANCE PREDICTION (REALLOCATED TO INCREASE
 SECONDARY MIRROR MISALIGNMENT ALLOWABLE ERROR)

$(\lambda_{\min} = 50\mu\text{m}; E = 30\%; D = 20 \text{ m})$

Figure 3.1.5-3

The secondary mirror to primary mirror spacing imposes the tightest requirement. This is due to the fast aspheric secondary mirror which magnifies the primary mirror focal ratio of 0.5 into a Cassegrain system focal ratio of 10. Shown in Figure 3.1.5-4 is the allowable despace error for varying operational conditions. The requirements for despace error set by the study are summarized in Table 3.1.5-1.



ALLOWABLE DESPACE ERROR
Figure 3.1.5-4

TABLE 3.1.5-1
DESPACE ERROR ALLOCATION

<u>CASE I</u>	
● Minimum operational wavelength	30 Micrometers
● Encircled energy	84%
● Maximum allowable despace error	4 Micrometers
<u>CASE II</u>	
● Minimum operational wavelength	50 Micrometers
● Encircled energy	30%
● Maximum allowable despace error	35 Micrometers

3.1.5.2 Required Technology Maturity Level - The technology appears to be a straight forward extension of current techniques demonstrated in DARPA and industry IR&D programs. There is a closely related approach used on the NASA Space Telescope. The LDR technology program has been configured for a demonstration of rigid body control to the LDR requirements (i.e., OAST Level 6 - engineering model tested).

3.1.5.3 On-Going Technology Developments and Estimation of Where The Technology Will Be in 1991 - The study defined the need for a "true" metering structure. A triple bipod approach was selected over either a shell or truss approach. The secondary mirror would be realigned between observations using the secondary mirror rigid body motion actuators. Metering requirements for LDR are similar to those for the NASA Space Telescope, for which a graphite-epoxy truss was selected.

Eastman Kodak Company as a subcontractor to LMSC defined a test program to measure metering structure performance in the Composite Optical Subsystem Structure (COSS) program. This development program was for a next generation optical support in space. The support is composed of both graphite epoxy and graphite aluminum composites. Kodak is investigating structural materials for high precision optical support structures in space applications. Kodak with Corning Glass Works is investigating the use of glass matrix materials. When coupled with glass optics the potential for extremely high metering performance is suggested. In addition, Kodak is developing a composite material for metering applications under IR&D. It potentially has very attractive metering properties and addresses the outgassing problem currently experienced in graphite ploymer composites. An attractive alternative approach to metering was used in the astrometric telescope of the U.S. Naval Observatory. Glass metering rods were used to maintain metering. External to these rods were aluminum tubes to maintain structural functions.

There are currently two approaches to secondary mirror alignment sensing. The first uses an external source approach: the wave front of a star is sensed. Mathematically this information is transformed into rigid body motion information. The Hubble Space Telescope utilizes such an approach. An alternate approach is to directly monitor the rigid body motions of the secondary mirror via internal sensors. Using this approach it can be demonstrated via on-ground measurement verification techniques that on-orbit alignment of the secondary mirror axis to the primary mirror axis can be accomplished. Kodak has demonstrated this concept of measuring misalignments directly. A tilt sensor optical beam reflects from a reference flat at or near the secondary mirror vertex. The decenter sensor optical beam reflects from

the mirror surface. The source concept is a small, illuminated, pinhole aperture imaged through a projection lens. Projection lenses of a solid Cassegrain construction to maintain high internal thermal structural stability have been breadboarded. The pinhole aperture, secondary mirror, and primary mirror are all located on a single cylinder.

3.1.5.4 Technology Shortfall and Augmentation Plan - The LDR development program would demonstrate a secondary mirror control approach (actuation and sensing). It involves the following activities:

- 1987 Integrated mirror design (mirror, sensing, control and support structure) (\$75K)
- 1988 Component testing (\$400K)
- 1989 Proof-of-concept demonstration (\$250K)

3.1.6 Noise Reduction in Control Moment Gyros (FSC)

3.1.6.1 Requirements Derived from Concepts - An evaluation of LDR technology issues relating to the spacecraft portion of the system, reveals that in the realm of spacecraft dynamic stability two of the subsystems may require advanced technology: the flexible-body dynamics related to the large extended solar arrays of the electric power subsystem may be most effectively obviated by the use of radioisotope power systems; and the control-moment-gyros required for spacecraft attitude control may need to be improved by reducing system inherent noise.

The quantitative validation of the requirements in each of these subsystems must await a dynamic modeling of system transient response to disturbance inputs.

The structural dynamics - advanced power system trade potential is discussed in Paragraph 3.3.1.

GMG wheel bearings are selected to meet simultaneous requirements on load bearing capability, speed, life, friction, and smoothness. In addition to wheel generated noise, CMGs produce noise at their gimbal torquers. Such noise results from imperfect gearing (when present), non-uniform torque output over a gimbal motor revolution, and friction effects.

The particular requirements of LDR torquing -- large torques required intermittently for slew, and small torques ordinarily required for control -- permit consideration of alternate CMG designs and torquer set configurations. Possibilities include use of hybrid CMG/reaction wheel configurations, wherein the CMGs are used for slew and coarse control and the wheels are used for fine control. Shock mounting the CMGs, which is reasonable because they run at constant speed, would minimize wheel noise transmission to LDR. Even the requirements for LDR wheel bearing design and manufacturing improvements will be eased by such an approach.

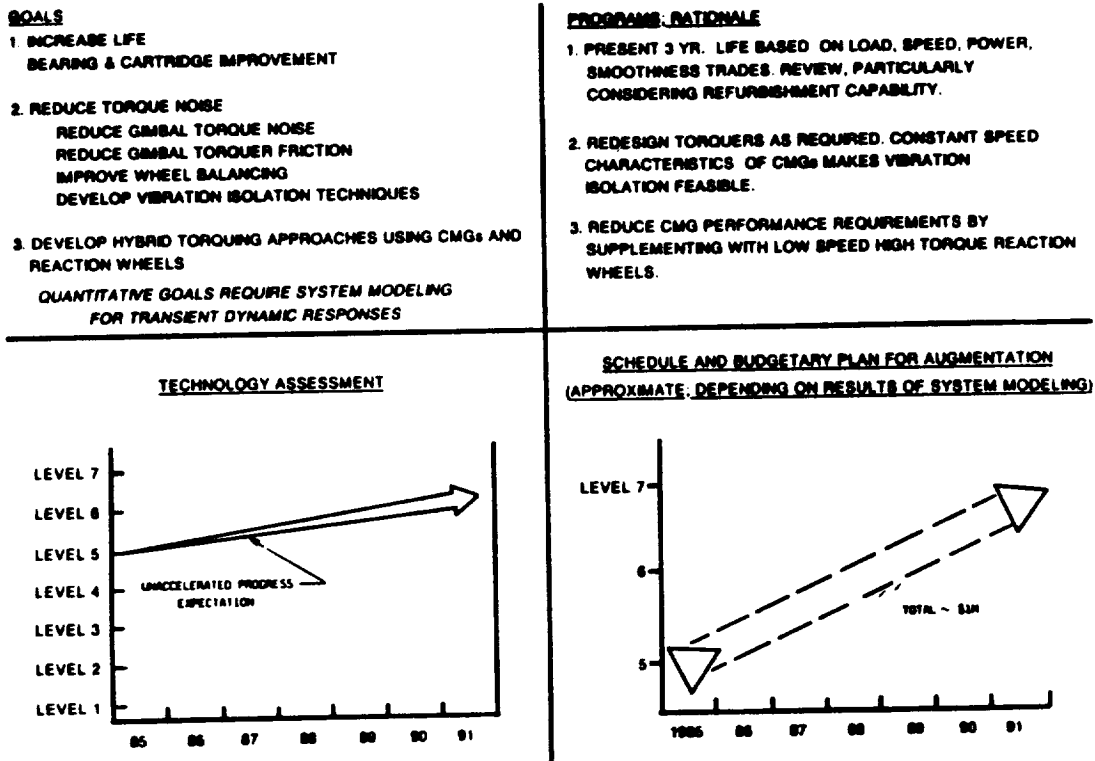
Technology advances for LDR torquers may be summarized as:

1. Improve bearing life consistent with load, speed, friction, and smoothness.
2. Improve torquer designs and components to reduce cogging, increase gear smoothness (with negligible backlash), and reduce friction.
3. Decrease noise torque transmission to LDR by improved bearings, wheel balancing, and vibration isolation of the full CMG.
4. Consider value of hybrid torquing systems which include CMGs and reaction wheels.

3.1.6.2 Required Technology Maturity Level - As stated above, a quantitative goal for LDR first requires a system modeling for transient dynamic response.

3.1.6.3 On-going Technology Developments and Estimation of Where the Technology Will Be in 1991 - The largest control moment gyros known to have been flown were the 2300 ft-lb-sec units used for Skylab control. These units are probably inadequate for LDR use primarily due to their limited life expectancy of 3-4 years. An estimation of the significance of their torque noise output depends upon predictions of total LDR dynamics. Reaction wheels for Space Telescope have required the special development of low noise bearings and wheel testing techniques. LDR's requirements may force an equivalent development for their CMGs. Current technology has been assigned a level 5 rating.

3.1.6.4 Technology Shortfall and Augmentation Plan - A program to raise the technology readiness from level 5 to level 7 might require an investment of \$1 million. Such a program is indicated in Figure 3.1.6-1, which summarizes the goals and rationale of the augmentation plan.



TECHNOLOGY ASSESSMENT NOISE REDUCTION IN CMG'S

Figure 3.1.6-1

3.2 MATERIALS, STRUCTURES, THERMAL, AND DYNAMICS (OAST CATEGORY B)

3.2.1 Dynamic Structural Control

Dynamic structural control of LDR is a fundamental requirement that directly follows from the desired optical performance of the telescope. Clearly, there is a quantifiable need to maintain: pointing stability of the telescope as a whole, angular stability of the fine guidance sensor with respect to some principal frame of reference in the main telescope, relative position of the primary mirror segments with respect to that frame of reference, as well as position of the secondary mirror, fold mirror and focal plane with respect to that frame of reference. Figure 3.2.1-1 presents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

KEY ISSUES

- Determination of the interrelationship between the spacecraft control system and the telescope control system (figure control and rigid body control).
- Can the primary mirror be established as the fixed reference for the telescope?
- Degree of dynamic structural control required?

OBJECTIVES

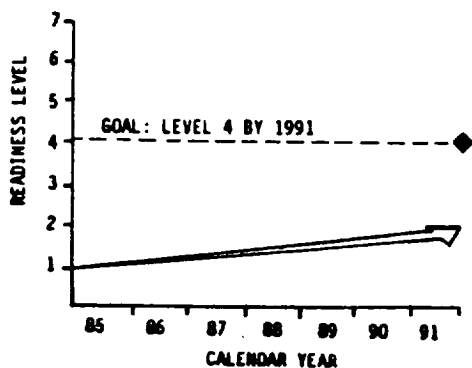
- Improve structural control software
- Conceptual LDR structural design
- LDR structural control model

RATIONALE

- New software is required to determine interrelationship between structural dynamics and control systems.
- "Smart" design concepts are needed to minimize hardware complexity.
- Advancements are needed in structural materials and structural joints.

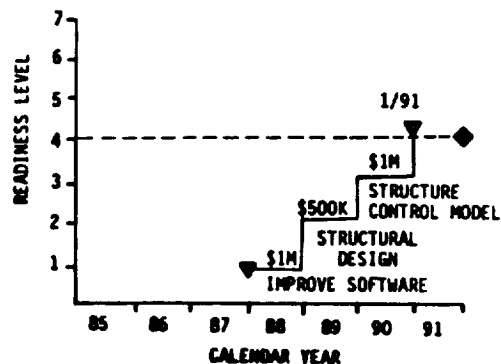
TECHNOLOGY ASSESSMENT

Parallel DoD and industry IR&D programs for structural control (hardware and software).



SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

Three-year program to advance dynamic structural control modeling.



CATEGORY B: MATERIALS, STRUCTURES, THERMAL AND DYNAMICS
 DYNAMIC STRUCTURAL CONTROL
 Figure 3.2.1-1

3.2.1.1 Requirements Derived from Concepts - It is clear that even though the optical performance requirements are not as stringent as in many visible light telescopes, the large aperture size and low overall weight will result inevitably in a relatively flexible structure that has the potential to be much more dynamic than a smaller space telescope. While conventional telescopes are often designed with the assumption that the primary mirror is absolutely rigid and can be used as a fixed reference for assuring stability of the rest of the telescope, the LDR is likely to be a very live structure with the dynamics of the central structure, primary optics, secondary optics, sunshade, and control system fully coupled.

The key issues which must be addressed are: (1) What is the interrelationship between the spacecraft control system and the telescope control system (figure control and rigid body control)? (2) Can the primary mirror be established as the fixed reference for the telescope? (3) What is the degree of dynamic structural control required for LDR?

3.2.1.2 Required Technology Maturity Level - In order to support an LDR program initiation in 1992, the overall dynamic control needs for LDR must be defined and well established. These needs are listed in Table 3.2.1-1. In summary, it specifies the need for materials and combinations of materials and lists the need for better analytical and modeling tools for a variety of special challenges presented by LDR. There are also some specialized design concepts that can have a major impact on the ability to achieve structural and optical control.

TABLE 3.2.1-1
DYNAMIC STRUCTURAL CONTROL
NEEDS FOR TECHNOLOGY IMPROVEMENT FOR LDR

MATERIALS

- LOW CTE MATERIALS NEEDED FOR STRUCTURE
- LIGHTWEIGHT, HIGH STIFFNESS, LOW CREEP, HIGH DAMPING
- COMPOSITE STRUCTURES--OPTIMAL COMBINATION OF MATERIALS

ANALYSIS TOOLS

- BETTER MEANS OF SYNTHESIZING AND OPTIMIZING COMPLEX STRUCTURES
- MORE ACCURATE, CAPABLE, FINITE ELEMENT DYNAMIC MODELING
- MATH MODELS OF JOINTS, NEW COMPOSITES, SENSORS, ACTUATORS
- BETTER MODELING FOR COMPLEX CONTROL SYSTEMS--POSSIBLY NON-LINEAR
- BETTER NON-LINEAR MODELING OF FRICTION, DAMPING, LARGE DEFLECTIONS
- TOOLS FOR MODELING EQUATIONS WITH TIME DEPENDENT COEFFICIENTS

DESIGN APPROACH

- RECOGNIZE INTERACTIVE NATURE OF SYSTEM--POINTING, MODAL RESPONSE, FIGURE CONTROL
- CONSIDER ACCURACY, RANGE, RESPONSE OF SENSORS AND ACTUATORS
- MAKE USE OF LONG RANGE DISTANCE MEASURING TECHNOLOGY TO SYNTHESIZE STIFFNESS
- TIERED APPROACH TO DISTRIBUTE CONTROL FUNCTIONS
- UNDERSTAND DISTURBANCES (OPERATIONAL, TRANSITORY)--ATTENUATE
- EXACT CONSTRAINT PHILOSOPHY
- MODAL DESIGN, PASSIVE AND ACTIVE DAMPING OF STRUCTURE, ISOLATION
- BETTER JOINT DESIGN

Currently there are parallel DoD and industry IR&D programs for structural control of space structures. However, due to the uniqueness of LDR it is not obvious that all the necessary dynamic structural control issues will be resolved without LDR sponsorship. Consequently, the LDR technology program should be self sufficient in establishing its own structural control philosophy. For this reason the LDR technology level has been set at OAST Level 4 (critical characteristic demonstrated) by 1991.

3.2.1.3 On-going Technology Developments and Estimation of Where the Technology Will Be in 1991 - Existing optical analysis computer programs can be used to predict system performance. Sensitivity analyses are performed with respect to fixed reference points in the telescope. Existing analytical methods are also available for calculating the LDR structural response as a function of specified inertial, mechanical, or thermal forcing functions. However, there still remain several gaps in the technology required to develop an LDR configuration and control system. In order to achieve the required level of structural and optical stability it may be necessary to: improve structural materials; develop a low CTE glass suitable for 200 degrees K operation; accelerate the development of metal matrix composites; etc. Other technology gaps are associated with the need for analyses and computer aided design tools that can be used to model, synthesize, and optimize an LDR type structure and control system. For example, in this latter category there is a need for better modeling of structural joints.

Maintaining the dimensional stability of the support structure will be essential. Kodak was a subcontractor to LMSC on the Composite Optical Subsystem Structure (COSS) program. The purpose of this program is to advance the state-of-the-art of passive metering structures in space using composite materials. Martin Marietta is developing critical vibration damping technology for large space structures in a program called Passive and Active Control of Space Structures (PACOSS). DoD also has issued related contracts to Boeing Aerospace Co. and to General Electric Space Systems Division for Reliability for Satellite Equipment in environmental vibration (RELSAT).

Vibration damping ground article tests are currently being undertaken at several locations in industry. They are aimed at flight testing a generic truss structure in space. The test could be performed on the Orbiter as early as 1988.

3.2.1.4 Technology Shortfall and Augmentation Plan - The technology shortfall is in understanding the degree of dynamic structural control required for LDR. The augmentation plan involves: (1) understanding the dynamics of the LDR observatory (telescope with spacecraft) as a whole and the required coupling with the telescope figure and rigid body control system; (2) ensuring that existing software is improved so that the interrelationships between the various structural and control subsystems can be understood; (3) establishing a design philosophy to achieve a design that meets the static and dynamic structural control requirements with existing materials and device technology in the 1991 time frame. The technology plan focuses on the ability to model and analytically design LDR. It involves the following activities:

- 1987 - Improve software - the capability to synthesize a structural design subject to specified constraints (\$1 M)
- 1989 - Baseline LDR structural design (\$500 K)
- 1990 - Develop LDR structural control model (\$1 M)

3.2.2 Dynamic Dimensional Stability (MDAC)

The key issues are vibration and thermal transient responses. Vibration isolation techniques are reasonably well understood but specific solutions are strongly dependent upon the operational design.

The thermal transient issue involves a direct trade between the performance of the step sunshield and the required thermal response stability of the structure. Since the requirements for the sunshield are undefined, LDR needs to pursue a near zero CTE material approach.

Figure 3.2.2-1 presents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

3.2.2.1 Requirements Derived from Concepts - The long term dimensional stability is determined by the changes in material properties. Set dimension is influenced by outgassing losses (i.e., water in resin composites), UV or other high energy degradation, erosion by atomic or molecular oxygen, life cycle microcracking or creep, and the accumulated effects of very small micrometeoroids. To a large extent these can be controlled by designed protection, shields and coatings.

Performance degradation produced by mechanical and thermal loading environments can be minimized by the use of structural materials which possess high specific stiffness, strength and self-damping characteristics. Dimensional stability of the LDR structure will also be significantly enhanced by the use of materials with near zero coefficient of thermal expansion (CTE) and which possess high thermal conductivity in order to minimize thermal gradients and stresses.

3.2.2.2 Required Technology Maturity Level - The alternative to a passive "metering" structure philosophy using near zero CTE materials is a system with complex active damping. The LDR technology program is based on demonstrating performance of passive control techniques at OAST Level 6 (engineering model tested).

3.2.2.3 On-going Technology Development and Estimation of Where the Technology Will Be in 1991 - Vibrations from on-board equipment may translate into distortions in the mirror support structure. These vibrations could be controlled by isolating the disturbance sources or by application of viscoelastic damping treatments. The task of isolating disturbances is aggravated by the fact that LDR will probably have a high modal density which makes it difficult to identify the offending modes. If an effective isolation system cannot be devised, viscoelastic materials (VEM) offer promise for achieving good vibration control. Unfortunately, in addition to being highly temperature and frequency dependent the structural characteristics of VEM's are not well defined and like composite members may be subject to material degradation in the space environment. Realistic VEM hardware suitable for LDR applications are just now being developed under programs like MDAC's "Passively Damped Joint Concepts" contract with the AFOSR and potential benefits of viscoelastic damping have been studied on programs like SASP (Science and Applications Space Platform) and ACCOS (Active Control of Space Structures).

Some design methods for integrating VEM concepts is state-of-the-art, but these are relatively heavy for an LDR class structure. Lightweight concepts are being experimentally developed under the AFOSR study. Progress to date is at essentially OAST Level 1 and a qualified concept is not yet achieved. Outlook is claimed to be optimistic with anticipated continuing efforts.

Key Issue

- Limit Structural Dynamic Response Deflections to Micron Level During Observation Periods
- Thermal Transients and Vibration Sources Are Principal Disturbances

Objectives

- Develop a Material for Truss Members Having a Near Zero CTE and a Low Δ CTE and Establish Fabrication Process, Property Data, Repeatability Expectations

Rationale

- Graphite/Epoxy Has a High Maturity Level and a Relatively Broad Properties Tailoring and Near Zero CTE Material Design is Essentially State of the Art Low Rejection Rate Fab is Part Dependent
- Vibration Attenuation Deferred to Phase B and is Contingent on the Signatures of Specific Selected Vibratory Equipment

Alternative

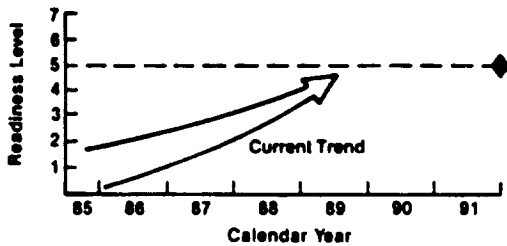
- CTE Value Goal May Be Tradable With the Performance Level of the Encompassing Thermal Control System

Risk Reduction

- Develop Metal Matrix Data and Processes
- Develop Structural Forms for Graphite/Glass

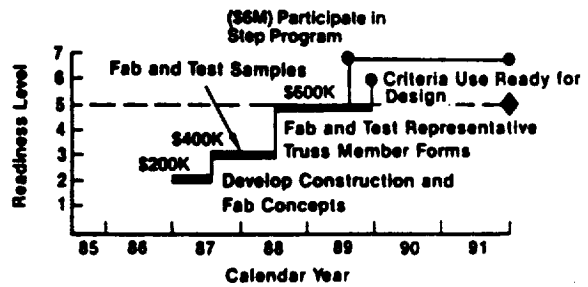
Technology Assessment

- Composite Property Tailoring is Well Advanced and Supported by Numerous Programs —
- Development Tailoring for Specific Application is Desirable



Schedule and Budgetary Plan for Augmentation

- Three Year \$1200K Will Provide Database for LDR Specific Composite Construction and Processes



CATEGORY B: MATERIALS, STRUCTURES AND DYNAMICS
 DYNAMIC DIMENSIONAL STABILITY
 Figure 3.2.2-1

3.2.2.4 Technology Shortfall and Augmentation Plan - The AFOSR efforts should be monitored. Contingent upon its progress it is recommended the LDR initiate parallel development efforts with VEM concepts directly related to LDR candidate structural member concepts. Part of the effort should be to develop high fidelity model capability for VEM concepts and support the general predictive analysis efforts. The technology project should culminate in performance demonstration with a STEP flight test experiment.

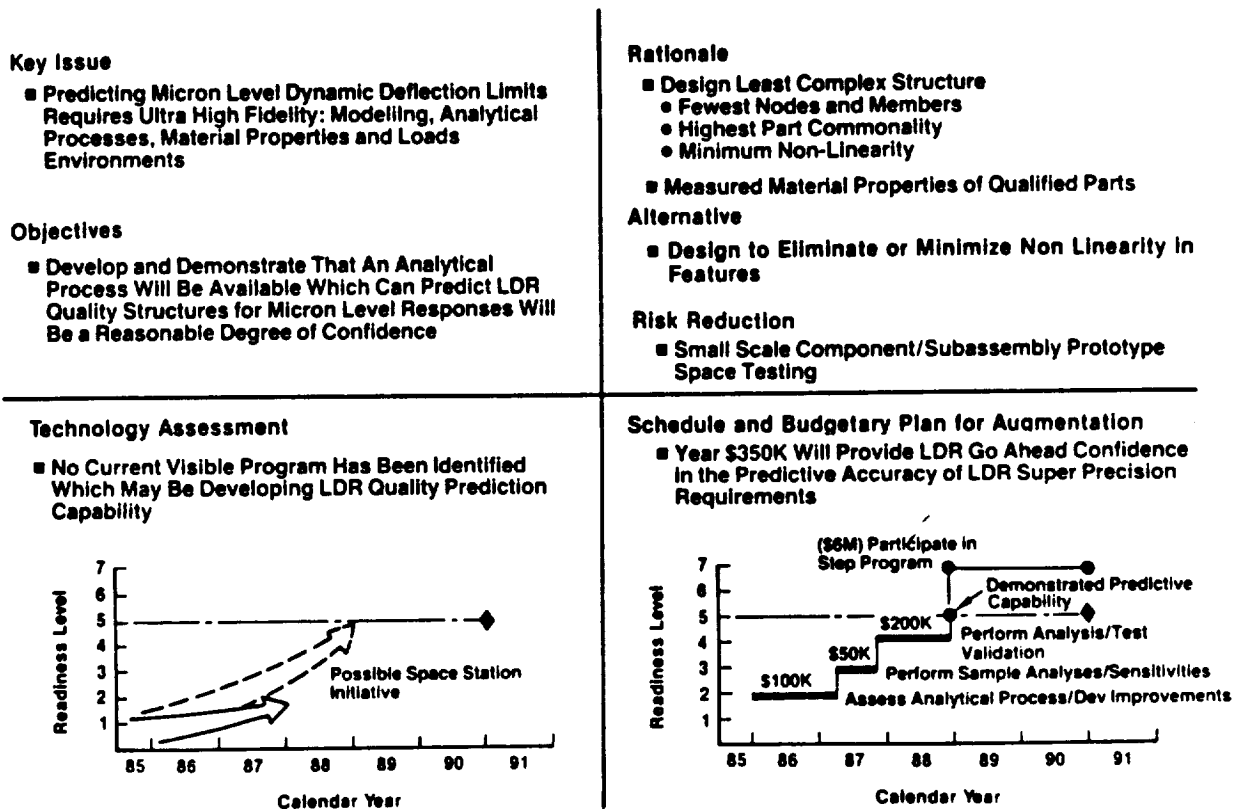
3.2.3 Dynamic Response Prediction Precision (MDAC)

The key issue is in predicting the structural responses to micron levels. Figure 3.2.3-1 presents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

3.2.3.1 Requirements Derived from Concepts - The key issue is in predicting the structural responses to micron levels. This requires accurate knowledge of materials properties and forcing functions. Also required are improved linear and non-linear structural design/analysis computer programs.

3.2.3.2 Required Technology Maturity Level - The alternative to a very high confidence in the ability to predict structural response to micron levels is large scale prototype testing in the space environment. The analytical process should be verified at least to OAST Level 5 for LDR go ahead.

3.2.3.3 On-going Technology Developments and Estimation of Where the Technology Will Be in 1991 - The basic analytical processes are adequate, however, analyses meeting LDR precision requirements and model complexity have not been demonstrated.



CATEGORY B: MATERIALS, STRUCTURES AND DYNAMICS
 DYNAMIC RESPONSE PREDICTION PRECISION
 Figure 3.2.3-1

3.2.3.4 Technology Shortfall and Augmentation Plan - No current program has been identified to develop prediction capabilities to LDR levels. Consequently this LDR technology program has been configured to meet this goal by 1991.

3.2.4 Structural Nonlinearity (MDAC)

LDR inherently has a large number of structural joints. Further development in the area of nonlinear dynamic modeling will be required. Figure 3.2.4-1 presents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

3.2.4.1 Requirements Derived from Concepts - A major critical issue which can be identified with the use of composite structures in a metering application is the joint between subsections. The isotropic properties can affect the demensional properties and therefore affect metering. The potential trouble areas include: built-in stresses, assembly variations, stress redistribution during repeat actuation and the material response to the operational environment.

Key Issues

- Interface Fittings and Their Attachment to Truss Members Typical Reflect Non Linear Qualities
- Joint Non Linear Models Are Not Well Defined
- Non Linear Dynamic Analysis Is Very Computer Intensive and Relatively Expensive

Objectives

- Develop High Fidelity Non Linear Modeling Techniques
- Develop Understanding of How to Effectively Reduce Joint Non Linearity
- Perform Correlation Testing

Rationale

- Design to Eliminate or Minimize Non Linearities
- Passive Damping Devices Contribute to Issue
- Non Linearities are Unavoidable
- High Fidelity Modeling Is Required for LDR Precision Goal

Alternatives

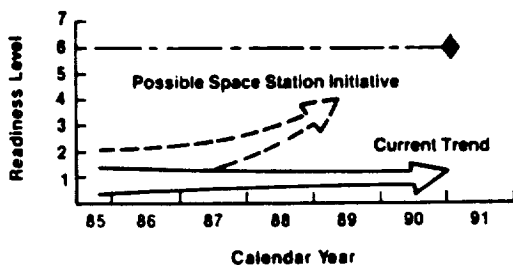
- Large Scale Prototype Space Testing

Risk Reduction

- Develop LDR Structural Configurations and Analyze for Sensitive Elements as Early as Possible
- Test Non Linear Parts to Verify Modeling as Early as Possible

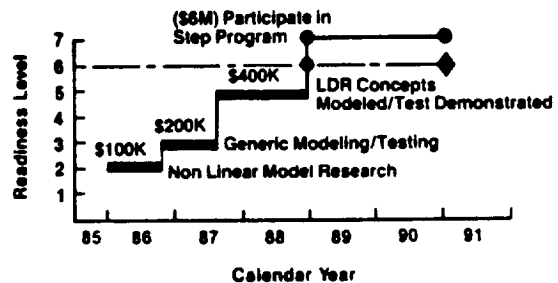
Technology Assessment

- No Visible Development for LDR Fidelity Reqs
- Low Level AFOSR Development
- Space Station Initiative May Contribute



Schedule and Budgetary Plan for Augmentation

- Two and One Half Year \$700K Program to Have Demonstrated High Fidelity Non Linear Modeling Capability



CATEGORY B: MATERIALS, STRUCTURES, AND DYNAMICS
 STRUCTURAL NON-LINEARITY
 Figure 3.2.4-1

3.2.4.2 Required Technology Maturity Level - Dynamic response prediction precision is directly related to the quality of nonlinear modeling and the amount of nonlinear elements in the whole mode. LDR has a very large number of joints where nonlinearity is common. Nonlinear modeling capabilities should be demonstrated to OAST Level 6 prior to investing substantially in system level analyses.

3.2.4.3 On-going Technology Developments and Estimation of Where the Tehcnology Will Be in 1991 - Nonlinear modeling is generally understood; however, few if any efforts have required the techniques to be developed and demonstrated for LDR required precision.

3.2.4.4 Technology Shortfall and Augmentation Plan - An effort is recommended to develop the techniques for nonlinear modeling of truss joint members. This includes modeling and experimental correlation testing. This project should also develop the design criteria to aid in minimizing nonlinear qualities of joints. This project should also support and culminate in demonstration of capability in the STEP flight test experiment.

3.2.5 Low Jitter and Rapid Settling (MDAC)

LDR inherently has a large number of joints. Because the stiffness characteristics of these joints are not well defined, they introduce an unwanted and unknown degree of flexibility into the mirror supporting structure. This unknown flexibility is a modal error that results in degradation of the optical system's performance. Figure 3.2.5-1 presents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

Key Issues

- Limit Jitter and Promote Rapid Decay of Dynamic Deflections From Both Vibratory and Altitude Maneuver Responses With Passive Techniques

Objectives

- Develop Visco-Elastic Material (VEM) Concepts for Use as Integral Structure Members
- Fabricate and Test LDR Specific Concepts
- Validate VEM Suitability by Mid 1988 for Critical Decision on Alternate Approach

Rationale

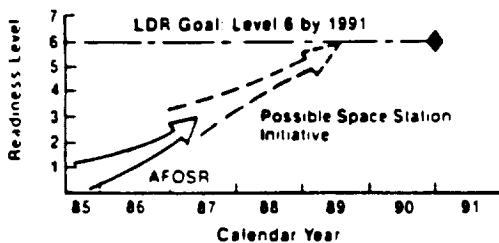
- System Simplicity of VEM Devices is Extremely Attractive — Currently in Development by AFOSR
 - Applicable to Both High and Low Frequency Damping
 - No Qualified Concepts to Date But Optimistic Outlook
- Alternative**
- Active Damping Control System

Risk Reduction

- Develop Both Active and Passive Damping Concepts in Parallel
- Perform High Fidelity Dynamic Analysis to Verify an Optimistic VEM Will Meet LDR Reqs

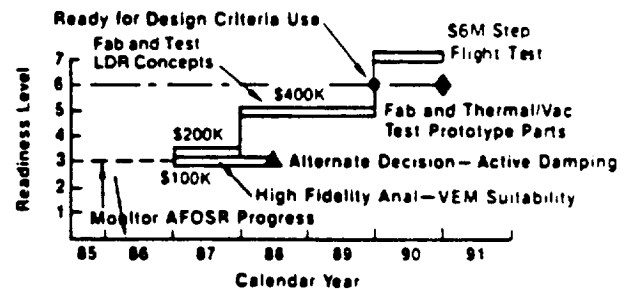
Technology Assessment

- AFOSR Development — Success and Development Continuation Uncertain



Schedule and Budgetary Plan for Augmentation

- Building on or Continuing AFOSR Effort — Three Years \$6.700K Program to Reach Goal by Early 1990



CATEGORY B: MATERIALS, STRUCTURES, AND DYNAMICS
LOW JITTER AND RAPID SETTling
 Figure 3.2.5-1

3.2.5.1 Requirements Derived from Concepts - Passive control is a candidate technique. Control of both high frequency vibration and low frequency maneuver responses is considered feasible with visco-elastic materials (VEM) integrally contained in the structure.

3.2.5.2 Required Technology Maturity Level - Since the alternative is a complex actively damped system, LDR should be based on demonstrated performance of a passive control technique at OAST Level 6 (engineering model tested).

3.2.5.3 On-going Technology Development and Estimation of Where the Technology Will Be in 1991 - The development of visco-elastic materials is currently being sponsored by AFOSR. These are applicable to low and high frequency damping. There are no space qualified concepts to date.

3.2.5.4 Technology Shortfall and Augmentation Plan - The LDR technology program has the following activities:

- Develop visco-elastic materials
- Fabricate and test LDR specific concepts
- Validate VEM suitability by 1988

3.2.6 Verification/Acceptance Ground Testing (MDAC)

Space testing is relatively expensive and is faced with limited schedules. It is important to be able to accomplish most structural development, verification, and acceptance testing on the ground. Figure 3.2.6-1 presents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

3.2.6.1 Requirements Derived from Concepts - In manufacturing LDR, with its large segmented mirror, on-ground testing will be required at all levels of buildup. The on-ground assembly issue involves initializing and checkout in "1g" (i.e., "0g" simulation) and recapturing and maintaining in "0g" an aggregate segmented mirror in which coherent phasing between segments is required.

3.2.6.2 Required Technology Maturity Level - The cost and schedule importance of ground testing indicates a need to demonstrate a basic capability of OAST Level 5 development prior to start of an LDR Phase B effort.

3.2.6.3 On-going Technology Developments and Estimation of Where the Technology Will be in 1991 - No programs to date have the need to ground test LDR class structures to required LDR precision levels. It appears that whole new techniques must be developed to test the large flexible structures to micro stress/strain levels and for accurate determination of such structural vibration modes and frequencies in the ground environment. Our judgement is that such a technology lies between OAST Level 1 and 2.

3.2.6.4 Technology Shortfall and Augmentation Plan - A project to develop the testing methodology and test data reduction process is recommended. It includes a phase to develop the concepts for a test plan, a phase for experimental testing to verify the process, and a phase to test sample structure as a proof-of-concept demonstration. This effort should support and participate in the STEP flight test experiment for a final correlation demonstration.

Key Issues

- Testing for Structural Response Characteristics for Micro Level Design Conditions Against the One G Biasing/Preloading Conditions of Ground Environment

Objectives

- Develop and Demonstrate Test, Procedure and Data Reduction in One G Environment of LDR Class Structures to LDR Required Micro Level Conditions and Response Limits
- Space Test Sample Structure for Correlation

Rationale

- Reciprocal Loading Tests, Scale Model Zero G Drop Testing in Vacuum Chamber Are the Available Modes of Ground Testing for Micro Strain, Preload Free Conditions
- Supplement Probable Space Station Initiative to Include LDR Micro Precision Goals

Alternative

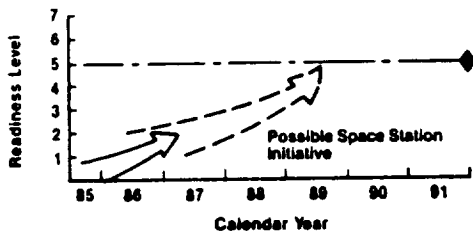
- Large Scale Prototype Space Testing

Risk Reduction

- Moderate Size Generic Truss Ground Tested and Comparison Space Tested

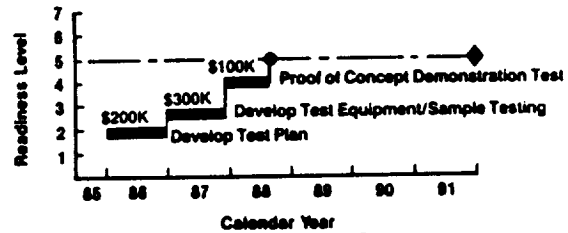
Technology Assessment

- Ground Environment Reduction and Micron Level Metrology for Large Flexible Structures Is Still Uncertain



Schedule and Budgetary Plan for Augmentation

- 2-1/2 Year \$600K Project Will Define Ground Test Capabilities and Level of Zero Space Testing



CATEGORY B: MATERIALS, STRUCTURES, AND DYNAMIC VERIFICATION/ACCEPTANCE GROUND TESTING
Figure 3.2.6-1

3.2.7 Mechanical Stability - Damage Tolerance (MDAC)

One element of long term stability for a 10 year life spacecraft is the damage tolerance of the structure from the micrometeoroid and space debris environments. Figure 3.2.7-1 represents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

3.2.7.1 Requirements Derived from Concepts - Current data indicates that there is a high probability of impact by particles as large as one centimeter. Two aspects of damage from micrometeoroid and man-made debris must be considered. The first involves the damage tolerance requirements needed in the structural materials. The second involves the redundance required in the structural elements.

3.2.7.2 Required Technology Maturity Level - High velocity particle impact phenomena has been demonstrated on the ground; however, the results are dependent upon structural material and structural shape. Consequently, the LDR technology plan has been established at OAST Level 6 to firmly establish the failure modes on representative LDR materials and structural elements.

3.2.7.3 On-going Technology Developments and Estimation of Where the Technology Will Be in 1991 - Basic impact technology is well advanced; however, technology should be applied to representative LDR structural arrangements.

Key Issues

- Micrometeoroid and Man Made Debris Criteria Show That Large Elements of LDR Have a 99% Probability of Impact by Particles > 1 cm and Mirror Support Structure by > 50 mm Particles
- The Debris Model May Be More Severe in the LDR Time Frame

Objectives

- Develop and Test Candidate Structural Member Concepts to Define Damage/Failure Modes and Design Criteria

Rationale

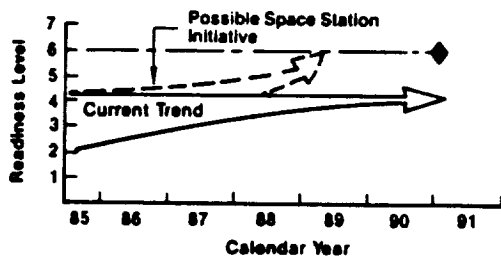
- Use Material With High Damage Tolerance
 - Graphite/Epoxy
- Use Structurally Redundant Concepts

Alternative

- Plan for On-Demand Repair Visits
- Risk Reduction**
- Implement a Thermal Shroud Which Will Provide Substantial Particle Shield Capability

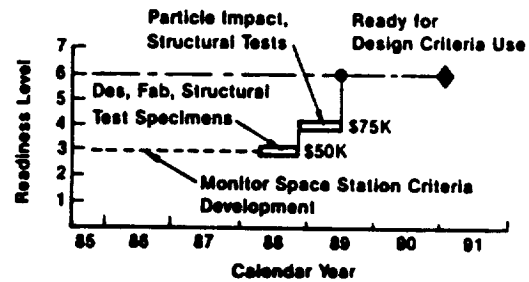
Technology Assessment

- Particle Impact Phenomena is Reasonably Well Understood But Damage Characterization is Somewhat Design Dependent



Schedule and Budgetary Plan for Augmentation

- 15 Month \$125 K Project Would Provide LDR Specific Design Criteria



**CATEGORY B: MATERIALS, STRUCTURES, AND DYNAMICS
MECHANICAL STABILITY - DAMAGE TOLERANCE
Figure 3.2.7-1**

3.2.7.4 Technology Shortfall and Augmentation Plan - A relatively small impact project is recommended to firmly establish the structural failure modes and define structural redundancy requirements.

3.2.8 Step Sunshield

3.2.8.1 Requirements Derived From Concepts - The LDR Primary Mirror must be maintained at a temperature level of $T \leq 200^{\circ}\text{K}$ and be protected from contamination and meteorite damage. For the specified optical telescope pointing requirements ($< 60^{\circ}$ - 90° to sun, and $\geq 45^{\circ}$ to the earth) it becomes necessary to employ a mirror shield for reducing the thermal loading into the mirror; otherwise the heat gains would be enormous for a 20 meter diameter mirror. The thermal shielding technique also enables a passive thermal control approach to be employed which offers the necessary high reliability. Furthermore, active cooling systems, even in conjunction with shields, would be very large, create vibrations, require momentum compensation, consume large amounts of power (which in turn requires thermal cooling), are costly, difficult to test, and offer minimal flexibility to design and system operational parameter changes.

The present design approach is to employ a 20 meter inside diameter x 20 meter high cylindrical step-geometry shield around the primary mirror. The thermal control finishes applied to the step surfaces will be specular with low solar absorption and high emittance on the top side and diffuse with high solar absorption and low emittance on the bottom side. This surface finish combination together with the step-geometry configuration of the shield directly reflects a majority of the in-coming solar and albedo energy from the shield cavity and both scavenges all internally bounced solar wavelength energy and reduces the direct IR wavelength energy radiated to the mirror from the underside shield surfaces which view the mirror. In addition to the shield thermal finishes the surfaces of all optics (primary and secondary mirror) will be highly specular with low solar absorption and low emittance coatings (polished silver).

The thermal shield must be configured and constructed to enable packaging within the space shuttle cargo bay and then be either deployed on-orbit or assembled from a space station. The materials of construction must not only meet structural and thermal requirements but must be non-contaminating to the optical surfaces. In fact, it is possible that the shield will serve as an on-orbit workshop to protect the mirror segments against contamination from the space station and cargo shuttles during mirror assembly and check-out.

It should be mentioned that a straight wall cylindrical shield would result in much higher thermal loads to the mirror and that a tapered shield while offering a somewhat reduced thermal load would become very large. The step-geometry configuration results in little increase in outside diameter (about 2.829 meters) and limits the heat gain to that of a large tapered shield. The steps are also more attractive in managing and reducing internal specular reflections.

3.2.8.2 Required Technology Maturity Level - Precise temperature control of the telescope primary mirror is essential to LDR. This can be accomplished with a reliable, passive thermal control approach which in part uses a step-geometry thermal shield. The shield is a vital component in the overall LDR telescope thermal control hardware and it must reach at least an engineering model technology maturity status (Level 6) by 1991. There are no major requirements needed in developing entirely new technology but a strong emphasis is needed on innovative engineering concepts and designs. The concepts must consider transport, human factors, deployment techniques, and safety. Effort is also needed in development of structural materials with non-contaminating and low out-gassing characteristics.

3.2.8.3 On-going Technology Developments and Estimation of Where Technology Will Be in 1991 - No current direct work is underway in the development of technology needed for the step-configuration mirror shield. The overall technology maturity status is no higher than Level 1; however, features of the shield, such as thermal finishes, deserve a higher ranking. Thermal finishes of the generic type needed have been space tested to Level 7; nevertheless, when considering the 10 year life requirements demanded by LDR it is believed more stable finishes are needed and their maturity level is likely no higher than Level 4.

Much work is underway in development of strong, lightweight structures employing both polymer and metal matrix composites but the non-contamination requirements for LDR will necessitate the development of improved materials.

3.2.8.4 Technology Shortfalls and Augmentation Plan - The use of composite materials is indicated for achieving a weight economical rigidized structural design for the step-geometry shield. The thermal properties and low CTE composites are also attractive features. Unfortunately, the out-gassing levels (water vapor and organics) from current polymer matrix composites is excessive for meeting the needed contamination level control of LDR. While metal matrix composites show less contamination they are exceedingly expensive and their thermal characteristics are not as attractive in terms of the thermal properties desired in the LDR shield design.

Thermal finishes with the features specified in 3.2.8.1 are available; however, there is considerable question as to their long term (10 year life) stability for LDR. The coatings must not be degraded by intensive long term solar (UV) exposure and by meteorite impact; this implies high chemical stability and mechanical hardness.

Novel engineering design concepts are needed to integrate the shield configuration into a package suitable for launch in the Space Shuttle followed either by on-orbit deployment or assembly from a space station. The assembly must further serve as an efficient protective workshop during assembly of the telescope mirror segments; again novel engineering is implied.

A 3.5 year, \$1M program is recommended beginning in 1988 with a funding level of \$0.1M for the first year followed by about \$0.9M spread about evenly over the next 2.5 years as outlined and broken down in the schedule plot of Figure 3.2.8-1.

3.2.9 Secondary Mirror Temperature Control

3.2.9.1 Requirements Derived From Concepts - To reduce the telescope noise background to a tolerable level a desired goal is to operate the secondary mirror at a temperature no higher than 125°K based upon the specified primary mirror maximum temperature of 200°K. Analysis shows that this can not be accomplished with a completely passive design (as in the 200°K primary mirror case) and that some cryogenic cooling will be needed. To meet the tight optical-path stability requirements all of the optical elements must be completely isolated from mechanical vibrations; this implies that no active refrigeration system (e.g., mechanical pumps) can be coupled to the optical elements. Accordingly, a more passive cooling approach is indicated such as provided by stored cryogenics.

The cooling approach that is implemented must avoid contaminating the optical surfaces. Further, thermal expansion must be managed in a manner as not to impact mechanical forces onto the optical elements and supporting metering structure.

KEY ISSUES

- Develop a shroud which meets the solar and energy exclusion angle requirements and maintains the primary mirror at 200°K ±1K. This shroud will also provide contamination protection during observatory assembly, operation and revisiting; therefore, the shroud cannot be made from material(s) which either outgas or emit loose particles.

OBJECTIVES

- Develop a step sun shield using coatings, materials, geometry to minimize overall sun shield size.
- Space qualification program (coatings and materials) if required.
- Proof-of-concept demonstration
- Engineering model test on-ground
- Engineering model test in space (?)

RATIONALE

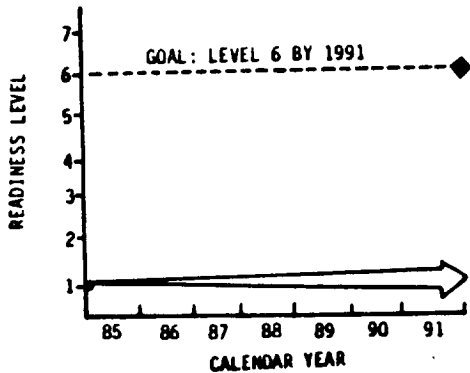
- 10 year life space qualified coatings (high ε low α's; low ε high α's; low ε low α's) for optical baffles are required.
- 10 year life space qualified reflective/transmittive coatings for optics are required.
- Non-contaminating lightweight structural materials and deployment hardware are required.

ALTERNATIVES

- Simple cylinder or tapered cylinder (overall size will be "much larger" for tapered cylinder; heat load will be "much higher" for simple cylinder).

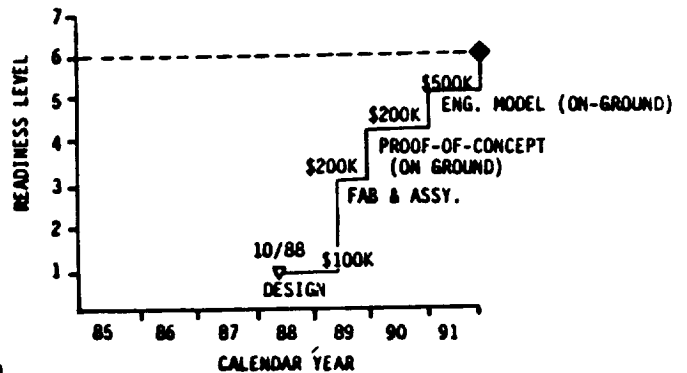
TECHNOLOGY ASSESSMENT

No other programs to develop step sunshield identified



SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

3 1/2 year, \$1M program to reach engineering model demonstration (on-ground) by January 1992.



CATEGORY B: MATERIALS, STRUCTURES, THERMAL, AND DYNAMICS STEP SUNSHIELD

Figure 3.2.8-1

Two approaches appear promising: a stored LN₂ cryogen system packaged directly onto the backside of the secondary mirror and a remotely located LN₂ cryogen system with the cryogens piped to the mirror via the mirror support structure. A 10-year life reliability goal for the system is needed; however, the design can be based upon cryogen replenishment and general overall servicing at 3 year intervals. Size of the system is important since it must fit into a space which will not obscure the optical path.

With or without a mirror cooling system it will be necessary to actively realign the optical position (in tilt, decenter, and despace). Chopping of the secondary may also be utilized. This added system capability will not fully compensate for the benefits gained by cooling the secondary mirror to 125°K.

3.2.9.2 Required Technology Maturity Level - The optical system background noise requirements for LDR require that the temperature of the secondary mirror be controlled at about 125°K + 1°K. A demonstration of the critical functions and characteristics (technology maturity Level 4), in terms of optical performance, should be available by 1991. It is believed that the actual space operational experience from other NASA and DoD programs for similar cryogenic system hardware will enable this Level 4 technology, specific to LDR, to be upgraded to an equivalent technology maturity at Level 6.

Important aspects of the LDR directed effort must address the issues of contamination control, complete optical isolation for structural mounting size in terms of not obscuring the optical path, remote robotic serviceability, damage protection such as from meteorites, and high reliability.

3.2.9.3 On-going Technology Developments and Estimation of Where Technology Will Be In 1991 - Effort is currently underway in the development of space oriented stored cryogenic systems and periodic refurbishment of these systems (e.g., SIRTf). Considerable technology, specific to cryogen storage and management, will be available from this work by 1991; however, in terms of integrating stored cryogens to a precision optical mirror, the technology maturity is currently only at Level 1 and will likely be no higher by 1991 without further specifically related work.

3.2.9.4 Technology Shortfalls and Augmentation Plan - Direct adaptation of a stored cryogen system for cooling the secondary mirror in a precision optical telescope assembly must be implemented with a design which avoids any motion or mechanical displacement of the mirror. This implies nearly complete isolation from structurally induced loads and mechanical vibration. Dimensional changes and stresses produced by the large cool-down temperature change (125°K) must also be isolated from the optical system. Considering first the need for this isolation and then the need for good thermal contact, in terms of cooling the mirror to 125° + 1°K, a difficult problem in engineering is created. Further, the system must be implemented to provide a 3 year life cooling capacity without obscuring the optical path. The flow of cryofluid and evolved gas must be managed to avoid or greatly suppress vibrations. The system must be further integrated to enable serviceability at 3 year intervals without introducing physical damage or contamination to the adjacent optical elements. The design must be compatible with thermal shielding surrounding the secondary and primary mirrors and must consider protection from meteorite damage. All design must have a reliability goal of 10 year life in space which is much more demanding than required by current programs.

A 2-1/4 year, \$0.7M program is recommended beginning in 1988 with a funding level of \$0.2M for the first year followed by \$0.5M spread over the next 1.5 years as outlined and broken down in the schedule plot of Figure 3.2.9-1.

KEY ISSUE

Secondary mirror temperature should be lower than primary mirror temperature (goal: 150 K) due to telescope background noise considerations. This will require active secondary mirror cooling. Maintaining alignment of secondary mirror alignment is of concern.

OBJECTIVE

Secondary mirror development program establishing the approach for temperature control and alignment control.

RATIONALE

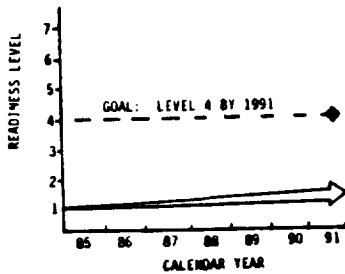
Two alternate temperature control approaches have been suggested: (1) self-contained cryogen package behind secondary mirror, (2) cryogen is transferred through the "legs" of the secondary mirror metering structure. In either case the cooling approach will impact the philosophy of secondary mirror alignment (i.e., is active or passive alignment maintenance required?)

ALTERNATIVES

(1) Secondary mirror is maintained at space ambient temperature throughout orbit. The secondary mirror will operate warmer than the goal (probably about 200 K). (2) Compensating secondary mirror support structure.

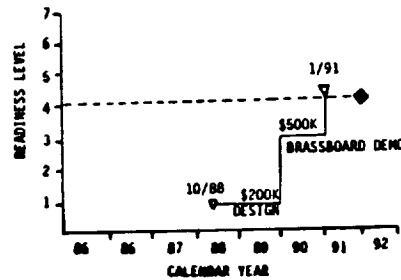
TECHNOLOGY ASSESSMENT

Related NASA and DoD programs. However, combination of requirements unique to LDR.



SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

2 1/4 year, \$500K program to reach goal by January 1992.



**CATEGORY B: MATERIALS, STRUCTURES, THERMAL AND DYNAMICS
SECONDARY MIRROR TEMPERATURE CONTROL**

Figure 3.2.9-1

3.2.10 Primary Mirror Temperature Control

3.2.10.1 Requirements Derived From Concepts - The specified temperature control uniformity for the LDR primary mirror is $\pm 1.0^\circ\text{K}$ and the base control temperature is specified as $T \leq 200^\circ\text{K}$. A semi-passive thermal control concept has been preliminarily analyzed which will meet these specified requirements. The primary mirror will be enclosed within a cylindrical step-geometry shield (discussed in the step sunshield technology assessment). The mirror will be temperature control modulated by means of a thermal control plate, with trim heaters, that face the rear surface of the mirror. This temperature control plate, in turn, views a thermal control cavity on the backside that is equipped with "space-viewing louvers". The louvers are opened to dump heat at times when excess thermal energy falls onto the mirror.

The system is described as semi-passive because it employs active but highly reliable electrical trim heaters for temperature control. The reliability will be further enhanced by using separate heaters and controls on each mirror segment. The moving louvers will use bi-metal control elements with over-riding electrical motor drives. It is believed this system can be designed and constructed to meet the 10 year life specified for LDR.

3.2.10.2 Required Technology Maturity Level - Precise temperature control of the telescope primary mirror is essential to LDR. This can be accomplished with a reliable semi-passive thermal control approach as described above. Excluding the shield, which was discussed in the step-sunshield technology assessment, the remaining elements in the suggested overall thermal control concept must reach a technology maturity Level 4 by 1991.

There are no major requirements needed in developing entirely new technology but a strong emphasis is needed on detailed thermal modeling and analysis, in innovative engineering design, and in system breadboard testing. Emphasis must be placed on component reliability and on simple backup (over-ride) features which add little complexity, weight, and power demands on the system. The entire design must consider assembly on a space station or direct deployment from the space shuttle.

3.2.10.3 On-Going Technology Developments and Estimation of Where Technology Will Be In 1991 - No current direct work is underway for the engineering requirements needed to fully analyze and implement the stated thermal control concept; thus, it would accordingly be rated at a maturity Level 1. This may appear misleading since the basic fundamentals are understood; however, they are not being focused into the necessary integrated design which must consider 10 year life reliability and on-orbit assembly and check-out.

3.2.10.4 Technology Shortfalls and Augmentation Plan - The basic fundamentals to the stated thermal control concepts are understood; however, they must be focused into an integrated design which considers 10 year life reliability and on-orbit assembly and check-out. Work is also needed to assess backup control features and how to best provide them. All designs and hardware must consider contamination of the optical surfaces; this will require careful selection of materials and may exclude lubricants on moving surfaces (e.g. louver pivots).

A detailed thermal model and analysis will be needed which will predict the thermal control performance under the full range of operational telescope pointing parameters and under "worst hot case" and "worst cold case" conditions of orbit parameters, thermal finishes, and system geometry.

A 2.5 year, \$0.7M program is recommended beginning in 1988 with a funding level of \$0.2M for the first year and \$0.5M over the next 1.5 years as outlined and broken down in the schedule plot of Figure 3.2.10-1.

KEY ISSUE

Telescope background subtraction techniques require maintaining primary mirror at a uniform temperature (Goal: $\pm 1^{\circ}\text{K}$)

OBJECTIVES

- Detailed design of primary mirror temperature control concept
- Critical function demonstration

RATIONALE

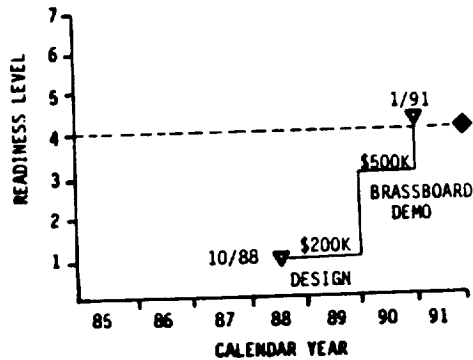
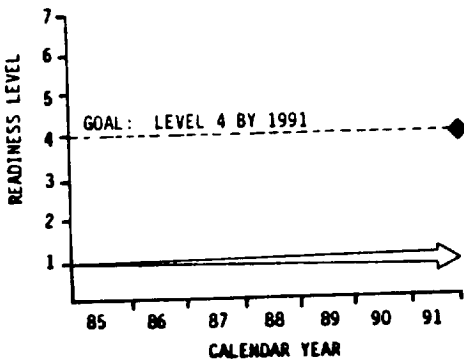
Alternate technical approaches to maintaining the primary mirror at $200^{\circ}\text{K} \pm 1^{\circ}\text{K}$ appear to exist. One approach preliminarily analyzed in this study involved the use of a step sunshield and trim heaters on a plate located behind the primary mirror which faces a cavity that is thermally controlled using "louvers" to view space.

TECHNOLOGY ASSESSMENT

No other programs identified with this operating temperature or temperature uniformity requirements.

SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

2 1/2 year, \$700K program to reach goal by January 1992.

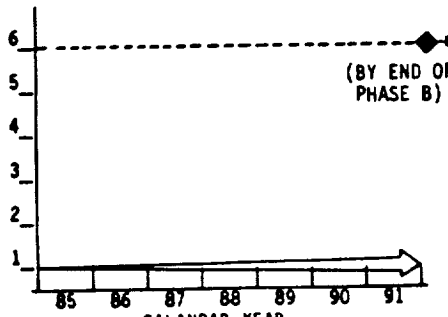


CATEGORY B: MATERIALS, STRUCTURES, THERMAL, AND DYNAMICS
 PRIMARY MIRROR TEMPERATURE CONTROL
 Figure 3.2.10-1

3.2.11 Collapsible Sunshield

Contamination control must be considered in all phases of the LDR buildup and end use. A concept to protect the primary mirror and secondary mirror from particulate contamination during Shuttle revisits and during servicing with space station is required. Figure 3.2.11-1 presents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

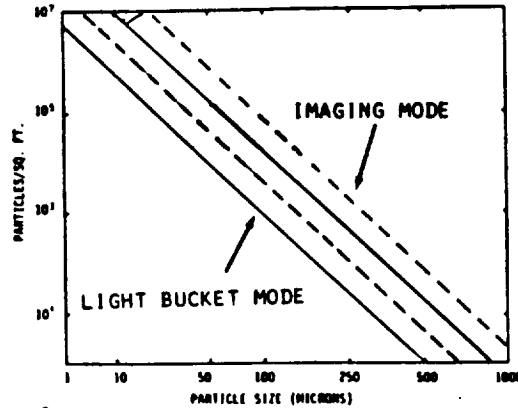
3.2.11.1 Requirements Derived From Concepts - A major concern in the boost, deployment, operation, and revisit/maintenance phases is contamination due to propulsion effluents. Throughput loss and/or optical quality degradation could occur with no protection. Particulate contamination increases the high spatial frequency content on the mirror surface. Figure 3.2.11-2 shows the effect on performance (light bucket mode and imaging mode) of particulate contamination.

<p>KEY ISSUE</p> <ul style="list-style-type: none"> Develop a concept to protect primary mirror and secondary mirror from particulate contamination after LDR observatory buildup --- During shuttle revisit and servicing with space station <p>OBJECTIVES</p> <ul style="list-style-type: none"> Define environment Evaluate alternate protection concepts Select concept as part of Phase B Study 	<p>RATIONALE</p> <ul style="list-style-type: none"> Techniques for contamination control during on-ground buildup via clean room environment and clean packaging are well established Recommend strippable coatings on primary mirror and secondary mirror during LDR observatory buildup <p>ALTERNATIVE</p> <ul style="list-style-type: none"> No LDR protection during shuttle revisiting and servicing---possibly resulting in throughput loss and/or optical quality degradation <p>RISKS</p> <ul style="list-style-type: none"> Seriously degraded system performance Difficult to recover performance
<p>TECHNOLOGY ASSESSMENT</p> <p>No other programs to develop these types of contamination protection identified. Close relationship to design of thermal shroud (See Step Sunshield)</p> 	<p>SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION</p> <p>Selection of concept should be part of Phase B Study</p>

CATEGORY B: MATERIALS, STRUCTURES, THERMAL, AND DYNAMICS
 COLLAPSIBLE SUNSHIELD
 Figure 3.2.11-1

	SURFACE ROUGHNESS WITHOUT <u>PARTICULATE CONTAMINATION</u>	SURFACE ROUGHNESS WITH <u>PARTICULATE CONTAMINATION</u>
(1) ● LIGHT BUCKET MODE ($\lambda \text{ min}=1\mu\text{m}$)	250 Å RMS	> 250 Å RMS
(2) ● IMAGING MODE ($\lambda \text{ min}=30\mu\text{m}$)	7500 Å RMS	> 7500 Å RMS

SURFACE PARTICLES



• MIL. STD. 1246A

CLEANLINESS REQUIREMENTS
Figure 3.2.11-2

3.2.11.2 Required Technology Maturity Level - No other programs to develop these types of contamination protection have been identified. A potential protective cover for LDR is a sunshield shroud combination which could be closed between telescope operations and during revisiting. The step sunshield development program is therefore closely coupled to the collapsible sunshield development program. Consequently, this development program is configured at OAST Level 6 (engineering model tested).

3.2.11.3 On-going Technology Developments and Estimation of Where The Technology Will Be In 1991 - No other programs to develop these types of contamination protection have been identified. MDAC has experience in containment shrouds for Shuttle orbit borne spacecraft. The first type is a soft shroud performing a thermal function only, which is integrated into the carrier pallet for Shuttle PAM D payloads. The second type is a metal shroud which is more representative of a contamination shroud which is deployed from the orbiter and jettisoned from the spacecraft away from the orbiter environment.

3.2.11.4 Technology Shortfall and Augmentation Plan - Currently there are no other programs identified that require this type of contamination protection. Alternate protection concepts should be evaluated with respect to an LDR "point" design. Therefore, selection of a contamination protection concept should be part of the LDR Phase B Study.

3.2.12 Spacecraft Buildup on Orbit (FSC)

Inasmuch as spacecraft and spacecraft subsystems are common elements in various space programs, many of the LDR spacecraft technology requirements are planned for development under other programs. Chief among these is the NASA Space Station program, in which numerous technology development efforts are being initiated.

The challenge to LDR will be to achieve careful evaluations of its specific needs in order to determine the relevance of Space Station and other development efforts, and to pinpoint capabilities which may fall short of LDR requirements, if any.

Most spacecraft requirements will grow out of overall system-level studies, at a phase A or phase B level of detail. At a pre-phase A level, trends and directions are revealed, which enable a qualitative estimation of the critical technology areas in the supporting spacecraft functions. It is useful to evaluate the spacecraft subsystems from this standpoint as a guide to the trend of requirements and possible shortcomings of contemplated developments.

3.2.12.1 Requirements Derived from Concepts - Concept 1 requires on-orbit assembly of system elements, and may require similar incremental buildup of spacecraft elements as well.

3.2.12.2 Required Technology Maturity Level - A readiness level of 7 by 1991 has been set as the LDR goal in this area.

3.2.12.3 On-going Technology Developments and Estimation of Where the Technology Will be in 1991 - The incremental buildup concept is a well-accepted Space Station requirement, although the subsystem level to be developed for assembly may be too large and not appropriate to the LDR spacecraft requirement. More directly applicable may be the Fairchild Leasecraft development, in which subsystem elements of the proper size (i.e., spacecraft subassemblies) will be exchanged and installed on orbit. For instance, a unit known as the Control Augmentation Module, which consists of a set of four Hubble Space Telescope reaction wheels, will be installed on the Leasecraft Platform on orbit when required by large payloads. The anticipated buildup of this capability as a result of the Leasecraft activity is shown in Figure 3.2.12-1. Based on the demonstrated on-orbit changeout of a spacecraft subsystem module on the Solar Maximum Repair Mission, this technology is currently Level 6.

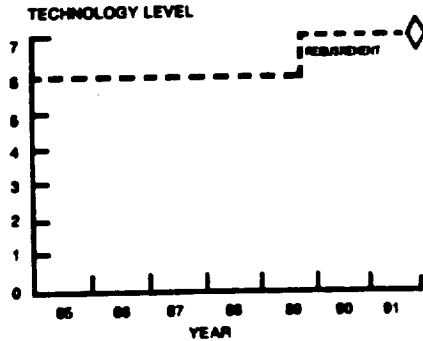
REQUIREMENT GOAL

CONCEPT 1 REQUIRES ON-ORBIT ASSEMBLY OF SYSTEM ELEMENTS, AND MAY REQUIRE SIMILAR INCREMENTAL BUILDUP OF SPACECRAFT ELEMENTS AS WELL. THIS CONCEPT IS A WELL-ACCEPTED SPACE STATION REQUIREMENT, ALTHOUGH THE SUBSYSTEM LEVEL TO BE DEVELOPED FOR ASSEMBLY MAY BE TOO LARGE AND NOT APPROPRIATE TO THE LDR SPACECRAFT REQUIREMENT. MORE DIRECTLY APPLICABLE MAY BE THE FAIRCHILD LEASECRAFT DEVELOPMENT, IN WHICH SUBSYSTEM ELEMENTS OF THE PROPER SIZE (I.E., SPACECRAFT SUBASSEMBLIES) WILL BE EXCHANGED AND INSTALLED ON ORBIT. BASED ON THE DEMONSTRATED ON-ORBIT CHANGEOUT OF A SPACECRAFT SUBSYSTEM MODULE ON THE SOLAR MAXIMUM REPAIR MISSION, THIS TECHNOLOGY IS CURRENTLY LEVEL 6.

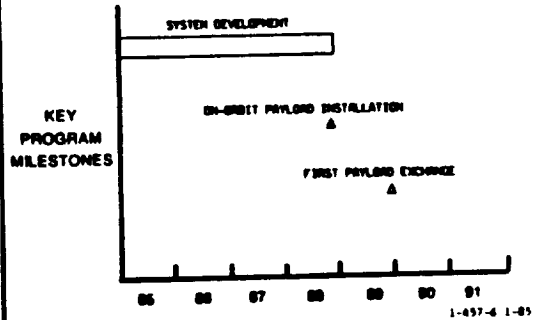
DESCRIPTION RATIONALE

- SMMR DEMONSTRATION VIA EVA
- LEASECRAFT PLATFORM TO DEMONSTRATE REMOTE ASSEMBLY AND DISASSEMBLY OF SUBSYSTEMS, PAYLOADS AND RMS AND REMOTELY-ACTUATED MECHANISMS.

TECHNOLOGY ASSESSMENT



SCHEDULE GOAL: NO AUGMENTATION MAY BE NECESSARY



TECHNOLOGY ASSESSMENT SPACECRAFT BUILDUP ON ORBIT
Figure 3.2.12-1

3.2.12.4 Technology Shortfall and Augmentation Plan - No augmentation may be necessary.

3.3 PROPULSION AND POWER (OAST CATEGORY C)

3.3.1 Structural Dynamics: Advanced Power System (FSC)

The spacecraft electrical power and attitude control subsystems fall into the same category: well-developed and state-of-the-art for most applications, possibly including LDR. However, in considerations of overall system dynamics, i.e., pointing control and stability, one or both of these subsystems may very well exhibit significant deficiencies. This cannot be ascertained with certainty without a dynamic modeling of the entire system and a study of the responses to transient inputs. Nevertheless, in the realm of flexible-spacecraft dynamics, LDR is likely to be a system of prime interest.

The electric-power system is of some concern in this connection because it is likely to contribute a major element of system flexibility: large solar arrays on long booms. If the solar exclusion angle for observations is less than 90 degrees, then these booms may need to extend beyond the shadow of the primary reflector, as great as 5 to 10 meters on each side. The arrays themselves will then extend an additional 10 to 20 meters beyond the end of the booms on each side.

Furthermore, this problem is not likely to occur in the same form on the Space Station. The station is expected to maintain a fixed orientation in space (with reference to Earth) and fine-pointing requirements are expected to be satisfied by individual, isolated, pointing control systems. By contrast, LDR will be re-orienting its pointing direction frequently, mainly to avoid observational exclusion zones, and will require rapid settling at its newly established pointing direction. Flexible extensions, most notably the large solar arrays, or noise introduced by the active elements of the attitude control subsystem, i.e., the control-moment-gyros, will be inimical to achieving this result.

3.3.1.1 Requirements Derived from Concepts - Most commonly, approaches to resolving the structural dynamic effects of extended solar arrays or other appendages involve structural stiffening, or alternatively, structural isolation. Neither approach has proven wholly satisfactory, and ultimately system workarounds and compromises are accepted.

Another alternative would be the complete replacement of solar arrays by a power system which is compact and not sun-dependent, e.g., nuclear power. In the power range of LDR interest radioisotope-dynamic-generators are most satisfactory.

3.3.1.2 Required Technology Maturity Level - A goal of achieving Level 7 by 1991 is recommended, if the advanced power system approach were adopted.

3.3.1.3 On-going Technology Developments and Estimation of Where the Technology Will Be In 1991 - A Department of Energy program conducted from 1975 to 1980 succeeded in bringing a radioisotope dynamic generator (DIPS) to a state of Level 5-6 readiness. This system is capable of satisfying the 2 to 10 kilowatt power range most satisfactorily. However, no mission requirement was evident and the program was discontinued in 1980.

Nuclear power systems currently under active development are either too low-power or too high-power for LDR. Radioisotope thermoelectric generators (RTG's) have been developed to Level 7 for power up to 300 watts per unit. Reactor power systems currently in development (Level 2) are designed for 100 kilowatts and higher (SP-100). Therefore, restoration of the DIPS system and completion of its development would be preferred for LDR. Application of DIPS to the LDR mission would essentially obviate the structural-dynamic effects of the major flexible appendage of this system.

3.3.1.4 Technology Shortfall and Augmentation Plan - A technology road map for restoring and completing the development of the dynamic generators is shown in Figure 3.3.1-1. The radioisotope heat source developed is already at Level 6. The necessity for reviewing, restoring, revalidating, and retesting the dynamic generator system(s) return this element to Level 4.

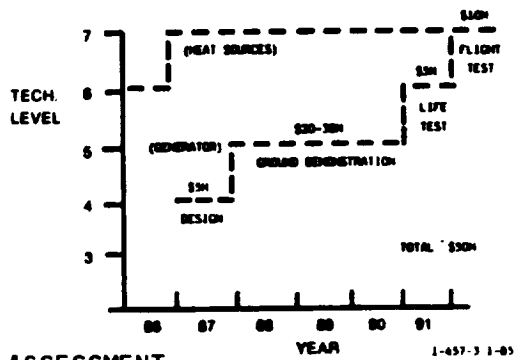
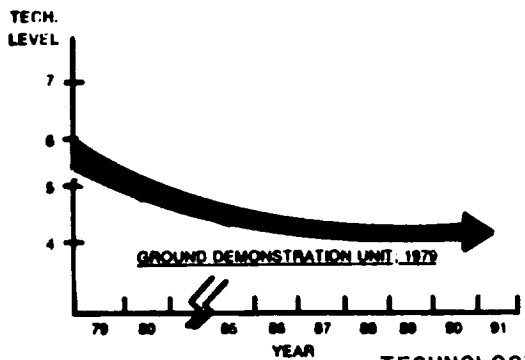
PROBLEM, REQUIREMENT, GOAL

LDR REPRESENTS A QUANTUM LEVEL INCREASE IN SPACE SYSTEM SIZE, AND IN THE IMPORTANCE OF STRUCTURAL-DYNAMIC MODELING. UNLIKE SPACE STATION, LDR WILL UNDERGO FREQUENT REORIENTATION AND WILL REQUIRE A HIGH LEVEL OF STRUCTURAL STABILITY. THE SOLAR ARRAYS ARE LIKELY TO CONTRIBUTE A MAJOR ELEMENT OF SYSTEM FLEXIBILITY TO AVOID SHADOWING BY THE PRIMARY REFLECTOR. THE ARRAYS WILL BE MOUNTED ON 5-TO-10 METER BOOMS, AND WILL EXTEND 10-TO-20 METERS BEYOND THE BOOMS. MOST COMMONLY, APPROACHES TO RESOLVING THE DYNAMIC EFFECTS OF EXTENDED SOLAR ARRAYS OR OTHER APPENDAGES INVOLVE STRUCTURAL STIFFENING, OR ALTERNATIVELY STRUCTURAL ISOLATION. NEITHER APPROACH HAS PROVED WHOLLY SATISFACTORY, AND ULTIMATELY SYSTEM WORKAROUNDS AND COMPROMISES ARE ACCEPTED. ANOTHER ALTERNATIVE WOULD BE THE COMPLETE REPLACEMENT OF SOLAR ARRAYS BY A POWER SYSTEM WHICH IS COMPACT AND NOT SUN-DEPENDENT. E.G. NUCLEAR POWER IN THE POWER RANGE OF LDR INTEREST RADIOISOTOPE-DYNAMIC-GENERATORS ARE MOST SATISFACTORY.

PERSPECTIVE, PLAN

FUTURE LDR STUDIES SHOULD INCLUDE A DETAILED SYSTEM DYNAMIC MODELING AND STUDY OF TRANSIENT RESPONSES AND SYSTEM SETTLING TIMES. DYNAMIC ISOTOPE POWER SYSTEM SHOULD BE INCLUDED IN THE MODELING AS WELL AS SOLAR ARRAYS. A DEPARTMENT OF ENERGY PROGRAM CONDUCTED FROM 1975 TO 1980 SUCCEEDED IN BRINGING A DYNAMIC ISOTOPE POWER SYSTEM (DIPS) TO A STATE OF LEVEL 5-6 READINESS. THIS SYSTEM IS CAPABLE OF SATISFYING THE 2-TO-10 KILOWATT POWER RANGE MOST SATISFACTORY. HOWEVER, NO MISSION REQUIREMENT WAS EVIDENT AND THE PROGRAM WAS DISCONTINUED IN 1980, LEADING TO A DECLINE IN TECHNOLOGY LEVEL. A PROGRAM TO RESTORE, REVALIDATE AND COMPLETE DEVELOPMENT OF THE SYSTEM IS SHOWN BELOW. SPACE-QUALIFIED RADIOISOTOPE HEAT SOURCES ARE ALREADY AT LEVEL 6 AND WILL MOVE TO LEVEL 7 IN 1986.

TECHNOLOGY ASSESSMENT



TECHNOLOGY ASSESSMENT
STRUCTURAL DYNAMICS: ADVANCED POWER SYSTEMS
Figure 3.3.1-1

3.3.2 Monopropellant Refueling (FSC)

3.3.2.1 Requirement Derived from Concepts - The requirement for on-orbit refueling of the LDR spacecraft propulsion subsystem presents itself as a true new-technology issue.

3.3.2.2 Required Technology Maturity Level - A goal of reaching Level 7 by 1991 is recommended, as indicated in Figure 3.3.2-1.

3.3.2.3 On-going Technology Developments and Estimation of Where the Technology Will Be In 1991 - On-orbit refueling has been identified as a key satellite service requirement of the Space Station, so that the availability of the requisite technology is highly probable. The estimate of the time-phased development level of this technology is shown in Figure 3.3.2-1. Based on the refueling demonstration experience of STS Flight 41G, this technology is currently Level 5.

3.3.2.4 Technology Shortfall and Augmentation Plan - No augmentation should be necessary.

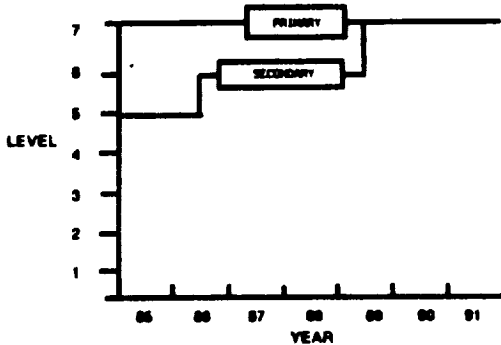
REQUIREMENT

- PRIMARY
 - REPLENISH HYDRAZINE ON ORBIT
- SECONDARY
 - VENT PROPELLANT TANKS
 - REPLENISH PRESSURANT

RATIONALE

- PROPELLANT TRANSFER EXPERIMENT ON FLIGHT 41G ALL TECHNOLOGIES NECESSARY FOR PROPELLANT TRANSFER
- VENTING OF POSITIVE EXPULSION PROPELLANT TANKS REQUIRES NO ADDITIONAL TECHNOLOGY
- PASSIVE FUEL MANAGEMENT TANKS REQUIRE TECHNOLOGY DEVELOPMENT FOR ZERO-G LIQUID GAS SEPARATION DURING VENTING
- PRESSURANT RESUPPLY TECHNICALLY STRAIGHTFORWARD

TECHNOLOGY ASSESSMENT



(NO AUGMENTATION SHOULD BE NECESSARY)

MONOPROPELLANT REFUELING

Figure 3.3.2-1

3.4 HUMAN FACTORS (OAST Category D)

3.4.1 Human Factors (MDAC)

The key issue for Human Factors on LDR is the extent to which space crews will be able to contribute to the challenging construction of such a large, complex, high-accuracy structure, as opposed to remotely controlled or robotic systems.

Some LDR-applicable technology advancements in this area will be developed on Space Station. However, by comparison, the Space Station structure is simpler and far less performance demanding than that of LDR. Consequently, since no other predecessor system has the unique type of structural challenges of LDR, certain LDR-dedicated Human Factors technology advancements are required to support a hardware go-ahead decision. Figure 3.4.1-1 presents an overview of the Human Factors technology program required to assure appropriate schedule readiness for an LDR system development initiation.

3.4.1.1 Requirements Derived from Concepts - LDR might be constructed on the Space Station as shown in Figure 3.4.1-2. Compaction and packaging of these large deployable/assemblable structural elements for shuttle transport to orbit present a major challenge not only for the LDR design but also for on-orbit construction operations. An extensive array of EVA functions will be involved.

Key Issues

- The Unique Crew Functions and Support Equipment/Tools Required for the Complex Construction of Large, High-Accuracy LDR Structures Will Not Be Available From Any Other Programs

Objectives

- Analyze LDR Construction Concepts and NASA Plans for Applicable Developments and Define Reqs For LDR EVA and Suppt Equip Technology Development
- Develop LDR EVA Technology in Concert With LDR Structures and Test Underwater, on Shuttle and Then on Space Station

Rationale

- Although Some Benefits Will Be Derived From Space Station Truss Work Construction, Much LDR Specific EVA/Equipment Technology Development is Required

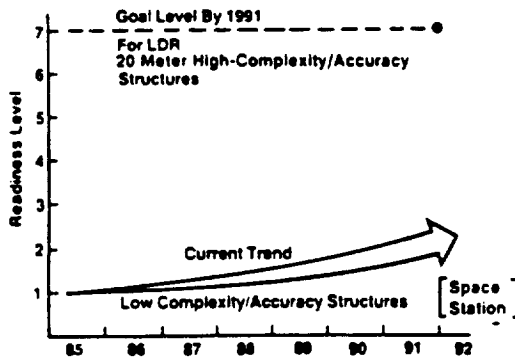
Alternatives

- Expensive, Questionably-Reliable, Self-Deployable Sections Assembled By Robotics of Extreme Complexity

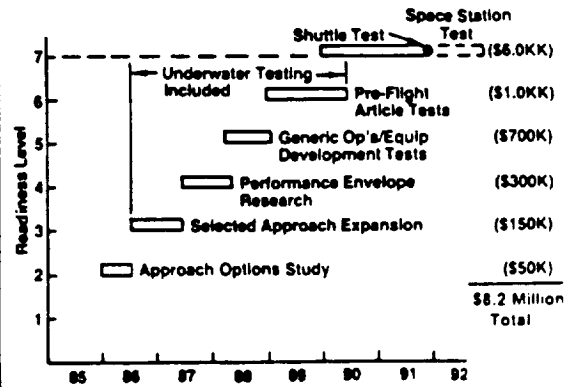
Risk Reduction

- Advanced EVA With LDR-Unique Support Equipment and STS-Type RMS Will Allow Estimatable, Low Risk

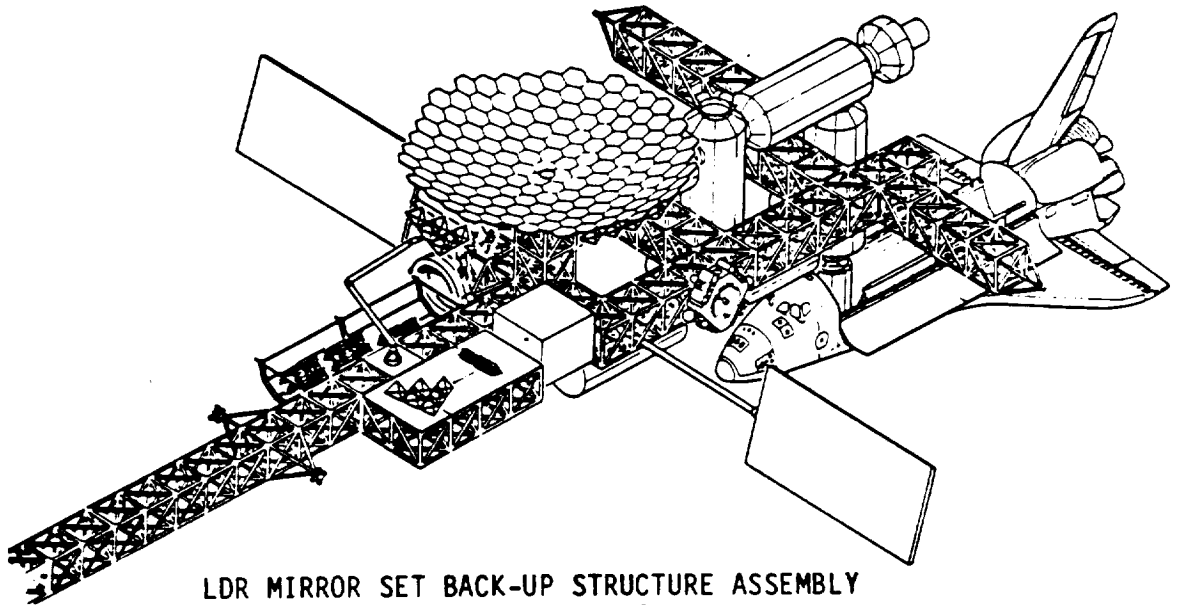
Technology Assessment



Schedule and Budgetary Plan for Augmentation



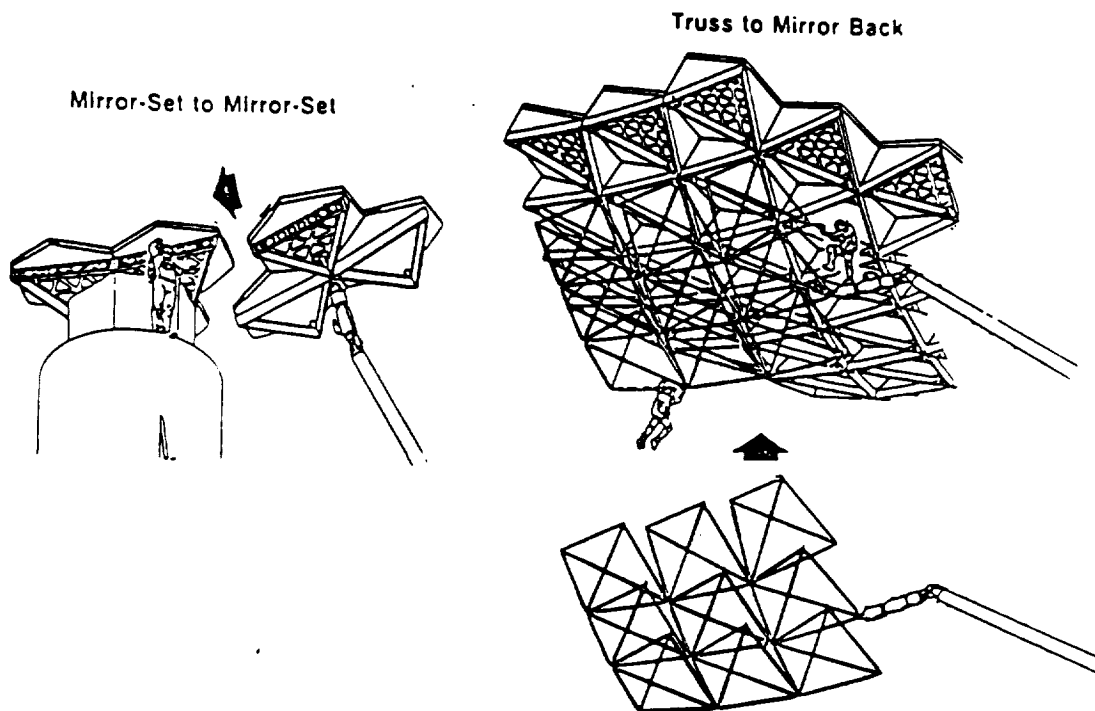
CATEGORY D. HUMAN FACTORS
Figure 3.4.1-1



LDR MIRROR SET BACK-UP STRUCTURE ASSEMBLY
Figure 3.4.1-2

The huge size of LDR forces the elemental fractionation for delivery of the system, such as the trusswork shown in Figure 3.4.1-3. The role of the crew in the very numerous assembly and deployment functions is critical, since automation thereof requires extensive remotely controlled fixtures, major and mini-manipulations and alignment, plus specific redundant automatic latches which are expensive and questionable as to linearity and capacity of structural loading. It is apparent that many crew/machine combinations are required to satisfy the spectrum of functions conceived. The objective of this technology plan is to determine the role-split most effective of humans and machines in LDR construction.

There are many unique human roles in prospect for LDR construction and a combination of supporting resources that are both uniquely LDR and presumed to be available for common use from the Space Station. Figure 3.4.1-4 presents an overview listing of the technology advancement needs envisioned for LDR by human role and supporting resource categories.



PRIMARY MIRROR ASSEMBLY PHASES
Figure 3.4.1-3

Unique Human Roles in Space For LDR

- EVA Construction/Alignment
- EVA Maintenance/Modification
- Integrated EVA/Robotics Operations
- Integrated EVA/IVA/Ground Specialist Operations

Support for Unique Human Roles in Space For LDR

- Special Tools and Aids (Unfold, Couple, Rigidize, Align and Latch)
- Real-Time Instruction/Reference Information System
- Logistics, Packaging and Stowage
- Space Station Accommodations
- Development Simulations
 - Ground (One-g and Underwater)
 - Shuttle-Based
 - Space Station-Based
- Space Suits
- Robotics and Manipulators and Crew Interaction
- Crew-Involvement Structures and Mechanisms

HUMAN FACTORS TECHNOLOGY ADVANCEMENT NEEDS FOR LDR

Figure 3.4.1-4

The major LDR elements and resources required for construction are listed in Figure 3.4.1-5, giving an overview of the extensive scope of construction required by LDR.

Elements

- Spacecraft
- Science Instrument Module + Core Primary Mirrors
- ~50 Primary Mirrors + Individual Delta Frame Assemblies
- ~50 Primary Mirror Support Trusses (Bundled)
- Secondary Mirror and Support Equipment Module
- Secondary Mirror Hexapod + Metering Rods
- ~6 Sunshield Frame
- ~6 Sunshield Panels
- ~2 Sunshield Attached Radiators

Resources

- Space Shuttle (Transport)
- Space Station (Construction, Checkout, Launch and Servicing)
- Space Station Core Crew Support
- LDR Special Crew
- EVA Aids and Tools
- Interior Control and Monitoring Consoles
- Exterior Stowage, Holding Fixtures, Hangar and Work Stations

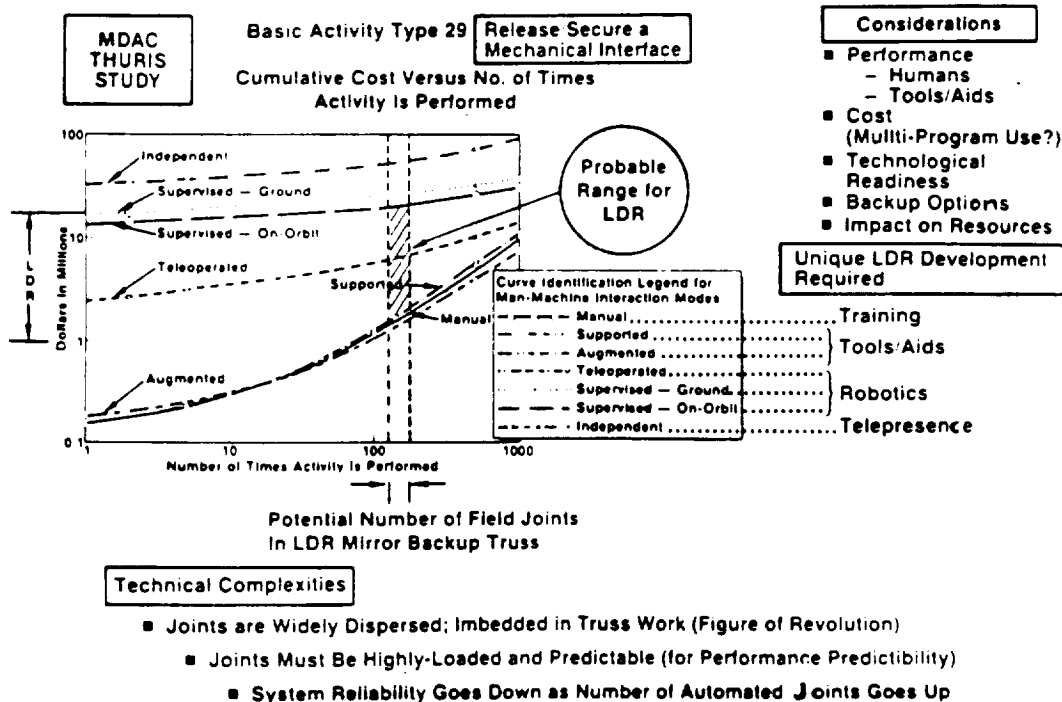
LDR CONSTRUCTION OVERVIEW

Figure 3.4.1-5

For example, the role of the crew in construction of one of 50 of the LDR primary mirror support structure sectors, will involve the following functions:

- Monitor bundle destowage from delivery pallet by movable RMS
- Guide bundle to work fixture and secure
- Release bundle securing device with aids
- Manipulate bundle into deployed state
- Override hangups with portable aids
- Rigidize numerous joints with aids
- Cooperate with remotely controlled manipulation of truss to vicinity of mirror assembly back-face
- Detach from manipulator and align for final latching with aids
- Attach and pre-load latches with aids
- Lock up latches with aids (may be repeated on completed assembly for final alignment)
- Connect instrumentation and utility lines with aids
- Cooperate with manipulator in affixing aft thermal shields with aids.

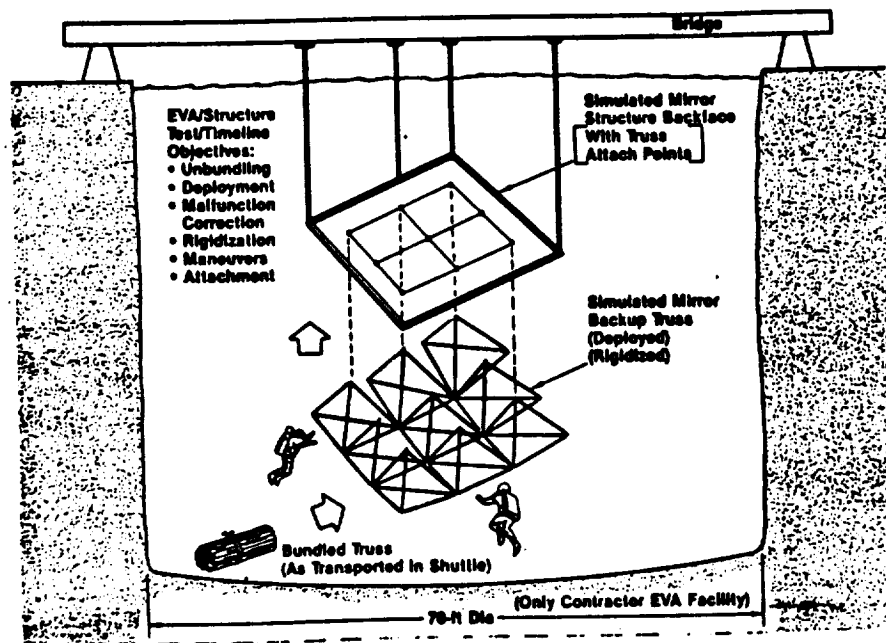
Similar EVA/machine functions and operational aids and tools will be required for assembly of the secondary mirror hexapod, despacing metering columns and the huge sunshield/radiator assemblage. Figure 3.4.1-6 illustrates the types of considerations in prospect for trading off EVA versus optional approaches to basic construction functions.



LDR BACKUP TRUSS CONSTRUCTION APPROACH TRADEOFF: EVA VS?

Figure 3.4.1-6

3.4.1.2 Required Technology Maturity Level - In order to support an LDR program initiation in 1992, it is vital that the Human Factors technology capabilities required by LDR construction be established earlier (1990-91) to support effective concept development. Since the zero-g environment is such a dominating source of design criteria in this technology, it is important that some flight test demonstration of proof-of-concept be performed to validate concept development assumptions for LDR-unique EVA/tools/aid capabilities. Since there will be only Human Factor technology developments for low-complexity/low-accuracy structures in the 1986-91 period (such as Space Station trusswork), LDR interests must develop certain unique Human Factor capabilities for their own needs. Consequently, the LDR technology program should be configured to build up progressively from analytical efforts and elemental underwater tests in 1986 to a shuttle flight test with the NASA Langley STEP pallet or the NASA Marshall MPSS pallet or both by 1991, i.e., OAST Level 7 (engineering model tests in space). These efforts should, of course, be coordinated with the structural/mechanical technology advancements for LDR. McDonnell Douglas Astronautics has current company-sponsored efforts in underwater EVA simulations of an LDR primary mirror support structure (see Figure 3.4.1-7). It is important to note that numerous important LDR structural/mechanical design decisions, including the cost aspects of various options, require inputs on human and human-aid capabilities that will not be developed by any other system or generic technology program.



LDR MIRROR BACKUP TRUSS TESTS
(In MDAC Underwater Test Facility)
Figure 3.4.1-7

3.4.1.3 On-going Technology Developments and Estimation of Where the Technology Will Be in 1991 - At the present time, there is technology development on-going for generic large beam-like truss structures for systems such as Space Station and platforms. The near-term EASE and ACCESS EVA construction experiments are aimed at such systems and address essentially large span, relatively low-complexity, low-accuracy (stability) box-like or planar structures. LDR is very different from such structures. Its structure will be a deep cross-section, parabolic, or spherical dish; it will be very high in complexity and its stability performance will require a stretch in the state-of-the-art of structures . . . far beyond Space Station. Consequently, so will the Human Factors technology required to assemble LDR. It is estimated that under current Human Factor technology development for space construction that the readiness level for LDR-type capabilities is now at Level 1. Further, it is estimated that without dedicated LDR activity, the state-of-art readiness level for LDR in 1991 would be between Levels 2 and 3. The challenge, therefore, for LDR interests is to fund and accomplish LDR-peculiar technology advancement to Level 7 by 1991 for the rationale described earlier.

3.4.1.4 Technology Shortfall and Augmentation Plan - Even if NASA's currently planned generic Human Factor Technology program is augmented substantially for Space Station, there will still be a significant shortfall in the capability of EVA and crew aids for construction of the high-complexity/high-accuracy/dished LDR structure in 1991.

The shortfall will primarily be in the areas of special crew techniques and aids for (1) unfolding, aligning, attaching, rigidizing, calibrating and adjusting a unique figure-of-revolution truss which requires numerous three-dimensional, nested-section joining, (2) assembling high-accuracy primary mirror segments, (3) integrating primary and secondary mirror assemblies with interconnecting multipods, and (4) erecting a combination of large area hard and soft goods panels for a sun shield and soft goods blankets over the entire aft side of the mirror support structure. The challenging operations are unique to LDR and are not required for any prior or parallel program. Moreover the degree to which humans with aids can perform such functions must be known as early as possible to influence the degree to which the concept for LDR construction must resort to expensive, questionably-reliable, automated construction and rigidization techniques.

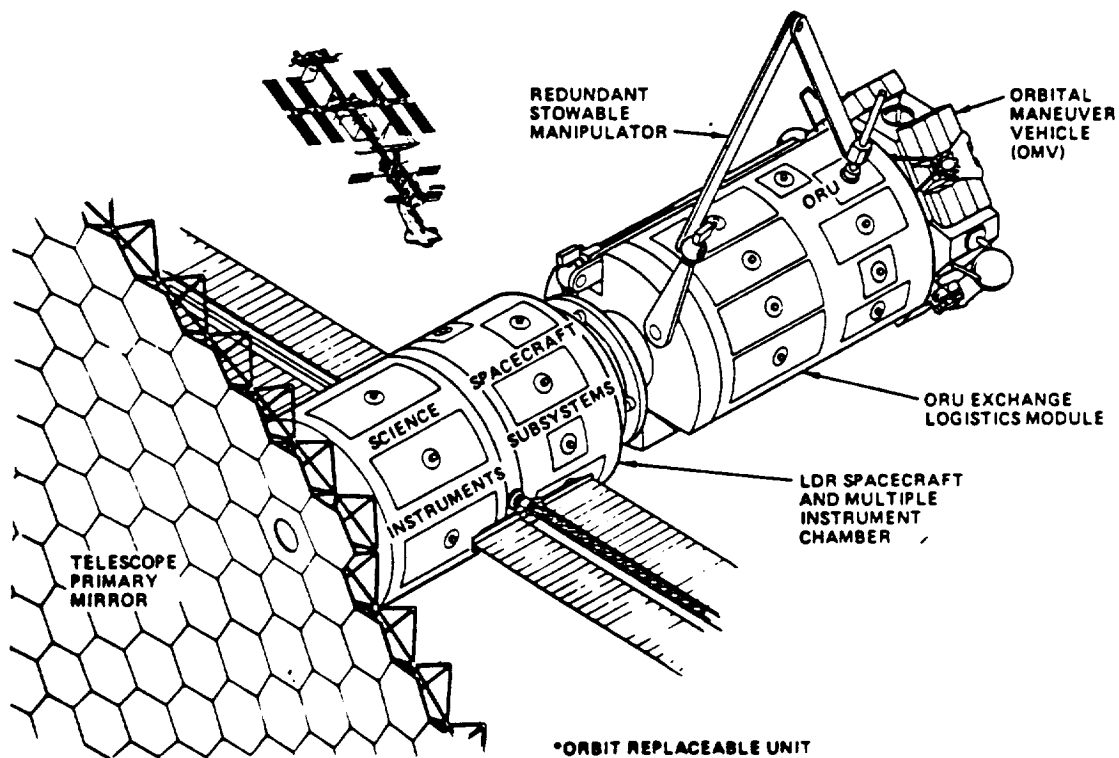
The LDR augmentation recommended for NASA's generic Human Factors Technology program involves the following progressive activities:

- 1986 - Study of approach options and human/aids/automation tradeoffs (assume contractor IRAD) (\$50K)
- 1987 - Expansion of selected approach definitions and low-cost start of long term escalatory underwater test program of structural/mechanical elements, techniques and equipments (\$150K)
- 1988 - Conduct Performance Envelope Research of various factors/aids and approach to quantify and calibrate capabilities potential (including underwater tests) (\$300K)
- 1989 - LDR-generic Operations/Equipment Development Tests (advanced fidelity, maturing design items) (including underwater tests) (\$700K)
- 1990 - Pre-flight article tests (ground testing of all elements of subsequent

- shuttle "STEP" flight test, i.e., pre-test of flightworthy items) (including underwater tests) (\$1.0M)
- 1991 - Shuttle-based test of 1990 developed/1991 converted test equipment to certify capabilities, problem-potential and contingency management approaches. (including STEP pallet rental) (\$6.0M)

Subsequent testing of equipment on Space Station is anticipated where extended duration flight will make more extensive testing, evaluation and concept-validation possible.

3.4.1.5 Related Multi-Program Technology Consideration - Since LDR will operate as a free-flyer after construction on the Space Station, it will be remotely serviced via some OMV-mounted module as shown in Figure 3.4.1-8. Consequently, the LDR program will place requirements on NASA's generic Remote Servicing Technology which includes human involvement for overall monitoring and selective basic and contingency control operations. The Human Factor-related technology involved in remote servicing will be developed to support many different free-flying spacecraft, therefore, it is not discussed or costed in detail here. However, LDR will levy certain unique requirements on such emerging crew/machine resupplying capabilities, and of course, help to justify its development by at least the mid-1990's.



ORU* EXCHANGE LOGISTICS
MODULE (OMV-BASED)
Figure 3.4.1-8

3.5 CRYOGENICS AND SENSORS (OAST CATEGORY E)

3.5.1 Hybrid Cryogenic System For Science Instruments

3.5.1.1 Requirements Derived from Concepts - The LDR scientific instruments will require operational cyrogenic cooling loads of about 8 watts at 77°K, 4 watts at 20°K, and 1 watt at 2°K. When considering initial cooldown requirements and the additional parasitic heat loads the total cryogen refrigeration capacity, over a 3 year life interval, makes the size of a stored cryogenic system exceptionally large and impractical. Further, the required capacity that would be needed is eventually impractical for active closed-cycle mechanical or chemical absorption cryogenic refrigeration machines designed for spacecraft operation.

It will be possible to meet these refrigeration requirements with a reasonably sized, practical and reliable "hybrid" cryogenic system consisting of a stored cryogen in conjunction with a closed-cycle active refrigeration machine. The stored cryogen will provide most of the initial cooldown refrigeration. The operational capacity requirement will be possible using active refrigeration machines sized for about 10 watts at 77°K, 1.5 watts at 20°K and 0.75 watts at 2°K. These are considered reasonable capacities. The stored cryogen can be packaged in concentric spheres with a maximum outer diameter of roughly 2.5 meters.

3.5.1.2 Required Technology Maturity Level - The cryogenic cooling system is absolutely essential to operation of the scientific instruments and accordingly it is necessary that a system be available which has demonstrated both satisfactory performance and reliability. The importance of this system justifies a technology maturity to space testing (Level 7) by 1991. The "hybrid" cryogenic system reliability goal should be aimed at a 10 year life in terms of all active mechanical pump components and controls. Innovative engineering and materials development is needed to improve the efficiency and performance of stored cryogen vessels in terms of improving insulation and structural mounts to reduce parasitic heat gains to the stored cryogen and plumbing. In addition, the efficiency of active refrigeration systems must be increased and more effective thermal radiators are needed to reject the large mechanical pump heat loads. An improvement is needed in the implementation of cryogen cooled thermal insulation shields, using spent cryogen, and to then recycle (i.e. recover) this cryogen. The simultaneous and continuous management of cryogen liquid and vapor within a common storage tank, in a zero-g environment, presents many engineering challenges.

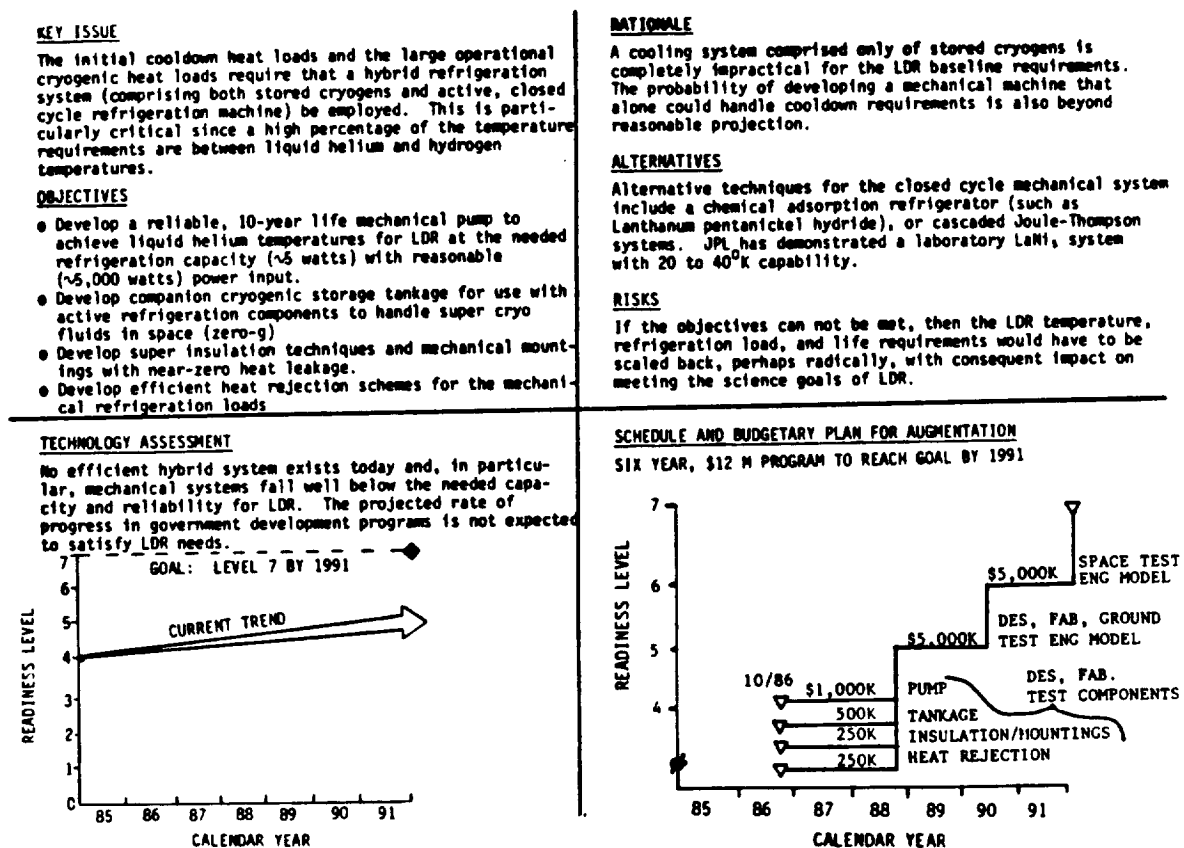
The hybrid system must be configured to enable on-orbit serviceability and/or component replacement. Although the 10 year life goal objective will not be compromised the design must be capable of easily accommodating replacement of the various active mechanical system components. Attention will also be given to multi-compartmentalized stored cryogen vessels to guard against cryogen loss such as caused by meteorite impact.

3.5.1.3 On-going Technology Developments and Estimation of Where The Technology Will Be in 1991 - Considerable effort is currently being expended by both DoD and NASA on the development of active closed cycle cryo-refrigeration machines; for example, the NASA Goddard/Philips 5W Sterling cycle machine and JPL Lanthanum Pentanickel hybrid absorption cycle. These efforts are well below the level needed to meet the much

more demanding capacity, temperature level, and reliability requirements needed by LDR. The current trend at best would accomplish a component Level 6 technology by 1991 with a more likely Level of 5. In terms of an integrated "hybrid" system the 1991 level would be even lower at possibly Level 4. A much more intensive effort is needed to increase the capacity of active machines and to achieve lower temperature levels of 2-4°K with highly reliable hardware. Cryogen fluid and gas management in a "hybrid" system is mandatory and involves technology and design issues not associated with separated stored cryogen and active mechanical equipment.

3.5.1.4 Technology Shortfalls and Augmentation Plan - A major shortfall in current technology is development of active closed cycle cryo-refrigeration machines with the LDR capacity requirements at 2-4°K. Machines designed for higher efficiency and much improved reliability (10 year life) are also indicated. Packaging and hardening of associated electronics will require considerable effort; current status resembles brassboard lashups with little attention to space hardware miniturization and packaging. Considerably more engineering thought and innovation is necessary for stored cryogen vessels, insulation, and structural mounting.

A \$12M total program is recommended beginning in 1986 with a funding level of about \$2M spread over three years followed by \$10M spread over the next three years as outlined and broken-down in the schedule plot of Figure 3.5.1-1.



CATEGORY E: CRYOGENICS AND SENSORS
HYBRID CRYOGENIC SYSTEM FOR SCIENCE INSTRUMENTS

Figure 3.5.1-1

3.5.2 Cryogenic Systems for Detector Temperatures Less Than 0.3°K

3.5.2.1 Requirements Derived From The Concepts - Certain scientific instruments

(e.g., 200-1000 μ m submillimeter camera) for LDR require NEP's of 1×10^{-16} w/hz^{-1/2}. To achieve these NEP levels cooling will be needed to about 0.1°K. Temperatures to 0.3°K can be obtained with evaporation of He³ which, in itself, requires a special refrigeration system (e.g., absorption pump and condenser pot) if the He³ is to be recovered. To achieve the much lower level of 0.1°K will require systems such as Adiabatic Demagnetization Refrigeration (ADR) or He³-He⁴ dilution refrigeration.

Any selected refrigeration system must be extremely reliable and capable of operation at zero-g. It must also be characterized by low weight, small size, and low operational power requirements for compatibility with spacecraft. Further, for LDR, this refrigeration system must be a logical selection in terms of how it integrates into the major cryogenic systems servicing the bulk cooling requirements of the science instruments.

3.5.2.2 Required Technology Maturity Level - To cool special science instruments to 0.1°K will require extensive development in active cryogenic cooling technology. The long life expectancy and reliability demanded by LDR necessitates system hardware development and testing through Level 7 by 1991.

A logical plan is to initially pursue at least two candidate approaches; the most likely are ADR and He³-He⁴ dilution. In the case of He³-He⁴ dilution, major technology barriers exist since this technique involves interface phase separations which will not occur in a zero-g environment. Accordingly, techniques such as semi-permeable membrane separation must be studied. In the case of ADR substantial technology and engineering improvements are needed in efficiency, size, magnetic superconductivity, thermal switches, insulation, thermal isolation, and general configuration packaging for integration into the total LDR cryogenic systems and for serviceability.

3.5.2.3 On-Going Technology Developments and Estimation of Where The Technology Will

Be in 1991 - Numerous laboratory ADR and He³-He⁴ dilution cryorefrigeration systems have been built, to date, and operated. In addition, NASA Goddard has designed an ADR system with features for operation in space. Several current DoD and NASA space programs are considering ADR hardware (e.g., AXAF and SIRTf).

While this past experience and current technology development effort provides a sound starting base for employing an ADR system in LDR it will be necessary to make further ADR technological advances in reliability, magnetic superconductivity control, and techniques to enable long periods of continuous cooling capacity. However, in the case of He³-He⁴ dilution refrigeration very little, if any, effort is being directed to a system compatible to space, zero-g operation.

At current rates of development an ADR system may conceivably reach Level 7 by 1991; however, as indicated it will most likely not meet the needed requirements for LDR and accordingly should be ranked no higher than Level 6. In the case of $\text{He}^3\text{-He}^4$ dilution refrigeration, the current rate of technology development will undoubtedly not exceed Level 3 by 1991.

3.5.2.4 Technology Shortfalls and Augmentation Plan - In the case of $\text{He}^3\text{-He}^4$ dilution refrigeration the major shortfall is in developing a system that can be operated in a zero-g environment. Novel concepts, such as semi-permeable membrane phase separation, are needed. This system is currently ranked no higher than about Level 1 and considerable effort is needed, early-on, to determine if it can realistically be considered as an LDR candidate cooling system. Nevertheless, the present technical judgement is that a $\text{He}^3\text{-He}^4$ dilution refrigeration system, capable of zero-g operation, is possible.

The major shortfall seen for an ADR system, in LDR, is in development of technology for much higher reliability and likely increased refrigeration capacity.

A \$13M total program is recommended, beginning in 1986, with a funding level of \$6M for ADR and \$7M for $\text{He}^3\text{-He}^4$ dilution refrigeration. Of course, if obvious impractical

technical barriers are encountered with the $\text{He}^3\text{-He}^4$ dilution refrigeration system this effort would be terminated; a decision point is indicated following the second year of effort. The funding level for ADR is about \$5M spread over the first four years, followed by \$1M over one year. The success path funding level for $\text{He}^3\text{-He}^4$ dilution refrigeration is about \$2M spread over the first two years followed by \$4M spread over the next three years, and ending with \$1M over one year. These fundings are outlined and broken-down in the schedule plot of Figure 3.5.2-1.

KEY ISSUES

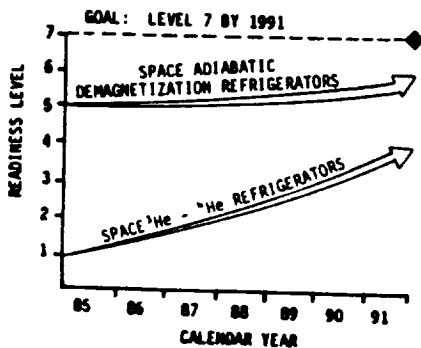
Some proposed LDR Science Instruments (e.g., 200-1000 μm submillimeter camera) may require cooling of the detectors to as low as 0.1°K (for NEP's of $10^{-16} \text{ W Hz}^{-1/2}$). Adiabatic Demagnetization Refrigerators (ADR) and ^3He - ^4He dilution coolers are two candidate approaches. However, these systems will require extensive technology development to become practical and reliable. The Helium dilution technique would not operate in zero-g as presently implemented and will require new techniques, such as semi-permeable membranes. ADR's are inefficient and require innovation to enable continuous refrigeration for long duration observation periods (~ 30 minutes per orbit assumed for LDR).

OBJECTIVES

o Develop a space-qualified reliable 10-year refrigeration system for achieving 0.1°K temperatures and necessary continuous refrigeration capacity. At least two approaches should be investigated, based on ADR or Helium dilution principles.

TECHNOLOGY ASSESSMENT

Both ADR's and Helium Dilution techniques have been used in laboratories for years. A flight-type ADR has been built and tested at GSFC. An ADR for an AXAF Spectroscopy instrument has been proposed.



RATIONALE

The proposed techniques to be developed are based on extension of known physical thermodynamic technology. Ground-based systems have been built and consideration is being given to spaceborne systems. A number of hardware development programs are currently underway, both at NASA and DoD.

ALTERNATIVES

No other practical physical thermodynamic approaches were identified that would satisfy the temperature requirements below 0.3°K.

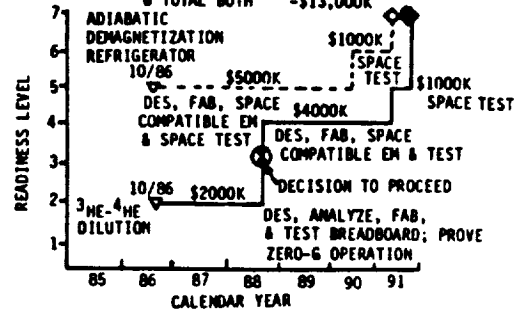
RISK

If these techniques are not fully developed, then instrument detector temperature objectives below 0.3°K (liquid ^3He limit) may not be attained or the useful life may be compromised. Accidental quenching of the superconductivity of the magnet in an ADR is a potential failure mode of concern.

SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

Competing programs to reach goal by end of 1991

- o ADR path total \$6,000K
- o ^3He - ^4He dilution path total - \$7,000K
- o TOTAL BOTH - \$13,000K



CATEGORY E: CRYOGENICS AND SENSORS

CRYOGENIC SYSTEMS FOR DETECTOR TEMPERATURES LESS THAN 0.3°K

Figure 3.5.2-1

3.5.3 Robotic On-Orbit Cryogenic Replenishment

3.5.3.1 Requirements Derived From Concepts - The total life requirements for LDR are at least 10 years with a goal of 15 years. The large demand for cryogenic cooling over this long period, becomes unmanageable in terms of stored cryogenics, and the reliability demands on active closed-cycle mechanical cryogenic refrigeration equipment would be totally unrealistic. Studies show that a "hybrid" system composed of stored cryogen and active closed-cycle mechanical or chemical absorption refrigeration systems are possible and practical over a three year life period. Accordingly, it will be necessary to reservice the cryogenic cooling systems from three to four times over the lifetime of LDR. Two approaches are possible: return LDR to the Space Station or conduct a robotic controlled service operation at the operational orbit position of LDR. The best technical judgement indicates servicing the cryogenic systems at the on-orbit location of LDR is feasible and that this approach will be the most economical and cost effective. Also, protection of the LDR Optical Telescope system from contamination at all times is mandatory, and this can be more realistically accomplished by OMV cryogenic system servicing.

3.5.3.2 Required Technology Maturity Level - The cryogenic cooling system for science instruments is absolutely essential for the successful operation of LDR. Thus, it becomes mandatory that a highly reliable technique be developed to service refrigeration equipment and replenish cryogenics on-orbit (OMV) at intervals of about three years. The importance of this robotic system justifies a technology maturity to complete space testing (Level 7) by 1991. The testing need not involve a full-size system; however, it must entail all essential functions including features to suppress and control contamination of the systems being serviced.

The on-orbit robotic servicing system must be implemented to allow both the replenishment of cryogenics and the general maintenance of, or complete module replacement of, equipment such as the active closed-cycle mechanical refrigeration pumps, plumbing hardware (valves, etc.), and controls. The LDR system hardware must be designed with this in mind. Major advances are needed in the technology of remote control of fluid handling and gas venting systems, and in the development of compatible plumbing hardware (particularly valves and connectors).

3.5.3.3 On-Going Technology Developments and Estimation of Where The Technology Will Be In 1991 - The technology maturity of robotic on-orbit cryogenic fluid replenishment and/or servicing of mechanical equipment is very low at an estimated Level 1. Some study is in progress for the SIRTf program to resupply cryogen at the Space Station but the technology required for the robotic system needs of LDR are much more demanding. At best, the current rate of technology development will reach a maturity level of about 5 by 1991; however, it is questionable that it will include all the features (e.g., 100% robotic operation, very high reliability, and contamination control) needed for the LDR system. The total technology status, in terms of LDR, will fall far short of a needed technology maturity at Level 7.

3.5.3.4 Technology Shortfalls and Augmentation Plan - The major shortfall in the current technology efforts (e.g., SIRTf program) associated with on-orbit replenishment and servicing of stored cryogenic refrigeration systems is that it is directed mainly to Space Station application. In this situation, astronaut assistance is available and

total 100% robotic operation is not essential. In addition, the requirements of non-contamination are not nearly as stringent as will be demanded by the LDR optical telescope and science instrument hardware plus the associated thermal/optical shields. Not only are the reliability requirements much higher for the LDR system but many added functions in terms of sensing, guidance, and maneuverability are essential. In addition, the LDR robotic on-orbit cryogenic refrigeration servicing system must accomplish dual functions of cryogenic fluid replenishment, general maintenance servicing of equipment and plumbing hardware, and capabilities for complete equipment module replacement. A substantially intensified technology development effort is justified.

A five year \$11.25M program is recommended beginning in 1986 with a funding level of \$0.75M for the first year, and doubling each year thereafter as outlined and broken down in the schedule plot of Figure 3.5.3-1. This is considered to be a minimal program and could exceed this estimate by a factor of 2x depending on the rate of technology gains expected from other similar on-going programs (e.g., SIRTf).

KEY ISSUE

Periodic replenishment of cryogens aboard LDR is critical to successful achievement of 10-year life. Robotic servicing from the shuttle or space station at regular intervals has been proposed but requires major development.

OBJECTIVES

1. Study, analyze concepts to efficiently resupply liquid helium at LDR operational altitude using OMV/Smart Front End.
2. Demonstrate selected technique, method.

RATIONALE

- OMV servicing at mission accessible orbit altitudes has been conceived for instrument change out, expendibles resupply, and other functions.
- Accessibility, contamination, reliability, safety, commonality need to be studied.

ALTERNATIVES

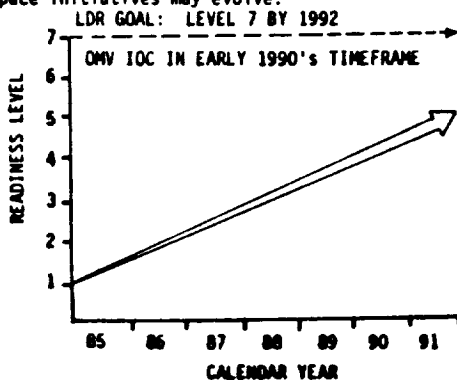
- Return LDR to shuttle/space station altitude for resupply.

RISK

- Without robotic, remote capability, replenishment costs and downtime are high.

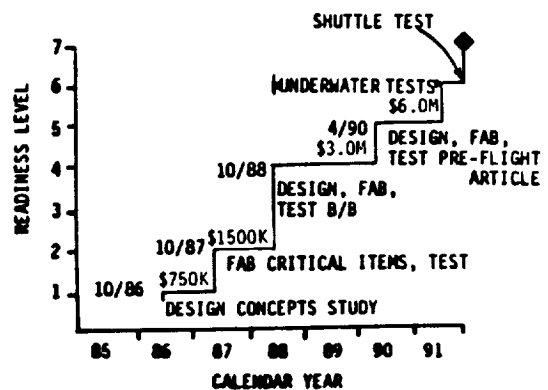
TECHNOLOGY ASSESSMENT

Study in progress for SIRTf Program to resupply at space station. Space station based OMV with "Smart" Front-End Servicers has been conceptualized. Military space initiatives may evolve.



SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

Five-year, \$11.25M program to reach shuttle test readiness.



CATEGORY E: CRYOGENICS AND SENSORS
 ROBOTIC ON-ORBIT CRYOGENIC REPLENISHMENT
 Figure 3.5.3-1

3.6 COMMUNICATIONS AND DATA HANDLING (OAST CATEGORY F)

No technology developments were specifically identified in this category. Within the proposed science instrument complement, some instruments have the potential for requiring autonomous science data handling and storage. The interface requirements between these S/I's and the LDR spacecraft requirements have not been well defined for this study.

In the area of data management, a major effort at developing fault-tolerant software and a more autonomous operating system is planned for Space Station. LDR is unlikely to require greater capability in these areas.

The requirement for high rate data storage and readout is driven by heavy government and commercial interest and is unlikely to be impacted directly by LDR.

3.7 OPTICS MATERIALS AND FABRICATION (OAST CATEGORY G)

3.7.1 Active Primary Mirror

The key issue is the degree of figure control required on the LDR Primary Mirror. Should the mirror be passive segmented (piston, tilt actuation only) or active segmented (figure, piston and tilt actuation)? Figure 3.7.1-1 represents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

3.7.1.1 Requirements Derived from Concepts - In manufacturing and operating a coherently phased mirror made up of segments, the technical issues can be divided into two types. The first involves the issue of manufacturing the mirror segments themselves (coherent phasing of a segment), and the second involves assembly issues of making an aggregate segmented mirror in which coherent phasing between segments is required. The requirements of coherent phasing of a segment and coherent phasing between segments, as established by the study, are as follows:

- Segment Surface Quality 0.5 Micrometer RMS
- Radius Mismatch 50 PPM
- Piston Error 1.3 Micrometers
- Tilt Error 0.6 Microradian

3.7.1.2 Required Technology Maturity Level - In 1989, a decision should be made to proceed with one of two segmented mirror concepts (Figure 3.7.1-2). The first concept is a passive segmented mirror (piston, tilt actuation only). The second concept is an active segmented mirror (piston, tilt and figure control).

In either case, rigid body motion control (piston and tilt) will be required. Consequently, the LDR technology program has been configured to demonstrate coherent phasing between two outer segments of the LDR mirror, using these

KEY ISSUES

- Should the LDR primary mirror be passive segmented (piston, tilt acuation only) or active segmented (figure, piston and tilt actuation)?

OBJECTIVES

- Parallel passive segmented and active segmented mirror designs
- Selection of one concept at preliminary design review (PDR)
- Engineering demonstration (on-ground) of selected concept--coherent phasing of two outer segments.

RATIONALE

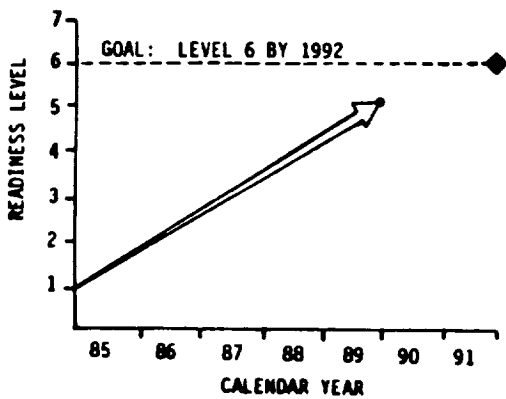
- Passive and active segmented mirror technology required for LDR is similar to current techniques demonstrated in DARPA and industry IR&D programs.

REQUIREMENTS (ESTABLISHED BY STUDY)

- Segment surface quality 0.5 micrometers rms
- Radius mismatch 50 PPM
- Piston error 1.3 micrometers
- Tilt error 0.6 microradians

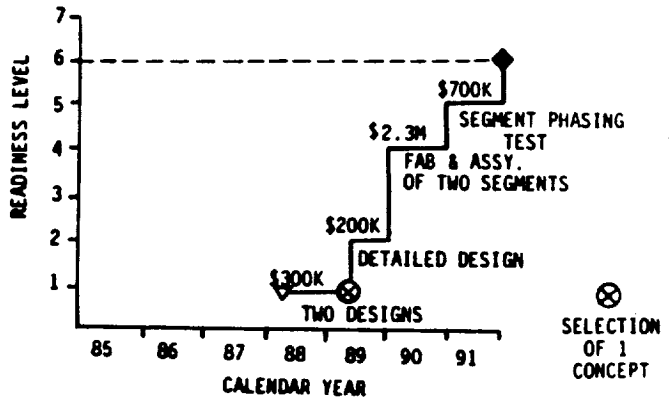
TECHNOLOGY ASSESSMENT

Related DoD activities with "similar" requirements. However, operational wavelength range and 200°K operating level unique to LDR



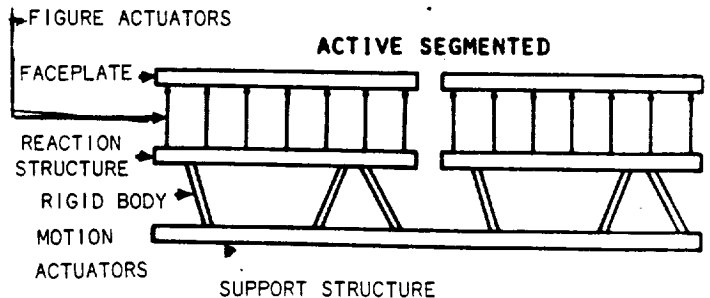
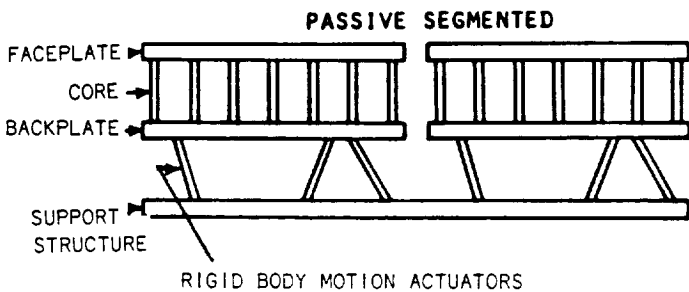
SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

5 1/2 year, \$3.5M program to reach goal by January 1992



**CATEGORY G: OPTICS MATERIALS AND FABRICATION
ACTIVE PRIMARY MIRROR
Figure 3.7.1-1**

FIVE TIER



**COHERENTLY PHASED MIRRORS
Figure 3.7.1-2**

actuators. The selection of a passive or active mirror will determine the degree of figure control required and the approach for coherent phasing of a segment and radius matching between segments. The demonstration has been configured at OAST Level 6 (engineering model tested) to be completed by 1992.

3.7.1.3 On-Going Technology Developments and Estimation of Where the Technology Will Be in 1991 - Passive and active segmented mirror technology required for LDR is similar to current techniques demonstrated in DARPA and industry IR&D programs. A schematic of an active segmented mirror is shown in Figure 3.7.1-3. An engineering model demonstration of this type of mirror is currently being undertaken by DoD. However, the LDR operational wavelength range (30 micrometers to 1000 micrometers) and the LDR operational temperature (200°K) are unique to LDR. The segmented mirror technology to meet these requirements might not be ready by 1991 without LDR acceleration.

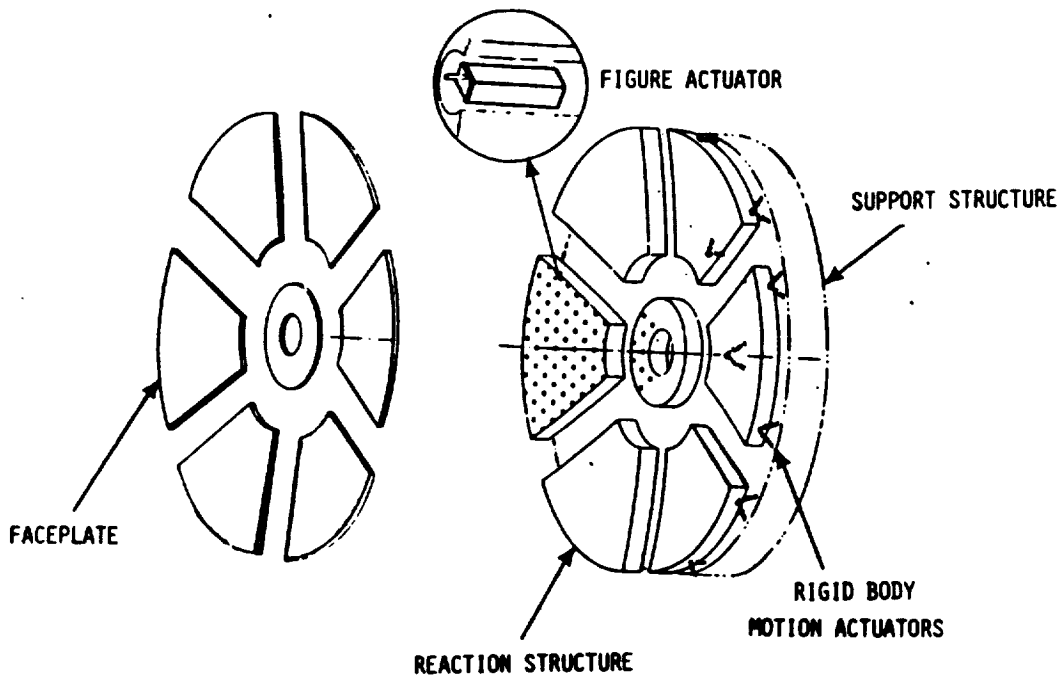
3.7.1.4 Technology Shortfall and Augmentation Plan - There are related DoD activities with "similar" requirements. However, the operational wavelength range and the operational temperature are unique to LDR. A primary mirror concept should be defined and demonstrated for the LDR program. The LDR augmentation recommended is: (1) parallel passive segmented and active segmented mirror design and (2) engineering demonstration (on-ground) of the selected concept. This demonstration would involve coherent phasing of two outer segments. The technology plan involves the following activities:

- 1988 - Parallel conceptual passive segmented and active segmented mirror designs (\$300K)
- 1989 - Detailed design of selected concept (\$200K)
- 1990 - Fabrication and assembly of two outer segments (\$2.3m)
- 1991 - Segment phasing test (\$700K)

3.7.2 Primary Mirror Contamination Protection

Contamination control must be considered in all phases of the LDR buildup and end use; in the design by selection of materials and coatings; in manufacture, assembly, and testing by defining facility and hardware cleanliness requirements, and in subsequent transportation, integration, pre-launch testing, deployment, and telescope operation. Figure 3.7.2-1 presents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

3.7.2.1 Requirements Derived from Concepts - The requirements for control of primary mirror contamination can best be stated in terms of performance. When chopping a source, it is important to obtain a uniform background signal. The presence of particulate contamination on the primary mirror will produce scattered radiation, contributing to a reduction in ability to remove background radiation.



ACTIVE SEGMENTED MIRROR
Figure 3.7.1-3

KEY ISSUE

Develop a concept to protect the primary and secondary mirror from particulate contamination during LDR observatory buildup.

OBJECTIVES

- Define environment
- Evaluate alternate protection concepts ("baggies", strippable coatings, etc.)
- Select and develop concept
- Fabricate, assemble, and test proof-of-concept on 2 mirror segments from segmented mirror demonstration

RATIONALE

- Techniques for contamination control during on-ground buildup via clean room environment and clean packaging are well established.
- Strippable coatings have been "successfully" implemented on small optics

ALTERNATIVE

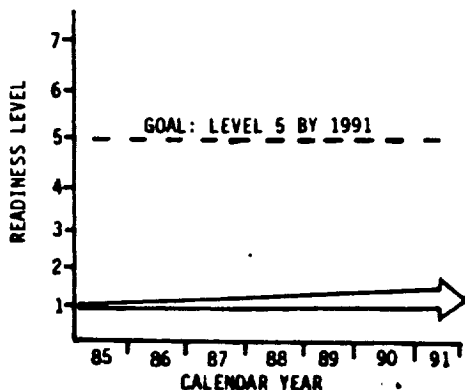
- No primary mirror protection---possibly resulting in throughput loss and/or optical quality degradation.

RISKS

- Seriously degraded system performance
- Difficult to recover performance

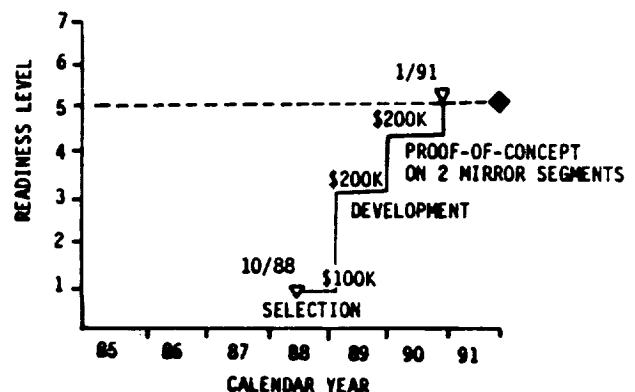
TECHNOLOGY ASSESSMENT

No other programs to develop these types of contamination protection identified.



SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

2 1/2 year, \$500K program to reach goal by January 1991



CATEGORY G: OPTICS MATERIALS AND FABRICATION
PRIMARY MIRROR CONTAMINATION PROTECTION

Figure 3.7.2-1

If molecular monolayers are deposited on the primary mirror, these may produce unwanted spectral absorption which will produce unknown effects on the radiometric performance of the instrument. In addition to these effects, the overall throughput of the instrument will be reduced because of reduced mirror reflectance. The presence of contamination may also alter the thermal performance of the optics by changing the emissivity and absorptance.

3.7.2.2 Required Technological Maturity Level - In order to achieve the requisite performance for LDR, techniques must be developed for contamination protection of the LDR primary mirror during launch, orbital assembly, deployment and subsequent refurbishment. These methods must be developed to at least OAST Level 5 (component tested) by 1991. The environment within which the LDR observatory will operate must be determined from a contamination point of view. Once the environment has been defined, the effects of the environment in producing mirror contamination must be estimated. This, in turn, will produce performance effects that must be estimated. The severity and nature of these effects will determine the technology required to protect against the contamination. It is anticipated that Level 5 maturity will be adequate to prepare for full scale LDR implementation.

3.7.2.3 On-Going Technology Developments and Estimation of Where the Technology Will Be in 1991 - Currently, no efforts are underway to develop contamination protection technology for space mirrors of the LDR size category. Eastman Kodak Company has had extensive experience in providing contamination protection for large optics during manufacture, and in placing strippable coatings on small optics. The required protection may range all the way from such strippable coatings for primary mirror segments to "clean" enclosures for orbital assembly operations.

Kodak currently has 12 glass samples on the Long Duration Exposure Facility (LDEF). It is expected that this facility may be returned to ground in 1987. These samples will be evaluated at Kodak for particulate contamination due to space exposure during LDEF's orbital life and also due to the Shuttle itself. These experiments are the first step (i.e., defining the contamination environment) in developing contamination protection for space optics.

3.7.2.4 Technology Shortfall and Implementation Plan - It is planned to develop packaging methods for primary mirror segment modules that will allow transportation from the clean factory environment to the orbital assembly location. The effort will be based on existing strippable coating technology for small optics. The environment will be defined, and its effects assessed. The overall program will cost approximately \$500K, and will take 2.5 to 3 years to complete. The final stage of this effort will involve a proof of concept demonstration on two primary mirror segments. Start is planned for 10/1/88, with completion on 1/1/91. Advantage will be taken of the LDEF data expected to be obtained in 1987. This will help to define the expected effects.

3.7.3 Glass Material for the Primary Mirror

The large primary mirror surface area justifies consideration of a new glass material for operation at 200°K. This may enable a passive (piston, tilt

actuation only) segmented mirror concept, thus, reducing dependency on complex figure control. Figure 3.7.3-1 represents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

3.7.3.1 Requirements Derived from Concepts - The selection of the mirror material requires careful consideration of the mirror design in "1-g" manufacture and "0-g" operation, as well as the mirror interface with the mounting arrangement, the control actuation, and the backup reaction structure. The material properties of Young's Modulus, density, thermal expansion, conductivity, and heat capacity must also be carefully weighed (See Table 3.7.3-1). The ability of a material to athermalize can be described by a figure of merit called thermal diffusivity: $(\text{conductivity})/(\text{density} \times \text{heat capacity})$. A material with a high diffusivity value will athermalize quickly. Most materials with low CTE, such as glass, have low conductivity and low specific heat. These materials athermalize (reach equilibrium) very slowly. This means that mirrors made of glass or glass ceramic materials (operating above 100°K) are more stable under thermal transients or gradients; however, they will take a very long time to reach thermal equilibrium. There is no "ideal" material for optical components that will perform over a temperature range because the CTE of all materials, changes with temperature (Figure 3.7.3-2). The low expansion glass materials (ULE™, Zerodur, and Cervit) have negligible thermal expansion near room temperature (300°K). Fused silica has a zero coefficient at about 140°K. The coefficient of expansion also varies with the amount of titanium dioxide doping. Corning's ULE™ material is fused silica doped with 7.5 percent titanium dioxide. From the figure, it can be seen that this biases the point where the instantaneous CTE is zero at approximately 300°K (room temperature). In a similar manner, a new ultra low expansion glass could be envisioned for the primary mirror at 200°K by using fused silica with 3 percent doping.

Glass and glassy ceramic materials have reached a level of maturity for space optical mirrors. The ability to lightweight, polish to excellent optical quality and retain this figure has been demonstrated on programs such as Space Telescope. Alternate state-of-the-art lightweighting concepts exist (machining; fusion welding; frit bonding). Shown in Figure 3.7.3-3 is the predicted areal density for a frit bonded mirror. The top curve shows a design optimized for visible light applications with an aspect ratio of 7 to 1 and a rigidity of a few waves. The lower curve was calculated for an aspect ratio of 20 to 1, reducing the weight at the expense of the inherent structural rigidity. The basic assumption is that larger deflections can be tolerated at far infrared and submillimeter operational wavelengths.

3.7.3.2 Required Technology Maturity Level - In 1989, a decision should be made to proceed with one of two segmented mirror concepts. The first concept is a passive segmented mirror (piston, tilt actuation only). The second concept is an active segmented mirror (piston, tilt and figure control). A glass material is a major candidate for implementation of a passive segmented mirror. Consequently, the LDR technology program has been configured to establish the technology to OAST Level 5 (component/breadboard tested) by 1989.

KEY ISSUES

- The large primary mirror surface area justifies consideration of a new ULE™ for operation at 200°K. This may enable a passive (piston, tilt actuation only) segmented mirror concept thus reducing dependency on complex figure control

OBJECTIVES

- Develop fused silica glass doped with approximately 3% titanium dioxide and compatible frit that meets CTE goal of $0 \pm 0.03 \times 10^{-6}$ per °K and low CTE variability.
- Fabricate and test frit-bonded proof-of-concept mirror segment

RATIONALE

- Tailoring fused silica doping and frit materials to meet LDR requirements appears to be straight forward extension of current techniques demonstrated on Space Telescope using ULE™ and in DARPA and industry IR&D programs.

ALTERNATIVES

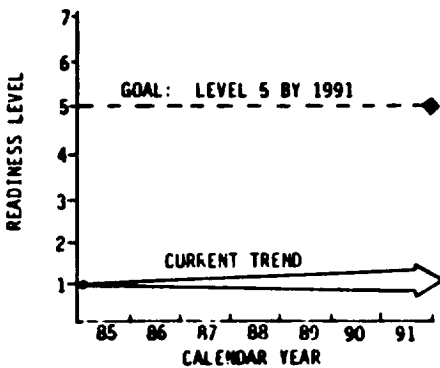
- Develop a composite material satisfying the same CTE/ΔCTE properties.
- Implementation of figure control with existing glass or composite mirror materials.

RISK REDUCTION

- Parallel primary mirror technology development projects would reduce risk.

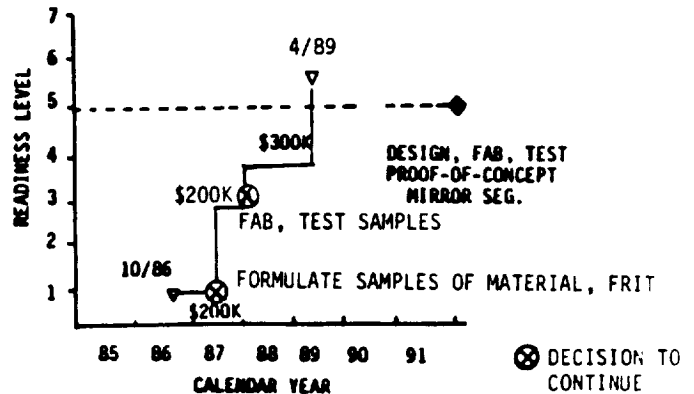
TECHNOLOGY ASSESSMENT

No other programs to develop near zero CTE material properties at 200°K identified. 200°K operating level is unique to LDR



SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

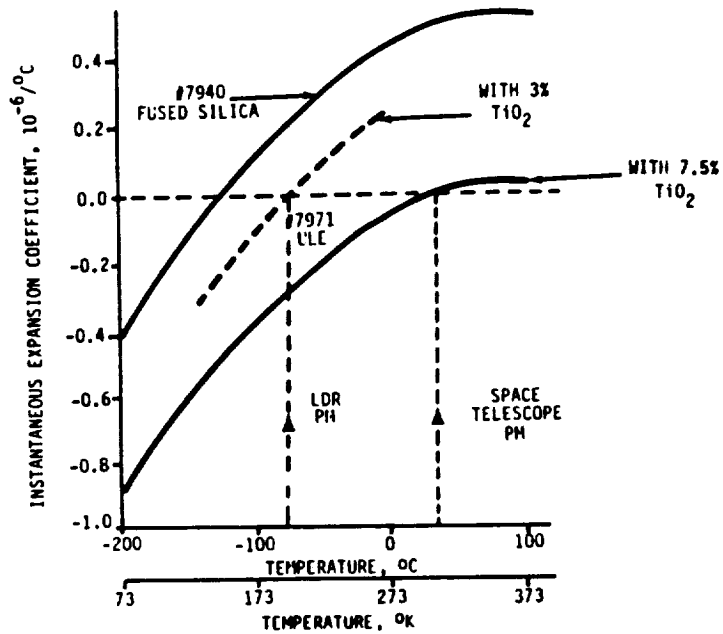
2-1/2 year, \$700K program to reach goal by April 1989



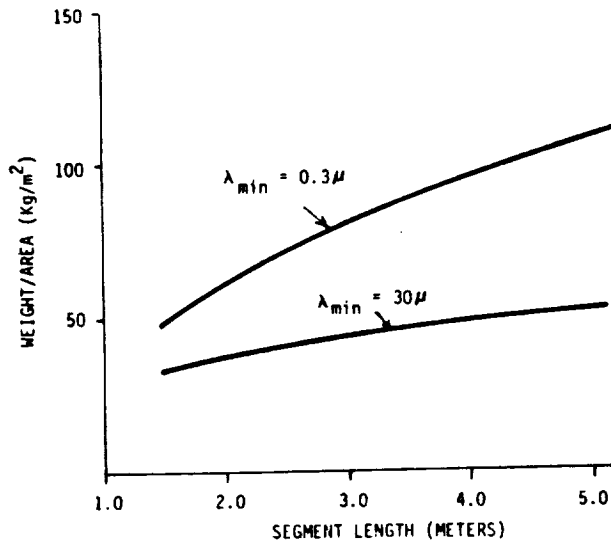
**CATEGORY G: OPTICS MATERIALS AND FABRICATION
GLASS MATERIAL FOR THE PRIMARY MIRROR
Figure 3.7.3-1**

**TABLE 3.7.3-1
REFLECTOR MATERIAL TRADE MATERIAL PROPERTIES**

							FIGURES OF MERIT		
	$\alpha @ 200^{\circ}K$ $\mu M/M^{\circ}K$	$\Delta\alpha$ $\mu M/M^{\circ}K$ PART/PART	E GPa	ρ GM/CM ³	κ WATT/M ² °K	C_p J/KG°K	E/ ρ SPEC. STIFF	D = $\kappa/\rho c$ DIFFUSIVITY	α/D THERMAL DISTORTION
GLASS/CERAMICS									
FUSED SILICA (3% TiO ₂)	0	±0.03	76.	2.2	1.4	740	34.5	8.6×10^{-4}	35
ZERODUR	0.16	±0.05	94.	2.5	1.6	821	37.6	7.8×10^{-4}	256.
PYREX	2.9		65.	2.2	1.1	753	29.5	6.6×10^{-4}	4395.
HEXALLOY (αSiC)	3.9 (RT)	±0.3	410.	3.1	125	1420	132	0.028	139. (RT)



THERMAL EXPANSION OF CORNING FUSED SILICA GLASS
Figure 3.7.3-2



The top curve shows a design optimized for visible light applications with an aspect ratio of 7 to 1 and a rigidity of a few waves. The lower curve was calculated for an aspect ratio of 20 to 1, reducing the weight at the expense of the inherent structural rigidity. The basic assumption is that larger deflections can be tolerated at far infrared and submillimeter operational wavelengths.

PREDICTED AREAL DENSITY (FRIT-BONDED)
Figure 3.7.3-3

3.7.3.3 On-Going Technology Developments and Estimation of Where the Technology Will Be in 1991

- For several years, Kodak has been engaged in developing passive fused silica mirrors which meet stringent weight budgets and optical figure quality requirements from room temperature to cryogenic temperature. This capability has been successfully demonstrated with ultra lightweight fused silica frit bonded mirrors with and without broad band multilayer high reflectance coating up to diameters of 0.5 meter. Technical issues addressed and resolved include the design and manufacture of ultra lightweight frit mirrors, CTE match, bond strength, CTE homogeneity, polishing to diffraction limited quality, optical stability, optical performance at cryogenic temperature and coating performance. Current work involves demonstration of the optical performance of these new generation ultra lightweight mirrors kinematically mounted and subjected to cryogenic environment. Key issues demonstrated are: (1) mirror optical performance from room temperature to 100°K, (2) strain-free mirror mount attachment (glass metal), and (3) flexured kinematic mount design.

Tailoring fused silica doping and frit materials to meet LDR requirements appears to be straight forward extension of current techniques demonstrated on Space Telescope using ULE™ and in DARPA and industry IR&D programs. However, no other programs to develop near zero CTE material properties at 200°K have been indentified. The 200°K operating level is unique to LDR.

3.7.3.4 Technology Shortfall and Augmentation Plan - The mirror design approach must not only be rugged, low risk, and reliable, but also capable of surviving a launch environment and enduring in space for many years. A design approach which meets performance requirements at 200°K employing passive mirrors (without figure control actuators, sensors, and electronics) made of glass, offers significant advantages in weight, performance, and reliability.

The LDR augmentation recommended is: (1) develop fused silica glass doped with approximately 3% titanium dioxide and compatible frit that meets CTE goal of $0 \pm 0.03 \times 10^{-6}$ per °K and low CTE variability and (2) fabricate and test a frit bonded subscale proof-of-concept mirror.

The technology plan involves the following activities:

- 1986 - Formulate samples of the glass material and frit material (\$200K)
- 1987 - Fabricate and test sample elements (\$200K)
- 1988 - Design, fabricate and test proof-of-concept subscale mirror segment (\$300K)

3.7.4 Composite Material for the Primary Mirror

Development of a composite material with high dimensional stability for operation at 200°K may allow either molding or replication to be used in manufacturing the mirror segments. Also, composites may enable a passive (piston, tilt actuation only) segmented mirror concept, thus, reducing dependency on complex figure control. Figure 3.7.4-1 presents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

KEY ISSUE

Development of a composite material with high dimensional stability for operation at 200°K. This may enable a passive (piston, tilt actuation only) segmented mirror concept thus reducing dependency on complex figure control.

OBJECTIVES

- Develop a composite material that meets CTE goal of $0 \pm 0.03 \times 10^{-6}$ per °K and low CTE variability.
- Fabricate and test proof-of-concept composite mirror segment.

RATIONALE

Anisotropic CTE is currently a problem with composite materials for mirrors. Can a new composite material be developed to maintain the surface figure quality passively (preliminary set at 0.75 micrometers)?

ALTERNATIVES

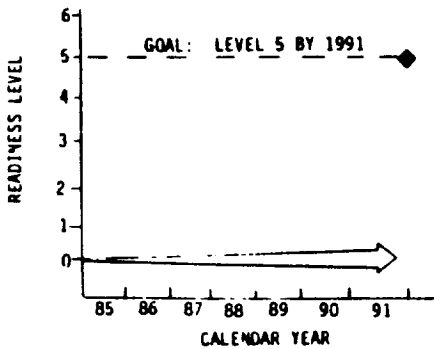
- Develop a glass material satisfying the same CTE/ Δ CTE properties.
- Implementation of figure control with existing glass or composite mirror materials

RISK REDUCTION

- Parallel primary mirror technology development projects would reduce risk.

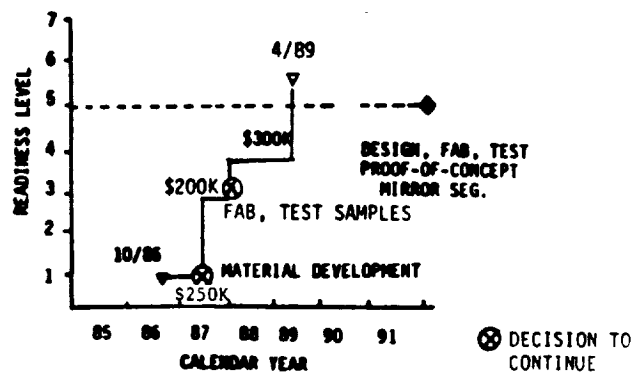
TECHNOLOGY ASSESSMENT

No other programs to develop composite materials with these properties identified



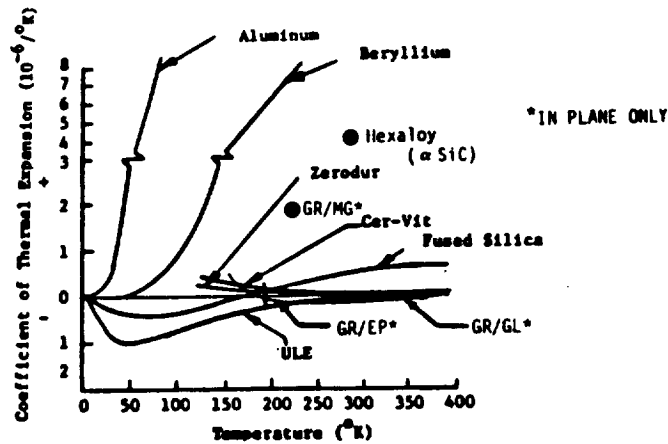
SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

2-1/2 year, \$750 program to reach goal by April 1989



**CATEGORY G: OPTICS MATERIALS AND FABRICATION
COMPOSITE MATERIAL FOR THE PRIMARY MIRROR
Figure 3.7.4-1**

3.7.4.1 Requirements Derived from Concepts - Shown in Figure 3.7.4-2 are the average coefficients of expansion of several materials. Due to the high quality needed from the primary mirror, materials that can provide coefficients of expansion (CTE) that are close to zero are desirable. Shown in Table 3.7.4-1, is a comparison of some candidate composite materials. Graphite fiber composites with polymer resins or metal matrix can be designed to provide this zero CTE characteristic. However, due to the layup approach, an anisotropic CTE and a relatively large CTE variability exists.



THERMAL-EXPANSION COEFFICIENTS
Figure 3.7.4-2

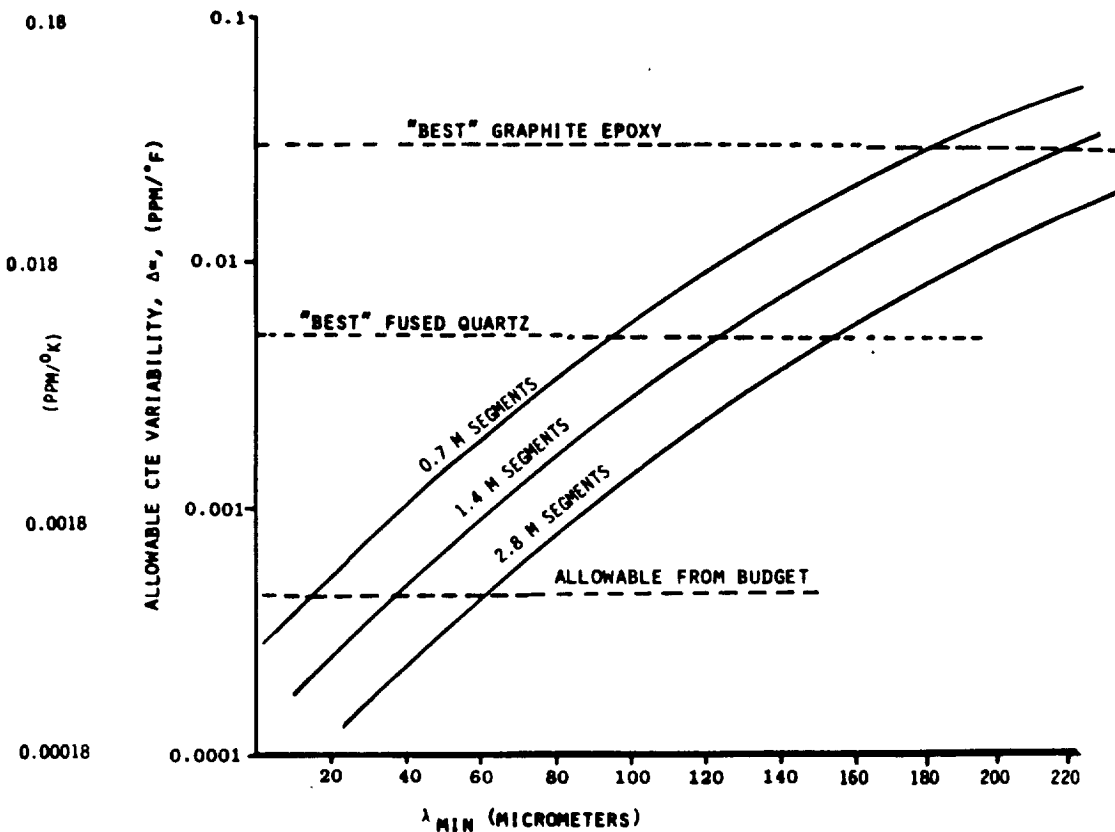
TABLE 3.7.4-1
REFLECTOR MATERIAL TRADE
MATERIAL PROPERTIES

		FIGURES OF MERIT								
		$\alpha @ 200^{\circ}\text{K}$ $\mu\text{M}/\text{M}^{\circ}\text{K}$	$\Delta\alpha$ $\mu\text{M}/\text{M}^{\circ}\text{K}$	E GPa	ρ GM/CM ³	κ WATT/M ² °K	C_p J/KG ⁰ K	E/ ρ SPEC. STIFF	D = $\kappa/\rho c$ DIFFUSIVITY	α/D THERMAL DISTORTION
COMPOSITES										
GLASS/GRAPHITE		-0.1	±0.1*	90.	2.0	27.3	837	45	0.016	6.2
TSC-1 (0/90)	⊥	4.0				2.25			0.0013	2976.
GRAPHITE MAGNESIUM (0/90)		1.5	±0.5*	210	1.8	26	962	117	0.015	100
GRAPHITE/EPOXY (GY70/CODE87)	 ⊥	0.1	±0.1*	100	2.0	23 8	960	50	0.012	8.4

*Orientation Variation (Estimated)

An additional issue is imposed on a coherently phased segmented mirror. A mismatch between radii of the segments and the design radius of the overall mirror ($\Delta R/R$), will also result in a wave front error. The system ($\Delta R/R$) requirement establishes the maximum allowable CTE variability. For coherent phasing at wavelengths longer than 30 micrometers, the radii of the segments must be matched to 50 PPM (Note: established by wave front budgeting allocation in the study). Shown in Figure 3.7.4-3 is the allowable CTE variability as a function of wavelength.

From this graph, three choices are possible using graphite epoxy: (1) lower the CTE variability of the material, (2) utilize smaller panels, or (3) operate at longer wavelengths. The intent in this technology program is to lower the CTE variability of the material.



SELECTION OF PRIMARY MIRROR SUBSTRATE MATERIAL
(300 $^{\circ}$ K \rightarrow 200 $^{\circ}$ K)
Figure 3.7.4-3

3.7.4.2 Required Technology Maturity Level - In 1989, a decision should be made to proceed with one of two segmented mirror concepts. The first concept is a passive segmented mirror (piston, tilt actuation only). The second concept is an active segmented mirror (piston, tilt and figure control). A composite material is a major candidate for implementation of a passive segmented mirror. Consequently, the LDR technology program has been configured to establish the technology to OAST Level 5 (component/breadboard tested) by 1989.

3.7.4.3 On-going Technology Developments and Estimation of Where the Technology Will Be in 1991 - Graphite fiber composites with polymer resins or metal matrix can be designed to provide the zero CTE characteristic. The graphite composite materials consist of continuous graphite fibers embedded in a thermosetting polymer matrix, such as 934 epoxy resin. The composite is made in laminated form by the successive layup of preimpregnated unidirectional tape. Near zero thermal expansion behavior is obtained by proper balance of the negative expansion of the fibers and the positive expansion resin. The use of metal matrix materials for orbiting optical structures that require very stringent dimensional tolerances is within the practical reach of technology. Thin layer unidirectional graphite/aluminum and graphite/magnesium laminates, as well as unidirectional pultruded structural members have been used in several space applications. The ultimate goal in this category is to obtain thin multilayer laminates with desired layup angles similar to the practice used for the graphite epoxy structures.

Due to the layup approach an anisotropic CTE and a relatively large CTE variability exists. It is the intent in this LDR technology program to address these two material properties. No other programs to develop composite materials with these requirements have been identified.

3.7.4.4 Technology Shortfall and Augmentation Plan - The mirror design must not only be rugged, low risk, and reliable, but also capable of surviving a launch environment and enduring in space for many years. A design approach which meets performance requirements at 200°K employing passive mirrors (without figure control actuators, sensors and electronics) made from a composite material offers significant advantage in weight, performance, and reliability. Composites offer a high payoff in producibility. If a composite material could be found that is sufficiently homogenous, molding or replication of the off-axis mirror segments become attractive alternatives to conventional processing (polishing).

The LDR augmentation recommended is: (1) develop a composite material that meets CTE goal of $0 \pm 0.03 \times 10^{-6}$ per °K and low CTE variability and (2) fabricate and test a composite subscale proof-of-concept mirror.

The technology plan involves the following activities:

- 1986 - Material development (\$250K)
- 1987 - Fabricate and test sample elements (\$200K)
- 1988 - Design, fabricate and test proof of concept subscale mirror segment (\$300K)

3.7.5 Off-Axis Mirror Segment Processing

Many mirror segments must be produced for the LDR primary mirror. For the 20 meter diameter case there are approximately fifty 2.8 meter segments. In addition, these segments are off-axis sections of a parabolic asphere with an extremely large asphericity (departure from best fit sphere). Figure 3.7.5-1 represents an overview of the technology program required to assure appropriate schedule readiness for an LDR system development initiation.

KEY ISSUE

The primary mirror segments (off-axis parabolic segments) have an extremely large asphericity (departure from best fit sphere)

OBJECTIVES

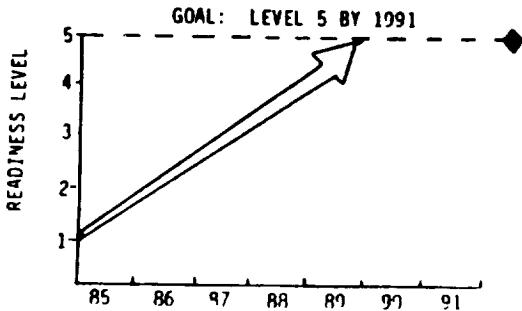
- Develop LDR primary mirror processing approach.
- Emphasize approaches that minimize polishing step and maximize grinding step. (for imaging mode)
- Investigate alternative processing approaches to meet specularly requirement (for light bucket mode)

RATIONALE

The technology of contour generation has improved in the last few years. This reduces the amount of formal polishing required and in some cases this later step could be eliminated completely. (i.e., only a "shine-to-remove" the gray would be required after contour generation to meet the specularly requirement)

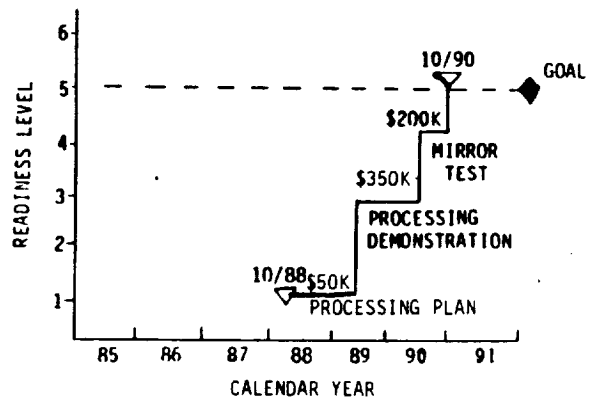
TECHNOLOGY ASSESSMENT

No other programs identified with the same performance requirements (surface quality, specularly, and wavelength range). Current techniques demonstrated in DARPA and in industry IR&D programs emphasize polishing step--- schedule and cost implications. These latter approaches should be available by 1991.



SCHEDULE AND BUDGETARY PLAN FOR AUGMENTATION

Two year \$600K program to reach goal by October 1990



CATEGORY G: OPTICS MATERIALS AND FABRICATION
OFF-AXIS MIRROR SEGMENT PROCESSING
Figure 3.7.5-1

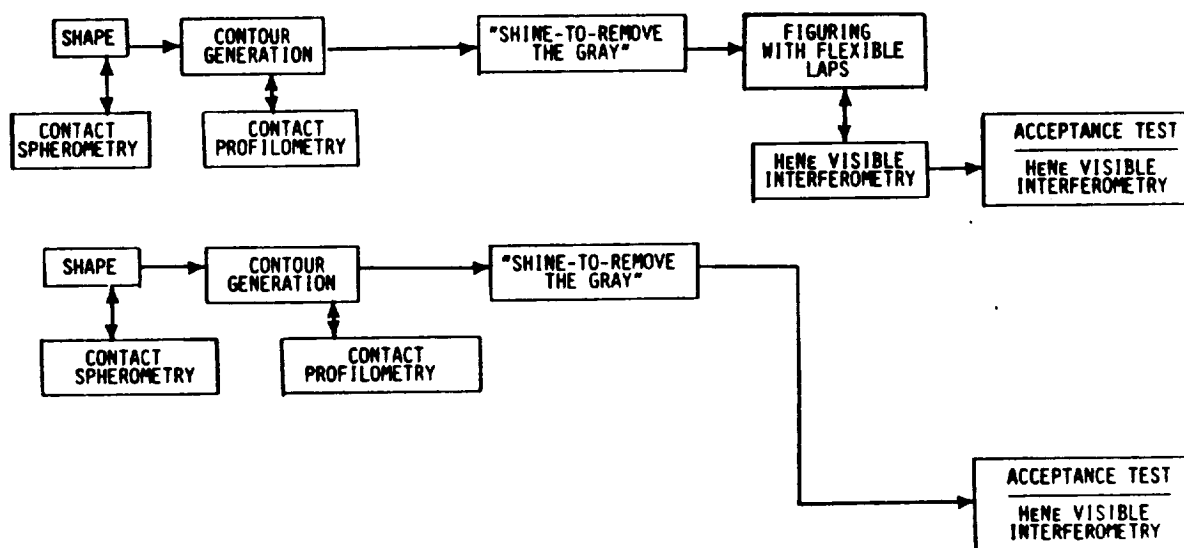
3.7.5.1 Requirements Derived from Concepts - The inability to manufacture an optical surface to perfectly match the designed surface results in degradation of performance (wave front error and scatter) of an imaging system. These surface deviations result in low spatial frequency figure error (global), medium spatial frequency error of surface ripple or quilting (core print-through) and high spatial frequency error surface roughness. An additional issue is imposed on a coherently phased segmented mirror. A mismatch between radii of the segments and the design radius of the overall mirror will also result in a wavefront error. The requirements as established by the study are summarized in Table 3.7.5-1.

TABLE 3.7.5-1
LDR DERIVED PERFORMANCE REQUIREMENTS

(To Meet Diffraction Limited and Light Bucket Requirements Simultaneously)

LOW SPATIAL FREQ.	MID SPATIAL FREQ.	HIGH SPATIAL FREQ.	RADIUS MISMATCH
(RMS Surface Error, μ) 0.5	(Autocorrelation Length/Pupil Dia.) 0.125	(RMS Surface Roughness, \AA) 250	(PPM) 50

3.7.5.2 Required Technology Maturity Level - Shown in Figure 3.7.5-2 are two alternatives to processing the LDR primary mirror segments. The first approach is the traditional Kodak method for manufacturing an aspheric mirror. This is a three step process: shaping, contour generation and figuring. The second approach eliminates the need for formal polishing. In this concept the contour generation step is extended past the traditional hand-off point of one micrometer to as close to the final desired asphere as possible. This maximizes the major material removal step (contour generation) and minimizes the polishing step. A demonstration has been configured at OAST Level 5 (component/breadboard tested) to be completed by 1990.



LDR PRIMARY MIRROR SEGMENT MANUFACTURE ALTERNATIVES
Figure 3.7.5-2

3.7.5.3 On-Going Technology Developments and Estimation of Where the Technology Will Be in 1991 - The current manufacture of an aspheric mirror is performed in a three-step process: shaping, contour generation, and figuring. In the shaping step a nominal sphere is generated onto the surface with a rough grinder. The goal is to leave the minimum of material to be removed in the following two steps. Loose abrasive grinding on a "tub grinder" in step two brings the contour to the desired aspheric shape and radius. A "shine-to-remove the gray" is performed to reduce the surface roughness and maximize fringe contrast. In the third step, the figure errors are divided into symmetrical and asymmetrical components. Full aperture tools are made to correct each component. These large tools minimize the mid to high spatial frequency error (ripple). The large aperture tooling approach developed by Kodak minimizes the mirror processing time (amount of time the tool is actually on the mirror). This allows parallel processing of mirror segments, thus reducing the need for a large number of mirrors. The technology of contour generation has improved in the last few years. This reduces the amount of formal polishing required and, in some cases this later step could be eliminated completely. (i.e., only a "shine-to-remove the gray" would be required after contour generation to meet the secularity requirement).

Current techniques demonstrated in DARPA and in industry IR&D programs emphasize the polishing step. Use of this traditional approach has schedule and cost implications for LDR. The newer precision contour generation approach is available now and should be directly applicable to the LDR segments. However, no other programs have been identified with the same performance requirements (surface quality, specularly, and wavelength range).

3.7.5.4 Technology Shortfall and Augmentation Plan - If the contour generation step (grinding) could reach the desired asphere, no formal polishing step would be required. The segment would require only a "shine to remove the gray" to meet the secularity requirement. Kodak has investigated and built a "proof-of-concept" contour generator under IR&D. It has been used to successfully generate large optics to tolerances similar to those of LDR. The LDR augmentation plan is to investigate precision contour generation for the LDR segments. The plan involves the following activities:

- 1988 - Establish mirror processing plan (\$50K)
- 1989 - Processing demonstration (\$350K)
- 1990 - Mirror segment test (\$200K)

3.8 OTHER (OAST CATEGORY H)

The two items in this category identify potential technology developments in transportation systems based on perceived LDR requirements. Assessments are not included.

3.8.1 ACC Contamination Protection/Remote Maneuvering Arm

Concept 3 assumes the use of the proposed Shuttle Orbiter/Aft Cargo Carrier transportation-to-orbit capability. Should this mode be developed, its application for carrying LDR to orbit and serving as a platform for assembly must be reviewed with respect to LDR contamination concerns and deployment concepts, in particular, and compatibility with LDR in general. Because of the location of Shuttle Reaction Control System nozzles with respect to the ACC, there may be a need to provide special contamination control packaging of the primary segments that are stored in and later removed from the ACC on orbit. In addition, to handle the primary mirror segments, a new remote maneuvering system, longer than the current arm on the Shuttle, would be required to reach to the ACC.

3.8.2 Shuttle Bay Contamination Protection

The sensitivity of LDR performance to contamination requires attention to protective measures throughout all phases of ground activities, launch, assembly on-orbit, and revisits.

The launch environment within the Shuttle bay may require the utilization of special protective control methods for LDR optical elements during ascent venting.

4.0 SUMMARY

The Kodak MDAC-FSC study team has identified 22 technology augmentation needs for LDR. These needs are judged to be beneficial to support an LDR schedule requiring technology readiness by year-end 1991.

Of these needs, five are considered of primary importance based on unique LDR requirements, lack of viable alternatives, high potential payoff, or anticipated long term developments. The 17 other needs rated medium are considered important and their implementation is recommended.

A plan that integrates the 22 individual technology augmentation needs into three fundamental issue groups has been created. The groups are:

- Reflector Quality Program
- Pointing and Stability Program
- Detectability Program

These program plans are enclosed as foldouts at the end of this volume.

4.1 TECHNOLOGY TASKS IN PRIORITY ORDER

<u>OAST CATEGORY</u>	<u>TECHNOLOGY</u>
	HIGH - 5
B	DYNAMIC STRUCTURAL CONTROL
D	HUMAN FACTORS
E	HYBRID CRYOGENIC SYSTEM FOR SCIENCE INSTRUMENTS
G	ACTIVE PRIMARY MIRROR
G	PRIMARY MIRROR CONTAMINATION PROTECTION
	MEDIUM - 17
A	PRIMARY MIRROR SEGMENT SENSING AND CONTROL APPROACH
A	FOLD MIRROR CHOPPING
A	SECONDARY MIRROR CHOPPING
A	FINE GUIDANCE SENSING AND CONTROL
B	DYNAMIC DIMENSIONAL STABILITY
B	DYNAMIC RESPONSE PREDICTION PRECISION
B	STRUCTURAL NONLINEARITY
B	LOW JITTER AND RAPID SETTLING
B	VERIFICATION/ACCEPTANCE GROUND TESTING
B	MECHANICAL STABILITY - DAMAGE TOLERANCE
B	STEP SUNSHIELD
B	SECONDARY MIRROR TEMPERATURE CONTROL
B	PRIMARY MIRROR TEMPERATURE CONTROL
E	CRYOGENIC SYSTEMS FOR DETECTOR TEMPERATURES LESS THAN 0.3°K
E	ROBOTIC ON-ORBIT CRYOGENIC REPLENISHMENT
G	GLASS MATERIAL FOR THE PRIMARY MIRROR
G	COMPOSITE MATERIAL FOR THE PRIMARY MIRROR
	LOW - 4
A	SECONDARY MIRROR SENSING AND CONTROL APPROACH
B	COLLAPSIBLE SUNSHIELD
B	SPACECRAFT BUILDUP ON ORBIT
G	OFF-AXIS MIRROR SEGMENT PROCESSING
	NOT RATED - 5
A	NOISE REDUCTION IN CONTROL MOMENT GYROS
C	STRUCTURAL DYNAMICS: ADVANCED POWER SYSTEM
C	MONOPROPELLANT REFUELING
H	ACC CONTAMINATION PROTECTION/REMOTE MANEUVERING ARM
H	SHUTTLE BAY CONTAMINATION PROTECTION

4.2 TASK MILESTONES

Milestones of tasks are included in each of the individual development plan schedules in Section 3.0.

Some milestones are also indicated on the foldouts of the three integrated plans at the end of this volume.

4.3 BUDGET MILESTONES

Budget milestones are indicated on each of the individual development plan schedules in Section 3.0

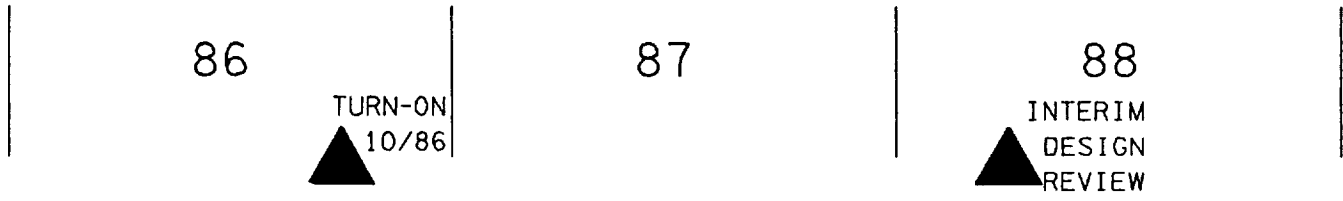
A time-phased budget summary of the three Kodak technology programs and their constituent projects is shown in Table 4.3-1.

TABLE 4.3.1
LDR-INTEGRATED TECHNOLOGY DEVELOPMENT PLAN

	1986	1987	1988	1989	1990	1991	TOTALS (K\$)
REFLECTOR QUALITY PROGRAM							
1 GLASS MATERIAL FOR PM	50	350	150	150			700
2 COMPOSITE MATERIAL FOR PM	50	400	100	50			<150>
3 ACTIVE PRIMARY MIRROR			100	200	2,300	700	<3,200>
4 PM SEGMENT SENSING & CONTROL				50			150
				200	3,550		3,750
(K\$) TOTALS	100	750	350	650	5,850	700	8,400
(M\$) CUM TOTALS	0.1	0.850	1.2	1.85	7.70	8.4	
POINTING AND STABILITY PROGRAM							
1 DYNAMIC STRUCTURAL CONTROL			1,000	500	1,000		2,500
2 DYNAMIC DIMENSIONAL STABILITY	50	150	300	550			1,200
3 DYNAMIC RESPONSE PREDICTION PRECISION	50	50	50	200			350
4 STRUCTURAL NONLINEARITY	50	50	200	400			700
5 LOW JITTER & RAPID SETTLING	50	250	200	200	6,000		6,700
6 VERIFICATION/ACCEPTANCE GROUND TESTING		150	550	100			800
7 MECHANICAL STABILITY-DAMAGE TOLERANCE			25	100			125
8 HUMAN FACTORS	25	150	325	700	1,000	6,000	8,200
9 FINE GUIDANCE				200		500	700
(K\$) TOTALS	225	900	2,700	2,950	8,000	6,500	21,275
(M\$) CUM TOTALS	0.225	1.125	3.825	6.775	14.775	21.275	

TABLE 4.3.1
LDR-INTEGRATED TECHNOLOGY DEVELOPMENT PLAN
(CONTINUED)

	1986	1987	1988	1989	1990	1991	TOTALS (K\$)
DETECTABILITY PROGRAM							
1 HYBRID CRYOGENIC SYSTEM FOR SCIENCE INSTRUMENTS	100	900	1,000 500	3,000	1,500 1,000	4,000	12,000 { 2000 5000 5000
2 CRYOGENIC SYSTEM FOR DETECTORS LESS THAN 0.3°K HELIUM DILUTION	100	1,000	900 500	2,000	1,500	1,000	7,000 { 2000 5000
ADIABATIC DEMAG.	100	900	1,500	1,500	1,000 500	500	6,000 { 4000 2000
3 STEP SUNSHIELD				100	200	700	1,000
4 PM TEMPERATURE CONTROL				200	500		700
5 SM TEMPERATURE CONTROL				200	500		700
6 SM CHOPPING			50	50 100	800		100 { 1100 900 100
7 FOLD MIRROR CHOPPING			50	50			
8 PM CONTAMINATION PROTECTION				200	400	400	1,000
9 ROBOTIC ON-ORBIT CRYOGENIC REPLENISHMENT	150	600	1,200	3,300	4,500	1,500	11,250
(K\$) TOTALS (M\$) CUM TOTALS	450 0.450	3,400 3.850	5,700 9.550	10,700 20.250	12,400 32.650	8,100 40.750	40,750
(K\$) GRAND TOTAL (M\$) CUM TOTAL	775 0.775	5,050 5.825	8,750 14.575	14,300 28.875	26,250 55.125	15,300 70.425	70,425



MATERIAL DEVELOPMENT PROGRAM

MIRROR DES

OAST CATEGORY G

GLASS MATERIAL FOR THE PRIMARY MIRROR

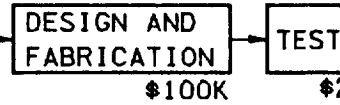


OAST CATEGORY G

COMPOSITE MATERIAL FOR THE PRIMARY MIRROR



SELECT



CONCEPTUAL DESIGN OF A PASSIVE SEGMENTED MIRROR (TILT AND PISTON ONLY) \$150K

OAST CATEGORY G

ACTIVE PRIMARY MIRROR

CONCEPTUAL DESIGN OF A ACTIVE SEGMENTED MIRROR (TILT, PISTON & FIGURE) \$150K

OAST CATEGORY A

PRIMARY MIRROR SEGMENT SENSING & CONTROL

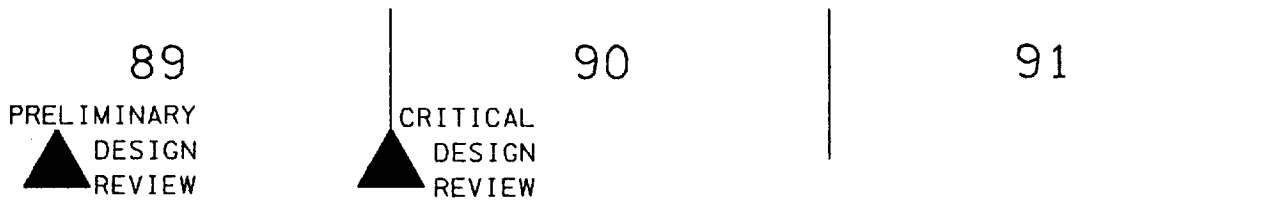
QUALITY PROGRAM

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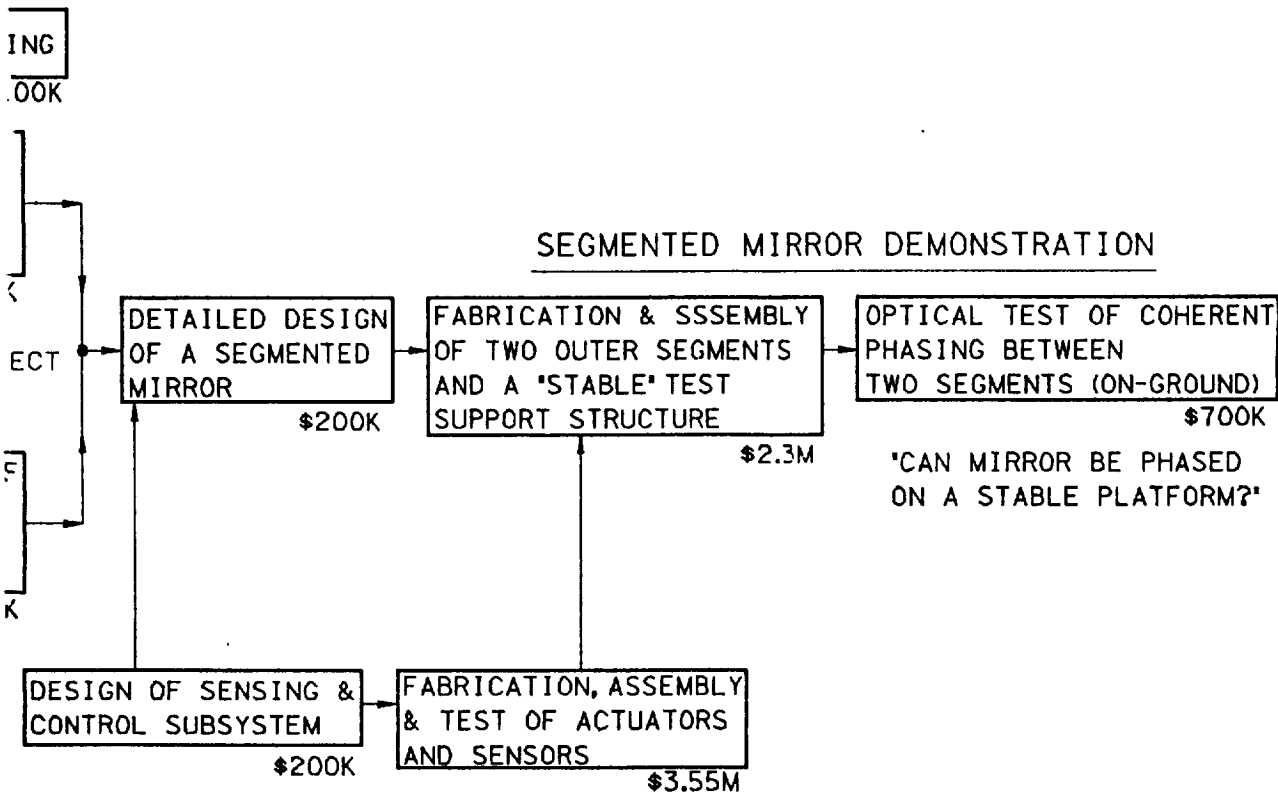
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YEAR



IGN PROGRAM

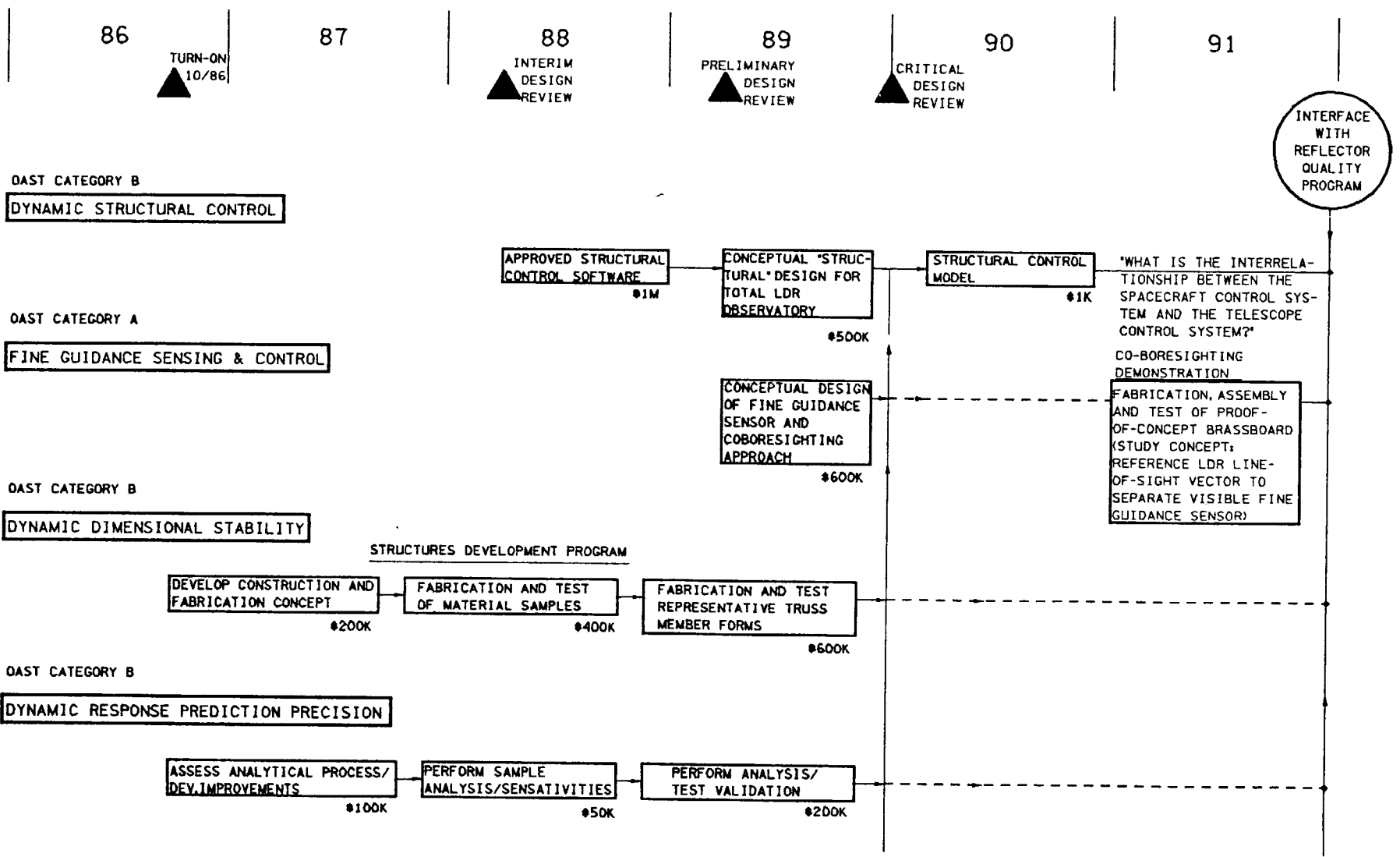


POINTING & STABILITY PROGRAM

(\$21,275,000)

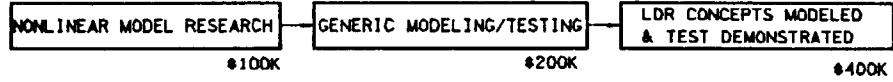
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CALENDAR YEAR



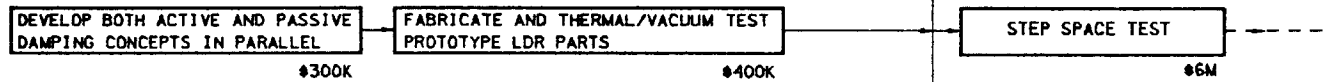
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STRUCTURAL NONLINEARITY



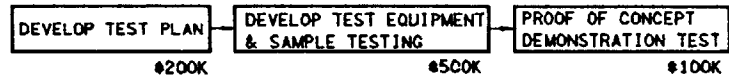
OAST CATEGORY B

LOW JITTER AND RAPID SETTLING



OAST CATEGORY B

VERIFICATION /ACCEPTANCE GROUND TESTING



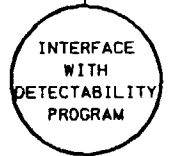
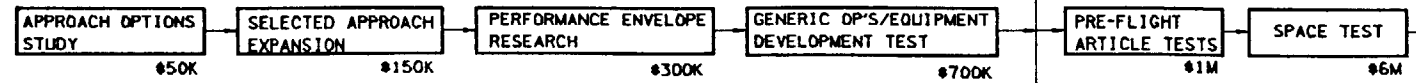
OAST CATEGORY B

MECHANICAL STABILITY-DAMAGE TOLERANCE



OAST CATEGORY D

HUMAN FACTORS



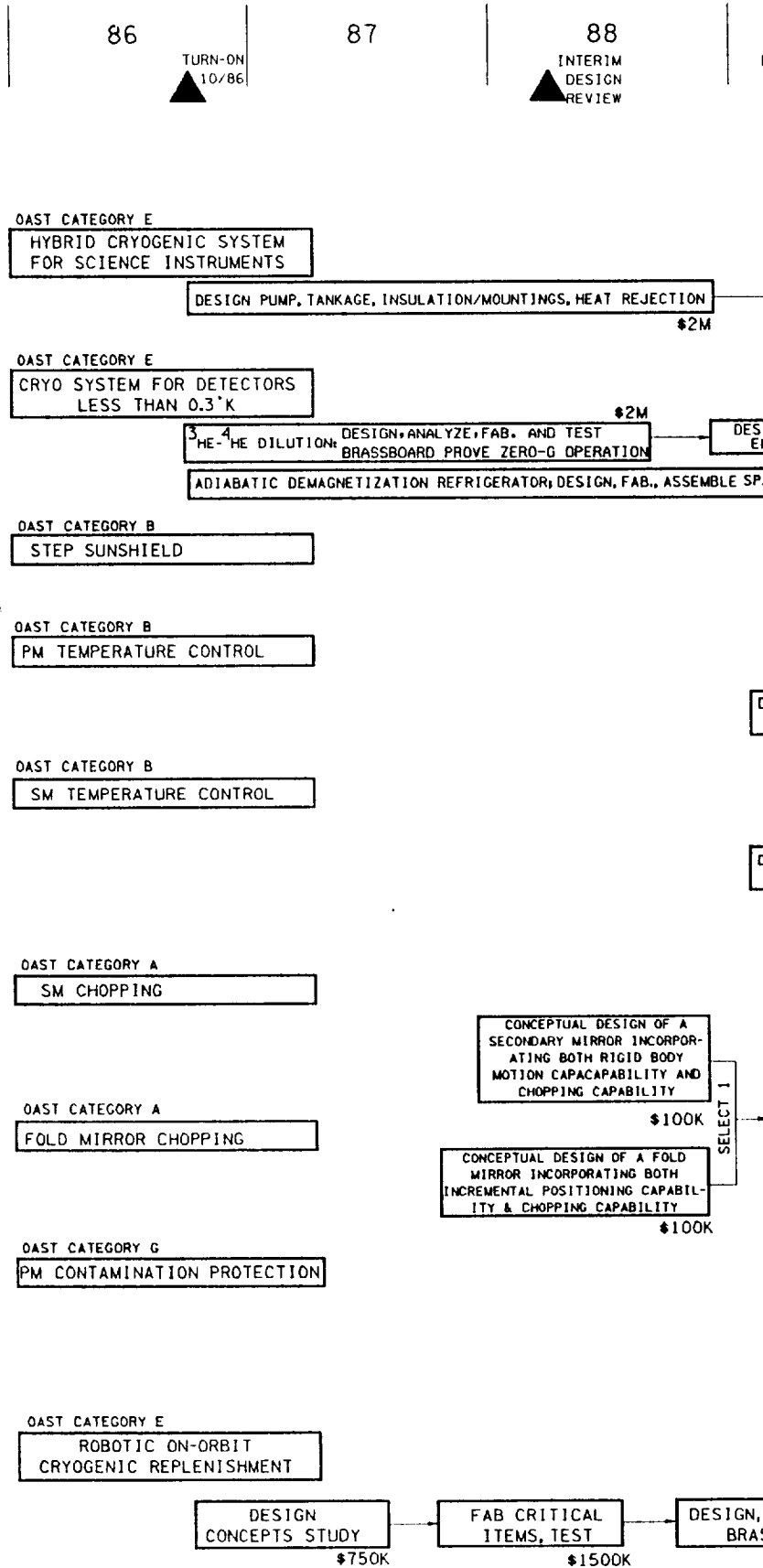
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DETECTABILITY

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CALENDAR Y

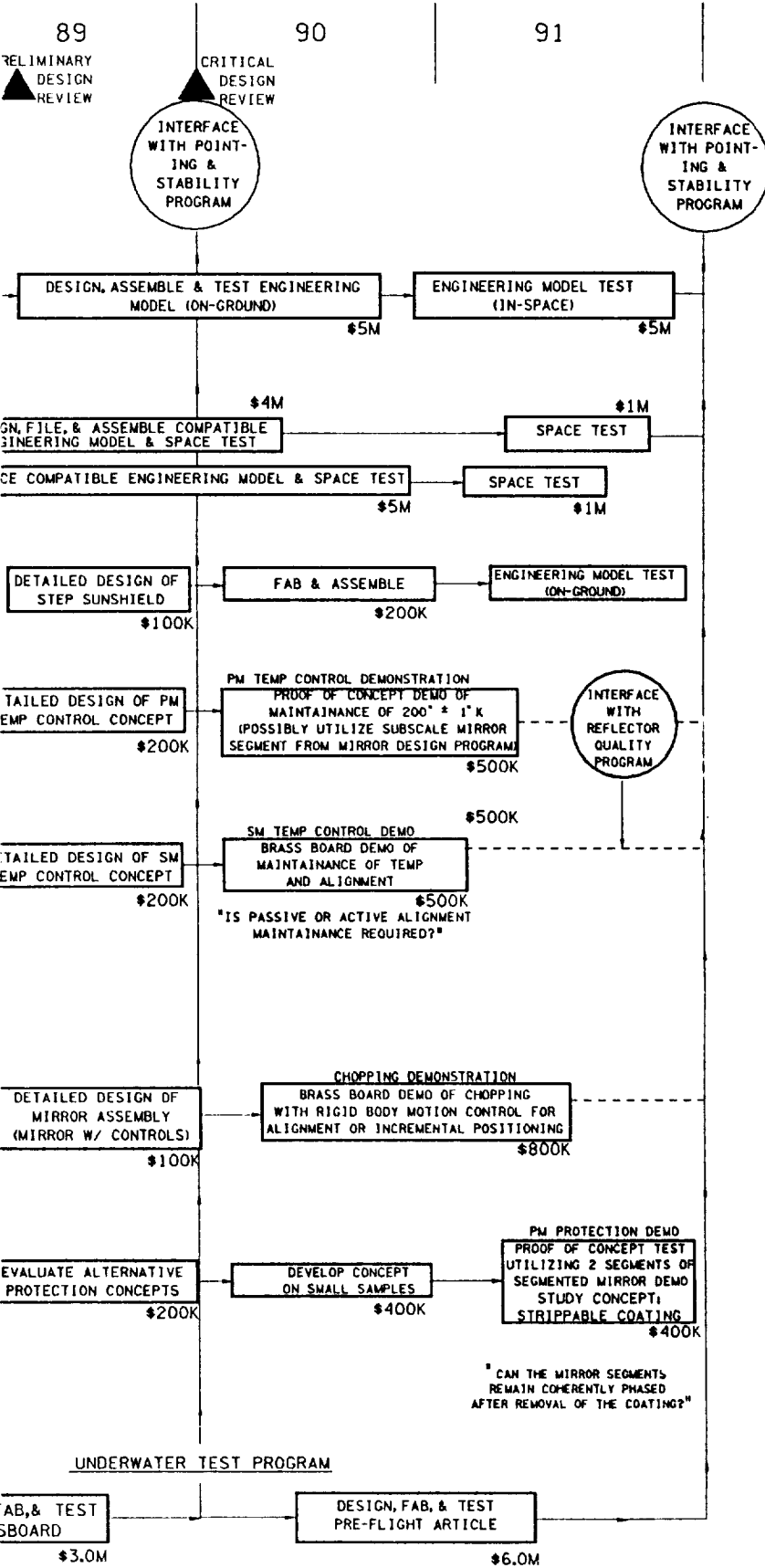


PROGRAM

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16. Abstract A study was conducted to define reasonable and representative LDR system concepts for the purpose of defining a technology development program aimed at providing the requisite technological capability necessary to start LDR development by the end of 1991. This Volume II presents thirteen technology assessments and technology development plans, as well as an overview and summary of the LDR concepts. Twenty-two proposed augmentation projects are described (selected from more than 30 candidates). The five LDR technology areas most in need of supplementary support are: cryogenic cooling; astronaut assembly of the optically precise LDR in space; active segmented primary mirror; dynamic structural control; and primary mirror contamination control. Three broad, time-phased, five-year programs were synthesized from the 22 projects, scheduled, and funding requirements estimated. Volume I (separate) contains the executive summary for the total study and a report of the systems analyses/trade studies.			
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