NASA Conference Paper 2407

Workshop on Technology Development Issues for the Large Deployable Reflector (LDR)

February 1986

(NASA-CP-2407) WORKSHOP ON TECHNOLOGY DEVELOPMENT ISSUES FOR THE LARGE DEPLOYABLE REFLECTOR (LDR) (NASA) 118 p CSCL 03B

N88-20235

Unclas

H1/90 0130535

National Aeronautics and
Space Administration

NASA Conference Paper 2407

Workshop on Technology Development Issues for the Large Deployable Reflector (LDR)

Edited by Kenji Nishioka, Ames Research Center, Moffett Field, California

February 1986

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

TABLE OF CONTENTS

Page

ACKNOWLEDGMENTS....iv

INTRODUCTION....1
  Summary....1
  Background....2

TECHNOLOGY PANEL REPORT SUMMARIES....2
  Systems and Simulations....2
  Sensing and Control Technology....3
  Optical Systems....4
  Structures and Materials....5
  Thermal and Power Technology Panel....6
  Science Instruments....6

SCIENCE COORDINATION GROUP SUMMARY....7
  LDR Unique Science....7
  Typical LDR Projects: Observing Time, Scheduling, Beam Stability, and Telemetry....8
  Major Technical Issues....8
  Program in Far-Infrared/Submillimeter Astronomy....8

CONCLUSIONS AND RECOMMENDATIONS....9
  Conclusions....9
  Five-Year Program Recommendation....9

REFERENCES....11

APPENDIX A: LDR TECHNOLOGY PLANNING WORKSHOP....19

APPENDIX B: LDR SYSTEMS AND SIMULATIONS PANEL REPORT....21

APPENDIX C: SENSING AND CONTROL PANEL REPORT....39

APPENDIX D: OPTICS PANEL TECHNOLOGY DEVELOPMENT RECOMMENDATIONS AND PRIORITIES....57

APPENDIX E: STRUCTURES AND MATERIALS TECHNOLOGY PANEL REPORT....77

APPENDIX F: THERMAL AND POWER TECHNOLOGY PANEL REPORT....85

APPENDIX G: SCIENCE INSTRUMENTS PANEL REPORT....99

PRECEDING PAGE BLANK NOT FILMED

ACKNOWLEDGMENTS

This report documents the pertinent results of the Large Deployable Reflector (LDR) Workshop, Asilomar II, held March 17-22, 1985, at Asilomar, California. Sponsored by NASA's Office of Aeronautics and Space Technology and Office of Space Science and Applications, the workshop evaluated and identified critical LDR technology issues and defined an "LDR Technology Initiatives Plan" to provide timely technology development for the LDR program.

The workshop LDR Asilomar II became a reality largely through the efforts of Bruce Pittman with encouragement and funding from NASA Headquarters' codes EZ and RS. The real success of the workshop resulted from the many active and enthusiastic participants from government, industry, and universities. The key to the workshop was the technology-issues summaries provided by the industry teams led by Eastman Kodak Company and Lockheed Missiles and Space Company. Special thanks go to the Technology Panel Chairmen for their leadership at the workshop and their follow-up efforts in documenting their panel results; they are: Kenji Nishioka (Systems and Simulations), Fernando Tolivar (Sensing and Control), James Breckenridge (Optics), Martin Mikulus and Robert Freeland (Structures and Materials), Peter Kittel (Thermal and Power), and James Cutts (Science Instruments). Contributions of the Science Coordination Group led by Stephen Strom and David Gilman were also invaluable to the outcome of the workshop.

Special thanks go to Meredith Moore, Paul Wercinski, Gwen Ritchey, and Kathleen Connell for providing the necessary logistics and administration support for the workshop.

Kenji Nishioka
NASA Ames Research Center
August 15, 1985

INTRODUCTION

Summary

In June 1982, NASA's Office of Aeronautics and Space Technology and Office of Space Science and Applications held its first Large Deployable Reflector (LDR) Workshop to define the scientific and technological requirements of the space telescope scheduled to be launched in the 1990s. The 2nd LDR Technology Review Workshop was held at Asilomar, California, March 17-22, 1985. The purpose of the workshop was to assess, identify, and prioritize the LDR technology issues, provide a consensus list of technology issues, and develop a technology initiatives plan. A group of about 100 experts in various technology disciplines from NASA, other government agencies, industry, and universities participated in the workshop. The workshop participants identified four high-priority areas for NASA-OAST technology development attention: (a) mirror materials and construction, (b) sensing and controls, (c) system-simulation and modeling capability, and (d) submillimeter instruments.

The starting point in the workshop was to listen to the LDR system study contractors' (Eastman Kodak Company and Lockheed Missiles and Space Company (LMSC)) results, and to have the six technology panels focus on their appropriate issues to evaluate the contractor results and report their findings to the general assembly. Final, overall consensus results from all six panels are reported here. The six technology panels were Systems and Simulation, Optics, Sensing and Control, Structures and Materials, Thermal and Power, and Science Instruments. In addition, the Science Coordination Group members outlined the science expectations for LDR. As seen from the agenda for the workshop (appendix A), there were several other presentations pertaining to LDR. First, the Jet Propulsion Laboratory (JPL) presented results of their recently completed LDR study. JPL's baseline constraints for their study were different than those used by the contractors, and thus results could not be compared directly. Latest state-of-the-art research activities in technology specialties were also presented. A presentation on space-frame design and construction using terrestrial construction techniques was made by Mr. W. Wendell of Space Structures International Corporation. This presentation highlighted the potential application of design techniques developed for constructing low-cost terrestrial structures to LDR structures to accomplish cost savings.

The workshop participants agreed that a great deal of technology development was required to ensure a successful LDR. Most participants agreed that the primary-mirror technology and materials along with the control and sensing technology were areas of high interest and concern for LDR. The third area of high concern identified was workable heterodyne detectors and receivers. Additional technology development areas of importance are identified by each of the six technology panels at

the workshop are contained in the appendices B-G. Most of the technological issues identified by the workshop are summarized by "quadrant" charts containing: (1) a statement of the technology requirement; (2) a rationale of what needs to be answered, why the technology is an issue, and why it is important; (3) an assessment of the state-of-the-art technology; and (4) the schedule and budgetary plan for accomplishing the technology advancement necessary to LDR. The overall cost identified for the desired LDR technology development is estimated at slightly over 185 million dollars including 100- to 120-million-dollar flight experiments.

Background

The early history of LDR has been described in the first LDR Asilomar Workshop (ref. 1) of June 1982. Since then, NASA has sponsored two parallel studies with private industry, and these results were presented at this second LDR Asilomar Workshop.

Showing a high interest in the LDR concept, JPL independently conducted a systems study (ref. 2) of a modified LDR concept using in-house funds. In addition, an LDR Science Coordination Group (SCG), headed by Stephen Strom and David Gilman, has been active during the past year in overseeing the industry studies, defining the science instrument package, and detailing the science concerns of LDR.

Results of the system concept studies presented by LMSC and Kodak at this workshop analyzed LDR assembly in space using the space transportation system (STS) and extravehicular activity (EVA). Recent approval of the Space Station Program has introduced an interesting assembly alternative for LDR. To identify the impact of the Space Station on LDR assembly and *vice versa*, the LMSC and Kodak contracts are being extended to study and identify any new requirements. Results from this study will be available in January 1986.

The following sections summarize the results of the deliberations of the six technology panels at the workshop. These results set the priorities for the most pressing LDR technologies. Details for each of these technology issues and additional technology issues considered at this workshop are provided in appendices to this report.

TECHNOLOGY PANEL REPORT SUMMARIES

Systems and Simulations

The Systems and Simulations panel, after listening to all of the presented materials (contractor reports and technology reports), developed evaluation criteria for LDR technololgy issues, based on system considerations. That is, the technology development priority was based on the technology's impact on the LDR as a whole. This panel recognized the importance of technology development for LDR instruments, especially submillimeter, but because necessary details on instruments were unavailable to this panel, the technology-assessment issue was left to the Science instruments panel to evaluate. Out of all the technology issues identified in the presentations, eight high-priority technology areas were identified as systems drivers (table I). These eight areas were then further segregated into three priority categories: Priority I for immediate attention, Priority II for near-future resolution, and Priority III for future resolution. Figure 1 identifies the two categories that were identified as critical: (1) mirror material and construction, and (2) pointing. The panel identified and recommended that the LDR program investigate other programs to benefit from their technology developments to help reduce LDR development costs.

An important recommendation of the panel was that the LDR program needs to develop a consistent set of mission/science performance requirements to replace the engineering and subsystem specific design requirements now in use. For example, the nodding and chopping requirements place an almost insurmountable engineering-design task because of LDR's size and mass. But if the nodding and chopping requirements were stated instead as an equivalent, but more general, background reduction requirement, then innovative engineering solutions may be developed to produce the necessary scientific result. With the development of performance requirements, the designer has the engineering flexibility for meeting the design requirements, which should result in a system-optimized design.

Based on its evaluations and the desire to provide a basis for an optimized LDR concept, the Systems and Simulation panel recommends that the following system and technology development studies and activities be integrated into the overall LDR Program:

1. Continue funding generic technology-development programs.

2. Fund development of science/mission performance specifications.

3. Fund systems study (parametric) using performance specifications to identify reference configuration for LDR.

4. Fund an expanded program for developing simulation and modeling tools.

These studies and activities will lead to a streamlined, more productive technology development program and a successful LDR design.

For further discussion of the systems and simulations panel report, see appendix B.

Sensing and Control Technology

The hundreds of degrees of freedom and the flexibility of the LDR, together with the need to meet stringent (0.02 arc sec) pointing stability and an optical-figure precision requirement of 1 μm in a 20-m-class system, imposes extreme and unprecedented demands on sensing and control technology.

Table II summarizes the seven key sensing and control technology areas which were identified as critical to LDR, ranked as high and medium priorities.

Of these, the first four areas were identified as having the highest immediate priority, where work should begin in the 1986 fiscal year. These areas address the following needs:

1. Dynamic control technology- To provide line of sight and wavefront stabilization via isolation of on-board dynamic contamination sources, passive damping, and active control. Stability is the area in which the Space Telescope has had some of its greatest problems.

2. Upgraded control analysis and simulation tools- To handle close to 1000 degrees of freedom with the required high precision. These tools are required for the modeling and simulation of the LDR to predict control-system performance and evaluate alternative control-system configurations.

3. Wavefront and figure control- To address the issues of sensing the wavefront within the telescope, relating this to figure errors of the primary and other elements of the optical train, and providing the appropriate means of wavefront correction.

4. Control technology integration brassboard- To evaluate the candidate control hardware and algorithms in a scaled, ground-based, proof-of-concept demonstration.

Optical Systems

The LDR wavelength region makes the system optically sensitive to diffraction and thermal effects. It is difficult to predict subtle but crucial behavior of the LDR in this quasi-optical domain. Problem areas include edge-diffraction behavior, standing-wave generation, chopping-signal modulation, and thermal-background management. The analysis tools currently available fall between laborious microwave-diffraction evaluation programs and the approximations of fast optical-optimization programs. These programs must be merged into a quasi-options analysis program to optimize performance in the LDR wavelength regions. The analysis tools for these interactive tasks that must be developed and verified are summarized in table III.

The astronomical behavior of the LDR is sensitive to the thermal, infrared background seen by the detector. Many effects enhance this background and each must be examined in a total-system context to see if the desired performance goals can be met with acceptable system impacts. The analysis tools for this task must be developed and verified.

There are two possible modes for correction of the assembly errors of the reflector panels, by actuators on the primary or by actuators at an exit pupil. The latter has special relevance to LDR because it opens the option for use of lightweight, composite-reflector panels; has simpler system deployment; and has the ability to meet astronomical operating requirements that are difficult to meet or that cannot be met by a Cassegrain telescope. The analysis tools for evaluating the panel and deployment errors and correction methodologies and their optical effects must be developed and verified.

The development of these analysis tools is essential to meet the requirements set for the LDR. These tools address interactive problem areas such as panel errors, deployment errors, and error sensing and control; these areas are also addressed in other sections of this technology plan.

Structures and Materials

The technology does not exist today for a lightweight, low-cost, optimized design, space assembly, and an accurate, on-orbit performance prediction for the LDR's mechanical system. The problem areas include lightweight reflector panels and support structure, structural-system's dynamic simulation, and the verification of these technologies by means of flight experiments. The technology development priorities are summarized in table IV.

The LDR light-bucket-mode requirements dictate the need for primary reflector panels that can be satisfied at this time only by glass technology. The weight of the primary reflector panels drives the weight of the entire structural system and has major impact on the total LDR system. Therefore, alternative lighter-weight materials for the primary reflector panels have great potential for accommodating a lightweight, low-cost LDR. Additionally, high structural performance with inherent reliability and predictability results in low-cost systems. The structural concepts for space deployment and assembly for the primary and secondary reflector and sun shield face a major challenge to meet these requirements.

The design-trade studies required to optimize the structural system and the generation of realistic estimates of on-orbit performances can be accommodated only by an analytical process with the capability of accounting for micrometer-level dynamic response. This process will have to accurately account for the effects of structural joint nonlinearity; the identification, characterization, and simulation of structural damping; and the extension of the current capability for accurately simulating structural dynamic behavior to the fidelity needed for LDR. This capability is essential for projecting how well the LDR structure meets its functional requirements.

A flight experiment will be required to characterize the LDR structural system and validate the high-fidelity modeling necessary to accurately predict system performance. Additionally, such an experiment will validate the on-orbit construction procedures required to assemble LDR. The resulting data base will significantly reduce program risks and uncertainties.

Thermal and Power Technology Panel

Table V summarizes the prioritization of the technology issues evaluated by the Thermal and Power Panel. High priority was given to instrument cooling and thermal analysis. Instrument cooling requires developing an active cooler and demonstrating cryogen resupply in space. These requirements are given high priority because neither exists and one or the other will be required to achieve an LDR as presently conceived.

Detailed thermal analyses are required to better understand the interplay between the various requirements, among the various LDR concepts, and among the various operational scenarios. Without more complete analyses, it is not possible to do a complete technology assessment. This task should include an evaluation of the thermal properties of proposed materials.

Medium-priority ratings were assigned to sub-Kelvin coolers and intermediate optical cooling. Sub-Kelvin coolers are given medium priority because they are not critical to the mission as a whole, but only to one particular instrument. Space-qualified coolers need to be demonstrated and checked against the requirements defined by the panel.

For intermediate optical cooling, applicability of coolers currently under development needs to be assessed and their progress tracked. The cooling was given medium priority because the requirements for this section of LDR (between the secondary mirror and instruments) are not defined, and thus the technology could not be adequately assessed.

Low priority was given to advanced power systems, which would require accelerating the development of power systems for the Space Station. This acceleration is required only if active coolers are used and if the system's impact of large, floppy, steerable, solar-cell arrays is unacceptable.

Science Instruments

The scientific observation of far-infrared and submillimeter radiation is the purpose of the LDR mission, and the instruments for discriminating, analyzing, and sensing this radiation are the crucial elements in the success of the LDR mission. Today, the technology for building the instruments needed by LDR does not exist and it cannot exist without a deliberate development program.

Some of the observational needs for LDR simply cannot be performed at all today, even in the laboratory. In other cases, laboratory and even ground-based instruments exist or could be built, but the technologies require far too much power and are far too unreliable to be flown in space. For many detector systems, performance falls orders of magnitude short of that of ideal quantum-limited detectors and so more than 99% of the radiation collected by the sophisticated reflector system would, in effect, be discarded. Finally, arrays of detectors, which have become a standard feature of large telescopes operating in other spectral regions, enhance the speed of data acquisition by many orders of magnitude, do not exist for the submillimeter range. The arrays are a critical enabling technology for using LDR as an imaging or mapping instrument.

These technology needs can be met by building on the core programs in submillimeter heterodyne technology and far-infrared, direct-detection technology that already exist in the sensor program sponsored by Office of Aeronautics and Space Technology. A plan for developing the needed technology is included in appendix G and table VI identifies the needed technologies and the priorities placed on them. These developments would be carried out in in-house programs at NASA centers, at universities, in industry, and at other government laboratories where the necessary expertise can be tapped.

An instrument definition and development program is also needed to guide and stimulate the development of the component-level sensor technologies. It would lead to a refinement of the performance requirements imposed on components so that these programs can be focused on specific devices as they mature. The development of advanced instrument systems technology is an inherent part of this instrument definition effort.

SCIENCE COORDINATION GROUP SUMMARY

The LDR SCG also attended the Asilomar Workshop. This meeting marked the end of the duties of this group, whose main charter was to oversee the two industry system studies, update the science rationale and technical requirements for LDR, and produce a report on "Instruments and Technology" for LDR (ref. 3). The SCG used the workshop to organize the draft of its final report to headquarters. This final report and the instruments document (ref. 3) detail the work of the SCG over the year and at the Asilomar Workshop. Here, we summarize some of the areas covered by the SCT and the principal conclusions.

LDR Unique Science

The LDR provides a unique observational capability because it lies above the atmosphere and has an unobscured view of the infrared and submillimeter universe, and because its large diameter and instrument complex provide a huge increase over existing observatories in the spatial resolving power, sensitivity, and spectral resolving power. The SCG has detailed the unique discoveries LDR is likely to make in the areas of cosmology, active galactic nuclei, star formation, stellar deaths, planet formation and detection of planets around nearby stars, and solar-system astronomy.

Typical LDR Projects: Observing Time, Scheduling, Beam Stability, and Telemetry

The scientific projects envisioned by the SCG for LDR require great mapping (imaging) sensitivity and spectral coverage. The integration times are long. The enabling technology is having detector arrays, even heterodyne mixer arrays, in the focal plane, and the SCG recommends an ambitious development program for these detector and heterodyne arrays. The SCG concern about beam stability resulted in the recommendation that the beam pattern not change by more than 5% everywhere within 20 half-power beam widths of the main lobe center. The telemetry requirements for sending data from arrayed detectors approaches several gigabaud (10^9 bits/sec).

Major Technical Issues

The SCG discussed five major technical issues:

1. The SCG recommends a 20-m LDR over a 10-m LDR because of substantial breakpoints in the observations of galaxies at high redshifts and in detecting planets around nearby stars.

2. The use of LDR in an interferometric mode in its initial configuration was discouraged, because of the lack of sensitivity in this mode (few objects could be detected at high spatial resolution).

3. The use of LDR as a light bucket in the 1 to 30-μm wavelength range was promoted if it could be obtained with little additional cost to the system (no more than an additional 20-30% of the cost).

4. The instrument complex environment for LDR strongly suggests the need for a vigorous instrument development program, especially in the arrays of heterodyne detectors and receivers and in detector arrays (imaging devices). The SCG in updating the Phillips and Watson report (ref. 3) suggests that about three, as opposed to eight, instruments fly on the initial LDR. Cryogen requirements are still difficult to meet. A strong recommendation was made that the concept of instrument replacement be a requirement, which mandates revisits to LDR and modular instrument design for a simple replacement procedure.

5. A detailed report on the background and chopping specifications for LDR has been prepared. One tentative conclusion is that the JPL chopping quaternary design may not sufficiently subtract the thermal background to make continuum observations feasible.

Program in Far-Infrared/Submillimeter Astronomy

The SCG defined "precursor activities" as all those activities in the pre-LDR era which are necessary to ensure the success of the LDR mission. Two of the principal concerns were the development and support of the submillimeter and infrared community of astronomers, and the development of instruments crucial to LDR's success. Thus, the SCG recommended the continuation and enhancement of such existing programs as theoretical modeling and laboratory astrophysics, which are relevant to LDR observations, and the infrared and submillimeter observatories such as the Kuiper Airborne Observatory (KAO). In addition, high priority was placed on future observatories which will develop the infrared/submillimeter community and further the progress being made in appropriate instrumentation. Two of the most promising "precursor" observatories are the Stratospheric Observatory for Infrared Astronomy, a 3-m telescope mounted in a 747 to replace the KAO, and a large (~3 m diam) space submillimeter telescope. A 3-m balloon-borne telescope would also be helpful.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The consensus of the panel chairmen was that funding should be provided for all the high-priority technology and systems issues identified at the Asilomar workshop and summarized in the preceding sections. But realistic funding levels of approximately 80 million dollars in the next 5 yr for LDR technology development are not likely, and thus the available funds should be focused on the highest priority technology areas. These areas include the development of modeling and simulation capability, and the development of submillimeter instruments, sensing and control, and mirror materials and constructions. These areas are identified as global issues for LDR and could be the major technology and cost drivers.

Five-Year Program Recommendation

Based on the workshop results, the 5-yr technology program outlined in figure 2 is recommended to continue development of the LDR program. This schedule was assembled for LDR using 1993 as the new program start date. In light of the numerous technology issues and funding constraints discussed in this report, we realize that this is an optimistic date for a new start. The proposed schedule, although tight, could probably be met if adequate funds for critical technology development can be found.

The development schedule emphasizes the need for activities in "simulation and modeling" and "systems verification," because LDR's large size requires special considerations such as orbital assembly and presents difficulties in ground-testing the assembled structure. That is, its size, weight, and structural flexibility coupled with the stringent dimensional tolerance requirements are adversely affected by the gravity loads; thus, meaningful ground-testing is not possible. The size of LDR will require a large test facility and fixtures for ground-testing, which implies high test costs. An alternative would be to verify the LDR design by analytic simulation and modeling to minimize or eliminate the physical testing of the fully assembled LDR mirror and structure. Thus, the need to develop accurate and precise simulation and modeling capability for analyses of LDR's expected behavior and performance is of paramount interest. This capability should be developed early in the program so it can be used and refined starting with the Phase B studies. It will be essential for Phase C/D. Some capability in this area already exists for structures and thermal simulation and modeling at NASA's Langley (LaRC) and Ames (ARC) Research Centers, as well as other NASA Centers and in industry, but these capabilities will need to be refined for LDR applications. In the case of sensing, control, and pointing simulation and modeling for LDR, no usable capability exists, and thus requires immediate attention. Table VII identifies the key tasks for the simulation and modeling activity. Analytic solutions are a necessity for LDR for the reasons just stated, but verification of the analytic results are also important to provide confidence in the system design. Therefore, the following systems-verification tasks are recommended.

The design concepts proposed for LDR's primary mirror and support structure are modular, and thus simplifies the systems-verification tasks. That is, the systems verification test requirements could be met by utilizing a representative module of the LDR mirror and structure for these tests. A strawman outline of the basic tasks and the sequence in which they will be done are shown in table VIII. The same pieces of structures and mirror segments can be used throughout the system verification activities, and thus help minimize LDR development costs. Also, since the SCG envisions precursor missions to LDR to stimulate instrument development and to modify science rationale, perhaps the later stages of this verification program could be integrated into a real, working precursor-telescope mission.

The engineering doability of the LDR concept will be validated by the successful simulation and modeling of the LDR design and the successful verification testing. Timely results are the purpose of the recommended 5-yr LDR development program.

REFERENCES

1. Leidich, Christopher; and Pittman, R. Bruce, eds.: Large Deployable Reflector Science and Technology Workshop, Vol. I, II, and III. NASA CP 2275, 1983.

2. Swanson, Paul N.: A Lightweight Low Cost Large Deployable Reflector (LDR)--A Concept Study by the Jet Propulsion Laboratory. JPL D-2283, 1985.

3. Phillips, T. G.; and Watson, D. M., eds.: The Large Deployable Reflector: Instruments and Technology. JPL D-2214, 1984.

4. Swenson, Byron: Large Deployable Reflector (LDR) system Concept and Technology Definition Study. NASA Contract NAS2-11861, 1985.

5. Swenson, Byron: Large Deployable Reflector (LDR) System Concept and Technology Definition Study. NASA Contract NAS2-11862, 1985.

TABLE I.- PRIORITY LIST FOR TECHNOLOGY DEVELOPMENT

Task	Priority rating
Mirror materials and construction:	I (immediate)
Composites	
Ultralow expansion (ULE)	
Lightweight	
Controls:	
Figure	
Structures	
Pointing	
Sensing	
Instrument cooling:	II (near future)
Stored cryogens	
Mechanical refrigerators	
Resupply	
Assembly and servicing by astronauts	
Spatial chopping techniques	III (future)
Contamination:	
Primary mirror	
Thermal surfaces	
Robotics/teleoperation:	
Assembly	
Servicing	
Resupply	
Configuration-dependent issues:	
Thermal control	
Sunshield	
Optical design	

TABLE II.- PRIORITIZED SENSING AND CONTROL TECHNOLOGY NEEDS

Technology need	Priority rating
Dynamic control technology: Jitter/structural dynamics Vibration isolation[a] Active control Passive damping	High
Analytical modeling/performance prediction: Components, dynamics, and disturbances System identification	High
Wavefront/figure control: Sensors and actuators	High
Control technology integration brassboard Ground-based proof of concept Model iterations	High
Fine line-of-sight guidance and offset pointing	Medium
Chopping devices	Medium
Flight-controls demonstration	Medium

[a]Equipment, including control moment gyroscopes (CMG).

TABLE III.- OPTICAL SYSTEM--TECHNOLOGY-DEVELOPMENT PRIORITIES

Technology classification	Task description	Priority rating
Analysis tools	Quasi-optics analysis methodology	High
	Thermal-background analysis methodology	High
	Image-optimization methodology	Medium-high
	Optical-testing methodology	Medium
Performance-related requirements	Thermal-background management	High
	Chopping behavior	High
	Standing-wave behavior	High
	Edge-diffraction behavior	High
	Primary-panel error correction	High
	Primary-deployment error correction	High
	Image-quality maintenance	Medium-high

TABLE IV.- STRUCTURES AND MATERIALS - TECHNOLOGY DEVELOPMENT PRIORITIES

Technology classification	Enabling technology	Priority rating
Concept development	Lightweight, low-cost reflector panels	High
	Lightweight, low-cost, deployable, erectable structures	Medium
Analytical tools	Structural system dynamic simulation	Medium
Flight experiment	Structural assembly concept performance, model verification, and refinement	Medium

TABLE V.- PRIORITIES ASSIGNED BY THERMAL AND POWER PANEL

Area	Issue	Priority rating
Front end cooling (sun shade; primary, secondary)	Thermal analysis	High
	Material degradation	High
Intermediate optical cooling (active optics, baffles)	Requirement definition	High
Instruments	Cryogen resupply	High
	Active cooler	High
Sub-Kelvin cooler	^3He cooler	Medium
	Adiabatic-De-Magnetization (ADM) cooler	Medium
Power	Advanced power systems	Low

TABLE VI.- SCIENCE INSTRUMENTS - TECHNOLOGY DEVELOPMENT PRIORITIES

Technology classification	Instrument type	Enabling technology	Priority rating
Components and devices	Heterodyne	Mixers/detectors	High
		Local oscillators	High
		Amplifiers and spectrometers	High
	Direct detection	Detector arrays	High
		Optics/mechanisms	Medium
		Support electronics	Medium
Systems technologies	Heterodyne and direct detection	Instrument definition	High
		Instrument systems technology	High

TABLE VII.- SYSTEMS SIMULATIONS AND MODELING STUDIES

Develop structural model and simulation software
Mirror segments
Mirror mounting structures
Instrument and spacecraft modules
Optics train
Loads model
Develop LDR thermal model and operations environmental simulation software
Thermal expansion
Thermal "creak"
Thermal loads
Temperature control
Develop pointing and control model and simulation software
Primary mirror segment figure control
Segment position sensing
Primary pointing control (CMGs or RWs - mag. t.)
Slewing, nodding, and chopping
FGS - primary beam alignment

TABLE VIII.- SYSTEMS VERIFICATION STUDIES AND EXPERIMENTS

Design and fabricate one LDR basic mirror support structure
Develop space assembly procedures for structure
Test structural assembly in neutral-buoyancy tank
Modify design as necessary
Revise space assembly procedures manual
Design and fabricate one basic mirror-segment module
Develop space assembly procedures for mirror
Test mirror segment and assembly structures in neutral-buoyancy tank
Modify design as necessary
Revise space assembly procedures manual
Design and conduct Shuttle flight experiment for space assembly and test
Deploy and assemble
Check out and leave in orbit
Disassemble and recover
Ground tests to provide structural modeling verification
Results feed into LDR Phase B or precursor mission

- MIRROR MATERIALS AND CONSTRUCTION
  - ULE GLASS
  - COMPOSITES
  - FOAM OR HEXCEL CORE
  - ACTIVE VERSUS PASSIVE CONTROL
- CONTROLS AND SENSING
  - FIGURE CONTROL
  - STRUCTURES (FLEXIBILITY)
  - POINTING
  - SENSING

Figure 1.- High-priority technology developments for LDR.

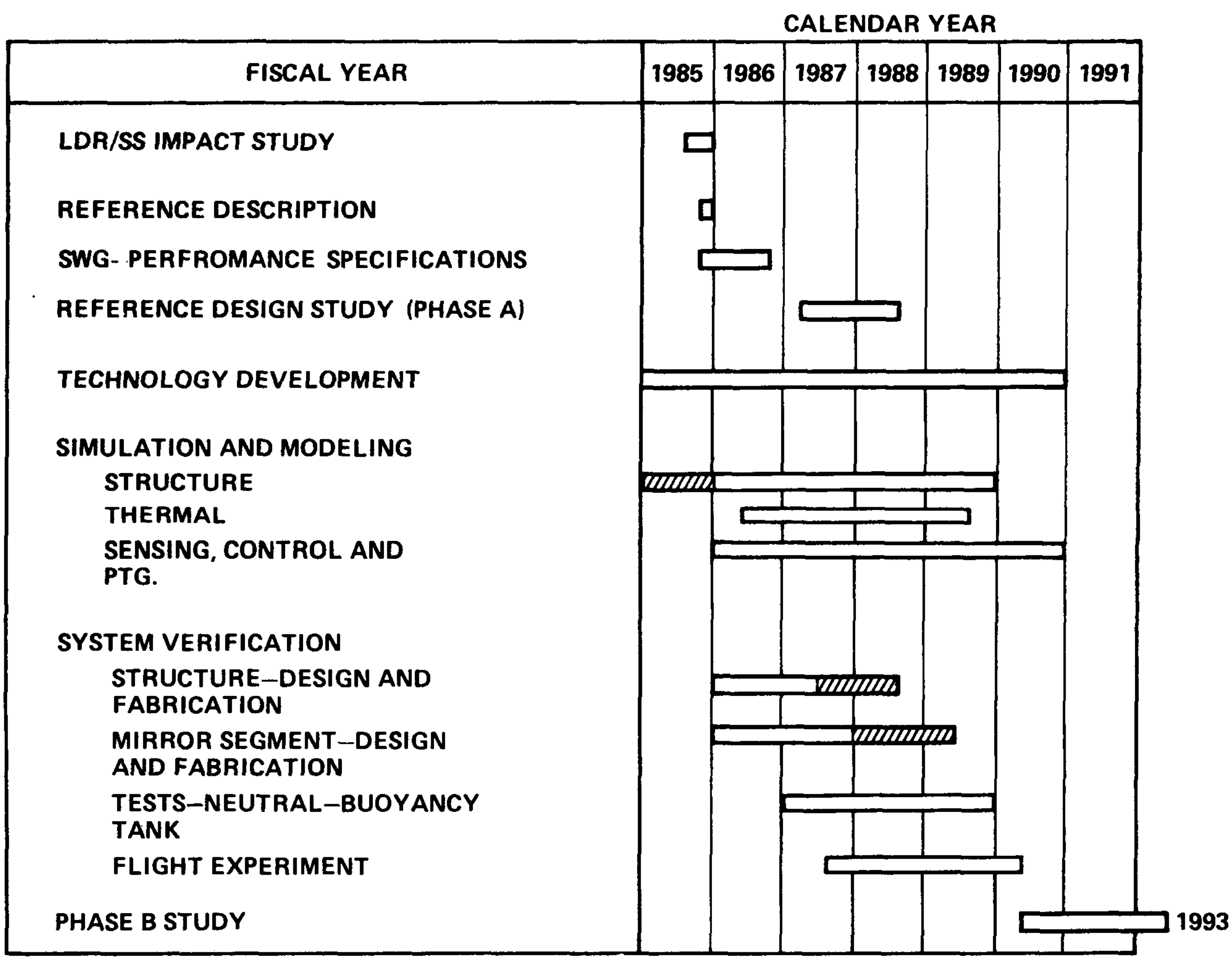


Figure 2.- LDR 5-year development schedule.

APPENDIX A

LDR TECHNOLOGY PLANNING WORKSHOP
ASILOMAR CONFERENCE CENTER
PACIFIC GROVE, CA
MARCH 17-22, 1985

Agenda

SUNDAY, MARCH 17

1:00	WORKSHOP REGISTRATION - ADMINISTRATION BUILDING
3:00	GENERAL SESSION - HEATHER: INTRODUCTION AND REQUIREMENTS REVIEW
5:30	CHECK INTO ROOMS
6:00	DINNER - DINING HALL
7:30	WINE & CHEESE RECEPTION - HEATHER

MONDAY, MARCH 18

7:30	BREAKFAST - DINING HALL
8:30	GENERAL SESSION - HEATHER: KODAK PRESENTATION
10:15	BREAK
10:30	GENERAL SESSION - HEATHER: LOCKHEED PRESENTATION
12:15	LUNCH - DINING HALL
1:15	GENERAL SESSION - HEATHER: JPL LDR CONCEPT
2:45	BREAK
3:00	PANEL SESSIONS
5:00	ATTITUDE ADJUSTMENT - HEATHER
6:00	DINNER - DINING HALL

TUESDAY, MARCH 19

7:30	BREAKFAST - DINING HALL
8:30	PANEL SESSIONS
12:00	LUNCH - DINING HALL
8:30	PANEL SESSIONS
1:00	GENERAL SESSION - HEATHER: PRESENTATIONS BOB FREELAND - Composite Panels RAMSEY MELUGIN - Glass Panels KAJAL GUPTA - LDR Simulation SCIENCE TEAM - Interferometers VAL MAKSIMOVIC - Space Station
5:00	ATTITUDE ADJUSTMENT - HEATHER
6:00	DINNER - DINING HALL

PRECEDING PAGE BLANK NOT FILMED

WEDNESDAY, MARCH 20

7:30	BREAKFAST - DINING HALL
8:30	PANEL SESSIONS
12:00	LUNCH - DINING HALL
1:00	GENERAL SESSION - HEATHER: PRELIMINARY REPORTS ON TECHNOLOGY PLANS & SYSTEM ISSUES
5:00	ATTITUDE ADJUSTMENT - HEATHER
6:00	AWARDS DINNER - DINING HALL: ANNOUNCE WINNER OF THE LDR RENAME CONTEST

THURSDAY, MARCH 21

7:30	BREAKFAST - DINING HALL
8:30	JOINT PANEL MEETINGS FOR INTERCHANGE IF NECESSARY
12:00	LUNCH - DINING HALL
1:00	PANEL SESSIONS
5:00	ATTITUDE ADJUSTMENT - HEATHER
6:00	DINNER - DINING HALL

FRIDAY, MARCH 22

7:30	BREAKFAST - DINING HALL
8:30	PANEL CHAIRMEN'S SUMMARY REPORTS - HEATHER
12:00	LUNCH - DINING HALL
1:00	ADJOURN

APPENDIX B

LDR SYSTEMS AND SIMULATIONS PANEL REPORT

Introduction and Summary

This workshop is essentially the first time that this panel (table B-I) has been convened, although a systems and missions panel with a different role was convened for the first LDR Asilomar conference. The task defined by this panel was to provide the broad, overall systems perspective to ensure that each technology area was reviewed with the total LDR requirements in mind. The panel used systems-impact issues (table B-II) as the criteria for evaluating the importance of each proposed technology development and subsequent prioritization for development funding.

The panel systematically reviewed each of the technology areas and their development prioritization as set by the contractors, and then evaluated them using systems impact as the criteria and arrived at a new priority listing as shown in table B-III. As the workshop progressed, it became clear that the technology development and associated funding list developed by the contractors instead of being compressed, was being expanded during the individual technology panel reviews. This development clearly indicated the need for our panel to look at LDR as a total system to identify a list of critical technologies for development. This transition to a system orientation for evaluating and identifying the future program tasks is a logical progression, indicating the maturing of the LDR concept.

It should be pointed out that the actual size of LDR is a historic and current problem, since space observatories this large have never been built or designed. Even the subsystems are larger and more complex than many current space systems. In the past, LDR has treated each subsystem independently, and if this practice continues, the result will be a suboptimized LDR, an undesirable result. A systems perspective is necessary to identify a realistic technology initiative program. Based upon this criterion the systems panel makes the recommendations that the generic-type technology-development projects currently funded be continued along with high-priority, new-technology areas clearly identified by this workshop; that overall science performance specifications be developed for LDR to replace the current mixture of engineering and science specifications/requirements; that the performance specifications be used in a systems study to define a reference concept for the LDR; and that simulations and modeling-tools development activities not only be continued, but be expanded.

Analysis and Results

The panel identified the systems issues shown in table B-II. The list is not in priority order. After systematic evaluations with lengthy discussions, detailed conclusions were reached for each of the technology areas listed. These conclusions are summarized here.

Science requirements- The consensus of the panel was that some of the requirements were system drivers and that they should be closely monitored and reviewed during the course of the LDR program. Also as this evaluation progressed, it became clear that science requirements should really be stated as performance specifications/requirements if the LDR program is to proceed in an orderly manner; that is, to become an overall systems-optimized design for both engineering and cost. This evaluation became evident when the technology panels reported their results.

Interaction matrix- An LDR-technologies interaction matrix was developed by the panel (fig. B-1) to demonstrate the interactions between the 20 technology-development areas identified by the contractors and to call attention to the necessity of a systems perspective for LDR. The sum of interactions for each technology area with the other 19 technology areas is shown on the right side of the diagram. This sum is obtained for each technology area by counting the dots in the diagram starting from the right side, moving horizontally to the left until the diagonal is intersected, then proceeding vertically up. To identify each interaction (as the dots on the horizontal are counted) follow vertically down from the dot to the diagonal then note the technology area for that line to the right; if counting dots on the vertical, the interacting technology area for that dot is noted to the right on that line. For example, in the case of thermal control, 12 interactions are shown. In summing the horizontal dots, they can be identified as follows: the first dot when encountered can be identified by proceeding vertically down from this dot to the diagonal and noting that this line is associated with C & DH. For the vertical dots, the first dot is identified as aperture size. These technology interactions have not been weighted, but highly interactive technologies could be cost drivers. Changes to one technology could have an impact on many other technology areas. This interaction matrix concisely highlights and summarizes the interrelations between technology areas, and shows the possible need to examine those highly interactive technology areas and attempt to quantify these impacts and develop a technology-development strategy before proceeding with LDR design and technology development.

Technology-development priorities- The extensive lists that were developed by the contractors were reviewed by the panel and grouped in the order shown in table B-III. The two most important of the seven areas identified are mirror materials and construction, and controls. The remaining five areas were grouped into two levels of decreasing importance. The assignment of the highest priorities to the selected two areas is obvious when the physical size, mass, and complexity of LDR is considered. As additional technology developments in these areas are undertaken and the problems are better defined, the priorities may change.

Evaluation of the three LDR configurations- Because of the time element, it was possible to do only a cursory evaluation of these configurations. The results are summarized in table B-IV. The design ground rules used by the two contractors were consistent, but differed from those used by JPL. Therefore, only a gross comparison could be made. The design approach taken by JPL was to start with a more general set of requirements (system level performance specifications) to arrive at their conceptual design. The JPL design appears to have a number of questions associated with it (table B-IV), but they could not be quantified since their concept was aired for the first time at this meeting.

Simulation and modeling- The panel recommended that a vigorous effort directed to developing analytical tools be undertaken by the LDR program. It was generally agreed that because of the size and complexity of the LDR, an analytical means of modeling and simulating the response of the system would be invaluable. Figure B-2 shows the varied inputs that should be developed for a valid structures and control (S/C) systems simulation. This area needs to be developed so that LDR parametric studies (e.g., for structures and controls) can be made to help develop a reference concept for an optimal LDR system. In addition, when the program proceeds to phase A and beyond, it will provide the means to quickly and efficiently evaluate contractor concepts and results.

Design and test- The panel attempted to identify those elements in design and test that could have a major impact on LDR. Manufacturing of mirror segments could be a pacing item during the hardware phase if it is not recognized and resolved early in phase C/D or as early as in phase B. Second, the test program must be planned early in the program since the sheer size of LDR precludes a full-scale test on the ground. Tests at the subassembly level need to be judiciously designed. Third, space assembly, refurbishment, and maintenance will certainly require early attention because these activities will place unique design requirements on the LDR and if not properly addressed early could become a program cost driver.

Space assembly, refurbishment, maintenance, and operations- Table B-V highlights some of the major systems concerns the panel has in this area. Out of all these concerns, two items need to be emphasized: 1) interfaces between the Space Station and LDR need early definition, and 2) assembly and science procedures will need early definition, considering that astronaut training and safety are important considerations. In the refurbishment and maintenance area, basic decisions need to be made such as where this activity will occur (e.g., in LDR operational orbit, or at the Space Station), how it will be conducted (by EVA or robotics), what are the orbital dynamics considerations (orbit phasing), and how will LDR be configured during this period. Orbital operations also need early attention to provide basic design input on how the LDR will be operated, what will be its operational orbital altitude, and how it will be maintained, how LDR will respond to emergencies such as loss of communications, will LDR have an automatic safe mode , and how will the maintenance and refurbishment be conducted. This entire area will drive the basic design of LDR and therefore needs to be addressed early.

Scan modulation- Scan modulation (chopping) is required for some LDR observations to reduce the background signal caused by sky background and optics emission. Since chopping can place significant systems design demands on LDR, the chop amplitude, frequency, and mode require careful study.

Previously, a constant chop amplitude (line-of-sight change) of 1 arc min was required along with a frequency of 1-2 Hz. The frequency is not likely to be reducible to a smaller value; the amplitude may be. The question of whether a constant chop is required, or whether the amplitude can vary with wavelength needs to be answered. For example, can the amplitude be proportional to wavelength and instead of being 1 arc min, possibly be only a few pixels (or Airy diameters)? Second, for what fraction of the time is chopping required? If a significant part of the LDR observations are line work and do not require chopping, the mechanical life expectancy of the chopping mechanisms can be significantly greater by not chopping all the time. The panel also feels that specific duty-cycle requirements should be defined.

Because secondary-mirror chopping has traditionally been the preferred method of scan modulation, that method was considered as the baseline for LDR. However, secondary chopping has a number of serious system disadvantages so that alternative methods were suggested by Kodak and LMSC/Itek, as well as by JPL:

1. Unbalanced forces of the secondary drive mechanism, even for "reactionless" chopping, can cause serious vibration input to the secondary support and lead to misalignment and image degradation, particularly since the chopping frequency and the lowest normal modes of the secondary truss are probably about 1-2 Hz.

2. The "pupil-wandering" on the primary associated with secondary chopping can cause a false signal if there are temperature or emissivity differences across the primary. This signal must then be removed by "nodding" the telescope--which may be difficult in terms of control authority and structural damping--or by letting the telescope line-of-sight (LOS) drift by the gravity gradient torques on the system, and then return the LOS to its origin when the edge of the target has been reached. In addition to temperature and emissivity gradients across the primary, there is a varying geometry of the gaps between mirror segments that will be seen by the oscillating pupil which can cause a false signal.

3. The secondary drive may input significant heat which may be difficult to remove and thus compromise the stringent secondary-mirror temperature-control strategy.

4. To avoid serious image deterioration caused by chopping about the vertex (in case of large chopping amplitude), chopping about the neutral point may be required. From a controls point of view, this neutral point chopping is even more difficult to achieve than vertex chopping.

An attractive alternative to secondary chopping is chopping with the quaternary flat in the four-mirror-modified Cassegrain optical configuration proposed by both contractors and JPL. In this approach, the problems associated with pupil wandering on the primary and with the vibration input to the secondary support structure at the near-resonant frequency disappear. Another alternative is to chop inside the instrument package. However, the reservations held by the infrared (IR) science community about chopping farther down in the optical train should be carefully considered and the optical and the mechanical/thermal system effects of quaternary chopping (or chopping inside the instrument package) should be examined for feasibility and practicality.

The feasibility and system impacts should be studied for the optical concept put forth by JPL, namely that which possibly combines wavefront correction and chopping in the same mirror, which is also segmented.

Mirror materials- Requirements for LDR mirror panels are (not necessarily in the order of importance) 1) satisfactory figure and surface quality, 2) light weight (low mass per unit area), 3) rapid fabrication, and 4) low cost. In particular, weight savings in the primary reflector surface (segments) could be magnified by related savings in support structure, and consequently, in inertia of the system, thereby resulting in reduced CMG torque and momentum storage requirements, which all result in mass and electrical-power savings. Furthermore, these savings have a ripple effect throughout the system, affecting nearly all subsystems, and consequently reduce total life-cycle cost (LCC). For example, if the system is weight-constrained, the savings in the primary mirror mass could be translated into added cryogen which in turn would reduce the frequency of cryogen replenishment; i.e., servicing of LDR. This reduction in servicing frequency is significant because servicing is expensive not only in terms of dollars, but also in telescope downtime and in risks associated with servicing. Systems trade-offs (system/trade) studies should be carried out to quantify the relationships between savings in mirror mass and total system impact, including LCC and risk reduction.

Candidate materials for the lightweight primary-mirror segments are: 1) low-expansion glasses (such as fused SiO), 2) composites (such as graphite/polymers, graphite/glass, and carbon/carbon), or 3) Hexcel or foam aluminum-core structures. For each of these candidates, questions on their suitability remain to be answered, such as: 1) Are ultralightweight glass panels (<20 kg/m) too fragile for LDR deployment or assembly? 2) What is the long-term dimensional stability of the graphite/polymer composite in the face of moisture changes or when exposed to high-energy radiation in space? 3) Are there possible contamination effects caused by outgassing of the polymer composites (postlaunch and STS or Space Station environment)? 4) Are there significant hysteresis effects during thermal cycling? 5) What are the problems associated with aluminum sandwich panels (i.e., what effect does venting have during ascent, what effect does anisotropy with Hexcel cores have on figure during manufacturing and maintenance/control, what effect does the high-expansion coefficient of aluminum have when there is a great discrepancy between manufacturing and operating temperatures of the primary mirror and there is a large difference between the coefficient of thermal expansion (CTE) of the panels and the support truss)? and 6) The issue of micrometeorite (and orbital debris) impacts on LDR during its lifetime has been raised--would one segment material have advantages over the others in terms of effects of such impacts?

As a result of these unanswered questions, we propose that technology development of primary-mirror materials focus to accomplish the following:

1. Determine if the ultralightweight-glass fragility issue is real, and if so, determine if this problem will be adequately addressed by Department of Defense

programs so that no significant funds need to be expended by LDR. Acoustic/vibration and other mechanical tests (including handling by astronauts as well as remote manipulation) should be conducted on ultralight glass panels to resolve this issue.

2. Obtain data on anisotropy effects and on the long-term dimensional stability of composites and the effects of the space environment on that stability by accelerated-life test experiments, analysis, and comprehensive survey.

3. Test the performance of metal-core segments (Hexcel or foam) in the vacuum; determine whether the anisotropy of Hexcel structure is a significant issue of manufacturing or maintenance/control of the segment figure. Determine by analysis, simulation, and experiment the dimensional effects between the metal mirror segments and their (low-expansion graphite/xx) support structure.

4. Determine if micrometeorite impacts on mirror panels significantly affect the optical system performance/life and if there are differences between the various candidate materials in this respect.

5. Carry out trades to determine the respective advantages and disadvantages of totally passive versus moderately active mirror panels. For example, it may be possible to use a lightweight and inexpensive material with, say, only focus control instead of another heavier, but passive, segment made of a more expensive material.

Instruments- There was some confusion on the reference number of instruments that LDR will accommodate; is it eight or is it four or three? The panel agreed that with eight instruments, the accommodations could definitely be a systems driver, especially with the stated desires of the scientists for individual dewars for their instruments. There is a definite question as to whether even with individual dewars, the concept of individual instrument change-out would be feasible, because the instrument module sits between the spacecraft and the backside of the primary mirror. Because the module must be designed to react spacecraft control loads, it may not be possible to design access doors without incurring large structural penalties. With individual instrument dewars, the cryogenic system could be extremely complex (with multiple cryogenic lines and connections) and servicing from a central cryogenic source may not be feasible. Therefore, each instrument will need to supply its own cryogen, leading to the question whether adequate storage space will be available. Orbital servicing of multiple cryogenic storage tanks could be a problem. The use of mechanical refrigerators is being considered, but this technology is not space-qualified nor proven for the levels of cooling required by LDR and thus requires development. A potential drawback of this technology is the vibration during its operation. Another potential systems problem may be the high power (3 kW) requirements of the science instruments. While 3 kW may not seem like much, by the time provisions are made for solar-panel degradation and for battery charging and power-conditioning losses, there is a major impact on the power system. Approximately 9 kW of solar-array power at the beginning of life is needed. Also battery power at these levels has not been designed and needs to be developed. The LDR may be forced into some other source of power.

The instrument concerns are summarized as follows:

1. Interface--accommodations

2. Servicing--refurbishment/replacement

3. Single dewar versus multiple dewars

4. Cryogenic--instrument/facility (cryogenic lines and connections)

5. Bending loads--impact on control loads

6. Power (electrical

   a. ~3 kW (peak)
      Solar array and battery

   b. ~9 kW beginning of life ≈ 100 m^2

Other programs that benefit LDR- Table B-VIII provides a summary of some other national programs whose technology development efforts may be of benefit to the LDR program, and these programs should be monitored by the LDR program.

Proposed future systems studies- When the panel completed its review and deliberations of the contractors' (Kodak and LMSC/Itek) defined technology development lists, it took on the task of identifying future systems studies that would be beneficial to the LDR program. The list of identified studies includes: point design(s) for LDR concept, primary-mirror mass; instrument accommodation concepts; orbits/flight mechanics; performance specifications (e.g., noise equivalent power); contamination (assembly, operations, servicing); optical forms (chopping); dynamic isolation; instrument servicing and replacement; pointing and control; assembly requirements, procedures, and options; redundancy; and simulation and modeling (analytic). This list is not prioritized. The panel assigned the highest priority to developing a set of LDR system performance specifications/requirements, the next highest to the identification of a reference/point design concept for LDR through a system design study using the performance specifications, and the third highest to the development of simulation and modeling tools. The list is provided as a starting point for developing a more systems-oriented LDR program.

Potential technology development benefits- A well-thought-out and well-conducted technology development program as complex and as large as LDR has certain key, qualitative, programmatic benefits, including: reduced program risk (design confidence); avoided schedule delays and cost escalations; enhanced program cost estimates (believable); provided possibility for system optimization; discovered performance breakthroughs; avoided program difficulties (figs. B-1 and B-2). The Systems panel was not able to assign quantitative values to the benefits that could be accrued from technology development funds provided for those areas identified by the contractors in the current LDR studies. But it is obvious that there will be benefits; therefore, this qualitative summary of benefits has been assembled.

Conclusions and Recommendations

The lists of technology development areas and priorities identified by the two contractors are comprehensive and were a good starting point for this workshop. The individual technology panels further developed these lists and reordered some of the development priorities. The outcome of this effort is the identification of a substantial development budget requirement if development work was to begin on all or a large part of the identified technology areas. This level of funding is probably unrealistic programmatically for NASA; therefore, the Systems Panel makes the following recommendations to ensure maximum return to the LDR program from the limited technology development funds that will be available:

1. Continue funding for the generic types of technology developments currently being funded, along with as many of the high-priority technology development areas that are identified by this workshop (e.g., mirror materials, controls, and heterodyne detectors).

2. Develop a set of consistent performance requirements for LDR to replace the current conglomeration of science and engineering specifications being used.

3. Conduct a systems trade study using the performance requirements from item 2 to develop a reference design for LDR. This activity will provide the basis to help focus the technology development program and also provide a solid basis for identifying a realistic development schedule for the LDR project.

4. Fund development of tools for analytically studying and verifying LDR systems and subsystems concepts (essential because LDR is a large and complex observatory). It is anticipated that much of LDR will be practical only for analytical verification because of its size and mass; therefore, development of a comprehensive set of analytical modeling and simulation software should be started.

TABLE B-I.- SYSTEMS AND SIMULATIONS PANEL MEMBERS

D. Agnew	Eastman Kodak Company
L. Bandermann	Lockheed Missiles & Space Co.
D. Burrowbridge	Fairchild Space Company
B. Garrett	NASA Langley Research Center
K. Gupta	Ames Research Center
W. Irace	Jet Propulsion Laboratory
V. Maksimovic	NASA Headquarters
M. Nein	Marshal Space Flight Center
K. Nishioka	Ames Research Center
J. Ransom	Aerospace Corporation
P. Repak	Rome Air Development Center (RADC)
F. Runge	McDonnell-Douglas Aircraft Co.
R. Russell	Langley Research Center
R. Schaupp	Ames Research Center
R. Sharp	Lewis Research Center
P. Swanson	Jet Propulsion Laboratory
J. Wong	Air Force Space Division

TABLE B-II.- SYSTEMS ISSUES

1.	Science requirements
2.	Development of technology interaction matrix
3.	Technology development priority
4.	Evaluation of the three LDR configurations
5.	Simulation and modeling
6.	Design and test
7.	Space assembly, refurbishment, maintenance, and operations
8.	Scan modulation
9.	Mirror materials
10.	Instruments

TABLE B-III.- TECHNOLOGY-DEVELOPMENT PRIORITY LIST

Priority rating	List
I. Immediate	Mirror materials and construction
	Controls:
	Figure
	Structures
	Pointing
	Sensing
II. Near future	Instrument cooling:
	Stored cryogens
	Mechanical refrigerators
	Resupply
	Assembly and servicing by astronauts
III. Future	Spatial-chopping techniques
	Contamination:
	Primary mirror
	Thermal surfaces
	Robotics/teleoperation:
	Assembly
	Servicing
	Resupply
	Configuration-dependent issues:
	Thermal control
	Sun shield
	Optical design

TABLE B-IV.- CONFIGURATION COMPARISON

<u>General differences</u>
Science requirements - design
Number of instruments
Exclusion angles
Servicing
Sunshade
<u>General similarities</u>
Primary optics
<u>Specific design questions</u>
JPL (contractor design as baseline)
Instrument change out (more difficult)
Composite (life/outgassing)
Registration while chopping
Lower mass provides control gain
Preassemble for alignment control
Improved temperature variations

TABLE B-V.- SPACE ASSEMBLY, REFURBISHMENT, MAINTENANCE, AND OPERATIONS

1. Assembly versus deploy: system studies
2. Shuttle
    - Launches
        - Back-to-back critical
    - Basic carrier spacecraft
        - "Building crane"; e.g., leasecraft, aft cargo carrier
    - Assembly schedule critical
3. Space Station
    - Multiple Shuttle launches
    - Drive Space Station manipulator capabilities
    - Internal control rack required
    - Temporary storage
        - Components
4. Assembly
    - Cold components
    - Preassemble instrument and components
    - Alignment and checkout (integrated alignment jigs)
    - Protective coating removal
    - Damage during assembly
    - Possible protective enclosure
    - Solar incidence (astronaut safety)
    - Illumination/temperature control
5. Human factors
    - Crew training
    - EVA
    - Safety
6. Constraints
    - Flight dynamics
    - Contamination
    - Environmental
    - Emergencies
    - Astronaut support
    - Station keeping
    - Reboost
    - Docking
7. Design
    - Make modular hardware repartition redundancy
8. Develop operations plan and identify technology impact
9. Identify refurbishment and maintenance schedule for components/modules
10. Conduct systems trades including cost versus component life
11. Redundancy

TABLE B-V.- CONCLUDED

12. Instruments
    - Replacement schedule
    - Refurbishment
        - Scheduled/emergency
    - Interface
13. Constraints
    - Robotics
    - Manned EVA
    - Contamination
    - Altitude/location on-orbit, STS, or Space Station
    - Space Station, STS, OMV capabilities, orbit phasing
    - Safing LDR for refurbishment and maintenance
    - Modeling and configuration control
14. Develop operations plan
15. Altitude
    - Transportation
    - Refurbishment and maintenance
16. Emergencies, contingencies
    - Safing - Automatic system protection
    - Back-up communication
    - Reacquire control
17. Communication
    - TDRSS
        - Limited access
    - Command and control
    - Data handling

TABLE B-VI.- SCAN MODULATION

1. Chopping requirements to be reexamined.
   - Amplitude (function of wavelength?)?
   - Duty cycle?
   - Percentage of time required?
2. Secondary chopping beset with difficulties.
   - Imbalance causes vibration input to secondary support truss (near resonant frequency)
   - Heat input by secondary drive
   - False signal caused by beam wandering on primary (difficult to remove)
3. Quaternary flat chopping viable alternate method needs examination.
   - JPL method of wavefront correction and chopping with quaternary appealing, but potential problems

TABLE B-VII.- MIRROR MATERIALS

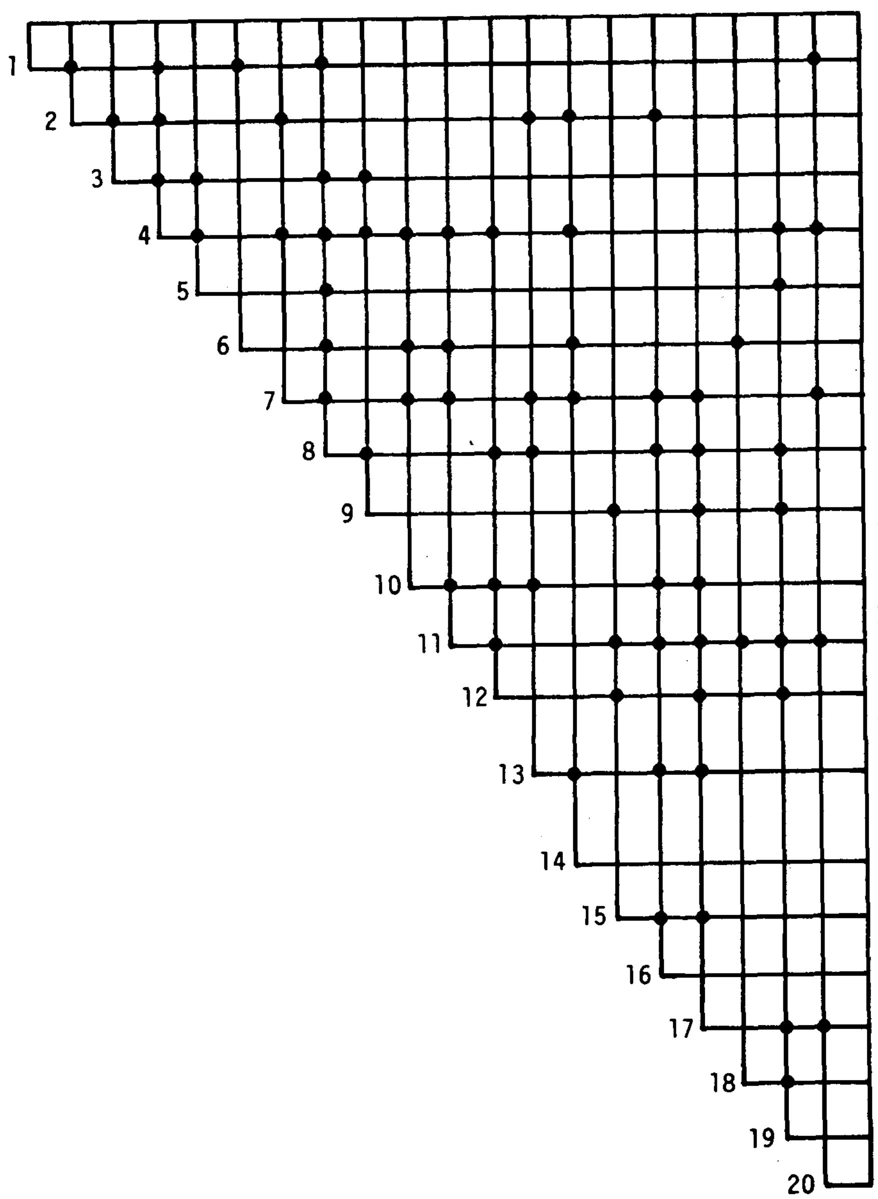
1. Candidates for ultralight primary-mirror panels
   - Ultralow-expansion glass (e.g., SiO_2)
   - Composites (Gr/polymers; Gr/glass; C-C)
   - Aluminum (Hexcel, foam core)
2. Concerns about the candidates
   - Fragility (glass)
   - Long-term stability (Gr/polymers)
   - Outgassing (Gr/polymers)
   - Anisotropy (composites, Hexcel)
   - Venting (Hexcel, Al foam)
3. Recommend addressing these concerns in near term
4. Decision point on materials selection needed as soon as possible because of significant system impact

TABLE B-VIII.- NOMENCLATURE OF LDR TECHNOLOGY INTERACTION WITH OTHER SYSTEMS

1. Optics materials
   - Rapid optical fabrication techniques
   - Lightweight mirror technology programs (space defense initiative (SDI) and space based laser (SBL))
   - Long duration exposure facility - optics materials
2. Dynamic structural control
   - Composite optical system structure
   - Passive and active control of space structures
   - Reliability for satellite equipment in environmental vibration
   - Air Force Office of Scientific Research - Visco-elastic damping
   - Space Station
   - SDI - Vibration control/attitude control
   - High attitude, large optics - Lockheed/Itek structure subtask
3. Actuators and sensors/figure control
   - Optical testbed for evaluation of control algorithms (RADC)
   - Large active mirror program
   - Keck telescope
   - National new technology telescope
   - "Relay" R&D program
   - Rapid optical fabrication techniques - active figure control, negative figuring
4. Fine guidence/active image stabilization
   - Updated fine guidance sensor - Talon Gold
   - ASTRO
   - SIRTF
5. Secondary-mirror control and metering
   - Space telescope
   - Composite optical system structure
   - Large optical demonstration experiment (now an inactive program - in hold status at Air Force Weapons Laboratory (AFWL))
   - Space based laser
6. Secondary temperature control
   - SIRTF
   - DOD
7. Chopping
   - SIRTF
   - SDI
8. Cryogenics
   - DOD - AFWL (Albuquerque), SDI, SBL, space surveillance tracking system
   - NASA Goddard Space Flight Center (Phillps Stirling Mechanical and Adiabatic DeMagnetization Refrig.)
   - JPL (Lanthanum Pentanickel Hybrid Absorption Cycle)
   - SIRTF (Replenishment at Space Shuttle/Station)

TABLE B-VIII.- CONCLUDED

9. Human factors
    - Space Station
    - Experimental assembly of structures in EVA
    - Assembly concept for construction of erectable space structure by EVA
    - DOD
10. Incremental buildup in space/deployment
    - Space Station deployment
    - Multi-mission spacecraft flight support hardware development
    - NASA Langley mast development
    - Space Station program
    - SDI
11. Environmental protection
    - DOD - Space based laser/phased arrays



Technology Areas	No. of Interactions
1. Orbit	5
2. Transport	7
3. Assembly/Deploy.	5
4. Servicing	13
5. Optics Configuration	4
6. Mission Profile	6
7. Aperture Size	10
8. Thermal Control	12
9. Cryo	6
10. Alignment and Figure Control	8
11. Pointing/Tracking	11
12. Chopping	7
13. Mirror Materials and Fabrication	7
14. Environmental and Contamination Control	5
15. Vibration Control	5
16. Structural Materials	7
17. Test and Verification	10
18. C&DH	3
19. Instrument Interface	8
20. Straylight	5

Figure B-1.- Technology interaction matrix.

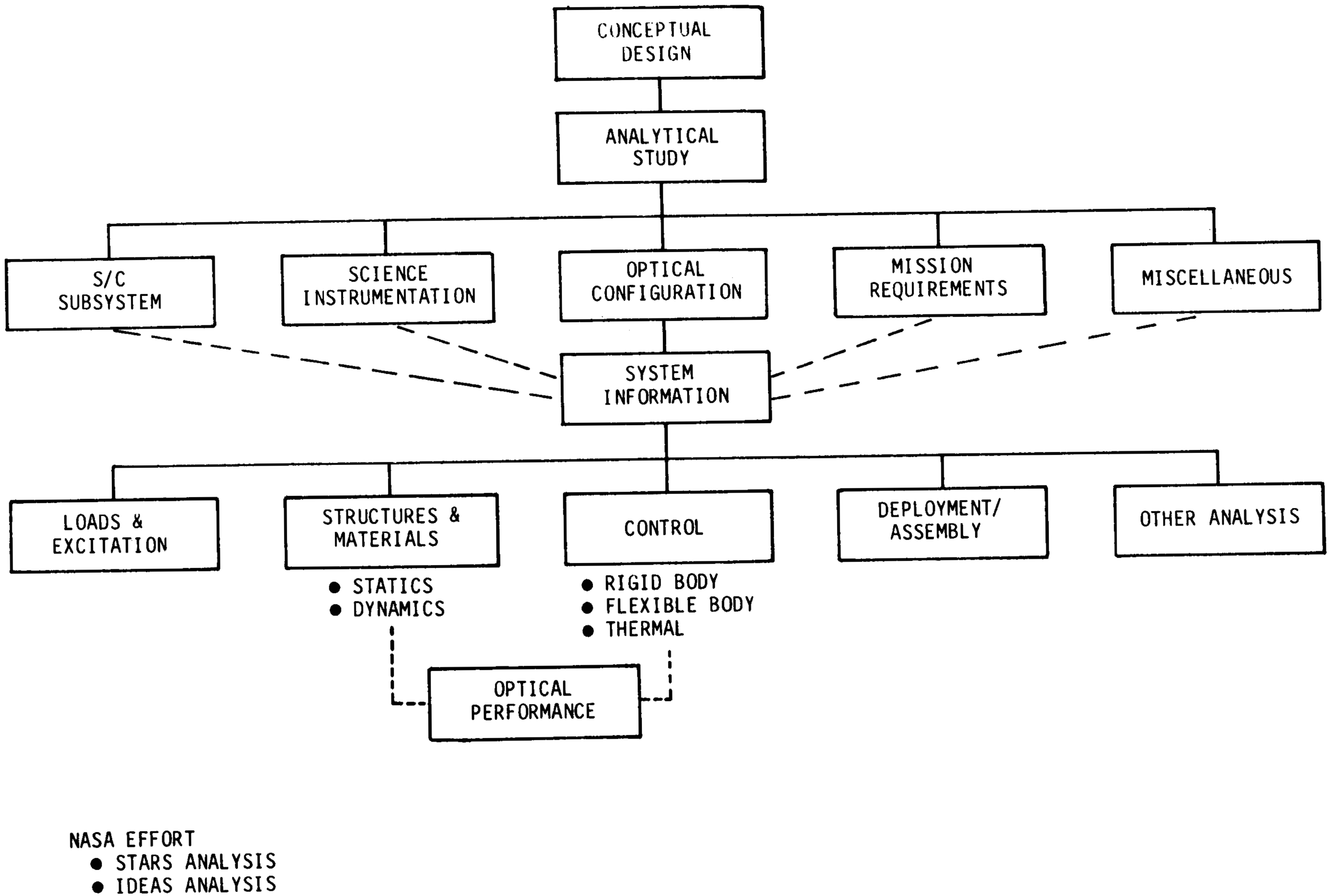


Figure B-2.- LDR - systems simulations.

APPENDIX C

SENSING AND CONTROL PANEL REPORT

Introduction

Sensing and control will constitute a major subsystem of the LDR and will be critical to its success. The subsystem must perform the following functions:

1. Provide slewing and pointing control of the entire telescope to subarc second accuracy: 0.05 arc sec (absolute), 0.02 arc sec jitter.

2. Provide active alignment, figure, and vibration control of a large (~20-m) optical system to tolerances of 1 μm.

3. Make the initial alignment of the optical system following deployment and periodically verify and adjust system alignment and optical performance during use.

The three major subsystems of the LDR control system needed to achieve these functions are telescope pointing, wavefront and figure sensing and control, and telescope calibration and wavefront control. Figure C-1 shows a representative control approach and the interrelationship among these subsystems for a direct behind-the-primary figure control implementation. Figure C-2 shows an alternate approach based on implementing the figure control at a much smaller quaternary optical element.

Although listed separately for purposes of discussion, these functions/subsystems are interrelated and also are closely connected to other parts of the system. This close interaction will require that development in all of these areas go forward simultaneously, and because of technical uncertainties, the work to meet these challenges should be undertaken as soon as possible.

It is particularly important that sensor, actuator, and control analysis and synthesis technologies be developed well in advance of any decision on the final LDR configuration. There are many critical system trades (such as the size of primary-reflector segments versus the number of actuators required) that can be made only if the sensing and control system technology is well understood.

There are a number of sensing and control techniques of potential application to LDR. Many of these techniques have been demonstrated in the laboratory, a few of them have been used in flight programs, but none of them has been applied to a system the size and complexity of LDR. The state of the art with respect to the various major functions of the sensing and control system is summarized in the following sections.

Sensing and Control Technology Needs and Status

Telescope Pointing- Although the requirements for pointing and tracking of the LDR will be numerically less demanding than those of the Space Telescope (ST), which will precede it in space, the size and flexibility of LDR will, in fact, make the pointing task the most demanding yet to be faced.

Part of the necessary pointing technology for LDR will be provided by the high-precision attitude-control techniques of the Space Infrared Telescope Facility (SIRTF) and ST. Specifically, attitude will be sensed by a combination of internal inertial reference and star tracking. Star tracking must be done with visible or near-visible wavelengths to achieve a suitable signal-to-noise ratio. Star tracking may be done either by a separate telescope or by a subaperture figured to visible-light tolerances. If a separate telescope is used, it is likely to have an optical aperture significantly larger than those used in other systems to achieve offset pointing from faint guide stars. Advanced solid-state star trackers and low-drift gyros are needed to meet the 0.05 arc sec accuracy and 0.02 arc sec jitter requirements.

Other aspects of the system are much less developed and understood. The attitude information, having been sensed, must be related to the focal plane of the main telescope. Since the main instrument is flexible, this transfer involves the systems used to sense and control the figure of the primary reflector and the position and orientation of the secondary mirror. Although there is some knowledge of how to make attitude transfers for optical systems consisting of rigid elements, making such transfers in systems with nonrigid elements will require the development of significant new technology for a suitable integrated opto-mechanical measurement and transfer system.

Stabilization of the entire LDR spacecraft to the low jitter levels needed for successful data taking will require nonimpulsive momentum transfer, using large CMGs (these must be large to control the large telescope and meet slewing requirements). Long life and ultraquiet operation are required. It will probably be necessary to provide a high degree of vibration isolation between the CMGs and the telescope structure.

Wavefront and Figure Sensing and Control- This function maintains the optical performance of the telescope by maintaining the quality of the wavefront. Since LDR must observe weak or diffuse sources, wavefront sensing cannot be a continuous process. Instead, periodic observations must be made of a bright, point-like astronomical source so that the wavefront within the instrument can be observed and the position and figure of the optical elements adjusted to bring the wavevfront quality to an acceptable level. It is then necessary to sense and control the position and figure of the optical elements using on-board sensors and actuators to maintain telescope performance throughout the subsequent observation period. At intervals it will be necessary to return to a point astronomical source and repeat the recalibration process.

The wavefront error can be corrected at more than one location in the optical system. Since the primary mirror is the chief source of error, the correction can be applied to its segments. Alternatively, the primary mirror can be reimaged at the exit pupil of the system and the correction applied to the segments of a mirror in this location. Although the area of wavefront sensing and control has progressed significantly in recent years, LDR will require considerable technology development to achieve: (1) a space-qualifiable system capable of sensing the large number of points required by LDR; (2) reliable figure actuators which can be made in large numbers (200-500) at reasonable cost; (3) control algorithms (and processing capabilities) to handle the data from many points simultaneously; and (4) precise LDR dynamic models and the technology to update them in flight.

There are two general approaches to the sensing of segment position. One is global in which the locations are measured from a central location by triangulation, trilateralization, interferometry, or similar techniques. The other is the local or edge-sensing technique in which the position of a segment with respect to its neighbors is measured by sensing the relative position of their edges. These techniques exist in the laboratory. The extension to a space-qualifiable system capable of handling the large number of points needed by LDR will require considerable technological development.

The control algorithms needed for the large number of degrees of freedom encountered in the figure-control task will be a significant extension beyond anything done to date, and a substantial increase in space-qualified computing capacity will be required. The need for accurate LDR dynamic models will require on-board system identification and adaptive control technology development to update the models in flight and carry out the necessary control-system corrections autonomously.

Important system tradeoffs will be involved in this area. For example, the tradeoff between the precision with which the system deploys and the ability of the sensing and control system to handle the initial misalignment. In a similar way there is another tradeoff between the cost of providing high surface quality on the segments, thus allowing calibration of the telescope at shorter wavelengths using existing techniques, versus the cost of developing wavefront sensing at longer wavelengths.

<u>Attitude-Figure-Wavefront Sensing and Control Integration</u>- Another significant technology issue is the incorporation of the attitude-, figure-, and wavefront-sensing control functions into the required overall telescope pointing and stabilization function. Technology development is necessary in this area covering a wide range of technology needs, from basic principles to demonstration of the concept consisting, as a minimum of: (1) development of extensive analytical simulation tools that integrate control, structure, and electromagnetic models, and (2) laboratory-scaled proof of concept to demonstrate functional capability, and correlation of actual and predicted performance to validate analysis and simulation tools.

LDR Control Technology Development Plan

This technology development plan was prepared by the Sensing and Control Panel based on the inputs made by the contractors in their final presentations and reports, as well as on individual follow-up discussions held with their technical representatives at the workshop.

Table C-I summarizes the seven key technology areas which were identified as critical to LDR, along with the independent priority assessments made by the contractors and by this panel (ranked as high and medium priorities). Each of these technology needs is discussed in the following sections.

Dynamic Control Technology- The stringent-pointing and low-jitter requirements of the LDR will require new design methodology for vibration and jitter beyond the state of the art. This design would include the active and passive damping of system dynamics, as well as the isolation of dynamic contamination sources. Experience in the Space Telescope Program indicates this area to be critical and it is expected that the area will be even more critical to LDR. Technology development in this area was considered to have the highest priority (fig. C-3).

Analytical Modeling/Performance Prediction- One of the key elements to a successful LDR operation is the development of accurate analytical tools for modeling the controls, optics, and structures components and assessing system and subsystem performance. Such tools are needed early in the project to study system-configuration alternatives, develop system requirements, and study subsystem interactions. As the project progresses, such tools are used to define the control-system parameters, assess the impact of design changes, and develop confidence in the overall success of the mission.

The crucial problem lies in the accuracy of modeling which must be achieved for LDR relative to the present state of the art. Active structural control requires accurate knowledge of system mode shapes, frequencies, and damping. Vibration suppression will require accurate characterization of the disturbance sources (e.g., CMG noise, sensor/actuator noise, external environmental disturbances). Design and testing of the system will require integration of all of these models into an overall framework which considers the interactions between the subsystems.

Current state of the art does not require modeling to the degree of accuracy needed for LDR. Vibration of the structural modes are passively damped or otherwise isolated from disturbance sources, and the performance requirements of present systems do not require the accurate knowledge of precise system alignments, such as is required in LDR (fig. C-4).

Wavefront/Figure Control- The size and flexibility of the LDR structure requires active wavefront control. The science observations are often carried out on weak objects, which precludes direct control by observation of the incident wavefront during periods of observation and forces a two-step process. At intervals it will be necessary to observe bright objects with the telescope and sense and correct the wavefront error by adjusting the system optical configuration. Between these intervals this alignment must be actively maintained by on-board sensors and actuators.

Wavefront sensing and configuration control is being done with systems much smaller than LDR. To meet the needs of LDR in this area, it will be necessary to select those approaches best suited to the LDR requirements, test the critical technologies, and design and fabricate an experiment on a scale large enough to demonstrate that these sensing and control functions can be provided in an operating LDR (fig. C-5). The proposed program would bring the technology to Level 4 (critical function demonstrated).

Fine-Line-of-Sight Guidance/Offset Pointing- LDR has stringent requirements on both pointing accuracy and stability. The structure is flexible and subject to both external and internal disturbances, particularly those of chopping. The telescope does not operate at visible wavelengths, and much of the science must be done with faint or diffused objects. Therefore, the system must be fitted with a high-precision visible-star sensor together with the means of transferring the line of sight established by the sensor to the science focal plane, with the necessary angular offset between the line of sight to the guide star seen by the tracker and of the line of sight to the object being observed.

Offset pointing and line-of-sight transfer have been demonstrated in laboratory experiments, but nothing has been done on the scale required for LDR (fig. C-6). The proposed program would establish a conceptual design, demonstrate the critical technologies, develop the necessary algorithms, and bring the development to that of Level 4 (critical function demonstrated).

Chopping Mechanisms- Infrared astronomy performed with Cassegrain-type telescopes is unique in its requirement for "chopping" the secondary mirror for the purpose of background noise subtraction. Although actively controlled monolithic mirrors have been and are being constructed for a number of challenging applications, including flight programs, infrared astronomy needs tend to push the state of the art, particularly in terms of agility, accuracy, balance, and power consumption. If the current LDR baseline design and performance requirements remain unmodified, technology will have to be advanced on at least three of these fronts when compared to nearer-term applications such as SIRTF.

Current design concepts call for matching the dynamic moment of inertia of the secondary mirror with a reaction mass to cancel as much as possible disturbances entering into the telescope structure from this source. Present practices will produce a net imbalance of a few tenths of a percent of the mirror moment of inertia, a number which causes concern, but is likely to be acceptable for 1-m-class instruments. If it is assumed that a squared/cubed power law holds approximately for the scaling between structural stiffness and mass, then it can be seen that this potential disturbance source will be much more important for the structure of a 20-m-class telescope. Similar arguments can be applied to estimates of actuator power requirements (fig. C-7).

Not only is the telescope structural flexibility of LDR a concern, but so is the secondary-mirror flexibility since it may be in the 2-m class itself. The possibility that secondary-mirror structural modes (or segmented quaternary modes) may be within the mirror controller bandwidth is a problem that is unlikely to be addressed prior to LDR and will directly affect the risk of not meeting mission requirements.

At the time of this assessment it is recognized by the Sensing and Controls Technology panel that the scientific justification for secondary chopping is under active debate and may be substantially altered in the operational time frame of LDR. If this proves to be true, then the relative priority of this technology item should be reviewed.

Control Technology Integration Brassboard- Inherent to the successful performance of a system as complex as the LDR will be the operational compatibility of a number of control systems. In addition to the controls commonly associated with astronomical systems, such as pointing and focusing, the large size and flexibility inherent in the LDR concept will require figure sensing and control of the segmented primary mirror (or of a segmented mirror optically conjugate to it), as well as dynamic alignment. In addition, the mediation of the effects of vibration, perhaps including active damping, will be an important function.

The integration of the control technologies related to these functions is seen as a critical step in proceeding to a full-scale LDR. The elements of this integration include: (1) the use of analytical models and computer simulations for predicting the performance of the various control systems, each in the presence of all the others and subject to their influences, and (2) a ground-based test bed for evaluating the integrated control hardware and algorithms in a scaled proof-of-concept demonstration. Test results would be used both to iterate the models, enhancing their reliability, and to fine-tune each of the sensor/control technologies (fig. C-8).

The test bed would also provide a means of evaluating alternative realizations of the same control function, if such comparisons were found to be desirable. Thus, for example, capacitive versus inductive devices might be compared as edge-sensing approaches to figure control.

Controls Flight Demonstration- Flight demonstrations are justified for issues involving mission-critical technology which are not possible or feasible to address in ground-based experiments. The issues falling in this category for LDR control systems are related primarily to the interaction of controls and structures in vacuum and under gravity release (fig. C-9).

To design a pointing and control system capable of meeting LDR's challenging performance requirements which is efficient in terms of mass, power usage, and complexity, it is important to accurately determine the damping characteristics of a structure which represents as closely as possible the final flight article. Determination of the damping characteristics is also important for performance prediction, through simulation, of the LDR design. Unfortunately the inherent damping of most structural shapes for small displacements and velocities is poorly modeled, not easily measured in the laboratory, and known to change in vacuum.

Other characteristics of complex structures which affect overall system dynamics fall in the category of nonlinear phenomena. Examples which are expected to be important for LDR include dead bands in joints and hinges, hysteresis in bolted or pinned joints, and thermal "creak." These phenomena are expected to be important not only because they are poorly characterized in terms of mathematical models, but also because they are likely to dominate the small-scale dynamics which will determine the capability of meeting the accuracy and stability requirements.

Similarly, the disturbances and interactions associated with the large, active mirror segments should properly be measured beyond the influence of gravity. Experimental verification of the control of these disturbances must also await an on-orbit flight demonstration.

Technology Development Schedule and Funding

The overall schedule and recommended funding for the sensing and control technology development plan is summarized in table C-II. The tasks are phased so that the first five support the last two. This assignment is particularly important with the first two tasks, the dynamic-control technology, and analytical-modeling and performance-prediction tasks, which support the brassboard and flight demonstration from the early phases of the development. The remaining tasks--wavefront/figure control, fine line-of-sight guidance and offset pointing, and chopping devices--feeding requirements into the two demonstration tasks during the early phases, can then proceed in parallel until the third year, when they begin to interact strongly with the brassboard and flight demonstration.

TABLE C-I.- SENSING AND CONTROL TECHNOLOGY NEEDS SUMMARY

Technology need	Priority[a] Panel	Kodak	LMSC
Dynamic-control technology	H	H	H
Jitter/structural dynamics			
Vibration isolation (equipment, CMGs)			
Active control			
Passive damping			
Analytical modeling/performance prediction	H	-	-
Components, dynamics, disturbances			
System identification			
Wavefront/figure control	H	M	M
Sensors and actuators			
Fine line-of-sight guidance and offset pointing	M	M	L
Chopping devices	M	M	M
Control technology integration brassboard	H	-	H
Ground-based proof of concept			
Model iterations			
Flight-controls demonstration	M	-	M

[a]H = high, M = medium, and L = low.

TABLE C-II.- SENSING AND CONTROL TECHNOLOGY DEVELOPMENT PLAN FUNDING SUMMARY

Task	Fiscal year funding, K$ 87	88	89	90	91
Dynamic control technology	200	300	450	450	--
Analytical modeling/performance prediction	100	150	250	100	--
Wavefront/figure control	200	700	1200	600	--
Fine line-of-sight guidance and offset pointing	200	300	500	500	--
Chopping devices	100	250	250	200	--
Control-technology integration brassboard	300	1000	1500	2000	2000
Flight-controls demonstration	100	1400	4000	5000	4000
Total	1200	4100	8150	8850	6000

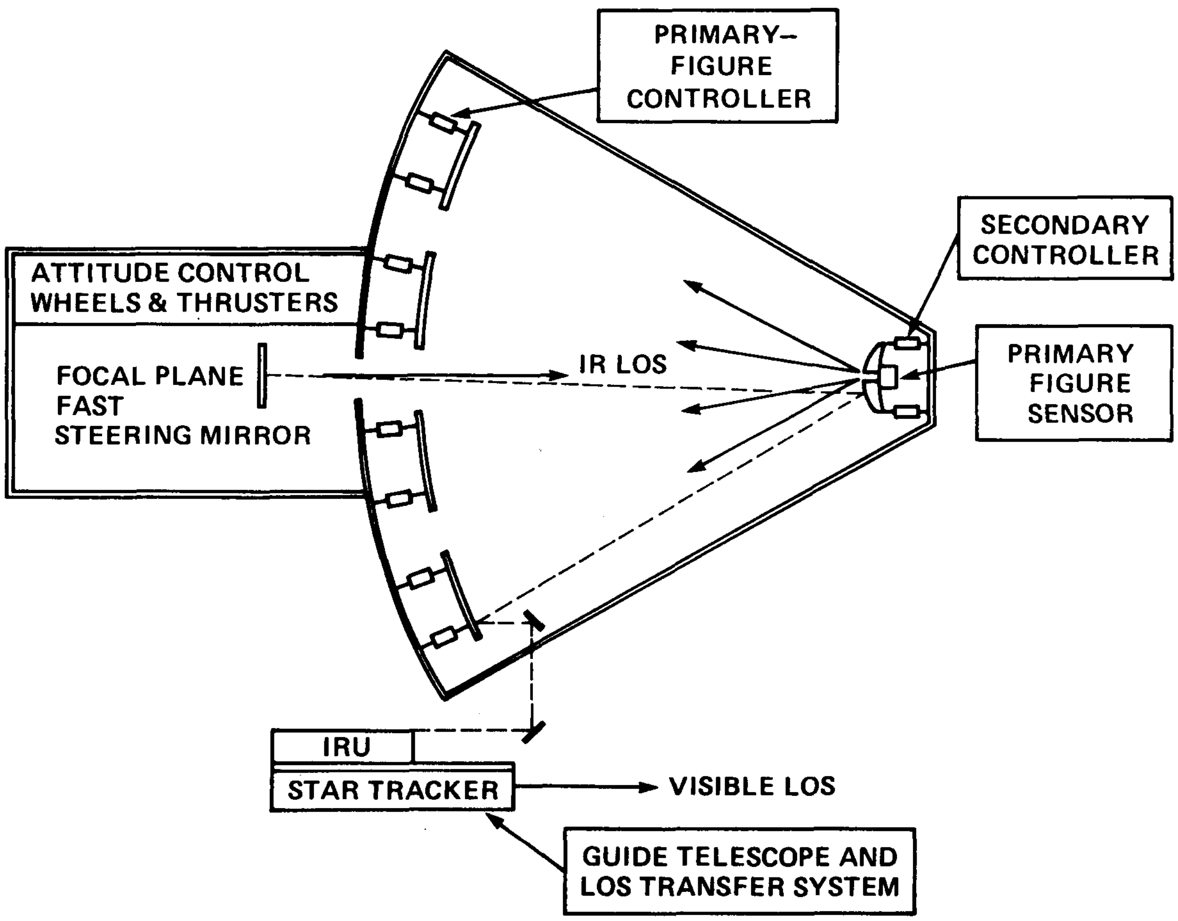


Figure C-1.- LDR representative control approach.

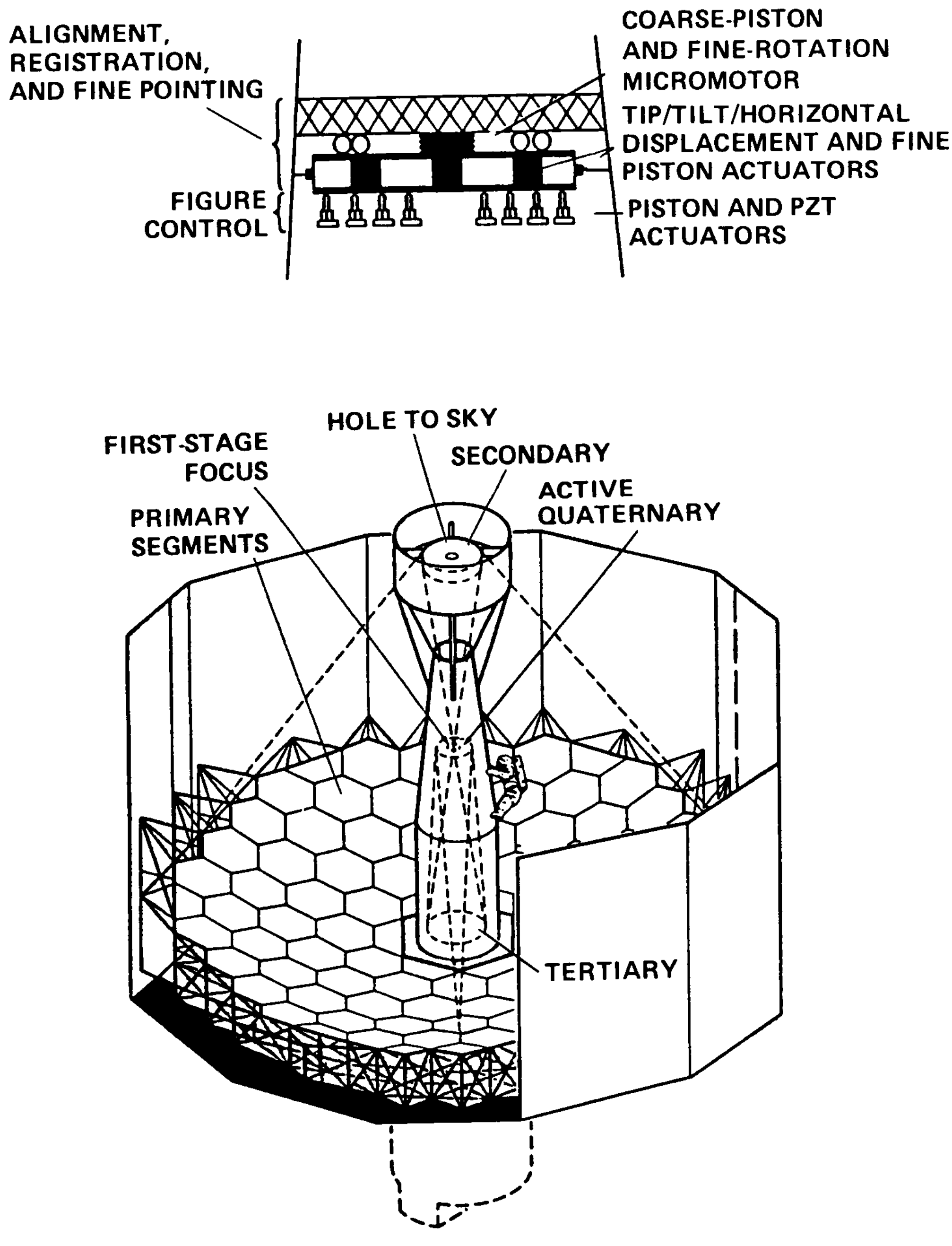


Figure C-2.- LDR quaternary figure control approach.

PROBLEM/REQUIREMENT/GOAL

KEY ISSUES

- CONTROL DESIGN METHODOLOGY FOR VIBRATION CONTROL, INCLUDING ACTIVE AND PASSIVE DAMPING, AND VIBRATION ISOLATION OF COMPLEX SYSTEMS

OBJECTIVES

- DEVELOP APPROPRIATE DESIGN METHODOLOGY FOR CONTROL AND ISOLATION
- COORDINATE WITH MECHANISMS AND MATERIALS WORK IN STRUCTURES AND PASSIVE DAMPING

RATIONALE/TRACE/PERSPECTIVE

RATIONALE

- HIGH PERFORMANCE NEEDED IN THE PRESENCE OF CONTROLS/STRUCTURAL INTERACTIONS, ACTUATOR NOISE, AND NONLINEARITIES
- SLEW REQUIREMENTS CREATE JITTER PROBLEM WITHOUT VIBRATIONAL CONTROL

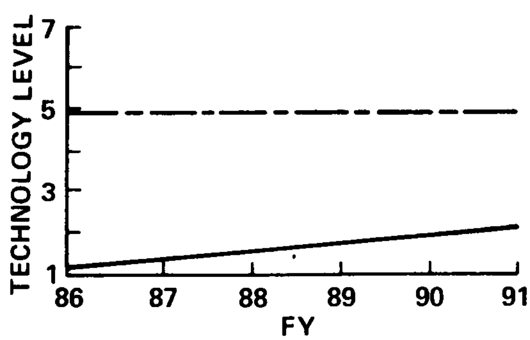
ALTERNATIVES

- NONE

RISKS

- INCREASED SETTLING TIME WITHOUT ACTIVE CONTROL MAY SEVERELY IMPACT MISSION TAKE

SOA EVALUATION AND PROJECTION



DEVELOPMENT PLAN

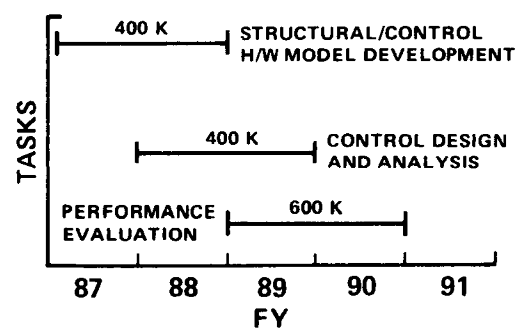


Figure C-3.- Dynamic control technology.

PROBLEM/REQUIREMENT/GOAL

KEY ISSUES

- ACCURATE MODELING AND PERFORMANCE ASSESSMENT OF COMPLEX SYSTEMS ENTAILING CONTROLS, OPTICS, AND STRUCTURES SUBJECT TO RANDOM DISTURBANCES IS REQUIRED

OBJECTIVES

- DEVELOPMENT OF MODELING/ANALYSIS TOOL REQUIREMENTS AND ASSESSMENT OF EXISTING TOOLS
- DEVELOPMENT OF APPROPRIATE MODELING/ANALYSIS TOOL ENHANCEMENT
- DEMONSTRATION OF NEW EVALUATION METHODOLOGY

RATIONALE/TRACE/PERSPECTIVE

RATIONALE

- INCREASED CONFIDENCE IN DESIGN
- SHORTER DESIGN/EVALUATION/TEST CYCLES
- INCREASED SYSTEM PERFORMANCE

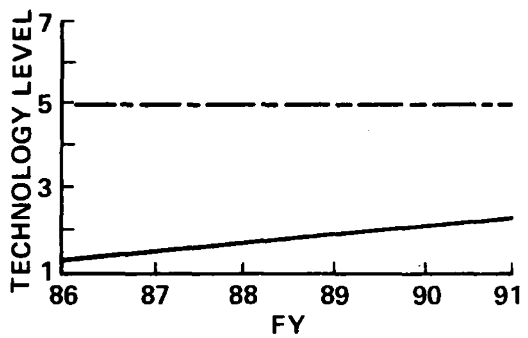
ALTERNATIVES

- EXTENSIVE GROUND AND FLIGHT TESTING

RISK

- RISK OF NOT MEETING PERFORMANCE OBJECTIVES

SOA EVALUATION AND PROJECTION



DEVELOPMENT PLAN

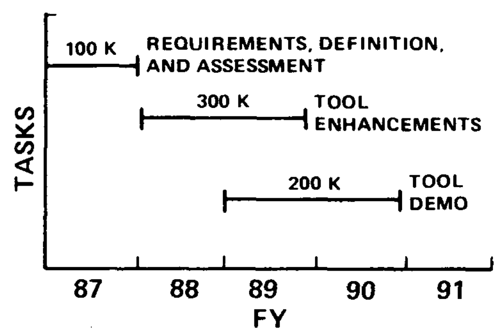


Figure C-4.- Analytical modeling/performance prediction.

PROBLEM/REQUIREMENT/GOAL

KEY ISSUES

- THE FLEXIBLE NATURE OF LDR REQUIRES ACTIVE CONTROL OF THE OPTICAL FIGURE TO ACHIEVE REQUIRED PERFORMANCE
- THE SENSING AND CONTROL TECHNOLOGY HAS ONLY BEEN DEMONSTRATED ON A MUCH SMALLER SCALE THAN LDR

OBJECTIVE

- DEVELOP AND DEMONSTRATE A CONTROL APPROACH THAT INSURES THE QUALITY OF THE WAVEFRONT THROUGHOUT AN OBSERVATION PERIOD

RATIONALE/TRACE/PERSPECTIVE

RATIONALE

- SIZE AND FLEXIBILITY OF STRUCTURE FORCES WAVEFRONT CONTROL
- SCIENCE REQUIRES FAINT-OBJECT OBSERVATIONS

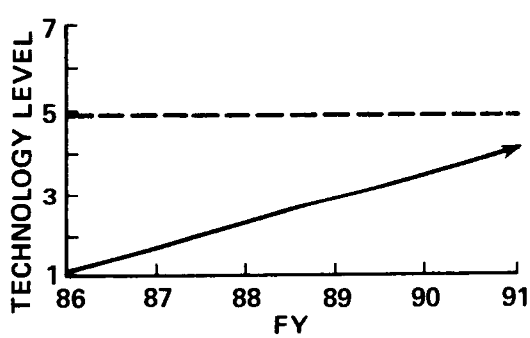
  TWO-STEP APPROACH REQUIRED

  - OBSERVE BRIGHT SOURCE AND CORRECT WAVEFRONT BY ADJUSTING CONFIGURATION
  - USE ONBOARD SENSORS AND CONTROLLERS TO MAINTAIN CONFIGURATION DURING OBSERVATION

ALTERNATIVES

- NONE

SOA EVALUATION AND PROJECTION



DEVELOPMENT PLAN

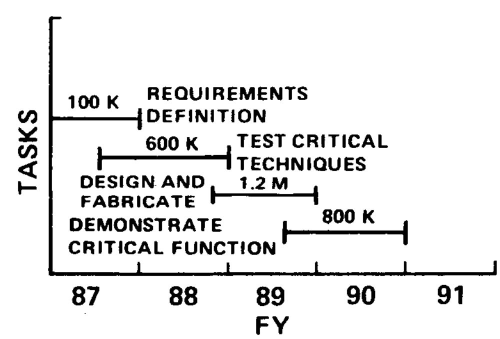


Figure C-5.- Wavefront/figure control.

PROBLEM/REQUIREMENT/GOAL

KEY ISSUES

- MAINTENANCE OF BORESIGHT ALIGNMENT OF A LARGE, FLEXIBLE TELESCOPE IN THE PRESENCE OF INTERNAL AND EXTERNAL DISTURBANCES
- PRECISION OFFSET POINTING FROM A VISIBLE SOURCE OF A TELESCOPE WHICH DOES NOT PROVIDE VISIBLE IMAGING

OBJECTIVE

- CONCEPTUAL DESIGN, IDENTIFICATION, AND TEST OF CRITICAL TECHNOLOGIES; CRITICAL FUNCTION DEMONSTRATION OF FGS

RATIONALE/TRACE PERSPECTIVE

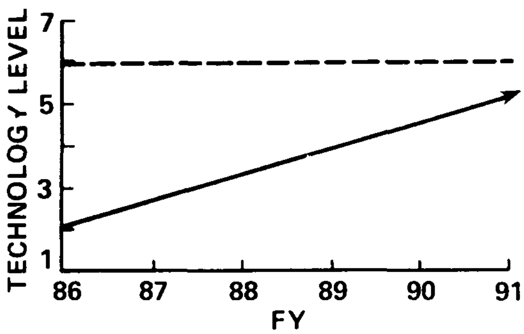
- POINTING STABILITY REQUIREMENTS ARE HIGH
- STRUCTURE IS FLEXIBLE
- CHOPPING CAN BE A MAJOR DISTURBANCE
- TELESCOPE DOES NOT OPERATE AT VISIBLE WAVELENGTHS
- SCIENCE OBSERVATIONS REQUIRE POINTING AT FAINT OBJECTS

MEANS MUST BE PROVIDED FOR TRACKING VISIBLE STARS WITH HIGH PRECISION AND TRANSFERRING THE LINE-OF-SIGHT TO THE FOCAL PLANE

ALTERNATIVES

- NONE

SOA EVALUATION AND PROJECTION



DEVELOPMENT PLAN

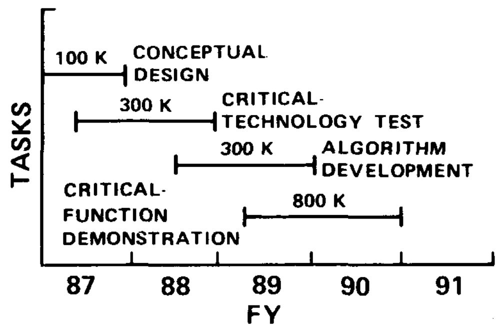


Figure C-6.- Fine line-of-sight guidance/offset pointing.

PROBLEM/REQUIREMENT/GOAL

KEY ISSUES

- JITTER INTRODUCED INTO TELESCOPE STRUCTURE BY MASS IMBALANCE
- POWER CONSUMPTION
- OPTICAL PERFORMANCE OF LARGE MONOLITHIC MIRROR IN DYNAMIC ENVIRONMENT

OBJECTIVES

- EXTEND CURRENT SOA BY INTER-DISCIPLINARY OPTIMIZATION TO SIZE AND FREQUENCY RANGE REQUIRED FOR LDR

RATIONALE/TRACE/PERSPECTIVE

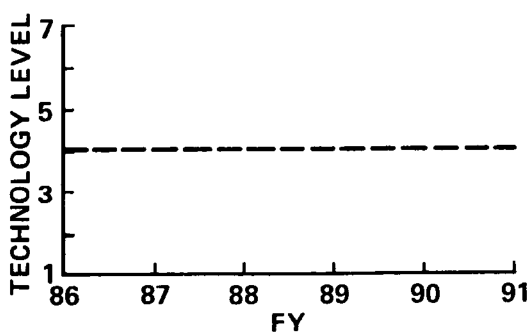
RATIONALE

- SECONDARY-MIRROR CHOPPING PREFERRED FOR BACKGROUND NOISE SUBTRACTION; CAN HAVE LARGE SYSTEM IMPACT

ALTERNATIVES

- CHOP WITH SMALLER OPTICAL ELEMENT

SOA EVALUATION AND PROJECTION



DEVELOPMENT PLAN

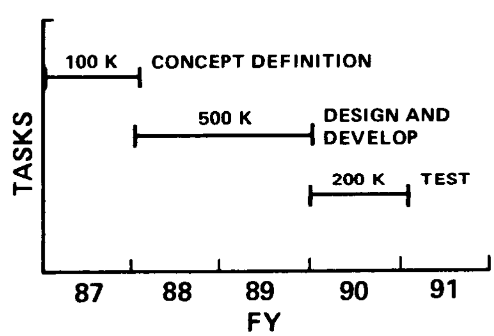


Figure C-7.- Chopping devices.

PROBLEM/REQUIREMENT/GOAL

KEY ISSUE

- INTERACTION OF MULTIPLE-CONTROL SYSTEMS REQUIRED FOR LDR

OBJECTIVES

- INTEGRATE RELEVANT SENSORS AND CONTROLS IN GROUND-BASED PROOF-OF-CONCEPT BRASSBOARD DEMONSTRATION
- EXAMINE PARAMETER SPACE APPROPRIATE TO PREDICTIVE MODELS
- ITERATE TO FINE-TUNE MODELS AND DYNAMIC CONTROL TECHNOLOGY

RATIONALE/TRACE/PERSPECTIVE

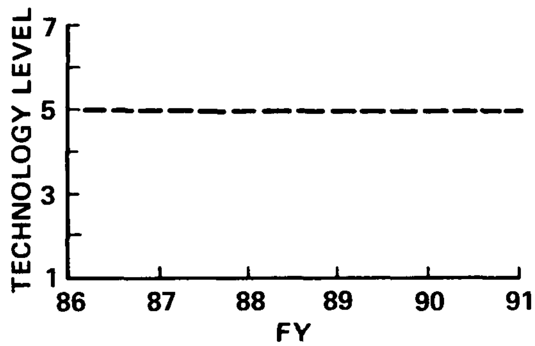
RATIONALE

- A WELL-CHARACTERIZED CONTROL HIERARCHY IS NECESSARY FOR COMPLEX FUNCTIONS RELATED TO ATTITUDE, CHOPPING, VIBRATION, ALIGNMENT, AND FIGURE CONTROL
- MODELING FIDELITY IS ESSENTIAL AND GROUND TESTS WITH BRASSBOARD CAN PROVIDE LARGE PART OF INFORMATION NEEDED
- COMPONENT TECHNOLOGY CAN BE TESTED (REFLECTOR SEGMENTS, ACTUATORS AND SENSORS, CONTROL ALGORITHMS)

ALTERNATIVES

- PROCEED TO SPACE TESTS WITH LOW CONFIDENCE IN CONTROL SYSTEM

SOA EVALUATION AND PROJECTION



DEVELOPMENT PLAN

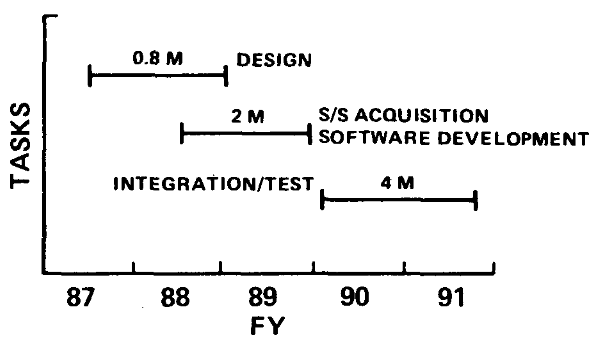


Figure C-8.- Control technology integration brassboard.

PROBLEM/REQUIREMENT/GOAL

KEY ISSUES

- SETTLING TIME FOR COMBINED STRUCTURE/CONTROL SYSTEM
- NONLINEAR DYNAMICS
- ON-ORBIT SYSTEM IDENTIFICATION

OBJECTIVES

- DEMONSTRATE ABILITY TO DESIGN COUPLED FLEXIBLE STRUCTURE/ CONTROL SYSTEM CAPABLE OF HIGH ACCURACY, RAPID SETTLING, AND LOW JITTER

RATIONALE/TRACE/PERSPECTIVE

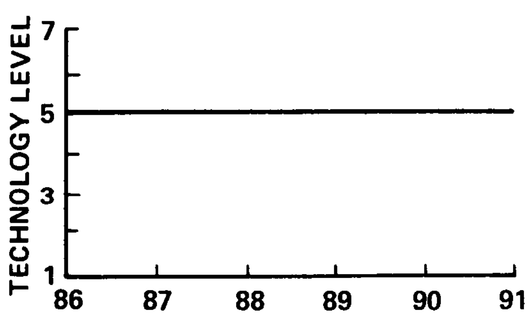
RATIONALE

- ZERO-G TESTS REQUIRED TO ASSESS DAMPING AND NONLINEAR CHARACTERISTICS OF LARGE SYSTEM UNDER REALISTIC CONDITIONS
- SETTLING TIME COULD HAVE LARGE EFFECT ON OBSERVATIONAL EFFICIENCY

ALTERNATIVES

- REDUCE EFFICIENCY
- ACCEPT WEIGHT AND POWER PENALTY

SOA EVALUATION AND PROJECTION



DEVELOPMENT PLAN

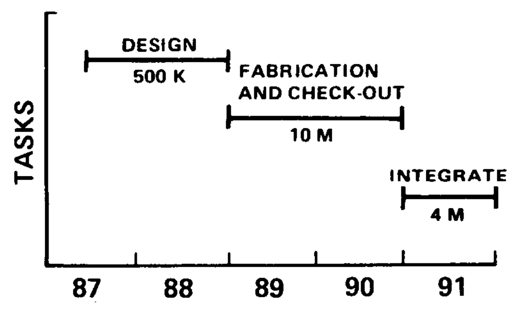


Figure C-9.- Controls flight demonstration (part of integrated controls/structures flight demonstration).

APPENDIX D

OPTICS PANEL TECHNOLOGY DEVELOPMENT RECOMMENDATIONS AND PRIORITIES

Optics Team

Emery Fletcher (Itek)
Peter Jones (Eastman Kodak)
Ken Lee (Itek)
Paul Repak (Rome Air Development Center)
william Hoffmann (University of Arizona)
John Stacy (Jet Propulsion Laboratory)
Dale Verbeck (Aerospace Corporation)
Ramsey Melugian (NASA Ames Research Center)
Aden Meinel (University of Arizona)
Marjorie Meinel (University of Arizona)
Jim Breckinridge (Jet Propulsion Laboratory)

Large Deployable Reflector Report

What is Optical Sciences Research? What is Optical Systems Engineering? What is optical systems Development?

Optical systems engineering is the end-to-end engineering analysis of an optical system in terms of the entire system performance across the required field of view at the focal plane. Optics is defined as that wavelength region from th4e soft X-ray to the submillimeter across which common analytical and engineering tools are used.

This interdisciplinary engineering field integrates the disciplines of materials, structures, and dynamics, thermal, pointing, and controls into the optical disciplines of ray-trace, vector and diffraction analysis; optical testing, interferometry, physical optics, radiometry, image processing, and detectors.

The tools of optical systems engineering which are developed through optical sciences research are used for development of space-flight optical instruments and systems such as the imaging spectrometer for remote sensing, cameras, and the space telescope.

Optical systems research is the basic and applied research required to develop new tools to enable optical systems engineers to design and build optical systems with new capabilities. Table D-I gives the recommendations and priorities chosen by the panel for the directions the optical technology development should take.

Quasi-Optics Analysis and Optimization- The LDR will operate in a wavelength between infrared telescopes and millimeter telescopes, in a domain where optical- and antenna-design programs have mutual difficulties. A large system like the LDR, thousands of wavelengths across, will act according to optical design descriptions (that do include diffraction at the image plane), but important factors are that some secondary optical surfaces are smaller and diffraction occurs at the boundaries of the surface. Further, when optical tile and piston errors occur, the effect on diffraction at the image plane is uncertain. It is necessary that such questions be answered for the LDR.

A software analysis package must be created that merges the two approaches so that an accurate system analysis will be possible. Because of the inherent complexity of the two disciplines, it will be necessary to verify predictions on simple test geometries that can be measured in the laboratory or on an antenna range. Predictions of telescope performance can ultimately be tested, along with the Telescope Thermal Emission (TTE) question, using an aerial or balloon telescope (fig. D-1).

Standing-Wave Optical Behavior- Standing waves are a recurring problem in millimeter-wave telescopes and are expected to be a potentially serious, limiting factor for LDR. Some sources are understood and easily eliminated, such as normal-incidence reflection between the feed and the first optical surface upstream. Others are more subtle, and one traditionally cuts and tries solutions until performance goals are met. This cut-and-try method may not be possible with LDR because it is expensive.

The need for segmented mirror panels with many edges that diffract energy is clearly a major potential source of the energy to initiate standing-wave buildup, the "narcissus effect." Questions such as edge treatment to disperse diffracted energy need to be explored, modeled, and finally tried out on an antenna range. The question of scaling down wavelengths to the limit of heterodyne detectors (~10 μm) may enable use of a subdiameter test system; otherwise it may be necessary to build a half- or full-scale functioning mock-up of the LDR optical system to solve this problem.

Wavefront Sensing- The key function in obtaining diffraction-limited performance from LDR is correcting the system to reduce the wavefront error to the necessary one-sixteenth wave root mean square.

Examination of a star in the focal plane is a fundamental way to detect and correct error in the telescope. Tilt correction to bring multiple images together is easy. Piston correction to phase wavefronts is more difficult. It requires imagery on a detector or array where the coherent rather than the light-bucket mode prevails; thus there is a dependence of technique in the nature of the telescope mirror panels. Much observing is done without a suitably bright object in the field; thus a backup system is required.

After alignment is achieved using a star or cooperative source, it is necessary to transfer wavefront sensing to an on-board system so that transient changes can be corrected.

There are many options for on-board sensing, but most have associated problems. It will be necessary to examine all possibilities in the specific context of LDR structural and assembly designs for a compatible wavefront-sensing system (fig. D-3).

Active Secondary or Quaternary*- Practical problems associated with an active 20-m primary to control the system imagery make it desirable to carefully consider doing the correction with a smaller optical element within the system. Both the secondary and quaternary in a two-stage configuration provide this possibility. If the field of view were essentially a single Airy disc, correction could be done by an active secondary. Study to date indicates that since a finite field of view is required, only the quaternary remains as an option because the correction must be done for a real image of the segmented passive primary.

The active quaternary has a number of associated advantages, including chopping, but a number of practical questions arise, including: diffraction effects at the quaternary segments, dynamic correction range, power dissipation by the actuators, and dynamic effects of chopping. Because of high leverage of the two-stage concept on LDR system weight and cost, there are important questions to be analyzed, engineered, and reduced to the necessary proof-of-concept test beds (fig. D-4).

Precursor- There are many critical performance aspects of the LDR that make it highly desirable to have a precursor system that can do astronomical observations in an approximation to the thermal environment. There are two possibilities, an aircraft or a balloon. The necessary aperture size to evaluate the questions should be about 3 m. Of the two, the balloon will be the better test bed because of the low temperature at float altitude. If necessary, an aircraft telescope will be used, but it will require a larger instrumental background because of a higher temperature.

The task would be to design scaled-down critical components, such as the second stage, with chopping quaternary, and evaluate them first in the laboratory and then in flight (fig. D-5).

Optical Contamination- Contamination of optical surfaces in the vicinity of the STS or the Space Station is potentially a serious problem. Prevention can be an expensive complication to LDR. At this time nothing is known about the optical effect of contamination in the 50- to 1000-μm wavelength region. It may or may not be a serious problem.

---

*The primary, secondary, and quaternary reflectors are referred to hereon as primary, secondary, and quaternary.

The task is to obtain information on the effect of contamination in the LDR spectral domain. Samples must therefore be included in the NASA ongoing program. Because of transient effects, simple recovery and postflight measurements are not sufficient. The samples should be instrumented so that in situ measurements can be made at intervals during the time the samples are in space (fig. D-6).

The results will then be integrated into the deployment and protection strategy for LDR.

Reflector Technology Program--Glasses- Glass panels have intrinsic properties exceeding those required by LDR and represent a mature, but expensive, technology. Ongoing work at the University of Arizona indicates that lower-cost materials and fabrication methods may reach the low-mass goals needed for LDR. Continued support at a modest level appears prudent until the reality of proposed new glasses and techniques can be assessed (fig. D-7).

Reflector Technology Program--Composites- The utilization of lightweight, durable, composite mirror panels is important to achieve an affordable LDR. The recent breakthrough in composite replicated panels is very encouraging and warrants increased efforts to scale up the experiments into the 2-m class. Composite panels may still have variations between replicated panels and changes after replication, but they appear to be within the range of wavefront correction via the two-stage concept, and hence operationally satisfactory for the wavelength range of LDR.

Thus far, composite technology development has been done without significant funding from NASA. Company-sponsored results now indicate the appropriateness of a specific user-funded program directed to the sizes and figure shapes needed for LDR or the precursor flight experiment (fig. D-8).

Aspheric Surfaces Fabrication- There is a need for the generation of off-axis aspheric mirror segments for the molds for composite replication techniques on mirror panels of glassy materials. There are several large precision machines that can produce surfaces almost good enough for LDR application. Upgrading these machines to the required accuracy, or developing alternate methods to polish and figure off-axis aspheres may require some specific support under the LDR program (fig. D-9).

Two-m Composite Panel Development- Mass and inertia have a strong influence on system cost; hence, achieving the goal of 5-kg/m^2 technology would tremendously increase the probability of success of having an LDR program. In creating this demonstration there should be no lingering doubts about scalability, surface performance, or stability. The reflectors must therefore be aspheric (perhaps elliptical), have surfaces suitable for figure sensing as well as long wavelengths, and have a goal of permanent figure stability. (Actuators and backing structure will be included in the 5-kg/m^2 areal density.) This shape will need a demonstration using 1-m coated panels to determine the stability of the panels and the coatings over 2 yr. This test would be followed by scaling up experiments to the full 2-m panels.

Thermal Background Management- The central problem of a far infrared (FIR) telescope is detection and accurate measurements of objects several hundred thousands of times fainter per unit solid angle than the background of the telescope thermal emission (TTE). There are many components of the TTE, and minimizing some may enhance others; thus a highly interactive management challenge arises.

Most telescopes solve the TTE problem by means of chopping, moving the detector from object plus sky to object at 10 Hz or more. Similarly, detector frequency noise is reduced. Mass motions in a space telescope, even when dynamically balanced, induce pointing oscillations; thus a solution to the TTE problem interacts with spacecraft dynamics. One must therefore explore all options that lead to minimizing TTE compatible with other system parameters affecting the scientific use of the system, such as diffraction analysis, radiometer analysis, coatings, and active control methods (fig. D-10).

Optomechanical Beam Switching- Meeting a low $\Delta B/B$ 10^{-6} and $(\Delta B/B)$ 10^{-3} is so essential to observational requirements that careful attention must be given to the analysis of possible beam-switching options. Because practical experience says that analysis alone is not sufficient, tests of proposed LDR chopping options are essential in actual use. Several options will probably be tested for use, first to operate at 10 μm on known (calibrated) terrestrial telescopes and later at 50 to 100 μm on a 3-m balloon telescope.

Stability of the LDR optical train is intimately involved in meeting the demanding requirements for background cancellation. Questions concerning chopping at a quaternary or within the instrument package and also the option for combining wavefront correction and the chopping function need to be answered with certainty.

This aspect of LDR has a top priority for early attention. If the scientific requirements cannot be met by the beam-switching, then alternate observing techniques must be adopted (fig. D-11).

Beam-Switching Optimization- This optomechanical function is central to optimizing system performance. It is clear that the usual techniques of chopping by moving the secondary has serious consequences because of diameter and mass. Alternatives have been tried in the past, but without general acceptance because of the demanding requirements of maintaining a stable TTE background. Therefore, it is urgent that alternate methods be designed and evaluated in actual astronomical use.

A number of options that in theory appear to meet the TTE stability requirement have been suggested. These options need further analysis, followed by engineering implementation and finally by test. The fluctuating thermal background of the atmosphere could hinder the interpretation of results; thus, astronomical tests must be carried out above most of the atmosphere, such as with an airborne balloon telescope.

Image-Quality Integration- This task is a continuing one over the duration of the program to enable overall management of the various inputs affecting the final optical performance of the system. There are many specific technical challenges are resolved, they will be integrated and communicated to the science oversight committee for comment and appropriate action.

Image Quality- The objective of the image quality task is to monitor the image-quality performance of the LDR as the optical configuration and design matures, and to readdress the error budget during the development program to assure that performance is maintained during design evaluation.

For each optical configuration under consideration, an end-to-end ray-trace model will be maintained and updated as design alterations are incorporated. The error budget for the full system, broken down to components, will be updated for each design modification and the top level effect of each change will be assessed (fig. D-12).

In addition, a full diffraction analysis of the design will be carried out to identify the limiting characteristics (e.g., aperture, segments) in the submillimeter region. As the design evolves, the impact of changes on the diffractive behavior will be assessed differentially; from time to time, as additive changes accumulate, a full diffraction analysis will be repeated to monitor the net system performance and confirm the validity of the model.

The system performance characteristics for the user community are the sole justification for the LDR. It is essential that continuous performance control, consistent with the needs of the scientists, be maintained during design evolution, and that further implications in terms of subsystem technology requirements be identified in a timely manner.

TABLE D-I.- OPTICS PANEL TECHNOLOGY DEVELOPMENT RECOMMENDATIONS AND PRIORITIES[a]

Technology	EK	Itek/Lockheed	Panel
Image quality	-	-	H
Thermal background management	-	-	H
Beam switching	-	M	M
Quasi-optics analysis and optimization	-	-	M
Active quaternary demonstration	-	-	H
Balloon precursor	-	-	M
Contamination	H	-	M
Standing waves	-	-	H
Off-axis mirror processing	L	M	L
Integrated technology experiments	-	H	H
Active primary demonstration	H	-	-
Wavefront sensing	H	M	M
Reflector technology composites	M	H	H
Reflector technology glassy	M	H	M

H = high, M = medium, L = low

[a]Recommendations by JPL were for reflector technology composites only, and the priority given was high.

OBJECTIVE

- CREATE A CAPABILITY TO ACCURATELY PREDICT THE PERFORMANCE OF THE LDR AND ITS INSTRUMENTS TO SUPPORT THE SYSTEM CONCEPTUAL DESIGN, DETAIL DESIGN, AND PERFORMANCE DURING THE MISSION

APPROACH

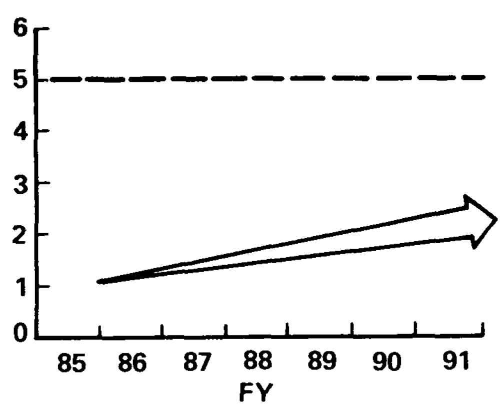
- CREATE SOFTWARE ANALYSIS PACKAGES TO MODEL THE VECTOR AND SCALAR DIFFRACTION BEHAVIOR IN TERMS OF COHERENT, PARTIALLY COHERENT, AND INCOHERENT RADIATION FOR IMAGING SYSTEMS IN THE 10 TO 1000-μm WAVELENGTH REGION. VERIFY THE ACCURACY OF PREDICTIONS MADE BY THIS MODEL USING LABORATORY AND FIELD MEASUREMENTS AND CORRECT SOFTWARE PARAMETERS AS NEEDED
- DEVELOP THE SOFTWARE BY COMBINING COMMERCIALLY AVAILABLE RAYTRACE, DIFFRACTION ANALYSIS, STRAY RADIATION, THERMAL, AND STRUCTURAL PROGRAMS AS NEEDED TO CREATE AN ACCURATE SYSTEM MODEL FOR LDR

RATIONALE

- EXISTING MODELS OF RADIO TELESCOPES AND MICROWAVE TELESCOPES DO NOT ACCURATELY PREDICT THE PERFORMANCE OF SUBMILLIMETER TELESCOPES AND IMAGING SYSTEMS. SOFTWARE TOOLS THAT ARE CURRENTLY USED TO PREDICT THE PERFORMANCE OF OPTICAL SYSTEMS IN THE VISIBLE AND THE NEAR INFRARED DO NOT ACCURATELY PREDICT THE PERFORMANCE OF SUBMILLIMETER TELESCOPES

ALTERNATIVES

- WITHOUT AN ACCURATE MODEL, IT WILL BE NECESSARY TO BUILD A FULL-SCALE MODEL OF THE LDR SYSTEM, PUT IT INTO A FULL-UP SPACE SIMULATOR AND MEASURE THE PERFORMANCE



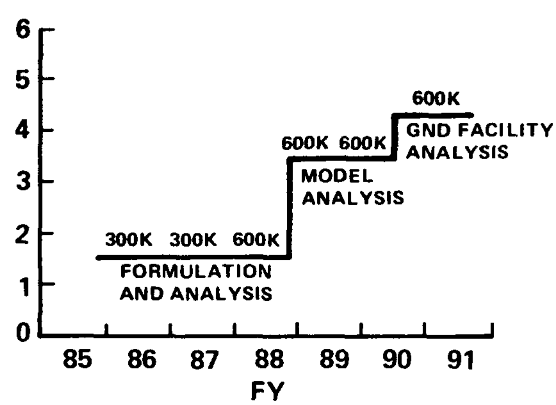


Figure D-1.- Quasi-optics analysis and optimization.

OBJECTIVE

- TO UNDERSTAND THE NATURE OF THIS PROBLEM FOR THE LDR CAUSED BY EDGES THAT ARE PRESENT IN THE OPTICAL BEAM, SUCH AS PERIPHERY OF THE APERTURE STOP, NORMAL INCIDENCE REFLECTIONS, SUPPORT STRUTS, AND SEGMENT GAPS; ALSO THE STABILITY OF THE STANDING WAVES WITH TIME AND CHOPPING

APPROACH

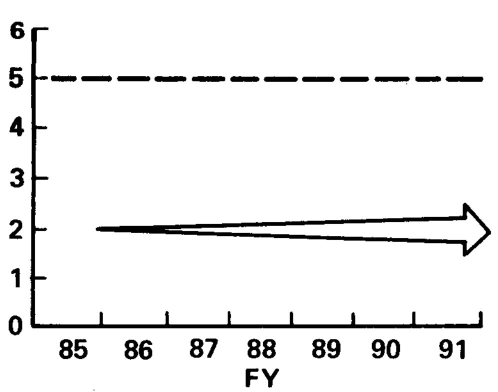
- CALCULATION IS A STARTING POINT, BUT THE RELEVANCE OF DETAILED CALCULATION IS OPEN TO QUESTION. IT WILL BE ESSENTIAL TO MAKE A SCALED-DOWN OR FULL-SCALE SIMULATION, POSSIBLY VIA ACTUAL OBSERVATIONS OF ASTRONOMICAL SOURCES IN AN APPROPRIATE WAVELENGTH. IT MAY BE POSSIBLE TO SCALE DOWN TO USE 10.6 μm RADIATION; i.e., A BEAM DIAMETER OF 2 m

RATIONALE

- STANDING WAVES ARE A POTENTIALLY LIMITING FACTOR IN SOME IMPORTANT OBSERVATIONS. ELIMINATION OF THE MOST SERIOUS ONES IS ESSENTIAL

ALTERNATIVES

- TO BE ANSWERED BY THE SCG



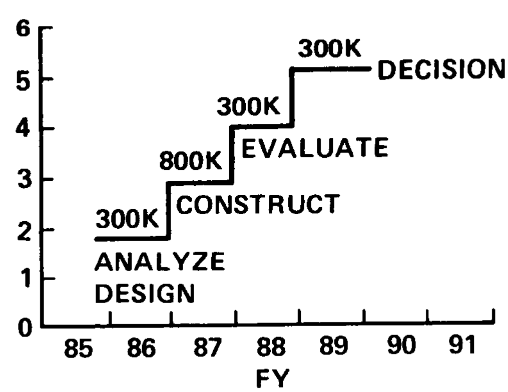


Figure D-2.- Standing wave optical behavior.

OBJECTIVE

- DETECT SYSTEM ERRORS IN THE SOURCE WAVEFRONT TO BE CORRECTED AT AN APPROPRIATE SURFACE

APPROACH

- NEED REVIEW FIGURE-SENSING AND/OR WAVEFRONT-SENSING TECHNIQUES IN THE CONTEXT OF THE ACCURACY APPROPRIATE TO LDR IMAGING REQUIREMENTS, AND CONSTRAINTS ON THE SENSING WAVELENGTH MUST BE DETERMINED

RATIONALE

- PASSIVE PERFORMANCE OF SPACE-ASSEMBLED OPTICAL COMPONENTS THE SIZE OF THE LDR IS NOT LIKELY. CORRECTION WILL BE ESSENTIAL; HENCE, ERROR DETECTION IS NECESSARY. A STAR CAN BE USED IN PRINCIPLE, BUT A STAR IS NOT ALWAYS AVAILABLE; THUS, AN INTERNAL METHOD ABOARD LDR MUST BE USED

ALTERNATIVES

- USE STAR AS A REFERENCE FOR ERROR DETECTION, RELY ON PASSIVE STABILITY OF OPTICAL ELEMENTS BETWEEN REFERENCE OBSERVATIONS, IMPOSES SEVERE CONSTRAINTS ON SYSTEM STABILITY

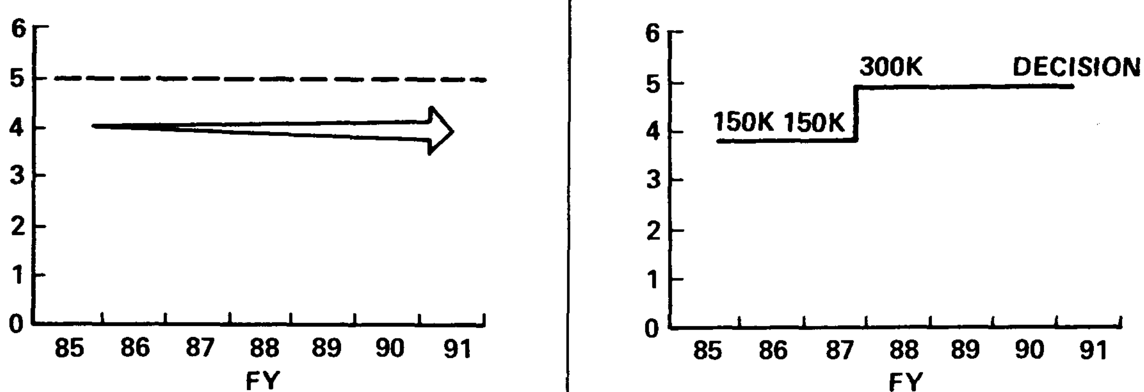


Figure D-3.- Wavefront sensing.

OBJECTIVE

- CONSTRUCT A POC TESTBED TO SHOW THAT ERRORS OF A SEGMENTED PRIMARY CAN BE CORRECTED FOR A FINITE FIELD OF VIEW AT A QUATERNARY (EXIT PUPIL) MIRROR
- EVALUATE LOW-POWER DISSIPATION ACTUATORS WITH APPROPRIATE DYNAMIC CORRECTION RANGE

APPROACH

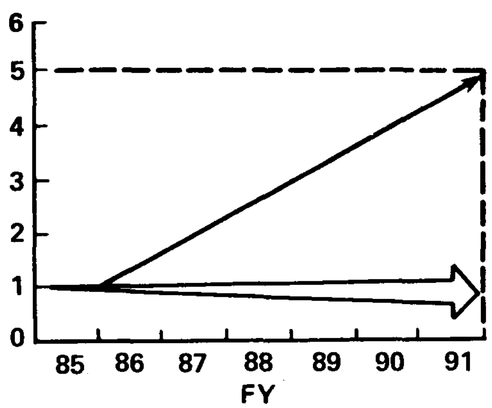
- USE TWO SCALED-DOWN PRIMARY SEGMENTS HAVING KNOWN FIGURE ERRORS
- PREPARE TWO WAVEFRONT-CORRECTING SEGMENTS THE ORDER OF ONE-TENTH THE SIZE OF THE PRIMARY SEGMENTS, WITH INTERFEROMETER OR EQUIVALENT MEANS FOR EVALUATING PERFORMANCE

RATIONALE

- CONTROL OF WAVEFRONT ERROR AT AN ACTIVE QUATERNARY HAS HIGH LEVERAGE ON LDR DESIGN, WEIGHT, AND COST, BUT IS NOVEL IN APPLICATION; THEREFORE AN ENGINEERING POC IS ESSENTIAL

ALTERNATIVE

- AN ACTIVE PRIMARY, WHICH WILL HAVE AN IMPACT ON SYSTEM DESIGN, WEIGHT, AND COST



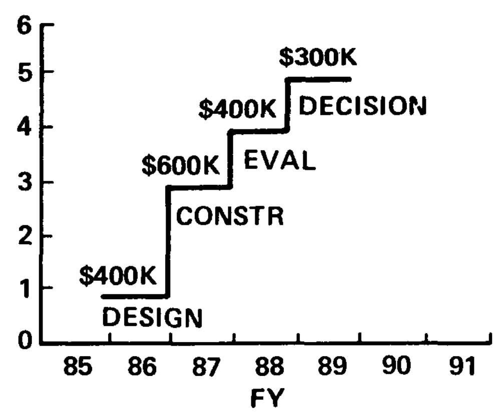


Figure D-4.- Active quaternary.

OBJECTIVES

- PROVIDE A FOCUS FOR DEVELOPMENT AND APPLICATION OF LIGHT-WEIGHT LDR MIRROR TECHNOLOGY
- EVALUATE PERFORMANCE OF NEW BEAM-SWITCHING TECHNIQUES REQUIRED FOR LDR
- PROVIDE A VEHICLE FOR DEVELOPING NEW FOCAL-PLANE INSTRUMENTATION FOR THE FAR INFRARED AND SUBMILLIMETER
- DEMOSTRATE APPROACH-BRIDGE GAP IN SCIENTIFIC UNDERSTANDING BETWEEN PRESENT 1-m STRATOSPHERIC TELESCOPES AND LDR

APPROACH

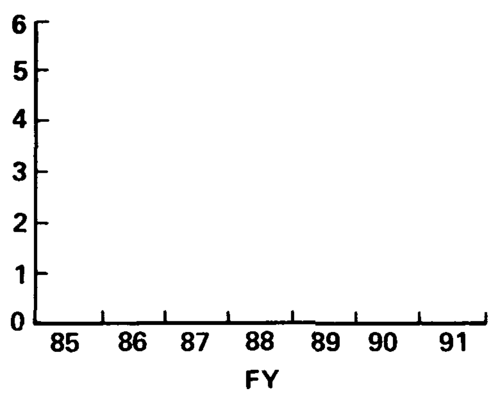
- CONSTRUCT AND OPERATE A 3-m BALLOON TELESCOPE FOR SEVERAL FLIGHTS PER YEAR WITH A NUMBER OF DEVELOPMENT INSTRUMENTS
- USE THE TELESCOPE AS A TEST BED FOR REFLECTOR TECHNOLOGY BEAM-SWITCHING TECHNIQUES, FIGURE CONTROL, AND NEW INSTRUMENTATION

RATIONALE

- SCIENTIFIC-BALLOONING ALTITUDES HAVE A SIMILAR THERMAL ENVIRONMENT TO LDR (220°K) AND HIGH-ATMOSPHERIC TRANSPARENCY AT LDR WAVELENGTHS. OPERATION OF A 3-m TELESCOPE IS WITHIN CURRENT STATE OF THE ART BALLOONING TECHNIQUES. A BALLOON TELESCOPE COULD BE IN OPERATION IN A TIME SCALE TO HAVE SUBSTANTIAL IMPACT ON LDR TECHNICAL AND SCIENTIFIC ISSUES

ALTERNATIVES

- RISK IN THE LDR DEVELOPMENT. SOME OTHER PROOF OF TECHNOLOGY AND SCIENCE DEVELOPMENT REQUIRED



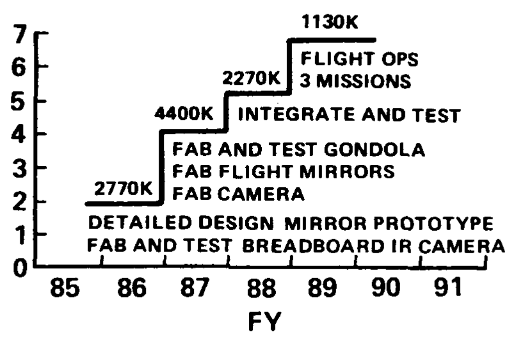
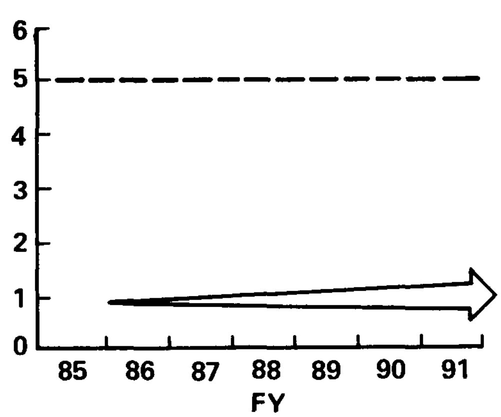


Figure D-5.- Precursor.

OBJECTIVES	RATIONALE
• ASSESS BY SPACE TESTING THE EXTENT AND NATURE OF CONTAMINATION OR DAMAGE TO THE LDR REFLECTIVE SURFACES BY THE STS OR THE SPACE STATION ENVIRONMENT • TAKE REAL-TIME MEASUREMENTS OF THE KEY SAMPLES IN THE WAVELENGTH RANGE 30 TO 300 μm APPROACH • ADAPT EXISTING SPACE-SAMPLE CARRIERS TO HOLD THE SAMPLES AND MONITORING EQUIPMENT TO BE DELIVERED BY THE STS AND REMAIN IN ORBIT FOR PERHAPS A 1-yr PERIOD BEFORE RECOVERY (NO DATA TRANSMISSION DURING THE STAY IS NEEDED, ONLY RECORDED DATA FOR LATER RECOVERY) • TEST COATINGS, SUCH AS Au AND Ag, AS SUITABLE OVERCOATS FOR PROTECTION	• DEGRADATION OF OPTICAL SURFACES, IF PRESENT, WILL REQUIRE EXPENSIVE PROTECTION STRUCTURES AND PROCEDURES IN ASSEMBLY AND RESUPPLY TO THE LDR ALTERNATIVES • NONE



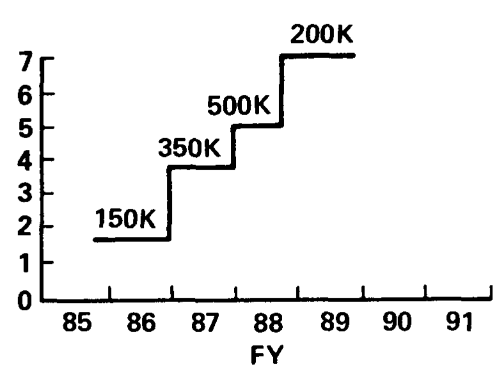


Figure D-6.- Optical contamination.

OBJECTIVE

- OBTAIN AND DEVELOP LOW-CTE GLASSES WITH LOWER FUSION TEMPERATURES THAN FUSED SILICA
- FABRICATE AND TEST LOW-COST, 1- TO 2-m SIZE, ULTRALIGHTWEIGHT (20 TO 30 kg/m^2) GLASS SEGMENTS

APPROACH

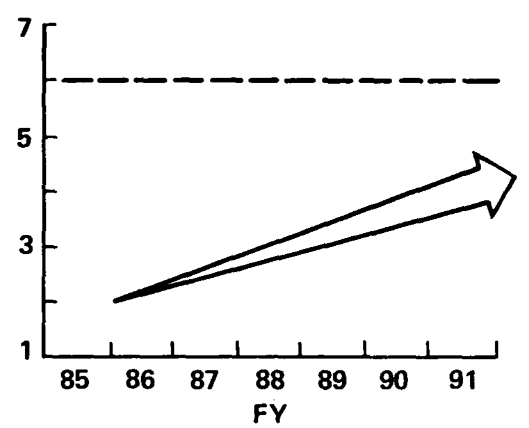
- EVALUATE AND DEVELOP MULTI-COMPONENT, LOW-CTE GLASSES FOR LOW-FUSION-POINT PROPERTIES, CONSIDERING UNIFORMITY AND LOW COST
- PREPARE MATERIAL SAMPLES FOR EVALUATION
- FABRICATE AND TEST SUBSCALE MIRRORS
- SCALE TO LARGER SIZES AND TEST ENVIRONMENTALLY

RATIONALE

- LOW CTE AT OPERATING TEMPERATURE REMOVES SENSITIVITY TO THERMAL PERTURBATIONS. LOW-FUSION POINTS PERMIT LOW-COST FABRICATION TECHNIQUES FOR ULTRALIGHTWEIGHT SEGMENTS

ALTERNATIVES

- HIGH-COST, HIGH-PERFORMANCE, OPTICAL-WAVELENGTH, ULTRALIGHTWEIGHT GLASS-MIRROR TECHNOLOGIES DEVELOPED FOR SDI AS PART OF THE DOD PROGRAMS



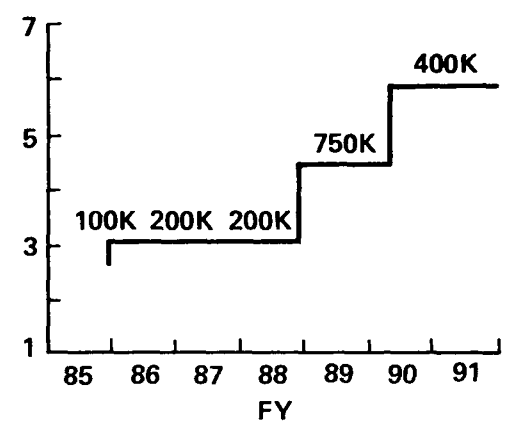


Figure D-7.- Reflector technology program--glasses.

OBJECTIVE

- DEVELOP AND EVALUATE PRIMARY-MIRROR COMPOSITE MATERIALS THAT ARE 5 TO 10 kg/m^2 WITH LOW CTE, SURFACE ROUGHNESS OF 2-μm rms, AND SPATIAL CORRELATION FOR A GAUSSIAN DISTRIBUTION APPROXIMATING 4 cm AND STABILITY OF FIGURE UNDER LDR THERMAL VACUUM ENVIRONMENT SUITABLE FOR 30-μm DIFFRACTION-LIMITED PERFORMANCE

APPROACH

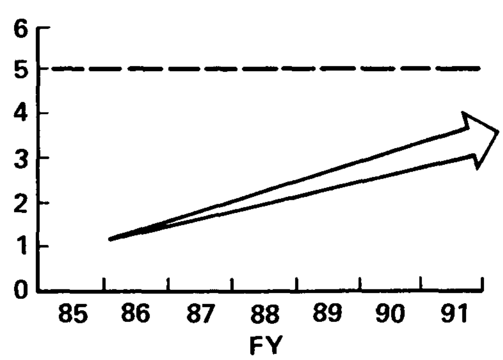
- PURSUE DEVELOPMENT AND LOW-TEMPERATURE FIGURE TESTING OF PROMISING COMPOSITE TECHNOLOGIES SUCH AS CARBON-FIBER-REINFORCED PLASTIC, CARBON-FIBER-REINFORCED GLASS, CARBON-CARBON
- CARRY OUT THE MOST PROMISING TECHNOLOGY TO 2-m SIZE
- USE THE RESULT IN AN LDR PRECURSOR ACTIVITY
- INVESTIGATE INFLUENCE OF METAL-REFLECTIVE COATING OPTIONS
- TEST MIRROR FOR HUMIDITY AND AGING EFFECTS

RATIONALE

- COMPOSITE-MIRROR PANELS HAVE EXPERIENCED A RECENT BREAKTHROUGH IN REPLICATION, ACCURACY, AND THERMAL STABILITY. THEIR PERFORMANCES ARE CLOSE ENOUGH TO LDR REQUIREMENTS TO WARRANT ADDITIONAL DEVELOPMENTS AND TESTING. THE BENEFIT TO LDR OF THIS APPROACH IS EXTREMELY LIGHTWEIGHT (ABOUT 8 kg/m^2), NONFRAGILE MIRROR MATERIAL. THE WEIGHT AND THERMAL PROPERTIES OF THE PRIMARY HAVE A LARGE IMPACT ON MANY LDR DESIGN ISSUES

ALTERNATIVES

- GLASS MIRROR STRUCTURES WITH GREATER WEIGHT AND FRAGILITY



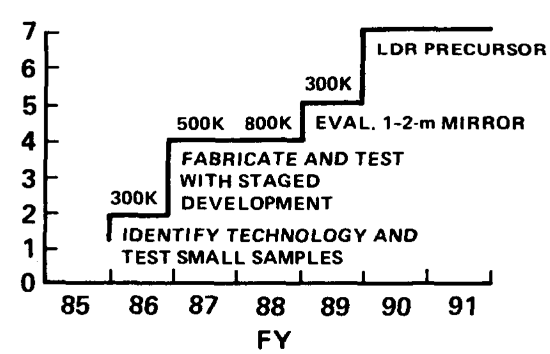
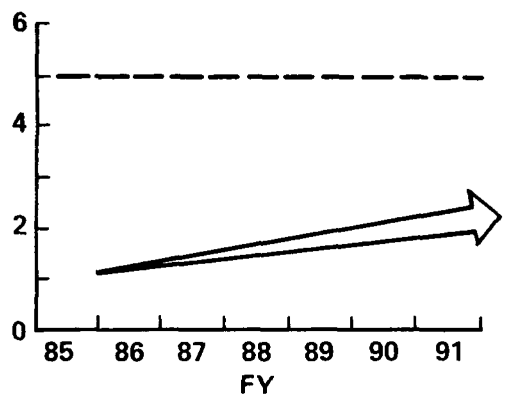


Figure D-8.- Reflector technology program--composites.

OBJECTIVE	RATIONALE
• DEMONSTRATE TECHNOLOGY FOR RAPID-PRECISION GENERATION OF LARGE (2-m) OFF-AXIS-ASPHERIC SURFACES IN GLASS WITH PRECISION OF LESS THAN 1-μm rms APPROACH • EXTEND TECHNIQUES DEVELOPED FOR SMALL, OFF-AXIS SEGMENT GENERATION OF 2-m SEGMENTS SUITABLE FOR LDR	• AN ESSENTIAL LDR REQUIREMENT IS PRECISION (LESS THAN 1-μm rms) GENERATION OF 2-m, OFF-AXIS ASPHERICS EITHER FOR MOLDS OR FOR REPLICATION OR FOR THE ACTUAL MIRROR SEGMENTS. DIRECT GENERATION OF THESE SURFACES WITHOUT CONVENTIONAL OPTICAL FIGURING OFFERS THE POTENTIAL FOR FASTER PRODUCTION AND SUBSTANTIAL COST SAVINGS ALTERNATIVES • CONVENTIONAL OPTICAL-POLISHING FIGURING



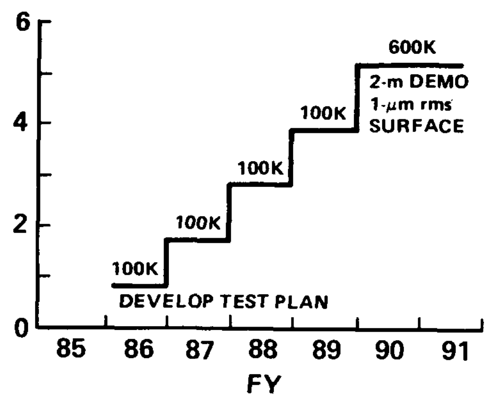


Figure D-9.- Aspheric surface fabrication.

OBJECTIVE

- MINIMIZE THERMAL FLUX ON THE DETECTOR
- MINIMIZE CHANGES IN THE FLUX CAUSED BY CHOPPER-MODULATED THERMAL GRADIENT OR TEMPORAL VARIATIONS

APPROACH

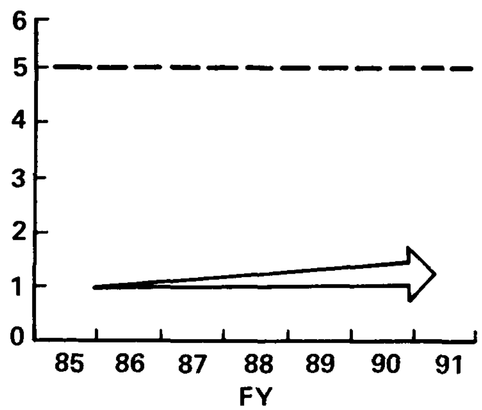
- EXPLORE OPTIONS TO MINIMIZING TTE COMPATIBLE WITH OTHER SYSTEM PARAMETERS SUCH AS
  - DIFFRACTION ANALYSIS
  - RADIOMETER ANALYSIS
  - COATINGS
  - ACTIVE CONTROL METHODS
  - MEASUREMENTS IN LABORATORY
  - OPTICAL CONTAMINATION (FLIGHT)

RATIONALE

- MAXIMIZE SNR

ALTERNATIVES

- PERFORMANCE COMPROMISED



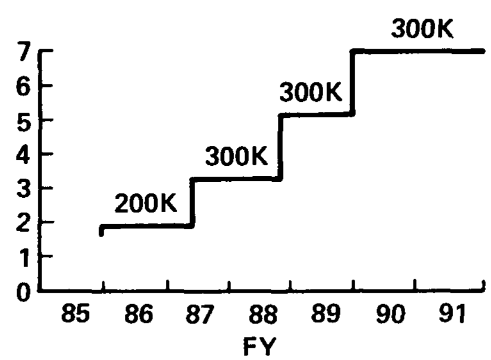


Figure D-10.- Thermal background management.

OBJECTIVE

- DEVELOP AND PROVE NEW BEAM SWITCHING WHICH MEETS THE UNIQUE REQUIREMENTS OF LDR

APPROACH

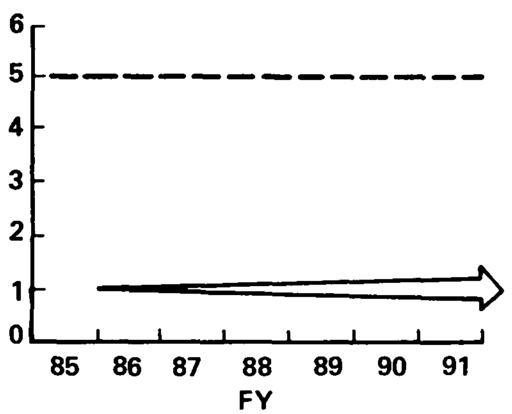
- DESIGN AND CONSTRUCT ONE OR MORE BEAM-SWITCHING DEVICES WHICH RELY ON REIMAGING THE PRIMARY MIRROR ON A SMALL FLAT WHICH IS TILTED FOR BEAM SWITCHING. THESE DEVICES WILL BE OPERATED ON SUITABLE GROUND-BASED TELESCOPES FOR INITIAL EVALUATION AND ON A 3-m BALLOON TELESCOPE FOR TEST AT LDR WAVELENGTHS AND THERMAL ENVIRONMENT

RATIONALE

- THE "SECONDARY CHOPPER" APPROACH, WHICH IS HIGHLY DEVELOPED FOR GROUND-BASED 10-μm TELESCOPE USE TO ACHIEVE BETTER THAN ONE PART IN 10^6 BACKGROUND SUPPRESSION, CANNOT MEET THE SPECIFICATIONS FOR LDR BECAUSE OF IMAGE DEGRADATION AND HIGH MOMENT OF INERTIA OF LDR SECONDARY. ALTERNATIVES TRIED IN THE PAST HAVE NOT ACHIEVED DESIRED SECONDARY CHOPPER PERFORMANCE. A NEW APPROACH IS REQUIRED. ACHIEVING BACKGROUND SUPPRESSION TO ONE PART IN 10^6 REQUIRES OPERATIONAL PROOF UNDER DEMANDING ASTRONOMICAL OBSERVING CONDITIONS

ALTERNATIVES

- LOSS OF LDR IMAGE QUALITY AND/OR INSTRUMENT SENSITIVITY



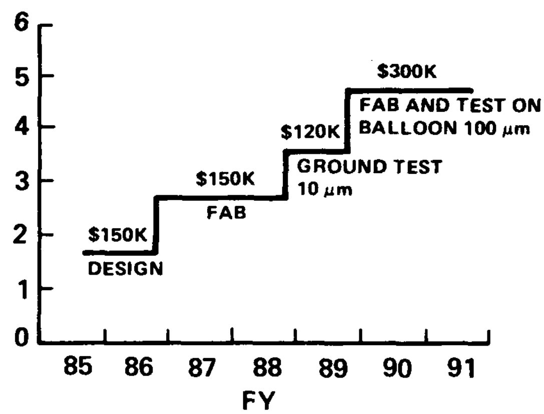


Figure D-11.- Design and evaluate beam switching technique suitable for LDR.

OBJECTIVE

- ASSURE THAT THE TECHNOLOGY TASKS WILL DEVELOP PRODUCTS CONSISTENT WITH THE IMAGE QUALITY SPECIFIED BY THE SCIENCE TEAM

APPROACH

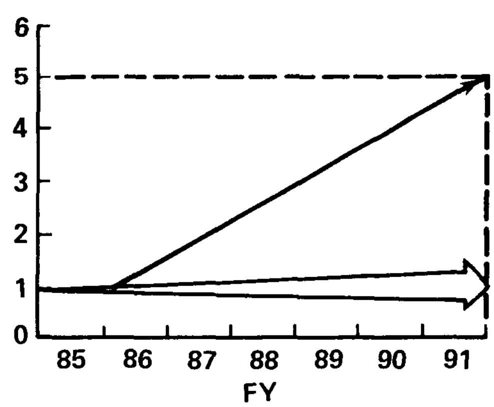
- USING ADVANCED OPTICAL SYSTEM DESIGN COMPUTER PROGRAM, PERFORM AN END-TO-END RAY TRACE AND DIFFRACTION ANALYSIS AND CONTINUOUSLY UPDATE THE PREDICTED PERFORMANCE BASED ON THE CONTINUALLY ADVANCING TECHNOLOGY TASKS

RATIONALE

- NEED FOR A SUPERVISORY EFFORT TO MONITOR THE TECHNOLOGY DEVELOPMENTS AND TRANSLATE THE DEVELOPING SUBSYSTEM PERFORMANCE PARAMETERS INTO IMAGE QUALITY FOR THE SYSTEM AND THE SCIENCE OVERSIGHT COMMITTEES

ALTERNATIVES

- COST INCREASE, PERFORMANCE COMPROMISED, SCHEDULE NOT MET



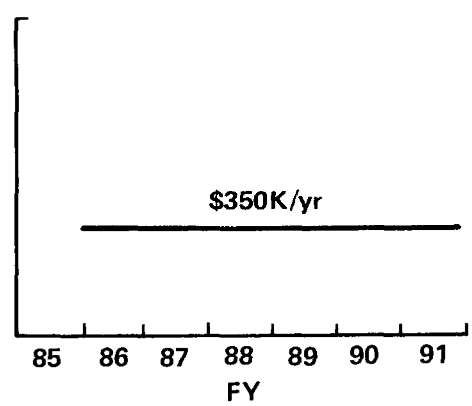


Figure D-12.- Image quality.

APPENDIX E

STRUCTURES AND MATERIALS TECHNOLOGY PANEL REPORT

Structural and Materials Panel Members

Martin Mikulus - Chairman	NASA Langley Research Center
Robert Freeland	Jet Propulsion Laboratory
John Hedgepeth	Consultant
Paul McElroy	Jet Propulsion Laboratory
Richard Russell	NASA Langley Research Center
William Witt	Rome Air Development Center

Structures and Materials Panel Approach

The structures and materials panel's approach to the LDR issues consisted of:

1. Data reviewed from contractor study reports and the JPL system study results.

2. Four basic technology areas selected for all proposed developments within the structures and materials areas.

3. Technology development plans generated for each of the areas.

4. The four technology areas prioritized with respect to the selected criteria.

The prioritization criteria were defined as low weight, low cost, and operational reliability. The structures and materials technology areas chosen were:

1. Reflector panels - low weight and low cost
    a. Structural composites
    b. Glass
    c. Other

2. Structural concepts - low weight and low cost
    a. Deployable
    b. Erectable
    c. Thermal shield

3. Structural system dynamic simulation
    a. Joint nonlinearity
    b. Structural damping
    c. Model fidelity

4. Flight experiments
   a. Structural assembly
   b. Concept performance
   c. Model verification and refinement

Structures and Materials Panel Conclusions

The panel made the following conclusions:

1. Light-bucket-mode requriements dictate the need for <0.5-μm-rms primary reflector panels which can be satisfied only by 20- to 30-kg/m^2 glass technology at this time.

2. Alternate materials for primary reflector panels have the potential for 1- to 5-μm-rms surface accuracy with areal densities of <10 kg/m^2 and low cost.

3. High structural performance with inherent reliability and predictability result in low-cost systems.

4. Structural weight has major impact on total LDR system.

5. Structural-system dynamic simulation with high-fidelity modeling is required for predicting micrometer-level dynamic response to achieve desired performance goals.

6. Structural space experiments are required to validate construction procedures, concept performance, and analytical modeling.

7. The highest-priority technology area is for primary reflector panels that are lightweight and low cost, and that demonstrate high surface precision.

Primary Reflector Panel Development

Based on the review of the contractor reports and the JPL study, it was determined that low-weight/low-cost primary reflector panels are a technology "driver" since their characteristics significantly affect the entire LDR design. The present state of glass technology does not meet these requirements and requires further development. The state of glass technology suggests that other candidate materials should also be considered seriously. The panel recommended that independent, but parallel, programs should be continued for the materials research and development of an affordable, lightweight ($\leq$10 kg/m^2) mirror panel with a high-precision reflector surface ($\leq$2 μm rms) which demonstrates long-term dimensional stability and low CTE behavior ($\leq 2\times10^{-6}$/ K). Other materials, such as metals, should also be investigated to determine their applicability to LDR primary-reflector requirements.

the technical approach is to evaluate a number of options to the point of sample panel fabrication then select one or more baselines that would be developed to the point of proof-of-concept hardware. At that time, selection will be made for a single prototype-panel fabrication (fig. E-1).

Structural System Dynamic Simulation

The design trade studies required to optimize the structural system and the generation of realistic estimate of on-orbit performance can be accommodated only by an analytical process with the capability of accounting for micrometer-level dynamic response. This process will have to accurately account for the effects of structural joint nonlinearity; the identification, characterization, and simulation of structural damping; and the extension of current capability for accurately simulating structural dynamic behavior to the fidelity needed for LDR.

Such an analytical capability will significantly enhance the design process used to eliminate or minimize the effects of joint nonlinearities, and effectively use the inherent system damping to reduce the amplitude responses and settling time. Additionally, this capability is needed to project how well the LDR structure meets its functional requirements. This technology will reduce the need for expensive flight experiments to characterize the LDR structural systems and validate performance estimates.

A significant portion of the estimated funding for the first 2 yr is for the hardware to be used for the structural characterizations. If hardware for structural joints and full-scale structural models is developed to support other related technology developments and is available for this technology development, substantial resources might be saved (fig. E-2).

Structural Concepts: Deployable and Erectable

Structural concepts for space deployment or assembly are required for the primary and secondary reflector and their support structures. An attractive combination of these two major elements is a great challenge and the combination must be low cost and lightweight in addition to being stiff and reliable.

The following goals were established:

1. Primary reflector structure.........<5 kg/m^2
2. Thermal shield......................<1 kg/m^2
3. Natural vibration frequency............>1 Hz
4. Passive damping.........................$>3\%$
5. Structural cost..................$<\$10,000$/kg
6. Primary structure accuracy.......≤ 100 μm rms

The rationale for establishing these goals is that the structural weight has a major impact on the total system; high structural performance and inherent operational reliability and predictability results in a low-cost system. It appears that

EVA and remote manipulation will be needed, but the total assembly times will be short and bounded.

The approach will be to evaluate a number of options for joints and deployable and erectable concepts analytically and with models for the first 2 yr. Then a baseline selection will be made and developed to the point of performance demonstration with realistic hardware models (fig. E-3).

Flight Experiment

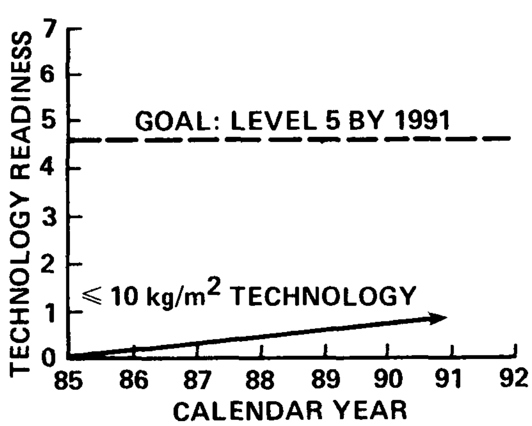
A structural flight experiment will be required to validate the high-fidelity modeling necessary to accurately predict the micrometer-level dynamic responses to achieve the desired LDR performance goals. This experiment will determine the overall dynamic structural behavior of the joints, structural members, panels, and damping in the space environment. In addition, this experiment will validate the construction procedures and the overall structures performance capability. This data base will reduce the program risks and uncertainties associated with high-fidelity modeling capability.

The experiment proposed is based on a reduced-size LDR system structure that requires the Space Station services as the full-scale LDR and demonstrates the same levels of performance for the critical technologies (fig. E-4).

KEY ISSUE	RATIONALE
• INDEPENDENT, PARALLEL DEVELOPMENT PROGRAMS OF COMPOSITE MATERIALS TO ACCOMMODATE LOW WEIGHT/LOW COST PRIMARY REFLECTOR TECHNOLOGY GOALS • AREAL DENSITY $\leqslant$ 10 kg/m^2 • AFFORDABLE LDR • SIZE: 1-2 m • ORBITAL STABILITY $\leqslant$ 2 μm rms • ON-ORBIT CTE $\leqslant$ 2 (10^{-6}/K) • LONG-TERM DIMENSIONAL STABILITY	• THE CHARACTERISTICS OF THE PRIMARY REFLECTOR PANELS SIGNIFICANTLY IMPACT THE ENTIRE LDR SYSTEM • RECENT DEVELOPMENTS IN COMPOSITE MATERIALS HAVE DEMONSTRATED HIGH POTENTIAL FOR LDR

TECHNOLOGY ASSESSMENT

• LIGHTWEIGHT, LOW-COST REFLECTOR PANELS NOT IDENTIFIED IN CURRENT PROGRAMS



SCHEDULE AND BUDGETARY PLAN

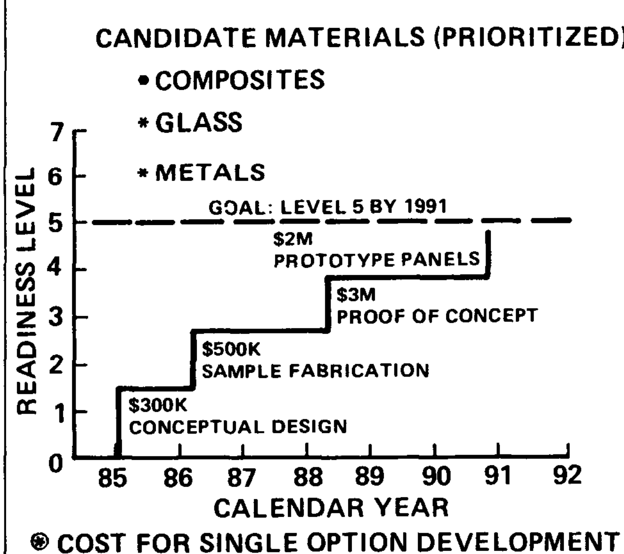


Figure E-1.- Primary-reflector panel development.

KEY ISSUES

- ACCURATE ACCOUNT FOR JOINT NONLINEARITY
- IDENTIFICATION AND ACCURATE CHARACTERIZATION OF STRUCTURAL DAMPING
- HIGH-FIDELITY NONLINEAR MODELING TECHNIQUES ADEQUATE FOR LDR NOT AVAILABLE

OBJECTIVES/GOALS

- DEVELOP AND VALIDATE AN ANALYTICAL PROCESS THAT WILL BE AVAILABLE WHICH CAN ACCURATELY PREDICT LDR μm-LEVEL DYNAMIC RESPONSES

RATIONALE

- THE EFFECTS OF JOINT NONLINEARITIES CAN BE ELIMINATED OR MINIMIZED BY DESIGNS
- EFFECTIVE USE OF DAMPING CAN REDUCE RESPONSE AMPLITUDES AND SETTLING TIMES
- HIGH-FIDELITY MODELING IS REQUIRED FOR LDR PERFORMANCE PROJECTION

ALTERNATIVE

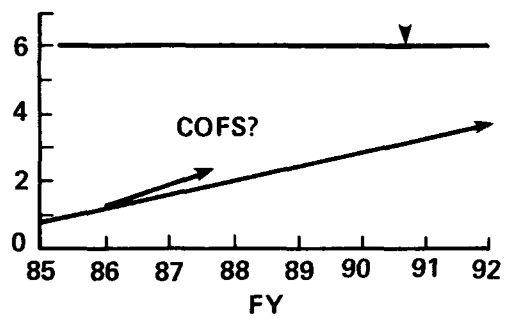
- LARGE-SCALE STRUCTURES SPACE CHARACTERIZATION

RISK REDUCTION

- PERFORM HIGHLY ACCURATE DYNAMIC SIMULATION TO VERIFY LDR REQUIREMENTS

TECHNOLOGY ASSESSMENT

- LDR-PERFORMANCE PREDICTIVE CAPABILITY NOT CURRENTLY IDENTIFIED IN PROGRAM



SCHEDULE AND BUDGETARY PLAN

TASKS

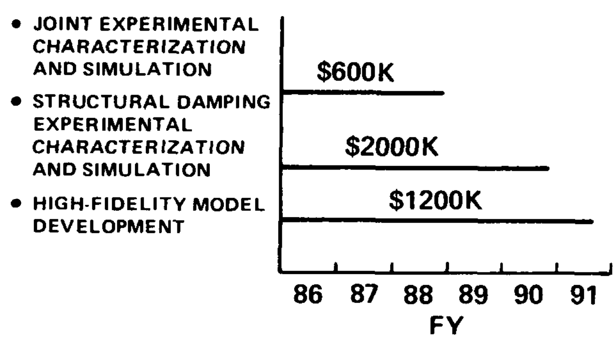


Figure E-2.- Structural system dynamic simulation.

KEY ISSUE

- THE STRUCTURE OF THE PRIMARY REFLECTOR AND THERMAL SHIELD MUST BE LOW COST AND LIGHTWEIGHT IN ADDITION TO BEING STIFF AND RELIABLE

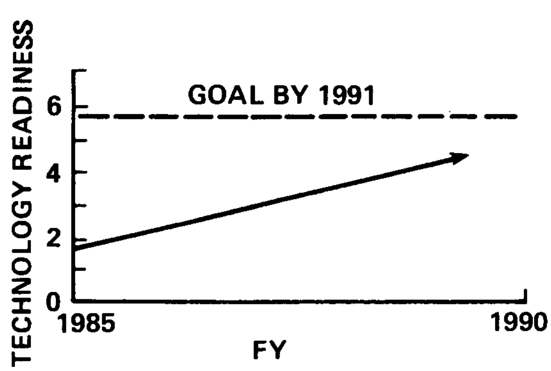
OBJECTIVES/GOALS

- PRIMARY REFLECTOR STRUCTURE $< 5\ kg/m^2$
- THERMAL SHIELD $< 1\ kg/m^2$
- NATURAL VIBRATION FREQUENCY > 1 Hz
- STRUCTURAL INSTALLED COST $<\$10,000/kg$
- PASSIVE DAMPING $> 3\%$
- DEVELOP AND EVALUATE PREDICTABLE JOINTS
- DEVELOP AND EVALUATE ASSEMBLY TECHNIQUES AND PROCEDURES
- PRIMARY STRUCTURE ACCURATE TO 100 μm rms

RATIONALE

- STRUCTURAL WEIGHT HAS A STRONG INFLUENCE ON THE TOTAL-SYSTEM COST
- HIGH-STRUCTURAL PERFORMANCE AND INHERENT OPERATIONS RELIABILITY AND PREDICTABILITY RESULT IN LOW SYSTEM COST
- EVA AND REMOTE MANIPULATION ARE CLEARLY NEEDED. TOTAL ASSEMBLY TIMES MUST BE KEPT SHORT AND BOUNDED

TECHNOLOGY ASSESSMENT



SCHEDULE AND BUDGETARY PLAN

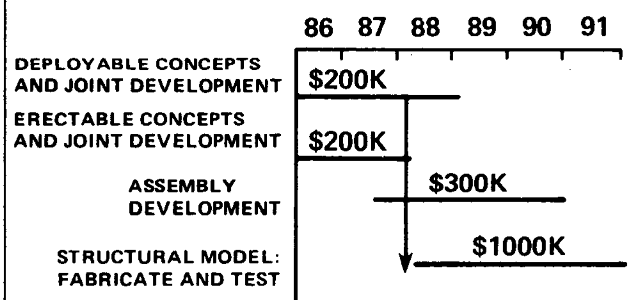


Figure E-3.- Structural concepts--deployable and erectable.

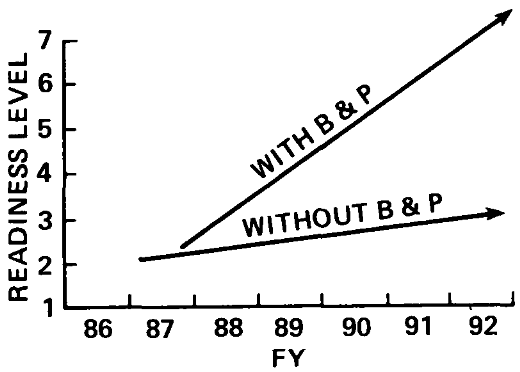
GOALS

- DETERMINE THE DYNAMIC STRUCTURAL BEHAVIOR OF THE JOINTS STRUCTURAL MEMBERS, PANELS, AND DAMPING TREATMENTS IN THE SPACE ENVIRONMENT
- VALIDATE THE LDR STRUCTURAL SIMULATION
- DEMONSTRATE CONSTRUCTION PROCEDURE

RATIONALE

- THE STRUCTURAL DYNAMICS HAS LARGE EFFECT ON PRECISION OF OPTICS
- A VALIDATED MODEL CAN BE USED TO PREDICT PERFORMANCE UNDER VARYING CONDITIONS
- REDUCES PROGRAM RISK
- FURNISHES HARDWARE-COST DATA BASE

TECHNOLOGY ASSESSMENT



SCHEDULE AND BUDGETARY PLAN

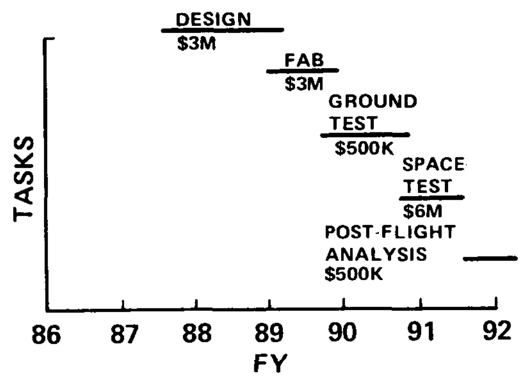


Figure E-4.- Flight experiments.

APPENDIX F

THERMAL AND POWER TECHNOLOGY PANEL REPORT

NASA Ames Research Center	Peter Kittel
Jet Propulsion Laboratory	Pete Masion
	Walt Petrick
	Manny Tward
	Bob Miyake
	Al Diner
Eastman Kodak Company	John Meyers
Fairchild Space Company	Bernie Rabb
Lockheed Missiles and Space Company	Ted Nast

LDR Thermal and Power Technology Panel

Discussion

At present, the thermal and power technology does not exist to meet the current LDR requirements. The present level of the system concept and requirements is inadequate for defining the thermal requirements. Further system studies that include thermal considerations are needed. A "point" design or designs that can be thermally analyzed would be a good start in this process. Such a design needs to evolve in an iterative process between all of the subsystems.

With the present level of requirement definition, it is not clear which of several possible technologies are best suited to LDR. Therefore, in some areas, parallel technology efforts need to be carried out, with a decision made at some later date (perhaps as late as Phase B).

The thermal aspects of LDR can be broken into several distinct regions. These are:

1. The front end, comprising the primary, the secondary, and the sunshade. The shear size of this part dictates the use of passive cooling techniques. Small amounts of power could be used for final trim. The drivers in this region are the ±1 K uniformity across the primary, the Sun- and Earth-avoidance angles, and the secondary temperature. The temperature-stability requirement is undefined.

Status: Preliminary analyses have been carried out which show that the uniformity requirement can only be met with a large sunshade and may still require some active control with heaters. The 125 K temperature on the secondary cannot be met with passive techniques.

Recommendations: More extensive modeling is needed to study the effect of all of the requirements and options. It is noted that some of the requirements may not need to be met simultaneously. For example, the uniformity requirement can be relaxed for most measurements. Thus, for those times when the ±1 K uniformity is needed, perhaps some other constraint can be changed, such as increasing the Sun- and Earth-exclusion angles, which would improve the uniformity at the expense of observation opportunities. Therefore, a second recommendation is that the requirements be reviewed to see which ones must be met simultaneously and which ones can be relaxed for certain types of observations.

2. The intermediate optical path, comprising the baffle, the beam splitter, and any other optical components between the secondary and the instruments. The driver in this region is the power dissipation, particularly if an active mirror (as in the JPL design) is used.

Status: Power and temperature requirements are unknown. For the high-power option (JPL design), an active cooler will be required. Such a long life, space-qualified cooler does not exist, but several different prototypes are under development at Goddard Flight Research Center (GSFC), JPL, and DOD. In the low-power option, it may be possible to use passive cooling. This option depends to a certain extent on which type of cooler is chosen for the instruments. The most favorable would be a single stored-cryogen cooler. The vent gas could be used to cool this subsystem.

Recommendation: First the cooling requirements need to be defined. Then the technology for this subsystem will need to be reassessed. If a mechanical cooler is required, a study of the applicability of existing development efforts needs to be done, followed by a tracking of those efforts to see whether the technology will be ready in time.

3. The instruments. The drivers here are the requirement for long-life (10-yr) single-instrument changeout on 3-yr intervals; the demountable interface and the cooling requirements range from 350 mW at 4 K to 100 mW at 2 K. The changeout requirements drive the design to separate instrument modules with their individual coolers. This separation has a large thermal impact. There are two approaches to the cooler design, (1) a passive stored-cryogen or (2) a low-power active refrigerator. The cooling requirements are in the region where it is not obvious which approach would be best. The current estimate for the instrument cooling requirements are given in Table F-I.

Status: Active coolers for these temperature and power requirements do not exist, even in ground-based applications. The required power levels are considerably lower than current ground-based refrigerstors. The stored-cryogen approach requires on-orbit resupply, which has not been demonstrated.

Recommendation: Since this is a critical part of the whole system, a parallel approach is recommended. An active cooler should be developed and cryogen resupply should be demonstrated. The requirement for separate instrument coolers should be reassessed. If the instruments could be put into a single chamber, the interface to LDR would be simplified. Furthermore, this simplification would allow the complete instrument package to be replaced with its cryogenic system every 3 yr. Such a replacement unit would use SIRTF-type technology and is within current capabilities.

4. The sub-Kelvin cooler. The driver here is the operating temperature. Above ~0.2 to 0.3 K, there are two choices: adiabatic demagnetization (ADM) or ^{3}He.

Status: ^{3}He coolers are being developed at ARC and ADM coolers are being developed at ARC and GSFC. At present, only components have been demonstrated. Space-qualified units are planned.

Recommendation: Fabricate and demonstrate space-qualified coolers.

5. Power. The driver here is the large amount of power required if active refrigerators are used, and the resulting system interactions with the large, floppy, steerable structure.

Status: Solar-cell power systems are a mature technology and are suitable if total power requirements are low (the case if passive coolers are used). If active coolers are used, the size of the solar cell panels may be unmanageably large and a more advanced power system such as planned for the Space Station may be required.

Recommendations: Study the system impacts of the power system on LDR. Accelerate the development of advanced power systems if the high-power approach is taken.

Technology-development plans have been formulated for each of the individual technologies called out in the preceding recommendations. These plans are summarized in four-quadrant charts. The charts for the front end of LDR are shown in figures F-1 through F-4. These cover the technologies involved in thermal-control surfaces, actuators, sunshade geometry and orbital constraints, and panel materials, respectively. The four-quadrant chart for the intermediate optical path is shown in figure F-5. This chart covers the technology for cooling the intermediate optics. The two technology options for cooling the instruments are shown in figures F-6 and F-7. These charts cover the passive- (stored-) and active-cooler options respectively. The chart for the subKelvin cooler technologies is given in figure F-8. Finally, figure F-9 covers the development plan for the power system.

These charts summarize the best estimates of the panel members. The charts are intended to guide the early phases of technology development for LDR. It is recommended that the charts be reviewed and modified periodically as the technologies develop and as the requirements evolve.

TABLE F-I.- HEAT LOADS

Instrument	Mass, kg	Temperature K		Heat load, mW		
		Required	Desired	Intrinsic	Aperture	Parasitic
High-resolution spectrometer, 3 mm-400 μm	200	20		300[a]		
		4	2	10	1-10	50[b]
High-resolution spectrometer, 500-200 μm	200	200			1-10	
		20		300	1-10	
Photoconductor spectrometer, 200-35 μm	200	20				200
		4	2	100	1-10	50
Fabry-Perot interferometer, 200-35 μm	180	20				200
		4			1-10	50
		2		40-80		
Grating spectrometer	150	20		100		
		4				
		2		6-40	1-10	50
Heterodyne array	200	20		1000[c]		
		4		350		
Far-infrared camera	150	20				300
		4				50
		2		30	1-10	
Submillimeter camera	200	20		200		
		4		10[d]	10	50
		0.1-0.3		0.01	small	
Beam splitter and baffle		100	70	2000-5000		

[a]May be reduced by Hemps technology to 60 mW.
[b]Conduction from 20 K.
[c]Possible heat reduction using Hemps technology to 200 mW.
[d]Estimated load caused by lower stage refrigerator.

PROBLEM/REQUIREMENTS/GOAL

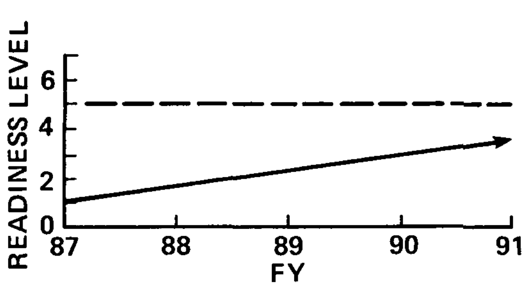
- LONG-TERM STABILITY
- CONTAMINATION TOLERANCE
- PENETRATION – MICROMETEOROID THREAT DEGRADATION
- LOW-TEMPERATURE THERMAL OPTICAL/ MATERIAL PROPERTIES

RATIONALE

- DEGRADATION OF SURFACE AFFECTS TEMPERATURE LEVEL AND ORBITAL TEMPERATURE CHANGE
- TEMPERATURE GRADIENT MAINTAINED
- CONTAMINATION AFFECTS THERMAL STABILITY
- SUPPORT CRYO/OTHER LOW-TEMPERATURE EQUIPMENT

TECHNOLOGY ASSESSMENT

- SAMPLES HAVE BEEN ORBITED (i.e., STS)
- THREAT RECOGNIZED, BUT NOT QUANTIFIED



DEVELOPMENT PLAN

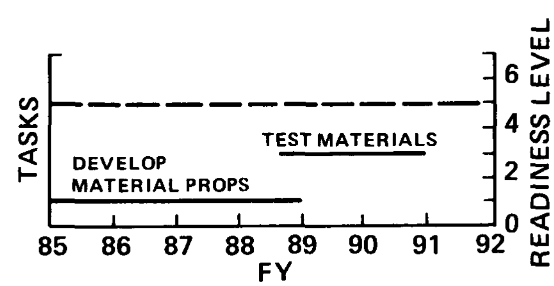


Figure F-1.- Thermal control surfaces--contamination/penetration hazzard.

PROBLEM/REQUIREMENTS/GOAL

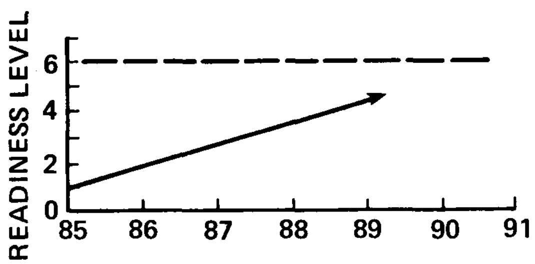
- FIGURE CONTROL MUST BE MAINTAINED UNDER THERMAL DEFORMATION EFFECTS

RATIONALE

- ACTUATORS ON BACKUP STRUCTURE COMPENSATE FOR BACKUP-STRUCTURE THERMAL DEFORMATION
- FIGURE-CONTROL ACTUATORS (ON REFLECTORS) COMPENSATE FOR PANEL THERMAL DISTORTION

TECHNOLOGY ASSESSMENT

- RELATED DOD ACTIVITIES WITH "SIMILAR" REQUIREMENTS
- LDR UNIQUE REQUIREMENTS MUST BE ADDRESSED



DEVELOPMENT PLAN

TO BE INCLUDED IN INTEGRATED FIGURE CONTROL TECHNICAL DEVELOPMENT

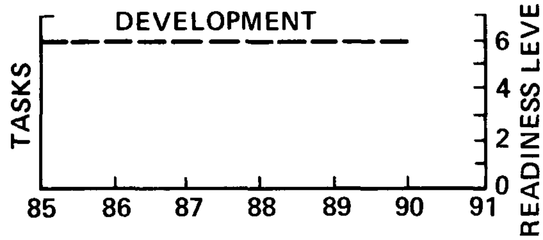


Figure F-2.- Actuator--figure control.

PROBLEM/REQUIREMENTS/GOAL

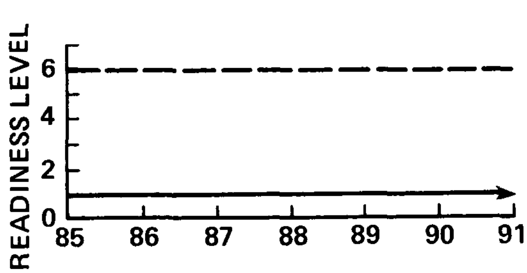
- SPACECRAFT POINTING AFFECTS SUNSHADE GEOMETRY; THUS REFLECTOR THERMAL ENVIRONMENT AFFECTS TEMPERATURE LEVEL, UNIFORMITY

RATIONALE

- TRADEOFF BETWEEN SUNSHADE AND ORBITAL CONSTRAINTS SHOULD BE ASSESSED AS THEY AFFECT SCIENCE OBJECTIVES
- THE EFFECTS OF ORBIT INCLINATION AND THERMALLY DICTATED SLEWING

TECHNOLOGY ASSESSMENT

- RELATED TO MISSION PLANNING



DEVELOPMENT PLAN

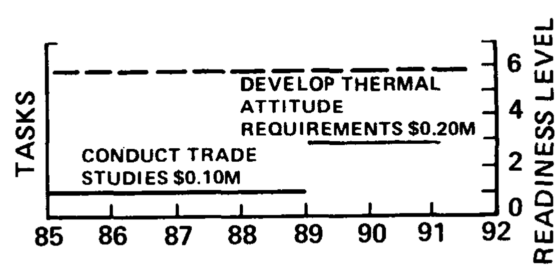


Figure F-3.- Sunshade geometry/orbital constraints--thermal.

PROBLEM/REQUIREMENTS/GOAL

- IDENTIFY STABLE PRIMARY REFLECTOR MATERIAL THAT MEETS THE LDR SCIENCE REQUIREMENT – PANEL THERMAL DISTORTION ~ 2 μm rms
- PRIMARY TEMPERATURE LEVEL – 200 K OR LESS
- PRIMARY TEMPERATURE GRADIENT – ±1.0 K (GOAL)

OBJECTIVE

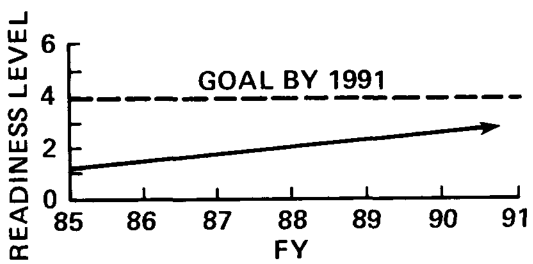
- DEVELOP PRIMARY REFLECTOR MATERIAL TO MEET REQUIREMENTS
- REFLECTOR MATERIAL DEMONSTRATION

RATIONALE

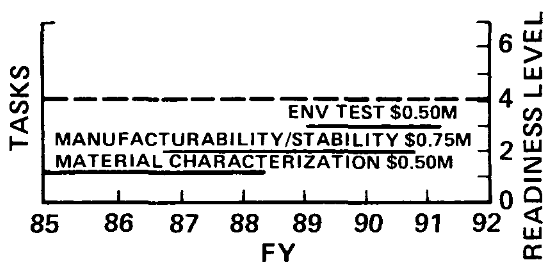
- CTE CHARACTERIZATION OF MATERIALS THAT WILL MEET LDR SCIENCE REQUIREMENTS (i.e., TAILORABILITY OF CTE)
- DEMONSTRATION OF MANUFACTURING REPEATABILITY
- LONG-TERM STABILITY

TECHNOLOGY ASSESSMENT

- SMALL-SIZE TECHNOLOGY DEVELOPMENT PANELS MADE THAT DEMONSTRATE MEETING LDR-THERMAL STABILITY REQUIREMENTS. FULL-SCALE DEMONSTRATION REQUIRED
- INITIAL ANALYTICAL CAPABILITY DEMONSTRATED. ADDITIONAL EFFORT REQUIRED TO VERIFY FULL-SCALE PANEL TAILORABILITY
- MANUFACTORABILITY AND LONG-TERM STABILITY HAVE NOT BEEN DEMONSTRATED FOR COMPOSITES



DEVELOPMENT PLAN



TOTAL $1.75 M

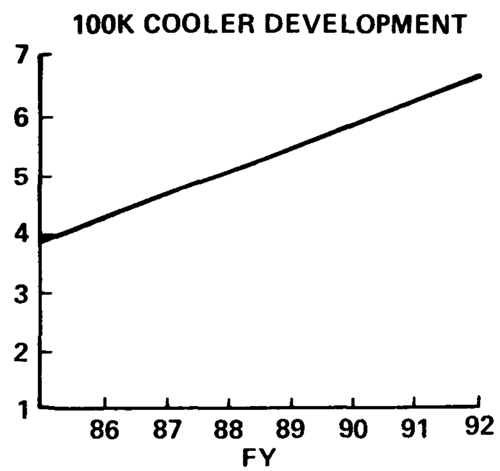
Figure F-4.- Panel materials--primary.

PROBLEM/REQUIREMENT/GOAL

- THE REAR OPTICS MUST BE COOLED TO 100 K. THE PRESENT EXISTING REFRIGERATOR TECHNOLOGY DEVELOPMENT ACTIVITY WILL BE INVESTIGATED FOR TECHNOLOGY THAT IS APPLICABLE TO THE LDR NEEDS. THE NECESSARY ANALYSIS MUST BE PERFORMED BASED ON DEMONSTRATED TECHNOLOGY TO ASSURE THE PRESENT TECHNOLOGY CAN BE APPLIED TO THE LDR NEEDS

RATIONALE

- AT PRESENT, THERE ARE NO LONG-LIFE (3-yr) SPACEBORNE COOLERS AVAILABLE TO SATISFY THE LDR NEED



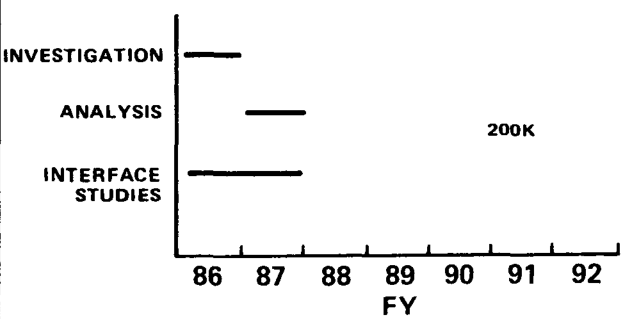


Figure F-5.- LDR intermediate optics cooling.

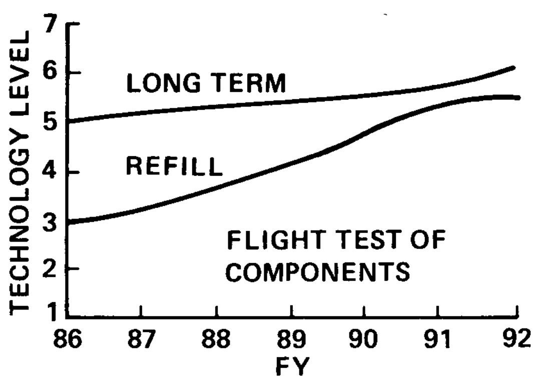
PROBLEM/REQUIREMENT/GOAL

- REFILL LIQUID He DEWAR IN ORBIT NOT YET DEMONSTRATED
- LONG-TERM STORAGE; 10-yr LIFE AT 350 mW

RATIONALE

- REQUIRED CRYOGEN STORAGE FOR 10-yr LIFE REQUIRES LARGE MASS
- ALTERNATIVE – REPLACE TANK WITH NEW INSTRUMENT PERIODICALLY
- SIMPLER INTERFACE (INSTRUMENT MODULE TO LDR) THAN ACTIVE SYSTEM:
  - NO POWER
  - NO HEAT REJECTION

SOA EVALUATION



PLAN

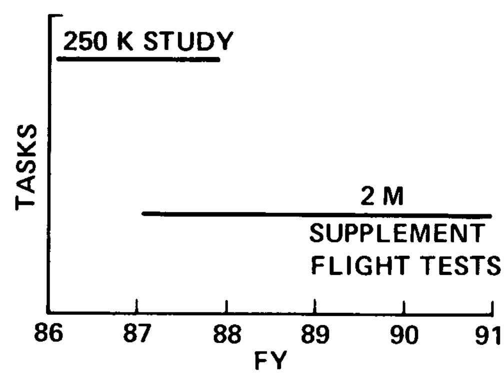


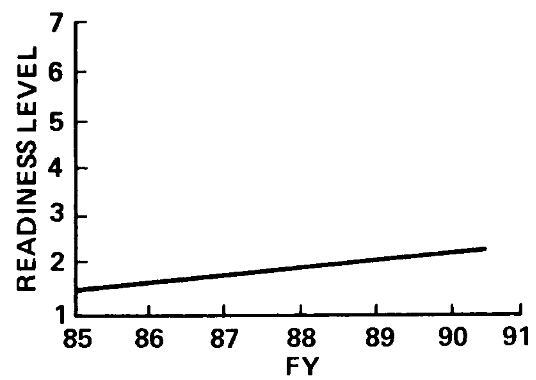
Figure F-6.- Instrument cooling subsystem (stored cryogen).

PROBLEM/REQUIREMENT/GOAL

- DEVELOP A 4 K, 3-yr REFRIGERATION SUBSYSTEM WITH A 350-mW MAXIMUM HEAT-LOAD CAPACITY AND A 2 K, 3-yr REFRIGERATOR SUBSYSTEM WITH A 100-mW MAXIMUM HEAT-LOAD CAPACITY
- INVESTIGATE EXISTING 12 K REFRIGERATION TECHNOLOGIES FOR APPLICABILITY TO LDR REQUIREMENTS OF 1 W AT 20 K AND 5 W AT 100 K
- INTERFACE REFRIGERATION SUBSYSTEMS WITH INSTRUMENT AND SPACECRAFT SYSTEMS TO INCLUDE THE FOLLOWING ISSUES:
  - INDEPENDENT, COLD INSTRUMENT CHANGEOUT
  - POWER, SIZE, WEIGHT
  - CONTAMINATION
  - VIBRATIONS, MICROPHONICS
  - FIELDS

RATIONALE

- LOW-TEMPERATURE (2 K TO 12 K) REFRIGERATION TECHNOLOGY IS NOT BEING DEVELOPED FOR SPACEBORNE APPLICATIONS
- A. F. REFRIGERATION TECHNOLOGIES NOT DIRECTLY APPLICABLE TO LDR NEEDS AND REQUIREMENTS
- LESS MASS THAN STORED SYSTEM



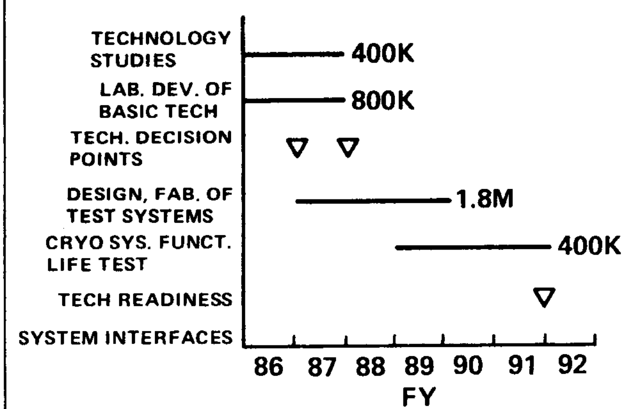


Figure F-7.- Instrument cooling subsystem (active).

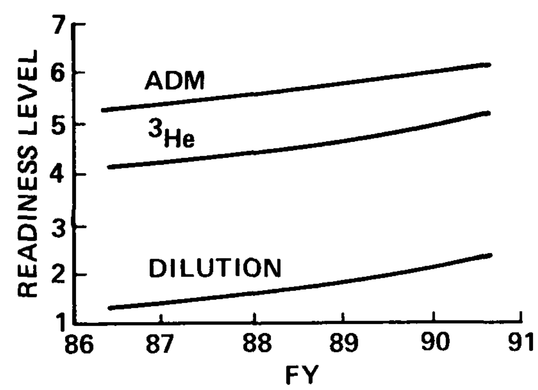
REQUIREMENTS

- PROVIDE COOLING FOR BOLOMETER (ARRAYS) IN 50-300 mK RANGE
- STAGE FROM 2-4 K
- LONG LIFE
- PRINCIPAL LOAD IS PARASITE

RATIONALE

- EXTENSIVE COMPONENT TESTING HAS BEEN DONE ON ^3He AND ADM
- SYSTEM LEVEL DEMONSTRATION OF SPACE UNIT DESIRABLE
- DILUTION REFRIGERATOR IS REFRIGERATOR OF CHOICE IN LAB, BUT SPACE UNIT IS AT CONCEPT LEVEL ONLY
- ^3He LIMITED TO A MINIMUM TEMPERATURE IN 0.2-0.3 K RANGE

ASSESSMENT



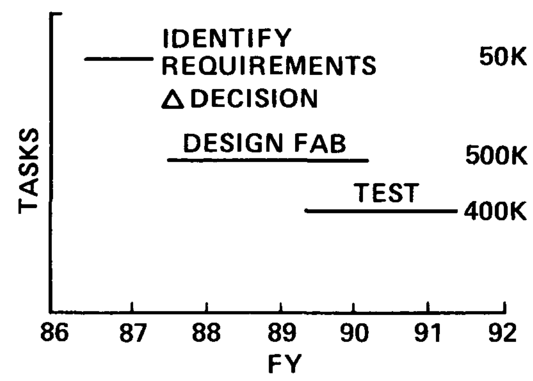


Figure F-8.- Sub-Kelvin coolers.

REQUIREMENT/OBJECTIVE

- 7-kW COOLER POWER
- 1-kW S/C COOLER — 10-kW TOTAL POWER
- 2-kW S/C POWER
- SOLAR ARRAY POWER — 25 kW
- SOLAR ARRAY AREA — $230 m^2$; SINGLE GIMBALLED
- SOLAR ARRAY BOOM — 10 m EACH SIDE IF SOLAR EXCLUSION ANGLE 90°

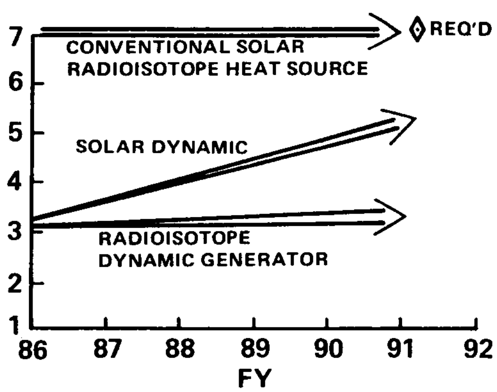
RISK AREA

- FLEXIBLE STRUCTURE PROVIDES SYSTEM DYNAMIC INPUTS WHICH DEGRADES STABILITY AND SETTLING TIME

PERSPECTIVE; PLAN/RATIONALE

- SOLAR EXCLUSION ANGLE 90° WILL AMELIORATE PROBLEM
- FUTURE STUDIES OF SYSTEM DYNAMICS AND TRANSIENT RESPONSE SHOULD INCLUDE ALTERNATE POWER SYSTEMS:
  - SOLAR DYNAMIC (TO REDUCE AREA)
  - RADIOISOTOPE DYNAMIC (TO ELIMINATE OPERATIONAL RESTRICTIONS OF SOLAR POINTING; TO REDUCE DEPLOYED AREA)

TECHNOLOGY ASSESSMENT



DEVELOPMENT PLAN

- SOLAR DYNAMIC: SPACE STATION DEVELOPMENT; NO AUGMENTATION FOR LDR PLANNING
- RADIOISOTOPE DYNAMIC: DEPENDING ON RESULTS OF SYSTEM DYNAMIC ANALYSES; TECHNOLOGY DEVELOPMENT REQUIREMENT \$20-30 M TO LEVEL 5 IN 1991

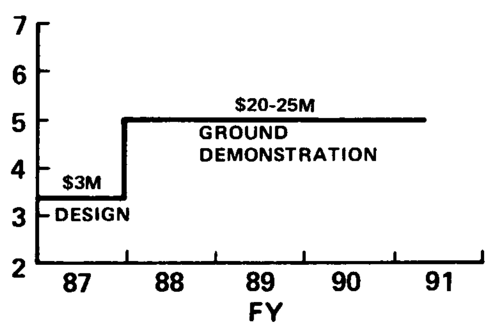


Figure F-9.- Power.

C-2

APPENDIX G

SCIENCE INSTRUMENTS PANEL REPORT

Introduction

The primary task of the Science Instruments panel was to prepare a technology augmentation plan for readying those instrument technologies that are critical to LDR. In addition, the panel examined those aspects of the LDR instrument complement that tax the resources of other spacecraft systems, and examined alternative instrumental approaches.

Neither contractor reports nor the JPL report define the need for special instruments and instrument technology. This subject was considered at the 1982 Asilomar meeting. However, a subsequent report by the SCG for LDR edited by Phillips and Watson provided the indepth analysis needed for the panel to perform its assignment. The Phillips/Watson report was augmented by preliminary abstracts of a report on submillimeter instrumentation which is in preparation at the GSFC.

Approach

The Phillips/Watson report addressed five issues of present interest: science requirements, comparison of instrument techniques, a strawman instrument complement, technology assessment, and technology development recommendations. The panel reviewed and, where appropriate, reassessed the findings and recommendations of the Phillips/Watson report. The review was not comprehensive and no particular attempts were made to critically assess the capabilities and performance goals of the strawman instrument complement. End-to-end performance of the LDR instruments is poorly understood at this time and issues such as background subtraction remain poorly understood.

The LDR strawman instrument complement (fig. G-1 and table G-I) specified by Phillips/Watson consists of eight instruments. It may be possible to reduce the number of instruments and still maintain the same overall capability. One approach is to extend the capabilities (range of frequency and frequency resolution) of individual instruments. Another is to deploy four of the instruments in the initial instrument module; after 2 to 4 yr of operation, these instruments would be replaced with four new instruments. However, we have used the eight-instrument strawman complement as the baseline for our technology plan.

Demands on System Resources

Resource requirements for the strawman payload were discussed in the Phillips/Watson report and reevaluated by the panel. Some of these requirements were iterated with other panels--the Science panel, the Systems panel, and the Thermal Power panel.

Power/Mass- Power/mass estimates for the LDR instruments are quite uncertain. These estimates were not updated by the panel. Power data were not determined explicitly. A summary is given in table G-II.

Temperature/Heat Loads- The required temperatures and the corresponding heat loads were discussed in some detail by Phillips/Watson (table F-I). The panel attempted to more accurately characterize the thermal characteristics and document the basis for those estimates so that they could be updated in the context of technology improvement. A summary is given in table F-I.

Data Processing/Communications- Data processing and communications needs are quite uncertain. Some of the considerations affecting these needs are outlined below.

The direct-detection-array instruments would use much smaller array sizes (64×64) than the Hubble Space Telescope (1800×1800 in each of two cameras). However, the readout rates for this high-background instrument will be much higher than for ST. It is likely that for the broadband instruments integration times may be as short as a few milliseconds. It would be appropriate to coadd these data to generate signals of adequate signal-to-noise ratio prior to communicating the data to the ground station.

The heterodyne instruments generate an intermediate frequency (IF) signal with bandwidth from 1 to 10 GHz. This signal can be processed into power spectra on the spacecraft which results in a large reduction in required data rate. This process is the approach used by the NASA Upper-Atmosphere-Research-Satellite/Microwave Limb Sounder. Analog processing techniques such as Surface Acoustic Wave Filters and acousto-optical spectrometers are one way of accomplishing the data collecting and the possibility of using digital Very High Speed Integrated Circuit technology was recently assessed. There have also been suggestions of relaying the IF signal to a ground processing station. Our judgment is that processing aboard LDR is most attractive at this time and that the analog approaches look most attractive. However, hybrid and all digital approaches may have application, in particular specialized applications.

Instrument Configuration- The Phillips/Watson report describes an instrument configuration in which each of the eight instruments is housed in an independent module $2 \times 1.3 \times 0.95$ m in size (fig. G-2). Instrument modules can be changed independently in orbit and a generic cooler or liquid helium pump provides coolant to individual modules. Each instrument is divided between cryogenic and ambient compartments (the subdivision shown in fig. G-2 is arbitrary). An eight-position pick-off mirror relays light to the eight instruments. Only one instrument can be operated at any one time.

The Thermal/Power Panel has considered the pros and cons of cooling the instrument payload with a mechanical cooler through the use of stored cryogens. The

Instrument Panel confined its attention to the thermal control of the instruments. Two configurations were compared: each instrument in an individual cryogenic envelope and the entire instrument module enclosed in a common cryogenic envelope (fig. G-3). No definite preference can be established until there is much more detail on the payloads, the actual number of instruments in the module, and the frequency of change out.

Science Instrument Technology Needs

Observational time will be LDR's most critical resource. Observation and mapping of faint astronomical sources requires long observation times, even with the enormous collecting area of LDR. Instrumental techniques that can reduce the time needed for making observations are equivalent to increasing the collecting area of the telescope. Conversely, instrument degradation is equivalent to diminishing the collecting area of the telescope. Instrument performance has tremendous leverage on the performance of the entire system. Enhancements can substantially reduce the total time needed to make an observation as well as the operational complexity of carrying it out.

Improved Detector Sensitivity- Improvements in the sensitivity of individual detectors can have tremendous payoff for LDR. A comparison with the current situation for astronomy in the visible is instructive. In that spectral region, available detectors have a quantum efficiency approaching unity and, except for the faintest sources, detector-sensitivity improvements will have only a marginal impact. For this reason, in the future the emphasis must be on increasing the collecting area. For the spectral region of interest to LDR, current detectors are far from the quantum limit and tremendous advantages will be realized from sensitivity improvement.

Arrays- An array of η-sensing elements of equivalent performance to the best individual sensor will reduce the time needed to map a given area of the sky by a factor of η times. The importance of this enhancement to LDR's capability to form continuum and spectral line mapping is discussed in the Science Panel report.

The full factor of η advantage will be realized only if the sensors in the array are of equivalent performance to the best individual sensors. This situation is virtually never realized in practice and it is desirable to make η large so that even with a degradation in the performance of the sensors there is still a substantial net advantage to using the arrays. Also, arrays reduce, or in some cases entirely obviate, the need for mechanical scanning.

The array sizes usable by LDR are limited now by the available technology, but will ultimately be constrained by the focal-plane area. In spectral instruments, one dimension of an array can be used to form the spectrum. The improvement in data-gathering efficiency through the use of arrays in the direct-detection instruments is illustrated in figure G-4.

Heterodyne Instrument/Heterodyne Arrays- The heterodyne instruments on LDR also provide an array advantage, but the spatial and spectral multiplexing is more complex than it is with a direct-detection instrument. The canonical heterodyne array spectrometer diagrammed in figure G-4 illustrates some of the concepts and technology relevant to the use of arrays in this type of instrument.

Simultaneous Use of Instruments- In the LDR instrument package design of figure G-2, only one instrument can be used at a time. This results in an inefficient use of telescope resources. Approaches to using more than one instrument at a time should be considered.

For the point-detector instruments (1, 2, 3), each of which uses only a small portion of the area of the focal plane and covers a different frequency region, it should be possible to implement systems for sharing the telescope by using dichroic filters and different parts of the focal plane. For a mapping task there should be negligible degradation of performance.

Each of the area array imagers on LDR will occupy most of the available focal-plane area. However, when the spectral coverage is nonoverlapping, it should be practical to time-share the telescope by using dichroic mirrors with minor performance degradation.

The ground-based astronomical community has avoided the use of beam splitters and dichroic filters to facilitate time sharing for a variety of reasons. The systems have seldom worked satisfactorily and have significantly degraded the performance relative to that achievable with a single instrument and a dedicated telescope. A second reason is that target objects may be of prime interest for investigations with one instrument, but not with others. Finally, even when there is value to observations with two or more instruments, the required observing times may be discordant so that there is little advantage to simultaneous operations.

The use of dichroic filters or focal-plane sharing should receive serious investigations for LDR. That investigation should include a critical assessment of performance degradation in light of ground-based experience.

Science Instruments--Technology Augmentation Plan

The technology for building the instruments needed by LDR does not exist today and it will not come into being without a deliberate program to develop it.

Some of the observational needs for LDR simply cannot be performed at all today, even in the laboratory. In other cases, laboratory and ground-based observatory capabilities exist or could be built, but the technologies require far too much power and are far too unreliable to be flown in space. For many detector systems, performance falls orders of magnitude short of that of ideal quantum-limited detectors and so most of the radiation collected by the sophisticated reflector system would, in effect, be discarded. Finally, the arrays of detectors which have become a standard feature of large telescopes operating in other spectral regions and which enhance the speed of data acquisition by many orders of magnitude do not exist for the submillimeter region. The arrays are a critical enabling technology for using LDR as a mapping instrument.

These technology needs can be met by building on the core OAST programs in submillimeter heterodyne technology and far-IR direct-detection technology. Augmentations to that core program have been identified for an FY 1987 OAST New Initiative. NASA centers, other government laboratories, universities, and industry all have important contributions to make to the core program and the augmentation program.

An instrument definition and development program is also needed to guide and stimulate the development of the component-level sensor technologies. The program would lead to a refinement of the performance requirements imposed on components so that these programs can be focused on specific devices as they mature. The development of advanced-instrument systems technology is an inherent part of this instrument definition effort (table G-III).

The areas of component technology needed for LDR instrumentation have been grouped into two general categories: heterodyne technology and direct-detection technology. These categories parallel the corresponding instrument types represented by the strawman payload. The science instruments panel divided each of these categories into three subcategories (fig. G-5) and characterized the state of technology development in each subarea. The development coding scheme used by Phillips and Watson was also used here. A comparison of these assessments of the state of the relevant technologies appears in figure G-6.

Agreement was close. Differences stemmed more from the recognition of new demands on the technology than from disagreements on the status or promise of any given technology development. These ratings refer to the character of the work needed to bring the technology to a state of readiness and not to the relative importance of these developments. Next, we review the technology status and outline a technology task plan to meet the needs of LDR. For the component technology categories of figure G-5, a set of funding task plans has been developed (fig. G-7). Funding estimates in each area were made at Asilomar and subsequently, as part of a NASA new-initiative exercise, were revised downward to the levels summarized in figures G-8 and G-9. Further work is needed to place these estimates on firmer ground and this process will be undertaken by the NASA Sensor Working Group during the next 12 mo.

In the remainder of this document, the state of the individual technologies is examined. A detailed program plan is included here for only one of the six areas. This plan and the remaining five plans will be reviewed by the members of the Asilomar panel and the NASA Sensor Working Group.

<u>Heterodyne Technology</u>- At present, the technologies needed to perform submillimeter observations from space do not exist. Anticipating the needs of LDR, the NASA/OAST initiated a program of submillimeter component development. The content of that program was described by panel representatives from JPL and GSFC. It should

be realized that the present OAST program addresses space science requirements in addition to those of astrophysics. Reports were also heard on the status of Department of Defence (DOD) activities in submillimeter heterodyne technology: a report on a recent NASA-DOD meeting on submillimeter/millimeter technology (F. De Lucia) and on activities at Lincoln Laboratories (G. Sollner).

Mixers: To cover the spectral region of interest to LDR, several mixer technologies are needed. At present, for most of the submillimeter region only Schottky technology is usable (fig. G-10(a)). The superconductor-insulator-superconductor (SIS) mixer exhibits superior performance at the lowest submillimeter frequencies. Germanium photoconductor technologies appear to be close to a successful demonstration for the highest frequencies. With vigorous development, we project that the domain of usability of the SIS and photoconductor technologies will be extended (fig. G-10(b)).

As well as the advantage of higher performance potential, the SIS and photoconductor technologies show great promise for the development of arrays. As noted earlier, arrays are essential for the efficient use of LDR's observational resources.

Objectives and rationale for a plan for mixer development are outlined in figure G-8.

Local Oscillators: Local oscillators are needed to cover the same spectral range required for the mixers. No single technology exists today for covering this broad spectral range and we cannot count on one single technology for the future. However, several promising technologies have been identified and intensive development is needed. A comprehensive discussion of local oscillator alternatives follows.

Four particularly promising approaches have been identified for vigorous development:

1. Backward-wave oscillators (BWO) have been developed in Europe and the Soviet Union. A NASA-sponsored development of a miniaturized device at NASA Lewis Research Center, Lincoln Laboratories, and the University of Utah shows exceptional promise and work on it should be intensified.

2. The molecular laser is not a new device, but it has never been developed in a form suitable for use in space. A research effort at GSFC is directed in part at this objective. This effort should be better funded and more sharply focused in order to develop as a viable alternative to the BWO approach.

3. The quantum well oscillator (QWO) is the most promising of a number of newer ideas that are not yet demonstrated on the ground. However, as solid-state devices, this concept should offer the advantage of compactness, ruggedness, low power and extended lifetime. However, substantial technical problems in device physics and microwave technology must be mastered before a QWO is realizable. The

NASA program involving JPL, GSFC, and Lincoln Laboratories is addressing these problems.

4. Frequency multipliers can also be used for generating the high frequencies that are difficult to produce with fundamental oscillators such as the BWO or existing solid-state oscillators (e.g., Gunn diode). Frequency multipliers are being used on an upcoming space mission, the Upper Atmospheric Research Satellite. For LDR the frequency range needed is much higher and there are substantial technical challenges to be overcome. Nevertheless, the frequency multiplication approach is likely to be the first technology to become available for the lower-frequency end of the submillimeter spectral band.

Although these technologies appear to be the most deserving of emphasis at this time, a continuing reassessment of the situation is needed. To provide the impetus for getting these local oscillator technologies to a state of readiness, we also advocate a 3-yr program cumulating in thorough review of progress and the selection of the most promising devices for prototype in FY 1987.

These activities will need additional support if they are to mature in time for LDR.

Amplifiers and Spectrometers: Amplifiers for the IF signal generated by the mixing devices and spectrometers for analyzing the spectral content of that signal are critical elements in the submillimeter spectrometer and one for which new enabling technologies have important contributions to make. Two devices most noteworthy are listed:

1. High Electron Mobility Transistor (HEMT). The HEMT device is a transistor suitable for amplifying the high-frequency signals in the IF output of submillimeter heterodyne mixers. These devices are currently under development for the JPL Deep Space Network, but are not expected to receive extensive development for commercial or military applications. Development of these devices would have several benefits to the LDR heterodyne instruments: lower heat loads in the focal plane (particularly for array instruments), higher bandwidth, and lower noise.

2. Multichannel IF Spectrometers. The current technology in space-qualified IF spectrometers requires large amounts of power per channel. For the large number of channels desired for LDR, the power and physical space requirements will restrict the number of channels. These constraints will be most severe for heterodyne arrays where a large number of filters would be needed to cope with the volume of data generated by the instrument. The acousto-optical spectrometer (AOS) has been developed to analyze a single spectral band of data from a single mixer. To process the data from an array of mixers, a corresponding array of spectrometers is needed. The AOS technology appears to be adaptable to this need.

Developmental Philosophy: The NASA activities in submillimeter technology are focused at three centers: JPL, GSFC, and Lewis Research Center (LeRC). In-house work is funded and a portion of the funding is directed toward other government laboratories, industry, and universities. The panel, with a representative from three of these arenas, felt that the current approach to development was working satisfactorily, but that it would be enhanced by periodic overview by disinterested experts in the relevant fields. The current program at OAST is restricted by charter to component development. The panel felt that conceptual design, definition, and breadboarding work on instruments and their use in actual observing environments is needed to focus the component technology efforts toward firmer performance specifications. This type of activity seemed to belong more properly in the domain of OSSA and should have a substantial university participation.

Direct-Detection Technology

Direct-detection instruments for LDR will be able to take advantage of the SIRTF heritage. However, the LDR needs for instruments with larger arrays operating at higher backgrounds poses significantly new demands on instrument technologies including a need for new concepts in long-wavelength focal planes and readouts and a need for improved signal-processing electronics.

Detector Arrays- For the region from 30 to 200 μm there is a need for arrays in doped germanium (Ge) up to 64 × 64 pixels in size, which achieve or approach the performance state-of-the-art doped silicon (Si) arrays at shorter wavelengths.

For 30 to 50 μm, Ge:Be (Germanium:Beryllium) appears to be the most promising material and its performance has now surpassed that of Ge:Ga (gallium) in this spectral range. Between 50 and 100 μm, Ge:Ga remains the detector material of choice, but to achieve spectral sensitivity from 100 to 200 μm, the material must be stressed. An alternative approach to stressed Ge:Ga is the use of the blocked-impurity band (BIB) structure in Ge:Ga. Recent development work in a collaboration between JPL and Hughes Carlsbad has resulted in a demonstration of spectral response for 100 to 200 μm without any requirement for stress. Beyond 200 μm, bolometers fabricated in either Si or Ge remain the only proven technology although some promising photoconductive techniques are being investigated.

If the image quality of LDR were adequate below 30 μm, large (128 × 128) arrays of high-performance detectors could be included as submodules in the LDR focal plane. The LDR environment is rather similar to those of some DOD systems for which much of this substantial technology base was developed. The extremely low, dark current levels required for SIRTF arrays will not be required for LDR, which is a significant technological simplification. Mercury cadmium telluride (HgCdTe), indium antimonide (InSb), and Si:x BIB (blocked impurity band) detectors all may have domains of applicability here.

Additional requirements for LDR include substantial well capacities for arrays, and low-power dissipation and low noise for readout electronics.

Optics, Mechanisms, and Cryogenics- LDR needs include Fabry-Perot filters for high spectral resolution ($\lambda/\Delta\lambda \sim 10^4$), narrow-band filters for beyond 30 μm, and cryogenic mechanisms. These needs are elaborated upon in a more complete report that is in preparation.

Supporting Electronics and Computational Capability for Direct-Detector Arrays- A substantial amount of work typically goes into designing, building, and optimizing the electronics necessary to drive and read out integrated arrays, as well as developing the data systems necessary to acquire and to efficiently organize the data which streams out of these arrays. For LDR, rugged, space-qualified, low-noise versions of these electronics, which even for traveling-field systems can occupy multiple equipment racks, will be needed. It is estimated that a raw-data rate of about 120 Mb/sec would be generated by a 64 × 64-Ge:Ga array read at 2500 frames/sec. It is clearly desirable to also add successive frames to build up adequate statistics, and to manipulate individual and long-term-averaged frames for flat-fielding, chopping, nodding, charged-particle hit, rejection, and other functions. As a beginning, a careful study of these requirements should be conducted; this should obviously consider the present and projected advances in microprocessor technology.

Thoughts on Development Philosophy- For a project of the size, cost, and scientific importance of LDR, an aggressive and forward-looking development program must be carried out. Full advantage of the experience gained on NASA (e.g., SIRTF, COBE) and DOD projects must be taken, but the unique spectral-array size and throughput considerations of LDR will require unique solutions. To help assure success for LDR, it is recommended that the following approach (principles) be followed:

1. For each of the instruments conceived for the Phillips/Watson Report, a strawman focal-plane design was identified. These designs should be treated as candidates rather than as givens. Even though the selections were consistent with the state of the art, various new concepts should also be considered. Advanced concepts would include, for example, a switched-field-effect transistor readout structure in Ge or GaAs, or other novel but promising detector designs. NASA should make its needs known to the widest possible community of device experts, including those in universities, industry, and government, and should support the development of multiple approaches wherever possible, through the early stages of the development. Increases in scientific return of factors of many are possible with good, well-executed ideas in this complex and rapidly moving discipline.

2. The laboratory characterization of LDR arrays should include testing with energetic particles over the range of backgrounds expected for LDR. Strategies for minimizing or, in some cases, "living with" radiation effects must be developed. Strategies include techniques for annealing the charge deposited on passage through such regions as the South Atlantic Anomaly.

3. Laboratory testing must be complemented with an appropriate level of telescope demonstration (and precursor mission) activity. It has been shown repeatedly that a real astronomical setting reveals device shortcomings not readily apparent in the laboratory. Collaborations between device physicists, device evaluators, and astronomers are to be encouraged.

4. Management and direction of the program is pivotal to its success. We suggest that some form of "expert panel" be used to guide the course of the program and to assist in selecting approaches as the field of candidates must be narrowed.

5. SIRTF devices, wherever possible cr applicable, should be evaluated under both low (SIRTF) and moderate (LDR) background conditions. Evaluations should be done in the near term, and it should not require significant time or expense, but could establish highly important technology benchmarks for future developments.

TABLE G-I.- LDR STRAWMAN INSTRUMENT COMPLEMENT

No.	Instrument	Type	Wavelengths
1	High-resolution spectrometer	Superconductor-insulator-superconductor (SIS) multichannel heterodyne receiver	3 mm - 400 μm
2	High-resolution spectrometer	Schottky diode multichannel heterodyne receiver	500 - 200 μm
3	High-resolution spectrometer	Photoconductor multichannel heterodyne receiver	200 - 35 μm
4	Medium-resolution spectrometer	Fabry-Perot interferometers with imaging detector arrays	200 - 35 μm
5	Medium-to-low-resolution spectrometer	Multichannel grating spectrometers	200 - 35 μm
6	Heterodyne array	SIS array	?
7	Far-infrared camera	Photoconductor arrays, broadband filters, interference filters	200 - 35 μm (5 - 1 μm)
8	Submillimeter camera	Bolometer arrays, broadband filters, interference filters Fourier Transform Spectrometer	1 mm - 100 μm

TABLE G-II.- LDR STRAWMAN INSTRUMENT COMPLEMENT: MASS AND DATA RATE

Instrument No.	Total mass, kg	Raw data rate, Hz
1	200	$1\text{-}5\times10^{9}$
2	200	$1\text{-}5\times10^{9}$
3	200	$1\text{-}5\times10^{9}$
4	180	2×10^{8}
5	150	2×10^{8}
6	200	$1\text{-}5\times10^{11}$
7	150	2×10^{8}
8	200	2×10^{8}

TABLE G-III.- SCIENCE INSTRUMENTS--TECHNOLOGY DEVELOMENT PRIORITIES

Technology classification	Instrument type	Enabling technology	Priority
Components and devices	Heterodyne	Mixers/detectors	High
		Local oscillators	High
		Amplifiers and spectrometers	High
Detectors	Direct detection	Detector arrays	High
		Optics/mechanisms	Medium-high
		Support electronics	Medium-high
Systems technologies	Heterodyne and direct detection	Instrument definition	High
		Instrument systems technology	High

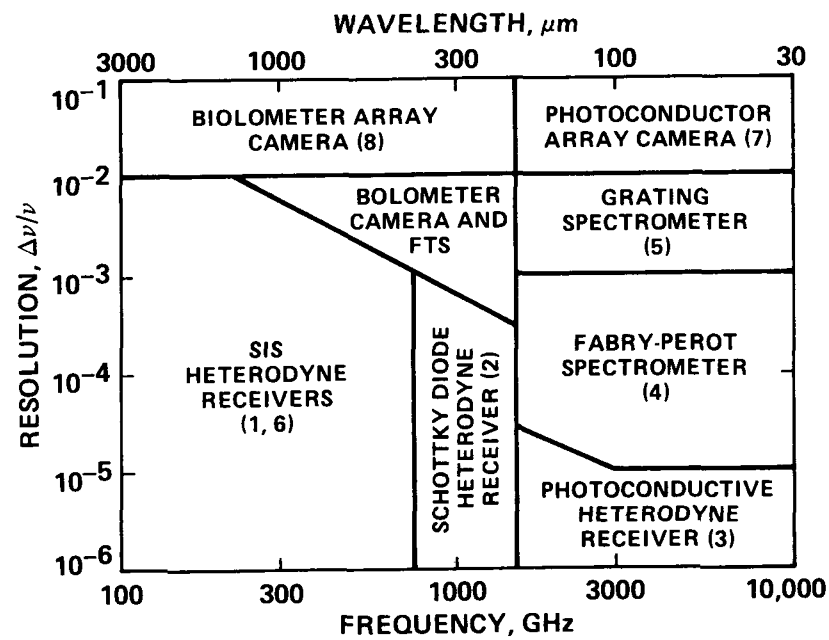


Figure G-1.- Frequency/frequency-resolution domain.

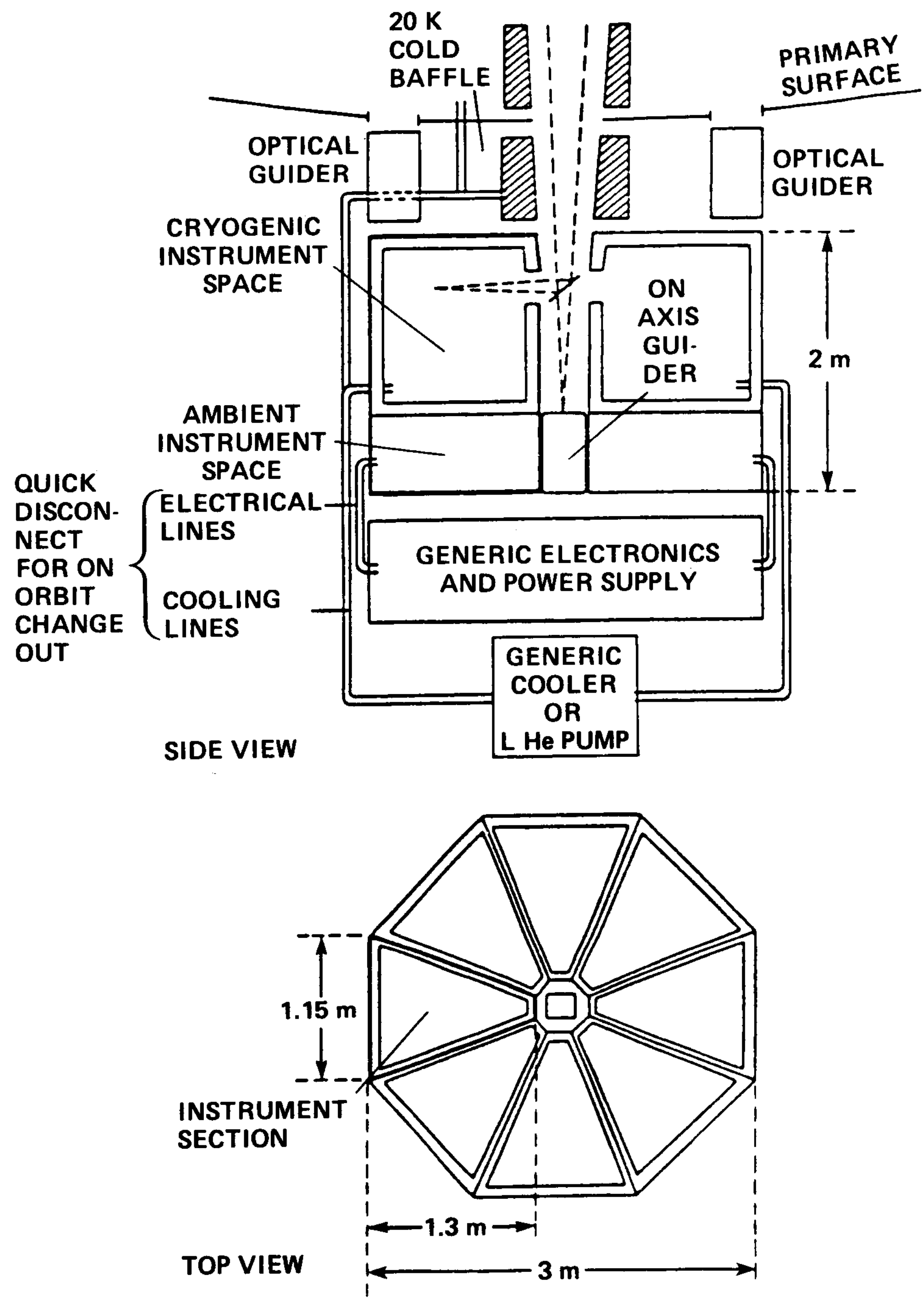


Figure G-2.- Strawman instrument configuration.

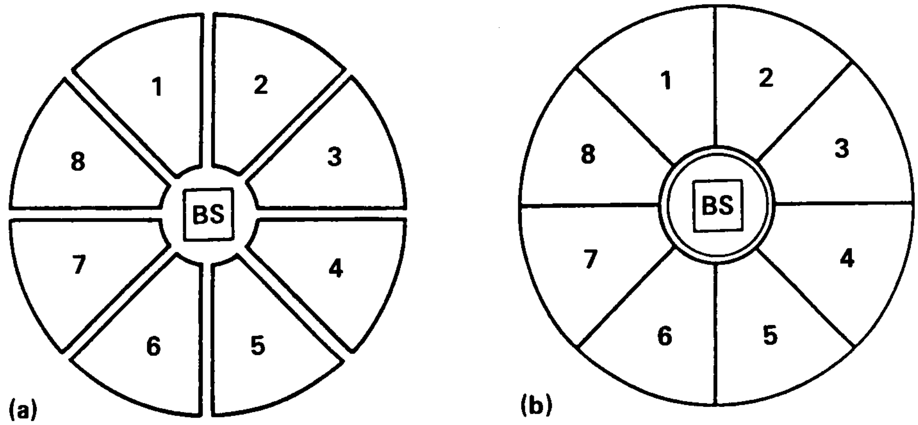


Figure G-3.- Science instruments configuration. (a) Individual instrument cryoenvelope; (b) instrument module cryoenvelope. BS = beam splitter.

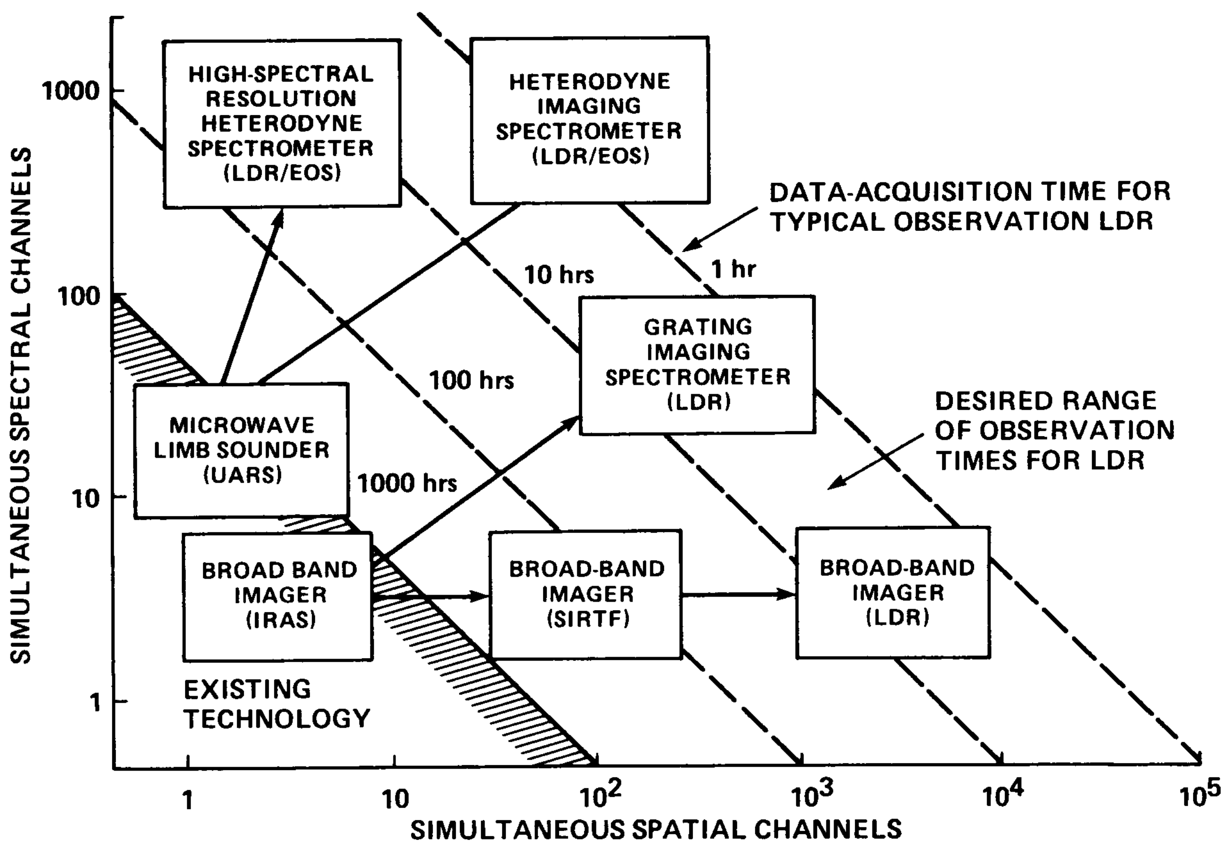


Figure G-4.- Submillimeter sensors: benefits of arrays of spatial and spectral channels.

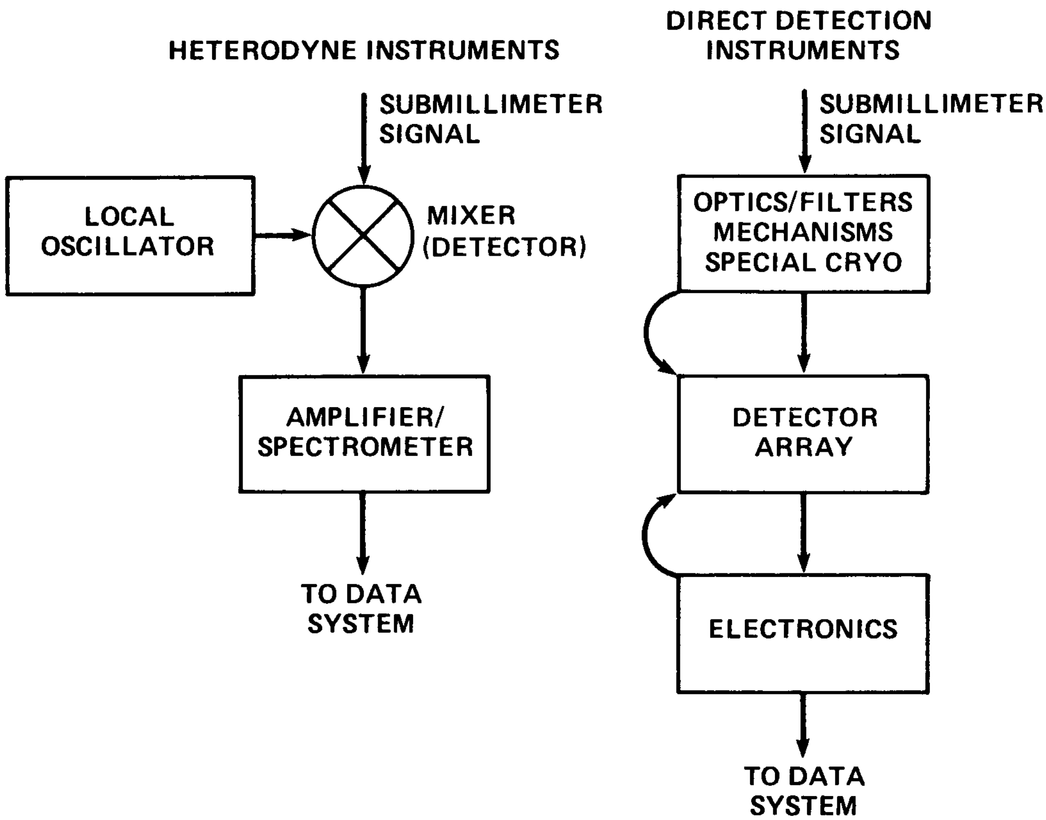


Figure G-5.- Submillimeter sensors technology component categories.

STRAWMAN INSTRUMENT		WAVE-LENGTH COVER-AGE	HETERODYNE TECHNOLOGY			DIRECT DETECTION TECHNOLOGY			COMMENTS
ACRONYM	TYPE		DETEC-TOR/ MIXER	L.O.	AMPL/ SPEC-TR.	DETEC-TOR ARRAYS	OPTICS/ MECH-ANISMS CRYO	SUP-PORT ELECT-RONICS	
1 HRS-L	SIS	3 mm-1 m, 1 mm-300µ	●	◒	○				
2 HRS-M	SCHOTTKY	1 mm-300µ	◒	●	○				
3 HRS-M	PC HETER-ODYNE	300 µ-100 µ, 100 µ-30 µ	◒ ●	○	○				
4 MRS	FABRY-PEROT	300 µ-100 µ, 100 µ-30 µ				◒	○		
5 MRLS	GRATING	300 µ-100 µ, 100 µ-30 µ				◒	○		
6 HA	SIS ARRAY	3 mm-1 m, 1 mm-300µ	●	◒	○ ●				
7 FIC	PC ARRAY	300 µ-100 µ, 100 µ-30 µ				◒	○		
8 SMMC	BOLO-METER ARRAY	1 mm-300µ, 300 µ-100 µ				○		◒	

CODING SCHEME BASED ON SCG REPORT, NOV 85

- ● RESEARCH NEEDED
- ◒ MUCH DEVELOPMENT REQUIRED
- ○ SOME DEVELOPMENT REQUIRED
- BLANK, EASILY CONSTRUCTED COMMERCIALLY AVAILABLE OR NOT APPLICABLE

NOTES: SINGLE CODE INDICATES OUR FINDINGS AGREED WITH THOSE OF SCG REPORT— WHERE TWO CODES APPEAR, LEFT ONE IS SCG, RIGHT ONE IS THE SCIENCE INSTRUMENT PANEL

Figure G-6.- Science instruments technology assessment.

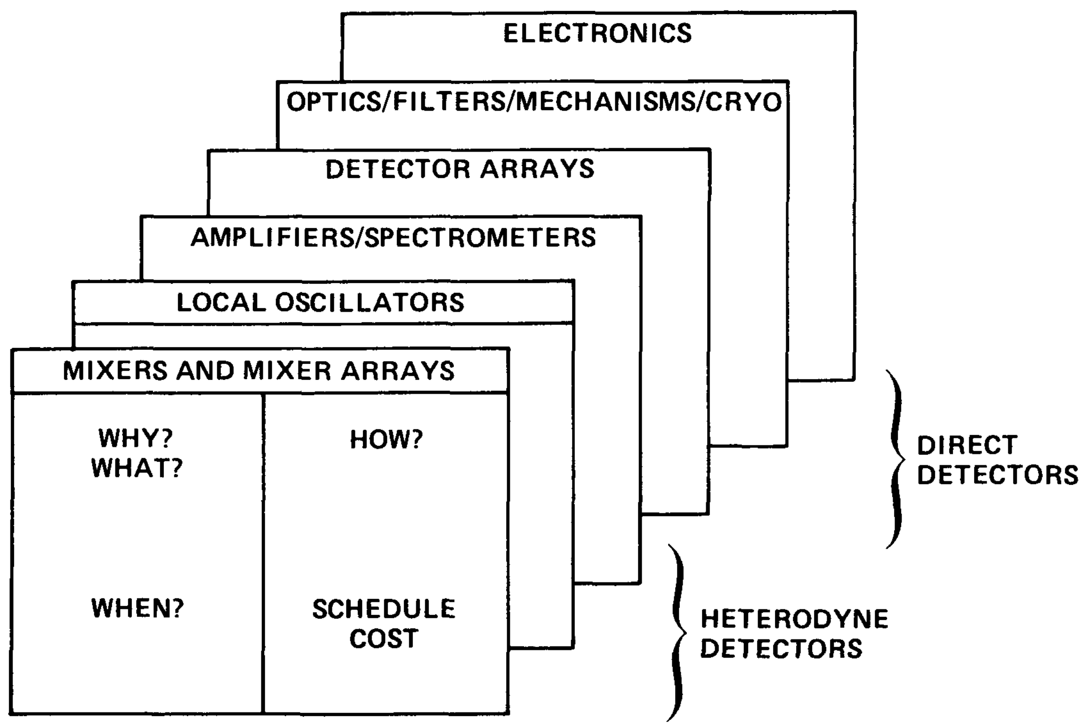


Figure G-7.- Submillimeter-components task plans.

OBJECTIVES

- DEVELOP MIXERS AND MIXER ARRAYS FOR 0.03 TO 3 mm WAVELENGTH
  - EFFECTIVE QE (> 10%)
  - HIGH IF BANDWIDTH (~ 5 GHz)
  - LOW, LOCAL OSCILLATOR POWER (< 1 μW)

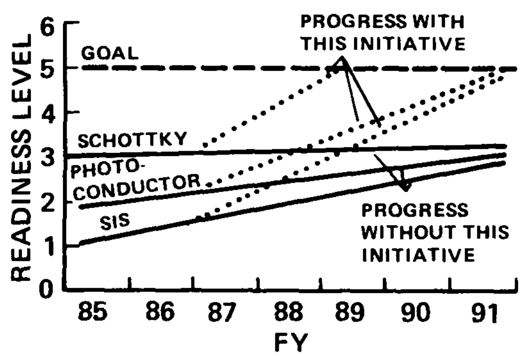
APPROACH

- DEVELOP THREE TECHNOLOGIES COVERING CONTIGUOUS SEGMENTS OF THE SUBMILLIMETER REGION

RATIONALE

- NO SINGLE TECHNOLOGY COVERS THE ENTIRE FREQUENCY RANGE OF INTEREST
- THREE TECHNOLOGIES EXIST WITH POTENTIAL FOR MEETING LDR NEEDS
  - SIS (LEAD, NIOBIUM)
  - SCHOTTKY
  - PHOTOCONDUCTOR
- ARRAYS NEEDED TO REDUCE OBSERVATION TIMES

TECHNOLOGY ASSESSMENT



DEVELOPMENT PLAN

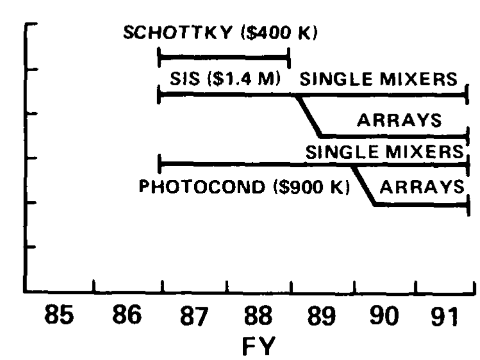


Figure G-8.- Submillimeter-components mixers and mixer arrays.

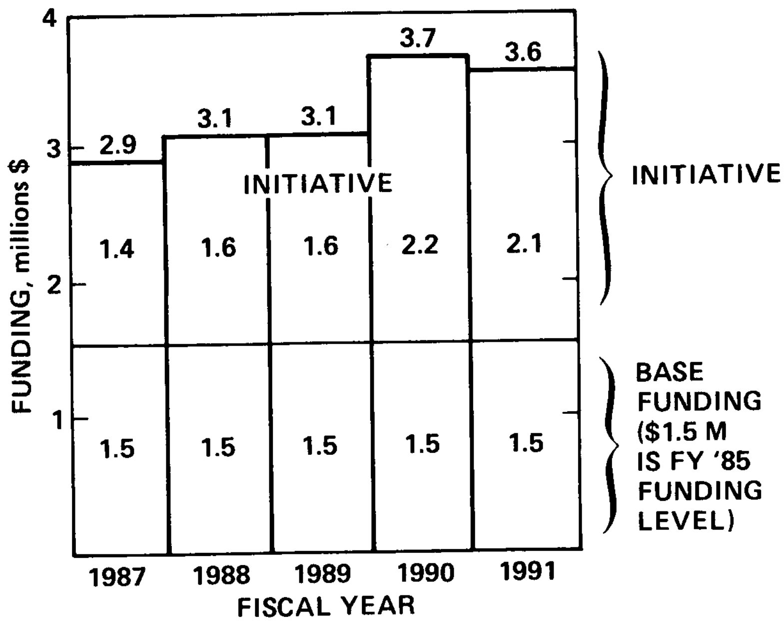


Figure G-9.- Science mission enabling technology submillimeter-components funding profile.

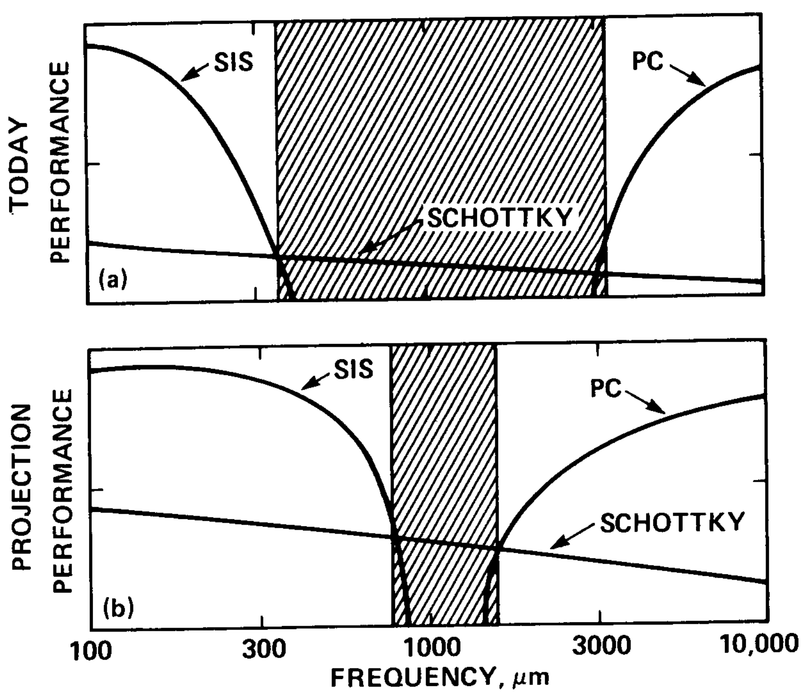


Figure G-10.- Superconductor-insulator-superconductor and photoconductor technology status.

1. Report No. NASA CP-2470	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle WORKSHOP ON TECHNOLOGY DEVELOPMENT ISSUES FOR THE LARGE DEPLOYABLE REFLECTOR (LDR)		5. Report Date February 1986 6. Performing Organization Code
7. Editor: Kenji Nishioka		8. Performing Organization Report No. A-85394 10. Work Unit No.
9. Performing Organization Name and Address Ames Research Center Moffett Field, CA 94035		11. Contract or Grant No. 13. Type of Report and Period Covered Conference Publication
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		14. Sponsoring Agency Code 506-62-21

15. Supplementary Notes

Point of Contact: K. Nishioka, Ames Research Center, MS 244-10, Moffett Field, CA 94035 (415) 694-6540 or FTS 464-6540

16. Abstract

This report summarizes the results of the 2nd Large Deployable Reflector (LDR) Technology Review Workshop held at Asilomar, California, March 17-22, 1985. The workshop was convened to update the LDR Technology status and to revise as necessary the results from the first LDR Workshop held in June 1982. There were about 100 participants at this workshop representing government agencies, industry, and universities. This Workshop's goal was to assess, identify, and prioritize the LDR technology issues based on studies conducted based on requirements identified by the first workshop. Four high-priority areas for technology development were identified at this workshop; they are (a) mirror materials and construction, (b) sensing and controls, (c) system-simulation and modeling capability, and (d) submillimeter instruments. The results of this workshop were used to provide a list of technology issues for the development of a technology initiatives plan for the LDR by NASA's Office of Aeronautics and Space Technology.

17. Key Words (Suggested by Author(s)) IR astronomy Submillimeter telescope Large IR telescope Segmented optics Cryogenically cooled focal plane instruments		18. Distribution Statement Unlimited Subject Category: 90	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 122	22. Price* A06

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