JPL Publication 88-23

Report of the Asilomar III LDR Workshop

M. J. Mahoney
Editor

August 15, 1988

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

This publication was prepared by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

ABSTRACT

This report summarizes the conclusions and recommendations of a workshop held at Asilomar, CA, on September 7-10, 1987, to study technology development issues critical to the Large Deployable Reflector (LDR); it was the third in a series of such workshops. LDR is to be a dedicated, orbiting, astronomical observatory, operating at wavelengths from 30 to 1000 μm, a spectral region where the Earth's atmosphere is almost completely opaque. Because it will have a large (20 meter), segmented, passively-cooled aperture, LDR addresses a wide range of technology areas. These include lightweight, low-cost, structural composite reflector panels, primary support structures, wavefront sensing and adaptive optics, thermal background management, and integrated vibration and pointing control systems. In addition, the science objectives for LDR present instrument development challenges for coherent and direct arrayed detectors which can operate effectively at far infrared and submillimeter wavelengths, and for sub-Kelvin cryogenic systems.


NASA

ACKNOWLEDGEMENT

This report summarizes the results of the Asilomar III workshop on technology development issues for the Large Deployable Reflector. There were five technical panels and one science panel at this meeting. The Chairmen of these panels, as well as the Workshop Chairmen, have made significant written contributions to the report. Their names, and the panels they chaired, are listed below:

Workshop Chairman	Paul Swanson	JPL
Workshop Co-Chairman	Bob Freeland	JPL
Science	Peter Wannier	JPL
Receivers and Cryogenics	Craig McCreight	ARC
Reflector Panels and Materials	Bob Freeland	JPL
	Darrel Tenney	LaRC
Controls and Pointing	Fernando Tolivar	JPL
Structures	Ben Wada	JPL
Optics and Systems	John Osantowski	GSFC
	Jim Breckinridge	JPL

In the **List of Participants** which follows this acknowledgement, the six panels are abbreviated by: SCI, R&C, P&M, C&P, STR, and O&S; workshop organizers and support personnel are indicated by ORG. A definition of the institutional affiliations used here can be found in the list of **Acronyms and Abbreviations** on the next few pages. It should be referred to whenever a mysterious combination of capital letters appears in the text. For convenience, it is broken into four categories: Organizations, Companies, Universities; Proposals, Projects, Missions; Computer Codes; and Technical, Miscellaneous.

As a departure from previous Asilomar reports, individual technical papers presented at the workshop panel meetings have been summarized as one or two page contributions; they are included as an **Appendix** to the report. Therefore, the more than forty presenters, as well as Bob Freeland, Eldred Tubbs, and Ben Wada, who helped summarize some of the presentations, are acknowledged for their contributions.

The contributions to this report varied significantly in size and style. Summaries and papers have therefore been edited to varying degrees in an attempt to present a consistent and balanced report. The Editor accepts responsibility for any errors that might have been introduced in this process.

MJ Mahoney
Editor
JPL

LIST OF PARTICIPANTS

Agnew, Don	EKC	O&S
Alff, Bill	LMSC	O&S
Allen, Tracey	JPL	ORG
Aubrune, Jean	LRL	C&P
Bandermann, Lothar	LRL	O&S
Bartman, Randy	JPL	C&P
Beichman, Chas	JPL	ORG
Betz, Albert	UCB	R&C
Borris, Pete	HXL	P&M
Bourke, Roger	JPL	ORG
Breckinridge, Jim	JPL	O&S
Brennan, Terry	AC	C&P
Briggs, Clark	JPL	C&P
Bush, Harold	LaRC	STR
Chen, Gun-Shing	JPL	C&P
Coombs, Yvonne	JPL	ORG
Coulter, Dan	JPL	P&M
Cutts, Jim	JPL	R&C
De Graauw, Thijs	GSRL	R&C
Dougherty, Hugh	LMSC	C&P
Fanson, James	JPL	C&P
Founds, Dave	KAFB	STR
Freeland, Bob	JPL	P&M
Frerking, Peg	JPL	R&C
Gartrell, Charles	GRC	C&P
Gluck, Ray	TRW	STR
Golden, Tom	BAC	P&M
Goldstein, Paula	JPL	ORG
Hedgepeth, John	ASTRO	STR
Helms, Rich	JPL	P&M
Helou, George	JPL	SCI
Hirschbein, Murray	HQ	STR
Hoffmann, Bill	UA	SCI
Hollenbach, Dave	ARC	SCI
Howard, Rick	JPL	O&S
Hudson, Wayne	HQ	ORG
Ibbott, Tony	JPL	R&C
Johnston, Bob	HXL	P&M
Johnston, Gordon	HQ	ORG
Jones, Peter	EKC	O&S
Keene, George	EKC	O&S
Kittel, Peter	ARC	R&C
Leibowitz, Lewis	LMSC	O&S
Leipold, Marty	JPL	R&C
Lorell, Ken	LRL	C&P
Lovelace, U.M.	LaRC	STR
Mahoney, MJ	JPL	O&S
Major, Carolyn	TRW	C&P
Mankins, John	JPL	P&M
Mason, Pete	JPL	R&C
Mast, Terry	UCB	O&S
Mayor, Ramon	UTRC	P&M
McCreight, Craig	ARC	R&C
McElroy, Paul	JPL	P&M
McLane, Pat	JPL	ORG
Meinel, Aden	JPL	O&S
Meinel,Marjorie	JPL	O&S
Melugin, Ramsey	ARC	O&S
Meyer, Stephan	MIT	R&C
Miyake, Bob	JPL	P&M
Nast, Ted	LRL	R&C
Nelson, Jerry	UCB	O&S
Osantowski, John	GSFC	O&S
Owen, Sherry	JPL	ORG
Padula, Sharon	LaRC	O&S
Pagano, Bob	JPL	O&S
Pawlik, Gene	JPL	ORG
Pitts, Tom	ITEK	O&S
Rapp, Don	JPL	P&M
Rea, Don	JPL	ORG
Richards, Ken	MMA	STR
Rockwell, Richard	PE	O&S
Russell, Richard	LaRC	STR
Schloerb, Pete	UMA	SCI
Scholl, Marija	JPL	O&S
Sirlin, Sam	JPL	C&P
Smith, Dennis	BAC	P&M
Smith, Pete	MIT	C&P
Sokoloski, Marty	HQ	ORG
Sollner, Gerhard	MIT	R&C
Stein, Bland	LaRC	P&M
Stier, Mark	PE	O&S
Swanson, Paul	JPL	ORG
Swearengan, Joy	KAFB	C&P
Tenney, Darrel	LaRC	P&M
Tolivar, Fernando	JPL	C&P
Tubbs, Eldred	JPL	C&P
Urbach, Bob	BASD	R&C
Van Zy, Jakob	JPL	O&S
Vaughan, Art	JPL	O&S
Venneri, Sam	HQ	ORG
Wada, Ben	JPL	STR
Wannier, Peter	JPL	SCI
Werner, Mike	ARC	ORG
Wilson, Bill	JPL	R&C
Woida, Pat	UA	O&S
Wootten, Al	NRAO	SCI
Wright, Ned	UCLA	SCI
Young, Erick	UA	R&C

ACRONYMS AND ABBREVIATIONS

ORGANIZATIONS, COMPANIES, UNIVERSITIES

AC	Aerospace Corporation
ARC	Ames Research Center
ASTRO	Astro Aerospace Incorporated
BAC	Boeing Aerospace Company
BASD	Ball Aerospace Systems Division
CIT	California Institute of Technology
CU	Cornell University
DOD	Department of Defense
EKC	Eastman Kodak Company
ESA	European Space Agency
GSFC	Goddard Space Flight Center
GSRL	Groningen Space Research Laboratory
HQ	NASA Headquarters, Washington, DC
HXL	Hexcel Corporation
ITEK	Itek Optical Systems
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KAFB	Kirtland Air Force Base, New Mexico
LaRC	Langley Research Center
LeRC	Lewis Research Center
LMSC	Lockheed Missiles and Space Company
LRL	Lockheed Research Laboratory
MIT	Massachusetts Institute of Technology
MMA	Martin Marietta Aerospace
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NRAO	National Radio Astronomy Observatory
OAST	Office of Aeronautics and Space Technology/HQ
OSSA	Office of Space Science and Applications/HQ
PE	Perkin-Elmer Corporation
SBRC	Santa Barbara Research Center
SCG	Science Coordination Group
UA	University of Arizona
UCB	University of California (Berkeley)
UCLA	University of California (Los Angeles)
UMA	University of Massachusetts
UR	University of Rochester
UTOS	United Technologies Optical Systems
UTRC	United Technologies Research Center
WPAFB	Wright-Patterson Air Force Base, Ohio

PROPOSALS, PROJECTS, MISSIONS

ACCESS	Assembly Concept for Construction of Erectable Space Structures
ABES	Aluminum Beam Expander Structure
CIT	Circumstellar Imaging Telescope
COBE	Cosmic Background Explorer
COFS	Control of Flexible Structures
CSTI	Civilian Space Technology Initiative
EASE	Experimental Assembly of Structures in EVA
EOS	Earth Observing System
FIRST	Far Infrared and Submillimeter Space Telescope
HST	Hubble Space Telescope
IRAS	Infrared Astronomical Satellite
ISO	Infrared Space Observatory
JOSE	Joint Optics Structures Experiment
KAO	Kuiper Airborne Observatory
LDR	Large Deployable Reflector
LODE	Large Optics Demonstration Experiment
PACOSS	Passive and Active Control of Space Structures
PSR	Precision Segmented Reflector
SAVI	Space Active Vibration Isolation
SBIR	Small Business Innovative Research
SFHE	Super Fluid Helium Experiment (Spacelab II)
SHOOT	Superfluid Helium On-Orbit Transfer
SIRTF	Space Infrared Telescope Facility
SMME	Submillimeter Explorer
SOFIA	Stratospheric Observatory For Infrared Astronomy
SPICE	Space Integrated Controls Experiment
TMT	Ten Meter Telescope (now W. M. Keck Telescope)
UARS	Upper Atmospheric Research Satellite

COMPUTER CODES

CAPPS	Custom Architectured Parallel Processing System
HAVOC	Holistic Analysis of Viscoelastic Omnidirectional Composites
IDM	Interdisciplinary Model
IIDA	Integrated Interdisciplinary Analysis
ISM	Integrated Structural Modeling
NASTRAN	NASA Structures Analysis
SINDA	Systems Improved Numerical Differencing Analyzer
TRASYS	Thermal Radiation Analysis System

TECHNICAL, MISCELLANEOUS

ACF	Autocorrelation Function
ADR	Adiabatic Demagnetization Refrigerator
AOS	Acousto-Optical Spectrometer
ATP	Acquisition, Tracking, and Pointing
B/B	Brassboard
BIB	Blocked Impurity Band
BWO	Backward Wave Oscillator
CFRP	Carbon Fiber Reinforced Plastic
CGH	Computer Generated Hologram
CMG	Control Moment Gyro
CTE	Coefficient of Thermal Expansion
Ep	Epoxy
ES	Expert System
FET	Field Effect Transistor
FIR	Far Infrared
FOV	Field of View
GHz	Gigahertz (10^9 cycles/sec)
Gl	Glass
Gr	Graphite
HMU	High Modulus Ultimate (tensile strength fiber)
IBC	Impurity Band Conduction
IR	Infrared
IRAC	Infrared Array Camera
IRS	Infrared Spectrograph
JFET	Junction Field Effect Transistor
LHe	Liquid Helium
LO	Local Oscillator
LOS	Line-of-Sight
MBCT	Multi-Boundry-Condition Tests
MBE	Molecular Beam Epitaxy
MIPS	Multiband Imaging Photometer for SIRTF
MLI	Multi-Layer Insulation
MR	Mechanical Refrigerator
MTF	Modulation Transfer Function
NEP	Noise Equivalent Power
NET	Noise Equivalent Temperature
OMC	Orion Molecular Cloud
PSF	Point Spread Function
RC	Resistor-Capacitor
RIBIT	Reverse Illumination Blocked Impurity Transducer
rms	root mean square
SAW	Surface Acoustic Wave
S/C	Spacecraft
SIS	Superconductor Insulator Superconductor
SRT	Supporting Research and Technology
THz	Terahertz (10^{12} cycles/sec)
TSC	Thermally Stable Composite
ULE	Ultra-Low Expansion
VLSI	Very Large Scale Integrated Circuit
WF(S)	Wavefront (Sensor)
WR-n	Waveguide size designation (n has units $\approx$0.01 inches)
ZPM	Zone Plate Mirror

TABLE OF CONTENTS

PRECEDING PAGE BLANK NOT FILMED

LIST OF TABLES

LIST OF FIGURES

34

N90-13450

I. INTRODUCTION

A. Background

The Large Deployable Reflector (LDR) is a system concept for a dedicated, orbiting, submillimeter/far infrared, astronomical observatory which has been studied by the National Aeronautics and Space Administration (NASA) since the late 1970's. Three Asilomar LDR workshops have been held to bring a wider range of expertise, both scientific and technical, into the LDR planning, definition, and critical technology development.

The first workshop, which is now called Asilomar I, was sponsored by the Office of Aeronautics and Space Technology (OAST). It was held in June 1982 at the Asilomar Conference Center at Pacific Grove, California. The purpose of the workshop was to define the science requirements, to derive the system functional requirements from the science requirements, to discuss the system concepts that would meet the functional requirements, to carry out a technology assessment, and to recommend a future course of action for LDR. The degree to which the workshop achieved its objectives can be demonstrated by noting that the science objectives, functional requirements, and system concept have survived from 1982 to the present with only minor, evolutionary changes.

The second workshop, Asilomar II, was held in March 1985; it was jointly sponsored by the Office of Aeronautics and Space Technology and the Office of Space Science and Applications (OSSA). Its purpose was to assess, identify, and prioritize the LDR technology issues, and to develop a technology development plan. This technology plan ultimately became the basis for the FY'88 Civil Space Technology Initiative/Precision Segmented Reflector (CSTI/PSR) program at Jet Propulsion Laboratory (JPL) and Langley Research Center (LaRC), and has strongly influenced the CSTI sensors program.

The third Asilomar conference was held in September 1987 and is the subject of this report. Its purpose was to review the latest system concepts for LDR, update the science requirements, and assess the status of the technology development that was recommended at Asilomar II. The technology development assessment included ongoing work within NASA, the Department of Defense (DOD), and various universities. Problem areas and technologies not being adequately addressed were to be identified and prioritized. In particular, the CSTI program in Sensors and Precision Segmented Reflectors was reviewed for appropriateness and progress relative to LDR technology needs.

B. Asilomar III Organization

The third Asilomar workshop was sponsored jointly by the Office of Aeronautics and Space Technology and the Office of Space Science and Applications. Attendance was by invitation, and included approximately 110 participants from NASA, industry, and universities, as well as a participant from the European Space Agency's Far Infrared and Submillimeter Space Telescope (FIRST) study group.

The workshop format alternated between panel working sessions of 10 to 20 people, and plenary sessions where the panel conclusions were presented to all participants. There were five technology panels: Controls and Pointing, Reflector Panels and Materials, Structures, Receivers and Cryogenics, and Optics and Systems. In addition, the LDR Science Coordination Group (SCG) was in attendance with its membership spread among the five technical panels.

The final agenda for the Asilomar III Workshop is shown in TABLE 1. The first two plenary sessions presented overview papers to bring all of the participants up to the same level of understanding concerning the LDR program and its status. This was followed by the first panel working sessions, at which technical papers were presented on specialized topics. The objective here was to assess the status of ongoing LDR-related technology in the areas represented by the five panels. This was followed by a plenary session at which a summary was presented by each of the five panel chairmen. The final working session of the panels discussed problem areas, technology voids, and suggested prioritized new thrusts. The summaries of the chairmen were again presented in a plenary session on the final day of the meeting.

TABLE 1. Asilomar III Final Agenda

Monday, September 7th		
1500	Asilomar check-in	(Administration Building)
1530-1800	Conference Registration and Reception	(Nautilus/Triton Rooms)
1630-1730	Meeting of Chairmen	
1800-1900	Dinner	
1900-2000	Plenary Session	(Nautilus Room)
	Welcome	Paul Swanson
	Procedures	Pat McLane
	Opening Remarks	Paul Swanson
	Lightweight Reflector Panels	Bob Freeland Paul McElroy

TABLE 1. Asilomar III Final Agenda (continued)

Tuesday, September 8th		
0830-0850	Plenary Session	(Nautilus Room)
	Opening Remarks	Sam Venneri (NASA)
		Don Rea (JPL)
0850-0930	LDR Baseline Concept	Bill Alff (LMSC)
0930-0950	SCG Report	Peter Wannier (JPL)
0950-1010	Submillimeter Explorer	Chas Beichman (JPL)
1010-1030	Break	
1030-1100	SIRTF, SOFIA, ISO	Mike Werner (ARC)
1100-1120	HST Metering Truss	Tom Golden (BAC)
1120-1140	CSTI/Precision Reflectors	Gene Pawlik (JPL)
1140-1200	CSTI/Sensors Program	Jim Cutts (JPL)
1200-1300	Lunch	
1300-1700	Panel Sessions / Technical Papers	
	Controls and Pointing	Marlin Room
	Panels and Materials	Surf and Sand Room
	Structures	Nautilus Room
	Optics and Systems	View Point East Room
	Receivers and Cryogenics	View Point West Room
1700-1800	Social	
1800-1900	Dinner	
1900-2000	Special Plenary Session on	Aden Meinel (JPL)
	Balloons and Precursors	Peter Wannier (JPL)

Wednesday, September 9th		
0815-1200	Plenary Session	(Nautilus Room)
	Panel Chairmen Summary Report on Status of ongoing technology development and present state of the art regarding LDR technology	
1200-1300	Lunch	
1300-1700	Panel Sessions / Technology Assessment	
1700-1800	Social	
1800-2000	Banquet	
	Speaker: Jerry Nelson, "The Keck Telescope"	

Thursday, September 10th		
0815-1200	Plenary Session	(Nautilus Room)
	Panel Chairmen report on problems, suggested plans and new thrusts.	
1200-	Check out / End of Workshop	
1200-1300	Chairmen meet to discuss writing of final report.	

C. Report Organization

This report on the Asilomar III LDR workshop nearly parallels the workshop agenda. Section II gives an overview of the LDR program, while Section III presents an account of programs and missions closely related to LDR. The summaries of the technical panel chairmen are given in Section IV for each of the five technical panels. Section V presents the concerns of the Science panel as determined by their participation in the five technical panels. Some of these concerns overlap those presented in Section IV, but the perspective is different. Section VI presents a synopsis of the workshop recommendations. Elaboration of these ideas for each of the technical panels can be found in Section IV under the subsections dealing with technology development recommendations. Finally, abstracted summaries of the individual papers presented during the technical panel working sessions are collected in the Appendix.

II. THE LDR PROGRAM - AN OVERVIEW

The Large Deployable Reflector is to be a dedicated, orbiting, astronomical observatory. It will operate as a diffraction-limited telescope in the wavelength region of 30 to 1000 microns where the Earth's atmosphere is almost completely opaque. It is presently a pre-phase A study carried out by the Jet Propulsion Laboratory and sponsored by the NASA Office of Space Science and Applications. The science rationale and requirements have been defined by the LDR Science Coordination Group and are presented in a 1986 report [5]; the current reference concept for LDR is discussed next.

A. Reference Concept for LDR

The reference concept for LDR has evolved since its introduction more than a decade ago. New opportunities, capabilities, and requirements have ensured this process. The current reference concept, which was presented at an early plenary session of the Asilomar III meeting, is summarized in a report [6] prepared by the Lockheed Missiles and Space Company (LMSC). It examined three previous studies -- one each by LMSC [7], the Eastman Kodak Company (EKC) [8], and the Jet Propulsion Laboratory [3], and chose the best features of these, subject to the constraint that the cost be minimized. The availability of the Space Station had an early impact on the requirements, but other drivers included the introduction of 2-stage optical designs, the decrease in the instrument count from eight to four, and the potential removal of the requirement for a light bucket mode of operation. The current LDR system requirements are summarized in TABLE 2.

TABLE 2. LDR System Requirements

PARAMETER	REQUIREMENT
Primary Mirror:	
Diameter	20 m
Temperature	< 200 K
Temperature Uniformity	<1 K
f/number	0.5-0.7
Secondary Mirror:	
Diameter	open
Temperature	< 125 K
Optical Form	2-stage on-axis
Field of View	> 3 arc-minutes
System f/number	≈10
Diffraction Limit	30-50 μm
Maximum System Emissivity	5 %
Pointing: Accuracy	0.1 arc-seconds
Stability (Jitter)	0.02 arc-seconds
Slew Rate	20 degrees/min
Scan Rate	1 degree/min
Tracking Rate	0.2 degrees/hr
Chopping: Frequency	2 Hz
Amplitude	1 arc-minutes
Duty Cycle	> 80 %
Sun Exclusion Angle	90 degrees
Earth Exclusion Angle	30-45 degrees
Number of Instruments	4
Useful Life	20 years
Refurbishing Interval	1-3 years
Orbit: Altitude	≈700 km
Inclination	28.5 degrees
Number of Shuttle Loads	<2 equivalent

The present concept for LDR is that of a 20-meter aperture reflecting telescope, diffraction-limited in the range 30-50 μm. The primary reflector is made up of approximately 90 lightweight, hexagonal panels, each two meters in size. The panels are supported by a deployable or erectable truss backup structure and surrounded by a sunshield to keep direct solar radiation from the primary surface. The reference concept for LDR employs a two-stage optical design in which primary figure errors are compensated for by means of a closed-loop servo system that measures the wavefront error and quasi-statically controls individual segments in a quaternary mirror which is conjugate to the primary. The focal plane instrument package will be made up of four instruments housed behind the primary vertex. The instruments will contain both direct detectors and heterodyne receivers, and will be cryogenically cooled to temperatures of 2 K and below.

Significant technical challenges exist in the areas of lightweight deployable structures, lightweight structural composite mirrors, and the control of pointing, vibration, and figure. The submillimeter heterodyne receivers are just emerging from the laboratory and heterodyne arrays have yet to be demonstrated. Cryogenic instrument coolers with lifetimes of 3 to 4 years are not yet available. The present LDR concept has served to define the technology that must be developed before the project can be started. Section IV discusses the present NASA technology efforts directed toward solving these fundamental problems.

B. A Tentative Schedule for LDR

FIGURE 1 shows a tentative schedule for LDR through the start of Phase C/D. This schedule is for planning purposes only and does not represent a NASA commitment to a project start at any particular time. The dark shaded arrows are funded activities in FY'88. The Science Coordination Group and the system definition are funded by the OSSA, while the telescope and sensor development are part of a more general technology development funded by the OAST. The Phase A study in FY'92 is dependent on many intangibles such as the overall NASA budget, new starts for AXAF and SIRTF, and the state of technology readiness of LDR in the early 1990's.

III. LDR-RELATED PROGRAMS AND MISSIONS

A. Civil Space Technology Initiative

Within the NASA Civil Space Technology Initiative (CSTI) are two programs of great importance to LDR. Plenary session presentations, which are briefly summarized below, were made on both of these programs.

1. Precision Segmented Reflectors (PSR)

The PSR effort is a joint project between JPL and LaRC under CSTI. The effort is managed by Code RM in OAST with a deputy manager from Code EZ in OSSA. The PSR technology program is a step in the development and validation of increasingly more precise segmented reflector technology that might ultimately be

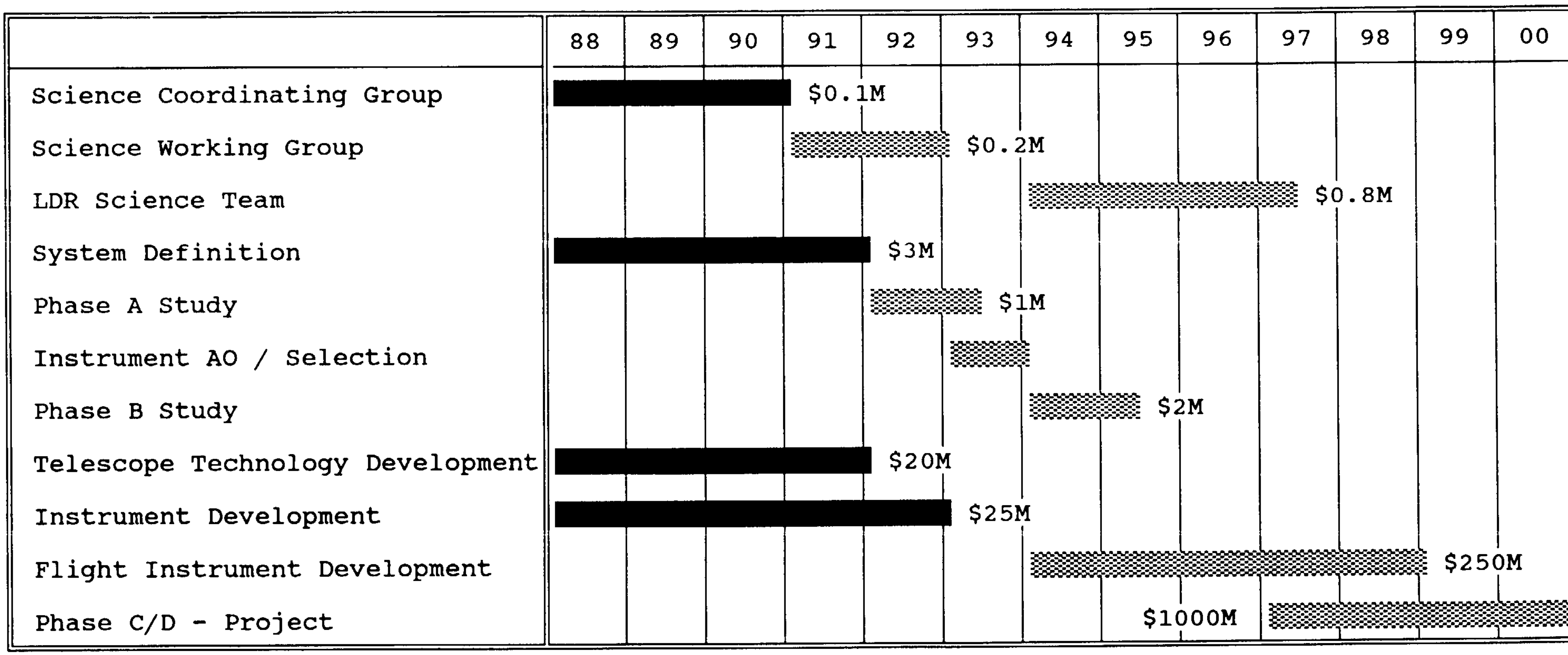


FIGURE 1. LDR Master Schedule to the Year 2000

used in space on projects such as the Large Deployable Reflector. These technologies include lightweight, structural composite panels, erectable and/or deployable space-like structures, advanced materials, and precision active control systems.

One of the objectives of the PSR program is to integrate the individual component technologies being developed within the program into a technology validation demonstration by the end of FY'91. The specific goal of the system is to demonstrate experimentally that a multi-segment, lightweight, low-cost reflector system can maintain a ≤ 5 μm rms overall surface accuracy when subjected to quasi-static thermal and mechanical disturbances representative of a space mission.

2. Science Sensor Technology

The science sensor technology program under the CSTI initiative involves work at a number of NASA centers in three main areas of relevance to LDR: submm receivers, direct IR detectors/arrays, and cryogenics.

In the submm receiver area, work is underway at CIT and JPL to develop high-sensitivity, space-qualifiable SIS mixers and arrays, improved antenna technology, and solid-state quantum-well devices for both local oscillator and frequency multiplier applications. Projects at LeRC and GSFC are aimed at bringing backward-wave oscillator, and CO_2-pumped far-IR gas laser technology, respectively, to sufficient levels of maturity and ruggedness to satisfy LDR LO needs.

Direct detector work is supported under CSTI at Ames Research Center (ARC), JPL, and Marshall Space Flight Center (MSFC). The Ames program focusses on extrinsic silicon and germanium array technology, including advanced LDR-scale multiplexers and improved long-wave detector materials. At JPL, the technology of Ge:Ga blocked impurity band (BIB) detectors is under development. Arrays of superconducting bolometers are under investigation at MSFC.

CSTI cryogenics technology development is being supported at GSFC, ARC, JPL, and MSFC. The Goddard work emphasizes multi-stage Stirling-cycle coolers and supporting cryogenic engineering developments in regenerators and compressors. At Ames, (zero-g) dilution and pulse tube refrigerators are under development, as is a concept for a 2 K high-capacity closed-cycle cooler. The JPL work includes sorption coolers for a range of temperatures, and research into electrostatic separation of fluids for dilution refrigeration. Work on a ^{3}He-^{4}He cooler, microchannel fountain-effect pump, and recuperative heat exchanger is underway at MSFC.

B. Missions

Presentations on the status of several funded or potential missions were made at Asilomar III plenary sessions and panel meetings. These talks discussed science and/or technology of direct interest to LDR; topics included the NASA Hubble Space Telescope (HST), the ESA Infrared Space Observatory (ISO) and Far Infrared and Submillimeter Space Telescope (FIRST), and the NASA Space Infrared Telescope Facility (SIRTF), Submillimeter Explorer (SMME), and Stratospheric Observatory for Infrared Astronomy (SOFIA). Since reports have been written on all of these missions, their details will not be pursued here. There was also a special evening session to discuss ballooning as a means for doing precursor science experiments. A technical paper discussing one of these, a proposed three-meter balloon-borne telescope, is included in Section F of the Appendix.

Although the spectral range of interest to these projects or proposals may overlap to varying degrees, all have significantly different performance characteristics. It is these attributes which must be traded against the science return and technology capabilities to determine those which should be pursued, and at what level. LDR stands to gain from these other projects in several important ways: general space telescope technology, science instrument development, and precursor science.

All of the missions require science instrument development which will greatly aid in defining the technology directions to explore for the LDR instrument complement. The SIRTF project, for example, is developing direct detector technology, which will benefit LDR, as well as an on-orbit superfluid helium transfer capability for stored cryogens. As these instruments are developed, it is imperative that they be tested in a flight-like environment, but it is equally important that they also make relevant precursor science measurements. Balloon, aircraft (SOFIA), and low-cost spacecraft (SMME) missions provide a logical progression in reaching this objective, and in refining the system requirements for LDR.

IV. TECHNOLOGY PANEL REPORTS

This section contains the summary reports written by the chairmen of the five Asilomar III technical panels. The summaries follow the following general outline: an introduction, with some brief comments on changes since Asilomar II; an identification of technologies the panels felt were critical to the development of LDR; and technology development recommendations. Implied references to individual technical papers presented in panel meetings are indicated by the presenter's name in round brackets. Summaries of the papers can be found in the Appendix.

A. Controls and Pointing

1. Introduction and Review

In recognition of the importance of pointing and control technology to LDR, a panel has been convened at each of the three workshops to assess and plan the development of the technology base. The charter and structure of the panel were similar in all cases. The panel was constituted with members that possessed direct experience on the current state of the art programs relevant to LDR. The members were invited to make presentations on their work, assess the state of the technology, and evaluate the scope and depth of the proposed technology program. The following is a summary of the LDR technology assessment, and the proposed LDR technology program.

The Controls and Pointing panel for the third Asilomar conference had three major objectives: to determine the state of the art in relevant LDR pointing and control areas; to identify the specific needs and concerns for LDR technology in this area; and to recommend a development program to bring these technologies to readiness in support of an LDR mission.

The Asilomar II panel identified and prioritized seven key sensing and control technology areas as critical. These were:

(1) dynamic control technology,
(2) modeling and performance prediction,
(3) wavefront and figure control,
(4) control technology integration brassboard,
(5) fine line of sight guidance and offset pointing,
(6) chopping devices, and
(7) flight-controls demonstration.

Of these, the first four were identified as having the highest immediate priority. The dynamic control technology is needed to provide isolation of on-board dynamic excitation sources and was seen as the area where the Hubble Space Telescope has had some of its greatest problems. Significant advancements in control analysis and simulation tools will be needed to handle with high precision the close to 1000 degrees of freedom which the LDR has. Sensing of the wavefront and relating this to the telescope figure was identified as an issue in the correction of wavefront errors. The integration brassboard was called for to demonstrate proof-of-concept of the control hardware and algorithms in a ground-based demonstration.

The Controls and Pointing panel prepared a program plan in each of these seven technology areas. The program reflected the recommended priorities, covered five years, and culminated in the ground brassboard, and the flight-controls demonstration. Evaluation of the state of the art in each area was provided along with the growth projection provided by the proposed program.

2. Identification of Critical Technologies

At Asilomar III, the seven critical technology areas identified above were recast into six pointing and control technology needs so that they could be distinguished from the several functions of the spacecraft control system. These needs were then assessed for technology status as demonstrated by current flight and ground programs. The needs were measured on the standard technology readiness scale.[1]

The most advanced systems demonstrating LDR technology are the Hubble Space Telescope (HST), which is a Shuttle-deployable telescope with excellent stability, maneuverability and a digital pointing control system, and the Keck Telescope, which is a segmented, ground-based 10 meter optical telescope. In addition, several research and development programs are preparing technology in pointing and control of large, flexible reflector systems. These include the Space Active Vibration Isolation (SAVI) program, the Joint Optics Structures Experiment (JOSE), and the Large Optics Demonstration Experiment (LODE). TABLE 3 compares the approach and expected contribution of these programs with the specific LDR technology needs.

---

[1]NASA Technology Readiness Levels:

Level	Definition
1	Basic principles observed and reported
2	Conceptual design formulated
3	Conceptual design tested analytically or experimentally
4	Critical function/characteristic demonstration
5	Component/brassboard tested in relevant environment
6	Prototype/engineering model tested in relevant environment
7	Engineering model tested in space

TABLE 3. LDR Controls and Pointing State of the Art

PROGRAM	APPROACH/EXPECTED CONTRIBUTION	NEEDED LDR CONTROLS TECHNOLOGY
HST	f-separation: 0.6 Hz control vs. 18 Hz truss plus constrained system & user disturbances Expected to demonstrate pointing of single monolith to 0.01 arcsec on 18 Hz truss	Lightweight (< 5 kg/m^2) Low power (< 10 W/m^2) Cooperative pointing of 70-100 elements to 0.1 arcsec on flexible spacecraft Integrated pointing, figure and vibration control Wavefront sensors suitable for LDR wavelength and surface quality Two-stage optics sensor/control concepts Accurate prediction/modeling tools Controls, Structures and Optics integrated analysis and evaluation tools
SAVI	Very high isolation of massive payloads in 100-2000 Hz with 12 actuator system using linear actuators and magnetic suspension	
JOSE	Application and evaluation of modern control theory methods and active truss members. 1-500 Hz	
LODE	4.0 m in 4 deformable segmented panels on a rigid support - WF control at high B/W	
KECK	0.05 μm segment control of 36 rigid monoliths on massive 5.4 Hz truss Segment control uses simple low performance approach: limited to 0.5 Hz by B/W stability Design approach: frequency separation, does not provide for vibration control or pointing interactions 108 Actuators: lead-screw plus 30:1 hydraulic mechanical advantage stage 168 capacitive edge sensors, and modified Hartmann tilt and piston sensor	

The two systems specifically designed for astronomical observation, the HST and the Keck Telescope, deal with control issues of great relevance to LDR: the precision pointing of spacecraft, and the precision control of a segmented primary reflector. Issues not addressed by these systems include the effects of spacecraft flexure on pointing, and the control of vibration in the segmented primary support structure. To a degree these are addressed by the three ground-based experiments, but not as specifically required for LDR. The Precision Segmented Reflector program, an element of the Civil Space Technology Initiative, will begin this fiscal year to develop quasi-static figure control technology, and has augmentation proposals for dynamic control and wavefront control. None of these programs support, or presently plan to support, pointing control, alignment of the multiple optical elements, or two-stage optics.

TABLE 4 is a matrix of the functional requirements for LDR as a function of the various pointing and control technology disciplines. It gives the consensus of the panel on the technology needs and the current development status. A goal of readiness Level 5 (component or brassboard tested in a relevant environment) was assumed to be required before a Phase A study can be started. The rankings ranged from fully developed for pointing sensors (gyros) and rigid body pointing analysis and design, to Level 2 (conceptual design formulated) for system integration. Across all control system functions, the absence of mission studies that define disturbances was noted as a serious deficiency that will impede technology development progress overall. Insofar as it is possible to identify a general, across-the-board level of readiness, the panel felt that Level 3 (conceptual design tested analytically) and Level 4 (critical function demonstration) should be the near-term technology development goal.

TABLE 4 is intended to be read in both directions, that is, it is an assessment of the functional requirements within a specific technology discipline, and it is an assessment of a specific functional requirement across all technology disciplines. In terms of the functional requirements, figure control in the presence of vibration is at a low level of readiness. Although several research and development programs have been specifically aimed at dynamic control of large space structures, none have integrated vibration control with other functions (such as figure control) or demonstrated the technology experimentally. In terms of the technology disciplines, modeling and disturbance analysis are areas with a low level of readiness. Although the basic algorithms for modeling, simulation, and design may be in place, code systems which can handle the extremely large number of degrees of freedom in a segmented telescope are currently experiencing numerical difficulties. The disturbance modeling has not been delayed for lack of techniques,

TABLE 4. LDR Controls and Pointing Current Technology Status

	SENSORS	ACTUATORS	ALGORITHMS DESIGN	MODELING/ ANALYSIS	DISTURB DEFINIT	TEST / VERIFICATION INSTRUMENT & METHOD
SEGMENT TO SEGMENT FIGURE CONTROL	3	3 (PM) 2 (QM)	5^r 2^v	5^r 2^v	0	-
DEFORMABLE SEGMENT FIGURE CONTROL^q	2.5	3	5	3	0	-
POINTING: Gyros Star tracker LOS transfer	7 5 2	6 3	7	7	0	-
SM and TM ALIGNMENT	3.5	6	7^r 2^v	7^r 2^v	0	0
WF CALIBRATION	3	-	3	2	0	large flat
DAMPING: Active Passive	3 -	3 -	3 -	2 2	0	μ-g acceleration x100 improvement
NODDING CHOPPING	- 6	- 4	2.5 4	2.5 4		0 0
INTEGRATED SYSTEM B/B and EVALUATION	-	-	2	2	-	facility system test bed

Notes: 1. Superscripts: ^{r} = rigid body, ^{v} = vibration, ^{q} = quasi-static.
PM, SM, TM and QM refer to the primary, secondary, tertiary and quaternary mirrors.
2. Levels of Readiness are defined in footnote on page 11.
3. The recommendation is to carry the technology to Level 5.

but for lack of definition, and study of realistic, viable candidate spacecraft. Although this will improve as the system concepts mature, control and pointing technology development is presently hampered for lack of these crucial inputs.

3. Technology Development Recommendations

The technology development needs were prioritized as shown in TABLE 5. Two areas were given the highest overall priority: segment-to-segment figure control, and the integrated system breadboard. The areas of vibration control and wavefront calibration were also given a very high priority. With only two exceptions, all the areas considered were judged to have high risk if not developed. Control of deformable panels and the control impact of the spacecraft nodding observation mode were identified as two areas requiring further definition.

Essentially the same technology needs were identified as high priority by the Asilomar II panel. At that time, dynamic

TABLE 5. Prioritization of Technology Development Needs

NEEDED TECHNOLOGY	OVERALL GRADE	DIFFI-CULTY	IMPORT-ANCE	RISK IF NOT DONE
SEGMENT TO SEGMENT FIGURE CONTROL	H1	H	H	H
DEFORMABLE SEGMENT FIGURE CONTROL	L	M	?	?
POINTING	M	M	H	H
SECONDARY, TERTIARY QUATERNARY ALIGNMENT	M	M	H	H
WAVEFRONT CALIBRATION	H3	M-H	H	H
ACTIVE DAMPING PASSIVE DAMPING	H2	H M	H	H
NODDING CHOPPING	M M	H M-L	? H	? H
INTEGRATED SYSTEM B/B and EVALUATION	H1	H	H	H

control technology (jitter control, structural dynamics, vibration isolation and active control) and the system breadboard demonstration were identified as the highest priority needs.

TABLE 6 contains a summary of the recommended technology development program. The limited resources available to the NASA technology community were recognized and only the essential program elements were included. Where possible, synergistic programs in place, or sponsored by other agencies, were utilized. For example, the technology of the PSR program is directly applicable to LDR, and is called out in TABLE 6 for augmentation only where absolutely necessary. The cornerstone of the development program is the integrated system demonstration where the level of development of control functions in addition to figure control, that is element alignment, pointing and deformable segment control, can be demonstrated. That program would be a six-year ground demonstration to finish concurrent with the initiation of the LDR Phase A studies.

TABLE 6. Recommended Technology Development Program

NEEDED TECHNOLOGY	ADDRESSED BY PSR	ADDITIONAL %	NEEDS M$
SEGMENT TO SEGMENT FIGURE SENSING & CONTROL	50%	50%	3
DEFORMABLE SEGMENT FIGURE CONTROL	10%	90%	1
POINTING		100%	2
SECONDARY, TERTIARY, QUATERNARY ALIGNMENT		100%	1
WAVEFRONT CALIBRATION		100%	2
ACTIVE & PASSIVE DAMPING	10%	90%	4
NODDING CHOPPING		100%	1
INTEGRATED SYSTEM B/B and EVALUATION	10%	90%	10[1]
		TOTAL COST COST/YEAR	24 4

Note: 1. Tool development ($2M), B/B description and development ($2M), fabrication ($4M), testing and evaluation ($2M).

B. Reflector Panels and Materials

1. Introduction and Review

The technology areas of panels and materials were combined with structures technology at Asilomar II. In this sub-section, we cover only the panels and materials recommendations of that group; the structures recommendations are reviewed in the following sub-section. The issues covered by the Reflector Panels and Materials panel included a review of Asilomar II results, the identification of critical technologies, and the specification of new functional requirements. Technical problems not addressed by the CSTI/PSR program were also discussed and evaluated.

The Asilomar II panel concluded that the development of lightweight, low-cost reflector panels that demonstrate high surface precision and thermal stability was the most critical technology. This recommendation was driven primarily by the unacceptable weight associated with using glass. The requirement for a light-bucket mode of operation was a secondary issue. Since glass panel technology could not meet the areal weight requirements, the recommendation of the Asilomar II panel was for the development of structural composite, glass, and metal panels. Since the light-bucket mode has now been removed (if it is a major cost driver), the recommendation of the Asilomar III panel is to focus only on lightweight structural composite panels because of their high potential payoff.

2. Identification of Critical Technologies

The specific technologies critical to the development of structural composite panels are discussed in this subsection. They include panel design, fabrication, coatings, surface refinishing, testing and analysis. Also included are the testing and analysis of alternate panel materials.

a) Panel Design

The design of structural composite panels entails the optimization of the baseline graphite/epoxy (Gr/Ep) material and layup, and possibly the development of new core concepts. The current baseline Gr/Ep materials, for example, can be optimized by enhancing the chemical bond between the carbon fibers and the epoxy matrix. Similarly, there are options for the current aluminum honeycomb panel core, such as composite honeycomb, composite tri-balance, and circularly symmetric. However, all of these options will have to be proven by the process of building and evaluating realistic size hardware. In this process, the manner in which the panel properties scale with increasing size will be determined and accounted for in the design and fabrication of full scale hardware.

The current baseline panel materials represent only one of a number of materials and their derivatives that might be suitable for the panel development program. The materials research program discussed below will identify or develop other materials for the baseline program.

b) Panel Fabrication

Fabrication addresses the processing, tooling, quality control, attachment, and mass production of panels. The large number of variables associated with composite material designs and their fabrication could result in a lack of consistency from panel to panel. Quality control techniques will have to be tailored for the baseline materials and processes. Since the fabrication of the baseline panel is based on experimental approaches, such as the laying up of facesheets by hand, consideration will have to be given to automating the process to accommodate the production of a large number of panels in a reasonable time frame. A significant contributor to the precision of the baseline Gr/Ep panels is the thermal stability of the ceramic tooling. Consequently, scaling factors associated with increasing tool size, will have to be developed to account for any differences in expansion rates and heat loading associated with panel curing.

The baseline panel fabrication involves the curing of single facesheets prior to the addition of the core. There are a large number of options for variations of this manufacturing process. Evaluation of promising variations might significantly enhance the panel development.

c) Panel Coatings and Surface Refinishing

The selection of coating materials could contribute to the ease with which panels can be polished, their reflectivity, and the amount of environmental protection afforded. Since these are all very important areas, panel coatings have great potential for improving the manufactured surface quality of lightweight composite panels. For post-fabrication surface refinishing to be effective, sufficient matrix material, or thick coatings, must be present to avoid fiber print through. Currently there are a number of options for polishing equipment and techniques, and they should be evaluated.

d) Testing

Extensive testing will be required for characterization of both the basic panel materials and the complete panels. At the present time, there is a lack of available test facilitates to meet the specific needs of this program. Chambers for thermal vacuum, thermal cycling, and vacuum thermal cycling tests of up to 2-meter panels at 200 K with thermal gradients will be required.

e) Analysis

Analytical simulation at the system, subsystem, and micromechanics level will be required to accommodate panel development. System simulation defines the orbital environment of the panels for specific classes of applications; subsystem analysis characterizes the panel materials, thermal, structural and optical performance for specific applications and test conditions; and micromechanics analysis is needed to characterize viscoelastic material behavior, residual stresses, thermal fatigue, moisture dryout effects, and criteria for failure and verification testing. The state of the art for system and subsystem analysis is marginally adequate to support panel development. However, significantly more capability will have to be developed in the area of micromechanics analysis.

f) Alternate Materials

Alternate advanced polymer matrix composite materials have the potential to improve the performance of the baseline panels. Examples of such materials and processes would be low thermal expansion matrix resins, improved carbon fibers, and improved fiber/matrix bonding. Thermoplastic and thermoset polymers, for example, need to be synthesized and characterized for their physical and mechanical properties. Emphasis will be placed on developing low expansion resins which can be processed at low temperatures to minimize residual stress in cured composites. These advanced polymers would then be combined with specially processed carbon fiber to produce an advanced composite for physical and mechanical characterization. Promising candidate composites would be processed into sub-size panels to verify panel fabrication procedures. These panels would be tested to fully evaluate alternate material concepts and compared with baseline Gr/Ep systems. The most promising materials would then be selected for full-size panel fabrication.

Graphite glass (Gr/Gl) has been selected as an alternate material with great potential for panel development, but its materials properties must be better understood. Another material, sol-gel, is also recommended for development and evaluation because it is processed at low temperatures.

3. Technology Development Recommendations

Before the conclusions of the Panels and Materials panel are given, two other issues should be noted: possible changes in panel functional requirements, and panel work being done under the CSTI/PSR program.

Functional requirements from the technology areas of Systems, Controls and Science can impose significant constraints on the development of structural composite panels. For example, on-orbit assembly, launch loading, and outgassing requirements could influence the basic design of the panels. Likewise, the optical properties of the panels needed to accommodate Controls and the high precision needed for the light bucket mode, if deemed necessary, affect the degree of technology development of the panels.

Materials issues currently not included in the PSR program should also be noted; these include the sunshade, the basic primary and secondary support structure, and the environmental effects on materials. The sunshade issues involve high performance polymer films, adhesives and coatings. Structural areas include composite tubes and adhesives while environmental concerns are related to atomic oxygen interaction with the materials and the effects of orbital contamination.

There was unanimous agreement within the panel regarding the general conclusions. Good progress has been made in developing an integrated panels and materials technology development plan. The key technical areas are being worked by PSR with support from the NASA materials base programs. There is a good probability of significant technology advancement at the current level of funding. However, system and operational constraints could turn out to be a major design driver and dilute to some degree, the specific technical tasks currently planned under PSR.

C. Structures

1. Introduction and Review

Structures recommendations at Asilomar II were made in three broad areas: structural concepts, structural system dynamic simulation, and flight experiments. The structural design goals established at Asilomar II were revisited, and the new goals are summarized in TABLE 7. The only significant changes are an increase in the thermal shield mass density (up from 1 kg/m^2), and an increase in the system natural frequency (up from 1 Hz). The primary structural system drivers are performance, weight, cost, and operational reliability.

TABLE 7. Structural Design Goals for LDR

Primary Structure Mass Density	$<$ 5 kg/m^2
Thermal Shield Mass Density	$<$ 3 kg/m^2
System Natural Frequency	$>$ 3 Hz
Structure Cost	$<$ \$10 K/kg
Passive Damping	$>$ 3 %
Primary Structure Surface (rms)	$\leq$ 100 μm
Predictable Joint Performance	

The deployable and erectable structural concepts discussed at Asilomar II for the primary reflector backup structure are now being evaluated as part of the CSTI/PSR program. On-orbit panel attachment may prove to be a design driver, and is also being evaluated in the CSTI/PSR program. The impact of the sunshield remains to be determined. The requirements for structural system dynamic simulation include evaluation of the micron-level static and dynamic characteristics, wave motion propagation, structural damping, and the development of analytical methods for their prediction. Although our understanding of these issues has improved, very little technical effort has been performed in the country to quantify the issues. These remain unresolved, as do issues associated with validation by ground test, which is expected to be a major technical challenge. The requirement for a flight experiment before LDR has now been relaxed under the assumption that other missions would help resolve key issues.

2. Identification of Critical Technologies

Three technology areas have been identified as important areas of research for LDR; they include structural concepts, structural system dynamics, and ground validation test methods. Their requirements are unique to large multisegment structures that require micron level figure definition.

a) Structural Concepts

Structural concepts needing further development include the sunshade, panel attachment, and adaptive structures.

i) Sunshade

The current sunshade concept consists of accordion folded multilayered insulation (MLI) blankets; these are deployed through a number of ASTRO-type mast structures uniformly distributed around the perimeter of the primary structure. The potentially large mass and relatively low modal frequencies associated with the sunshield may significantly affect the technology requirements for LDR. An effort to better define the sunshade characteristics is recommended as being necessary to help assess the potential problems and to assure the proper direction for technology development in structures and controls.

ii) Panel Attachment

Panel attachment by astronauts and/or robotic means is seen as another area requiring better definition. Key questions include how to attach the panels to the structure from the front without being able to see the attachment points, how to protect the mirror surfaces during assembly/disassembly, and how to remove a panel (if necessary). Currently, no feasible structural concepts exist to achieve the assembly and disassembly of the panels. An effort in panel attachment and removal is recommended so that a feasible approach can be identified which meets the requirements of LDR.

iii) Adaptive Structures

A structural concept referred to as adaptive structures could have a significant impact in helping to meet LDR structural requirements. It involves the use of active structural elements which, by either local or remote control, respond to adjust relevant structural parameters. With the ability to control micron-level displacements in the frequency range from 0-200 Hz, appropriately placed active elements can be used to: (1) provide increased structural damping, (2) adjust the initial static position of the structure if required, (3) maintain relative positions during temperature changes, and (4) provide a means to preload joints and provide structural isolation. A significant advantage of adaptive structures is that they may be utilized with a ground test program to validate the on-orbit performance of a structural system.

b) Structural System Dynamics

i) Micron Level Response

At the present time it is not possible to analytically predict either the static or the dynamic micron-level response of large structures constructed of struts and joints. This is not limited to the prediction of modal eigen-parameters, but also includes the quasi-static response to thermal changes, and the prediction of the initial static position in space. This information is important to establish the static and dynamic range requirements for sensors and actuators. Existing test data for deployable trusses indicate that joint nonlinearity (or "slop") prevents the identification of modal eigen-parameters at about the 0.1-g level, and that existing measurement capabilities are limited at about the 0.001-g level. Therefore, at the anticipated response levels of interest to LDR (a peak displacement of 1 μm at 1 Hz corresponds to $4 \cdot 10^{-6}$-g), a high probability exists that a structure cannot be modeled in terms of its eigen-parameters, and some other means must be found to characterize it. More accurate test measurement methods must be developed to obtain the data necessary to help in the formulation of the analytical model, which may possibly be statistical in nature.

ii) Wave Motion

During testing of the Space Station structure, the transfer of energy through the structure (when it was subjected to an external force) was visually observed; the path of energy transfer depended on the location and direction of the applied force. Although this wave motion could in principle be described as a superposition of eigenvectors, the large number of eigenvectors, and their associated uncertainties, quickly deteriorates the fidelity of the representation. The impact of this wave motion on LDR must be evaluated.

A semi-empirical approach to develop an energy transfer model is recommended. When a reasonable model is developed, methods to attenuate the wave energy by a damping mechanism (such as an active element) near the source of the energy input, or in the path of the energy transfer, should be employed.

c) Ground Validation Tests

A ground test capability is needed to measure micron-level structural deformations be they static, quasi-static, or dynamic. In addition, ground test approaches must be able to accurately extrapolate results of thermal vacuum tests from subsystems to entire structures because a thermal vacuum chamber capable of testing an entire structure is not available. In addition, the gravitational loading on an entire structure may result in unrealistic preloads, and thus in unrealistic thermal conductance characteristics. Without the development of the ground validation test techniques for critical performance parameters, the LDR program office may never commit to a flight project. Adaptive structures concepts may provide additional ground test/analysis options.

Preliminary analysis of a LDR deployable backup structure has indicated that the structural stiffness may be sufficiently high to allow a determination of its on-orbit static deformation by ground test. The quasi-static and dynamic characteristics will be much more difficult to quantify, and ground test limitations are anticipated. When determined, either new ground test approaches must be developed, or the structural concepts must be modified to fit within the ground test limitations. The committee recommended this approach be used for LDR; a flight test is not absolutely required.

3. Technology Development Recommendations

Structural technology development recommendations follow directly from the critical technologies identified in the previous subsection.

Although several erectable or deployable LDR backup structure concepts exist, which appear to meet the current program objectives, they do not take account of the LDR sunshade. Because of its potentially large torques and low modal frequencies, the sunshade may be an important design driver. A representative LDR structure with a sunshade must therefore be evaluated. A question exists as to whether a meaningful PSR test model, and program to address the LDR technologies, can be developed.

Other structural concepts needing definition include methods for attaching panels and employing adaptive structures. The latter may in fact help define a meaningful ground test program.

The extrapolation of limited experimental evidence indicates potential difficulty in predicting on-orbit wave motion and micron-level structural responses. Better test and analytical methods will have to be developed to understand these structural performance characteristics, and establish their impact on the LDR mission. If the current structural concepts do not meet the necessary performance characteristics, alternative concepts must be developed. Efforts to develop ground test/analysis methods to validate the performance of the structural system is required.

A flight test is not considered mandatory for LDR but would be highly desirable. This statement rests on the assumption that other missions would be flown prior to LDR that would help to resolve the important structures technical issues.

D. Receivers and Cryogenics

1. Introduction and Review

At the Asilomar II workshop, the technology areas of receivers and cryogenics were considered separately; receiver technology was studied by the Science Instruments panel, and cryogenic technology was part of the Thermal and Power Technology panel. Since stored cryogen mass and lifetime are such important considerations for LDR, it seemed essential that cryogenicists be able to interact directly with receiver developers. Hopefully in this way, realistic numbers might be found for anticipated operating temperatures and heat loads.

As the result of the discussions of the Receivers and Cryogenics panel, it was evident that a broad and diverse, although generally immature, technology base exists in this area. The following summary represents a general consensus of the panel. It was evident that progress has been made in all technology disciplines since the previous Asilomar workshop; in some cases, the progress was spectacular. However, as has been stated before, without a long-term, focussed development program, the technology base will fall well short of LDR instrument requirements.

2. Identification of Critical Technologies

The technology areas critical for LDR instrumentation include submillimeter heterodyne receivers, direct infrared detectors and detector arrays, and cryogenics. This subsection evaluates their status and requirements.

a) Submm Heterodyne Receivers

Significant progress is being made in this field, which until recently was largely unexplored. Systems are now working in the laboratory and in ground-based and airborne observing environments. Expertise is developing in a number of institutions in the US and Europe, as was evidenced by the lively debate which occurred on various issues. One needs to keep in mind, however, that in absolute terms this area is still quite new, and well below the level needed for LDR instrument development.

i) Mixers

A number of groups are now using GaAs Schottky diode mixers very successfully in operational systems. For example, the Kuiper Airborne Observatory (KAO) has used this technology at wavelengths longward of 150 μm. Relative to other mixer technologies, GaAs Schottky diodes have the advantages of wide frequency response, only modest (~60 K) cooling requirements, and availability. In the 100 GHz region, these systems have achieved (double sideband) noise temperatures ~20 times the quantum limit; at about 1 THz, this factor is about 150 times the quantum limit (Betz). They do, and will, require local oscillator (LO) power on the order of mW's. At present, there is only one useful source of these GaAs diodes (U. Virginia).

There is a very high level of interest now in superconductor-insulator-superconductor (SIS) mixer development, with about 10 groups in the US and Europe pushing the state of the art. At this point, Pb-based SIS junctions (≤ 4 K) have been operated up to 1.1 THz in the laboratory (Frerking). For frequencies <200 GHz, a system noise about 10 times the quantum limit (double sideband) has been achieved. A promising recent development involves the use of Nb-based alloys for SIS mixers. NbN mixers should be more rugged, operate at somewhat higher temperatures, and ultimately achieve higher frequencies (possibly 3 THz). SIS mixers require only low levels of LO power (order of μW's) and have wide IF bandwidths.

Encouraging progress has been made in the use of SIS mixers. At lower frequencies, inductive elements have been added across the junctions to effectively tune out capacitance. A range of creative antenna technologies has emerged as well; this work also supports the move toward arrays of mixers.

A measure of the progress in this area is the opinion that the heterodyne array instrument conceived of in the 1984 LDR Phillips-Watson report, which was then considered to rest on technologies which were "only a hope," was felt to be quite feasible now. It was felt that with sustained support, the necessary technologies for a linear array could be demonstrated in less than five years, with efforts focussed on achieving smaller device dimensions.

Photoconductive mixers were briefly discussed, but it was felt that these devices were not competitive with Schottky and SIS mixers because they have slower response times and require tunable local oscillators for spectroscopy.

ii) Local Oscillators

CO_2-pumped far-infrared lasers (~1-3 THz) have been successfully implemented in ground-based and airborne systems (Betz). They are adequately compact, and provide the milliwatts of drive power needed by Schottky diode mixers. Although the LO power is available only at specific frequencies determined by the transitions of the lasing gases, many of the most interesting astrophysical lines are accessible with CO_2-pumped far-IR lasers. An effort is now starting to make these LO's space qualified, and to develop means of extending the CO_2 pump laser lifetime.

Significant improvements have been made in the area of resonant tunneling oscillators (quantum well oscillators) (Sollner). Through the use of layered structures in the GaAlAs system, solid-state submm "electronic Fabry-Perot" oscillators have been demonstrated. Early this year, output power of about 0.2 μW was demonstrated at 200 GHz. (Thirteen months earlier, the upper-frequency limit was 20 GHz.) The series resistance and thickness of the device have been identified as limits to the performance; with continued improvements in these parameters, operation up to ~1 THz is projected.

As a result of this work, a dramatic advance has also been seen in multiplier technology. It has been shown that odd harmonics can be generated when a sine wave is swept over the I-V characteristic of the resonant tunneling oscillators. With this new technique both third-harmonic (67 converted to 200 GHz, with 250 μW output) and fifth-harmonic (42 GHz converted to 210 GHz, with 10 μW output) multiplication has been demonstrated. Other new results establish quantum well multipliers as already being competitive with conventional GaAs-diode triplers. Higher-harmonic generation is also possible with multiple quantum well structures.

Work on backward wave oscillators (BWO's) is underway in Europe and the U.S. The U.S. effort involves a planar, photo-lithographically-produced structure which should have better efficiency than the machined structure pursued by ESA, although this work has not yet achieved a clear demonstration of useful output power. There was concern about whether BWO technology could be space qualified, although the Europeans have achieved 950 GHz using carcinotrons, and are baselining these tubes for space applications.

iii) Back-end Electronics

Acousto-optical spectrometers (AOS's) are in common use on ground-based systems. In Europe, they are favored for space applications. It is felt that the AOS can be space-qualified and made more efficient through the use of polarizing Bragg cells and laser diodes. The digital autocorrelator approach has the advantages of being smaller and presumably more reliable, but power dissipation is higher. Digital systems now operate at ~0.1 W/channel; it was projected that through optimal design and application of VLSI technology, the power consumption could be reduced by an order of magnitude (Wilson).

b) Direct Infrared Detectors

In contrast to the relatively uncharted field of submm heterodyne receiver technology, the ongoing development program focussed on SIRTF needs is providing a significant technological heritage for LDR instruments (McCreight). This work is applicable directly for wavelengths >30 μm, and also indirectly, since low-noise readouts and materials advances for shorter wavelengths provide supporting experience. SIRTF technology will not be optimum for LDR, however, since the comparatively high LDR background and the larger desired long-wavelength detector array formats will require development, characterization, and optimization.

i) Detector Materials

A wide range of extrinsic silicon and germanium detector materials is being evaluated. Both conventional bulk photoconductive and impurity band conduction (IBC) (e.g., blocked impurity band (BIB)) detectors are under investigation. Ge:Ga IBC detectors have recently demonstrated long-wavelength response (~200 μm) and promising quantum efficiency in a non-optimum device. This development has the potential of replacing the conventional (stressed and unstressed) bulk Ge:Ga arrays on SIRTF (and LDR). Studies of Ge:Ga geometrical effects have shown the advantages of using a beveled back face to increase optical absorption.

ii) Modular IR Array Technology

The very low inherent noise of Si JFETs has been exploited in recent advances in integrating readouts. Both single-channel and 16-channel versions have been produced, with read noise on the order of 10 electrons (Young). Vibration tests have indicated that this technology is space-qualifiable, and it may see application in the HST second-generation instruments, SIRTF, and ISO. These readouts are in principle compatible with any IR detector material, and array sizes up to 32 x 32, or 64 x 64, are presently planned.

iii) Hybrid Arrays

Tremendous interest has been shown in the application of integrated IR array technology (<30 μm) in astronomy. Arrays of intrinsic and extrinsic materials, in photovoltaic, bulk photoconductive, and IBC forms, are being evaluated. Formats of 64 x 64 are now common, with larger arrays being actively developed. In general, integrated arrays have shown responsivities comparable to those of good discrete detectors, read noises at and below 100 electrons, dark currents in the range 1-100 electrons/second, and modest (<1 mW) power dissipation. The body of knowledge and experience in the photometric use of these arrays in astronomical observations is growing. This provides an important adjunct to SIRTF technology developments for LDR. While the overall capabilities of arrays have been demonstrated, finer points such as temporal response, response to energetic particles, and imaging properties remain to be fully proven. These may be crucial for space applications.

iv) Bolometer Arrays

Small arrays of bolometers are being used in ground-based and airborne systems. For space applications in the 200-1000 μm range, they are presently the technology of choice. A small array of bolometers is baselined for the SIRTF photometer instrument; for this project, the initial thrust has been in the design and definition of a workable adiabatic demagnetization refrigerator to achieve 0.1 K. Discrete bolometers at this temperature have demonstrated NEP's of approximately 10^{-16} W/$\sqrt{}$Hz (Meyer). The challenges associated with application on LDR include building arrays of ~10 x 10 elements, and optimizing these systems to the background loads of LDR.

c) Cryogenics

The cryogenics specialists on the panel had great difficulty in matching the state of the art to LDR requirements, since the LDR heat loads, minimum temperature requirements, instrument configurations, and operational timelines are poorly defined. A strong recommendation was made to improve the definition of the LDR system configuration, and to establish an active dialogue between the cryogenicists, the users, and systems engineers. Despite the level of uncertainty, the following general description emerged from the discussions of the panel.

Space hardware experience with stored cryogens (i.e., superfluid He) has been gained through IRAS, the Spacelab Infrared Telescope, and the upcoming COBE mission. For a 1 W·yr load to the dewar, 10 m^3 of He II are needed, or about 1400 kg of liquid. (Tankage, shielding, and supports could increase the mass by as much as a factor of ten (Mason).) Assuming a negligible instrument load, it has been estimated that stored He II technology could provide up to five years of cooling in space. The control of the liquid is the primary issue in long-life containment, and the achievement of a long-lived LDR would rely upon reliable resupply techniques. The Superfluid Helium On-Orbit Transfer (SHOOT) experiment will address this issue; it is planned for flight in advance of SIRTF, which baselines this approach.

A range of active coolers has been supported by NASA and DOD. Some progress in this field has been evident, for example, the ~2 year unattended lifetime demonstrated with Vuilleumier and Stirling coolers. There is also encouragement about progress with various Brayton-cycle machines such as the Turbo-Brayton and Rotary-Reciprocating Refrigerator coolers. Stirling technology has achieved a minimum temperature of 40 K. These coolers require about 3 kW of input power, and for space, a substantial radiator to reject heat. Concerns about vibration and lifetime might require that multiple, switchable active coolers be used on LDR. Sorption coolers are becoming increasingly effective for cooling in the 20-80 K range. These units operate with thermal efficiencies lower than those of the Vuilleumier and Stirling coolers, but they are free of vibration, and could conceivably utilize waste heat. No lifetime demonstrations have been carried out for this technology. Joule-Thomson expansion concepts may be applicable, particularly in cascaded configurations. However, this approach, while simple, suffers from low efficiency and the possibility of clogging. There is a renewal of interest in magnetic cooling concepts for the 10-15 K range. Progress here seems to be materials-limited. There is also a 2 K magnetic cooler about to reach the commercial market.

In the sub-Kelvin cooler area, the adiabatic demagnetization refrigerator, under development for SIRTF, is capable of reaching <0.1 K with an inherently gravity-independent system, but with some concerns over the effects of magnetic quench (Kittel). For 0.2 to 0.3 K, ^{3}He systems are reasonably advanced. A component-level laboratory demonstration has shown successful operation in an inverted (minus 1-g) geometry, and a ^{3}He cooler is planned to fly on an upcoming sounding rocket experiment. There is also substantial laboratory experience with ^{3}He/^{4}He dilution refrigeration. Efforts are now beginning to adapt this technique to the microgravity environment of space.

The panel discussed the feasibility of changing out LDR instruments. Studies for SIRTF have generally found this to be a very challenging proposition, although it is considered feasible. The desirability of automating these operations, both in manipulating instruments and in retrieving the telescope system from higher orbits, would involve significant additional complexity. Another approach would be to configure the LDR focal plane with about four instruments, with an integral cooler, and to replace this with another module every few years. Another bold notion emerged in discussion: launch the LDR warm, and cool it on-orbit (Nast). While sacrificing the ability to check-out the operability of instruments on the ground before launch, this approach would greatly reduce the system mass by eliminating the need for the vacuum shell.

The panel revisited the heat load estimates on the strawman instruments from the Phillips-Watson report developed at Asilomar II (cf., [4], p. 88). It was concluded that substantial reductions were possible if instrument configurations were optimized to minimize loads on the cryogenic system. This preliminary revision was by necessity done quickly, and much more detailed work is needed. It does, however, reflect technological progress in the past 2-3 years, and illustrates the sizeable improvements possible in this area. The key improvement was achieved at 2.5 K, where the load was reduced from ~1 W to ~1/4 W, making a stored-cryogen system feasible. The revised estimates of instrument power dissipation (expected to dominate over aperture and parasitic loads) are tabulated in TABLE 8. The columns headed "old" refer to Asilomar II estimates of the receiver operating temperatures and power dissipation; the "new" values represent the current estimates.

3. Technology Development Recommendations

As was stated above, the panel concluded that significant progress has been made since the last Asilomar meeting as a result of the LDR technology development plan. There was a general endorsement of the goals and directions of that plan. However, the following recommendations were developed by the panel to help focus, and in some cases redirect, the key development areas. They are listed roughly in order of priority.

a) General

o With the critical dependence of the mission on a reliable and workable instrument cooling scheme, support should be given to the development of techniques or configurations which would reduce instrument power levels and heat loads, and/or to increase the temperatures at which instruments reject heat to the cooling system.

o Continuing development and experience has indicated that some of the instrument types (and their frequency limits) conceived at the time of Asilomar II should be reconsidered. As an example, there now appears to be no advantage in including a photoconductive heterodyne receiver (cf., [2], Fig. 3-1, p. 32); its role could be assumed by extended-range SIS and Schottky diode receivers. The photoconductive receiver would offer advantages at the shorter wavelengths if bandwidths were increased or tunable LOs available.

o The panel recommends that observational testing of advanced receivers/arrays should be treated as an integral part of the LDR technology program. In the case of heterodyne receivers, platforms such as the KAO and SOFIA provide an excellent proving ground for development and optimization.

o In the continuing definition of the LDR focal plane, the issue of "light pollution" must be addressed. The panel was concerned about the presence of local oscillator sources, and warm instrument components, in close proximity to instruments which cannot tolerate stray radiation.

o It appeared that with the significant background levels of LDR, the conceived bolometer array instrument would not require cooling below 0.2-0.3 Kelvin.

TABLE 8. Old and New Instrument Power Dissipation Estimates

Instrument	Operating T		Dissipation	
	Old (K)	New (K)	Old (mW)	New (mW)
1. High-Resolution Spectrometer 400-3000 μm	20 4	40 8	300 10	100 1
2. High-Resolution Spectrometer 200-500 μm	20	20	300	20
3. Photoconductor Spectrometer 35-200 μm	20 4	20 2.5	- 100	10 5
4. Fabry-Perot Interferometer 35-200 μm	4 2	4 2.5	- 40-80	5 100
5. Grating Spectrometer 35-200 μm	20 4 2	- 4 2.5	100 - 6-40	- 1 50
6. Heterodyne Array	20 4	40 8	1000 350	1000 10
7. Far-Infrared Camera 35-200 μm	2	2.5	30	60
8. Submm Camera 100-1000 μm	4 0.1-0.3	2.5 0.3	10 0.01	10 1

Instrument Operating Temperatures	Total Dissipation	
	Old	New
0.3 K	0.1 mW	0.1-1 mW
2.5 K	980 mW	225 mW
8 K	360 mW	11 mW
20 K	2610 mW	(?) mW
40 K	- mW	1110 mW

b) Submm Heterodyne Receivers

o With the promising initial steps in NbN SIS mixer development, support in this area should definitely be continued. At present, only one institution (JPL) is involved in this work; it is desirable that another source (e.g., U. Illinois) be developed.

o Means must be found to correct the intermittent support given to the U. Virginia group which produces GaAs Schottky diode mixers; continuous and direct funding at a modest level needs to be arranged. An increased level of technical dialogue between these investigators and the user community would also be helpful.

o The recent progress in quantum well oscillators and multipliers has been dramatic. The panel recommends that funding in this area to the MIT/Lincoln Laboratory be increased.

o Funding for the planar backward-wave oscillators should be phased out, due to the lack of significant progress to date. (Note: Promising BWO data became available after the Asilomar III workshop. This recommendation should thus be reevaluated.)

o CSTI funding has recently been obtained for development of an LDR-oriented FIR/CO_2 laser (GSFC). Support for this project should be sustained for a period of time to access the feasibility of a space-qualifiable system.

o The panel concluded that support for Gunn-LO/multiplier development is at present adequately funded from non-LDR sources.

o The development of VLSI chips for a low-power, high-bandwidth digital autocorrelator was supported.

o It was suggested that additional KAO/SOFIA flights be funded as a means of developing and gaining experience with prototype LDR instruments.

c) Direct Infrared Detectors

o The ongoing SIRTF developments are providing an important foundation for LDR detectors, and support for this work should be maintained. The panel supported efforts to adapt SIRTF designs for LDR needs (e.g., minimizing thermal conductance of leads, optimizing circuits).

o The Ge:Ga IBC/BIB detector development(s) should be continued. Exploratory projects now underway for SIRTF should incorporate or anticipate LDR needs, where possible.

o In view of the cryogenic challenges presented by LDR, is was recommended that improved low-temperature, low-dissipation FET's and multiplexers, with characteristics such as charge-handling capacity tailored for LDR, be developed.

o Support should be given to the development of LDR-scale bolometer arrays. Optimization of the size and geometry of the bolometer elements, and their time constant, is needed.

o LDR instruments will require a range of optical elements (Fabry-Perot filters, mirrors, gratings) with large physical dimensions. Development of large prototype elements is recommended.

d) Cryogenics

o As was indicated above, the panel emphatically recommended that the definition of instrument heat loads, temperatures, and duty cycles be improved. Improved means of managing the thermal loads from the LDR aperture should be identified. A formal dialogue between the cryogenic experts, the sensor and instrument developers, and system engineers should be established, and improved system studies should be undertaken.

o The panel identified means of reducing the cold-end heat loads to well below 1 W. Given this, a stored-LHe cooling system should be considered to be a workable option. On-orbit resupply then becomes a key element in achieving a long-life LDR. Ongoing developments on resupply for SIRTF should be closely monitored.

o The panel recommended continuing the development of active cooler technology for the 2.5-10 Kelvin range, as another important option. Support for sorption coolers should be sustained. Magnetic-cycle coolers appeared attractive for LDR; selected developments in this area should be pursued. The panel noted that present funding levels for active coolers are inadequate to seriously address LDR cooling needs.

o Resupply needs for LDR should be incorporated in the design of the He II Tanker, by August 1988.

o The definition of instrument changeout concepts must be improved. Changeout of a module including a number of instruments and an integral, "throw away" cooling system should be studied. The prime LDR instrument configuration must be developed in close coordination with the cooling concept.

o For cooling of the bolometer arrays, if a minimum temperature of 0.3 K is acceptable, the existing ^{3}He cooler technology is adequate. If 0.1 K is required, the SIRTF-baseline adiabatic demagnetization refrigerator should be closely monitored; in addition, exploratory dilution refrigerator concepts should receive continued support.

E. Optics and Systems

1. Introduction and Review

The technical disciplines of Optics and Systems were combined into a single panel for the Asilomar III workshop. In part, this was a response to the fact that LDR will operate in the submillimeter wavelength spectral region, where neither infrared nor radio techniques alone are sufficient for dealing with the optical design. Because this region cannot be adequately observed from earth, the incentive has not existed, as for other spectral windows, to develop the needed technology. The effect of diffraction in a segmented aperture, and the impact of background radiation from a passively cooled telescope, become very important system drivers which are unique to LDR. It is therefore essential that a very close interaction occur between all LDR technology areas, particularly optics and systems.

The Asilomar II Optics panel recommended work in the five general areas summarized below:

(1) optical design and modeling
- quasi-optics analysis and optimization
- image quality evaluation and optimization
- chopping and thermal background management
- standing wave behavior

(2) technology demonstration
(3) precursor science
(4) wavefront sensing
(5) optical contamination

With the exception of optical contamination -- which awaits requirements for panel emissivity and reflectivity -- some progress has been made in each of these areas. At the two panel sessions during this meeting, the primary issues centered on the baseline design performance, chopping as a system driver, science instrument definition status, and optical testing for panel figure and alignment.

At Asilomar II, a JPL report introduced the concept of a two-stage, or four mirror, optical configuration for the LDR [3]. Although this design had several important advantages, subsequent studies have helped to reveal some of its limitations. A thermal background stability of about 1 part in 10^9 is required for submillimeter continuum measurements. This is achieved by moving the telescope beam back and forth on the sky ("chopping") with everything else held constant. In principle, the unwanted thermal background radiation is subtracted out and only the source radiation is measured. In the two-stage optical design, chopping can be accomplished by tilting the quaternary mirror. This is advantageous because the mirror is flat, which minimizes image degradation, and it is small, which minimizes vibration (compared to chopping a more massive secondary mirror). Recent analysis, however, indicates that the hole in the quaternary mirror can cause an unbalanced sidelobe energy loss during chopping; this reduces the effective beam stability to about 1 part in 10^4 (Wright). Assumptions in this analysis need to be reviewed. In addition, there are potential problems arising from thermal variations, structural motions, and pointing control system errors. Discussions at the panel meetings strongly suggest that there are several key issues in regard to beam chopping that must be resolved before further progress can be made on updating the baseline design concept. Two options need to be considered for the updated baseline design: (1) a two-mirror Cassegrain with a chopping secondary, and (2) a modification of the four-mirror two-stage case. Both have potential problems, and understanding the trade-offs is essential.

At Asilomar II, it was recommended that a software analysis package be created to accurately model the optical system in terms of the Gaussian beam and white light performance. Between the two Asilomar meetings, a diffraction model of the LDR baseline system was used to determine qualitatively the side-lobe heights in a segmented aperture (Van Zyl), but much more work is needed to quantitatively evaluate the LDR quasi-optical design. This analysis has shown that the large secondary mirror of the baseline design causes unacceptable degradation of the diffraction pattern.

Wavefront sensing was recognized to be an important aspect of LDR for panel alignment. Work has been done on the application of a Shack interferometer to an alignment scheme for the Keck telescope (Vaughan), and on a technique for imbedding a weak diffraction grating in panels that could be used for real time sensing of panel alignment (Stier).

At Asilomar II, technology demonstration was called for in the area of reflector panels (both glass and composite), aspheric surface fabrication, and the development of two meter composite panels. This work is now funded under the CSTI/PSR program at JPL and LaRC, or planned augmentations to this program. There was substantial discussion as to the relationship of PSR to LDR technology issues. The PSR program is a natural vehicle for systems-level testing -- in hardware -- that could greatly benefit future LDR technology development and evaluation.

Progress was also seen in the area of optical metrology and the testing of panel performance over the needed temperature range. Several Dornier 50 cm panels have been measured in air at the Steward Observatory (Hoffmann) using a modified commercial interferometer provided by the JPL Optical Sciences and Applications Section. The total figure change observed was within the acceptable range for LDR applications. The next major hurdle will be to scale the testing capabilities to the full two-meter panels. To improve the surface quality of the panels, thick SiO coatings have been applied to a Dornier panel, which was then polished using conventional techniques (Woida). This approach works, and has no affect on the panel figure change with temperature. Conventional polishing, however, would seem to be too expensive for the large number of panels needed for LDR. Overall, the work on panel development has been well coordinated and ap-pears likely to achieve the goals required for the LDR reflector.

2. Identification of Critical Technologies

The basis for current LDR studies is given in a JPL report [3], and is also reflected in the Lockheed reference concept presented at this meeting [6]. Adjustments were made to accommodate refinements in the science requirements for the light bucket mode, and the shortest wavelength for diffraction limited performance. Consideration must also be given to the potential diffraction problems noted above, since this can impact the background rejection and faint source detection capabilities of the current two-stage optical design.

a) New Functional Requirements

New functional requirements were felt to be needed in a number of areas: thermal background suppression, panel surface properties, a system error budget, optical requirements on the control and pointing systems, and wavefront sensors.

i) Panel Surface Properties

Uniformity of the panel reflectivity and emissivity, as well as the possible need to have specular panels in the visible, requires the establishment of a specification for the coating/substrate system. Panel durability and aging must also be better understood. During the past two years, coatings have been developed over a Gr/Ep facesheet to enable the surface to have a high reflectivity for a period of several days -- long enough for a measurement of the optical wavefront. However, long-term stability of the LDR panels, and the spatial variation of emissivity, contamination, and staining have not been addressed. The use of glassy compounds for mirror surfacing must also be investigated.

ii) Science Instrument/LDR Modeling

As yet, no firm functional requirements for the desired LDR sensitivity limits at different wavelengths exist. These are clearly driven by science needs, and must be defined.

iii) System Error Tree

A complete system error budget is badly needed. To this end, subsystem functional requirements for the tilt, piston, and de-center of each of the panels, and for the ensemble of panels, are needed. These will driven by the science requirements and could be evaluated by studying the time-dependent modulation transfer function (MTF). An optical interferometry experiment is also required to measure the opto-mechanical properties (e.g., CTE, hysteresis, joint non-linearities) of candidate opto-mechanical structural configurations. Ultimately, this should produce a comprehensive error tree for a given system performance/science requirement trade.

b) Optical System Design for LDR

Members of the Optics and Systems panel feel that an on-going optical system design activity should be initiated to provide a point design for LDR; this activity should take into account technology developments during the past three years, and should include a strawman payload of instruments. The panel recommends that the optical design activity continue during the LDR development program to provide ongoing support. A specific design activity would be the tolerancing of one- and two-stage segmented LDR mirrors in terms of the focal plane point spread function (PSF). This task should be performed for both an on-axis system and an off-axis system.

c) Modeling and Verification

A thermal model for the one- and two-stage LDR optical trains must be developed. These models should be of such precision that temperature and emissivity variations across mirrors, or between mirrors, can be evaluated in terms of noise power at the detector of a modeled science instrument.

Additional diffraction analysis of the segmented one- and two-stage LDR options must also be performed. This will require the merging of radio and optical analysis techniques into new software which can be used to compare model predictions with laboratory measurements.

Questions were raised about the reliability of the current panel measurement system, because it lacks adequate environmental control during testing. The recommendation was made that panels developed for space-based applications be tested in a thermal vacuum.

d) Adaptive Optics/Interferometric Metrology

Adaptive optics and interferometric metrology were identified as important technology areas. Time-dependent deformations in large telescopes reduce image acuity, and will certainly affect LDR. Solutions to this potential problem will require the use of deformable mirror technology and optical image reconstruction techniques.

3. Technology Development Recommendations

In order to formulate a set of final recommendations the following questions were submitted to the panel for consideration:

o Is the baseline design adequate? If not, what should the updated baseline be?

o Are the control concepts able to deal with panel control, chopping, and pointing?

o Is a strawman science payload required in order to do an end-to-end system analysis?

o Is the current development work relevant?

As indicated in the prior discussion, there are concerns about the baseline design and the control concepts for meeting the background stability requirements. In a broader sense, it seems that many of the key issues, such as the impact of chopping on the system, will need a better definition of the science instruments in order to make the appropriate design trades. Current development efforts seem well directed in the structures and materials technology areas, as indicated by the excellent progress made in panel development. However, the Optics and Systems panel was clearly concerned about the integration of point technology developments into the LDR systems concept. Based on these concerns, the following recommendations were agreed on:

o Establish multi-disciplinary teams to study the chopping problem and to select a set of science instruments that can be used for systems definition and performance analysis.

o Develop alignment concepts and a systems error budget for the baseline design to establish the functional requirements for the PSR program.

o Model the optical system from end-to-end in order to answer critical issues affecting LDR science objectives and their implementation.

o Develop an updated baseline optical configuration for LDR, and identify the associated trade-offs, especially in the area of background stability. The numerical requirement for the level of background stability must be provided by the Science panel.

V. SCIENCE PANEL REPORT

A. Introduction

The Science Panel at the Asilomar III workshop consisted entirely of members of the LDR Science Coordination Group (SCG). The SCG serves the LDR project in several capacities: by providing the science rationale, by establishing system requirements, and by serving as an advocacy group. At Asilomar III individual science panel members were in attendance at each of the technical panel meetings, where they served several roles. One was an interactive role: to relate the LDR design to its science goals and to help define the key areas to be addressed. Sometimes the issues were unclear, leading to a second role: to determine the need for in-depth studies to refine the LDR design. Several of these studies involve system-level modeling to determine the effects at the focal plane of telescope vibration, thermal fluctuations, and the overall optics design. A third, and important role for the science panel, was to learn more about the LDR mission design, and to set up priorities for a science program leading to LDR itself. In some cases, LDR technologies are driven by astronomy goals which could be made more specific with preliminary results in hand. These results are usually observational, but could also be theoretical.

The main product of the science panel is therefore a preliminary plan to sharpen the science input to LDR and to keep the science needs closely related to the NASA-supported technology program. A detailed plan will be formulated in subsequent meetings of the SCG. The tentative plan includes special studies, workshops, and experimental and theoretical activities. Where observational data are required, these are usually at submillimeter and far-infrared wavelengths. Some use may be made of ground-based techniques, such as from the submm/FIR instruments on Mauna Kea. However, as might be expected, most of the spectral range is unobservable from the ground and more often, the needs point to aircraft and balloon platforms, and to small space missions.

B. Discussion of Some Baseline Concepts

While recognizing the usefulness of having a single reference, or 'baseline' concept, the science panel urges that the project not confine itself too narrowly during its "pre phase-A" studies. There are major system trade-offs which have not been fully examined and it may be necessary to maintain two or more baseline concepts at this point. Each concept should be periodically reviewed for its scientific potential.

1. Orbits and Serviceability

One major system-level trade concerns on-orbit serviceability. The present baseline configuration assumes a long lifetime and frequent (bi-annual) manned visits. This scenario assumes a relatively low, circular orbit compatible with the space station. In the "frequent re-visit" configuration, the science instruments could be periodically changed out, and expendibles (such as cryogens) could be replenished often. Because of the low orbit, the telescope design would have to allow for fast retargeting (every 20 mins or so), and the thermal design must be such that the fast changes in radiative input do not adversely affect the telescope performance. An alternate approach is used on the ESA's FIRST project, which employs a highly elliptic 24-hour orbit and a dewar with a long hold-time.

2. Mission Design

Related to the choice of instruments and orbits is the need to establish a strawman observing sequence. Sky coverage and integration times can affect the choice of orbits. The IRAS mission, which uniformly sampled the sky and had stringent Earth and Sun avoidance angles, was ideally suited to a polar orbit. LDR would also profit from a benign thermal environment, but LDR, unlike IRAS, will carry out primarily pointed observations of galactic, extragalactic, and solar system objects. Also, different scientific experiments have different tolerances for scattered radiation and thermal emission from the telescope. A balance needs to be established between extragalactic surveys, with fairly uniform sky coverage; galactic observations, with sources clustered in a few regions of the sky; and solar system observations, which may place difficult constraints on Sun avoidance angles. A strawman mission, including a representative sample of sources and observing times, will establish the need for thermal stability, frequent slewing, and long integrations.

3. Photometry Requirement

One of the requirements most tightly driving telescope design is that for carrying out short wavelength (50-200 μm) photometry. At issue is how to determine a practical sensitivity limit. There are three fundamental limits: those set by available instruments, those set by natural statistical fluctuations in the thermal emission from the telescope, and those set by "systematic" changes in the temperature and shape of the telescope. The first two are readily defined, and set fundamental sensitivity limits. The third noise source is more difficult to evaluate. It is impacted by many telescope properties: vibration suppression, the number of panels, Earth and Sun avoidance angles, the optical design, the geometry and cycle time of optical choppers, detector stability, cold baffling, etc.

The SCG has been repeatedly called upon to define a photometry requirement, but feels that a more interactive procedure is needed. This one requirement could significantly affect the complexity (cost) of LDR, and should be examined at several different levels against the science pay-off. A sensible requirement could then be set.

Given a photometry requirement, its interpretation in terms of design is not readily apparent. If the telescope were thermally uniform, small vibrations and deformations would not be so serious. Deformations and thermal instabilities could be forgiven with a suitably designed chopper; presumably rapid and involving the secondary, if not the primary. Other issues involve the need for active control of the panels (or their counterparts deeper in the optical path) and of the sunshade design. Also, much might be achieved in the focal-plane instruments themselves, in terms of internal chopping, imagery and instrument stability.

C. LDR Instruments

The NASA sensor technology program is well suited to the development of sensors, loosely defined to be the active elements at far IR and submillimeter wavelengths. The submm program within NASA is commendable and farsighted. The IR sensors program is also fruitful, driven in part by the more immediate SIRTF needs. However, some LDR instrument needs are not adequately met. One example is the need for heterodyne spectrometers.

1. Heterodyne Spectroscopy

Unlike the direct detector spectrometers, heterodyne spectroscopy is not carried out at the observing wavelength, but at a much longer wavelength. New heterodyne spectrometer designs for ground-based applications are being continuously and aggressively developed. However, most ground-based spectrometers have volume, mass, and power requirements which make them unsuitable for LDR use. Also, LDR has specifically identified heterodyne array instruments as essential; straining even the ground-based designs.

2. Update of Focal Plane Design

The SCG, in the period between the Asilomar I and II workshops, made an initial report on the LDR focal plane [2]. In this report, the wavelength coverage and the spectral resolution needs for LDR were transformed into an instrument complement which would satisfy all LDR requirements. Now, an update is needed to evaluate the weight, power, cryogenic loading, and output data rate. The update should account for technological progress, much of which was presented in the previous section. It should also include a scenario for instrument upgrades.

3. Instrument Changeout

An issue affecting the entire operating philosophy of LDR concerns the practicality of on-orbit changeout of the instruments. The science panel was called upon to define a need, but felt that it had insufficient information. On the one hand, a small package, changed frequently, decreases power, weight, and cryogenic needs, as well as the possible data rate. Also, it allows the more mature instruments to fly first, thereby simplifying the instrument technology program. On the other hand, changeouts are inconvenient and expensive, restrict the choice of orbits, and demand a spacecraft flexible enough to handle the special needs of each payload.

There are several questions which must be answered. Is it practical to change individual instruments, or must the instrument payload be considered as a whole? Can such changeout be considered by unmanned means, or must astronauts be involved? Can a cryogenic system be made suitably flexible to service different instruments? What is the impact of orbit height, inclination, and eccentricity? This issue should be the subject of a special study, possibly in the form of a workshop with the attendance of scientists, instrument and cryogenic engineers, and mission analysts.

4. Multi-Instrument Operation

There will be scientific pressure on the LDR to observe simultaneously with several instruments. This mode of operation provides the most efficient use of the telescope, and eliminates many problems raised with serial observations (due to variations in pointing and gain). Because this mode is important, its impact on the focal plane design needs to be considered. Since the simultaneous use of array imaging with several instruments can have an impact on cryogenic consumption and on data transmission rates, those issues should also be investigated.

The benefit of simultaneous observations can be appreciated from experience with ground-based millimeter telescopes. By observing several transitions and isotopic variants of CO simultaneously it is possible to establish temperatures and densities in interstellar clouds. The same will be true for the hotter, denser regions available at the higher-frequency transitions available to LDR. For example, it will be desirable to observe the [C I] lines at 610 and 370 microns at the same time as the [CII] line at 158 microns, as these lines provide important and complementary information about cloud boundaries.

The observing times necessary for these observations are not likely to be very discordant.

During the Receivers and Cryogenics panel meeting, there was a reassessment of the cryogenic needs. It was apparent that much of the instrument heat load is developed between the leads from cold detector to warm amplifier, and this was an area where improvement could be obtained. To allay the cooling problems, that panel determined that all instruments could be turned off when not in use. However, and this is a point where the science panel voiced strong objections, a serious evaluation of this point is needed.

As was noted in the Asilomar II Workshop on Technology Development Issues ([4], p. 102), the "use of dichroic filters or focal-plane sharing should receive serious investigations for LDR." This technology is becoming increasingly used. From the point of view of observing efficiency, it is just as important to cover frequency space with an array of instruments as it is to cover the focal plane with an array of detectors at single frequencies.

D. Technology Development Recommendations

Panel members were encouraged by the start of a funded NASA technology program, and the group anticipates significant advances in the LDR design. Panel members expressed several concerns about implementation of the technology program. One general concern was how the technology efforts would specifically support LDR needs. The maintenance of a system-level design effort is needed, operating in parallel to the individual technology programs, both for the telescope and for the instrumentation. Also, a clear need was seen for an aggressive science program leading up to the launch of LDR. That effort must involve ground-based and airborne techniques in addition to precursor space missions.

The Science panel feels that a serious study of the photometry requirement is needed. It became clear at the workshop that the same photometric requirement was being independently tackled at several levels in the system. A trade-off study will identify the best way to satisfy the requirement, and may point to the technology(ies) most likely to support photometric science.

An integrated focal plane package should be designed, complete with transfer optics and a cryogenic system serviceable according to LDR mission concepts. New developments in instrument technology might alter the existing strawman payload and some account should be taken of the plans for instrument changeout and for simultaneous operation of instruments.

E. The Pre-LDR Science Program

LDR will be the major, world-class observatory operating in the 30-1000 micron wavelength range. Its design must be on the mark both technically and scientifically. This implies a supported program of submillimeter and far-infrared science and technology. The technology program has been the subject of intensive planning and is now receiving substantial support. The scientific support is less developed, and is clearly needed. Observations are paramount, but some laboratory and theoretical work is also needed.

A scientific program at LDR wavelengths implies astronomical observations, both to learn about the sky and to learn about the operation of instruments at submm/FIR wavelengths. Such a program would certainly lead to modifications of the LDR mission design, which would both enhance its output and increase its reliability. Such an observing program can be approached in two ways: (1) by modest orbital missions; and (2) through whatever wavelength windows are accessible from mountaintops, airplanes, and balloons. A balanced program is clearly the best approach.

Modest orbital missions provide the only access to several vital spectral lines and the only experience with operating LDR-type instruments in space. Operating apertures could be from 1 to 4 meters. Balloons, for short missions, can provide access to most of the LDR wavelengths, and can support a similar range of telescope apertures. Balloons have space-like requirements for instrument weight, power, and hands-off operation. Experience in several programs has demonstrated how balloon instruments have led directly to space application. Airplane-based telescopes can provide more flight opportunities, though with reduced wavelength coverage and with more limited telescope apertures. Hands-on operation makes access easier for scientists and allows for testing of new instruments and techniques, leading to potential devices for space application. Mountaintop observatories can gain only very limited access to the LDR wavelength band, but they provide the only opportunity for science using LDR-like telescope apertures. At relatively low cost, ground-based observations encourage development of the new technologies which are needed for LDR instruments.

Supporting theoretical and laboratory work is also essential to the efficient design of the LDR mission. On the laboratory side, it should be noted that without LDR-motivated support, there is really no incentive to measure the frequencies and strengths of astronomically important spectral lines. Also of concern are certain chemical reaction crosssections directly affecting the predicted abundances of the heavy element hydrides which are vital to the LDR science program. Obtaining laboratory data relevant to LDR is a long-range activity best pursued hand-in-hand with a vigorous theoretical activity.

A steady program of funded theoretical work is also essential to the LDR mission. Where direct observations provide partial information, theoretical models of astronomical sources can help to predict signal strengths for sources and spectral lines otherwise inaccessible. For example, a modest aperture orbital or balloon experiment might yield spectral line strengths in nearby extended sources, but may be inadequate to observe interesting protostellar and extragalactic objects. Theoretical models, including physical and chemical codes in addition to radiative transfer calculations, are essential to help assess the goals for LDR and the design of its instruments.

A balanced pre-LDR science program is vital to LDR. Advance support will sharpen the LDR science objectives, will lead to resolution of several technology challenges, and will improve the LDR mission design.

VI. SUMMARY AND CONCLUSIONS

Rather than repeat the recommendations of the technology and science panels verbatim from the previous two sections, we will attempt in this summary to identify the major issues confronting the LDR project at this time. One theme is particularly apparent, and not unexpected; it is the different perspectives of the science and the technology panels. The Science panel would like to leave some of their options open -- for very good reasons -- and not take a hard stand on all of the functional requirements needed to reach their science goals. The Technical panels, on the other hand, would like specific requirements defined--again, for very good (but different) reasons -- so they do not spend time developing technology which might not meet the ultimate science needs. This theme is played over many times, and it will be the role of the LDR management to bring the two viewpoints together in a timely manner.

To help further refine our concept of what LDR will be, several outstanding issues must be addressed. The issue of thermal background subtraction in the currently baselined on-axis two-stage optical design is certainly one of the most urgent, since it places fundamental sensitivity limits on the science that LDR can do. In this regard, it is also very important that a detailed photometry specification be developed by the SCG, and that it clearly identify just how steep the scientific slopes are as drivers for aperture size.

A great deal of LDR-directed effort is now being made in the CSTI/PSR program to build space-like telescope structures, utilizing lightweight composite panels and an active precision position control system. Although both erectable and deployable structures are being developed, they may not be dynamically representative of LDR in that they may not be able to take account of the LDR sunshade. In addition, this effort does not currently include an over-guideline request for an integrated control system.

Although excellent progress is being made in the fabrication and testing of composite panels, detailed functional requirements do not yet exist for their optical, thermal, mechanical, and environmental properties. Unless these are developed, the existing PSR effort may be partially misdirected. The LDR program must do all that it can to provide guidance for this very important NASA program.

In a similar vein, it is important that a systems-level error tree be developed for LDR. Until this is done, it will be impossible for the different technology disciplines to understand their own goals, let alone the impact they might have in other areas. Implicit in this are two requirements: the need for realistic modeling/simulation capabilities in all disciplines, and the need for an interdisciplinary systems-level design team. The systems-level approach to specifications for LDR was called for by all panels.

In the area of science instruments, good progress is being made -- in some cases, beyond what would have reasonably been expected a few years ago. Specific recommendations have been made for both heterodyne and direct detector development. Methods to reduce heat loads or increase operating temperatures remain a primary concern. In addition, the instrument complement requires redefinition, as does its heat load.

Progress is already being made on many of the issues raised in this report. With adequate funding, good progress should be possible in all areas. If a single recommendation were to be made, it would be the need to revisit, using a systems-level approach, both the science and technical requirements for LDR.

VII. REFERENCES:

1. Asilomar I Report:
Large Deployable Reflector Science and Technology Workshop; Volumes I,II, and III, edited by Christopher A. Leidich and R. Bruce Pittman, NASA Conference Publication 2275, June 1984.

2. Phillips-Watson Report on Focal Plane Instruments:
The Large Deployable Reflector: Instruments and Technology, A Report by the LDR Science Coordination Group, Focal Plane Instruments Subcommittee, T.G. Phillips and Dan M. Watson, JPL Report D-2214, November 30, 1984.

3. JPL Reference Concept:
A Lightweight Low Cost Large Deployable Reflector (LDR), Paul N. Swanson, JPL Report D-2283, June 1985.

4. Asilomar II Report:
Workshop on Technology Development for the Large Deployable Reflector (LDR), edited by Kenji Nishioka, NASA Conference Paper 2407, February 1986.

5. SCG Report:
The Large Deployable Reflector (LDR) Report of the Science Coordination Group, JPL Publication 86-46, October 1986.

6. Lockheed Reference Concept:
Large Deployable Reflector (LDR) Reference Concept, Lockheed Missiles and Space Company, Inc., Final Report for JPL Contract 957514, LMSC Publication F230421, September 1987.

7. 1985 Lockheed Reference Concept:
Large Deployable Reflector (LDR) System Concept and Technology Definition Study, L. Bandermann and W. Alff, Final Report for NASA Contract NAS2-11862, NASA Publication CR-177364, 1985.

8. Eastman Kodak Reference Concept:
Large Deployable Reflector (LDR) System Concept and Technology Assessment Study, D. Agnew et al., Final Report for NASA Contract NAS2-11861, NASA Publication CR-177414, 1986.

VIII APPENDIX: ASILOMAR III TECHNICAL PAPERS

A. Controls and Pointing Papers

35

N90-13451

A Figure Control Sensor For the Large Deployable Reflector

R. Bartman and S. Dubovitsky
Jet Propulsion Laboratory
Pasadena, CA 91109

A sensing and control system is required to maintain high optical figure quality in a segmented reflector. Upon detecting a deviation of the segmented surface from its ideal form, the system drives segment-mounted actuators to realign the individual segments and thereby return the surface to its intended figure.

When the reflector is in use, a set of figure sensors will determine positions of a number of points on the back surface of each of the reflector's segments, each sensor being assigned to a single point. By measuring the positional deviations of these points from previously established nominal values, the figure sensors provide the control system with the information required to maintain the reflector's optical figure.

The physical properties of the segment support structure and the control system itself are two of the major factors determining the performance requirements imposed on the figure sensors. Information available at this time allows us to define preliminary estimates of the sensor's resolution, overall measurement range, and update rate. On the basis of the estimates for these requirements, three technologies have been identified as the most promising for the development of the figure sensor: optical lever, multiple wavelength interferometer and electronic capacitive sensor.

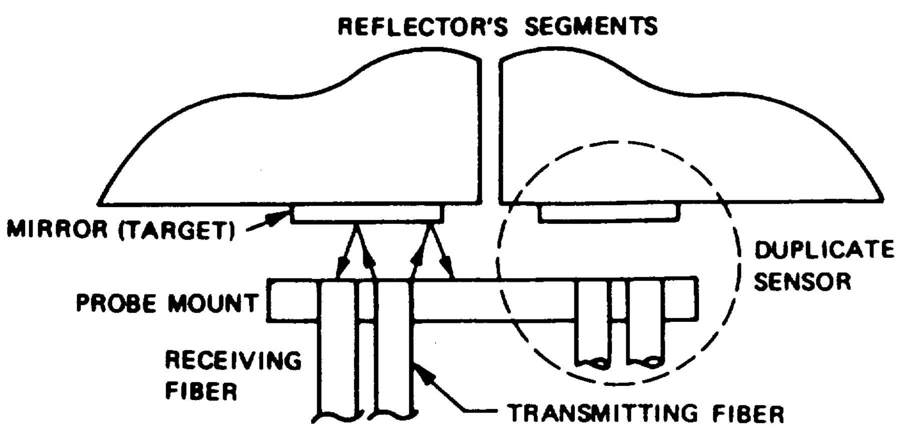


FIGURE 1. Optical Lever

The optical lever concept, which is illustrated in FIGURE 1, is an intensity-based method for determination of position. The amount of light intercepted by the collecting fiber depends on the target-probe separation and, therefore, can be used to measure position of the target relative to the probe. Optical lever sensors need to be deployed in pairs, as shown in FIGURE 1, to determine relative edge displacement of adjacent segments.

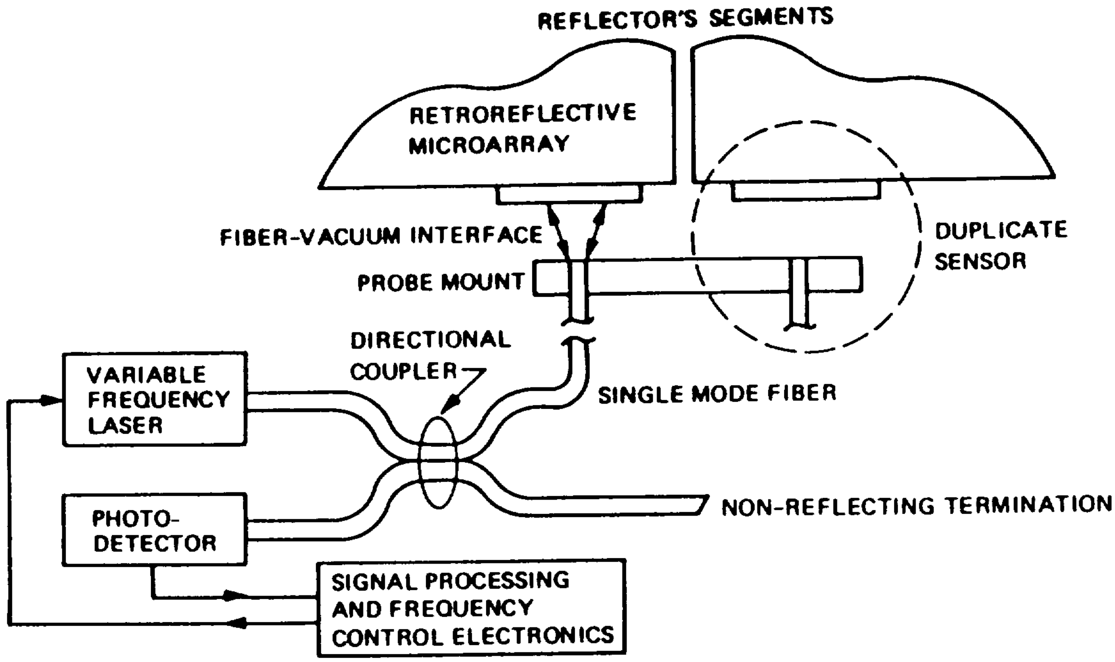


FIGURE 2. Multiple Wavelength Interferometer

An implementation of a multiple wavelength interferometer is shown in FIGURE 2. Optical radiation returned by the retro-reflector interferes with that reflected from the fiber-vacuum interface. In this approach, the target-probe separation is arranged to be the path difference between the two arms of the interferometer. Multiple wavelength operation is required to resolve the $\lambda/2$ range ambiguities. Sensors of this type also need to be deployed in pairs.

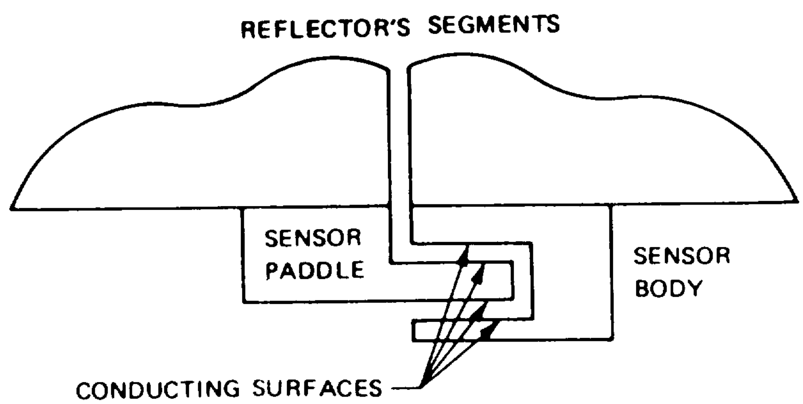


Figure 3. Electronic Capacitive Sensor

Basic operation of an electronic capacitive sensor (which is to be used on the Keck telescope) is illustrated in FIGURE 3. The electrical capacitance formed between two or more parallel conducting surfaces is measured to determine their separation.

To select a particular implementation of the figure sensors, performance requirements will be refined and relevant technologies investigated further.

550171 p2

N90-13452

Expert Systems for Adaptive Control of Large Space Structures

Charles F. Gartrell
General Research Corporation
McLean, Virginia

It is expected that space systems for the future will evolve to structures of unprecedented size with associated extreme control requirements. The current methods for active control of large space structures suffer from basic limitations: strong dependence upon high fidelity parameter estimates, and the inability to recognize system performance changes.

A method is necessary that is sufficiently general to initiate stable control of a vehicle and subsequently "learn" the true nature of the structure. It is the author's contention that a suitably constructed expert system (ES) would be capable of learning by appending observations to a knowledge base. To verify that an expert system can control a large space structure, numerical simulations of a simple structure subjected to periodic vibrations and the performance of a classical controller have been performed. The expert system was then exercised to show its ability to truthfully mimic nominal control and to demonstrate its superiority to the classical controller, given sensor failures.

An ES-generating software package named TIMM™ (The Intelligent Machine Model) was employed in this study. It uses the pattern matching technique. TIMM does not attempt exact matching of patterns, because this poses too stringent a requirement. Instead it incorporates a model of inexact reasoning, i.e., partial match inferencing.

A simple beam was chosen as a model. A numerical simulator was constructed to show the open loop behavior of the structure, and its behavior when controlled (closed loop). The controller was exercised to show nominal action, plus its behavior when various sensors failed. This data was subsequently used to create the various data bases needed to develop and exercise the generated expert system.

FIGURE 1 illustrates the performance of the ES using both data models as the knowledge base. This case simulates the learning by an adaptive controller from experience by appending the "in-space" truth observations to the "ground-based" truncated knowledge base. As can be seen, the force ranges selected for the truth data with data dropout are virtually identical to the actual truth forces, in spite of the erratic behavior of these force values. This dramatic result appears to show that an expert system can be highly effective at "learning" from experience.

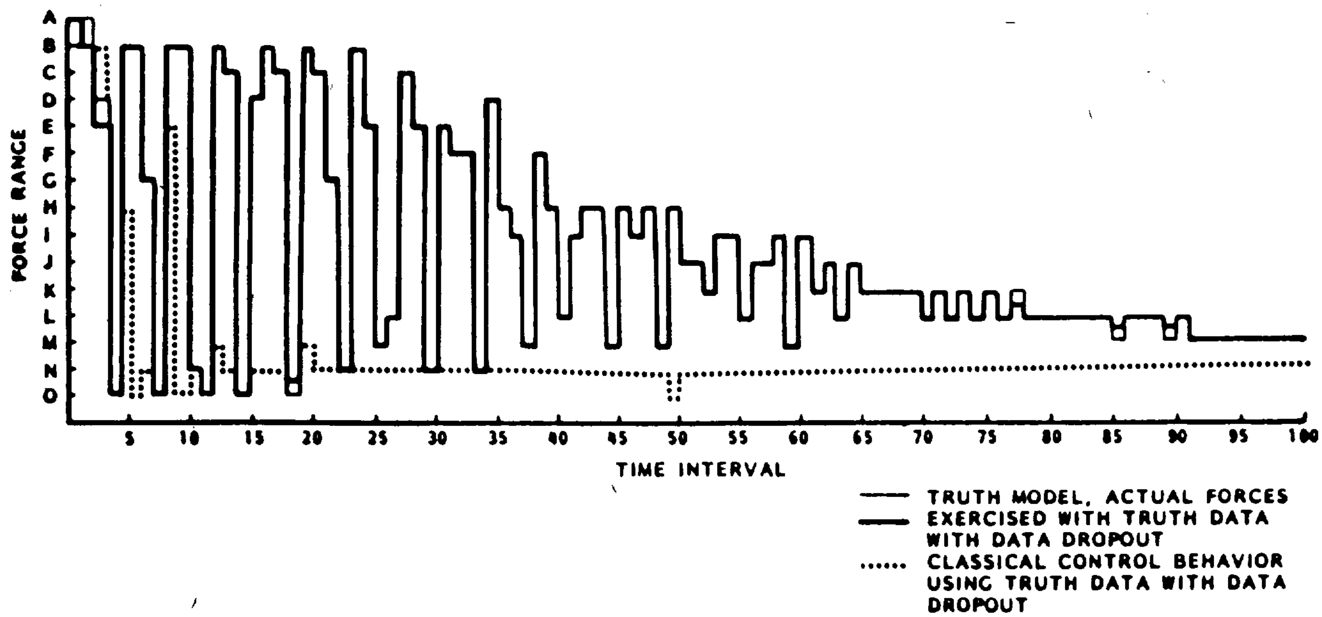


FIGURE 1. Data Loss for Expert System Trained with Truncated and Evaluation Models (Learning)

N90-13453
550179 ρ2

Pointing Control for LDR

Y. Yam and C. Briggs
Jet Propulsion Laboratory
Pasadena, CA 91109

One important aspect of the LDR control problem is the possible excitations of structural modes due to random disturbances, mirror chopping, and slewing maneuvers. This problem is particularly significant for LDR with its very stringent set of control and pointing requirements. An analysis has been performed to yield a "first-order" estimate of the effects of such dynamics excitations.

The analysis involved a study of slewing jitters, chopping jitters, disturbance responses, and pointing errors, making use of a simplified planar LDR model which describes the LDR dynamics on a plane perpendicular to the primary reflector. The model simulates the dynamics of the primary reflector, the sunshade, and the center column of mirror supporting structure and instrument module via flexible beams. Seven modes, three of them rigid body modes, are included in the analysis. As such, the model captures the essential LDR dynamics and still enables manageable study of the dynamic excitation problem.

FIGURE 1 presents the results for the chopping analysis. During LDR operation, the quaternary mirror is to be chopped at a 2 Hz frequency with a one arc-min amplitude in an effort to eliminate the effect of sky and telescope background. The simulation was conducted assuming that the quaternary module is located at a specific position in the center column and that the system manages to counterbalance 99% of the chopping torque. The figure shows the residual chopping torque the system reacts to in newton·meters and the resultant pointing error in mrad. The quaternary chopping contributes to the pointing error in two ways. One is the quaternary module rotation due to the bending of the central column. Structural rigidity of the center column is the key in minimizing this error. The other is the center column rotation about the primary reflector. The analysis shows that the steady state pointing error due to quaternary chopping in this simplified study is around 55 x 10^{-6} mrad, orders of magnitudes lower than the pointing requirement.

Study of jitter excitations due to LDR slewing and on-board disturbance torque was also included in the analysis. Briefly, the results indicate that the command slewing profile plays an important role in minimizing the resultant jitter, even to a level acceptable without any control action. An optimal profile should therefore be studied. For disturbance torque, its allowable level at the bus is determined to be around 0.025 nut-m (standard deviation) given an allocated allowable pointing budget of 0.01 mrad out of a total of 0.1 mrad.

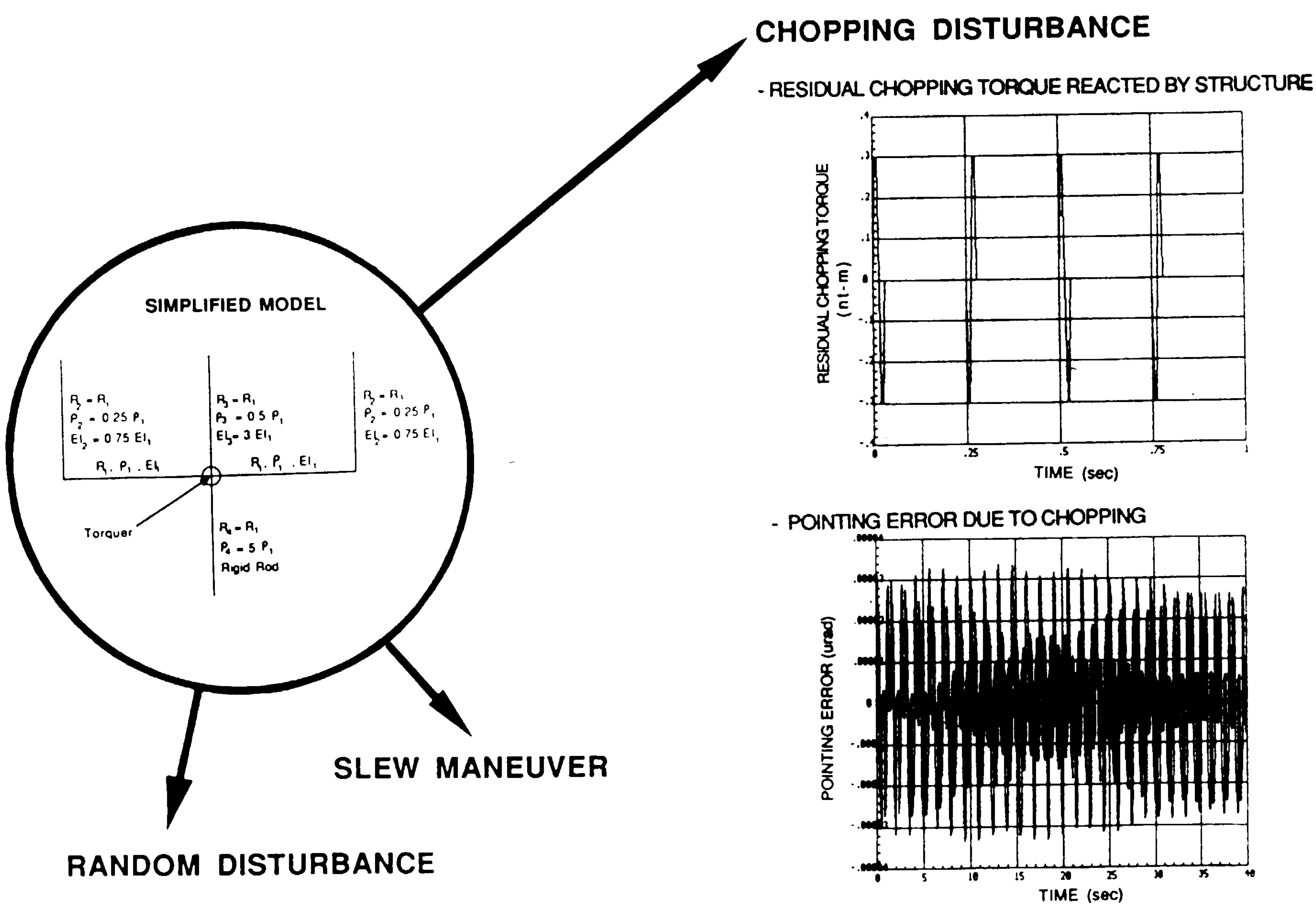


FIGURE 1. LDR Residual Chopping Torque and Pointing Error due to 2 Hz Quaternary Chopping

N90-13454

550180

Space Telescope Pointing Control

Hugh Dougherty
Lockheed Missiles and Space Company
Sunnyvale, CA

The Space Telescope pointing control system is designed to meet the fine pointing performance of 0.007 arc-sec stability, maneuver the telescope 90 deg in 18 min, or less, and provide the capability for deployment from, and retrieval by, the space shuttle. The pointing control system objectives are met using fine guidance sensors for attitude information, reaction wheel assemblies sized to provide both the torque required for maneuvering and the precision control torques during fine pointing, and magnetometers and magnetic torquers for momentum management. A digital computer is used to calculate the control law, attitude reference, momentum management law, and command generator. The command generator shapes the acceleration and incremental angle commands to the control system to limit structural mode excitation.

The input to the control system (see FIGURE 1) is the command generator acceleration and incremental position commands, rate gyro assembly "incremental" angles per 25 ms and the fine guidance sensor angle output for attitude. The rate gyro assembly data can be used for both rate and short-term attitude. The control system uses position, rate, and integral compensation. A digital filter is used in the rate path to suppress Space Telescope structural modes. The optical telescope assembly modal parameter values are large and require suppression to maintain adequate stability margins.

The acceleration command effectively goes directly to the reaction wheel torquers and puts an instantaneous torque on the vehicle. The reaction wheel torque response is governed only by the feed forward path, which has a bandwidth of approximately 80 Hz. Therefore, the vehicle follows the shaped acceleration commands. The feedback provides an error correction path to account for variances in parameters such as the vehicle inertia estimate and the reaction wheel feed forward gain. A closed loop on the reaction wheel provides compensation to overcome the bearing drag torque and has a bandwidth of approximately 0.1 rads/s.

The control loop is a high gain system and all input to the control system must be smoothed by the command generator to prevent loop saturation and the resulting vehicle instability from initiating backup mode entry. Disturbance torques, e.g., gravity gradient and aerodynamics, act upon the Space Telescope causing the wheel speeds of the reaction wheel assemblies to increase. To prevent the reaction wheels from reaching a saturated condition that would cause a loss of vehicle control, a momentum control system that manages the speed buildup in the reaction wheels is provided. Momentum control operates concurrently with the primary loop. This system uses a magnetometer or an onboard computer model of the Earth's magnetic field, and magnetic torquers for control torques.

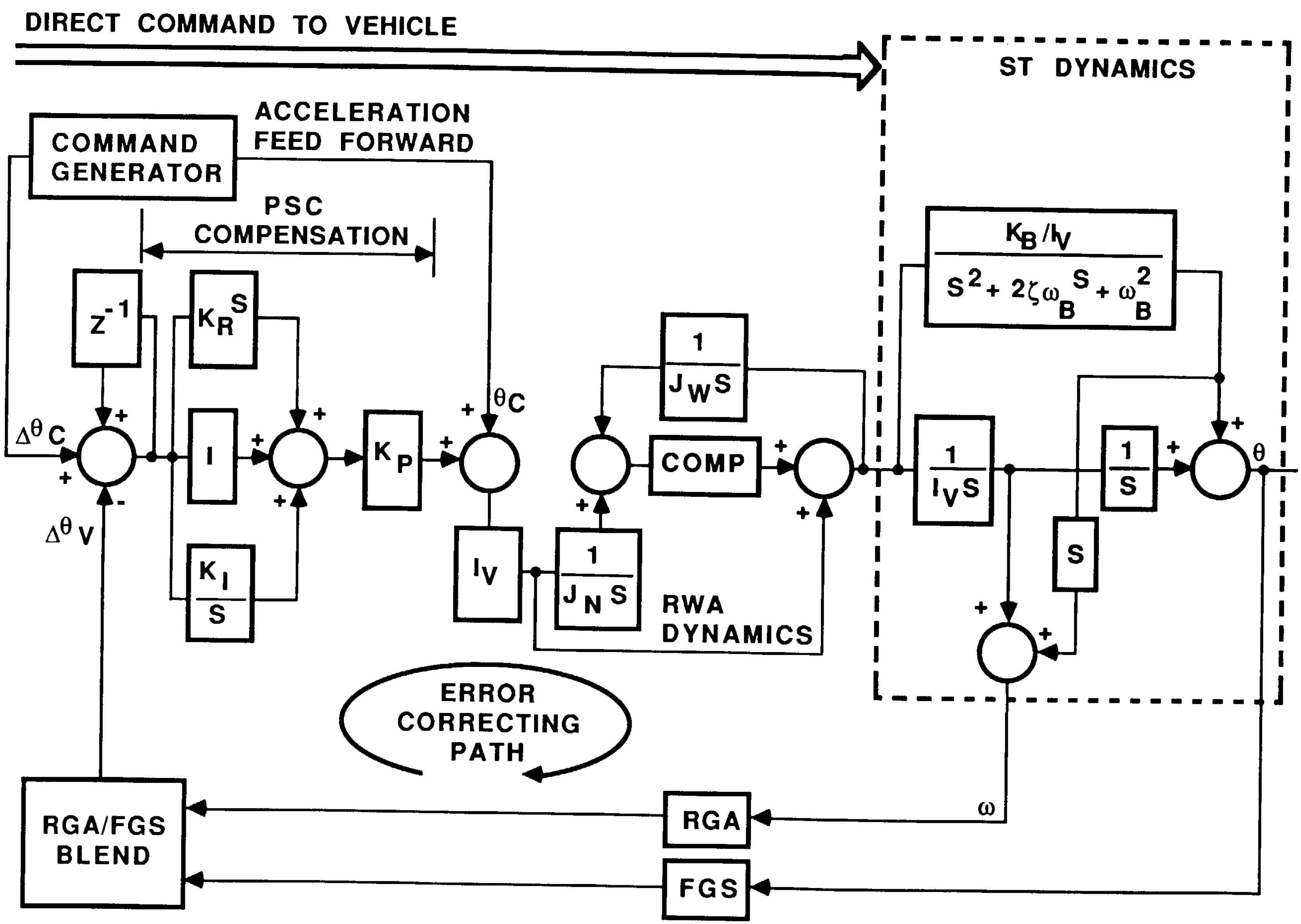


FIGURE 1. Schematic Diagram of the Space Telescope Fine Pointing Mode

N90-13455 550181 p2

Wavefront Error Sensing for LDR

E.F. Tubbs and T.A. Glavich
Jet Propulsion Laboratory
Pasadena, CA 91109

Wavefront sensing is a significant aspect of the LDR control problem and requires attention at an early stage of the control-system definition and design. The question has been addressed specifically for the two-stage optical configuration described at the last Asilomar conference. A combination of a Hartmann test (FIGURE 1) for wavefront slope measurement and an interference test for piston errors of the segments has been examined and is presented as a point of departure for further discussion. The assumption is made that the wavefront sensor will be used for initial alignment and periodic alignment checks but that it will not be used during scientific observations. Implicit in this is the assumption that there are point-like astronomical sources of sufficient brightness at the required wavelengths.

The Hartmann is a good initial test because it is a geometrical test and does not require the system to be near diffraction-limited performance. In addition to the source, the Hartmann test requires a diaphragm or mask pierced with multiple apertures which divide the incoming wavefront into separate beams and an array detector near the focal plane which can intercept the beams on a reference surface. The individual beams define the normal to the wavefront and their intercept on the reference surface can be calculated from the software model of the system. Comparison of calculated and measured intercepts gives a measure of the slope error of that portion of the wavefront.

The two-stage configuration of LDR facilitates the use of a Hartmann test. The mask is located at the fourth element. It must be deployable, but this can be accomplished by making it segmented as shown in the figure. The 12 segments are hinged along their outer edges. The apertures shown in the figure are approximately 40 mm in diameter and there is one aperture per segment. The mask itself is approximately one meter across. The array detector shown in the figure is 55 mm on a side and is located 0.5 m in front of the focal plane. The diffraction spreading of the spot limits the wavelength to less than 5 mm. Since the spots are spread by diffraction they will cover several pixels permitting accurate centroiding.

Once the Hartmann test has been used to correct wavefront slope, piston errors can be addressed. For this an interferometric test at wavelength for which the science detectors can be used offers significant advantages. Possible methods are the point diffraction (Smartt) interferometer and the Zernike phase-contrast test. Both generate reference waves from the central peak of the diffraction pattern of a point source and interfere them with the wavefront under test. These methods require that the piston errors be small compared to the wavefront used in the measurement. For this reason it is advantageous to use as long a wavefront as practical, given the limitations of the available astronomical sources and the sensitivity of the science detectors.

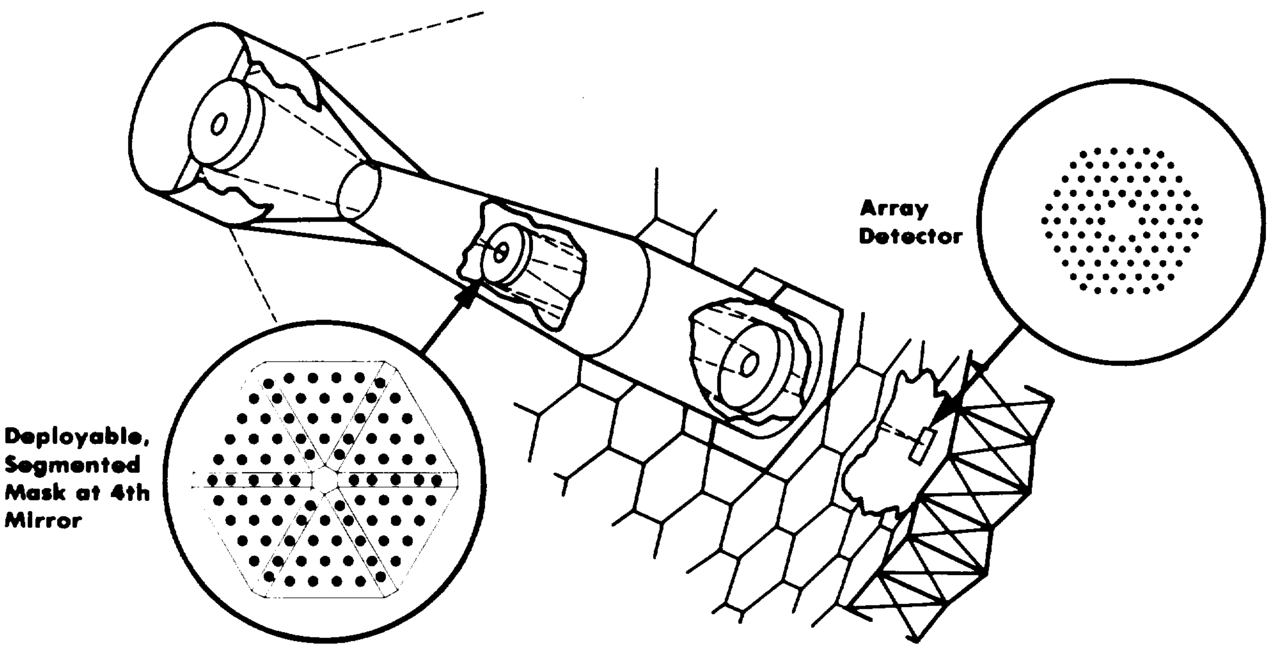


FIGURE 1. Hartmann Test for Wavefront Slope Errors

N90-13456

An Approach to Optical Structures Control

R.P. Iwens, R.J. Benhabib and C.S. Major
TRW Space and Technology Group
Redondo Beach, CA 90274

The stabilization of a large, spaceborne Cassegrain telescope is examined. Modal gain factors and known characteristics of disturbances are used to determine which structural modes affect line-of-sight (LOS) the most and are candidates for active control (FIGURE 1). The approach is to: (1) actively control and maintain alignment of optical components; (2) place structural control actuators for optimum impact on the selected modes for active vibration control; (3) feed back the best available estimate of LOS error for direct LOS control. Local analog loops are used for high bandwidth control and multivariable digital control for lower bandwidth control (FIGURE 2). The control law is synthesized in the frequency domain using the characteristic gain approach. Robustness is measured by employing conicity, which is an outgrowth of the positivity approach to robust feedback system design. The feasibility of the design approach will be demonstrated by conducting a laboratory experiment on a structure similar to a scaled version of the telescope. A low power laser beam is injected into the secondary mirror. Measurements assessing control system effectiveness are then performed on the outgoing beam as it is reflected from the primary.

Relative displacements and tilts of the optical elements are controlled up to some frequency with six alignment actuators per mirror element. Structural control actuators and sensors embedded in some of the members of the optical structure damp out vibrations at higher frequencies. Direct LOS feedback from an "internal" LOS sensor located on the structure is used to trim out the remaining LOS error. Modeling is in two parts: determination of LOS and wavefront errors given structural/mirror motion; and determination of structural/mirror motion given a disturbance. The design model assumes linearity. Performance assessment requires nonlinear models. Classical gain and phase margin obtained by breaking the control loops one-at-a-time can be misleading when evaluating the sensitivity of strongly coupled control loops.

Verification of the design is first accomplished by simulation using high fidelity models of actuators, sensors, and structures. The fundamental question in design verification of control systems for large, spaceborne optical structures is whether we can predict on-orbit behavior with present structural modeling and identification practices. The design and ground test of such a system is the first important step. The next step is demonstration of the same system in space. Once it is known how well we can construct mathematical models on the ground that predict on-orbit behavior, design verification of large structure control systems in space can be separated into ground verification by simulation and on-orbit parameter identification for final control tuning.

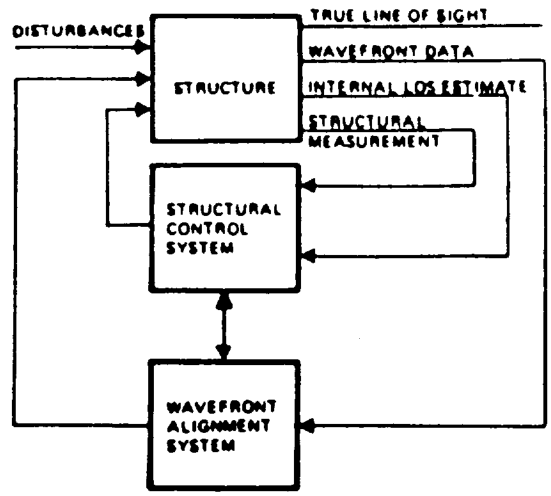


FIGURE 1. Top-Level System Block Diagram

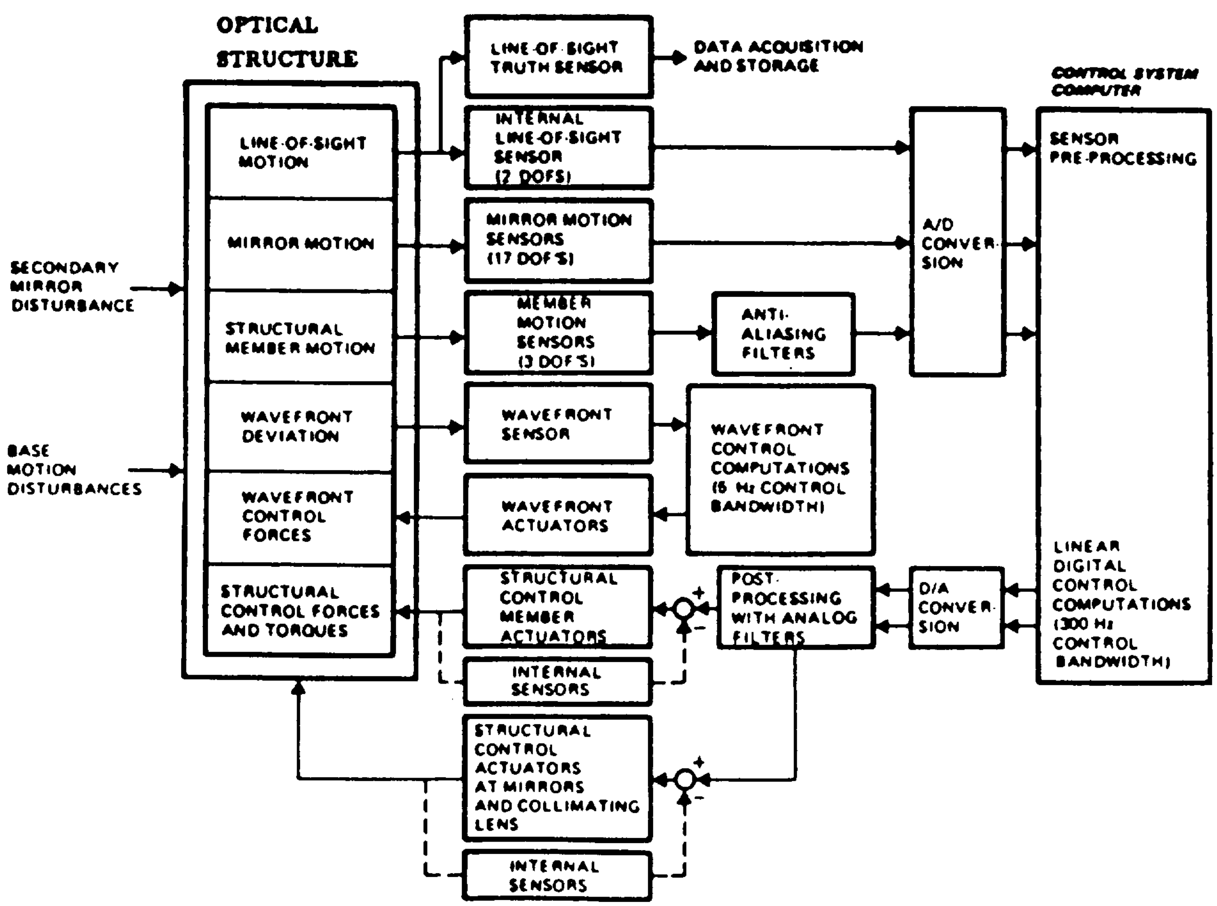


FIGURE 2. Block Diagram for a Laboratory Demonstration

N90-13457
550184

Segment Alignment Control System

J-N Aubrun and K.R. Lorell
Lockheed Palo Alto Research Laboratory
Palo Alto, CA

The segmented primary mirror for the LDR will require a special segment alignment control system to precisely control the orientation of each of the segments so that the resulting composite reflector behaves like a monolith. The W.M. Keck Ten-Meter Telescope, currently being constructed on the island of Hawaii, will utilize a primary mirror made up of 36 actively-controlled segments. Thus the Keck primary mirror and its segment alignment control system are directly analogous to the LDR. The problems of controlling the segments in the face of disturbances and control/structures interaction, as analyzed for the TMT, are virtually identical to those for the LDR.

In the TMT, the precise positioning of the segments so that their combined surfaces act as a uniform parabola is accomplished through the use of special actuators and sensors that form the segment alignment control system. FIGURE 1 is a plan view of the TMT primary mirror showing the segments and the locations of the actuators and position sensors. FIGURE 2 is a schematic diagram of the segment alignment control system. It illustrates the signal flow path and the way in which the sensors measure the relative displacement of two adjacent segments. An algorithm implemented in the control system computer calculates the angular position and the axial displacement for each segment relative to the desired orientation for the segment. Position commands, based on the computed errors, are sent to each of the 108 segment positioning actuators several times a second so that the surface of the mirror remains in the desired paraboloidal shape independent of deformations of the cell structure.

An analysis of the interaction between the segment alignment control system, the structural dynamics of the mirror cell, and the telescope optical system has been performed to determine to what extent disturbances, in particular aerodynamic forces from the wind acting on the primary mirror, would induce structural vibrations in the telescope and degrade optical performance. A second and equally important aspect of the study was to examine the structural dynamic/control system interaction. The primary effect of this interaction was to limit the bandwidth of the segment alignment system and, therefore, its ability to improve the optical performance in the presence of disturbances.

The three-dimensional plots of FIGURES 3 and 4 represent the total energy distribution at the prime focus. These plots are a good indication of how well the telescope's optical system and control system are performing because they show how photons arriving at the prime focus would be distributed. The improvement in the concentration of energy when the control system is engaged, as seen in FIGURE 4, is impressive. The dramatic improvement seen by comparing FIGURES 3 and 4 indicates that the energy concentration is improved by nearly a factor of three when the control system is turned on. Residual spreading of the image can still be seen, but the relative magnitude is quite small.

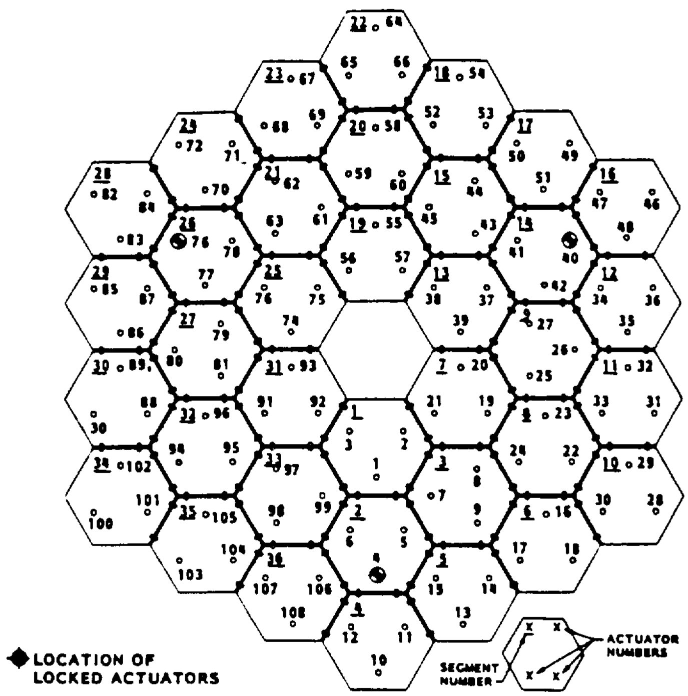


FIGURE 1. TMT Primary Mirror Plan View

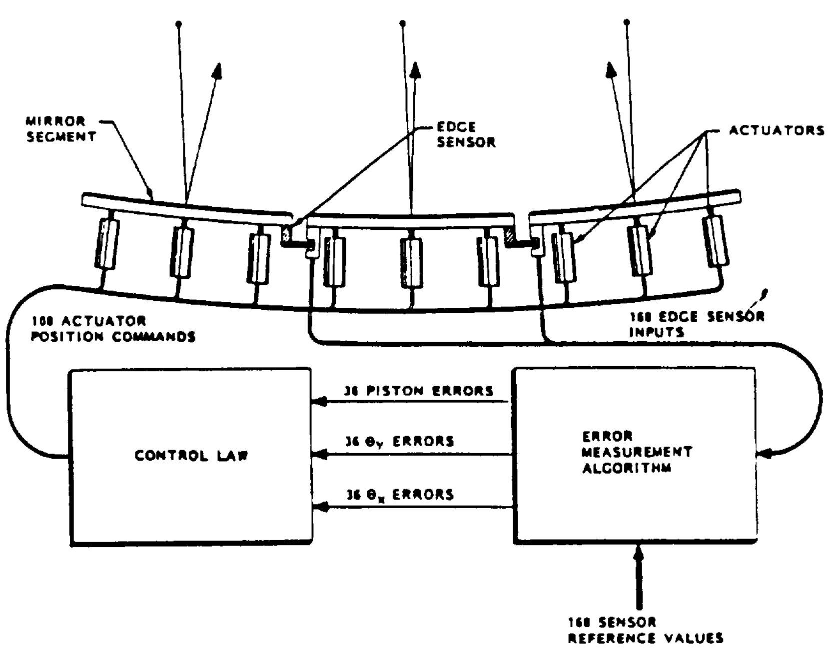


FIGURE 2. Schematic of the Segment Alignment Control System

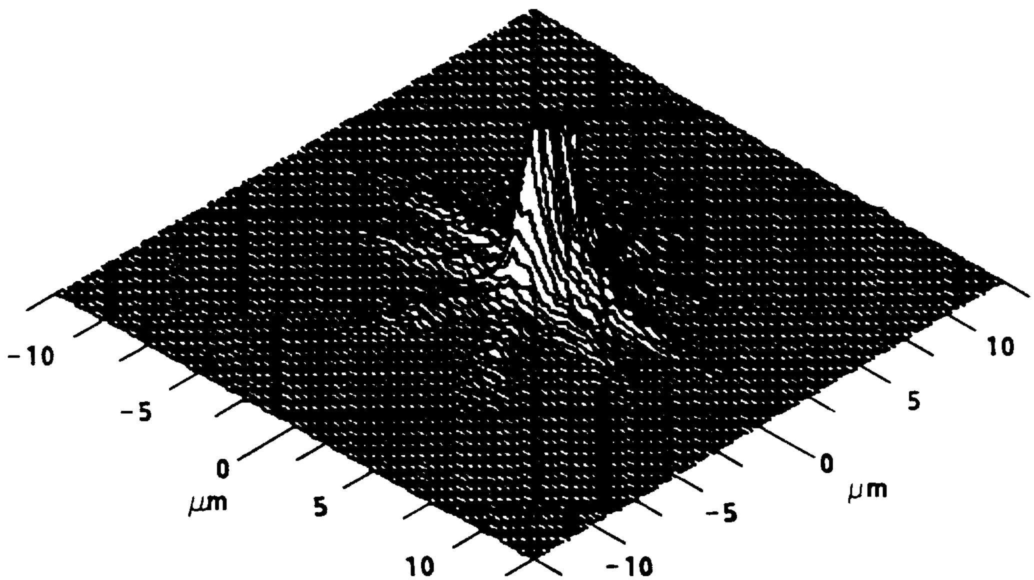


FIGURE 3. Prime Focus Energy Distribution (Open-Loop)

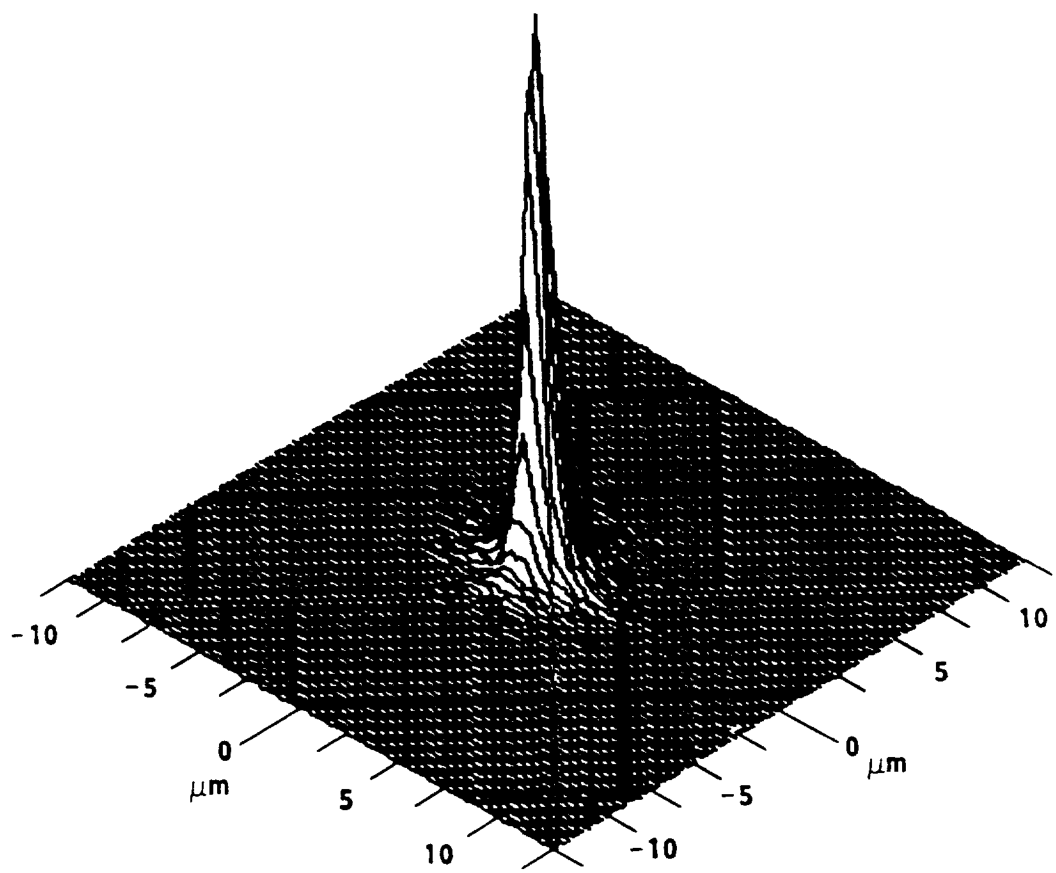


FIGURE 4. Prime Focus Energy Distribution (Closed-Loop)

B. Panels and Materials Papers

N90-13458

Composite Panel Development at JPL 550186 p2

P. McElroy and R. Helms
Jet Propulsion Laboratory
Pasadena, CA 91109

Parametric computer studies can be used in a cost effective manner to determine optimized composite mirror panel designs. To this end JPL has created an InterDisciplinary computer Model (IDM) to aid in the development of high precision reflector panels for LDR. The materials properties, thermal responses, structural geometries, and radio/optical precision are synergistically analyzed for specific panel designs. Promising panel designs are fabricated and tested so that comparison with panel test results can be used to verify performance prediction models and accommodate design refinement. The iterative approach of computer design and model refinement with performance testing and materials optimization has shown good results for LDR panels. These panels must maintain their RMS surface figure to the one micron level.

The JPL IDM analysis is an innovative systems approach using a balanced interplay of state-of-the-art analysis tools (NASTRAN, TRASYS, SINDA, HAVOC, Mini-Optics) from several technology disciplines (see FIGURE 1). Sophisticated detailed analytical models designed by specialists are interfaced via a system superstructure that coordinates processing and the flow of data. This superstructure uses a generalized format that allows the substitution or modification of analysis modules without any major reprogramming effort. This has facilitated the prediction of the performance of LDR panels in different test chamber environments, orbits, and orbital configurations (single panel, panel arrays). The IDM can also be run in a semi-automated mode that allows the examination of intermediate stages of the analysis, and the interjection of various test data where appropriate. This facilitates the focus of specific sensitivity and optimizations studies.

Materials Module

An advanced materials model (HAVOC) is currently under development at JPL, and will be used to analyze the composite panel facesheets. Single ply and laminate composites can be optimized for mechanical, thermal, and optical properties. Three dimensional analyses can be performed in a statistical manner. The module is easy to use and has a built-in materials database.

Thermal Module

The panel configuration and thermo-mechanical properties from the materials module are input into the thermal module. Thermal loading is simulated by a specialized test environment and on-orbit (TRASYS) models. The thermal analyzer (SINDA) is then used to determine the panel's thermal response and temperature profiles.

Structures Module

The structures model (MSC/NASTRAN) incorporates the configuration, materials properties, thermal material response, temperature profiles, and panel geometry into a structural analysis that determines thermally induced surface displacements.

Optics Module

Panel surface displacement contours are optically characterized by using Zernike polynomials. JPL's Mini-Optics model was patterned after University of Arizona's FRINGE program. RMS surface and specific optical figure errors such as defocus, astigmatism, spherical aberration, and coma, along with radio telescope performance parameters, Strehl ratio, and diffraction limit are output as contours, profiles, graphs, and tables. All data is formatted so that direct comparison can be made with test performance data.

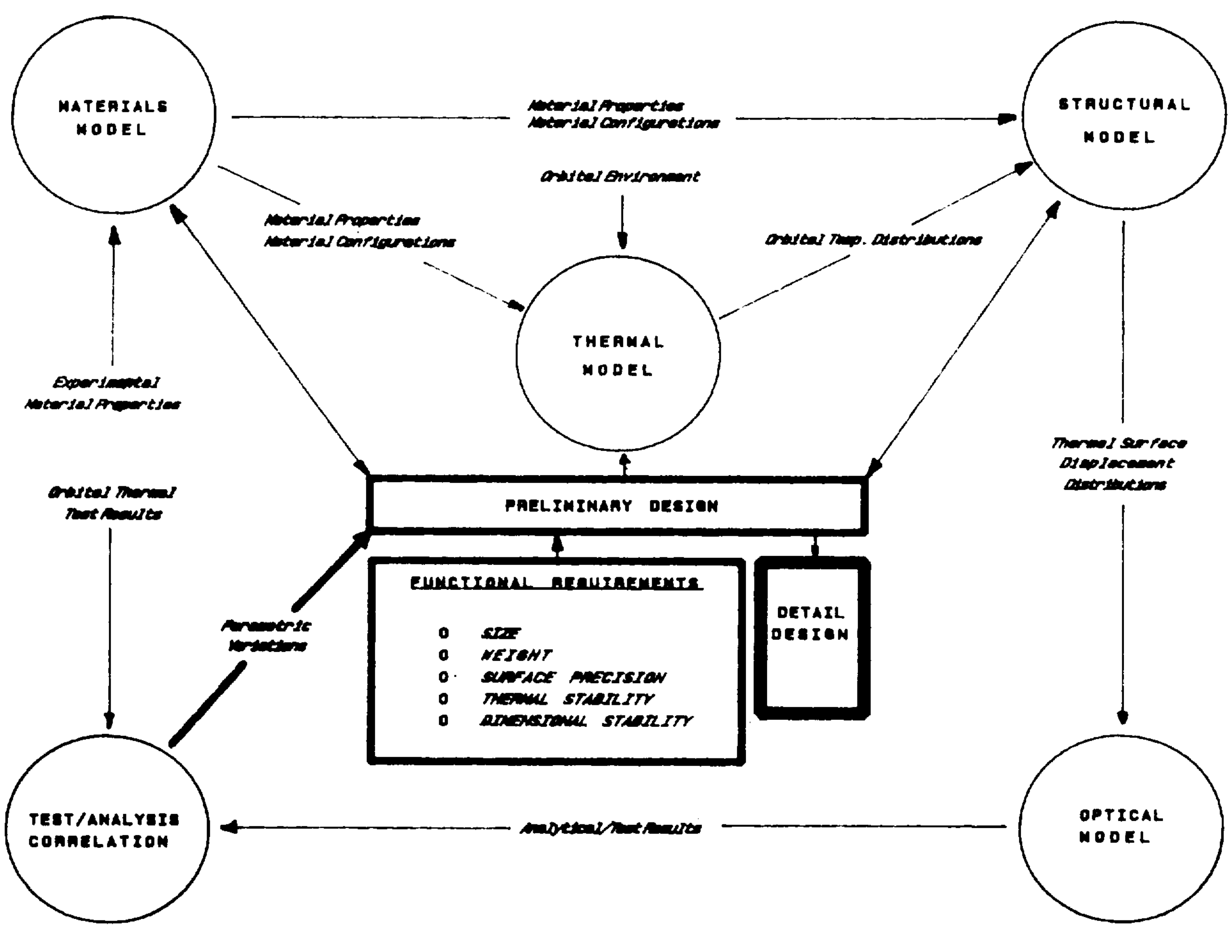


FIGURE 1. Composite Panel Development

N90-13459

550187

Status of Gr/Glass Composites Technology at UTOS

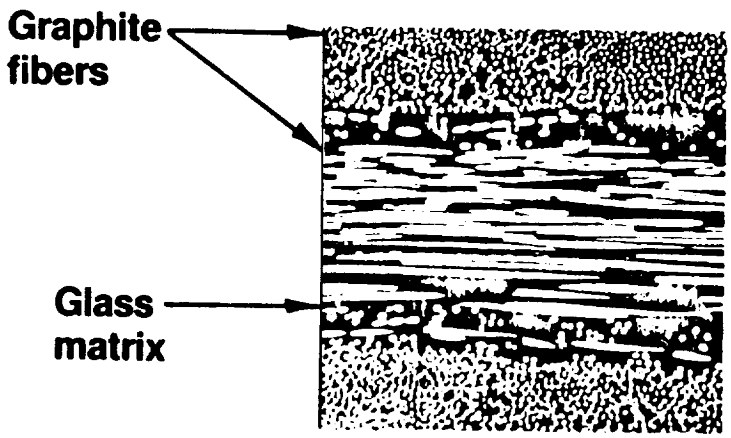
Ramon A. Mayor
United Technologies Optical Sytems (UTOS)
Optics and Applied Technology Laboratory
West Palm Beach, FL 33410-9660

TSC^{tm} (Thermally Stable Composite) refers to a family of graphite reinforced glass matrix composite materials developed by the United Technologies Research Center. This fiber/matrix combination exhibits low coefficients of thermal expansion (CTE), exceptional dimensional stability, high specific strength and stiffness, adequate fracture toughness, and space environment compatibility. Since there is a considerable need for applications involving space-based precision components (such as LDR), TSC offers a high potential for these applications.

TSC evolved from a concept for a hot structure environment application to become a leading candidate for thermally stable applications, once it was realized that a near-zero CTE, that was also relatively constant with temperature, could be attained with this material. For instance, two TSC formulations consisting of continuous HMU and discontinuous GY-70 graphite fibers, respectively, in a borosilicate (Pyrex) glass matrix, exhibit composite CTE values that closely parallel those of ultra-low expansion (ULE) glass, and are somewhat lower than those of fused silica glass. These formulations are an example of the tailorability of the material properties. For instance, the continuous HMU fibers are disposed in an alternating orthogonal sequence (0/90) which produces a low in-plane CTE at just above room temperature. On the other hand, the more uniform, isotropic distribution of the discontinuous (chopped) GY-70 fiber, not only exhibits a low CTE, but it is also relatively constant over a wide temperature range.

The dimensional stability of a TSC mirror structure was experimentally characterized at the Steward Observatory, University of Arizona. A 30-cm diameter non-plano (f/2.5) TSC mirror was assembled from hot-pressed and frit-bonded TSC details into an egg-crated sandwich structure. A HMU (3 K)/Pyrex (45% fiber volume, nominally) system was used to fabricate this panel with (0±45/90) facesheets and (0/90) core webs and backsheet. The resulting area density of the final assembly was 11.4 kg/m^2. The facesheet was polished and reflectively coated to provide a surface adequate for 10.6 μm interferometry. Focus and astigmatism errors were 1.8 μm (p-p) and ±0.8 μm (p-p), respectively, over the ±0°C to -60° test temperature range. Residual distortion was approximately 0.3 μm RMS. Also, print-through of the egg-crate core was not observed, unlike some of the other composite panels.

Preliminary results indicate that TSC is significantly more thermally stable than most other current structural composite materials. In addition, the use of lower CTE glass matrix materials, such as 96% silica glass, have the potential for producing Gr/glass panels with expansion rates and stability comparable to that of fused silica.



- **Graphite fibers in a glass matrix provide**
  - **Tailored CTE/dimensional stability**
  - **High specific strength & stiffness**
  - **High fracture toughness**
  - **Flexible fab procedures**

FIGURE 1. TSC^{tm} - Thermally Stable Composites

N90-13460

Large Deployable Reflector Thermal Characteristics

R. N. Miyake and Y. C. Wu
Jet Propulsion Laboratory
Pasadena, CA 91109

The thermal support group, which is part of the lightweight composite reflector panel program, has developed thermal test and analysis evaluation tools necessary to support the integrated interdisciplinary analysis (IIDA) capability. A detailed thermal math model of a panel and a simplified spacecraft thermal math model have been written. These models determine the orbital temperature level and variation, and the thermally induced gradients through and across a panel, for inclusion in the IIDA. To support test verification, the detailed panel math model utilized test boundary conditions. FIGURE 1 shows the schematic of how the panel model interfaces with the space environment to develop the orbital temperature response, and the test environment to develop test temperature data for analytical verification.

A detailed thermal model of a panel, utilizing a thermal analyzer (SINDA) was developed for the integrated interdisciplinary analysis effort. This panel model was integrated with a structural analysis tool (NASTRAN), a materials model, an optical model, and a test/analysis correlation tool. This interdisciplinary tool will allow the development of facesheet lay-ups and core material design for specific optical properties.

To determine the environmental and spacecraft boundary conditions imposed on a panel, a simplified system spacecraft configuration was developed, into which the detailed panel model was input. The SINDA thermal analyzer tool, along with the TRASYS geometric view factor and orbital environment tool, were used. This model allows the determination of panel temperature response expected for the LDR when subjected to the baseline orbital conditions.

The detailed panel thermal math model was also integrated into a thermal test evaluation tool by developing a thermal model that, instead of using a spacecraft interface, used test boundary conditions. This model was also incorporated into the IIDA tool, so that test data could be correlated with the predicted panel performance.

N90-13461

Advanced Composite Materials for Precision Segmented Reflectors

Bland A. Stein and David E. Bowles
NASA Langley Research Center
Hampton, VA 23665-5225

The objective of the Langley Research Center (LaRC) program in the NASA Precision Segmented Reflector (PSR) Project is to develop new composite material concepts for highly stable and durable reflectors with precision surfaces. The LaRC Program is focusing on alternate material concepts such as the development of new low coefficient of thermal expansion (CTE) resins as matrices for graphite fiber reinforced composites, quartz fiber reinforced epoxies, and graphite reinforced glass. Low residual stress fabrication methods will be developed. When coupon specimens of these new material concepts have demonstrated the required surface accuracies and resistance to thermal distortion and microcracking, reflector panels will be fabricated and tested in simulated space environments. An important part of the LaRC program is analytical modeling of environmental stability of these new composite materials concepts through constitutive equation development, modeling of microdamage in the composite matrix, and prediction of long-term stability (including viscoelastic behavior). These analyses include both closed form and finitè element solutions at the micro and macro levels.

Examples of the use of this modeling capability for prediction of material properties is shown in FIGURES 1 and 2. One goal of new materials development for PSR is to reduce through-the-thickness (t-t-t) CTE of polymer matrix composites to minimize distortions in composite panel face sheets. FIGURE 1 shows that a reduction of CTE by an order of magnitude (CTE Ep/10) is a good goal for low CTE epoxy development. It also shows that the modulus of the graphite reinforcement fiber does not affect t-t-t CTE. Also shown in FIGURE 1 is the low t-t-t CTE of Gr/glass which makes it a candidate material for PSR applications.

FIGURE 2 shows further use of the modeling capability to predict maximum thermally induced matrix stresses at the micro level for the composite materials of interest. Both the conventional Gr/Ep and the Quartz/epoxy have residual epoxy tensile and compressive stresses higher than 10 ksi, with a maximum ΔT (from stress-free temperature to service temperature) of -450°F. The Gr/low-CTE epoxy residual stresses are below 1 ksi. Gr/glass composites, with ΔT's in the range of -900 to -1100 °F, develop residual glass compressive stresses approaching 40 ksi.

These analyses have indicated the high payoff directions for alternate materials research for PSR: Low CTE resin matrix composite development, minimization of residual stresses in conventional epoxy matrices reinforced with graphite or quartz fibers, and development of glass matrix composites with low fabrication temperature and/or thermal treatments to minimize stress in Gr/Gl.

C-2

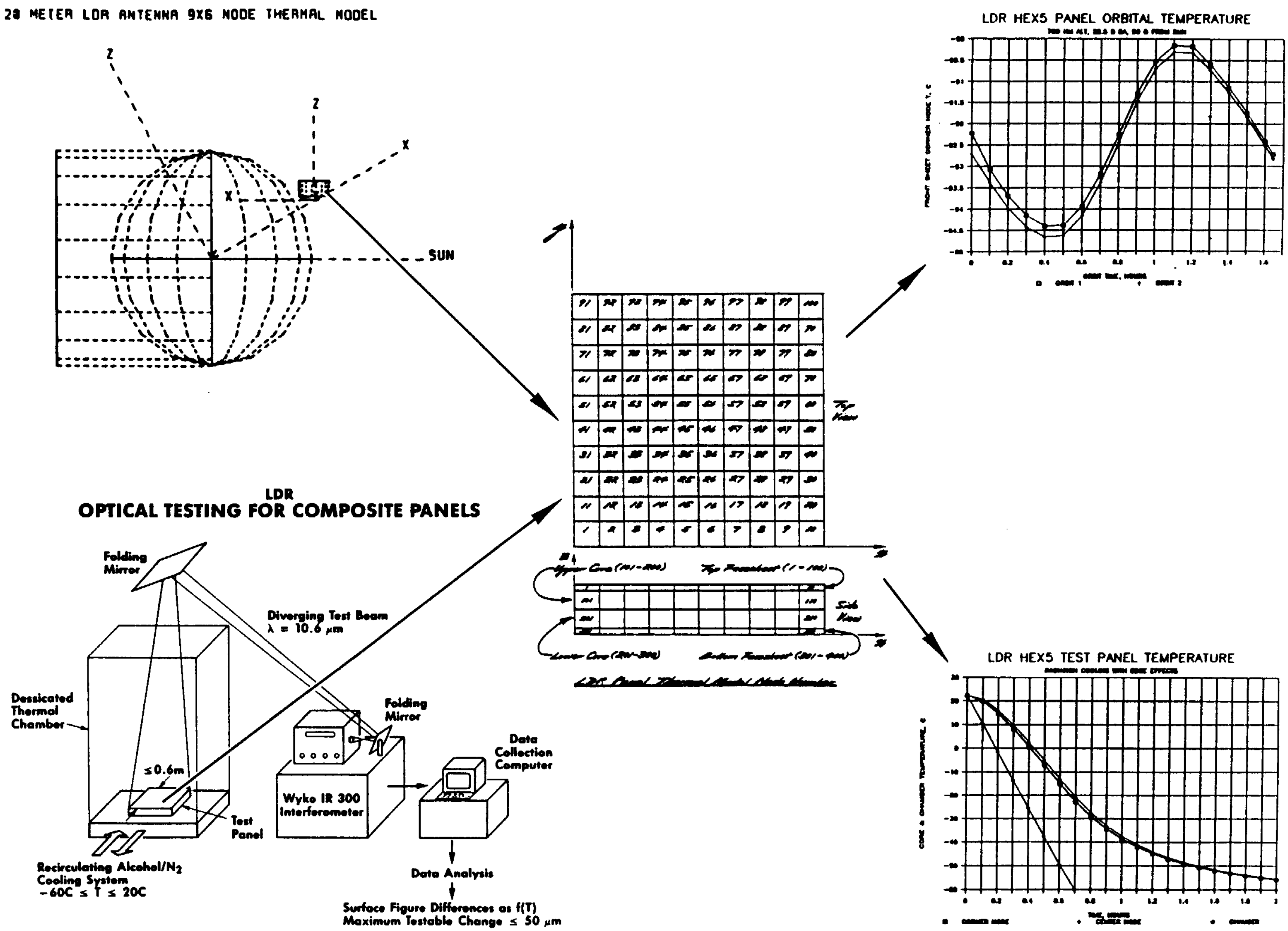


FIGURE 1. Composite Panel Development -- Thermal

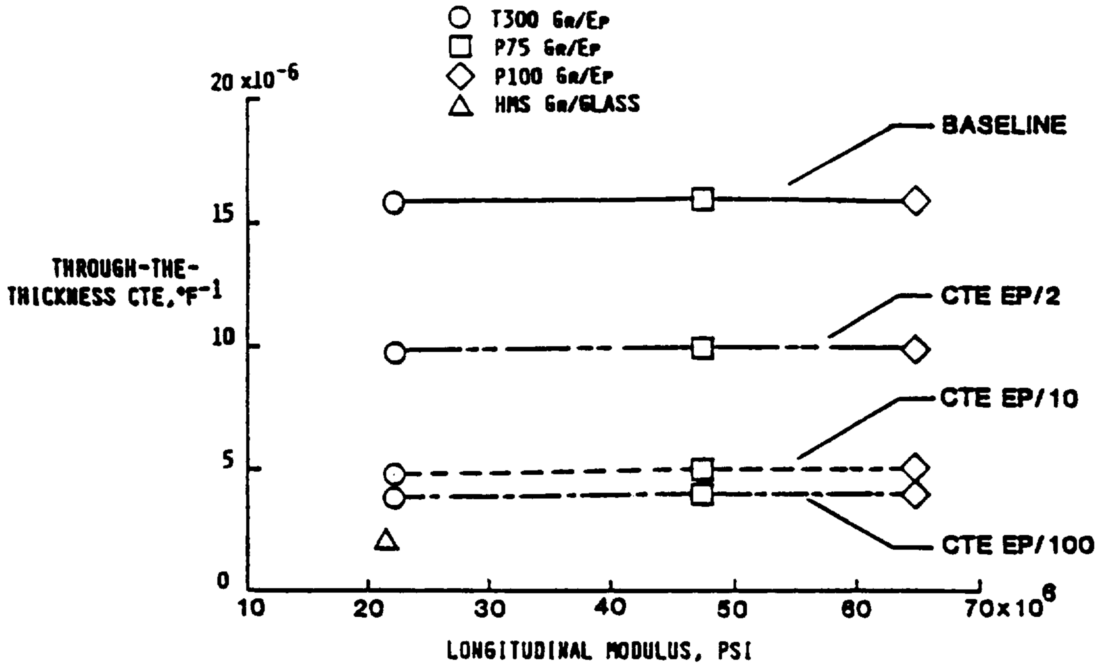


FIGURE 1. Effect of Matrix CTE on Lamina Properties

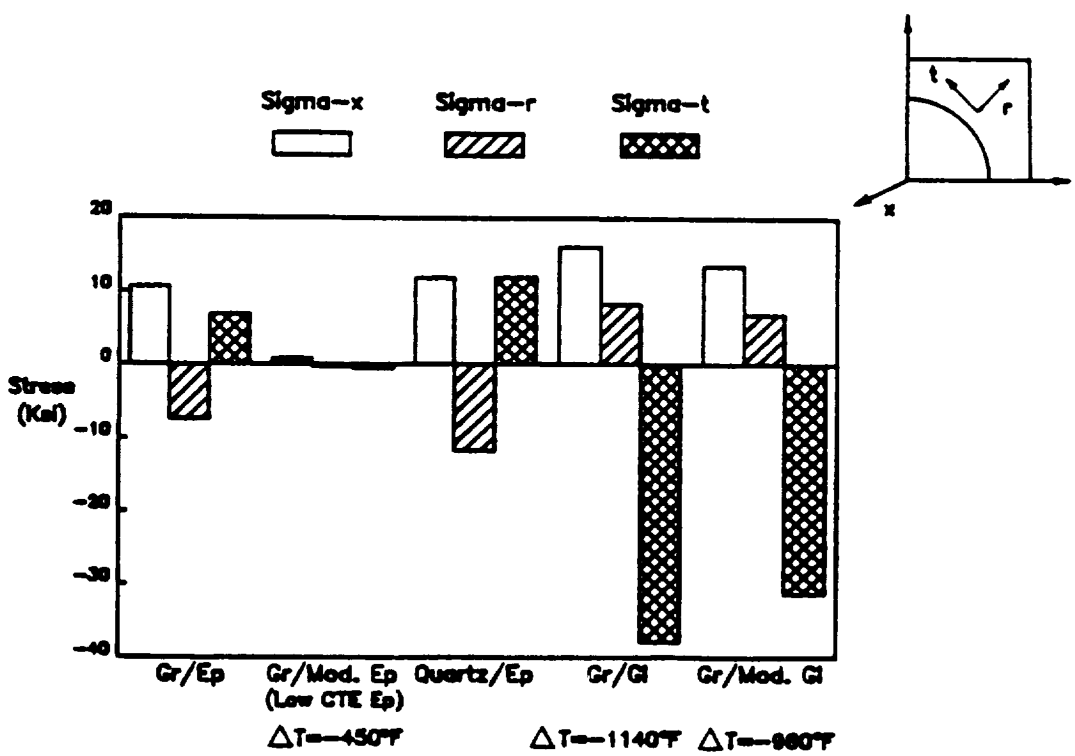


FIGURE 2. Maximum Thermally Induced Matrix Stresses in a Single Unidirectional Layer

N90-13462

Lightweight Composite Reflector Panels

R. E. Freeland and P.M. McElroy
Jet Propulsion Laboratory
Pasadena, CA 91109

Since the last Asilomar workshop, Hexcel Corporation has produced additional composite panels, based on JPL designs, that (a) have increased the panel size from 0.15 meters to 0.40 meters, (b) have improved the as-manufactured surface precision from 3.0 μm to $\approx$1.0 μm RMS, (c) have utilized different numbers of face sheet plys, (d) have improved face sheet fiber orientation, (e) have variations of aluminum honeycomb core cell size, (f) have combined Gr/Ep face sheets with E-glass honeycomb cores, and (g) have used standard aluminum core with face sheets composed of combinations of glass, Kevlar, and carbon fibers. Additionally, JPL has identified candidate alternate materials for the facesheets and core, modified the baseline polymer panel matrix material, and developed new concepts for panel composite cores. Dornier designed and fabricated three 0.6 meter Gr/Ep panels (one with a Kevlar core), that were evaluated by JPL. Results of both the Hexcel and Dornier panel work were used to characterize the state-of-the-art for Gr/Ep mirrors, as shown in FIGURE 1. The solid lines represent a combination of performance for panels of different sizes, designs, materials, and manufacturers. The dashed lines indicate estimates of progress possible within the PSR program.

JPL initiated evaluation and implementation of techniques for panel post-fabrication surface refinishing. Gr/Ep face sheets were lap-polished with a rotary disc using diamond dust to reduce short wavelength surface errors. A few hours of polishing, using standard mirror refinishing techniques, significantly improved the local surface characteristics. A number of additional techniques have been identified for evaluation.

The integrated interdisciplinary analysis (IIDA) program at JPL for composite panels has recently been completed and evaluated. This simulation capability includes modeling and data transfer in the areas of materials, thermodynamics, structures, and optics. FIGURE 2 depicts the functional use of this capability for composite panel development. Since it is generic in nature, the program can be applied to other composite materials, such as carbon-carbon or graphite/glass, and other types of structural elements such as truss members.

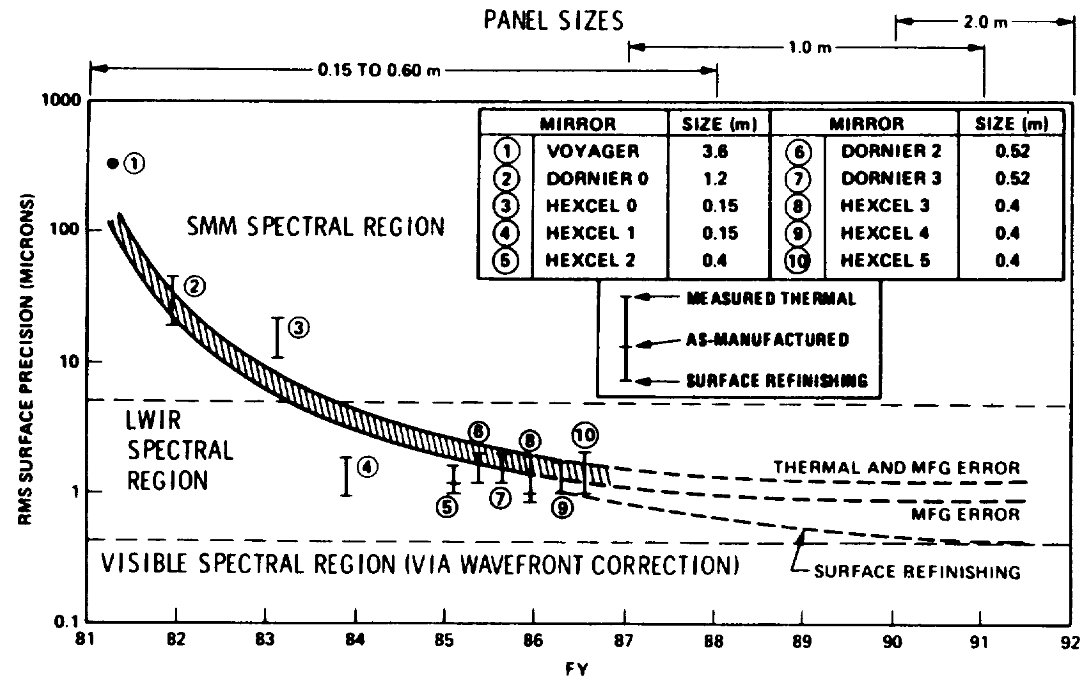


FIGURE 1. Estimate of Gr/Ep Structural Composite Mirror Surface Precision

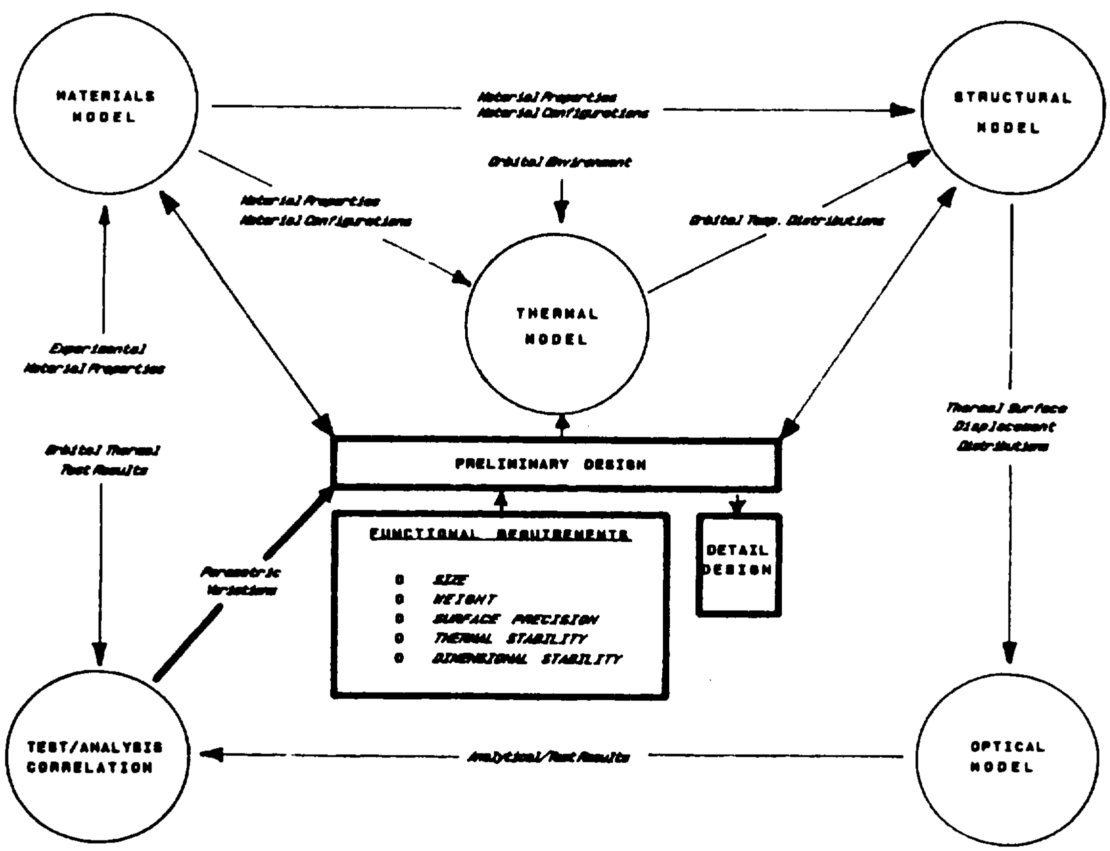


FIGURE 2. Structural Composite Technology Approach

N90-13463

Low Temperature Optical Testing of CFRP Telescope Panels

William F. Hoffmann, Patrick Woida, Thomas Tysenn
Steward Observatory, University of Arizona
Tucson, AZ 85721

Since 1984 we have been engaged in low temperature optical testing of very lightweight mirror panels for possible use in balloon and space infrared and submillimeter telescopes. In order to accomplish this testing, we have created an ambient pressure 0.5 meter test chamber operating from 20°C to -80°C, developed techniques for measuring non-optical quality mirrors with phase modulated 10.6 μm interferometry, and created the interferogram reduction program. During the course of the program, we have tested nineteen mirrors from four manufacturers: Carbon Fiber Reinforced Plastic (CFRP) aluminum honeycomb sandwich panel mirrors from Dornier System and from a Hexcel/JPL collaboration, a CFRP sandwich panel with an added glass face-sheet from Mitsubishi Electric Corporation, and carbon fiber reinforced glass panels from United Technology Research Center. In this report we summarize the results of our panel development and test program with Dornier System which was begun in 1984 and is now complete with the fabrication and testing of five 0.5 meter panels procured directly from Dornier and an additional four panels from JPL.

Our proposed Three-Meter Balloon-Borne Telescope places several requirements on the mirror which are very similar to those of LDR. It must: (1) be very lightweight (<10 kg/m^2), (2) have 30 μm diffraction-limited figure quality and provide visible light imaging for alignment and guiding, (3) maintain its figure at room temperature for testing and at an operating temperature of -50°C, (4) come to rapid thermal equilibrium, and (5) survive high gravity loading. CFRP sandwich panels appear to be very promising candidate mirrors if they can meet the figure accuracy and temperature stability requirements.

At the time this work was started, Dornier panels achieved 350 μm diffraction-limited figure accuracy in two meter panels for ground-based submillimeter astronomy. During the development program, the 0.5 meter octagonal Dornier mirrors have shown spectacular improvement: the surface replication accuracy has improved by a factor of two, and the thermal stability, by a factor of twenty-five. In general, the largest replication errors and temperature-induced changes have been large-scale effects; primarily focus and astigmatism changes.

FIGURE 1 shows the change with temperature of the focus, XY astigmatism (the dominant astigmatism term), spherical aberration, and residual RMS (after removal of the first eight Zernike polynomial terms) for QUAD 25, the last of the Dornier panels tested. All measurements except the residual are peak-to-valley distortion over the mirror. The total change including all effects over the 80 C temperature range is 1 μm RMS. These measurements show no hysteresis above the measurement scatter. The achieved performance is summarized below:

Replication Accuracy (including the mold)	2.5 μm RMS
Residual Error (with astigmatism removed)	0.8 μm RMS
Figure change from 20 C to -60 C	
Focus (peak-to-valley)	2.5 μm
Astigmatism (peak-to-valley)	1.5 μm
Total Change	1.0 μm RMS
Change without focus and astigmatism	0.7 μm RMS

The Dornier panel, Quad 25, meets the 30 μm diffraction-limited requirements for replication accuracy and thermal stability for the balloon telescope at the 0.5 meter size. Similar performance remains to be demonstrated: (1) with the JPL Hexcel program, (2) with 1 and 2 meter panels, and (3) at the LDR operating temperature (-100 C). In addition, the surface quality must be improved to achieve optical imaging.

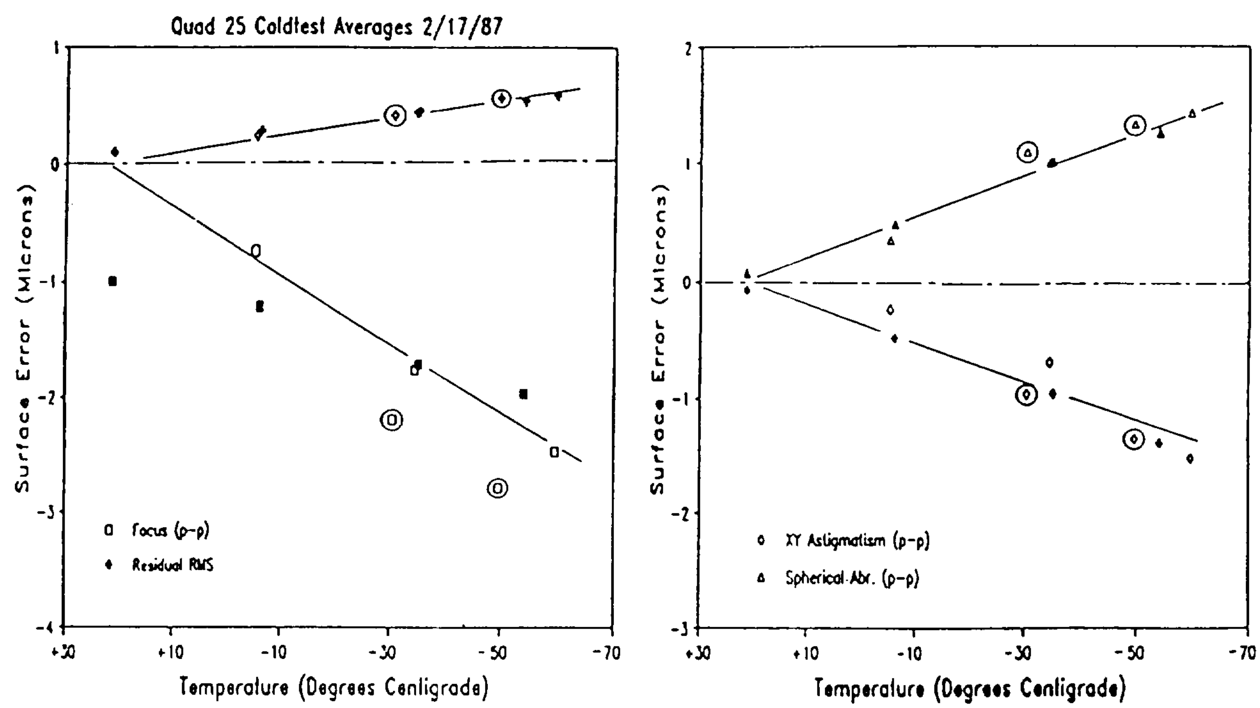


FIGURE 1. QUAD 25 Test Results showing focus, XY astigmatism, spherical aberration and residual RMS. The open, filled, and encircled symbols represent measurements made during the cool down, the warm up to room temperature, and a second cool down, respectively.

C. Receivers and Cryogenics Papers

N90-18464

Status of Direct Detector and Array Development

Craig R. McCreight
NASA Ames Research Center
Moffett Field, CA 94035

Programs are now underway to develop and demonstrate the detector/array technology needed for the Space Infrared Telescope Facility (SIRTF) [1], LDR, and other future NASA missions. The development goal is to achieve focal plane sensitivities, at extended integration times over the 2-700 μm range, limited only by the low astrophysical backgrounds encountered in cryogenic telescopes such as SIRTF. In a coordinated and cooperative manner, developments are now being carried out by the SIRTF instrument definition teams, with funding from the Office of Space Science and Applications (OSSA), and with advanced technology funding through the Office of Aeronautics and Space Technology (OAST). The former program is coordinated between the three SIRTF conceptual instrument teams, and the efforts are focused toward the requirements and scientific goals of the proposed instruments. The OAST IR astrophysical detector program aims to provide a general base from which a number of instrument and system technologies can be drawn. The OAST projects take a longer view, and represent more speculative approaches for potential future applications. In some cases the projects are co-sponsored by OAST and OSSA, to support baseline SIRTF instrument technologies. (In addition to work on basic detector materials and their associated cryogenic preamplifiers and multiplexing readouts, the SIRTF program also supports development of beamsplitters, specialized cryogenic mechanisms, and adiabatic demagnetization refrigerators.) The NASA programs fund selected technology developments, and in addition support a number of groups in the scientific community to carry out the detailed laboratory characterizations necessary before optimized devices and well-conceived instruments can be achieved for SIRTF. By striving to meet SIRTF goals, these programs are accumulating important experience which will be of substantial benefit when LDR instruments are designed. The SIRTF detector development program has been nicely summarized [2]; the following remarks on the OSSA work draw heavily on this description.

As is indicated in the TABLE 1, the OSSA-sponsored SIRTF Technology Program involves work on a range of intrinsic and extrinsic IR detectors and arrays, and for >200 μm, small arrays of bolometers. The <30 μm arrays utilize switched-MOSFET multiplexers, and have in general been shown to have very good low-background performance: read noise at or below the 100 e^- level, good responsivity, and dark currents at and below the 100 e^-/s level. Complementary work on optimized detector materials [Si:x and Ge:x, in both bulk photoconductive and impurity band conduction (IBC) forms] and JFET integrators for smaller, higher-sensitivity arrays has been similarly successful. The work in the range of direct LDR interest, λ>30 μm, includes further characterization of extrinsic Ge materials, and development of suitable schemes to apply stress to Ge:Ga and package relatively small Ge:Be and Ge:Ga arrays, and a Ge:Ga IBC project at Rockwell

TABLE 1. SIRTF Detector Technology Program [2]

Wavelength	SIRTF Instrument		
	IRAC	IRS	MIPS
2 - 7 μm	InSb,Si:In 58x62 UR	InSb 58x62 UR	Si:In UA
4 - 30 μm	Si:Ga 58x62 GSFC	Si:As BIB 10x50 CU	Si:Ga Si:Sb Si:B UA
	Si:Sb 58x62 ARC[1]	Si:Sb 58x62 ARC[2]	Si:As RIBIT UCB[1]
28 - 120 μm	---	Ge:Be 2x25 CIT	Ge:Ga 1x16 UA
		Ge:Ga 2x50	Ge:Ga MATERIALS Ge:Be TEST UCB[2]
		Ge:Ga BIB CIT	Ge:Ga BIB JPL
114 - 200 μm	---	STRESSED Ge:Ga 1x20 CIT	STRESSED Ge:Ga UCB[2]
200 - 700 μm	---	---	Ge Bolometers UCB[2]

Notes:

1. ARC (1.McCreight, 2.Roellig)
   GSFC (Gezari)
   UCB (1.Arens, 2.Richards)
   CIT (Watson)
   JPL (Beichman)
   UR (Forrest)
   CU (Herter)
   UA (Young)

2. See page vii and following for explanation of unfamiliar acronyms and abbreviations.

and Caltech. This latter effort has been making substantial progress lately (viz. detection at 200 μm and promising quantum efficiency with a non-optimum device). The IBC technology has the potential of eliminating the stressed detectors and significantly improving sensitivity, both for SIRTF and LDR.

The OAST program [3] provides support for a number of the items mentioned above. In addition, work on the development and characterization of the Rockwell Si:As solid-state photomultiplier, various IBC arrays in Si:As (Rockwell 10 x 50 and 1 x 10, Hughes 20 x 64, Aerojet 16 x 32) and Si:Ga (Hughes 58 x 62), and SBRC 58 x 62 InSb arrays are, or shortly will be, underway. A 1 x 8 test Ge:Ga array has been built at Aerojet, and is now under test in the Ames lab. A prototype GaAs JFET was recently found to have good noise characteristics at 4.2 K. Within the next few months development projects on improved low-noise multiplexers and improved ≥ 30 μm arrays should be initiated.

While these programs have produced devices and low-background data which approach (and in some cases already meet) SIRTF goals, significant additional work, particularly in the areas of imaging properties and the effects of energetic particles, is needed.

To summarize, dramatic progress has been made in the last two to three years in integrated array and detector systems for low-background astronomical applications. With the broadly based developments and laboratory characterizations now underway for SIRTF and similar space applications, coupled with the rapidly expanding art and science of ground-based astronomical imagery with arrays [4], the potential for effective utilization of arrays on LDR appears to be very good, provided that support is available to (a) adapt and optimize directly relevant technologies from SIRTF, and (b) pursue new developments for specific LDR needs (e.g., larger Ge:x arrays designed for higher background operation).

References:

1. M.W. Werner, J.P. Murphy, F.C. Witteborn, C.B. Wiltsee, Proc. Soc. Photo-Opt. Instrum. Engineers, 589, 210 (1986).

2. J.R. Houck, "Infrared Detectors for Space Applications," Proc. Workshop on Ground-Based Astronomical Observations with Infrared Array Detectors (C.G. Wynn-Williams and E.E. Becklin, eds.), 108 (1987).

3. C.R. McCreight, M.E. McKelvey, J.H. Goebel, G.M. Anderson, J.H. Lee, Proc. Soc. Photo-Opt. Instrum. Engineers, 686, 66 (1986).

4. C.G. Wynn-Williams and E.E. Becklin, eds., Proc. Workshop on Ground-Based Astronomical Observations with Infrared Array Detectors (1987).

N90-13465

Far-Infrared Heterodyne Receivers

Albert Betz
Space Sciences Laboratory, University of California
Berkeley, CA 94720

The development of open-resonator mixer structures and laser local oscillators has made heterodyne spectroscopy at far-infrared (FIR) wavelengths between 150 μm and 400 μm a reality. Several laser-based receivers are now part of the instrument complement flown aboard the Kuiper Airborne Observatory (KAO). Lasers are eminently practical as FIR local oscillators whenever there is close frequency coincidence (<15 GHz) between a strong laser transition and the Doppler-shifted astronomical line. While it is of course desirable to have continuous frequency coverage in a spectrometer, it should be recognized that most astronomers will focus their interest on the few spectral lines deemed optimum for probing the cosmos. For example, at millimeter wavelengths almost twenty years after the first detection of interstellar CO, most observations still seem to be devoted to just the 1-0 and 2-1 lines of CO, even though complete frequency coverage is available. At FIR wavelengths, most of the more important spectral features, such as CI (370 μm), CII (158 μm), OI (145 μm), and CO and H_2O (118 to 432 μm) have usable laser coincidences.

An example of a FIR heterodyne spectrometer designed for airborne astronomy is the UCB instrument illustrated schematically in FIGURE 1. The receiver consists of a corner

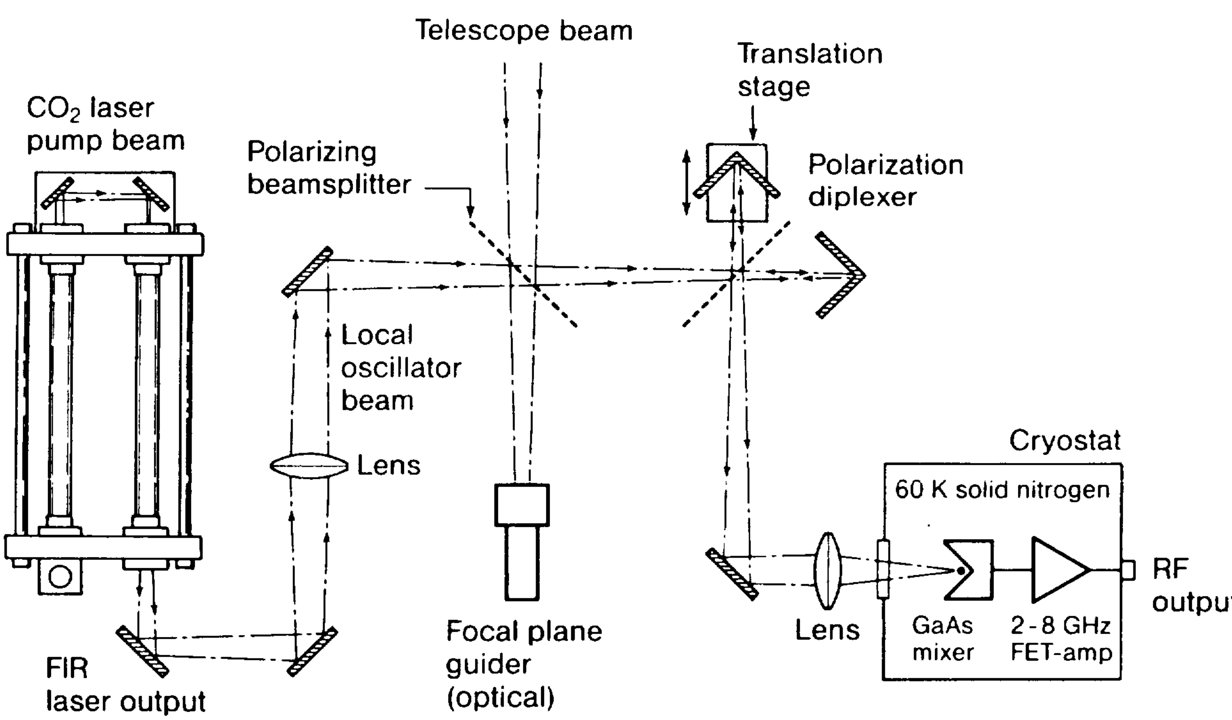


FIGURE 1. Airborne Far-Infrared Heterodyne Spectrometer

reflector mixer and a 1-m FIR laser-LO pumped optically by a 10 W CO_2 laser. The entire system has a mass of 100 kg contained in a volume of 1.4 x 0.4 x 0.4 m^3. The spectrometer has flown on the KAO over the past three years and produced a number of unique observations of line emission from neutral and ionized carbon in the interstellar medium. FIGURE 2 shows representative spectra of the CI (800 GHz) and CII (1900 GHz) lines in the Orion Molecular Cloud (OMC) at resolutions of 1.8 and 0.8 km/s, respectively.

Observations at wavelengths as short as 100 μm (3000 GHz) require careful attention to mixer design, because some dimensions must be maintained with a tolerance of about 10 μm. Heretofore, the standard design for a corner reflector mixer has a 4-λ whisker-antenna spaced 1.2 λ from the vertex of a 90° corner reflector. At short wavelengths, difficulties in fabricating a 4-λ antenna accurately make it desirable to use a longer antenna and a larger vertex spacing. In general, the optimum position of the antenna is at the peak of the standing-wave distribution of the electric field induced inside the reflector by a plane wave incident at the main-lobe angle of the long-wire antenna. This spacing is easily calculated for any

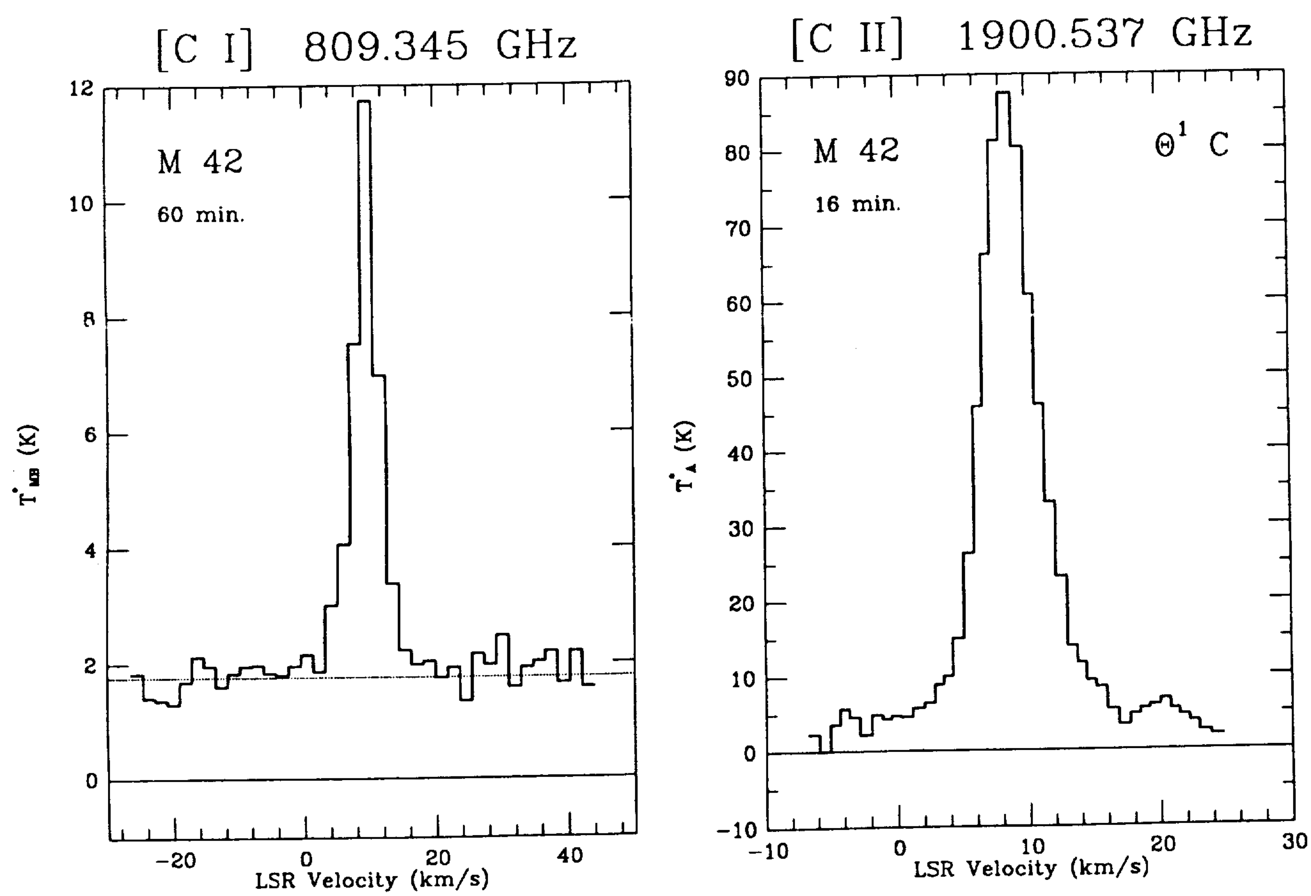


FIGURE 2. Representative spectra of CI and CII in the OMC

antenna length L from the relationship: $s = \lambda/2 \sin(\theta)$, where the main lobe angle is given by: $\theta = \arccos(1 - 0.371\ \lambda/L)$. Antenna patterns calculated with whisker lengths between 4 and 10 λ give approximately symmetric main lobes with widths ranging from 14 to 8 degrees, and agree with our laboratory measurements.

The immature development of our FIR mixer technology is apparent from the somewhat high noise temperatures of 8000 K and 28000 K (SSB) achieved in observations at 809 and 1900 GHz, respectively. These sensitivities, although quite usable, are about 200 times worse than the quantum-noise limit, but will certainly improve in the near future. Recent advances in the fabrication of GaAs diodes optimized for short wavelengths should lead to a steady reduction in noise temperatures similar to that experienced with millimeter-wave mixers during their first decade of development. Although conventional SIS-type mixers may appear to offer strong competition at the longer wavelengths, the GaAs devices have cooling requirements more amenable to space applications. Regardless, for the next few years the advantage in fieldable systems seems likely to remain the Schottky technology. Ultimately, the development of a reliable thin-film technology for the new high-temperature oxide superconductors may favor SIS-type devices for all wavelengths in future space-based FIR receivers.

N90-13466

Advances in SIS Receiver Technology

M. A. Frerking
Jet Propulsion Laboratory
Pasadena, CA 91109

Significant advances in SIS receiver technology since the last Asilomar meeting include: superconductor materials, integrated inductive tuning elements, and planar mounting structures. The effect of these advances is to push the upper frequency operating limit from about 600 GHz to 1500 GHz, and to enhance the feasibility of focal plane arrays of heterodyne receivers.

A fundamental high frequency operating limit of SIS mixers is set by the superconducting energy gap. The high frequency cutoff associated with the energy gap occurs when the photon-assisted reverse tunneling current is a significant fraction of the total photon assisted tunneling current. Nearly all operational SIS mixers are currently fabricated using lead alloy technology. The energy gap for these superconductors is about 2.7 meV, resulting in a cutoff frequency of about 600 GHz. Recently, fabrication techniques for SIS junctions using higher energy gap materials have been developed [1]. Niobium nitride has an energy gap of about 6 meV, corresponding to cutoff frequencies of about 1500 GHz. NbN-MgO-NbN junctions with low subgap leakage currents have been fabricated but not yet tested as a mixer. The discovery of high T_c superconductors may push this frequency limit yet higher.

A practical limitation for high frequency operation of SIS junctions is their parasitic capacitance and resistance. The performance of the mixer will be degraded by the RC roll-off. Considerable effort has been put into reducing the RC product by optimizing device geometry. The normal state tunneling resistance decreases exponentially with barrier thickness while the capacitance varies inversely so that the smallest RC product occurs for the thinnest barrier. The figure of merit typically used to describe the speed of the SIS material is the Josephson critical current density, which varies inversely as the normal tunneling resistance. High quality NbN-MgO-NbN tri-layers have been fabricated with J_c of 14 kA/cm^2 corresponding to an ωRC product of 1 at about 150 GHz [1]. This implies an ωRC of 3 at 500 GHz and 10 at 1500 GHz.

Recently, several designs have been reported for inductive elements integrated on the same substrate as the SIS junctions to tune out the bulk junction capacitance [2]. This allows high frequency operation of lower speed devices over an instantaneous bandwidth determined by the ωRC product. The integration of the tuning element onto the substrates has several significant advantages over external tuners. They can be placed close to the junction increasing bandwidth and decreasing loss. Their primary disadvantage is that they are not tuneable. With a factor 2, ωRC can be regarded as the Q-factor of the junction. Mixers with an ωRC product of 5 have about a 20% 1 dB bandwidth for a matched mixer which should be adequate for most applications.

Most millimeter SIS-based heterodyne receivers have used waveguide coupling structures. Since waveguide elements have dimensions on the order of a wavelength, they are extremely difficult to fabricate for use at submillimeter wavelengths. Further, they are hard to replicate in arrays. Several forms of planar antennas, both on thick and thin substrates, have been developed which can be fabricated using photolitho-graphic techniques, thus making them integral with the SIS junction [3]. In addition, they become readily fabricated in arrays. A SIS mixer mounted on a planar antenna has been demonstrated in the laboratory to 1000 GHz [4].

In summary, technology has advanced to the state where programs that have a high probability of success can be defined to produce arrays of SIS receivers for frequencies as high as 1500 GHz. This is in contrast to the situation three years ago, when the SIS receivers were proposed for frequencies to 600 GHz, and the heterodyne array was described as "only a hope, rather than a firm expectation."

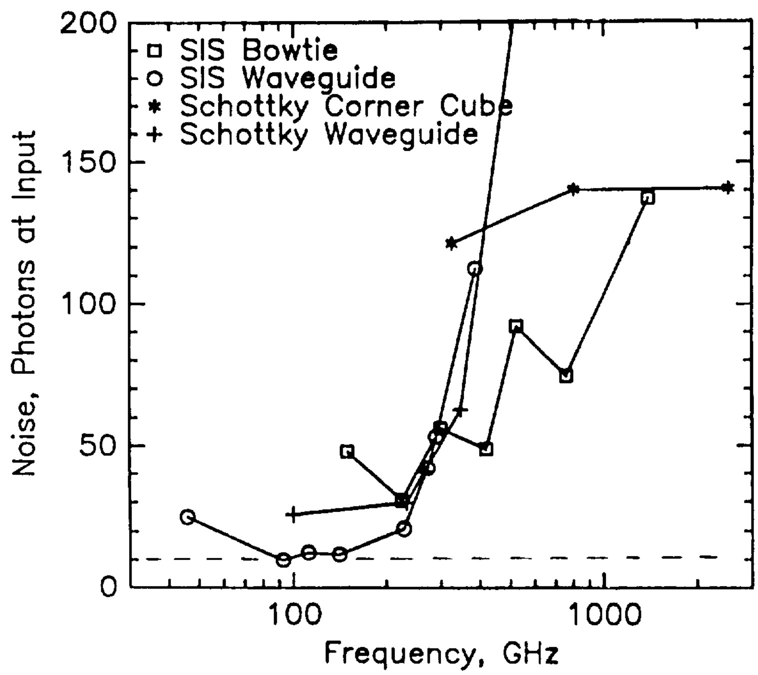


FIGURE 1. Photon Noise at Input vs. Frequency

References:

1. H. G. LeDuc, S. K. Khanna, and J. A. Stern, "All NbN Tunnel Junction Fabrication," to be published in International Journal of Infrared and Millimeter Waves, Oct. 1987.
2. A. R. Kerr, S. K. Pan, and M. J. Feldman, "Integrated Tuning Elements for SIS Mixers," presented at the 1987 International Superconductivity Electronics Conference, Aug. 1987.
3. G. M. Rebeiz, W. G. Regehr, D. B. Rutledge, R. L. Savage, and N. C. Luhmann Jr., "Submillimeter-Wave Antennas on Thin Membranes," to be published in International Journal of Infrared and Millimeter Waves, Oct. 1987.
4. T. Phillips, private communication.

N90-13467

Resonant-Tunneling Oscillators and Multipliers for Submm Receivers

T. C. L. Gerhard Sollner
Lincoln Laboratory, MIT
Lexington, Massachusetts 02173

Resonant tunneling through double-barrier heterostructures has attracted increasing interest recently, largely because of the fast charge transport it provides [1]. In addition, the negative differential resistance regions that exist in the current-voltage (I-V) curve (peak-to-valley ratios of 3.5:1 at room temperature [2-4], and nearly 10:1 at 77 K, have been measured) suggest that high-speed devices based on the unique character of the I-V curve should be possible. For example, the negative differential resistance region is capable of providing the gain necessary for high-frequency oscillations [5]. In our laboratory we have been attempting to increase the frequency and power of these oscillators [6] and to demonstrate several different high-frequency devices.

Oscillators and mixers

Our recent room-temperature, millimeter-wave oscillator results are summarized in FIGURE 1. The initial experiments at 20 GHz were performed in a coaxial circuit, but the other resonators were made in waveguide. In particular, the oscillations around 30 and 40 GHz were achieved in WR-22 and WR-15 resonators, respectively [6]. A significant improvement in the quality of the devices, especially the use of thin AlAs barriers in place of AlGaAs barriers, resulted in oscillations near 55 GHz in the WR-15 resonator. The oscillations near 110 GHz were obtained with the same AlAs-barrier material in a WR-6 structure, and those at 200 GHz used a WR-3 resonator [7]. As can be seen from FIGURE 1, progress to higher frequencies of oscillation has been a rapidly increasing function of time. However, to continue in this direction will require material with a higher cutoff frequency. The derivation of the maximum frequency of oscillation, marked f_{max} in FIGURE 1 for each MBE-grown wafer, is described in Sollner et al. [8]. There it is concluded that optimized materials may be capable of fundamental oscillations as high as 1 THz. More information on oscillator design, frequency limits, and material growth parameters can also be found in Brown et al. [6] and Goodhue et al. [4].

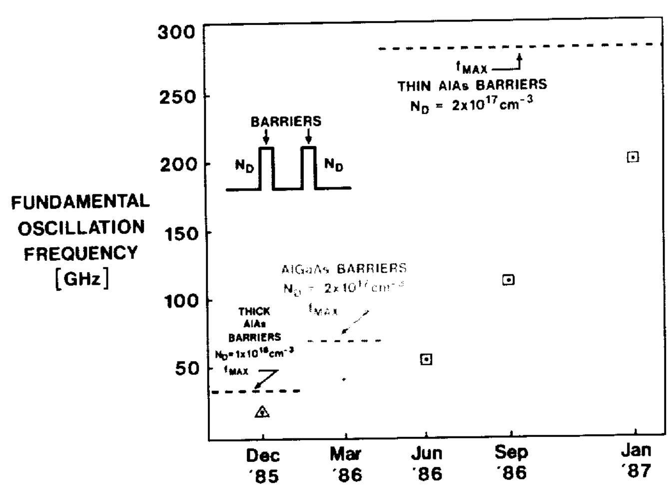


FIGURE 1. Resonant-Tunneling Diode Oscillators

Resistive multipliers

The undulations of the dc I-V curve of a resonant-tunneling diode suggests that there should be large harmonic content to the current waveform, leading to an efficient harmonic multiplier. Shown in FIGURE 2 is the experimental power spectrum for a resonant-tunneling diode when mounted in a 50-Ω coaxial circuit and pumped at 4.25 GHz. The most striking feature of this spectrum is the fact that the fifth harmonic provides the largest available power after the fundamental. This would simplify the design of mm-to-submm wavelength multipliers significantly.

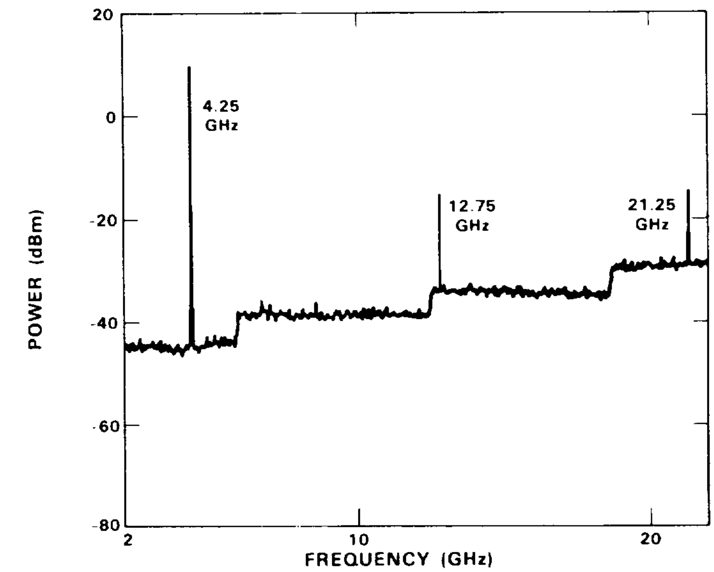


FIGURE 2. Multiplier Power Spectrum

Although the measured efficiency of about 0.5% is competitive with existing multipliers, it is significantly less than the theoretical prediction. This discrepancy can possibly be attributed to the circuit, which does not allow independent tuning of the harmonics. Ideally, one would want to terminate the fifth harmonic with a resistance greater than the source resistance. These concepts are also applicable to higher harmonics, and work is continuing in that direction.

References:

1. T.C.L.G. Sollner, W.D. Goodhue, P.E. Tannenwald, C.D. Parker, and D.D. Peck, Appl. Phys. Lett. 43, 588 (1983).
2. M. Tsuchiya and H. Sakaki, p. 662, IEEE Int. Electron Devices Meeting, Washington, DC, 1985.
3. T.J. Shewchuk, P.C. Chaplin, P.D. Coleman, W. Kopp, R. Fischer, and H. Morkoc, Appl. Phys. Lett. 46, 508 (1985).
4. W.D. Goodhue, T.C.L.G. Sollner, H.Q. Le, E.R. Brown, and B.A. Vojak, Appl. Phys. Lett. 49, 1086 (1986).
5. T.C.L.G. Sollner, P.E. Tannenwald, D.D. Peck, and W.D. Goodhue, Appl. Phys. Lett. 45, 1319 (1984).
6. E.R. Brown, T.C.L.G. Sollner, W.D. Goodhue, and C.D. Parker, Appl. Phys. Lett. 50, 83 (1987).
7. E.R. Brown, T.C.L.G. Sollner, W.D. Goodhue, and C.D. Parker, Device Research Conference, Santa Barbara, CA, June 1987. Paper IVA-2.
8. T.C.L.G. Sollner, E.R. Brown, W.D. Goodhue, and H.Q. Le, Appl. Phys. Lett. 50, 332 (1987).

N90-13468

Spectrometer Technology Recommendations

William J. Wilson
Jet Propulsion Laboratory
Pasadena, CA 91109

A typical heterodyne remote sensing system contains three major elements: the antenna, the radiometer, and the spectrometer. The radiometer consists of the local oscillator, the mixer, and the intermediate frequency amplifiers. This subsystem performs the function of down converting the high frequency incident thermal emission signal to a lower intermediate frequency. The spectrometer measures the power spectrum of the down-converted signal simultaneously in many contiguous frequency channels. Typical spectrum analysis requirements involve measurement of signal bandwidths of 100-1000 MHz with a channel resolution of 0.5-10 MHz.

Three general approaches are used for spectrometers: (1) filter banks, (2) Acousto-Optic Spectrometers (AOS's), and (3) digital autocorrelators. The filter banks are the most commonly used because of their simplicity; however, for spectrometers with greater than 100 channels, their size, weight, and power make their use for space instruments very undesirable. The AOS is an optical processing approach in which a laser beam is diffracted from acoustic waves in a piezo-electric crystal and detected on an optical array. The AOS has recently come into use in a few radio astronomy observatories. However, because of their temperature sensitivity, low dynamic range, laser reliability questions, size, weight and power requirements, the AOS appears to be a poor choice for a spaceborne spectrometer.

In contrast to the two frequency domain techniques described above, an autocorrelator works in the time domain. The auto-correlation function (ACF) of the incoming signal is computed and averaged over the integration time. The averaged ACF is then Fourier transformed to obtain the signal power spectrum; this needs to be done only once every several seconds. It should be noted that the averaged ACF has the same number of data points as the corresponding filter bank spectrum. The autocorrelator is very stable, has a large dynamic range, and has an effective filter response which is easy to characterize and is the same for each frequency channel.

The digital autocorrelator has been used in many radio astronomy observatories for many years and is a proven method for radiometer spectrometers. The disadvantage of considering present laboratory autocorrelators for space applications is that they have been constructed with medium scale digital integrated circuits and that they involve a large number of parts and consume considerable power. However, with the latest developments in supercomputers and VLSI, it is now possible to plan the technology development of a very low power and small digital autocorrelation spectrometer.

The digital approach with its inherent flexibility, stability, high speed, and low power make this an extremely attractive research area. Also there is the promise of further, very large scale integration to significantly reduce the size and weight. Another advantage is that digital circuits have very high reliability and can be radiation hardened to survive in space. It is important that research be started to establish a baseline so we can better judge the necessary directions for future developments to achieve the required high speed and low power for missions like LDR which will require 10^5 channels.

OAST funds an ambitious development program for applying heterodyne techniques to remote sensing in the millimeter and submillimeter wavelength regions. Astronomy and planetary programs fund airborne and ground-based mm and submm observations, and there are proposals to fly a Submillimeter Explorer Telescope and a Large Deployable Reflector (LDR). The program in Earth atmosphere observations using mm-wave spectral line radiometers is also active, involving balloon observations, the Upper Atmospheric Research Satellite (UARS), and a planned system for the Earth Observing System (EOS) polar platform.

Significant progress has been made in the development of submm antennas and radiometers. It is now time to begin research in the development of low power spaceborne spectrometers and to reduce their size and weight. The near-term research goal will be to develop a prototype digital autocorrelation spectrometer, using VLSI gate array technology, which will have a small size, low power requirements, and can be used in spacecraft mm and submm radiometer systems. The long-range objective of this technology development is to make extremely low power, <10 mW/channel, small and stable wideband spectrometers which can be used in future mm and submm wavelength space missions such as the Large Deployable Reflector.

N90-13469

A Four Channel ^{3}He Cooled Balloon-borne Bolometer Radiometer

Stephan Meyer
Massachusetts Institute of Technology
Cambridge, MA 02139

A four channel ^{3}He cooled balloon-borne bolometer radiometer has been constructed at MIT. The principal goal of the instrument is to measure the anisotropy of the 3 K cosmic background radiation on angular scales of 4 to 180°. Our goal is to improve the sensitivity of the measurements to $\Delta T/T < 10^{-5}$. A secondary goal is to survey the galactic thermal dust emission in the submillimeter range.

The detectors are cooled to 0.23 K using a ^{3}He evaporation cryostat. At this temperature the detectors operate with an electrical NEP of about 1.5×10^{-16} watts/$\sqrt{\text{Hz}}$.

The response curves of the four radiometer channels are shown in FIGURE 1, which is a plot of the absolute efficiency; this includes the losses of the high-frequency blocking filter and the losses of all the optics and the detectors. The radiation sensitivity to a Planck emitter at 4 K is about 0.2 mK/$\sqrt{\text{Hz}}$ for the three lower frequency channels. The fourth channel is well above the peak of a four degree emitter, and so has a lower NET. This channel is sensitive to the galactic dust. The bands are defined by a system of resonant mesh filters. The band-pass filter efficiencies are better than 50% peak.

For the LDR effort, a bolometer system consisting of several bolometer arrays, each operating in a different spectral band, would be the detector system of choice for broadband imaging in the submm band. A filter system not too different from that in our radiometer would serve to split the incoming radiation to the different arrays. The system would operate from 400 μm to 1 mm with 4 to 6 spectral channels. Such a system would have an NET considerably below that of a quantum-limited heterodyne system with an IF bandwidth of 1 GHz.

Due to the relatively high background on LDR, there is no requirement for temperatures lower than what can be reached with ^{3}He cooling. This depends somewhat on the bandwidth chosen for each spectral channel. If the number of channels is kept below 6 to keep the complexity of the system to a manageable level, the detectors would be limited by the emission from the hot primary reflector.

For the measurement of the flux and spectral character of broadband sources in the submm, this would be the detector system of choice. Thermal sources with a temperature <15 K are examples of such sources. The science which goes with such sources ranges from cosmology to star formation.

There are several groups in the process of making bolometer arrays on a small scale. There is no reason to believe that the construction of arrays which cover the entire field of LDR with about 10 x 10 elements will not come about on its own on the time scale of LDR. Filter systems which are large enough to cover such a large area are probably also possible, although space qualifying such a thing will be difficult.

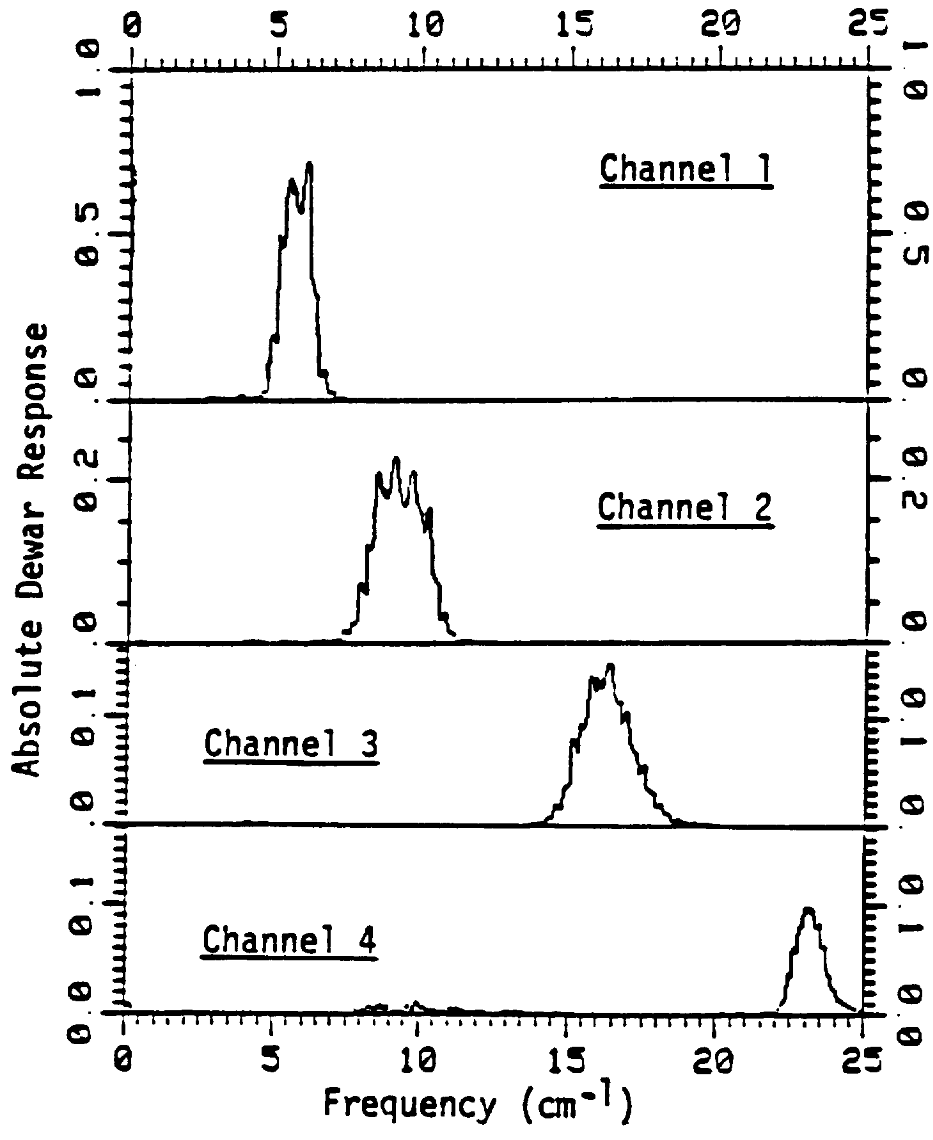


FIGURE 1. The response of the MIT bolometer dewar. The figures represent the absolute dewar efficiency and can be used to convert the electrical NEP to a radiation NET at the input aperture of the radiometer.

N90-13470

Cryogenic Systems for the Large Deployable Reflector

Peter V. Mason
Jet Propulsion Laboratory
Pasadena, CA 91109

There are five technologies which may have application for LDR, one passive and four active. In order of maturity, they are passive stored cryogen systems, and mechanical, sorption, magnetic, and pulse-tube refrigerators. In addition, deep space radiators will be required to reject the heat of the active systems, and may be useful as auxiliary coolers for the stored cryogen systems. Hybrid combinations of these technologies may well be more efficient than any one alone, and extensive system studies will be required to determine the best trade-offs.

Stored cryogen systems have been flown on a number of missions. They are capable of meeting the temperature requirements of LDR; superfluid helium systems provide temperatures as low as 1.2 K, and its boil-off gas can probably provide the necessary cooling at higher temperatures. Stored solid neon systems can provide temperatures as low as 15 K. (Solid hydrogen can provide about 10 K, but it involves severe safety issues.)

The size and weight of stored cryogen systems are proportional to heat load and, as a result, are applicable only if the low-temperature heat load can be kept small. With a heat load of a few hundred milliwatts, replenishment will be required at about three year intervals. If instrument changeout is required, this will not add greatly to the complexity of orbital operations. NASA is now preparing a demonstration of the technology to transfer superfluid helium in orbit, and a 10,000 liter tanker, capable of being lifted to a high orbit, is under development. If the heat load at 2-4 K is <300 mW, and replenishment at three year intervals is acceptable, stored cryogen systems may meet LDR needs.

Mechanical refrigerators have had wide application in ground-based systems. A number of machines capable of delivering 10 K exist and can be fitted with a Joule-Thomson expander to provide temperatures in the 2-4 K range. They will require substantial power and heat radiating capability. Rough estimates suggest a total power drain of 5-10 kW, and radiators capable of handling an equal amount of power at 200-300 K.

Demonstrated system lifetime without maintenance for conventional 10 K mechanical refrigerators is about one to two years. A 60 K system using magnetic bearings, sponsored by GSFC, has demonstrated a lifetime of two years with no degradation, but it is not clear that a 10 K system can be built on the same principles. There has been a large investment by NASA and the USAF to arrive at the present capability and, without a very large additional infusion of money, it is unlikely that a ten-year lifetime will be available for a project start in the mid-nineties. Various schemes have been proposed to overcome the inherent unreliability of mechanical refrigerators. One such scheme would fly several refrigerators with heat switches to allow replacement of a failed unit with a functioning one.

Systems using chemisorption and physical adsorption for compressors and pumps have received considerable attention in the past few years. They are expected to be reliable and noise-free, but have relatively poor efficiencies. A major effort is now underway at JPL to develop a system capable of delivering 60-80 K. Some attention has been given to schemes capable of delivering temperatures below 10 K. Multistaging and use of new fluid-absorbent combinations will be required. Careful evaluation of expected efficiencies is required. Since there are few or no moving parts, lifetime is expected to be long, but this remains to be demonstrated. Such a demonstration is part of the current JPL research program.

Systems based on adiabatic demagnetization of paramagnetic salts have been used for refrigeration for many years. In the past they have been limited to temperatures below a few kelvin, but current investigations are likely to result in cycles working up to 20 K. In addition, the use of the new high T_C superconductors may increase efficiency and allow operation at higher temperatures.

Current designs function in one of two ways: either the salt is moved mechanically in and out of the field, or the field of a superconducting magnet is ramped up and down. Mechanical motion leads to concerns about reliability. However, current designs use low speed rotation on standard bearings and have the potential for long life. In the past, ramping the superconducting magnetic field required heat dissipation at low temperatures, resulting in the need for substantial refrigeration capacity. Use of high-T_C superconductors may reduce refrigeration requirements substantially. However, the new superconductors cannot as yet carry the necessary current in the wire form needed for magnets. Several years of research will be required to solve this problem.

Pulse-tube refrigerators have recently been proposed which show relatively high efficiency for temperatures in the 60-80 K range. They are simple and should be reliable. They are candidates for higher temperature cooling, which will be necessary for any of the active schemes, and may be useful in reducing the size and weight of a stored cryogen system. A modest program of such is now underway, which should resolve whether pulse tube refrigerators are viable candidates. To sum up:

o The instrument heat loads and operating temperatures are critical to the selection and design of the cryogenic system. Every effort should be made to minimize heat loads, raise operating temperatures, and to define these precisely.

o No one technology is now ready for application to LDR. Substantial development efforts are underway in all of the technologies discussed and should be monitored and advocated. Magnetic and pulse-tube refrigerators have high potential. They are the least well defined, and should be assessed by detailed studies.

N90-13471

Cryogenics for LDR

Peter Kittel
NASA Ames Research Center
Moffett Field, CA 94035

This paper addresses three cryogenic questions of importance to LDR: the primary cooling requirement, the secondary cooling requirement, and the instrument changeout requirement.

Principal LDR Cooling Requirements

The principal cooling requirements of LDR (1 W @ 2 K) cannot be met with present technology. There are two general choices for developing technology to satisfy this requirement: closed cycle coolers, and stored cryogens.

No closed cycle cooler exists that can meet the cooling requirement on the ground, let alone that are space-qualified or have a multiyear demonstrated lifetime. The DOD has spent a great deal of effort trying to develop coolers for the 7-10 K range. These might have the required lifetime. There is an effort to develop a 4 K magnetic refrigerator that might operate from the DOD coolers and reach 2 K. A multistage version of the GSFC/Magnavox cooler might reach 7-10 K. ARC will start a CSTI-funded effort in FY'88 to develop critical components of a cooler for this temperature range (probably a magnetic refrigerator). From the Strobridge tables one can estimate that a cooler to meet these requirements would require 7.5 kW of input power (2% of Carnot with heat rejection at 300 K) and an equal amount of heat rejection ability (a huge radiator). The cost to develop and qualify such a unit is about 10% of the estimated LDR program funds.

A number of stored cryogen systems have flown (IRAS, IRT, and SFHE) that provide cooling near 2 K. However, these did not have to provide such a large amount of cooling for so long. LDR would need 10,000 liters of superfluid helium per year. This is the current planned capacity of the liquid helium tanker. Thus, to ensure that LDR instruments never warmed up, LDR would have to be serviced at least every nine months (a resupply cannot be 100% effective). The technology to do helium resupply has not been demonstrated. A joint ARC/GSFC/JSC program plans to demonstrate the technology in the 1991 flight of the SHOOT (Superfluid Helium On-Orbit Transfer) experiment.

Secondary LDR Cooling Requirement

There is a secondary cooling requirement for a cooler in the 0.1-0.3 K range. There are three alternative approaches: ^{3}He coolers, magnetic refrigerators, and dilution refrigerators. ^{3}He coolers can reach 0.3 K. A unit that works upside down has been demonstrated at ARC. A space-qualified unit is being developed by an ARC/UC Berkeley collaboration for a flight on a Japanese mission.

For 0.1-0.3 K temperature range, magnetic coolers are being developed for SIRTF by ARC and for AXAF by GSFC. The outstanding problem is finding a better refrigerant: one that does not have water of hydration. This would greatly simplify the integration of a flight unit. This area is being worked at ARC.

Dilution refrigerators are the coolers of choice for ground operations in this temperature range. Only preliminary work has been done on developing a zero-gravity unit. There are a number of alternative ways that a zero-gravity unit could be developed; these are being pursued by ARC, JPL, and MSFC.

LDR Instrument Changeout

LDR instrument changeout requirements are poorly defined, and there has been little work in this area. SIRTF has looked at both cold and warm instrument changeout options. Cold instrument changeout involves the changing of a cold instrument without changing the cryo system. This is so difficult that it is impractical. The principal difficulties are contamination, excessive thermal loads during changeout, alignment, and making good thermal contact.

Warm instrument changeout places severe requirements on the cooling system (excessive cryogen or power to recool the instrument) as well as raising alignment and contamination questions.

Recommendations

Based on the above considerations, a number of recommendations can be made:

- Re-examine the cooling requirements to see if they can be eased to the point that stored cryogens become feasible with a 2-3 year servicing interval.
- Incorporate LDR needs into the helium tanker design.
- Support the development of a 2 K cooling stage and of sub-kelvin coolers.
- Improve definition of instrument changeout (instrument vs. all instruments at once; separate cooler for each instrument vs. common cooler; etc.).

N90-13472

LDR Cryogenics

T. Nast
Lockheed Research Laboratory
Palo Alto, CA 94304

A brief summary from the 1985 LDR Asilomar II workshop of the requirements for LDR cryogenic cooling is shown in FIGURE 1. The heat rates are simply the sum of the individual heat rates from the instruments. Consideration of duty cycle will have a dramatic effect on cooling requirements. There are many possible combinations of cooling techniques for each of the three temperatures zones. The 0.2 K requirement can be satisfied possibly by ADR, He^3, or dilution refrigerators, while the 2-4 K region could use either He-II or a mechanical refrigerator (MR). The 20 K region can be satisfied by vapor cooling from the He-II at 2-4 K. The vapor on the average will provide approximately 4 watts cooling at 20 K for every watt at 2 K.

T K	Q mW[b]	All-Stored	Hybrid	All Mechanical
0.2	.01	ADR, He^3, Dilution	ADR, ^3He, Dilution	ADR, ^3He, Dilution
2-4	980	He-II[a]	He-II	MR
20	2,610	He-II Boil-off[c]	MR[d,e]	MR

Notes:
(a) Approximately 20,000 liters for 2 years.
(b) Duty cycle needs better definition.
(c) Vapor cooling can provide approximately 4 W cooling.
(d) MR is Mechanical Refrigeration.
(e) Use of MR at 20 K allows He vapor usage elsewhere.

FIGURE 1. LDR Cooling Requirements

For the all refrigerator approaches there are several options for the 20 K stage (Stirling, pulse tube, etc.), while the 2 K requires development of a new refrigerator technology. The continuous-cycle magnetic refrigerator is an efficient system thermally, but has the undesirable feature of moving parts at a low temperature. Much new technology is required here.

Satisfaction of the cooling requirements by an all-stored cryogen system (He-II) may require as much as 20,000 liters based on a 2-year orbital resupply interval. Current orbital tanker studies for He-II may have capabilities in the area of 10,000 liters; therefore, two tankers would be required to resupply 20,000 liters.

If an all-stored He-II approach is pursued it may be worthwhile to consider a new approach: that of launching the system dry (without helium), assembling in space, and then filling with He-II. This option has only recently become viable due to the work on orbital He-II supply. Some of the advantages and disadvantages of a dry launch are summarized in FIGURES 2 and 3, respectively. It is expected that additional advantages and disadvantages will be exposed upon further study. The principal drivers appear to be related to instrument considerations and weight benefits.

- o Reduced weight since vacuum shell not required (or increased lifetime for same weight).
- o Reduced cost (elimination of vacuum shell simplifies design).
- o No safety problems (catastrophic loss of vacuum).
- o No complex ground operations for top-off/fill of helium.
- o Reduced risk of sensor contamination by condensibles (air leakage through O-rings on ground eliminated).
- o Lower heat leak through support since weight of LHe not carried during launch.
- o Opportunities for astronaut-adjusted supports in orbit (warm) to reduce heat leak.
- o Permits assembly of components on-orbit without special design or precautions/measures to limit heat rates prior to assembly of sunshields, etc.

FIGURE 2. Advantages of Dry (without LHe) Launch Approach

- o Additional helium fill in orbit.
- o Additional risk of particulate contamination? (No vacuum shell)
- o Instrument cool-down in orbit (operation and alignment not checked just before launch).
- o Additional structural requirements due to ascent depressurization (vapor cooled shields).

FIGURE 3. Disadvantages of Dry Launch

It is clear that much further system study is needed to determine what type of cooling system is required (He-II, hybrid or mechanical) and what size and power is required. As the instruments, along with their duty cycles and heat rates, become better defined it will be possible to better determine the optimum cooling systems.

N90-13473

Development of FIR Arrays With Integrating Amplifiers

Erick T. Young
Steward Observatory, University of Arizona
Tuscon, AZ 85721

We describe the development of optimized photoconductor arrays suitable for far infrared space astronomical applications. Although the primary impetus is the production of a 16 by 16 element Ge:Ga demonstration array for SIRTF, we consider the extension of this technology to LDR. The optimization of Ge:Ga and Ge:Be photoconductor materials is discussed. In collaboration with Lawrence Berkeley Laboratory, we present measurements of FIR photoconductors with quantum efficiencies greater than 20% at 100 μm, and dark currents below 300 electrons/s.

Integrating J-FET amplifier technology is discussed. The current generation of integrating amplifiers has a demonstrated read noise of less than 20 electrons for an integration time of 100 s. We show the design for a stackable 16 x n Ge:Ga array that utilizes a 16-channel monolithic version of the J-FET integrator. A novel part of the design is the use of a thin, thermally insulating substrate that allows the electronics to operate at the optimum temperature of 50 K while maintaining thermal and optical isolation from the detectors at 2 K. The power dissipation for the array is less than 16 mW. The array design may particularly be applicable to high resolution imaging spectrometers for LDR.

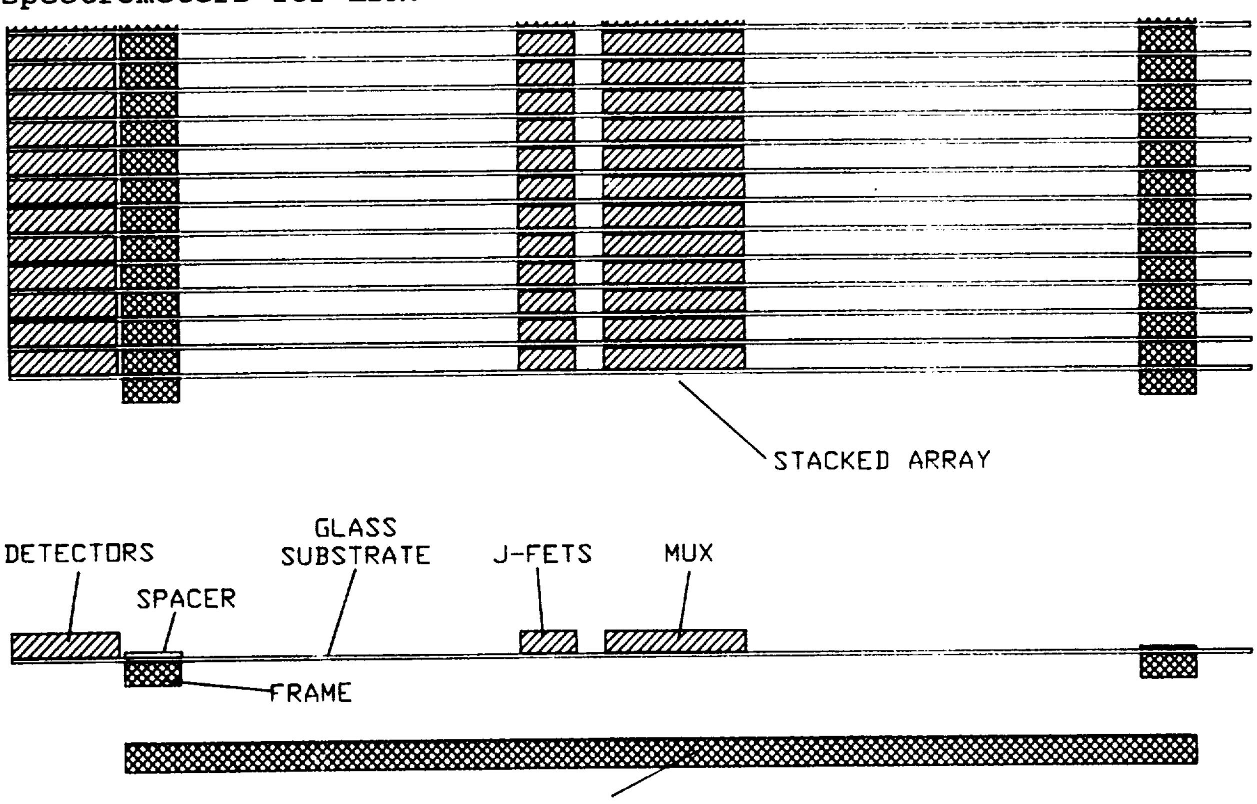


FIGURE 1. J-FET

D. Optics and Systems Papers

N90-13474

Coherent Phasing of Segmented Mirrors

Peter A. Jones
Eastman Kodak Company
Federal Systems Division
Rochester, NY 14650

The technical issues associated with a coherently phased segmented mirror can be divided into two types. The first involves the issues of manufacturing the surface quality of the mirror segments themselves (coherent phasing of individual segments). The second involves assembly issues of initializing in "1G" and retaining in "0G" an aggregate segmented mirror (coherent phasing between individual segments).

Using a rectangular coordinate system at the vertex of a mirror segment, the rigid body motions are the six translational and rotational degrees of freedom. Assuming that two translational degrees of freedom and one rotational degree of freedom of the segments are constrained within the tolerance allocations, the unconstrained degrees of freedom of concern for sensing and control are, therefore, the two remaining rotations (segment tip and segment tilt) and one translation (segment piston).

Shown in FIGURE 1 are the radii of a 20-meter diameter, f/0.5, parabolic mirror. The inability to manufacture an optical element to the designed meridional and zonal radii directly affects the lens focal length and can contribute to spherical aberration. For a monolithic aspheric mirror, the radius is manufactured during the contour generation step and measured to the final known accuracy in an interferometric test configuration, using a null corrector. An additional metrology issue is imposed on a coherently phased segmented mirror. A mismatch between radii of the segments and the design radius of the overall mirror will also result in a wavefront error.

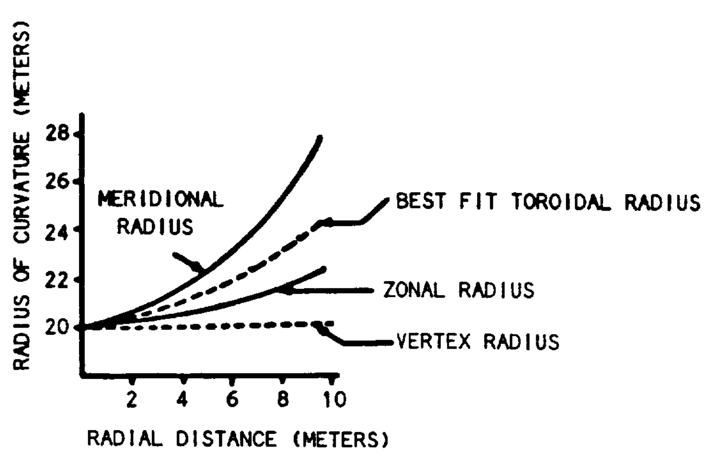


FIGURE 1. Radii for an f/0.5 Parabolic Mirror

A "first cut" primary mirror wavefront error budget is shown in FIGURE 2. For a minimum operational wavelength of 30 micrometers, the derived values from the budget are: segment surface quality (0.45 μm RMS), radius mismatch (50 PPM), segment piston error (1.3 μm), segment tip/tilt error (0.6 μrad).

Either active or passive segmented mirrors can be addressed, but if the surface quality of the off-axis segment and the radius matching requirements can be passively met, then only segment alignment (that is, segment tilt and segment piston error) need be sensed and controlled during operation in orbit. For the active mirror case, dimensional stability of the mirror material during operation is a key factor in establishing the degree of active figure control required. The impact of CTE variability on the minimum operating wavelength can be reduced by: (1) utilization of a smaller segment, (2) operation at a longer minimum wavelength, (3) development of a composite material that meets the CTE goal of $<0.03 \times 10^{-6}$ /K with low variability, and (4) active radius control (for a sphere) or active figure control (for an asphere).

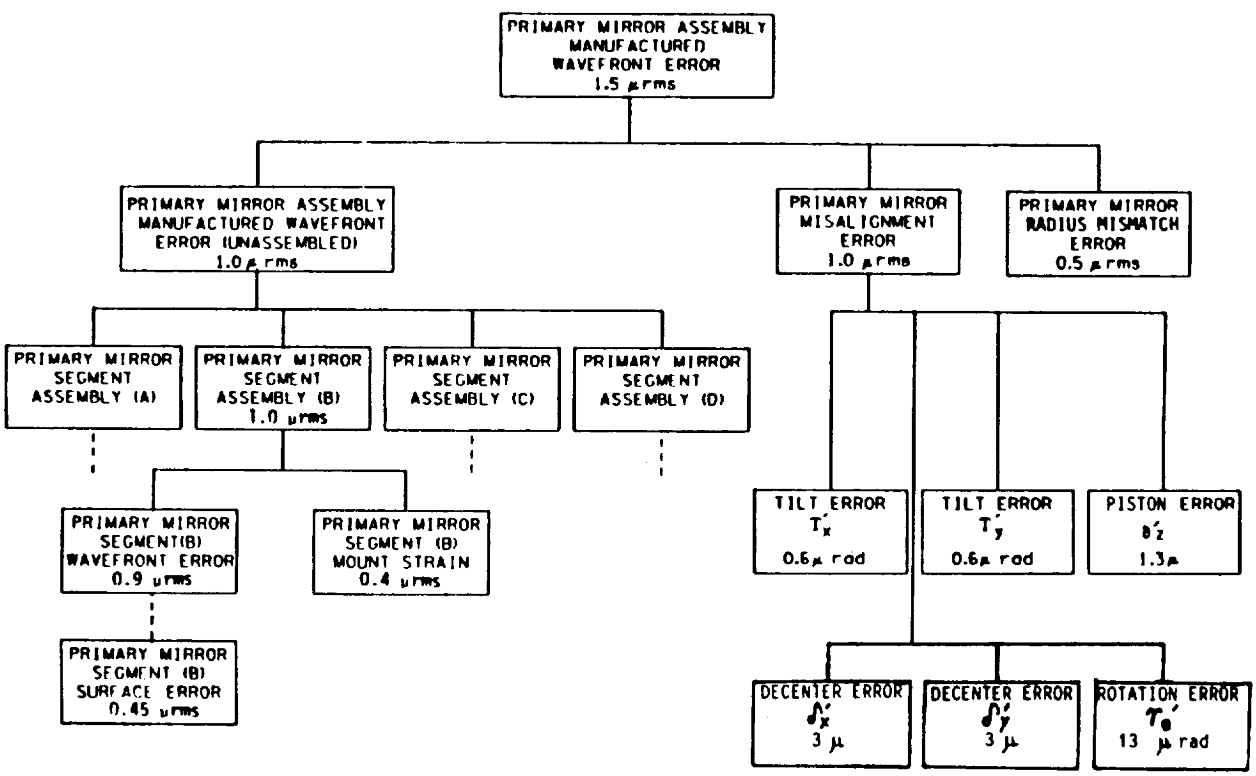


FIGURE 2. Primary Mirror Wavefront Error Budget

N90-13475

Effect of Central Obscuration on the LDR Point Spread Function

Jakob J. van Zyl
Jet Propulsion Laboratory
Pasadena, CA 91109

It is well known that Gaussian apodization of an aperture reduces the sidelobe levels of its point spread function (PSF). In the limit where the standard deviation of the Gaussian function is much smaller that the diameter of the aperture, the sidelobes completely disappear. However, when Gaussian apodization is applied to the LDR array consisting of 84 hexagonal panels, it is found that the sidelobe level only decreases by about 2.5 dB [2]. The reason for this is explained in FIGURE 1a-d.

FIGURE 1a shows the PSF of an array consisting of 91 uniformly illuminated hexagonal apertures; this array is identical to the LDR array, except that the central hole in the LDR array is filled with seven additional panels. For comparison, the PSF of the uniformly illuminated LDR array is shown in FIGURE 1b. Notice that it is already evident that the sidelobe structure of the LDR array is different from that of the full array of 91 panels. FIGURES 1c and 1d show the PSF's of the same two arrays, but with the illumination apodized with a Gaussian function to have 20 dB tapering at the edges of the arrays. While the sidelobes of the full array have decreased dramatically, those of the LDR array changed in structure, but stayed at almost the same level. This result is not completely surprising, since the Gaussian apodization tends to emphasize the contributions from the central portion of the array; exactly where the hole in the LDR array is located.

The two most important conclusions from this work are: (1) the size of the central hole should be minimized, and (2) a simple Gaussian apodization scheme to suppress the sidelobes in the PSF should not be used. A more suitable apodization scheme would be a Gaussian annular ring [2].

References:

1. "Quasi-Optics Modeling Program Applied to the Large Deployable Reflector (LDR)," Jakob J. van Zyl, LDR Technical Memorandum 87-2, JPL Document D-4440, June 1987.

2. "Space Telescope Low-scattered Light Camera: a Model," J. B. Breckinridge et al., Optical Engineering, 23, pp. 816-820.

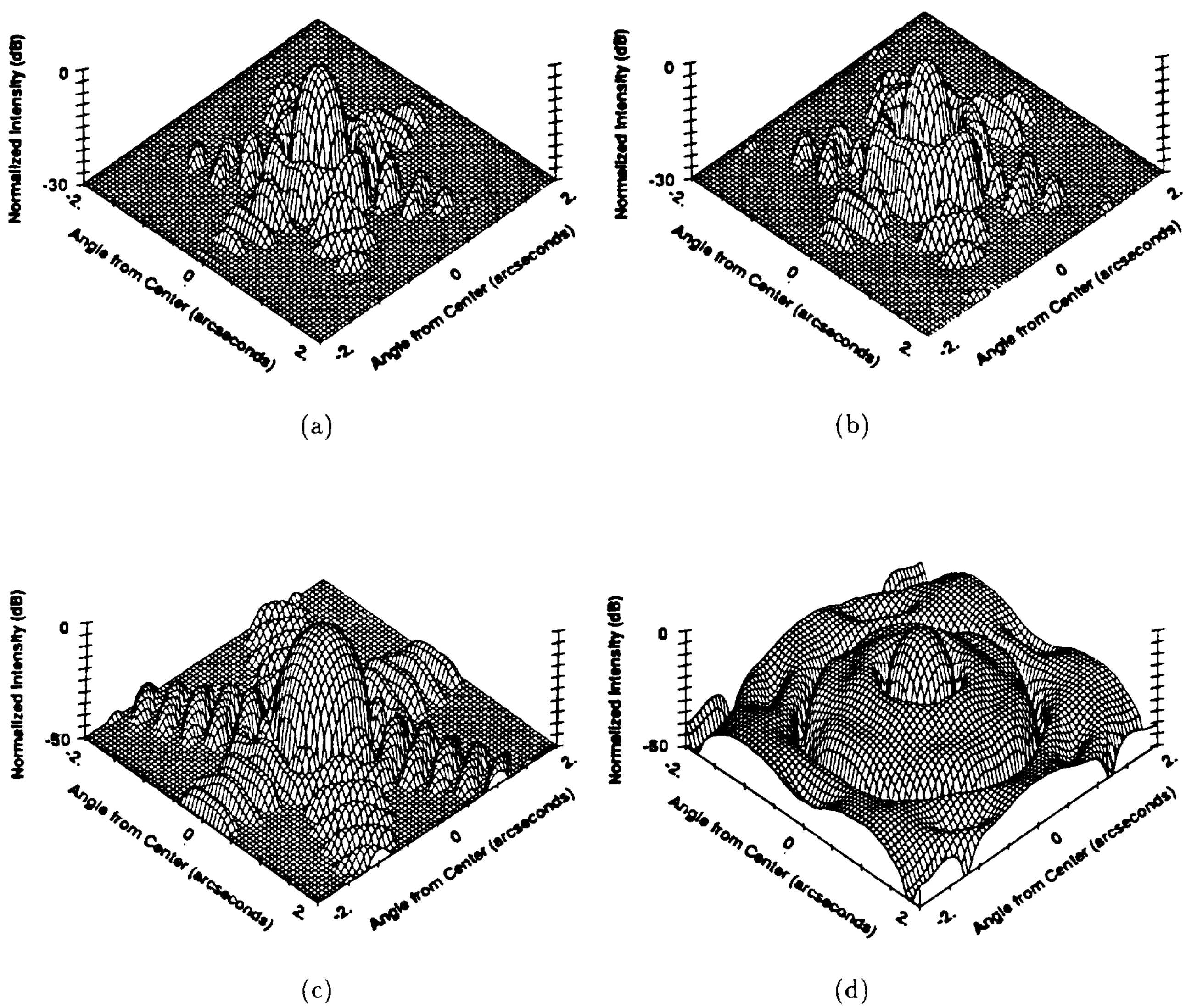


FIGURE 1. (a) Point spread functions for a full array of 91 hexagonal panels with uniform illumination (c) and Gaussian apodization (b) the LDR array of 84 hexagonal panels with uniform illumination (d) and Gaussian apodization. In both cases, the Gaussian apodization is centered on the array and provides 20 dB illumination tapering at the array edges. The psf's were calculated for a wavelength of 30 μm.

N90-13476

Diffraction, Chopping, and Background Subtraction for LDR

Edward L. Wright
University of California, Los Angeles
Los Angeles, CA 90024

LDR will be an extremely sensitive infrared telescope if the noise due to the photons in the large thermal background is the only limiting factor. For observations with a 3 arcsec aperture in a broadband at 100 μm, a 20-meter LDR will emit 10^{12} photons per second, while the photon noise limited sensitivity in a deep survey observation will be 3,000 photons per second. Thus the background subtraction has to work at the 1 part per billion level. Very small amounts of scattered or diffracted energy can be significant if they are modulated by the chopper.

This paper presents the results of 1-D and 2-D diffraction calculations for the lightweight, low-cost LDR concept developed at JPL that uses an active chopping quaternary to correct the wavefront errors introduced by the primary. Fourier transforms have been used to evaluate the diffraction of 1 mm waves through this system. The JPL concept tries to fit a badly aberrated image through a small hole in the quaternary mirror, and several percent of the energy in the sidelobes is lost. **During the chopping cycle, the amount of sidelobe energy lost on one side of the throw differs from the loss on the other side, leading to a modulated signal in phase with the signal from astronomical sources.** As the errors of the primary change due to thermal modulation or other causes, the aberrations of the intermediate image change, so that the unbalanced signal also changes, giving rise to an excess noise of up to 10^{10} photons per second in the example above.

CASE	TERTIARY	HOLE	SECONDARY
No Errors or Chop	0.011166	0.011498	0.000086
Errors, No Chop	0.033212	0.084272	0.000386
Errors, +0.5' Chop	0.033314	0.009161	0.000848
Errors, -0.5' Chop	0.032887	0.090453	0.000830

TABLE 1. Light Losses on Mirrors

TABLE 1 shows the fraction of the light lost off the edges of various mirrors for the 2-D calculation. The values for cases with errors are random variables whose range in principle includes the no error cases. As can be seen in photographs, using the quaternary to correct the errors of the primary converts the intermediate image at the quaternary hole from the diffraction pattern of the LDR as a whole, to a speckle pattern whose envelope is the diffraction pattern of a single segment. Far out in an Airy pattern the light lost outside an angle θ varies as $\lambda/D\theta$, so that changing D from 20 meters to 2 meters should increase the light lost by a factor of 10, which is observed. The light loss should be 10 times smaller at λ = 100 μm, but this is still unacceptable. The hole in the quaternary should be much larger to reduce the light loss due to diffraction, but it needs to be at least ten times larger, giving a diameter of 1.4 meters. Since the quaternary is an image of the primary, this would require a quaternary diameter of 7 meters! An off-axis design for the tertiary-quaternary stage could allow a large clearance for the intermediate image without requiring such large mirrors.

The PHOTOGRAPHS of the illumination of the secondary show another effect of the small quaternary hole. The image of the primary in the strongly curved secondary is quite close to the secondary, so these pictures approximate the illumination on the primary. With no errors one has fairly uniform illumination, as expected. With large step-function phase errors, the illumination becomes quite nonuniform. The small quaternary hole allows only a low resolution image of the quaternary on the primary, so when the phase jump at an edge is close to π the complex amplitude goes through zero instead of achieving a sharp jump in phase at the panel edge. The width of the misilluminated strip can be estimated as:

$$w = (\lambda L_{qs} D_p)/(D_{qh} D_s)$$

where:
- L_{qs} is the distance from the quaternary to the primary image in the secondary,
- D_p is the primary diameter,
- D_s is the primary image diameter in the secondary, and
- D_{qh} is the quaternary hole diameter.

For the case evaluated here w = 0.5 meters! The sidelobes in the beam pattern produced by these misilluminated edges are large, time varying, and they cannot be reduced by tapering the illumination with the feed horn. Again, a very large quaternary hole is required to reduce the width of the misilluminated strips to the width of the cracks between segments.

Unbalanced signals due to dust and thermal gradients have also been studied. When the light from the sky is concentrated onto small mirrors before the chopper, the sensitivity to dust is greatly enhanced. As a result, focal plane choppers give poor performance in high background situations like the LDR. The chopping secondary design, on the other hand, has only the primary between the sky and the chopper. The light on the primary is not concentrated at all, so dust or nonuniformities on the primary are not a big problem.

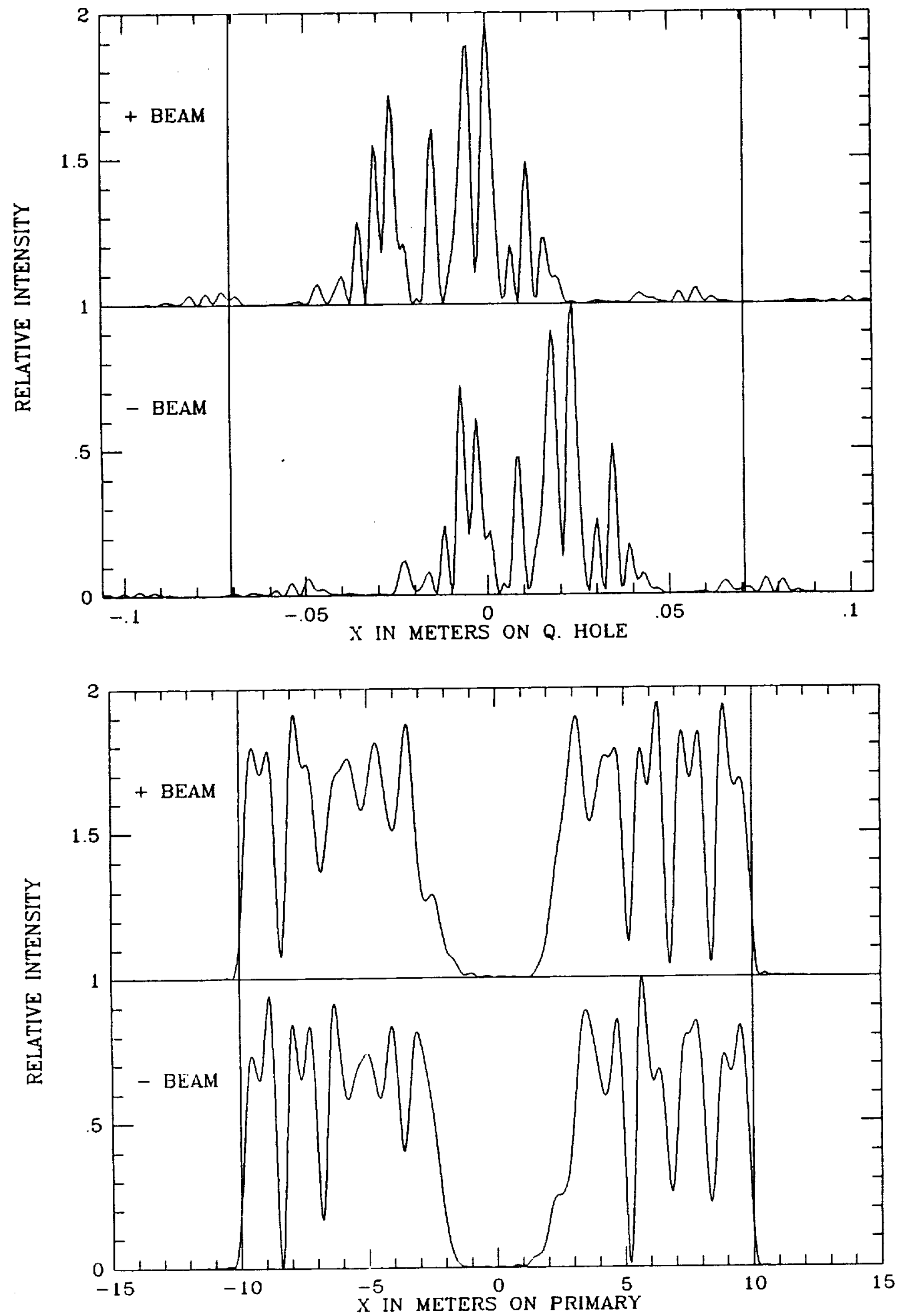
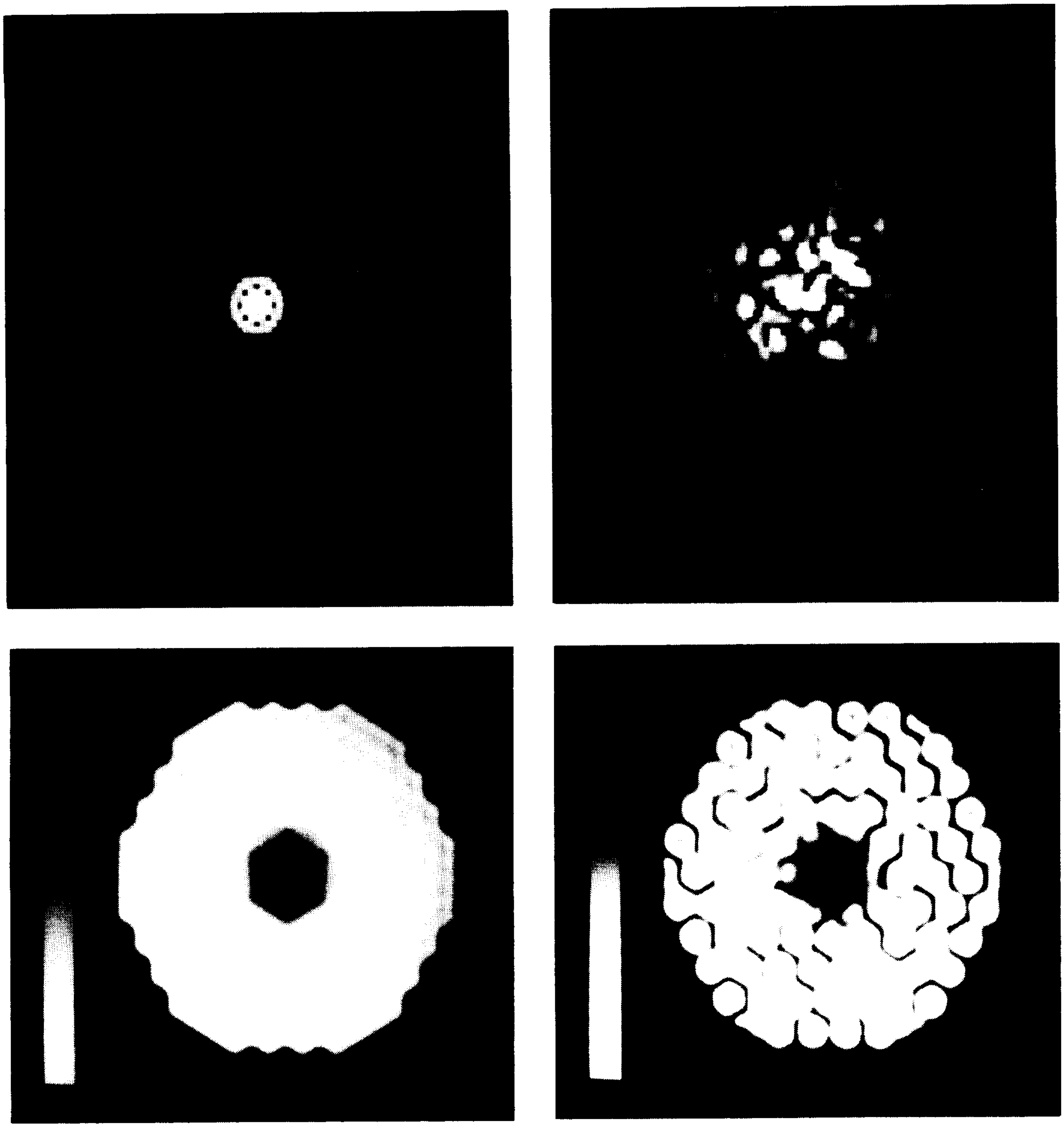


FIGURE 1. The intensity due to a source at the detector position for the on-axis, active chopping quaternary concept: (above) at the intermediate focus in the central hole of the quaternary, and (below) on the surface of the primary, for a 1-D diffraction calculation assuming 290 μm RMS wavefront errors on the primary, and a wavelength of 1 mm.



PHOTOGRAPHS: Results from a 2-D diffraction calculation for the on-axis active chopping quaternary concept at wavelength of 1 mm. Top: The illumination due to a source at the detector position at the quaternary hole; without errors (left) and with 290 μm rms wavefront errors (right).
Bottom: The illumination on the secondary without errors (left) and with 290 μm rms wavefront errors (right).

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

N90-13477

A Laboratory Verification Sensor

Arthur H. Vaughan
Jet Propulsion Laboratory
Pasadena, CA 91109

Channan, Nelson and Mast [1] described the use of a variant of the Hartmann test proposed by R. Shack [2] to sense the co-alignment of the 36 primary mirror segments of the Keck 10-meter Telescope. The Shack-Hartmann alignment camera, illustrated schematically in FIGURE 1, is a surface-tilt-error-sensing device,operable with high sensitivity over a wide range of tilt errors. An interferometer, on the other hand, is a surface-height-error-sensing device. In general, if the surface height error exceeds a few wavelengths of the incident illumination, an interferogram is difficult to interpret and loses utility. The Shack-Hartmann alignment camera is, therefore, likely to be attractive as a development tool for segmented mirror telescopes, particularly at early stages of development in which the surface quality of developmental segments may be too poor to justify interferometric testing.

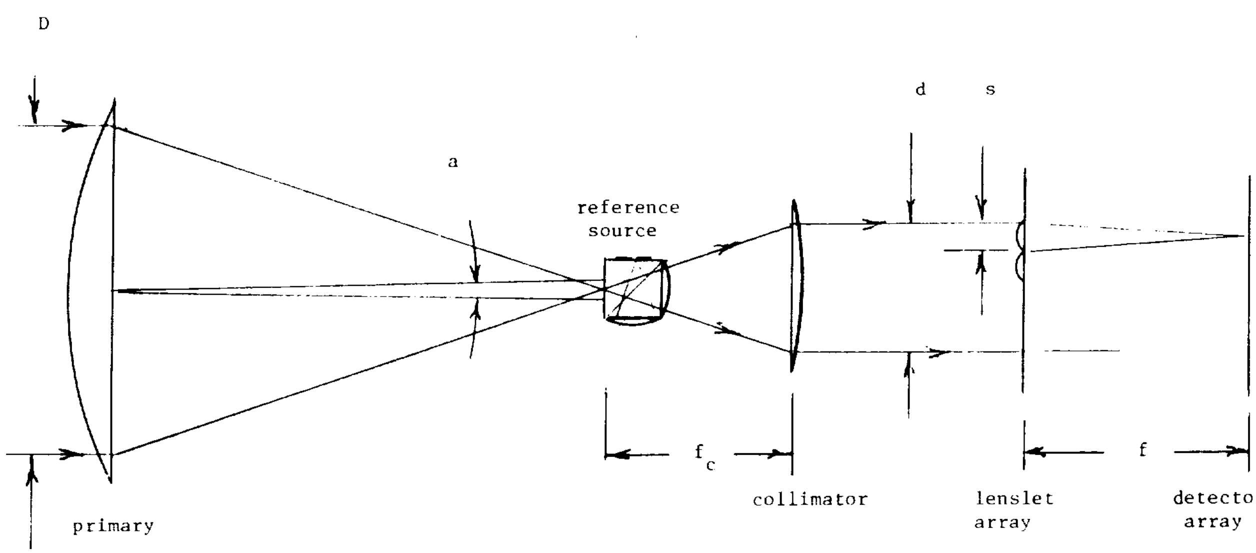


FIGURE 1. Parameters of a Hartmann-Shack Alignment Camera

The purpose of this discussion is to examine the constraints that would define the first-order properties of a Shack-Hartmann alignment camera and to investigate the precision and range of measurement one could expect to achieve with it. For this discussion it is sufficient to assume that the camera will be used as a focal-plane instrument and illuminated by starlight from the telescope. As shown in FIGURE 1, the starlight is allowed to fall on a collimating lens, L, which forms an image of the telescope primary mirror on the surface of a two-dimensional array of small lenses (lenslets). Each of these lenslets in turn forms an image of the star in a final image plane where a detector array is located. Since the lenslet array is at an image of the mirror, each lenslet samples the wavefront from a specific subarea of the mirror. If that area suffers a tilt error, the star image formed by the corresponding lenslet will be displaced. A reference wavefront can be introduced by means of a beam splitting cube in such a way as to sample the camera optics identically, so that a measurement of the displacement between the star image formed by the same lenslet will be independent of errors inherent in the camera optics.

If the alignment camera is to be used with a segmented mirror consisting of hexagonal segments, it might be natural to arrange the lenslets in a hexagonal array. In this case, it can be shown that the segments of the mirror will be sampled uniformly if the number of lenslets per segment is 6N+1 (N=0,1,2...). Hence if the mirror contains 36 segments, one finds the following possibilities:

Samples per Segment	Samples Across Aperture	Total Samples
1	7	36
7	21	252
19	35	684
25	49	900
etc.	...	...

However, considerations might arise in which other sampling schemes are advantageous, so that such "quantization" is not necessarily a fundamental issue.

Fundamental constraints do arise, however, from consideration of (1) geometrical imaging, (2) diffraction, and (3) the density of sampling of images at the detector array. Geometrical imagining determines the linear size of the image, and depends on the primary mirror diameter and the f-number of a lenslet. Diffraction is another constraint; it depends on the lenslet aperture. Finally, the sampling density at the detector array is important since the number of pixels in the image determines how accurately the centroid of the image can be measured. When these factors are considered under realistic assumptions (for example, 1-2 arcsecond seeing conditions), it is apparent that the first order design of a Shack-Hartmann alignment camera is completely determined by the first-order constraints considered, and that in the case of a 20-meter telescope with seeing-limited imaging, such a camera, used with a suitable detector array, will achieve useful precision.

References:

1. Chanan, G.A., Nelson, J.E, and Mast, T.S. (1987), Alignment Camera Preliminary Design, W.M.Keck Observatory Report No. 168.
2. Shack, R. (1976), Private communication to A.H. Vaughan.

N90-13478

SiO Overcoating and Polishing of CFRP Telescope Panels

Patrick Woida and William F. Hoffmann
Steward Observatory, University of Arizona
Tucson, AZ 85721

Our work on the development of carbon fiber reinforced plastic (CFRP) panel overcoating and polishing is structured in two parts. The first part utilized a short series of experiments to determine the feasibility of overcoating and polishing CFRP panels, and the second part will employ a systematic approach to optimize techniques learned. The initial work has been completed successfully and is the primary topic of this paper.

Questions which required answers in our initial investigation are summarized below:

1. Will silicon monoxide (SiO) bond well to CFRP?
2. Will the coating hold up under temperature cycling?
3. Can suitable coating rates and thicknesses be achieved?
4. Can a panel withstand the temperatures in a coating chamber?
5. Can large mirrors be coated?
6. How is the optical performance of a coated panel affected by thermal deformations?
7. Will the coating create any bimetal surface effects?
8. Will films remain bonded during polishing?
9. What is the effect of polishing a hard substance on a soft substrate?

Tests were performed in the Steward Observatory's 2.2 Meter Vacuum Coating Chamber, which employs evaporation sources symmetrically placed on rings beneath the mirror, with a glow discharge for plasma cleaning. For the SiO deposition, open tantalum boats were filled with SiO and heated using embedded tungsten coils.

Tests began with 3 cm square pieces of CFRP facesheet material. A deposition of 0.2 μm, which is typical of protective overcoatings for astronomical mirrors, bonded well and was abrasion resistant. A deposition of 4.0 μm could be machine polished for several hours without debonding the coating.

Next, a 10 cm square and one-inch-thick CFPR-Aluminum core panel was tested. The panel was coated to 12.5 μm thickness in about five hours. No visible coating deterioration was noticed during rapid temperature cycling (between +40°C and -70°C), and machine polishing resulted in noticeable improvement. It was, however, noticed during polishing that the mirror had warped significantly. This was attributed to the >80°C substrate temperature measured during the SiO deposition. The coating temperature was therefore reduced to 50°C, typical of what might be expected during shipping in Arizona in summer.

Tests were then conducted on a 0.5-meter-square Dornier panel (QUAD 4) with CFRP facesheets on two-inch aluminum Flexcore. The panel had a 10-meter radius of curvature. Using the Steward Chamber in its normal configuration with 12 deposition boats caused the 50°C temperature limit to be exceeded before any significant coating could take place. Switching to only 2 boats, however, achieved the desired deposition rate and thickness, and the temperature stayed well below the 50°C limit. This panel was then used to test various hand polishing techniques. A pitch tool with 1-3 μm diamond dust produced the best compromise between polishing time and mirror finish.

To complete the initial study, a previously characterized 0.5 m Dornier panel (QUAD 23) was coated and hand polished (until breakthrough started to occur). FIGURE 1 illustrates the before and after panel figure errors relative to a surface expressed as Zernike polynomials. As is clearly seen, the focus and large astigmatism follow the previous "as replicated" data. The mirror's optical performance was not affected by the SiO coating. It is important to note that the temperature cycling did not damage the polished coating of this panel, even though distortions in excess of 30 μm were experienced.

With the success of this initial program, work is now beginning on the optimization phase in conjunction with the JPL panel development program. A dedicated vacuum chamber has been built to work with panels as large as 50 cm. For larger panels (up to 2 m), the Steward Chamber will be used. Tests will be conducted on new evaporation sources, heat shielding, and the like to optimize the coating process. The work will concentrate on polishing to optical specifications.

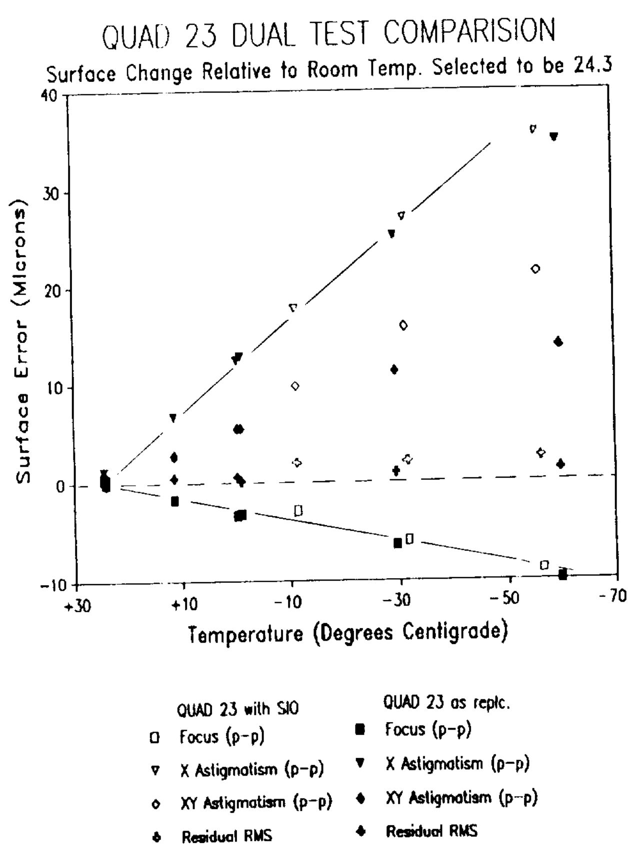


FIGURE 1. Panel Comparison Tests Before and After SiO Coating

N90-13479

Real-Time Sensing of Optical Alignment

Mark T. Stier and Alan B. Wissinger
Perkin-Elmer Corporation
Danbury, Connecticut

The Large Deployable Reflector and other future segmented optical systems may require autonomous, real-time alignment of their optical surfaces. We have developed gratings located directly on a mirror surface to provide interferometric sensing of the location and figure of the mirror. The grating diffracts a small portion of the incident beam to a "diffractive focus" where the desired diagnostics can be performed. If the grating (or gratings) adequately samples light across the mirror, the diffracted signal will track the reflected signal as the mirror is mechanically or thermally disturbed.

We have fabricated mirrors with diffraction gratings in two separate ways. FIGURE 1 describes the formation of a holographic grating over the entire surface of a mirror, thereby forming a Zone Plate Mirror (ZPM). The ZPM could be used as shown in FIGURE 2. The depth of the grating and the exposure of the hologram are used to determine the efficiency and focal length of the ZPM. We emphasize that the grating is very shallow, and since the final reflective coating is done after the formation of the ZPM, the mirror is highly reflective and does not have the appearance of a typical diffraction grating. We have fabricated several very high precision spherical mirror zone plates, and tests indicate that with typical grating efficiencies of a few percent, diffraction-limited point spread functions are produced at both the reflective and diffractive foci.

We have also used computer-generated hologram (CGH) patches for alignment and figure sensing of mirrors. As shown in FIGURE 3, the computer-generated pattern is produced with electron beam lithography equipment. The grating patches are formed on the mirror substrate using a flexible mask and contact replication. As in the two-beam holography method described above, the final reflective coating subsequently placed on the mirror leaves a surface that appears to be a conventional mirror. We have successfully tested this approach with a breadboard containing three grating patches on a large curved substrate.

When appropriately illuminated, a grid of patches spread over a mirror segment (FIGURE 4) will yield a grid of point images at a wavefront sensor, with the relative location of the points providing information on the figure and location of the mirror. A particular advantage of using the CGH approach is that the holographic patches can be computed, fabricated, and replicated on a mirror segment in a "mass production" 1-g clean room environment; it is not necessary to simulate the thermal and 0-g environment that may be needed for the more conventional holographic approach.

ZPM Fabrication

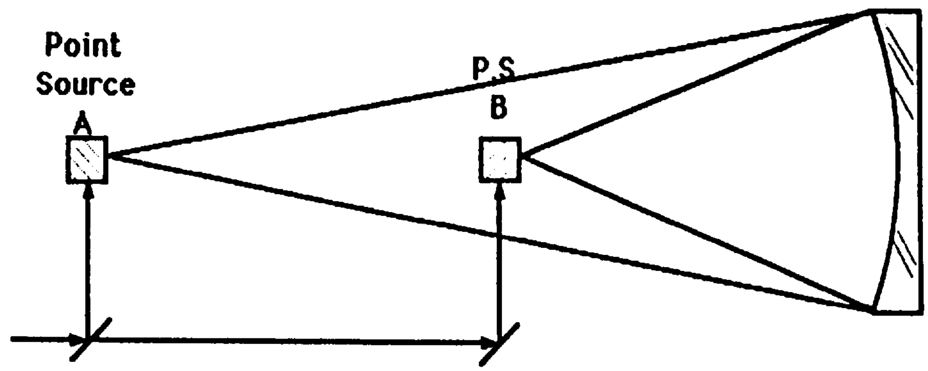


FIGURE 1. The Zone Plate Mirror is produced by illuminating the mirror with coherent point sources at A and B, and recording the interference pattern.

ZPM Application

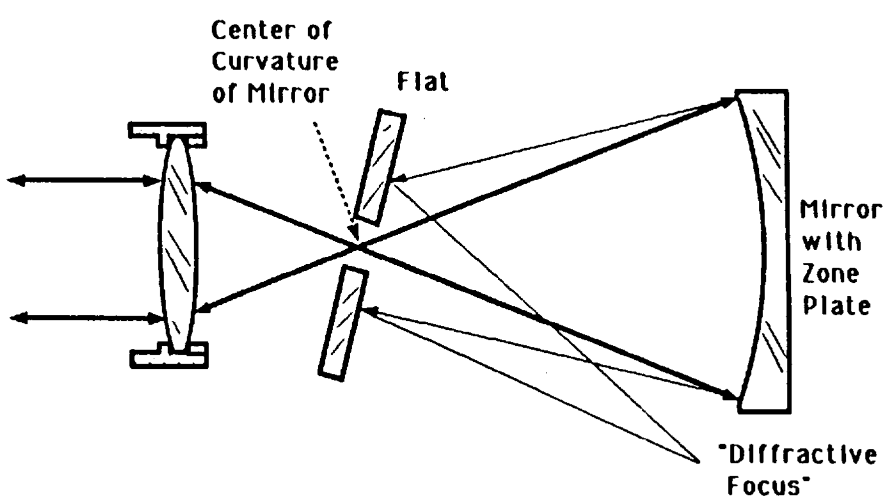


FIGURE 2. The Zone Plate Mirror produces an image at a convenient location for on-orbit alignment.

Grating Patch Fabrication

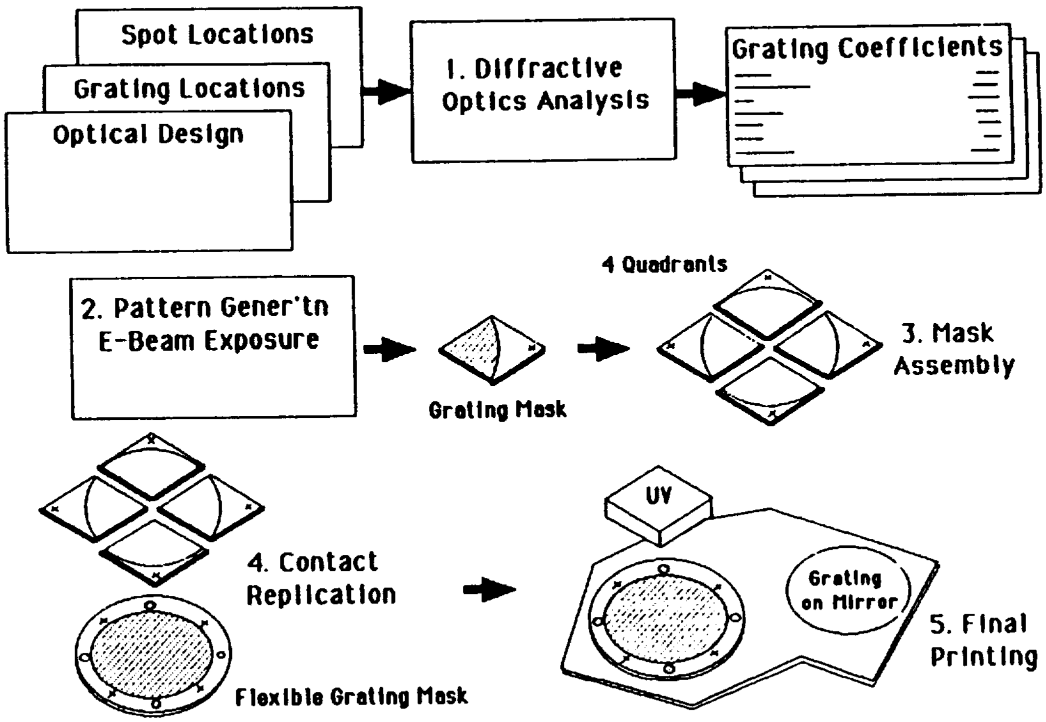


FIGURE 3. Flow chart illustration of the steps required to create computer-generated holographic (CGH) patches.

Mass Production by Contact Printing

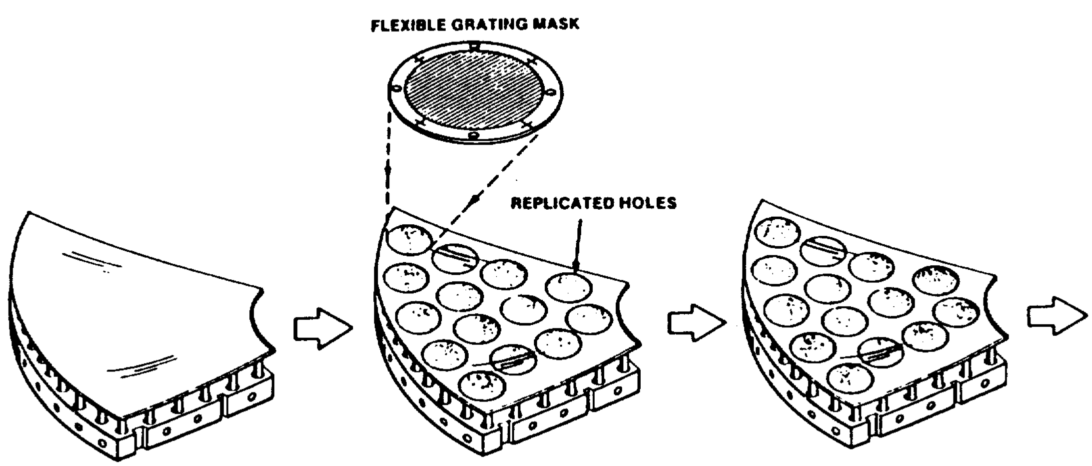


FIGURE 4. A set of reusable flexible grating masks can be used to replicate a grid of patches across the surface of mirror segments.

E. Structures Papers

N90-13480

Assembly Considerations for Large Reflectors

H. Bush
Langley Research Center
Hampton, VA 23665-5225
Summarized by Ben K. Wada

This paper discusses the technologies developed at LaRC in the area of erectable structures. The information is of direct value to LDR because an option for the LDR backup structure is to assemble it in space. The efforts in this area, which include development of joints, underwater assembly simulation tests, flight assembly/disassembly tests, and fabrication of 5-meter trusses, led to the use of the LaRC concept as the baseline configuration for the Space Station Structure.

The Space Station joint is linear in the load and displacement range of interest to Space Station; the ability to manually assemble and disassemble a 45-foot truss structure was demonstrated by astronauts in space as part of the ACCESS Shuttle Flight Experiment. The structure was built in 26 minutes 46 seconds, and involved a total of 500 manipulations of untethered hardware. Also, the correlation of the space experience with the neutral buoyancy simulation was very good. As shown in FIGURE 1, sections of the proposed 5-meter bay Space Station truss have been built on the ground.

Activities at LaRC have included the development of mobile remote manipulator systems (which can traverse the Space Station 5-meter structure), preliminary LDR sun shield concepts, LDR construction scenarios, and activities in robotic assembly of truss-type structures. Some preliminary studies on the effective strut stiffness, as affected by metal joints and the CTE of composite struts, have also been examined.

In summary, the technology of erectable structures in space for the LDR backup structure has been successfully developed. The other activities are directly of value to LDR and should be continued.

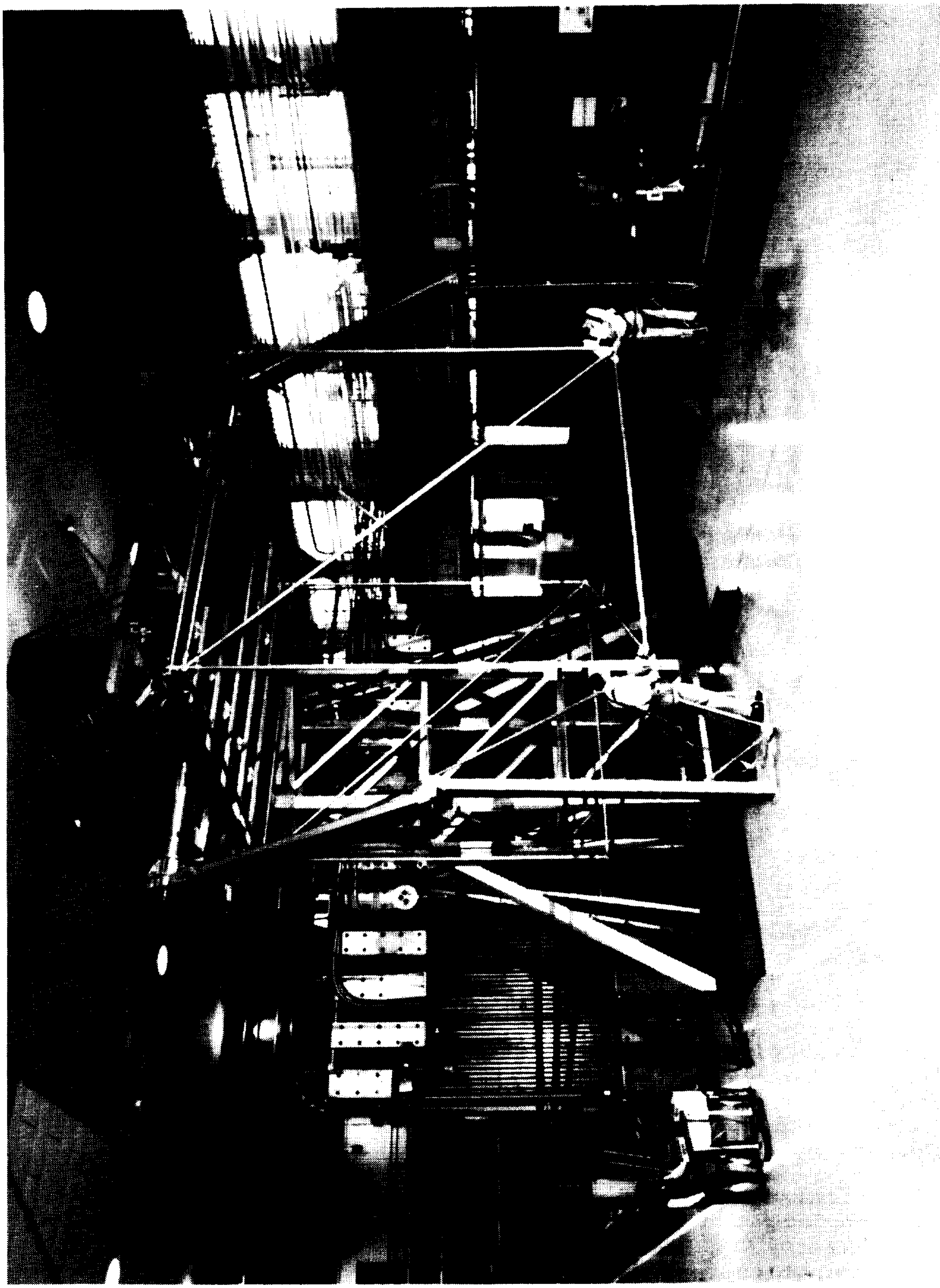


FIGURE 1. Space Station Structural Model

N90-13481

Explicit Modeling and Concurrent Processing in the Simulation of Multibody Dynamic Systems

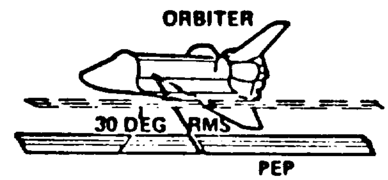
R. Gluck
TRW Space and Technology Group
Redondo Beach, CA 90278
Summarized by Ben K. Wada

The objective is to present the activities at TRW in developing the capability to simulate the behavior of large flexible multibody space structures. The features of the simulation tools are (1) to accommodate all rigid/flexible body degrees-of-freedom which incorporate the control system models and external forces, (2) to provide the flexibility to incorporate engineering-defined models and to retain parameters of significance to the engineer, (3) to reduce the computation cost by one order of magnitude (two orders of magnitude compared to a CRAY 1S), and (4) to keep it versatile so that radical variations in anticipated space structures can be accommodated. The current computer tools to simulate multibody systems appear not only to be very costly and time consuming, but also do not produce the desired fidelity of the mathematical models.

The activities can be divided into the development of the models, the design and fabrication of a Custom Architectured Parallel Processing System (CAPPS), and the development of a balanced computational load distribution for concurrent processing. The development of the model, or the basic equations of motion, is defined by the engineer using a symbol manipulation program to obtain explicit equations of motion for the dynamic characteristics of the system with a reduced simulation time. The engineer can now fully participate in the derivation of the model to the degree required for a specific problem.

The CAPPS system contains any number of computational units, each being a high-speed digital computer capable of operating independently, i.e., each computational unit has its own memory devices, an arithmetic module, and a complete input/output capability. To establish the potential benefits of CAPPS, a benchmark problem (Orbiter-Remote Manipulator System-Power Extension Package spacecraft) was modeled using an existing program (DISCOS) and solved using 10 commercially available computing systems. The resulting comparisons are shown in FIGURE 1. The parallel processing capability of the CAPPS was demonstrated with a simulation of a despin maneuver of a whirling flexible beam with the first version of CAPPS, which had two computational units. The results indicated that this CAPPS exceeded the CRAY 1S by 100%, and the CAPPS measured performance exceeded the analytical estimate by 60 %.

A computational load distribution software is in development which consists of the following three iterative optimization subroutines: (1) partitioning, (2) assignment, and (3) sequencing, which together seek to minimize the execution time of the simulation problem in a manner transparent to the user.



41 DEGREES OF FREEDOM (RIGID - AND FLEXIBLE - BODY)
130 SIMULTANEOUS DIFFERENTIAL EQUATIONS
100 SECONDS MANEUVER IN REAL TIME

COMPUTER	VENDOR	CPU TIME/ REAL TIME	LENGTH OF RUN (CPU HRS)	COST OF RUN ($)	
IBM 3090/600E	IBM	157.17	4.37	7,170	MEASURED RESULTS
CRAY XMP	CRAY RESEARCH INC.	163.92	4.55		
CRAY 1S	BOEING COMPUTER SERVICE	183 12	5 09	8.433	
CRAY 2	CRAY RESEARCH INC.	272.86	7.58		
FPS 264/VAX 785	FLOATING POINT SYSTEMS	333.86	9.27		
CYBER 205	CDC	410 0	11 38	33.920	
XPI	CONVEX COMPUTER	710.11	19.73		
IBM 3081	IBM CORP.	792.3	22 01	39,329	
SCS-40	SCIENTIFIC COMPUTER SYSTEMS CORP.	905.91	25.16		
IBM 3033 (TRW)	IBM	1670.0	46 39	49,000	
CAPPS (20 CUs)		10.8	0 30	LESS THAN 50	ESTIMATED RESULTS

CAPPS COSTS ARE CONSERVATIVELY PREDICTED TO BE <1% OF THOSE OF THE BEST AVAILABLE MAINFRAME COMPUTER SYSTEM

FIGURE 1. Simulation Results for the Orbiter-RMS-PEP Spacecraft Benchmark Problem

In summary, a multibody simulation tool will be developed in the near future which will allow solution of the dynamics and controls of the deployment of the LDR backup structure, or the problem associated with the robotic assembly of the structure. The tools will allow the engineer to define the modeling technique and solve problems in less time and at reduced cost.

N90-13482

Initial Test Results for the Mini-Mast

L. Horta and G. Horner
Langley Research Center
Hampton, VA 23665-5225
Presented and Summarized by Ben K. Wada

The objectives of the 20-meter Mini-Mast were (1) to learn how to efficiently test this type of large truss structure, (2) to relate component testing to the overall behavior of the structure, and (3) to update the associated analytical model based upon the experimental data. The Mini-Mast represents structural characteristics similar to the COFS beam which is planned to be flown on Shuttle to perform on-orbit structures and controls experiments. The information is of interest to LDR because it represents analysis and test information on a truss-type structure which may be similar to the LDR backup structure. The structure has a total of 111 titanium joints; the joint in the center of the truss element is the near-center latch joint presented in the paper by M. Rhodes.

The successful identification of the first three modes (< 10 Hz) indicated excellent agreement of the two bending modes with analysis, whereas the torsion test mode was about 20 % higher than predicted. The modal damping data were approximately 0.5 % indicating "tight" linear joints in the joint dominated structure. Comparison of the static test results to the analytical predictions shows excellent correlation up to a static deflection at the tip of the beam of about 0.22 inches.

As noted in FIGURE 1, the near-center latch joint represented a significant mass in the center of the beam. At higher resonant frequencies, the many local modes represented by all members with the near-center latch joint were excited; difficulty existed in extracting all the local modes. The frequencies of the local modes were slightly different; the difference could be partially attributed to the different compressive loads in the truss members. The compressive loads were higher in the lower members due to the gravitational loads of the structure above the members.

The results of this research indicate that linear deployable-type structures can be built, but difficulties do exist in extracting modes with identical frequencies; gravitational loading does affect the ground test results; and prediction of truss-type-structure dynamic characteristics is not trivial.

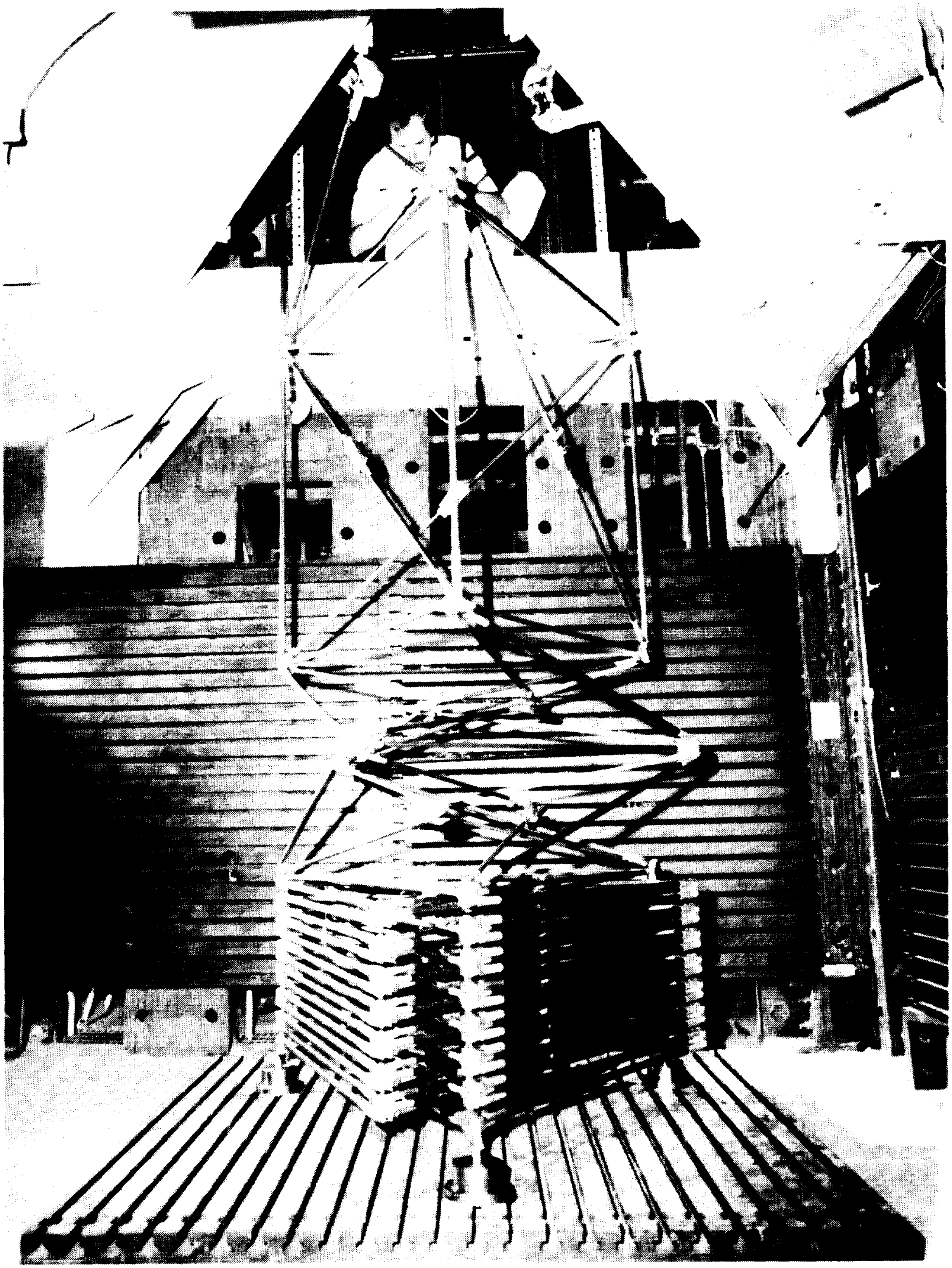


FIGURE 1. The Mini-Mast

N90-13483

LDR Structural Experiment Definition

R. A. Russell
Langley Research Center
Hampton, VA 23665-5225
Summarized R. E. Freeland

A system study to develop the definition of a structural flight experiment for a large precision segmented reflector on Space Station was accomplished by The Boeing Aerospace Company for NASA's Langley Research Center. The objective of the study was to use a JPL LDR baseline configuration [1] as the basis for focusing an experiment definition, so that the resulting accommodation requirements and interface constraints could be used as part of the mission requirements data base for Space Station.

The ground rules for the study were that (1) the experiments would be conducted on the space station, (2) the test hardware would serve as a test bed for future precision segmented structures experiments, (3) the primary mirror would use the deployable PAC truss structure, (4) the primary mirror facets would be assembled using telerobotics, (5) the system identification techniques would already have been developed, (6) structural characterization would be required, and (7) chopping would occur at the sensors that require it.

Results of the study define three Space Station-based experiments to demonstrate the technologies needed for an LDR-type structure. The basic experiment configurations are the same as the JPL baseline except that the primary mirror truss is ten meters in diameter instead of twenty. The primary objectives of the first experiment are to construct the primary mirror support truss and to determine its structural and thermal characteristics. Addition of an optical bench, thermal shield and primary mirror segments, and alignment of the optical components, would occur on a second experiment. The structure would then be moved to the payload pointing system for pointing, optical control, and scientific optical measurement for a third experiment.

As shown in FIGURE 1, Experiment 1 will deploy the primary support truss while it is attached to the instrument module structure. If possible, it will be deployed repeatedly to demonstrate reliability of kinematic deployment. After each deployment, the structural adequacy will be measured. After final deployment, the dynamic and thermal characteristics will be measured. The ability to adjust the mirror attachment points and to attach several dummy primary mirror segments with a robotic system will also be demonstrated.

Experiment 2 will be achieved by adding new components and equipment to experiment one. The optical bench structure, including the preassembled secondary, tertiary, and quaternary mirrors, will be attached to the instrument module. The thermal shield will then be attached after several lightweight composite mirror segments have been assembled. After installation of the

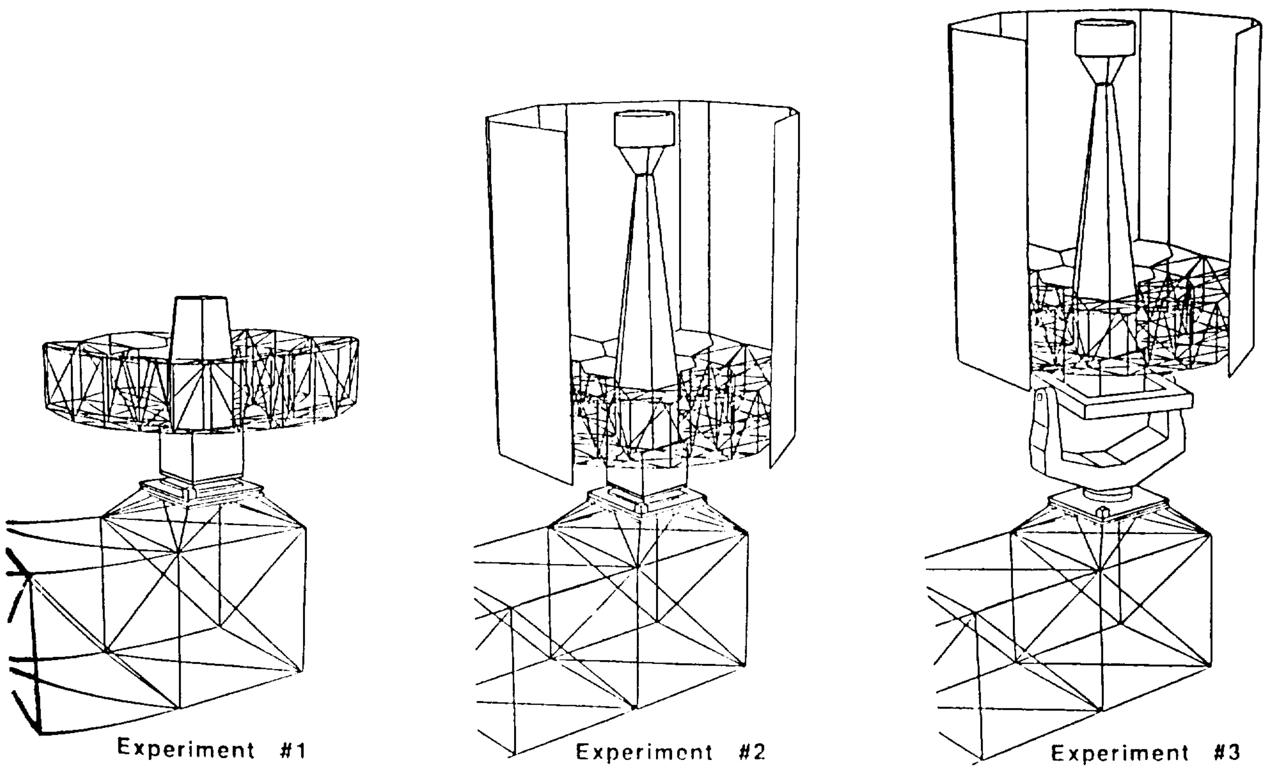


FIGURE 1. The Large Precision Segmented Structures Testbed

optical alignment system and prototype cryogenic cooling system, the optical system will be evaluated.

Experiment 3 will demonstrate advanced control strategies, active adjustment of the primary mirror alignment, and technologies associated with optical sensing; there will be particular emphasis on sensing for the alignment and control of the quaternary mirror elements. Equipment to be added for this experiment will include a payload pointing system, fine pointing system, star tracker, and primary mirror alignment system. This experiment will also address the feasibility of providing an electro-mechanical quasi-static adjustment mechanism for the primary mirror panels.

Reference:

1. A Lightweight Low Cost Large Deployable Reflector (LDR), Paul N. Swanson, JPL Report D-2283, June 1985.

N90-13484

Control of Optical Systems

D. Founds
Air Force Space Systems Command
Kirtland Air Force Base, NM 87117-6008
Summarized by B. Wada

This paper summarizes some of the current and planned activities at the Air Force Systems Command in structures and controls for optical-type systems. Many of the activities are contracted to industry; one task is an in-house program which includes a hardware test program.

The objective of the in-house program, referred to as the Aluminum Beam Expander Structure (ABES), is to address issues involved in on-orbit system identification. The structure, which appears similar to the LDR backup structure, is about 35 feet tall, and is shown in FIGURE 1. The activity to date has been limited to acquisition of about 250 hours of test data. About 30 hours of data per excitation force is gathered in order to obtain sufficient data for a good statistical estimate of the structural parameters. The data has not been reduced [It now has. Ed.].

The development of an Integrated Structural Modeling (ISM) computer program is being done by Boeing Aerospace Company. The objective of the contracted effort is to develop a combined optics, structures, thermal, controls, and multibody dynamics simulation code.

Two contracts to demonstrate by test the capability to develop Space Active Vibration Isolation (SAVI) exist with Honeywell Space Systems and Martin Marietta. One effort is to develop 80 dB isolators that have the ability to transmit large loads for use with 6000 kg payloads with a bandwidth from 1-2000 Hz. The other activity is to develop 80 dB isolators for a 200 kg payload with a bandwidth from 1-2000 Hz.

A contract with TRW, referred to as the Joint Optics Structures Experiment (JOSE), also exits. As the test structure, the composite HALO truss structure, which has well-characterized modes up to 100 Hz and about 2% modal damping, will be used to demonstrate the active control of space structures technology on a complex optical system. The objective is to provide active control over 1-500 Hz bandwidth.

The other contracted programs are related to areas of interest which are not directly applicable to LDR. The objectives of these areas include (1) demonstration of passive acquisition and tracking, (2) demonstration of active illumination techniques in acquisition and tracking, (3) demonstration of the designation and maintenance of aimpoint at operational ranges, (4) demonstration of the ATP inertial reference unit functions necessary for fine tracking, and (5) demonstration of precision tracking at operational ranges in a ground brassboard.

Many of the requirements appear to be much more stringent than those needed for LDR. The efforts on ABES and JOSE should provide valuable information for the LDR program. The technology under development for SAVI, for example, may help guide activities for providing isolation in the LDR structure.

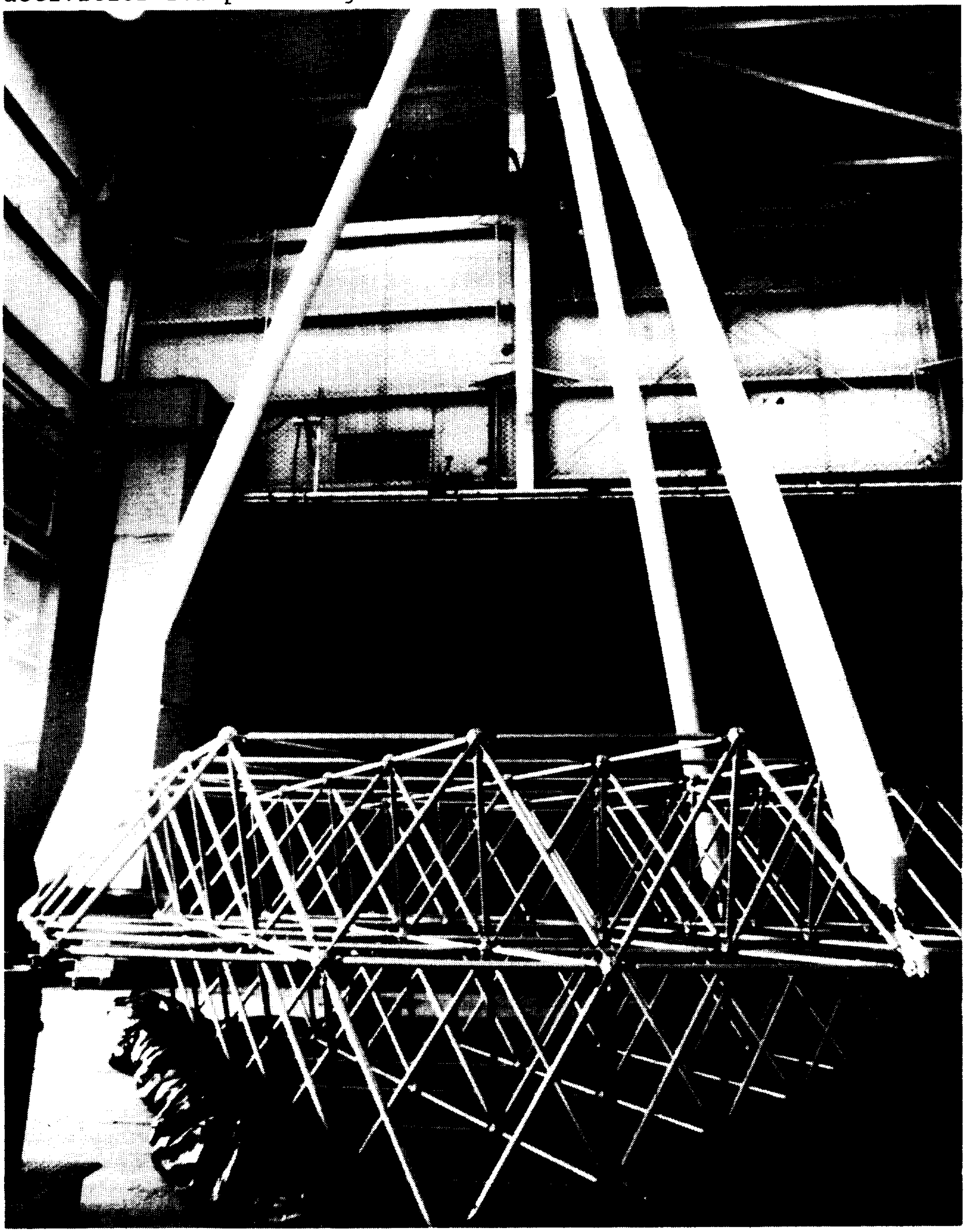


FIGURE 1. The ABES Structure at Kirtland Air Force Base

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

N90-13485

Hybrid Deployable Support Truss Designs for LDR

J. Hedgepeth
Astro Aerospace Corporation
Santa Barbara, CA 93101
Summarized by B. Wada

The paper discusses concepts for a 20-meter diameter LDR deployable truss backup structure, and analytical predictions of its structural characteristics. The concept shown in FIGURE 1 is referred to as the SIXPAC; it is a combination of the PACTRUSS concept and a single-fold beam, which would make up the desired backup structure. One advantage of retaining the PACTRUSS concept is its packaging density and its capability for synchronous deployment. Various 2-meter hexagonal panel arrangements are possible for this Hybrid PACTRUSS structure depending on the panel-to-structure attachment strategies used.

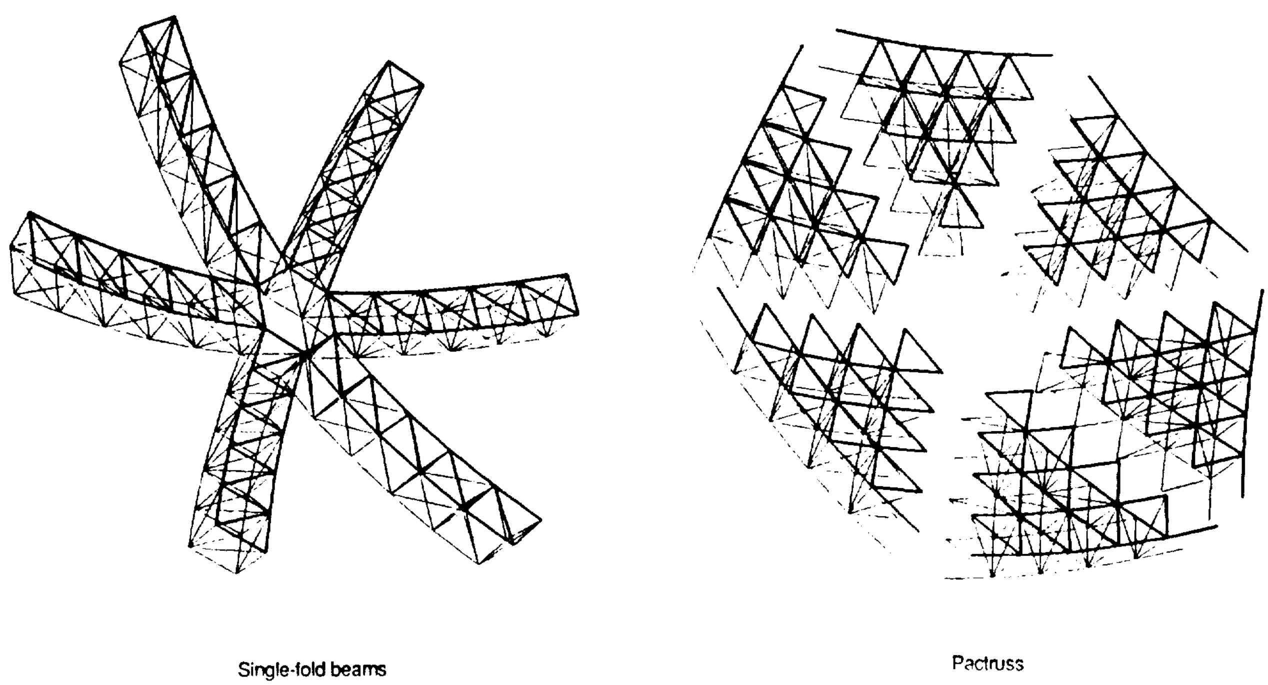


FIGURE 1. The Parts of a Hybrid PACTRUSS

A dynamic analysis of a SIXPAC concept for the LDR structure resulted in a relatively stiff structure; the first two resonant frequencies, which represented rocking about the two orthogonal axis of the structure, were both 10.4 Hz, and the third resonant frequency, which represented rotation about the axis perpendicular to the plane of the structure, was 11.7 Hz.

Static analyses of the SIXPAC using various assumptions for truss designs and panel masses of 10 kg/m^2 were performed to predict the tip displacement of the structure when supported at the center. The tip displacement ranged from 0.20-0.44 mm without the panel mass, and from 0.9-3.9 mm with the panel mass (in a 1-g field). The data indicate that the structure can be adequately ground tested to validate its required performance in space, assuming the required performance in space is approximately 100 μm. The static displacement at the tip of the structure when subjected to an angular acceleration of 0.001 rad/sec^2 were estimated to range from 0.8-7.5 μm, depending on the type of truss elements.

A joint concept, which would allow rotation of the joint during the deployment and yet provide a tight joint in its deployed state, was also presented.

In summary, a deployable structural concept exists which can meet the LDR back-up structure requirements. The analysis indicates that the structure is relatively stiff (first resonance of $\approx$10 Hz) and is therefore amenable to ground verification tests.

N90-13486

Effects of Joints in Truss Structures

R.Ikegami
Boeing Aerospace Company
Seattle, WA 98124
Presented and Summarized by B. Wada

The response of truss-type structures for future space applications, such as LDR, will be directly affected by joint performance. Some of the objectives of research at BAC were to characterize structural joints, establish analytical approaches that incorporate joint characteristics, and experimentally establish the validity of the analytical approaches.

The test approach to characterize joints for both erectable- and deployable-type structures was based upon a Force State Mapping Technique initially proposed by E. Crawley and K. O'Donnell; it is shown in FIGURE 1. The approach pictorially shows how the nonlinear joint results can be used for equivalent linear analysis. Testing of the Space Station joints developed at LaRC (a hinged joint at 2 Hz and a clevis joint at 2 Hz) successfully revealed the nonlinear characteristics of the joints. The Space Station joints were effectively linear when loaded to ±500 pounds with a corresponding displacement of about ±0.0015 inch.

- **Reference: "Identification of Nonlinear System Parameters in Space Structure Joints Using The Force State Mapping Technique", E. F. Crawley and K. J. O'Donnell SSL #16-85, July 1985**
- **Represents force transmitted by joint as function of displacement and velocity across joint**
- **3 dimensional plot provides compact graphical description of nonlinear joint behavior**
  - **Established testing procedure**
  - **Common nonlinearities easily recognizable**
  - **Results directly usable for equivalent linearization analysis**

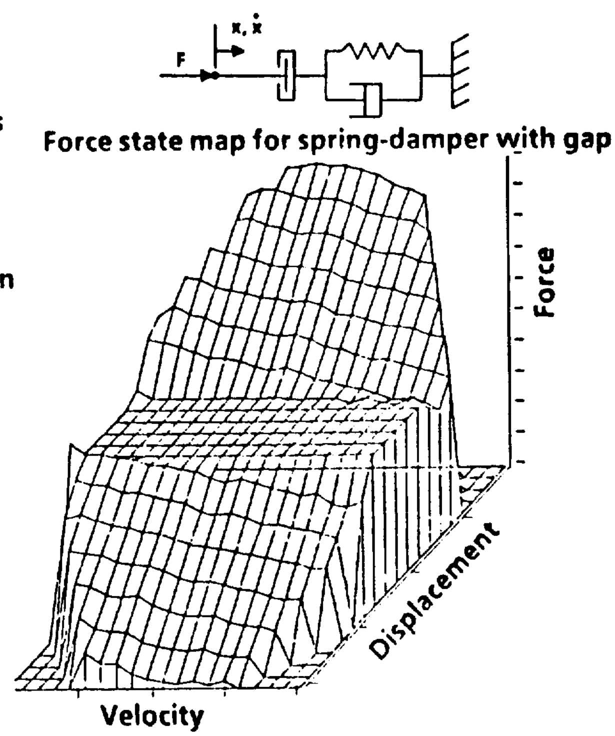


FIGURE 1. Joints Characterization - Force State Mapping

The analytical approach employed represented the characteristics of the joint as a superposition of a linear portion and a nonlinear portion. Thus, in the governing differential equations, the linear portion is retained with the terms representing the linear equations of the structure; these can be solved by many standard approaches. The nonlinear portion is represented as a forcing function to the linear equation and is referred to as the Residual Force. The Residual Force is a function of the relative motion and velocity of the joint. This approach has been applied to the 60 meter COFS truss, which has nonlinear joints, but remains to be validated by test.

A BAC Compact Deployable Space Truss, built of Graphite Epoxy members with clothes pin joints in the center of the members, has been tested. The objectives were to assess the difficulty in obtaining the experimental eigenparameters, and to validate the analytical predictions. Some success was achieved in predicting the of the lower modes, but difficulty was encountered in obtaining good modes at the higher frequencies, due to excitation of local modes and the non-linearities in the system.

The study indicated that good linear joints exist which are compatible with erected structures, but that difficulty may be encountered if nonlinear-type joints are incorporated in the structure.

N90-13487

PACOSS Program

Presented by K. E. Richards, Jr.
Martin Marietta Aerospace
Denver, CO 80201
Summarized by B.K. Wada

The objectives of the PACOSS program were to demonstrate the respective roles of passive and active control for structures that represented future Large Space Structures (LSS), to develop means to introduce passive vibration control, and to experimentally verify the damping predictions and the control algorithms. In order to meet the objectives, the program was divided into an analytical simulation phase to establish the respective roles of passive and active damping on a LSS-type structure, and a design, analysis, and test phase to validate the passive damping and the control algorithm performance for a structure.

The objective of the analytical simulation was to control the line-of-sight of the configuration shown in FIGURE 1 during slew. The desired performance was the rigid-body response. Using active modal control only if required, the goal was to determine the control energy required to achieve the desired performance for various levels of realizable passive damping. The results from the study were that a proper combination of passive and active damping delivers the desired performance, at the same time reducing the number of active control components, and the energy and power requirements. In addition, the passive/active system can lead to more robust, reliable, and less expensive systems. The conclusion was future LSS should be designed to facilitate the effective utilization of passive damping.

One of the principal objectives of the test phase of the program was to establish the capability to design and analytically predict the passive damping characteristics of LSS-type hardware by comparison with the experimental data. A dynamically representative article of the LSS was fabricated. Other requirements on the test article were that it be inexpensive, contain negligible unpredictable damping, and suitable for testing in a 1-g field. The approach taken in the analysis and test effort was to divide the system into six subsystems; each subsystem analytical model was in turn validated by modal tests. Subsystem coupling techniques were then used to couple the subsystems to obtain the system damping and eigenparameter estimates. Excellent correlation was achieved between the analytical estimates of damping, and the system test damping values. The test data indicated that the higher modes of precision structures do not necessarily have significant inherent damping.

In conclusion, predictable amounts of damping can be designed into a LSS structure, the best control strategy uses a combination of passive damping and active controls, and a more optimum system can be achieved by an early interaction between the structural designer, controls engineer, and the damping designer.

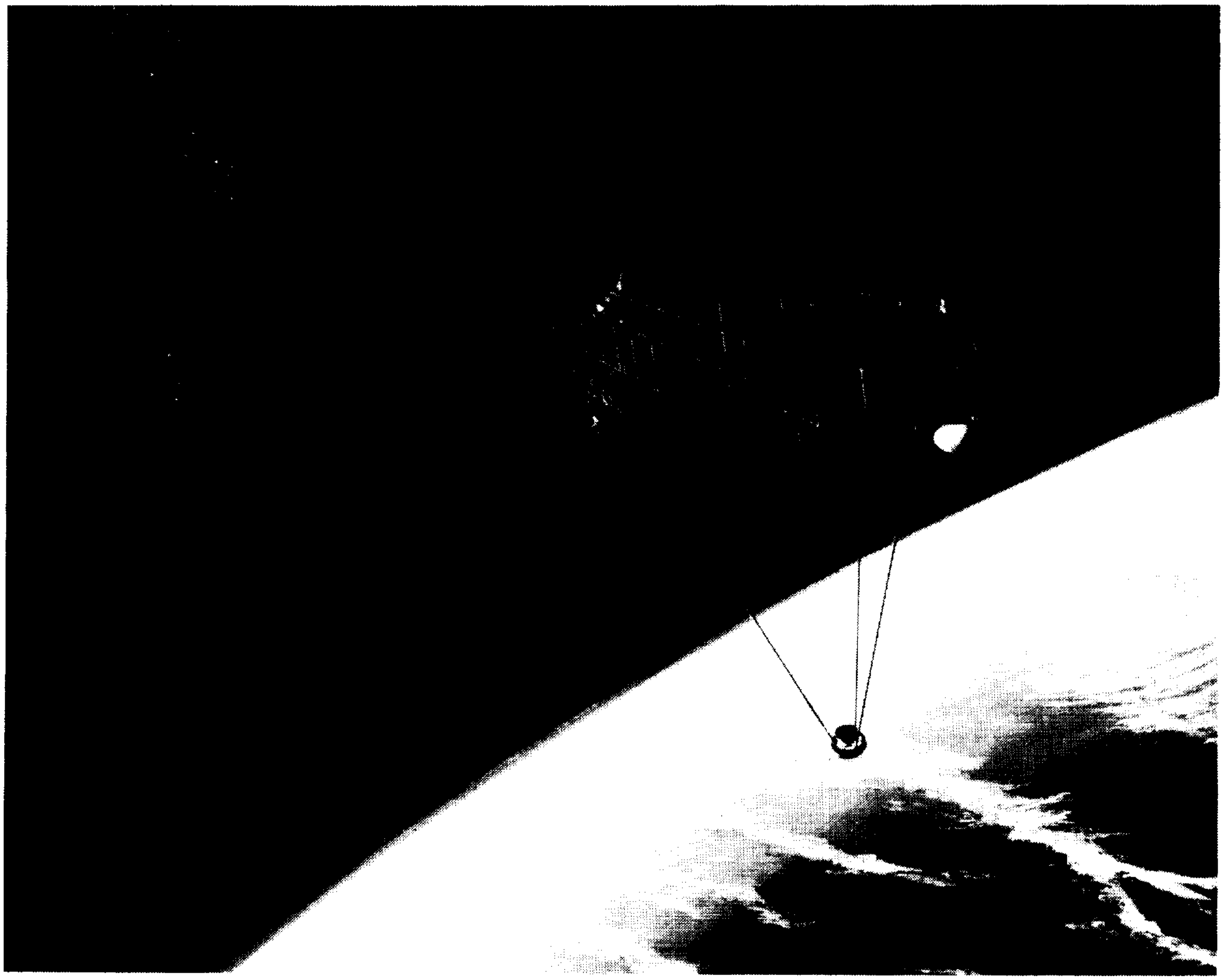


FIGURE 1. The PACOSS Large Space Structure

N90-13488

LDR Structural Technology Activities at JPL

Ben Wada
Jet Propulsion Laboratory
Pasadena, CA 91109

This paper summarizes the status of the LDR technology requirements and the availability of that technology in the next few years. The research efforts at JPL related to these technology needs are also discussed. LDR requires that a large (20 meters in diameter) and relatively stiff (frequencies ≥5-10 Hz) truss-type backup structure have a surface accurate to 100 μm in space (initial position with thermal distortions) and the dynamic characteristics predictable and/or measurable by on-orbit system identification for micron level motion. This motion may result from the excitation of the lower modes or from wave-type motions. It is also assumed that the LDR structure can be ground tested to validate its ability to meet mission requirements. No program manager will commit a structural design based solely on analysis, unless the analysis is backed by a validation test program.

Technology development is required for new ground test approaches to validate the LDR structure; the current state of the art is not adequate because of the adverse effects of the terrestrial environment. Ground test approaches under investigation at JPL, which would allow testing of structures, include multi-boundry-condition tests (MBCT), initial position determination, and proper identification of interface effects. Almost no efforts exist in trying to experimentally evaluate the micron level static and dynamic characteristics truss-type structures dominated by joints.

Technology is required to analytically characterize the micron level and wave motion behavior of structures. Based on experience to date, current state of the art analytical approaches are inadequate. A combined analytical/experimental program is required to develop acceptable models.

Current system identification methods are unable to identify the characteristics of a structure; the situation is compounded when identification of micron-level and wave-type characteristics are required.

Concepts of adaptive or active structures are under development at JPL, and will lead to solutions of the many technology challenges for LDR. Adaptive structures allow the adjustment of a structure in space at the micron level and/or at large displacement levels. Active elements within the truss system can detect nanometer level relative displacements and apply the forces necessary to provide damping, isolation, submicron positioning. Active structures thus alleviate some of the ground test requirements because the structure can be adjusted in space to meet the in-space requirements. Since active members can detect small motions, they can be directly used to sense and add damping to micron level modal and/or wave-type motions. They can also be used to excite and then sense the displacements and forces for on-orbit system identification. Since active elements only impart equal and opposite forces into the structure, they cannot impart rigid body motions into the structure. The objective is to place local controls at the active elements, and to decouple them from the system used to provide rigid body control for the spacecraft. The local controls would be invisible to this central control system and have a benign effect on it.

N90-13489

Joints in Deployable Space Truss Structures

M. Rhodes
Langley Research Center
Hampton, VA 23665-5225
Presented and Summarized by Ben K. Wada

Since the response of deployable structural concepts being considered for the LDR backup structure will be dominated by the response of joints, the joint characteristics are significant. This presentation is an overview of the research activities at LaRC on the static behavior of joints for deployable space truss structures.

Since a pin-clevis-type joint will be utilized in deployable structures, an experimental research program to characterize the joint parameters which affect stiffness was conducted. Some of the parameters evaluated were the effects of the pin and joint material properties, the tolerance between the pin diameter and the hole, and the effect of pin diameter on joint stiffness. Based upon the experimental studies, the design recommendations for pin-clevis joints were established. FIGURE 1 shows the joint stiffness efficiency for tensile and compressive loads for various joint materials.

An experimental research program was conducted on a second type of joint, referred to as a near-center latch joint. It was used in the center of members on the deployable truss structure for the Control of Flexible Structures (COFS) flight experiment. The design features of the joint are (1) the parent joint material is titanium and the pin material is steel, (2) the linkage members in the load path take only axial loading, (3) all pins and holes have light interference fits, (4) critical pin holes are drilled on assembly fixture, and (5) an interior preload of 80 pounds was applied. The test results of the near-center latch joint and the member with the joints indicated that the stiffness of the near-center joint is linear and stiffer than the stiffness of the total member, and that non-linearities in the stiffness characteristics of the total member were due to bending introduced at the ends of the member. The resulting data indicates that stiff linear folding joints can be designed and that bending load paths should be avoided whenever possible. In summary, for deployable structures, special attention to the joint and the structure design is required to minimize the undesirable structural non-linearities.

$$\text{Efficiency} = \frac{\text{Maximum measured stiffness}}{(E\ A\ /\ L)_{\text{Test section}}}$$

Joint Material	Efficiency Tension	Efficiency Compression
Steel	30%	38%
Titanium	43%	59%
Aluminum	50%	76%

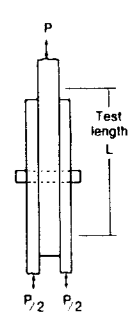


FIGURE 1. Joint Section Efficiency

F. Special Session on Ballooning

N90-13490

Three-Meter Balloon-Borne Telescope

W.F.Hoffmann, Steward Observatory, University of Arizona
G.G. Fazio, Smithsonian Astrophysical Observatory
D.A. Harper, Yerkes Observatory, University of Chicago

The Three-Meter Balloon-Borne Telescope is planned as a general purpose facility for making far-infrared and submillimeter astronomical observations from the stratosphere. It will operate throughout the spectral range 30 microns to 1 millimeter which is largely obscurred from the ground.

The design is an f/13.5 Cassegrain telescope with an f/1.33 3-meter primary mirror supported with a 3-axis gimbal and stabilization system. The overall structure is 8.0 m high by 5.5 m in width by 4.0 m in depth and weighs 2000 kg. This low weight is achieved through the use of an ultra lightweight primary mirror of composite construction. Pointing and stabilization are achieved with television monitoring of the star field, flex-pivot bearing supports, gyroscopes, and magnetically levitated reaction wheels.

Two instruments will be carried on each flight; generally a photometric camera and a spectrometer. A 64-element bolometer array photometric camera operating from 30 to 300 μm is planned as part of the facility. Additional instruments will be derived from KAO and other development programs.

The scientific capability of this facility is based on two crucial features: the balloon altitude of 100,000 feet, where less than 1% of the Earth's atmosphere remains, including its water vapor, and the three meter aperture. The latter provides high angular diffraction-limited resolution approaching eight arcseconds at 100 μm wavelength, and a large collecting area, making possible sensitive high resolving power spectroscopy. The small residual atmosphere permits measurement of astronomical atomic and molecular spectral lines, which are obscured by similar atmospheric lines at lower altitudes, and provides a low sky emissivity resulting in greater detector sensitivity. The high angular resolution makes it possible to resolve and study in detail such objects as collapsing protostellar condensations in our own galaxy, clusters of protostars in the Magellanic Clouds, giant molecular clouds in nearby galaxies, and spiral arms in distant galaxies. Sensitive spectral line measurements of molecules, atoms, and ions can be used to probe the physical, chemical, and dynamical conditions in a wide variety of objects.

A NASA-supported design study has been carried out by the Smithsonian Astrophysical Observatory, University of Arizona, and Yerkes Observatory. This has resulted in an optimized optical, structural, and dynamic design which meets the overall scientific performance goals and is compatible with National Scientific Balloon Facility launch weight and other requirements.

This project deals with many technical issues directly relevant to NASA space missions such as the Large Deployable Reflector (LDR), and provides a focus for advancing required technologies at a reasonable size, time schedule, and cost. Already, considerable progress has been made in the development and testing of very lightweight composite mirrors which maintain 30 micron diffraction-limited figure quality at low temperature. Other related technologies include two-stage optics concepts, alternative approaches to secondary mirror chopping, and the development and operation of far infrared remotely operable instrumentation.

It is envisioned that the three-meter telescope would fly approximately five times a year. Each flight would carry two instruments, enabling an active guest observer program both for providing new instruments and for making astronomical observations. The definition study projects a three-year period for final design and construction, with initial flight operations of three flights during the fourth year. Subsequently, it is planned for five flights per year, each with a duration of ten hours or longer. A summary of the telesope parameters is given in TABLE 1.

TABLE 1. Three-Meter Balloon Telescope Parameters

Telescope	3 Meter Aperture f/13.5 Cassegrain
Spectral Range	Visible to millimeter, diffraction limited to 30μm (2.5")
Field of View	IR: 5' unvignetted, Optical: 15'
Secondary Chopper	16 Hz at 5 arcminutes (max.)
Pointing Stability	1 arcsec rms maximum, 0.25 arcsec goal
Aspect Sensing TV	
Acquisition	5° Field 11th magnitude sensitivity
Star Tracker	1° Field 10th magnitude sensitivity
Focal Plane	15' Field
Slew Rate	10 arcminutes/sec
Raster Scan Rate	24 arcseconds/sec max.
Telescope Observing Range	
Azimuth	360°
Elevation	-10° to +65°
Cross Elevation	$\pm$ 3°
Power System	Gondola and Experiments 250 amp-hrs each, max 15 amps at 28V each
Weight	
Telescope and Instrument	1724 lb.
Gondola	2026 lb.
Typical Flight Observing Time	10 hours at 29-31 km altitude
Experiments	Two per flight @ 115kg, 140 watts (typically photometric camera plus spectrometer)
Initial Photometric Camera	8 x 8 array of ^{3}He-cooled silicon bolometers covering 30μm to 300μm in several bands $0.1 < \Delta\lambda/\lambda < 0.5$, pixel $1.22\lambda/D$ (switchable magnification)

Photometric Sensitivity	NEFD/pix (chopping),	point source in 4 pixels 10σ in 30 minutes (chopping)
50μm	.09 Jy/√Hz	.04 Jy
100μm	.15 Jy/√Hz	.07 Jy
200μm	.19 Jy/√Hz	.09 Jy

END DATE MAR 2, 1990