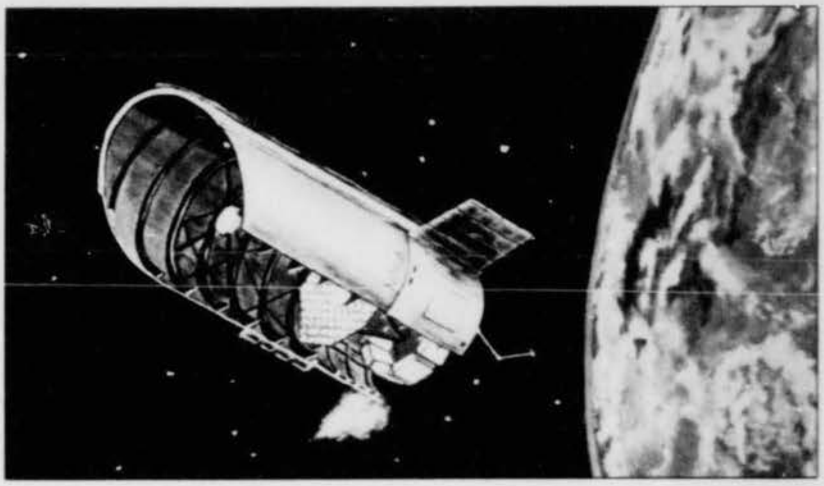
ASTROTECH 21
WORKSHOPS
SERIES II

VOLUME
4

SERIES II MISSION CONCEPTS AND
TECHNOLOGY REQUIREMENTS

Workshop Proceedings: Technologies for Large Filled-Aperture Telescopes in Space



September 15, 1991

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SERIES II MISSION CONCEPTS AND TECHNOLOGY REQUIREMENTS

Workshop Proceedings: Technologies for Large Filled-Aperture Telescopes in Space

Editors

Garth D. Illingworth
Dayton L. Jones

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Cover illustrations.

Top: Artist's concept of a Large Orbiting Telescope.

Bottom: Artist's concept of a Large Lunar Telescope.

WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

ABSTRACT

In 1989, the Astrophysics Division of the Office of Space Science and Applications initiated the planning of a technology development program, Astrotech 21, to develop the technological base for the Astrophysics missions developed in the period 1995 to 2015. An infusion of new technology is considered vital for achieving the advances in observational techniques needed for sustained scientific progress. Astrotech 21 was developed in cooperation with the Space Directorate of the Office of Aeronautics, Exploration and Technology, which will play a major role in its implementation. The Jet Propulsion Laboratory has led the planning of Astrotech 21 for the Agency.

The Astrotech 21 plan was developed by means of three series of workshops dealing respectively with: Science Objectives and Observational Techniques, Mission Concepts and Technology Requirements, and Integrated Technology Planning. Traceability of technology plans and recommendations to mission requirements and impacts was emphasized. Proceedings documents are published for each workshop. A summary report has also been prepared which synthesizes the results of the planning effort.

The workshop on Large Filled-Aperture Telescopes in Space was held in Pasadena, California, on March 4 and 5, 1991. Most of the first day was devoted to invited talks on science goals and on the current state-of-the-art in various technology areas. The participants then split into six working groups, which met during the latter part of the first day and most of the second day. The working group topics were optics, structures, detectors, sensing and control, and mission-specific issues for both orbiting and lunar-based instruments. The workshop concluded with a plenary session at which the working group chairpersons presented their group's technology development recommendations, followed by a general discussion of the recommendations by all participants. A report from each of the working groups is included in these proceedings.

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TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

Doubletree Inn, Pasadena
March 4–5, 1991

WORKSHOP AGENDA

Monday, March 4, 1991

8:30 a.m. -- Introductory talks:

M. Kaplan	HQ overview
G. Illingworth	Workshop goals
J. Cutts	Astrotech 21 program
J. Fordyce	Astrotech 21 infrastructure
P. Stockman	HST experience

10:00 a.m. -- *Break*

10:15 a.m. -- Current concepts:

P. Bely	Orbital-mission concepts
M. Nein	Lunar-mission concepts
D. Meier	Partially filled-aperture concepts

11:30 a.m. -- Technology overviews:

- Optics for large telescopes:

J. Nelson	Keck telescope / ion polishing
J. Nelson	Keck telescope video

12:00 noon -- *Lunch*

1:00 p.m. -- Technology overviews (cont'd):

- Optics for large telescopes (cont'd):

R. Angel	Stressed-lap polishing
R. Wilson	ESO thin mirror / NTT
J. Zimmerman	Large space optics

- Structures and control systems:

R. Laskin	Control of large space structures
M. Krim	Active mirror compensation
G. Beals	Pointing control

3:00 p.m. -- *Break*

3:15 p.m. -- Technology overviews (cont'd):

- Detectors and instrumentation:

B. Wilson	Report on sensors workshop
B. Woodgate	UV / visible detectors
C. McCreight	IR detectors

4:10 p.m. -- Formation of working groups:

- Instructions to working groups (J. Cutts)
- Initial working group meetings (All)

Topic:	*Chairperson:*
1. Optics.	R. Angel
2. Structure	B. Wada
3. Detectors	R. Thompson
4. Sensing and control	D. Tenerelli
5. Mission-specific issues (lunar)	J. Burns
6. Mission-specific issues (orbiting)	P. Stockman

5:30 p.m. -- *End of first day*

Tuesday, March 5, 1991

8:30 a.m.	--	Discussion of working group issues
8:45 a.m.	--	Working group parallel sessions (All)
10:15 a.m.	--	*Break*
10:30 a.m.	--	Working group parallel sessions (All) (cont'd)
12:30 noon	--	*Lunch*
2:00 p.m.	--	Plenary session:
		Reports from working group chairpersons
3:30 p.m.	--	*Break*
3:45 p.m.	--	Plenary session (cont'd)
5:15 p.m.	--	*End of workshop*

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WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

EXECUTIVE SUMMARY

GARTH ILLINGWORTH, LICK OBSERVATORY

Large filled-aperture UV-visible-IR space telescopes offer the unparalleled advantages of low background, uninterrupted wavelength coverage and a stable point-spread function for high dynamic range observations. Many fundamental astronomical problems can be tackled only with filled-aperture telescopes that combine high spatial resolution with large light-gathering capability. An 8 m-class passively cooled telescope in high earth orbit would have unprecedented power for problems as diverse as planet searches around nearby stars to the way in which galaxies formed in the young universe. It will build upon the discoveries and astronomical understanding of many decades of research with astronomical observatories, and is the natural successor to the Hubble Space Telescope (HST) and the new generation of large 10 m-class ground-based telescopes.

INTRODUCTION

It is clear that a large space telescope is needed to tackle a broad range of astrophysical problems. Many of these scientific issues cannot be adequately addressed with current or planned telescopes. The Hubble Space Telescope is clearly a powerful telescope, though its potential will not be fully realized until instruments that use contemporary technology and corrective optics are implemented. Even then, since it is the first of its kind, it does not fully exploit the potential of space telescopes in the crucial 0.1-10 micron range.

The primary advantages of large space telescopes are the combination of continuous spectral coverage unavailable from the ground, low background, a stable diffraction-limited point-spread function, and extremely high dynamic range from the ability to apodize low-scattering optical surfaces. The gains from the lower background are particularly large in the IR. Background reductions of a million times can be expected out to ~ 10 microns in systems passively cooled to ~ 100 K. Contemporary telescopes would not be competitive. Adaptive optical systems on ground-based telescopes have the potential for substantial gains in imaging performance, but will not result in telescopes that have the overall capability of space-based instruments. The Strehl ratio (a measure of the concentration of energy in the diffraction-limited core) will vary both with time and across the small field defined by the atmosphere, making high dynamic range, quantitative measurements impractical. The HST is limited by its small aperture, which leads to low sensitivity for spectroscopic observations and low spatial resolution in the IR, and by its warm optics and structure that lead to high background in the IR for wavelengths > 2 microns.

The science presentations at the *Next Generation Space Telescope* (NGST) workshop in Baltimore[1] gave excellent examples of both the breadth of the scientific issues that could be tackled, as well as the unique opportunities that such a telescope would bring for certain key problems. It was clear that many central problems in astrophysics require a large space telescope with forefront imaging and spectroscopic capabilities across the ~

0.1–10 micron wavelength range. Examples of such problems are: the nature and structure of high redshift galaxies; planet detection and spectroscopic analysis of their atmospheres; structure in star forming regions; and analysis in the UV of current-day counterparts of high-redshift objects.

The question of planet detection is one of great interest, but one that is extremely difficult from the ground or with the HST. Angel, Cheng and Woolf[2] analyzed the problem of detecting and spectroscopically measuring earth-like planets. They concluded that the optimum configuration was a filled-aperture, 16 m diameter, passively cooled telescope with low-scattering optics for use at 10 microns. Angel[3] has further refined this argument and suggested that a close-packed array of four 8 m telescopes would be better. Whichever approach is finally chosen, it is clear that the problem is an extremely challenging one. However, it is one that must rank high as a goal for any long-term program of space astrophysics.

Together these scientific goals have led to the development of a concept for a large, passively cooled filled-aperture space telescope with ~ 8 m diameter primary utilizing advances in technology since the HST was conceived. This is an ambitious program, but it appears to be practical for launch in the first decade of the 21st century.

SCIENCE GOALS

As noted above, the Baltimore NGST workshop volume contains several papers describing some of the scientific goals for space telescopes of the 8–16 m class. Further discussion of the science programs that could be carried out with a large space telescope can be found in the report of the *UV-Optical in Space* panel of the Astronomy and Astrophysics Survey Committee[4]. One of the striking features of NGST is the range of astrophysical problems for which it would provide substantial gains in knowledge; almost every major area of astronomical research would benefit greatly. A few examples of key problems to be tackled with NGST are:

- Detection and spectroscopy of gas giant to earth-like planets around nearby stars. The size of the planets and the distance to which they can be studied depends upon the size, optical configuration and the temperature of the optical system, but planets of a broad spectrum of sizes could be detected and studied spectroscopically with 8-16 m telescopes passively cooled to ~ 100 K.

- Study of nearby star-forming complexes with resolutions from 5-50 astronomical units (AU) in the visible and IR. Star formation is another key problem that is greatly compromised by the limitations of ground-based telescopes in the IR. The complexity of the structure associated with star-forming processes and protostellar disks, and the very high dynamic range required, make this a problem that will benefit greatly from the capabilities of large space observatories. Protostellar disks 1000 AU in size could be detected throughout the disk of our galaxy. Such a disk in Orion could be studied with 40 AU resolution, i.e., with 25 independent spatial resolution elements.

- Measurement of stellar populations in a variety of environments. The past history of our galaxy and nearby galaxies centers on the study of faint, mostly unevolved stars. With its ability to detect stars with S/N=10 in 10^4 s in the visible to 31 mag, NGST could age date the oldest populations by measuring below the main sequence turnoff anywhere in the Local Group of galaxies.

- Spatially resolve and map complex structures in the inner narrow line regions for active galactic nuclei and quasars (AGNs and QSOs). The complexity of the structure in such regions and the high dynamic range pose problems for ground-based observations with adaptive optics and for interferometric systems. This difficult problem will benefit from observations with large telescopes like NGST that can resolve $< 10^{20}$ cm at 3C273, the nearest QSO.

- Structure and evolution of (forming?) galaxies at redshifts $z > 1$. Large space telescopes can give resolutions on galaxies *at any redshift z* comparable to that for galaxies in the nearest cluster of galaxies, the Virgo cluster. These resolutions range from ~ 100 parsec (pc) to 1 kpc from the visible to the IR. The ability to resolve the dominant structures in galaxies (spiral arms, star-forming complexes, merger or interaction filaments or "tails", characteristic disk and bulge length scales, etc) will be crucial if we are to understand the evolutionary events that occur as galaxies form and change with redshift.

An additional great benefit of space observations with a passively cooled telescope is that "sky"-limited observations can be made in the zodiacal background "window" around 3.5 microns. This "window" occurs between the scattered solar spectrum and the thermal emission from the zodiacal dust. This may well prove to be the wavelength at which we detect galaxies in formation. These would be the highest redshift objects in the universe. Opening up the full wavelength region from ~ 0.1–10 microns to sky-limited observations with resolutions 10 to 100 times smaller than that from the ground would have a dramatic impact on galaxy studies in the young universe. Even with adaptive optical systems ground-based telescopes will not be competitive. These galaxies are low surface brightness objects and the structures in them will be swamped by the 10^6 times brighter background in the thermal IR from the ground.

To further demonstrate the power of large space telescopes for investigating galaxies at high redshifts, some simulations have been developed and are shown in Figure 1. They were made by J. E. Gunn for his paper in the NGST workshop in Baltimore[5]. They are of a "typical" spiral galaxy at a redshift $z \sim 1$ as it would appear through the 10 m Keck telescope in Hawaii, through the HST and through the NGST (in this case a 16 m NGST). Galaxies at $z \sim 1$ would be seen when they are about 8 billion years younger, when the universe was between one-third and one-half the age it is today. While the gains with the HST are impressive, those with the NGST are truly astonishing. An 8 m NGST would have gains much closer to the 16 m than to the HST.

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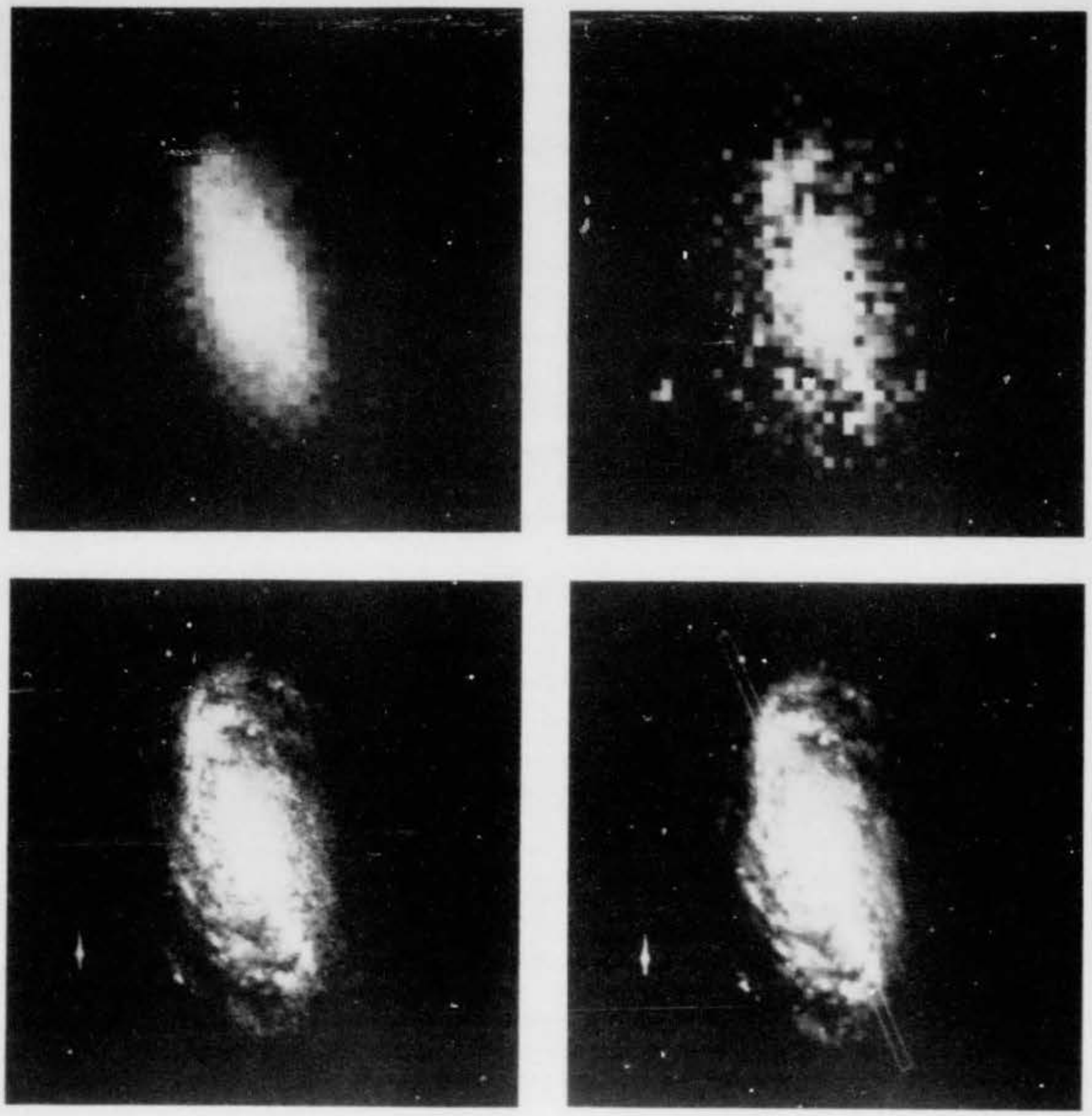


Figure 1. Simulations of the imaging performance of the 10 m Keck telescope, the HST and of a 16 m diffraction-limited telescope for a $z = 1$ Sc spiral using a CCD image of the galaxy at 10 Mpc. (a) Upper left: A two-hour integration with the Keck telescope. The image has high S/N but low resolution. (b) Upper right: A three orbit (approximately 2 hours) exposure with the Wide Field Camera from the HST. The (undersampled) resolution is about 1 kpc. The image has much higher resolution, but lower S/N. (c) Lower left: The 16 m with a 2 hour integration. The imaging performance is spectacular. This is the resolution with which we image *Virgo cluster galaxies from the ground*. Except for noise it is almost indistinguishable from the original CCD image of the 10 Mpc galaxy (from which the simulations were made). (d) Lower right: Finally, a 24 hour integration, with a superimposed spectrograph slit. The slit width is *ten times* the resolution of the telescope. Gunn noted that his original data of this nearby galaxy (taken with a large ground-based telescope) barely has the S/N and resolution needed for this simulated observation with the 16 m. An 8 m NGST would have intermediate performance, but would be much closer to the 16 m than to the HST.

NGST CHARACTERISTICS

Discussions extending back to the early 1980s about the power of large space telescopes have focused on the combination of collecting area and resolution as being the appropriate figure-of-merit for astronomical problems. It was realized in the mid-1980s that cooled systems would make a major improvement in the sensitivity of such a telescope[2,6]. The key characteristics of the NGST observatory and its supporting systems that have developed over the last few years are summarized here:

- 8-16 m diameter filled-aperture telescope with lightweight optics.
- Wide bandwidth system: 0.12 mm to ~10 mm.
- Diffraction limited in visible and IR; high Strehl ratio in UV if technologically feasible. Resolutions of 10-20 milliarcsec (mas) at 0.6 microns.
- Low-scattering, smooth optics for clean, easily apodized point-spread function for extremely high dynamic range.
- Passively cooled to 100 K or less for reduction of background by 10^6 beyond 2 mm.
- Active optics to compensate for thermal and aging effects. Fine pointing by optical element motion in lieu of body pointing.
- High sensitivity. The small PSF (point-spread function) and low backgrounds result in remarkable sensitivity. Can measure >31 mag (V-band) and <25 nJy (3 micron) objects in 10^4 s at 10:1 S/N.
- State-of-art UV-IR imaging and spectroscopic instrumentation with wide field, large format detectors and multiplexed operation.
- Compact optical system (e.g., small baffle for high earth orbit (HEO) operation to lessen constraints on launch vehicle) .
- HEO operation results in savings on size, weight, power, operational complexity plus gains in performance. Preliminary assessment indicates that it is comparable to the HST in weight, thereby breaking away from the HST cost curve.
- Siting and size trade-offs. Discussions regarding siting have noted that a 16 m diameter primary is highly desirable but impractical in orbit. A site on the lunar surface is likely to be the only practical one for such a large facility. It would be near the lunar base for assembly and maintenance.
- Near term 8 m HST successor in HEO. Precedes lunar 16 m.

International participation is a highly desirable goal. Observational data in the UV-visible-IR plays an essential and central role in astrophysics. Thus a unique space observatory in this wavelength region naturally becomes a program for international collaboration. It should receive very widespread scientific support. Furthermore, it has the capability, longevity, and "presence" to be attractive as a truly international scientific venture for the first decade of the new century.

"UV-OPTICAL IN SPACE" PANEL RECOMMENDATIONS

Contemporaneously with NASA's Astrotech 21 planning activities, the Astronomy and Astrophysics Survey Committee (AASC) at the National Academy of Science (NAS) was performing an assessment of future ground- and space-based programs. The AASC, which was chaired by John Bahcall, took recommendations from a number of sub-committees (panels).

The actual program recommended by the *UV-Optical in Space* panel[4] is summarized in the table below. The start date and the launch or completion date is also shown. The projects are grouped by their expected costs, into small, moderate and large programs. A line for technology development was explicitly highlighted, since it is clear that budget and schedule problems can be minimized for projects of any scale by having the demonstrated technologies in place *before* the start of a project.

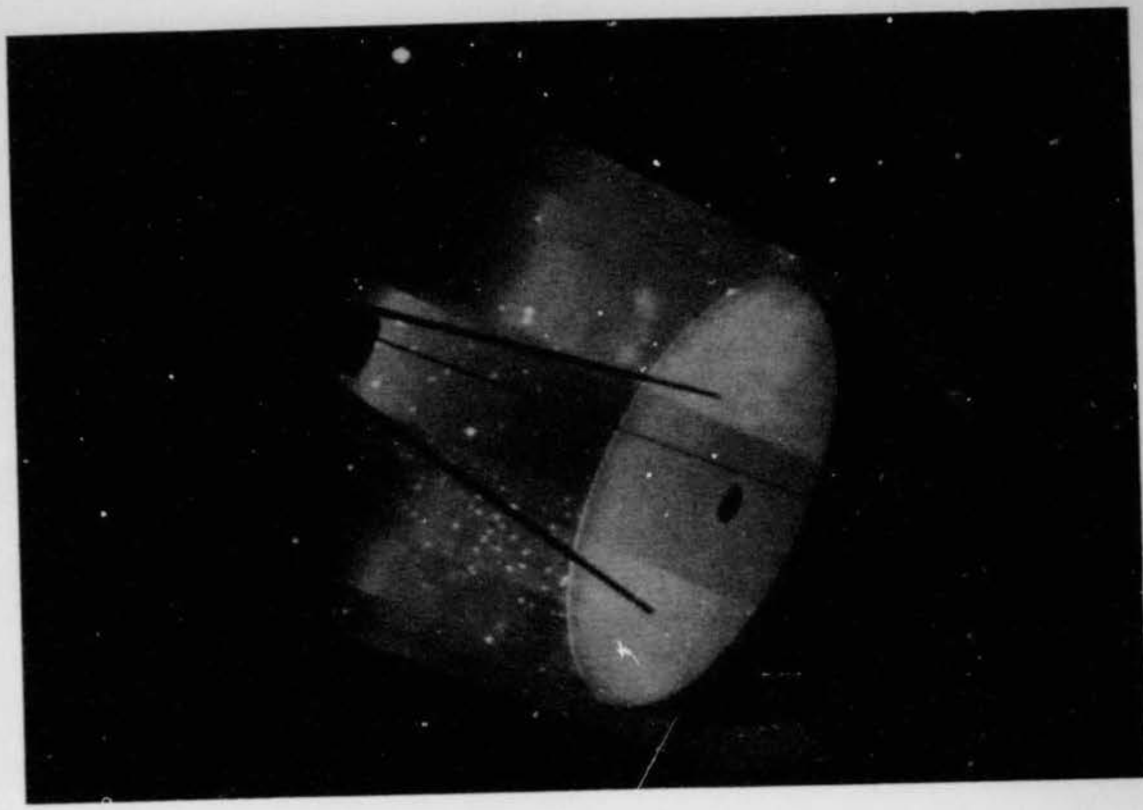
SIZE	PROJECT	Start	Finish
Large:	6 m HST Successor	1998	2009
Moderate:	Explorer Enhancement	1993	2000
Moderate:	HST Third Generation Instruments	1994	2000
Moderate:	Imaging Astrometric Interferometer	1997	2004
Small:	Small Explorer UV Survey	1995	1998
Small:	Space Optics Demonstration	1993	2000
Small:	Supporting Ground-based Capabilities	1993	2000
Technology:	Technologies for Space Telescopes	1993	2000

The Panel took the view that large missions, in particular, require a long-term plan that incorporates appropriate technology developments and demonstrations and precursor missions. They noted that the scientific case was strong for a successor to the HST. The panel then recommended:

- that a successor to the HST be ready to fly within a few years of the end of HST's nominal life;
- that this be a 6 m UV-Visible-IR, passively cooled telescope in HEO;
- and that, in the long-term, there be a 16 m telescope on the lunar surface, sited near the large lunar interferometer.

An artist's view of of NGST for HEO operation is shown in Figure 2a, and a schematic view of such a telescope is shown in Figure 2b. The schematic view is one of the several conceptual models that have been considered for an orbiting NGST. The dimensions are for a 6 m telescope, but could be scaled for 8 m or larger (see the Baltimore NGST workshop[1]). Optical considerations may result in a longer focal length system, but this change has minimal impact on the overall weight. The key features are a short baffle, body-mounted solar panels, radiative cooling, lightweight optics and structures, and the less demanding support system requirements of HEO. Together these lead to a telescope whose weight would be *comparable to that of the HST* (< 1.5x).

a)



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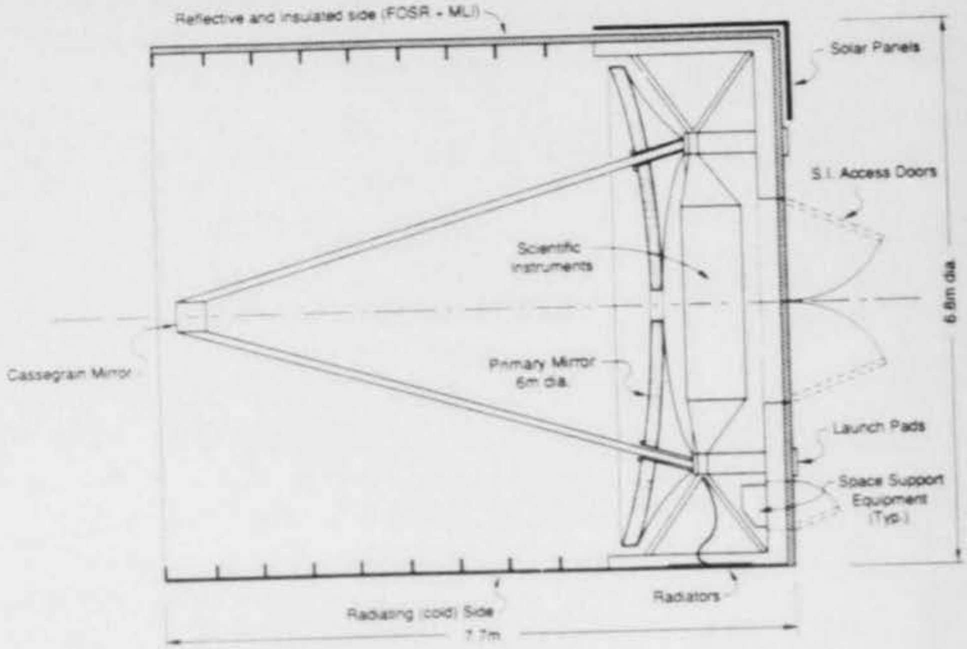

Figure 2. a) An artist's view of the 8 m NGST in HEO.
b) A schematic view of an HEO HGST (6 m - see text).

There will clearly be pacing items for lunar-based telescopes that are unique to such facilities and so it is appropriate to continue evaluations of such questions (e.g., dust control, shielding, precision motion under low-gravity vacuum conditions, optical designs for feeding sub-surface instruments). Broadly, the outstanding technical issues for all these telescopes are optics, pointing and control systems, UV performance in a passively cooledcooled system (the contamination issue), and detector performance under a high background of particle events.

8 M HEO NGST

Given a strategy that has as its immediate goal an 8 m wideband, passively cooled, telescope in HEO, there is clearly a need to begin the definition of the characteristics of the telescope and its supporting instruments. The overall goals are a telescope with diffraction-limited optics in the visible and the IR, and a "high" Strehl ratio in the UV, that covers from 0.12 microns to ~ 10 microns by passively cooling the optical system to <100 K. The PSF would have a core with a FWHM (Full Width at Half Maximum) of about 15 milliarcsec at 0.6 microns that scales directly with wavelength. A few other key characteristics should be noted, since they are crucial for many of the high priority science goals.

- Low scattering optics for high dynamic range, particularly for AGN and QSO studies, for planetary searches, and for star formation studies. This constraint is much tougher than the nominal l/20 for diffraction-limited images. For certain problems, notably the planet search problem, surfaces as smooth as l/1000 may be necessary, though this requirement may only have to be satisfied at 5-10 mm. Both the goal of diffraction limited UV images and the low-scattering optics lead to the challenging requirement of surface errors that are < 5 nm.

- The pointing and control system (PCS) requirements are also demanding. The jitter in the tracking should be at 10% (or less) of the resolution. This translates into ~1 milliarcsec or better. The PCS system will need to be able to acquire and track features on planets and planetary companions. Spectroscopic apertures and slits will need to be located to a fraction of the width of the images, i.e., to < 5 milliarcsec.

- The focal plane field should be large. The ability to multiplex the operation of imagers and spectrographs will prove to be a very valuable feature of the HST that should be retained for NGST. Ultra-deep imaging surveys can then be carried out in parallel with spectroscopic observations.

- The imager fields should be large so as to accumulate efficiently high S/N observations over field sizes of astronomical significance (e.g., high redshift clusters and young embedded star clusters). Fields of 2-3 arcmin in the visible and IR and 0.5-1 arcmin in the UV should be attempted. This will require mosaics of arrays to ensure adequate sampling of the PSF over those fields (> 10^4 X 10^4 pixels in the UV and visible; > 2000 x 2000 in the IR).

- High-throughput spectrographs, with multi-object capability, particularly for very faint resolved/partially resolved objects or structures, are also a crucial component of the system. Wavelength resolutions (l/Dl) from 10^3 to ~ 10^5 will be needed.

- The particle background will be substantially higher in HEO than in low earth orbit (LEO). Detectors with low read noise will need to be combined with onboard processing to minimize the data volume to be transmitted. The small PSF and low backgrounds will result in remarkable sensitivity for point sources. The visible (V-band) background is ~ 31 mag per resolution element, i.e., ~ 4000 times fainter than ground-based observations of unresolved objects, while the 3-4 micron background is 18 mags per resolution element *less than that on the ground,* i.e., ~ ten million times fainter than ground-based observations of unresolved objects. This means that for integrations of 10^4 s, 10:1 S/N can be achieved for 31 mag visible objects and for 25 nJy objects at 3 microns (50x the sensitivity of SIRTF at > 8x the resolution).

While these are challenging goals, they are not out of line with reasonable developments of contemporary technology.

BREAKING AWAY FROM THE HST COST CURVE

The total cost of the HST has been quoted as being in the vicinity of $1.5B to $2B. What is usually not realized is that a very substantial fraction of the cost of the HST has been incurred by the software and hardware for the ground operational system and by the engineering analysis, spare parts inventory, and additional management needed for the Maintenance and Refurbishment (M&R) program. Both of these elements are driven primarily by HST's location in LEO. An additional factor was the lack of maturity of instrumental and spacecraft technology and the lack of experience with such a large, complex spacecraft. While it is not clear what the actual costs are, reasonable estimates place the ground and operational system costs at ~ $400M and comparable amounts for the M&R program. Thus the actual cost of the flight hardware system of the HST is closer to $1B than $2B. This provides a valuable baseline number for discussions related to the cost of the NGST.

Why should the cost of NGST not be proportionally larger by the usual scaling laws? There are several very good reasons why the NGST would lie on a very different cost curve from the HST. An obvious one is that the HST is the first of the UV-Visible Great Observatories, and that it is based on technology that is now nearing 20 years in age. We have learned a lot since the HST was conceived, and technologies in many areas have advanced significantly (e.g., optics, electronics, computers and control systems, and instruments). Such technological advances will make a very significant difference to the construction and operation of the NGST. Another useful guide to cost has been spacecraft weight. A preliminary analysis of the likely weight of an HEO NGST is that it will be *comparable to the HST*. While not obvious at first sight, this result is quite plausible.

The technological developments that lead to substantial weight savings over the HST are many. In addition, substantial efficiencies accrue from operation in HEO. Together they make a dramatic difference. First, new optics polishing and fabrication technologies (e.g., ion polishing, stressed lap polishing) will lead to lighter, higher-performance optics. Second, a simpler structural support for the secondary with active location to compensate for modest thermal and aging variations leads to a lighter and less demanding optical assembly. Third, the fast focal ratio leads to a short structure, and a very short baffle is practical because of the HEO location. Constraining the telescope to point no closer than 90 degrees from the earth and the sun is realistic in HEO. Fourth, the instruments can be comparable to those in the HST, and could well be modest developments from the HST Second and Third Generation systems. Fifth, the power requirements are lower and much less complex because there is no rapid charge-discharge battery cycling. Sixth, more durable and reliable body-mounted solar panels would be used. Seventh, HEO operation plus an active optical element for fine pointing, combined with large area detectors for field acquisition and guiding, would eliminate the three massive Fine Guidance Sensors (FGSs) and greatly simplify the Pointing and Control System. This has been one of the most demanding elements of the HST. Finally, by taking the step to a non-human-rated, non-maintainable observatory (except possibly for robotic replacement of cryogens, if active cooling systems do not reach maturity) considerable further savings can accrue. While we have discussed NGST as being a single all-purpose UV to mid-IR telescope, it has been suggested that it may well be cheaper to design and configure two spacecraft, one for the UV-Visible and the other for the Visible-IR. This is not obviously the case. Technical feasibility studies need to be combined with cost trade-off analyses to establish the most cost-effective and timely route to fruition of the program. The current baseline is to consider NGST as a single HEO telescope.

TECHNOLOGY ISSUES

A major element of the the MSFC studies and the workshops on NGST has been the identification of areas of technological development that are crucial for NGST to accomplish its scientific goals. The workshop in Pasadena organized under the auspices of the Astrotech 21 program had as its objective the generation of a list of such issues that needed to be addressed and resolved as the project progressed. The *Top Ten Issues* that resulted from this meeting (as noted by the author at an early stage in the generation of the working panel reports) were:

- Can a single passively cooled telescope be designed for the ~ 0.1-10 mm wavelength region? Even if it can be, should it be, or should two telescopes be developed, one IR/Visible, the other UV/Visible?

- Where is the breakpoint in size between monoliths and segmented mirrors? While not universal, it was thought practical to have a monolithic mirror at 6 m, and impractical at 10 m and beyond; they would be segmented beyond 10 m. Is 8 m OK for a monolith? Should it be?

- How does one best carry out the conceptual development? This involves interplay between optics and optical technologies, optical design, structures, system dynamics, pointing and control systems, detectors, and instruments. Then, of course, one must develop a methodology for making the inevitable trade-offs among the science goals, cost, technology, and space logistics and infrastructure (including projected launch capability).

- What are the best materials and approaches for fabricating the optics for such passively cooled systems? It is particularly challenging where the surface errors required are below 10 mm; surface errors in the vicinity of 3 mm would be desirable for UV performance and low scattering. What will be the test strategy? Such demanding goals require that we develop a demonstration that the technology and methodology are in hand. A large, smooth, accurate optic needs to be polished and then tested at the operational temperature of 100 K, and iterated until the figure component of the error budget is met.

- Can contamination of the large, cold optical surfaces be controlled such that the UV transmission of the system is not compromised? In effect, is a UV-Visible-IR system practical?

- Can all the required tests during the design/demonstration phase be carried out on the ground, or do tests or demonstrations need to be performed in space? What degree of subsystem and system level testing is appropriate during construction? How can system level tests be carried out on such a spacecraft?

- What is the likelihood of the availability of a launch vehicle (Heavy Lift Vehicle / Advanced Launch System, HLV/ALS) with the appropriately sized shrouds? The current concept for HLV and the upgraded Upper Stage has the required sizing and capacity (more below). Is servicing desirable? What are the cost, risk trade-offs? Will the technology be available in HEO? Should it? What are the prospects for robotic systems?

- Can the required pointing, tracking and slewing capabilities be developed for a system with such demanding requirements. The structure, the PCS, and any drive sources and cooling systems will have to be such as to limit tracking jitter to less than 1 mas. Such a stringent limit is required if the 10 mas diffraction-limited images of an 8 m NGST are not to be compromised. This may require an active optical element (e.g., the secondary) instead of body pointing. A simpler acquisition and guide system is required. Would array detectors with onboard processing to measure image centroids suffice? Such a system would save substantially on the weight and complexity compared to the HST FGSs.

- Will the appropriate management, oversight and review structures be in place? A repeat of HST's problems would not be desirable.

- The radiation environment in HEO is significantly worse than that in LEO. How can high QE detectors be operated in such environments so as to minimize any effects on the data? Can onboard processors be adequately rad-hardened for reliable operation?

To this list it would be very reasonable to add a few more specific areas which were not directly identified during the workshop, but which are necessary to carry out the scientific program. These are:

- Use of active optical and possibly structural components to correct for figure errors and for pointing control. This requires a sensing system for wavefront errors and control of the optical surfaces at low spatial frequencies. The primary mirror would then have actuators for active control of its figure. The system also would require active control of the location of optical elements (e.g., secondary) for compensation and for fine pointing.

- Attention will need to be paid to minimizing the mechanical noise in the system. If an active cooling system is to be used for the IR detectors, it must have very low levels of mechanical noise. The PCS system will clearly need low "noise" components.

- The instruments and detectors also pose a challenge. The overall throughput must remain high and be combined with low read noise and onboard processing to ensure adequate removal of particle events. This may even involve close arrays for coincidence detection. The detectors will need to be mosaics of individual units to get the areal coverage required.

LAUNCH CAPABILITY

The current state of launch vehicles is in flux. A new generation of large capacity launch vehicles is being discussed and design decisions are being made. This is a joint Air Force/NASA ELV (expendable launch vehicle) program, which has variously been known as the ALS (Advanced Launch System) or the HLV (Heavy Lift Vehicle) program. Conceptually it is a modular system with a wide range of carrying capacities - to >100K kg in LEO. In addition to its large lift capacity, a design goal is to ensure low cost access to space, a goal that could not be accomplished with the human-rated, very capable, but necessarily complex Shuttle system. The projected cost per pound is low, varying from \$600/lb for the 50K kg model to \$300/lb for the largest model (one tenth that of Shuttle which is \$2K-\$5K/lb). One assessment[7] of the HLV program noted that the large HLV with an upgraded Centaur upper stage was projected to have 12-28K kg lift capability to HEO with an envelope of 13-24 m length by 10-13 m diameter. Such an envelope and weight range is more than adequate for the NGST.

To be more specific, for an 8 m NGST we will need to put a 9.5 m diameter, 15-20 m long envelope with mass ~14-18K kg (1.2-1.5x HST) into 100K km HEO. It is interesting to note that the USSR Energia has such capability, with the possible exception of an adequate upper stage. The discussions and the NASA projections shown at the Baltimore NGST workshop led to a consensus that the required launch capability would likely be available for large telescopes in the 2000-2010 time frame. No guarantees can be made for such projections, but the recent Augustine Committee Report[8] emphasis on new HLV capability adds to the likelihood of such capability being available. I think that it is appropriate to take the view, as was noted in the presentation regarding launch vehicles at the Baltimore NGST workshop, that "space telescope planning should not be constrained to current launch vehicles." However, it is clear that the NGST constraints do need to be input to plans for HLV.

MANAGEMENT ISSUES

With the realization that the spherical aberration problem on the HST was not one that derived from limitations of technology, but one that resulted from limitations in management, review and oversight[9], it would be remiss of any discussion of a major program to ignore the challenges of managing such projects. This challenge must be faced squarely, and must be given the same level of attention as that required for the technological developments. Management issues are at least as demanding as the technical challenges. Problems and mistakes are to be expected in projects of such scale. The process must have mechanisms that allow for the early identification and rapid correction of such occurrences. A crucial element of the successful management of such a project is ensuring that project managers, engineers and scientists of the highest caliber and experience are involved in the program and that their involvement is a long-term commitment. In addition, it must involve fully the end users of the mission in the process. That is, it must involve the scientific and engineering resources of the scientific community. The lessons from the HST should not be neglected as we move ahead with large projects like NGST.

This is a complex subject, but a key step should be the early formation of a standing science-engineering working group (SEWG) from the broad space science community. This group should comprise a core of scientists and engineers who meet for frequent insight into and analysis of technical and management issues. The SEWG should be fully involved in reviews and any cost-performance trade-offs. An essential element of the success of this group in carrying out its role will be the technical support that is available to it for analyses. The SEWG input and the issues that it raises should have solid technical underpinnings. This will require that the SEWG has a technical support team that broadens the expertise base of the SEWG and interfaces with the NASA and industry groups.

The SEWG should develop a close working relationship with the project manager. Ideally this should be a supportive relationship built upon mutual respect. The project manager and his or her team should have a long-term commitment to the program, with a clear understanding that they would be appropriately rewarded for their commitment. Within the project itself there should be clear lines of authority and responsibility. Unlike previous programs, there should not be any parallel division of authority between organizations. In addition to the SEWG and the Project structure, the designated science center should be implemented early and be fully involved with technical support for continuing analyses.

The analyses and studies that are performed must extend through to system-level analyses, simulations and tests, with appropriate degrees of redundant tests. It would be extremely valuable to analyze systematically and objectively the HST experience, to use that as a learning tool, and to incorporate the experience of other large successful programs, *including some of comparable scale done within other agencies and non-government supported industrial projects*. Successful high-technology projects done within DOE, DOD and, for example, Boeing could well be utilized as a source of further experience for project management. A means of coupling those directly involved in such programs in some structured way (a small workshop or retreat?) that allows open exchange of ideas and experience would be valuable for all.

The ability to successfully carry out a large space science program is governed in part by the degree of confidence that resides within the political environment that all the elements, science, technology, and management will come together to bring about the program's successful conclusion. The Challenger and the HST will dog us all through the difficult job of making a convincing case for such major projects in the future. We may find it impractical to obtain the funding for those key projects that are at the heart of astronomy if we fail again.

ACKNOWLEDGEMENTS

The author greatly appreciates the encouragement and support of a wide community of scientists and engineers for the NGST concept. Their excitement and enthusiasm for the possibilities offered by large space telescopes has greatly helped the project. The supporting studies and the workshops have resulted in a broad range of valuable inputs on the vast range of scientific, technical and managerial aspects of such a program. I am grateful for the financial support of NASA for NGST study activities. While I am always concerned about overlooking a key contributor when listing names, I particularly appreciate the support given by R. Angel, P. Bely, J. Burns, C. Burrows, J. Cutts, B. Davis, J. Fordyce, R. Giacconi, D. Jones, M. Kaplan, M. Nein, R. Stachnik, P. Stockman, D. Tenerelli, R. Thompson, E. Weiler, and B. Woodgate.

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I. CHRONOLOGICAL SUMMARY OF INVITED WORKSHOP PRESENTATIONS AND SELECTED DISCUSSIONS AND QUESTIONS

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WORKSHOP PROCEEDINGS: TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

INTRODUCTION

GARTH ILLINGWORTH, LICK OBSERVATORY

G. ILLINGWORTH: In September 1989 in Baltimore we had our last meeting about what we have come to call the next generation space telescope, the NGST. This is a generic term for future large broadband (UV/optical/IR) telescopes in space. And we've talked about orbiting telescopes and telescopes on the Moon as I'll discuss in a little more detail and you'll see much more of that later this morning.

Now at the time when we held the NGST meeting, we talked about a 10 meter telescope in high earth orbit and a 16 meter on the Moon. We were very ambitious and, of course, that's the right way to be at an early stage in a project. Nobody is ever going to suggest that you increase the scope as you go along in a project. And so, you want to look at the scientific goals and look and see what sort of program, what sort of projects will allow you to carry out those goals. And then, get a feel for the scale of what you need and look at the technologies and iterate to some final solution which, of course, we're not at yet.

The discussion was very broad ranging. One of the things that I think was very clear at the meeting was how incredibly powerful these sorts of telescopes are scientifically.

Now the second activity which was occurring in this timescale was the Bahcall Committee, the Astronomy and Astrophysics Survey Committee - astronomy in the 1990's basically. Every decade astronomers get together and sit down and try and prioritize programs for missions in the next decade. The UV Optical and Space Panel of the Bahcall Committee clearly was involved in thinking about a variety of missions and programs, but in particular one aspect of that was discussions about large space telescopes. As you can imagine, this led to a lot of lively discussion. Discussion of large telescopes compared to smaller missions is an ongoing debate in the science community these days. The panel report itself doesn't come out until next month and I'm not going to go into details but I can certainly give you a general flavor of what some of the discussion was like. It was clear that there was very great concern about the length of time it would take to put large missions together these days, and HST is an example of that. You're looking at certainly more than a decade, two decades typically for these sort of programs.

I'll touch briefly on the actual title of my talk, which was the goals of the workshop, and as I mentioned Jim Cutts will deal with these in much more detail later this afternoon. It was clear at the workshop in Baltimore a year and a half ago that we needed a workshop where we would focus in on the required technologies and the demonstrations that need to be done to verify that the technology is in hand. We need to prioritize those technologies, look at the most crucial areas and also look at those that may be generic to both lunar based and orbiting telescopes.

(Presentation material from G. Illingworth follows)

8 m UV-VISIBLE-LR LARGE SPACE TELESCOPE (NGST)

Characteristics

- 8 m diameter filled-aperture with lightweight optics.
- Diffraction-limited in visible and IR; in UV if technologically feasible.
- Resolutions from 8 mas at 0.25 μm, to 20 mas at 0.6 μm and 100 mas at 3 μm.
- Low-scattering smooth optics for high Strehl ratio in UV.
- Clean, easily apodized point-spread function for extremely high dynamic range.
- Active optics to compensate for thermal and aging effects.
- Wide bandwidth system: 0.12μm to ~ 10μm.
- Passively cooled to 100 K or less for reduction of background by 10^6 in IR beyond 3 μm.
- Compact, fast optical system with small baffle for HEO operation.
- High sensitivity - can measure 31 mag (V-band) and 25 nJy (3 μm) objects in 10^4 s at 10:1 S/N.
- State-of-art UV-IR imaging and spectroscopic instrumentation with wide field, large format detectors and multiplexed operation.
- High Earth Orbit (HEO) operation - savings on size, weight, power, operational complexity plus gains in performance - comparable to HST in weight - breaks away from HST cost curve.
- International participation highly desirable.

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NGST SCIENTIFIC GOALS

The high sensitivity across the UV-IR (and particularly in the IR) gives remarkable imaging and spectroscopic performance at resolutions ranging from 8 mas in the UV to 100 mas in the zodiacal "window" at 3 μm.

- Study of star-forming complexes with resolutions of ~ 20 AU in the nearest star-forming complexes and 40 AU at Orion at 3 μm (3 and 6 AU at 0.5 μm, respectively) - structure and dynamics of protostellar disks (25 spatial resolution elements across a 1000 AU disk in Orion) - background per resolution element is ~ 10-7 (18 mags fainter) that from ground.

- Stellar populations: S/N=10 in 10^4 s in visible at 31 mag; Initial Mass Function to +18 in nearest globular clusters, +12 in outer clusters and LMC/SMC, below main sequence turnoff to +7 in M31, M32, M33.

- Structure and evolution of (forming?) galaxies at redshifts $z > 1$; with 20 mas resolution galaxies can be studied *at any redshift* z at the resolution that is < 2x worse than that seen for Virgo galaxies from the ground (~ 150 pc).

- Study of high-redshift objects in the zodiacal background "window"; ~ 1 kpc resolution at any redshift matches characteristic scales of structure (0.2 - 5 kpc) in galaxies (bulge and disk length scales, star forming regions, spiral arms, merger "arms and tails").

- Detection and spectroscopic measurements of giant planets around the nearest stars using apodizing/interferometric systems to maximize contrast against the stellar light and the zodical background.

- AGNs and QSOs - high dynamic range imaging and spectroscopy of narrow line region - resolution of < 10^{20} cm at 3C273; 4 x 10^{18} at NGC 4151.

- High spectral resolution UV studies of absorption-line systems in a large sample of low redshift QSOs.

- Differential galaxy counts from $z \sim 0.3$ to ~ > 3 using Lyman break in spectral energy distribution - series of low-pass filters to define redshift limit.

- Evaluating mass (dark matter?) distributions in galaxies and clusters (and elsewhere?) from structure and distribution of gravitionally lensed objects.

- Galactic nuclei: resolves < 1 pc at Virgo, spectroscopy in inner narrow line region in IR, complements interferometers for regions of complex structure when full U-V plane coverage not available.

- ISM - the evolution of the ISM with redshift; enhanced UV sensitivity for high spectral resolution studies - size, physical state, composition.

- Imaging and spectroscopic studies of planets- resolves 40 km on Io at 0.4 μm.

- Stellar astrophysics: wide UV-IR bandwidth, high temporal resolution studies, very faint limiting magnitude (~ 31), high spatial resolution for crowded fields.

- Distances: parallaxes to > 5 kpc, distances to Local Group galaxies (M31) from proper motions of objects in circular orbits, astrometry with 100 marcsec centroids for objects fainter than 25 mag. Distances over large volumes from extended "classical" tests (cepheids, Fisher-Tully, etc.) plus new techniques (surface brightness fluctuations, planetaries, etc.) for mapping galaxy distribution in 3-D.

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NGST PERFORMANCE GOALS

- Large Space Telescope: Nominal 8 m passively cooled, diffraction-limited, wideband, High-Earth Orbit (HEO) telescope.

- Bandwidth: 0.12 μm to ~ 10μm.

- Diffraction-limited: 8 milliarcsec (mas) at 0.25 μm; 20 mas at 0.6 μm; 100 mas at 3 μm.

- Low scattering optics for high dynamic range, particularly for AGN and QSO studies, and for planetary searches.

- Passively cooled: ~ 100 K; IR background < 10^{-2} that of ground at 1-2 μm, and ~ 10^{-6} at 3-5 μm in the dark window between zodiacal scattering and emission.

- High sensitivity: Visible background 31 mag per resolution element, i.e., ~ 4 x 10^3x fainter than ground-based observations of unresolved objects; 3-4 μm background is 18 mags per resolution element *less than that on the ground,* i.e., ~ 10^7x fainter than ground-based observations of unresolved objects.

- For integrations of 10^4 s, 10:1 S/N to be achieved for 30 mag visible objects and for 25 nJy objects at 3 μm (50x the sensitivity of SIRTF at > 8x the resolution).

- Wide-field: Large focal plane field; Individual instruments- ~ 2-3 arcmin in Visible and IR; ~ 0.5-1 arcmin in UV; allows imaging (and multi-object spectroscopy?) of large groups/small clusters at high redshift, embedded star clusters in young clouds throughout the galaxy, etc.

- Detectors: wide-field and high-resolution require detector arrays of > 10^4 x 10^4 pixels in UV and Visible, > $2x10^3$ x $2x10^3$ in IR.

- High-throughput spectrographs, with multi-object capability (MOS), particularly for very faint resolved/partially resolved objects or structures; wavelength resolutions from 10^3 to ~ 10^5.

- Multiplexed operation of imagers and spectrographs for, e.g., ultra-deep surveys.

- Acquisition and tracking of features on planets and planetary companions.

- Stable tracking to 10% of resolution, i.e., ~ 1 mas. Pointing to 10-20 mas.

AREAS OF TECHNOLOGY EMPHASIS FOR NGST

- Manufacture of large, lightweight optics, with the goal of diffraction-limited performance at ~ 0.2 µm.
- Low-scattering optical surfaces for high dynamic range observations (e.g., planet detection, AGNs, QSOs).
- Active sensing of wavefront errors and control of the optical surfaces at low spatial frequencies.
- Passive cooling of the optics and structure to 100 K.
- Fabrication and test procedures for optics to be operated at low temperatures.
- Active control of the location of optical elements (e.g., secondary) for compensation and for fine pointing.
- System level testing of the telescope on the ground.
- Low mechanical noise, active cooling systems for IR detectors and instruments.
- Low vibration, "quiet" environment to ensure image quality.
- Low "noise" pointing and control (PCS) systems.
- Simplified PCS systems using imaging arrays and onboard processing.
- Tracking to ~ 1 mas; pointing to 10 mas; active control of focal plane metrology.
- High throughput optical systems for instruments.
- Detector mosaics with > 10^4 x 10^4 px in the UV and Visible, > $2x10^3$ x $2x10^3$ px in the IR.
- Detectors with cosmic ray discrimination .

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ASTROTECH 21 SUMMARY

8 m HEO UV-Visible-IR Telescope

Program Summary: The Next Generation successor to HST would be a 8 m passively cooled, diffraction-limited, wide-band, filled-aperture telescope operated in High Earth Orbit (HEO). The telescope would have a fast, lightweight, primary and be passively cooled to ~100 K for outstanding sensitivity in the IR.

Science Objectives: The 8 m telescope would combine remarkable imaging performance, with resolutions ranging from ~ 8 milliarcsec in the UV to some 100 mas in the dark zodiacal "window" at 3 μm, with even greater capability for spectroscopic observations of faint and/or low surface brightness objects at the highest spatial resolution. It would have unprecedented power for tackling a wide range of the most fundamental astrophysical problems, ranging from the detection of planets, to star and planetary system formation, to the structure and evolution of the ISM/IGM, and to the structure of (forming?) galaxies at redshifts $z \gg 1$.

Instrument Description:

- Filled-aperture, passively cooled UV-IR telescope.
- 8 m diameter primary.
- Low-scattering, diffraction-limited optics.
- Detector cooling requirements from ~ 4 K to ~ 270 K.

Performance Goals:

- Bandwidth: 0.1 μm to ≅10 μm.
- Diffraction-limited: 8 milliarcsec (mas) at 0.25 μm; 20 mas at 0.6 μm; 100 mas at 3 μm.
- Low-scattering optics for high dynamic range, particularly for UV imaging and for planet searches at 10 μm.
- High sensitivity: Visible background 31 mag per resolution element;
- Passively cooled: 100 K or less;
- Wide-field: > 2 arcmin in Visible and IR; > 30 arcsec in UV;
- Stable tracking to 10% of resolution, i.e., <1 mas, and pointing to 10 mas.
- Acquisition and tracking of features on planets and planetary companions.

Pacing Technologies:

- Manufacture of large optics, with the goal of diffraction-limited performance at 0.2 μm.
- Lightweight optics with precision support and control systems.
- Active sensing of wavefront errors and control of the optical surfaces at low spatial frequencies.
- Active control of the location of optical elements (e.g., secondary) for compensation and for fine pointing.
- Passive cooling of the optics and structure to 100 K, or less.
- Active cooling systems for instruments.
- Tracking to < 1 mas; pointing to 10 mas - calibratable focal plane metrology.
- Detector mosaics with > $10^4 \times 10^4$ px in the UV and Visible, > $2\times10^3 \times 2\times10^3$ px in the IR.
- Detectors with cosmic ray discrimination.

Mission Description:

- High Earth Orbit - ~ 10^5 km to minimize detector background.
- New-start date: TBD
- Launch date: Post HST.
- Launch vehicle: Shuttle-C; ALS.
- Launch mass: modular - total 30,000-40,000 kg.
- Duration and servicing: >20 years, with instrument upgrades and servicing every 5-8 years.
- Estimated cost: TBD but >$2 billion.

Spacecraft Systems:

- Total power requirements: 5-10 kW.
- Power source: solar panels around body of telescope sunshield.
- Thermal Control: passive (radiation).
- Propulsion requirements: pointing and tracking.
- Data bandwidth nominally 10 MHz.

Needed Support Technologies:

- System level testing of very complex telescope prior to launch.
- Fabrication and test procedures for optics to be operated at low temperatures.
- Low vibration, "quiet" environment to ensure image quality.
- Heavy-lift launch and transfer vehicles.

Program Status: This telescope was endorsed in the 1988 study *Space Science in the Twenty-First Century: Imperatives for the Decades 1995-2015* by the National Academies of Science, of Engineering and of the Institute of Medicine. It is one of the two long-term programs highlighted in the 1989/90 UVR MOWG (Management Operations Working Group) Strategy Report, and was the subject of the *The Next Generation: A 10-16 m UV-Visible-IR Space Telescope* workshop held in Baltimore in 1989. Initial discussions have highlighted the power of this telescope for a wide range of fundamental astrophysical problems and have shown some early design concepts. In conjunction with the Astronomy and Astrophysics Survey Committee for the 1990s (the "Bahcall" report), critical technologies are being identified for a technology development program.

References: See the proceedings of the workshop *The Next Generation: A 10-16 m UV-Visible-IR Space Telescope*, and the "UV-Optical in Space" Panel report of the *Astronomy and Astrophysics Survey Committee* "Astronomy in the 1990s" (the "Bahcall" committee) – available late March 1991.

Information provided by: Garth Illingworth, UCO/Lick Observatory, University of California, Santa Cruz, CA 95064; (408) 459-2843; (Fax) - (408) 426 3115.

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WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

ASTROTECH 21 GOALS

JIM CUTTS

JET PROPULSON LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California

March 4, 1991

J. CUTTS: I would like to welcome you to the Astrotech 21 workshop on Technologies for Large Filled-Aperture Telescopes in Space. My name is Jim Cutts and I am the the manager of the Advanced Instruments Program Office at Jet Propulsion Laboratory (JPL) which is responsible to NASA for performing the Astrotech 21 study.

In Spring of 1989, the Astrophysics Division (Code SZ) at NASA headquarters initiated the planning of a technology development program called Astrotech 21 to develop the technology base for the Astrophysics missions developed in the period 1995 to 2025. The impetus for this came from the director of Code SZ, Dr. Pellerin, who recognized that new technology would be needed to sustain the momentum of exploration begun with the Great Observatories. The Jet Propulsion Laboratory was tasked by the Astrophysics Division to lead the planning of Astrotech 21 for the agency. I led the Astrotech 21 study at its inception; however, we have recently assigned Jess Fordyce to take over the leadership of the study. He is being supported by Juan Ayon and Dayton Jones. Jess reports to Mike Kaplan, Chief of Advanced Programs in Code SZ. The Astrotech 21 program is being defined in cooperation with the Space Directorate (Code RS) of the the Office of Aeronautics, Exploration, and Technology (OAET), which will play a major role in Astrotech 21 implementation.

Astrotech 21 Study Organization

I would like to say a few words about how the Astrotech 21 study has been structured. First, we recognized that to formulate a viable technology plan it had to be a focused plan. The agency does not have the resources to spread funds in a multiplicity of directions. To provide this focus we needed to develop a much clearer picture of needs and opportunities for using new technology. We needed to update ideas on science opportunities and priorities and in particular to identify emerging observational techniques with the potential for orders of magnitude improvements in resolution or sensitivity. We also needed to take a look at specific mission conceptions designed to realize some of these scientific objectives and exploit new techniques because it is often only when you attempt to design something, that the real problems emerge. Equally important was to expose our study team to new technology developments with a potential importance in space astrophysics. Finally, we needed to perform a synthesis of technology needs and opportunities into a coherent technology plan. Our scheme for accomplishing all this is illustrated in the viewgraph showing the Astrotech 21 Planning Process.

Three JPL people are leading different parts of the study: Dayton Jones is handling the definition of Science Objectives and Observational Techniques, Jess Fordyce is handling Mission/System

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Studies and Technology Requirements, and Juan Ayon is covering Integrated Technology Planning. Jess Fordyce, as I mentioned earlier, is also now responsible for the entire study.

The Astrotech 21 study is being implemented through a series of workshops involving scientists, engineers, and managers for NASA, universities, industry, and other government laboratories. Several hundred individuals have been involved so far and the findings and recommendations are being documented in a series of reports and proceedings, as will this one. The viewgraphs illustrate some of the workshops that we have held and provide some detail on the content of the three Integrated Technology Workshops on Informations Systems, Sensor Systems, and Optical Systems which represent the final output of the Astrotech 21 plan in these three technology areas.

Originally, we expected the scope of the study to be limited to Earth-orbiting missions. However, following the President's announcement in July 1989, the Astrotech 21 work was focused on Space Exploration Initiative (SEI) observatory concepts in support of the 90 day study. Although this work is now complete, it has resulted in a widening of the scope of missions to be supported by Astrotech 21. Study efforts purely on lunar missions for that period of time ultimately widened the scope of missions considered to include the Moon. In the latest "New Century Astronomy Program" candidate mission set (viewgraph), only one lunar mission, the Lunar Transit Telescope, is obvious. However, several missions including the Next Generation Space Telescope that we are discussing at this meeting are now considered to have lunar deployment as an option.

A few remarks are in order concerning the timing of this particular meeting. Originally, we had hoped that the workshops would take place sequentially beginning with Science and Techniques, proceeding to Missions and Technology Requirements and culminating in Integrated Technology Planning. Accordingly, we had hoped that this meeting on the Next Generation Space Telescope would take place sometime last year midway through the sequence of Mission workshops. This did not work out for two reasons. First, a conference on the Next Generation Space Telescope had already taken place in Baltimore, Maryland, in September 1989 and it was far too early to undertake such a similar meeting before the Baltimore proceedings (Ref. 1) were published. Second, the activities of the Bahcall committee, which Garth Illingworth was heavily involved in as chair of the UV/Optical panel, were in full swing and we were compelled to delay the meeting until now. It now has a dual identity: as a logical follow up to the Baltimore workshop, which was held outside the Astrotech 21 planning framework and as a key element the Mission/Systems and Technology Requirements element of our Astrotech 21 planning process.

So what were the consequences of the delay in the meeting. First and foremost, we have already conducted two Integrated Technology Planning workshops to finalize technology requirements in Information and Sensor Systems whereas we would have liked to have held them after this meeting. The Information Systems workshop was held last year and its proceedings are about to be published. The Sensor Systems Workshop was only held last month and when we held our 1-day planning meeting for this Large Filled-Aperture workshop in December, the Sensor Systems workshop organizers were invited and we were able to ensure that the NGST needs were reflected to some degree in its recommendations.

Fortunately, we were able to defer the Optical Systems Technology until after this meeting. In fact it takes place right after the meeting, back-to-back with it, and many of you here will be participating in both sessions. Bear in mind as you participate in this workshop that we will want to carry a cogent set of recommendations forward to the meeting later in the week.

Structure of this Workshop

As I mentioned, Garth Illingworth and a number of the other members of the organizing committee met (in Columbia, Maryland) in December to lay out a suitable format for this meeting. Let me now describe the format and the topics we will be covering.

We begin with Jess Fordyce and a description of a document that the Astrotech 21 study team has put together which projects the space infrastructure that will exist in the time period of interest. For example, it includes an assessment of the likely launch vehicle capability which will determine how large an NGST can be launched.

Next, we have a briefing from Peter Stockman on the status of the HST. Actually, we have asked Peter to go a little beyond this and cover some of the lessons learned from the HST which will guide some of our discussion in the next 2 days.

A session follows with several papers on mission concepts. Pierre Bely of STScI will discuss some of the trades between orbiting telescopes with monolithic and segmented primaries and will examine a specific design concept for a 6 meter monolithic mirror in high Earth orbit. Then we will hear from Billy Davis of MSFC, who will discuss a segmented concept for high Earth orbit. Max Nein of MSFC will go on to discuss segmented telescopes on the lunar surface which have been examined in some detail as part of MSFC's SEI activities. The last paper in this session is from Dave Meier of JPL, who describes Partially Filled-Aperture Telescopes for Earth orbital deployment. This class of telescope was actually covered in two Astrotech workshops on Space Interferometry (Refs. 2 and 3) held last year. Although it is a little outside the scope of this workshop, we thought that this concept, which lies somewhere between a filled-aperture telescope and an interferometer, would be an interesting reference point. It also represents a class of deployable telescope which provides very large aperture but can be launched with existing launch vehicles.

The next session deals with optics technology. Jerry Nelson will describe the segmented optics used on the Keck 10 meter telescope; Roger Angel of Steward Observatory will cover stressed lap polishing for very large rigid monolithic mirrors for ground-based telescope; and R. Wilson of the European Southern Observatory will describe lightweight active monolithic mirrors used in the New Technology Telescope. Jerry Zimmerman of Itek will conclude this section with a discussion of low mass mirrors for space telescopes.

From there we continue with three papers on structures and control systems. Bob Laskin of JPL will describe NASA's Control Structures Interaction Program, Mike Krim of HDOS will discuss the problems of controlling large segmented space systems, and Gary Beals of Lockheed will discuss the design of the Pointing and Control System for the HST.

The discussion on Detectors and Instruments begins with a report from Barbara Wilson of JPL who chaired last month's Astrotech 21 Sensor Technology workshop. This will be followed by Bruce Woodgate of GSFC on CCDs and photoemissive detectors specifically emphasizing the needs of the NGST. Craig McCreight of ARC will conclude this session with a discussion of the infrared technology status and his assessment of NGST IR detector needs.

At that point, we will divide up into Working Groups and you will be meeting with your Chairpersons in the designated rooms. There are six working groups or panels. I will be providing detailed guidelines to the panels just before we break. We will resume with a final plenary session on Wednesday morning when each panel chair will report his panel's finding. The meeting will conclude with a wide ranging panel discussion.

References

1. P.-Y. Bely, C.J. Burrows, and G. Illingworth (eds.), *The Next Generation Space Telescope* , Space Telescope Science Institute, Baltimore, Maryland, 1990.

2. M. Shao, S. Kulkarni, and D. Jones (eds.), *Science Objectives and Architecure for Optical Inferometry in Space* , Astrotech 21 Workshop Proceedings, Series I, JPL Internal Document D-8540, Vol. 1, Jet Propulsion Laboratory, Pasadena, California, May 15, 1991.

3. Stephen P. Synnott, M. Shao, and D. Jones, (eds.), *Technology for Optical Inferometry in Space*, Astrotech 21 Workshop Proceedings, Series II, JPL Internal Document D-8541, Vol. 1, Jet Propulsion Laboratory, Pasadena, California, September 15, 1991.

(Presentation material follows)

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ASTROTECH 21
OBJECTIVES & RATIONALE

- THE PRIMARY THRUST OF THE ASTROTECH 21 PROGRAM IS TO DEVELOP THE TECHNOLOGICAL BASE FOR THE ASTROPHYSICS MISSIONS FOR THE PERIOD 1995-2015
- NEW TECHNOLOGY IS VIEWED AS VITAL FOR ACHIEVING THE ADVANCES IN OBSERVATION CAPABILITY THAT ARE NEEDED FOR CONTINUING SCIENTIFIC PROGRESS

JPL

ASTROTECH 21
ORGANIZATIONAL ROLES

- ASTROTECH 21 IS BEING PLANNED BY
  - OFFICE OF SPACE SCIENCE AND APPLICATIONS (OSSA) ASTROPHYSICS DIVISION (CODE SZ)
  - OFFICE OF AERONAUTICS, EXPLORATION AND TECHNOLOGY (OAET)
- THE TECHNOLOGY AND ADVANCED DEVELOPMENT PROGRAM WILL BE IMPLEMENTED JOINTLY BY THE PARTICIPATING ORGANIZATIONS
- JPL IS ASSISTING THE AGENCY IN PLANNING ASTROTECH 21

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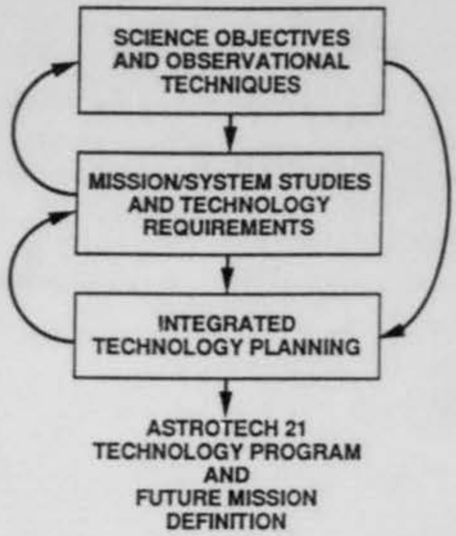
ASTROTECH 21
PLANNING PROCESS



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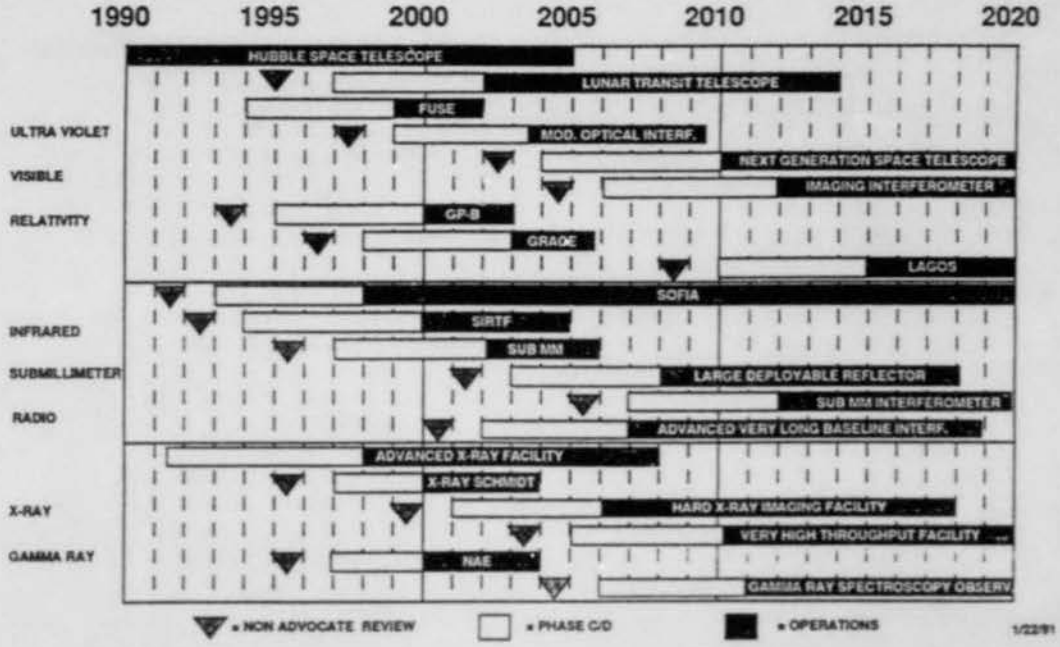
NEXT CENTURY ASTROPHYSICS PROGRAM: CANDIDATE MAJOR AND MODERATE MISSIONS: 1995 - 2020 (FOR TECHNOLOGY PLANNING PURPOSES)



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ASTROTECH 21

MISSION/SYSTEM STUDIES AND TECHNOLOGY REQUIREMENTS

INTERFEROMETRY MISSIONS

TECHNOLOGIES FOR OPTICAL INTERFEROMETRY IN SPACE
CHAIR, S. SYNNOTT (314)
APRIL 30 – MAY 2, 1990

TECHNOLOGIES FOR SUBMILLIMETER ASTRONOMY FROM SPACE
CHAIR, COLIN MASSON (SAO)
DECEMBER 10-11, 1990

ADVANCED SPACE VLBI TECHNOLOGY
CHAIR, DAVID H. ROBERTS (BRANDEIS UNIVERSITY)
COCHAIR, GERRY LEVY (310)
12-13 FEBRUARY 1991

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ASTROTECH 21

MISSION/SYSTEM STUDIES AND TECHNOLOGY REQUIREMENTS (CONT.)

HIGH THROUGHPUT MISSIONS

LARGE FILLED APERTURE TELESCOPE IN SPACE
CHAIR, GARTH ILLINGWORTH (UC SANTA CRUZ)
MARCH 4-5, 1991

TECHNOLOGIES FOR FUTURE SUBMILLIMETER MISSIONS
LEAD, TOM FRASCHETTI (383)
INTERNAL STUDY

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ASTROTECH 21
MISSION/SYSTEM STUDIES AND TECHNOLOGY REQUIREMENTS (CONT.)

GRAVITATIONAL WAVES

TECHNOLOGIES FOR LASER GRAVITATIONAL WAVE OBSERVATION IN SPACE
CHAIR, RON HELLINGS (314)
APRIL 19-20, 1990

MILLIMETER WAVE INTERFEROMETRIC GRAVITY WAVE OBSERVATORY
LEAD, JESS FORDYCE (312)
INTERNAL STUDY

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ASTROTECH 21 INTEGRATED TECHNOLOGY PLANNING
INFORMATION SYSTEMS

WORKSHOP CHAIR

ED NG (366)

PANEL CHAIRS AND COCHAIRS

- MISSION PLANNING AND OPERATIONS
  - HERMAN MARSHALL (UC BERKELEY)
  - DAVE LAVERY (NASA HEADQUARTERS)
- SPACEBORNE DATA SYSTEMS
  - MIKE HENRY (JPL, 348)
  - GEORGE RICKER (MIT)
- SPACE-TO-GROUND COMMUNICATIONS
  - ROBERT BROWN (NRAO)
  - ROBERT ROMANOFSKY (NASA HEADQUARTERS)
- SCIENCE DATA SYSTEMS
  - MILT HALEM (GSFC)
  - ETHAN SCHREIR (STScI)
- DATA ANALYSIS, INTEGRATION AND VISUALIZATION
  - JEFF LINSKY (JILA)
  - BOB PRICE (GSFC)

ASTROTECH 21 INTEGRATED TECHNOLOGY PLANNING

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SENSOR SYSTEMS

WORKSHOP CHAIR

BARBARA WILSON

PANEL CHAIRS

- HIGH ENERGY DETECTORS
  - ANDREW SZYMKOWIAK (GSFC)
- ULTRA VIOLET/VISIBLE DETECTORS
  - GETHYN TIMOTHY (STANFORD)
- INFRARED DETECTORS
  - CRAIG McCREIGHT (ARC)
- SUBMILLIMETER WAVE HETERODYNE SENSORS
  - ROBERT WILSON (BELL LABS)
- DETECTOR SIGNAL PROCESSING AND ARRAY DETECTOR MULTIPLEXING
  - ERIC FOSSUM (JPL)
- CRYOGENIC SYSTEMS FOR SENSORS
  - RON ROSS (JPL)

ASTROTECH 21 INTEGRATED TECHNOLOGY PLANNING

JPL

OPTICAL SYSTEMS

WORKSHOP CHAIR

JIM BRECKINRIDGE (385), TOM GLAVICH (385)

PANEL CHAIRS

- OPTICAL SYSTEMS INTEGRATED MODELLING
  - ROBERT SHANNON (UNIV. OF ARIZONA)
  - ROBERT LASKIN (JPL, 343)
- OPTICAL MATERIALS AND STRUCTURES
  - TED SAITO (LLNL)
  - SHARON LANGENBECK (JPL, 355)
- OPTICAL FABRICATION
  - ROGER ANGEL (STEWARD OBSERVATORY)
  - RICK HELMS (JPL, 354)
- WAVEFRONT SENSING AND CONTROL
  - TOM PITTS (ITEK)
  - GEORGE SEVASTON (JPL, 343)
- OPTICAL SYSTEMS TESTING
  - JAMES WYANT (WYKO CORP, UNIV. OF ARIZONA)
  - ERIC HOCHBERG (JPL, 385)
- ADVANCED OPTICAL INSTRUMENT TECHNOLOGY
  - MIKE SHAO (JPL, 385)
  - MIKE CRISP (JPL, 385)

QUESTIONS:

B. WOODGATE: Can you tell how the funding of this will be implemented? Will there be an Announcement of Opportunity.... and will there be schools participating?

J. CUTTS: There's a lot of discussion about that and the only thing I can say at this point is that the community is being listened to for its advice on how this might be done. I think there's a strong interest in seeing funds go to the universities. That's certainly something that's become very clear so far.

P. STOCKMAN: You mentioned that major funding is most likely to start in '94, '95; do you see this as the start of a long term initiative? How will this be attempted?

J. CUTTS: The attempt is that the program be a 10 year program. Now the question is how do you oversee the content of the program such that it continues to be directed appropriately. I think that there should be oversight bodies of various kinds to ensure that the program is properly organized. So I wouldn't envisage necessarily a workshop like this being invoked again to do that, but certainly I would expect some of the people in this room to participating in an appropriate oversight committee.

G. ILLINGWORTH: Jim, I have a question. An information systems workshop was held some time ago. What is the mechanism for getting inputs back into that and is there a report available? I can see clearly there are some things that will come out of this sort of program like the high data rates...

J. CUTTS: Let me say a word about how we plan to handle the process here and I'll say a little more about this this afternoon. We are not looking for isolated statements about technologies. We need to have an ability to trace those requirements to specific missions, so in response to your question, there will be opportunities to update this. We're structuring these reports so their content can be updated periodically. So as the mission schedules change, as the missions drift around on the schedule that appears on the slide (and some of them will doubtless drop off), then the program can be adjusted accordingly. But as far as the information systems is concerned, I know people at this meeting are interested in any new things that have come up that may modify the earlier recommendations and there are in fact people here who participated in the information systems workshop.

R. ANGEL: While we're still at a fairly high level: This is such a long program, Mike [Kaplan], that we're talking about here. Has there been any talk given to educational aspects? In other words, a lot of work we're talking about can be done by the next generation. Is there any conscious component of the program that would involve the education of the students who are going to do this?

J. CUTTS: NASA has established the last few years a program of space engineering research centers, something like 6 or 7 of them have already been established to selectively pursue certain areas of technology. There is one that was set up in Michigan, for example, specifically centered on submillimeter sensors for astrophysics and Earth science. One aspect of this that we've been encouraging is the use of this particular program because it is an established way in which funding can be funneled into universities. I think the other aspect of it is that if we do get a sufficiently large program, we're anticipating that universities in particular will be participating, and that would in turn make possible innovative research activities in the Astrotech 21 program.

R. ANGEL: It might be worth thinking whether you might want to include a specific educational part of that, not as a bootleg aspect, but as a definite channel of the program.

J. CUTTS: I'm glad that you brought that up and perhaps I should have said if there are other things like education that occur to you, obvious things that need to be done with that part of the charter I've given you, please raise them as you just did, Roger. That is one thing I think maybe we need to be much more specific about.

P. DAVIS: You captioned these things for the periods beginning 1995, yet that's part of a 10-year program and technologies to be launched about 2000 are close to closeout for input right now. Would it be fair to say that things we discuss now are more likely to effect missions launched beginning about 2005 or perhaps 2010?

J. CUTTS: Yes, I think so. We're talking about the 1990s on. You can see that there's a whole suite of missions beginning in this time frame so I think if you have a 10 year program, if you just concentrate on the missions that start in 2005, it's not a very healthy program. You have to spread things out a little bit. Perhaps an ideal program is one where applications continually spawn off over say a 5 to 15 year period.

R. THOMPSON: Following up on what Roger Angel said: We really cannot do another project like HST, and I'm not really referring to the specific problems of HST, but the whole way in which we do these space projects. It's inefficient and it spends far more money than needs to be spent. The funding profiles are wrong. I think if anything should be done, it should be to work out how you conduct a program to reach a technological achievement like the next generation telescope. This is probably the only way we're going to have influence on changing the way NASA and the government does business, so I think it is as critical to look at the way we conduct a project like this as the technologies. And I see us falling right into the same trap immediately, the same structures, the same ways of proceeding that we did a long time ago. So if there's any way to consider how to not fall into these traps, then I think we ought to consider that as part of the...

J. CUTTS: Why don't you, Ethan [Schreier], react to that because you participated in the information systems workshop where this was widely discussed.

E. SCHREIER: I have to say to you some of his exact same words - I don't know if they made it into the final report, but a very strong recommendation was: change the way NASA does business in information systems topics because it was clear that we couldn't afford to do any kind of information systems for any future projects if we don't do that. And there was a lot of emphasis on going back to the community, allowing projects to develop within the community, and not to create massive infrastructures that were going to create systems for the other programs to use. That would be a disaster. I don't know how much of the recommendations actually got through because they were politically charged comments, but as much as the actual technology discussions, there were those discussions. At least one of the other workshops has agreed.

A. MEINEL: We should realize that, after the Hubble problem, you're apt to have more overlays rather than less. We just went over this on some planetary missions ... we accepted a larger probability of failure by having more missions, and the bottom line was we can't afford any failures and that's the driver that really puts the big cost burden. The past history of the Hubble is going to make it harder than ever to shed that overlay of structure.

R. THOMPSON: I think that's the wrong way to work this because if we don't have the guts to change it - and it's not so much the requirements, it is the time, the stretchouts - it's hard on the project, it's hard on the people. You are constantly reviewing decisions and coming up with the same ones or different ones, and I think it's time the astronomical community takes this up. It's easy to say there's not much we can do about it, but as people who actually carry out these projects we have to start refusing to go along with the way NASA works. It's the only way it's going to happen.

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VOL 4

OVERVIEW OF ASTROTECH 21 SPACE INFRASTRUCTURE HANDBOOK

JESS FORDYCE

JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California

March 4, 1991

(Copies of the handbook were distributed at the workshop)

(Presentation material follows)

4

ASTROTECH 21:

OVERVIEW OF ASTROTECH 21 SPACE INFRASTRUCTURE HANDBOOK

Jess Fordyce
March 4, 1991

ASTROTECH 21

- The Space Infrastructure Handbook provides a "snapshot" of the existing and proposed support technologies relevant to the New Century Astronomy Program mission set. These support technologies include:

  - Space Transportation Systems
  - Space Station Freedom & Lunar Outpost
  - Telecommunications
  - Cryogenics
  - Power Systems
  - Servicing & Robotics
  - Near Earth Radiation Environment
  - Radiation Efffects on Electronic Devices
  - Near Earth Orbital Environment
  - Lunar Environment

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Table 1.1 Existing and Proposed Launch Vehicles

Launch Vehicle	Availability (Year)	Performance[1] (kg) LEO[2]	GTO	GSO[3]	SSO[4]	Payload Envelope Available (m) L	D	Cost Estimate (1989 $M)	Remarks
Scout	Current	250	—	—	180	1.61	0.96	10-12	Option for 5th Stage
Pegasus	1990	450	—	—	300	1.93	1.17	6-8	
Taurus	1991	1650	—	—	1100	3.93	1.17	15	
Delta II 7920	1990	5000	—	—	3490	5.78	2.80	40-50	
Delta II 7925	1990	—	1800[5]	—	—	4.67	2.80	40-50	Configured for GTO
Atlas I	1990	5800	2245	—	—	9.40	3.65	65-70	Configured for GTO
Titan II	Current	—	—	—	1675	6-12	2.80	30-35	
Titan II + 8 Castor IVA	Proposed	—	—	—	3250	6-12	2.80	—	
Atlas II	1991	6500	2675	—	4900	9.40	3.65	70-80	Configured for GTO
Atlas IIA	1992	7000	2810	—	5300	9.40	3.65	80-90	Configured for GTO
Atlas IIAS	1992	8500	3490	—	6500	9.40	3.65	100-110	Configured for GTO
Titan III	Current	14300	—	—	7000 (800 km)	12.35	3.65	130-160	
Titan III + TOS	1992	—	5900	—	—	7.27	3.65	150-225	
Titan III + IUS	Current	—	—	1825	—	7.35	3.65	150-225	
Ariane 44L (Europe)	Current	9600 (i=5.2)	4200	—	6200	12.35	3.65	100-110	Configured for GTO
HII (Japan)	1993	10K	—	925	5500	10-15	3.7-4.6	100-120	Configured for GTO
Titan IV (SRMU)[6]	1991	22K	—	—	12K	17.00	4.60	175-230	
Titan IV (SRMU)/IUS	1992	22.5K	—	3600	—	12.00	4.60	230-290	
Titan IV (SRMU)/Centaur	1992	—	—	5760 (Centaur 3-burn)	—	11-17	4.60	230-300	
Ariane 5	In development	21K	—	—	13K	4.5-12.0	4.60	90-100	
Shuttle C	Proposed	70K	—	—	—	24.40	4.50	—	Space Station
Shuttle C/Centaur	Proposed	—	—	8750	—	15.60	4.50	—	HEO, Planetary Mission
HLV (100,150,225 Klb)	Proposed	45,68,102K	—	—	—	24.4/38.0	10/13	$300/lb	For LEO
HLV/Upgraded Centaur[7]	Proposed	—	—	11.5,18.6,28K	—	12.8/23.8	10/13	—	HEO, Planetary
Energia + Cryogenic Upper Stage[8]	Current	100K	—	25K	—	—	—	NA	LEO, Planetary

Notes:

1. Payload system mass which includes loaded spacecraft, launch vehicle/spacecraft adapter and flight support equipment, and does not include launch vehicle margins and reserves
2. 185 km circular, i = 25.5° low earth orbit
3. 35,700 km circular, i = 0° geosynchronous orbit
4. 500 km circular sun synchronous orbit
5. 200 km perigee, 35,700 km apogee, i = 28.5° geotransfer orbit
6. Titan IV with solid rocket motor upgrade
7. General Dynamics proposed upgraded Centaur C-2
8. Not optimally sized upper stage

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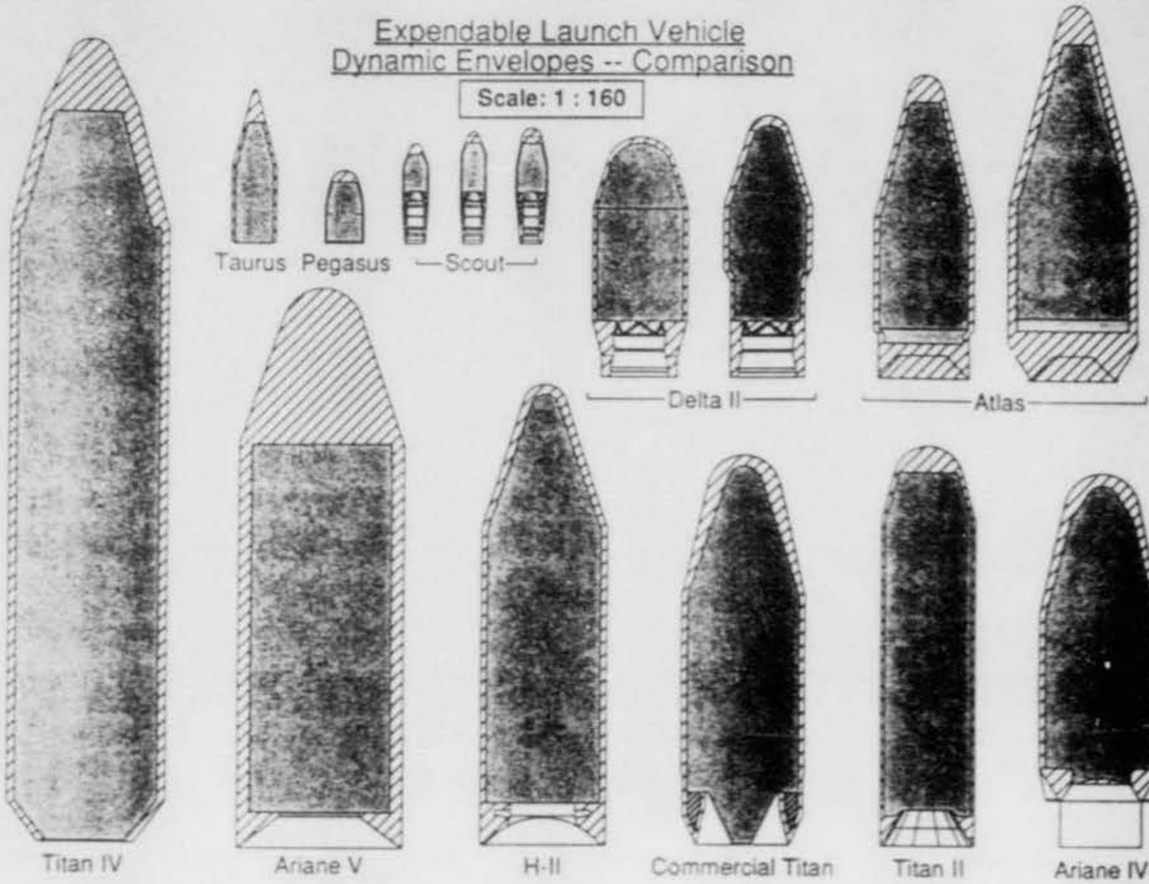


Figure 1-1

Table 1.2 Upper Stage and Motor Data

Upper Stages and Motors	Description	Availability	Booster Compatibility and Use	Cost Estimate $M(1989)	Stage Data: $M_{initial}$ (kg)	M_{BO} (kg)	I_{SP} (sec)	Length (m)	Diameter (m)
Star Motors (Morton Thiokol)									
Star 30BP	Solid motor	Current	AKM (SATCOM, GSTAR, etc.)		542.6	32.6	292.0		
Star 30C	"	"	AKM (GSTAR)	1.5-2.0	626.1	34.1	284.6		
Star 30E	"	"	AKM (SKYNET)	1.5-2.0	667.3	39.8	289.2		
Star 37FM	"	"	AKM(FLTSATCOM)		1148.5	73.0	289.8	1.69	0.935
Star 48B	"	"	PAM-D (Delta), STS Magellan s/c, Atlas		2141.4	116.9	292.1	2.03	1.245
Star 63D	"	"	Atlas, STS, Titan III		3500.0	230.4	283.0		
Star 75	"	Development	STS, Titan III		8065.0	546.6	288.0		
IRIS (Italy)	Solid, spin stabilized stage	Development	Atlas, STS		1830.0	250.0	290.0		
OMV									
STV									
Upgraded Centaur C-2 (General Dynamics)	LOX-LH2, 3-axis stabilized, inertially guided, multiple start stage, on orbit assembly possible	Proposed	STS-C, ALS (HLV), Titan V		39/58/86K	4.5/5.4/6.8K	446.4	10.6-19.0	4.330

Table 1.2 Upper Stage and Motor Data, Cont.

Upper Stages and Motors	Description	Availability	Booster Compatibility and Use	Cost Estimate $M(1989)	Stage Data: $M_{initial}$ (kg)	M_{BO} (kg)	I_{SP} (sec)	Length (m)	Diameter (m)
Centaur (General Dynamics)	LH2-LOX restartable, 3-axis stabilized inertially guided stage	1990	Titan IV, STS-C, HLV Planetary, GTO	61.5	23768	3205	444.4	8.90	4.32
Inertial Upper Stage (IUS) (Boeing Aerospace)	2 stage solid, 3-axis stabilized, inertially guided	Current	STS, Titan III, Titan IV, STS-C Planetary, GSO	60.0	14735 3893	4997 1154	292.9 301.1	5.10 total	2.34
Transfer Orbit Stage (TOS) (Orbital Science Corp./ Martin Marietta)	1st stage IUS motor, 3-axis stabilized, inertially guided	1992	STS, Titan III	60.0	10822	1066	292.9	3.31	2.34
Payload Assist Modules (McDonnell Douglas)									
PAM-A	Single solid motor (Minuteman 3rd stage), spin stabilized stage	Current	STS		3783	318	274.3		
PAM-D	Single solid motor (Star 48), spin stabilized stage	Current	STS, Delta	6-10	2204	194	285.1		
PAM-DII	Single solid motor (Star 63), spin stabilized stage	Current	STS, Titan III	9-10	3723	445	281.7		
Shuttle Compatible Orbit Transfer Stage (SCOTS) (General Electric)	Single solid motor, spin stabilized stage	Proposed	STS		4410	500	298.0		

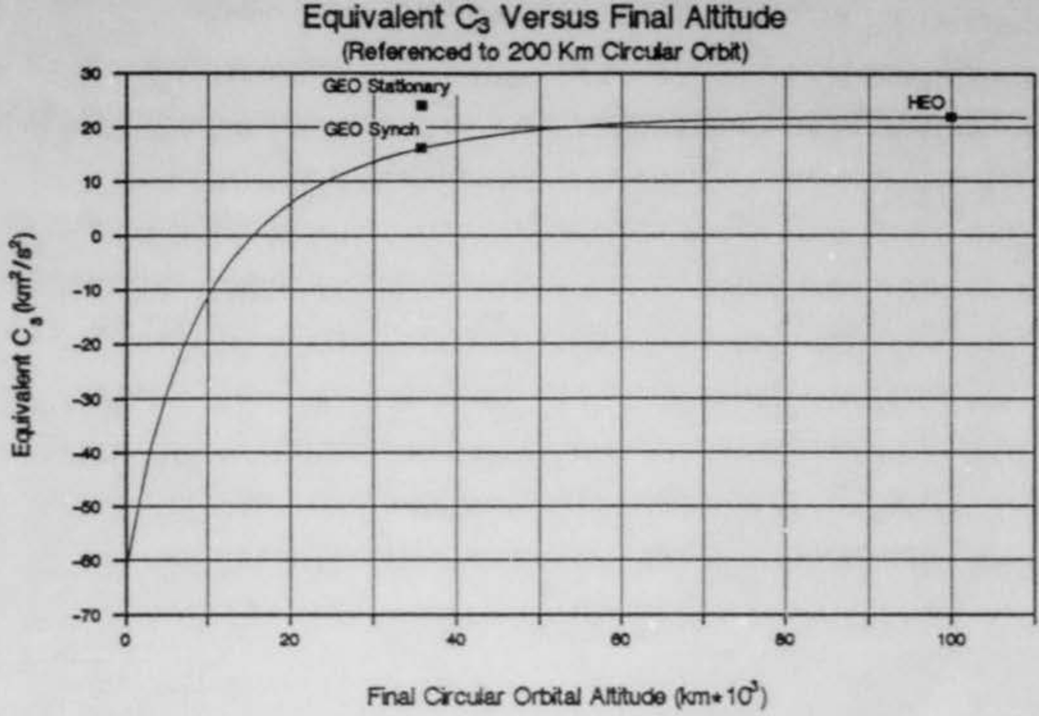


Figure 1.2

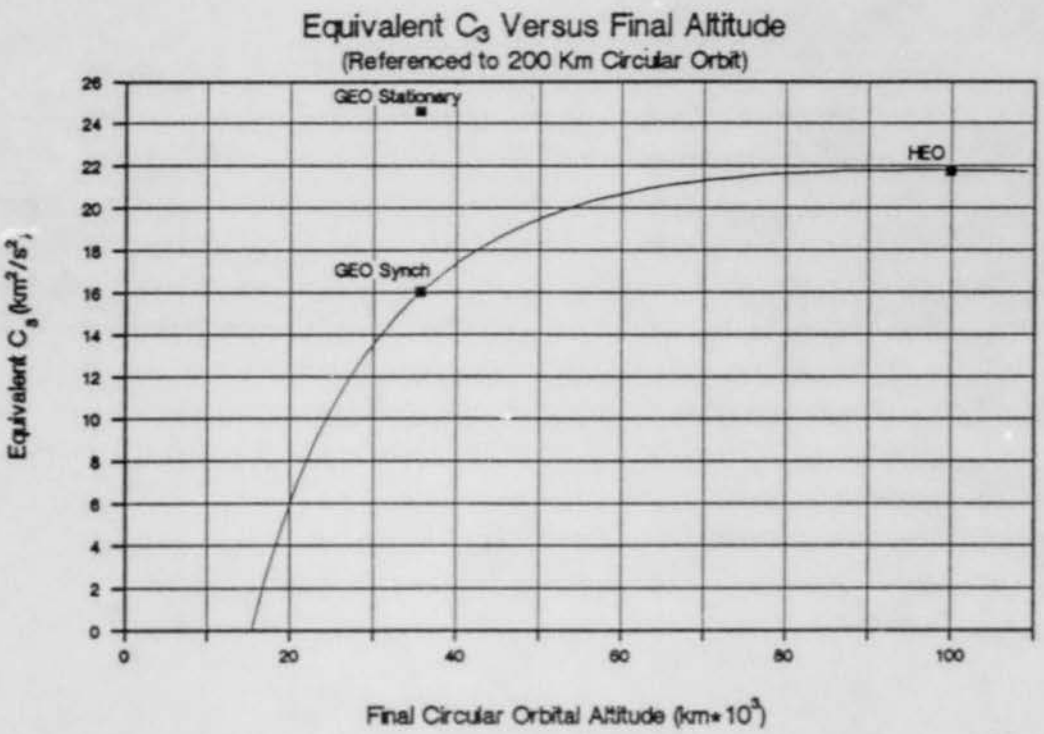


Figure 1.3

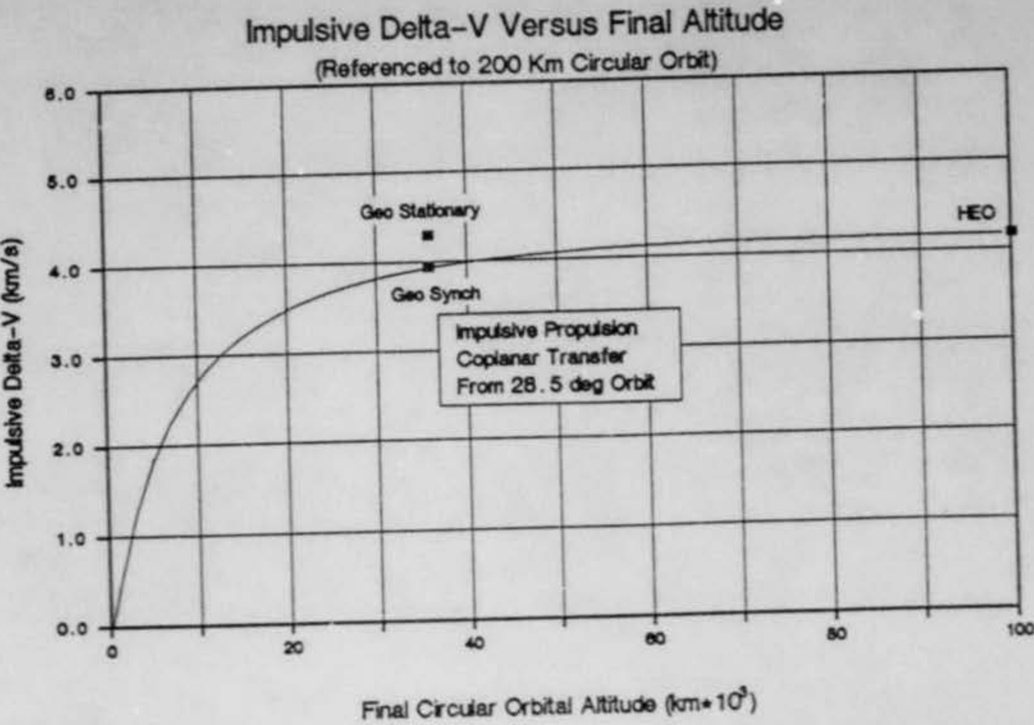


Figure 1.4

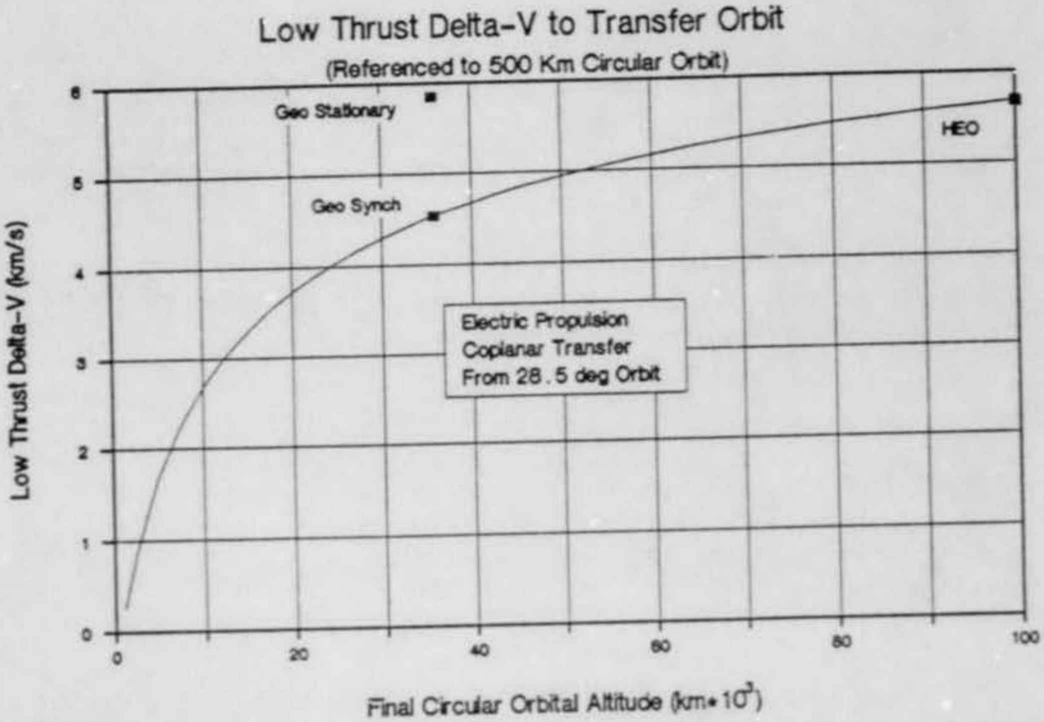


Figure 1.5

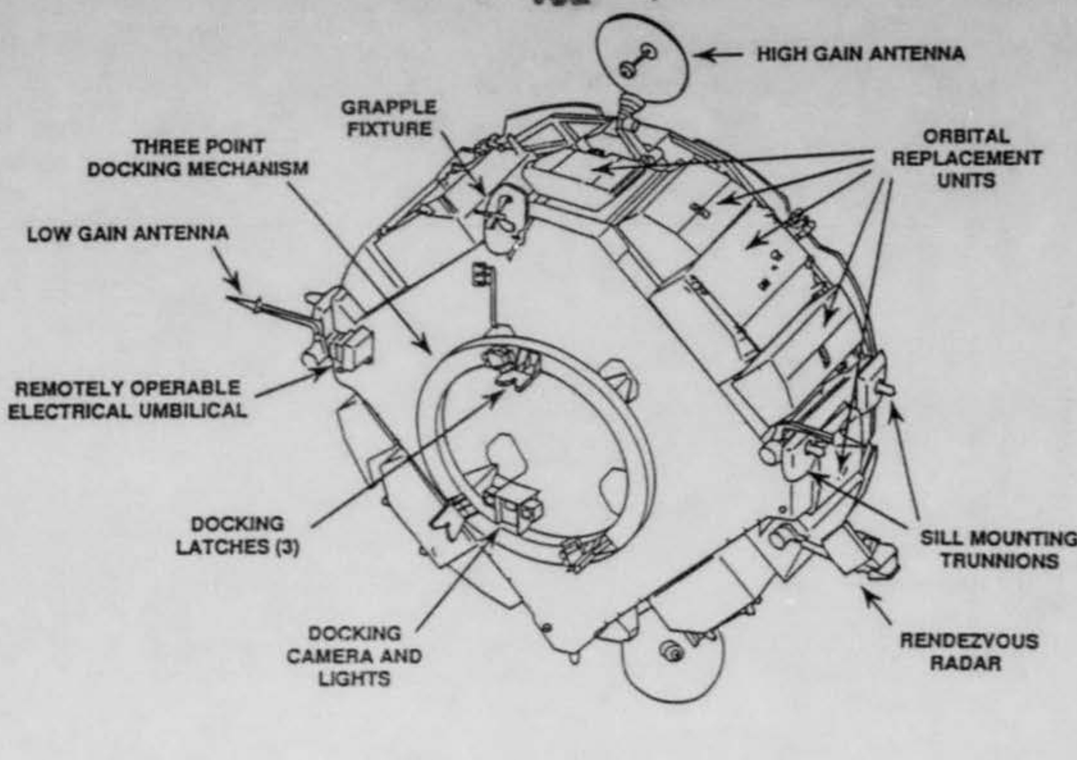


Figure 1.6 OMV Front View

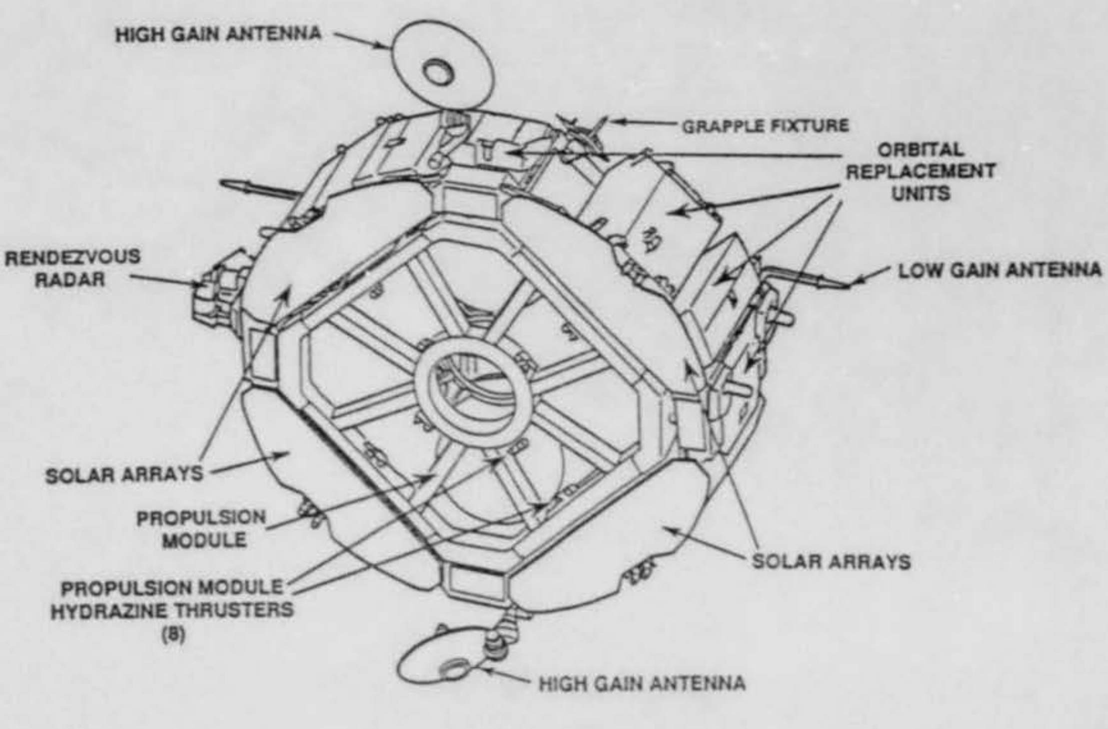


Figure 1.7 OMV Aft View

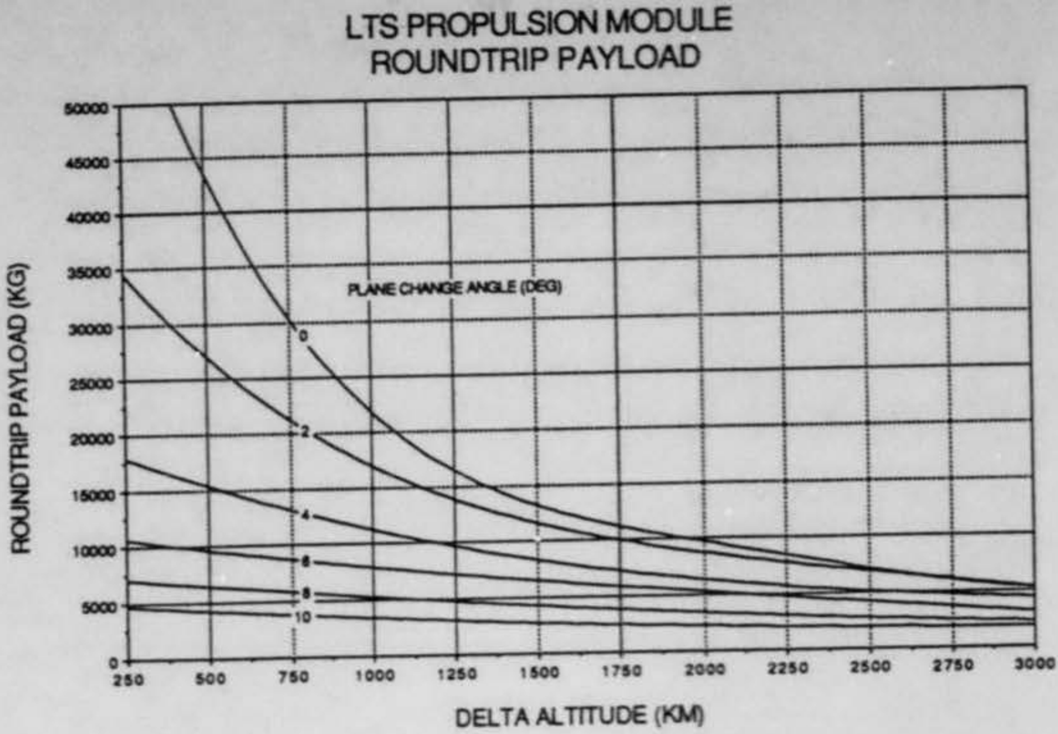


Figure 1.9 STV Round Trip Payload VS. Altitude and Plane Change.

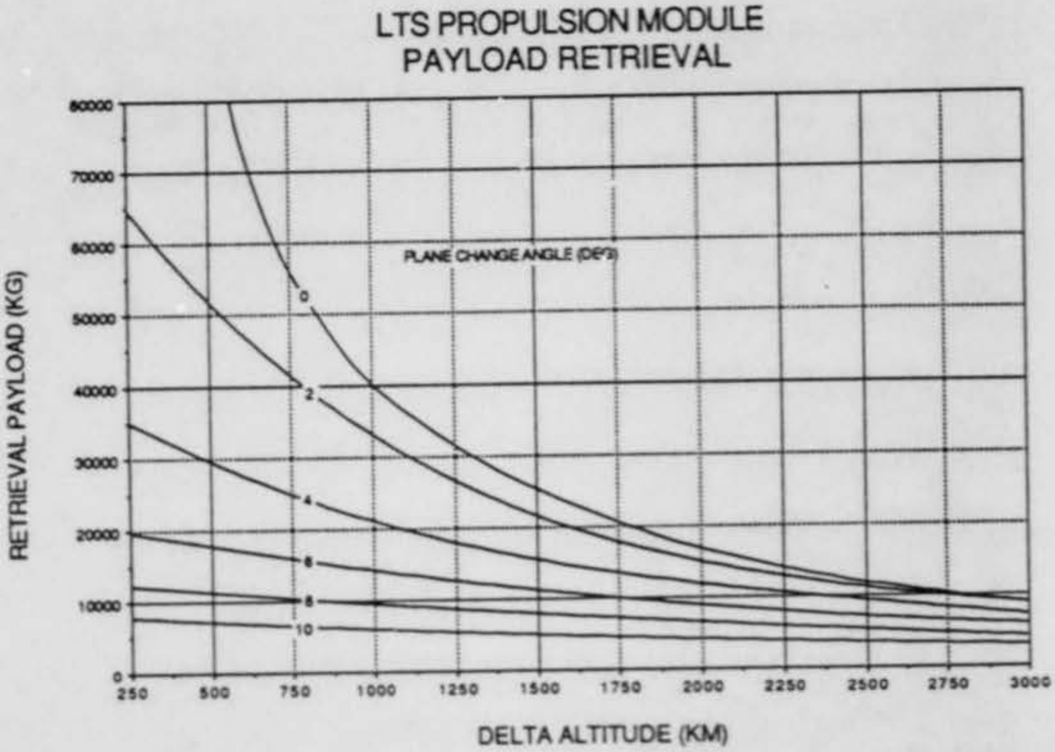


Figure 1.10 STV Payload Retrieval VS. Altitude and Plane Change.

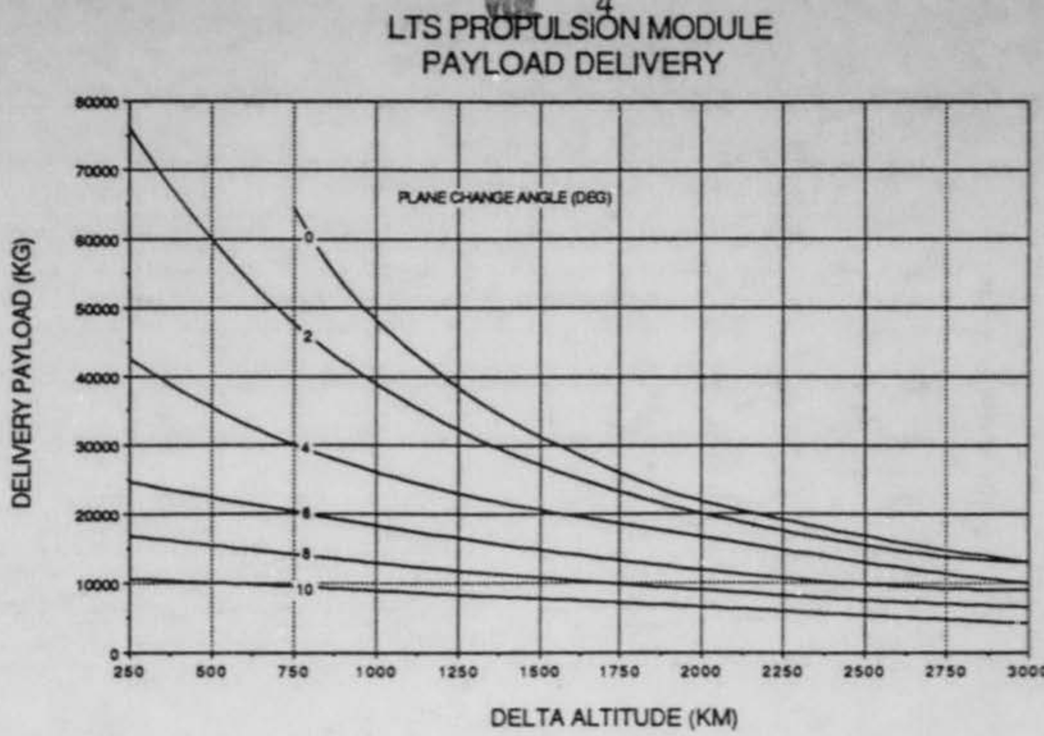


Figure 1.11 STV Payload Delivery VS. Altitude and Plane Change

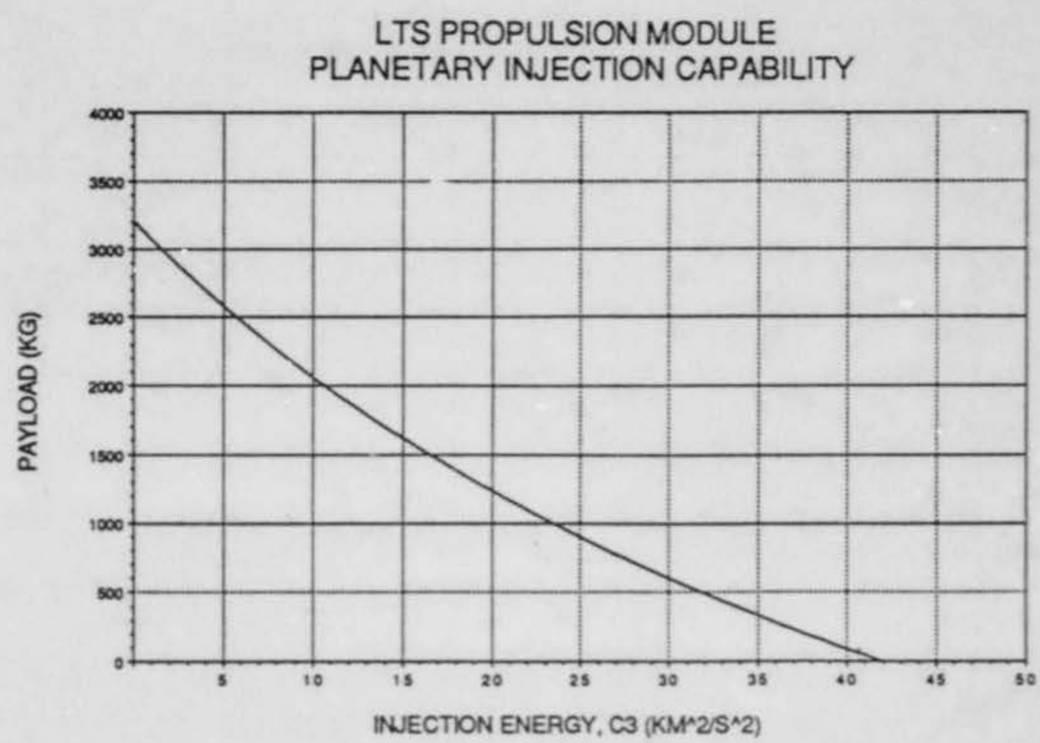
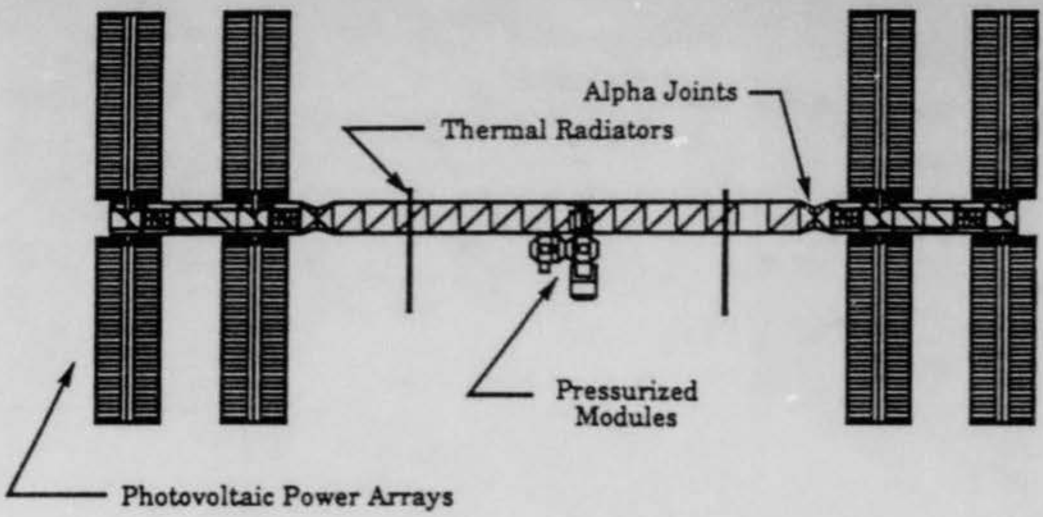
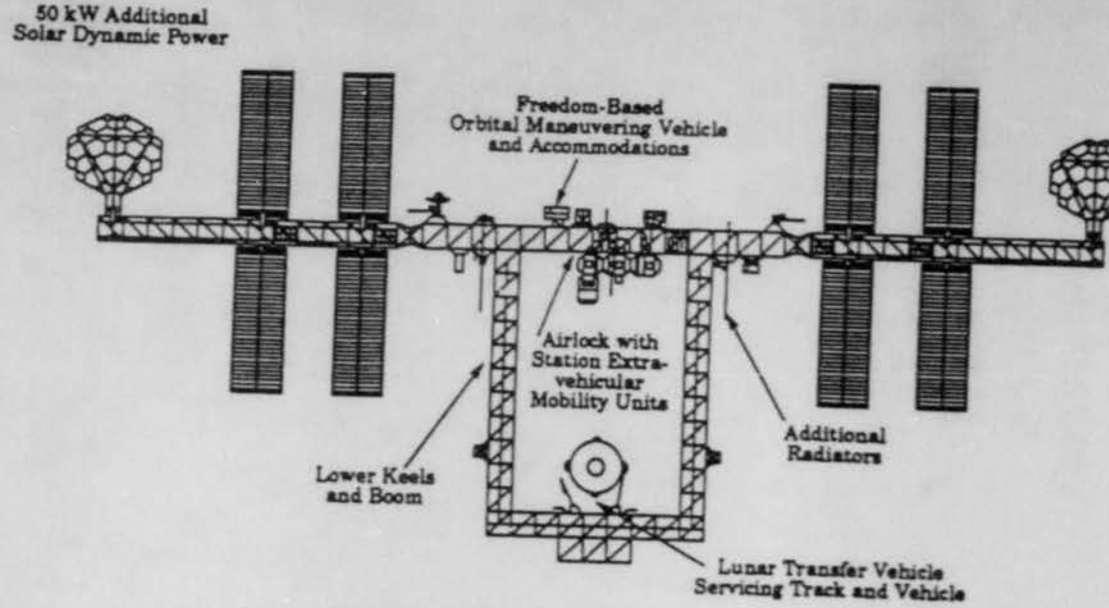


Figure 1.12 STV Planetary Injection Payload VS. Injection Energy (C3).

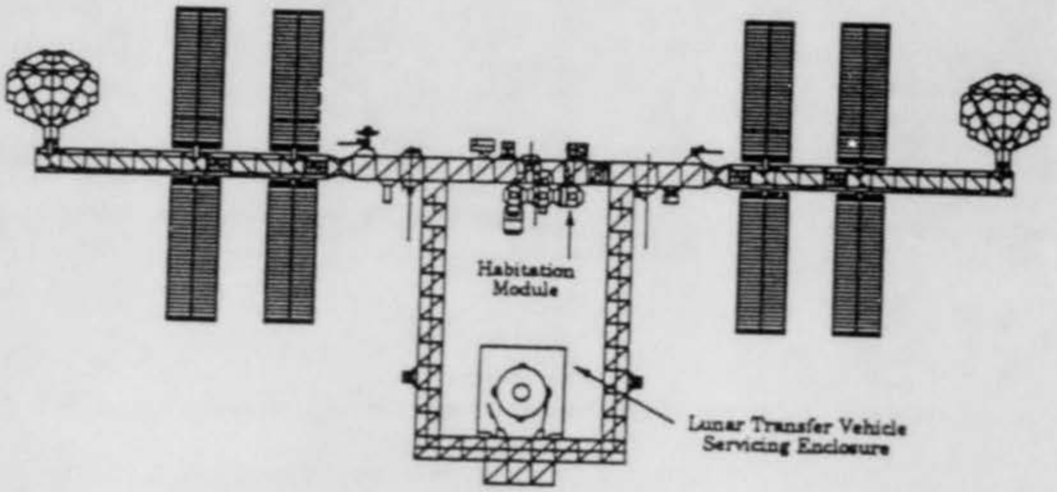


Element	Description
Modules	o 3 laboratory (1 U.S., 1 European, 1 Japanese), 1 habitation
Truss Structures	o Transverse boom 145 meters in length
Power & Thermal	o 75 kilowatt power generation and heat rejection capability
Crew	o 8 permanent
Attached Payload Accommodations	o Accommodations for 2 attached payloads on transverse boom including power and high data rate service
Remote Manipulator (Canadian), Mobile Transporter	o 1 providing access to all faces of the transverse boom

Figure 2-1: Space Station Freedom Assembly Complete Configuration



a) **Lunar Transfer Vehicle Verification Flight Configuration**



b) **Expendable Lunar Transfer Vehicle Operations Configuration**

Figure 2-2: Space Station Freedom Evolutionary Configurations

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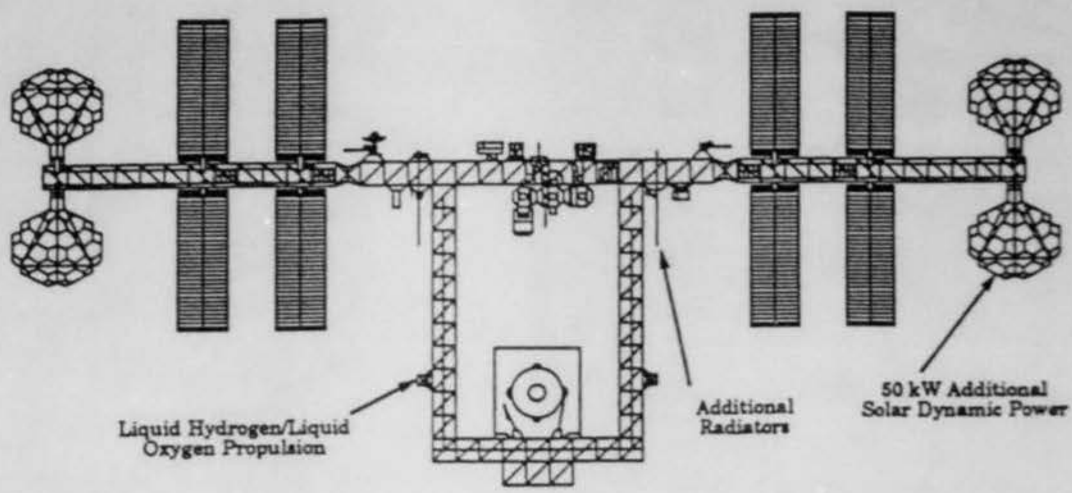
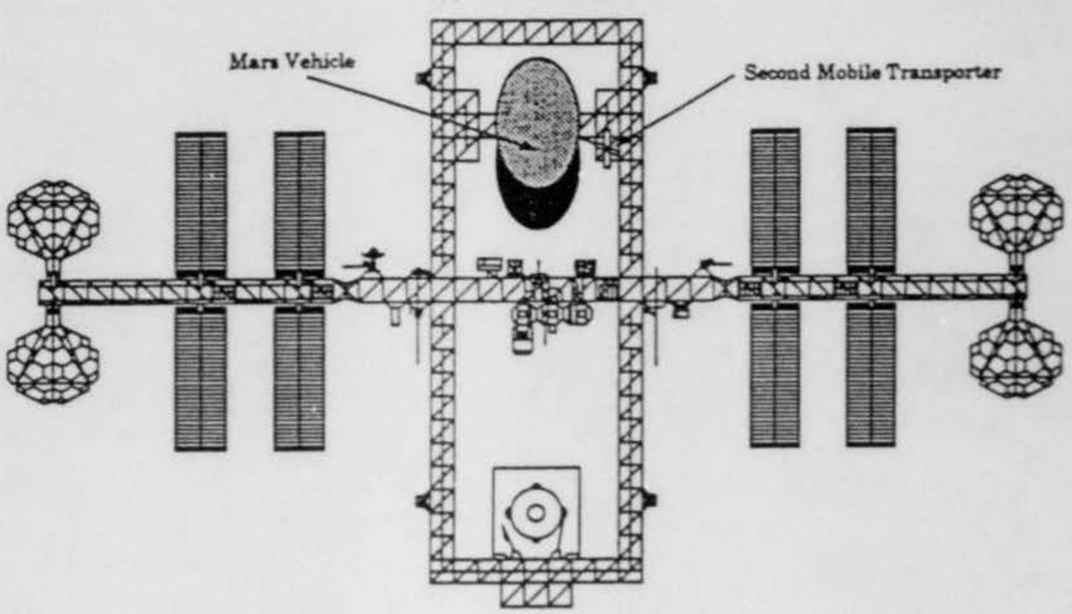


c) Reusable Lunar Transfer Vehicle Operations Configuration



d) Lunar and Mars Operations Configuration

Figure 2-2: Space Station Freedom Evolutionary Configurations

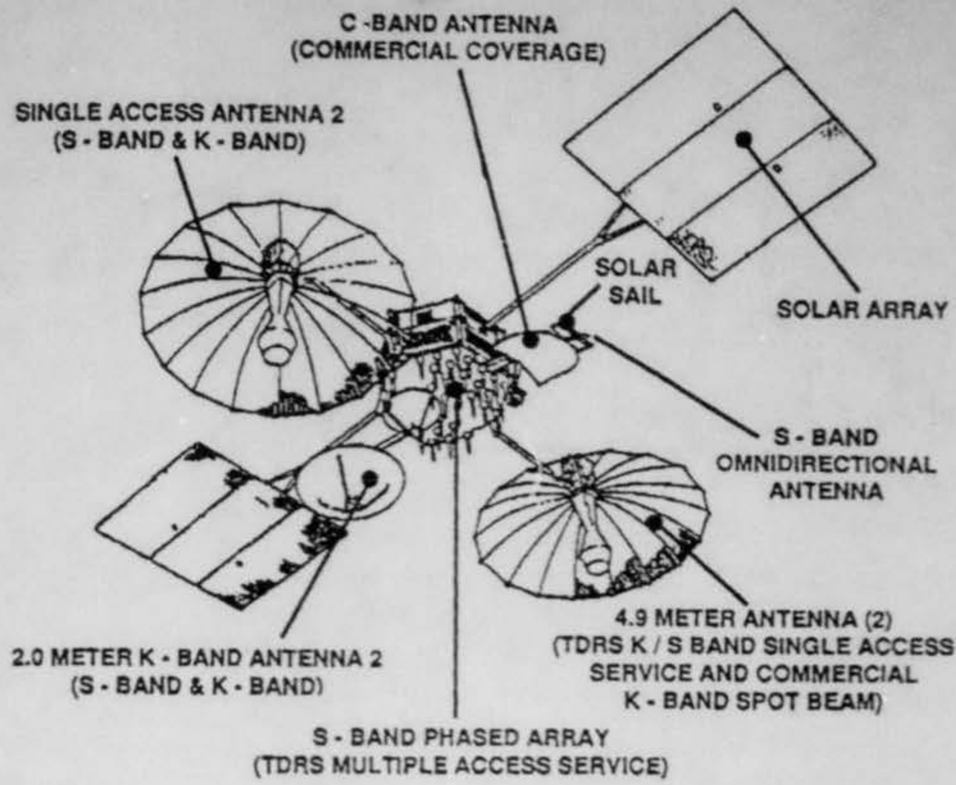


Figure 3.1: TDRSS Spacecraft

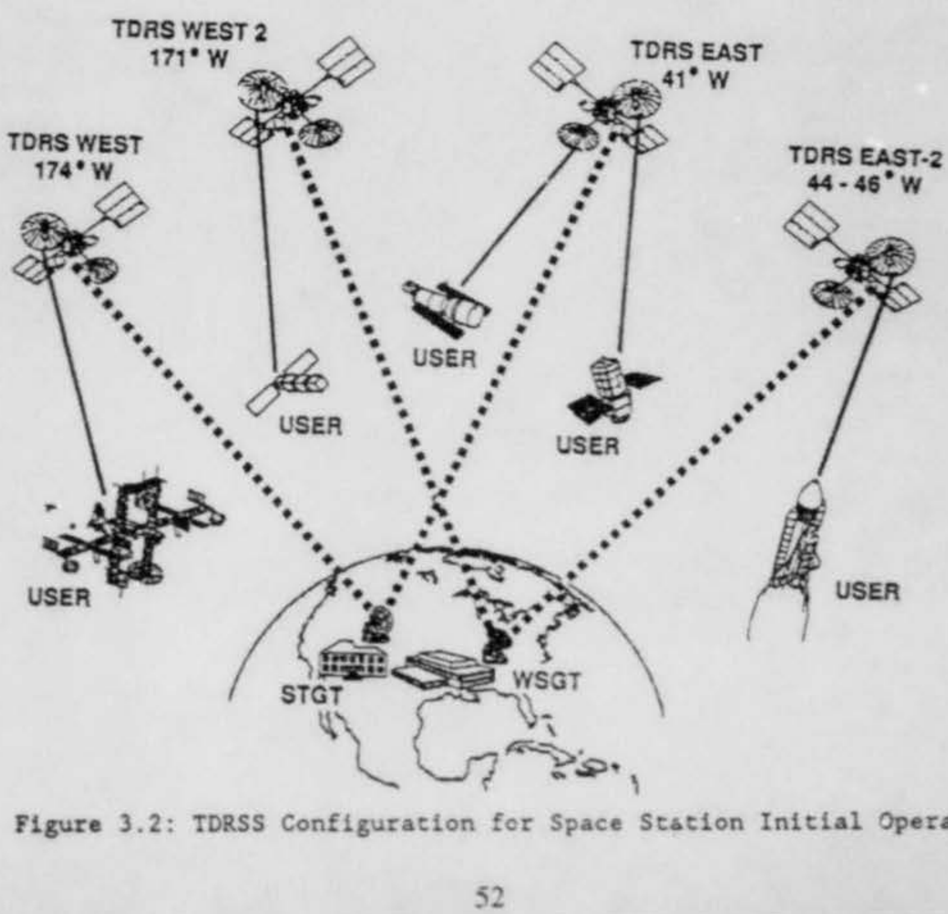
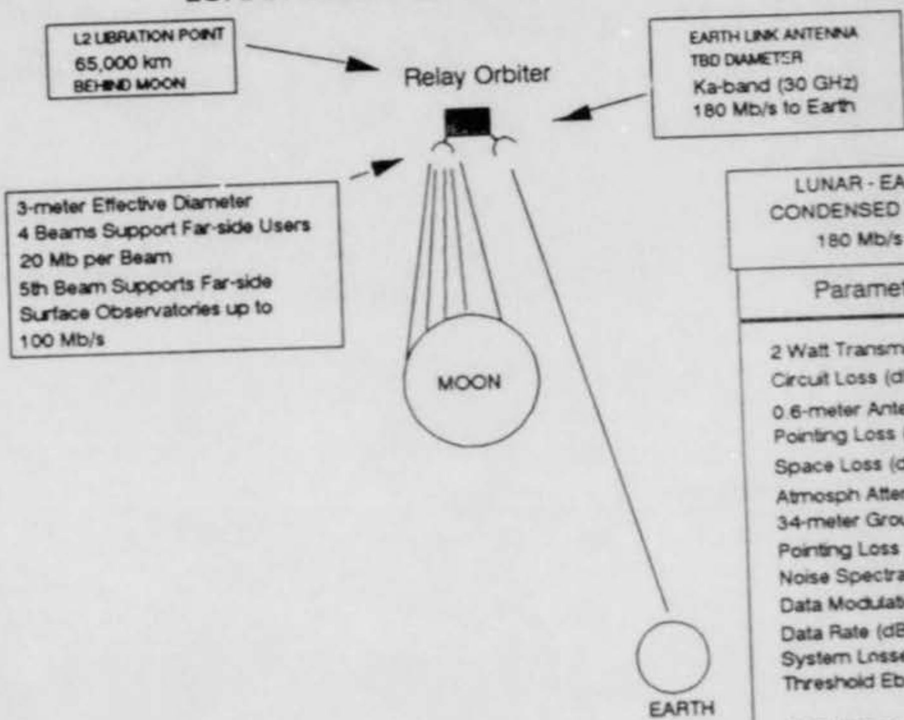


Figure 3.2: TDRSS Configuration for Space Station Initial Operation.

Table 3.1 TDRSS/ATDRSS Baseline Service Comparison

SERVICE			TDRSS (1990)	TDRSS (1996)	ATDRSS (2003)	NOTES
SA	S-BAND	FWD	300 kbps	300 kbps	300 kbps	• SSA WORKLOAD (≤ 3 MBPS) OFFLOADED TO ENHANCED MA
SA	S-BAND	RTN	6 Mbps	6 Mbps	6 Mbps	
SA	Ku-BAND	FWD	25 Mbps	25 Mbps	25 Mbps	
SA	Ku-BAND	RTN	300 Mbps	300 Mbps	300 Mbps	
SA	Ka-BAND	FWD			50 Mbps	• 22.55 to 23.55 GHz
SA	Ka-BAND	RTN			650 Mbps	• 25.25 to 27.50 GHz
SA	INDEPENDENT LINKS		4	8	8	• There is one "independent link" per 16 ft diameter, steerable antenna. • "Simultaneous links" are possible by using more than one frequency band (e.g. S and Ku bands) with the same steerable antenna, provided the ground stations are both located within the high gain antenna beamwidth.
SA	SIMULTANEOUS LINKS		4 SSA 4 KuSA	8 SSA 8 KuSA	8 SSA 8 KuSA 8 KaSA	
SA	ON-ORBIT SPARE		YES	NO	YES	
MA (S-BAND)		FWD	2 @ 50 kbps	4 @ 10 kbps	4 ea. (3 dB OVER TDRS MA FWD)	
MA (S-BAND)		RTN	20 total @ 50 kbps	20 ea. @ 50 kbps	12 ea. @ 3 Mbps	
TRACKING			150 METERS, 3 σ	150 METERS, 3 σ	150 METERS, 3 σ	• ONE ATDRSS STUDY IMPROVED USER TRACKING AS AN ENHANCEMENT (50M, 3σ)

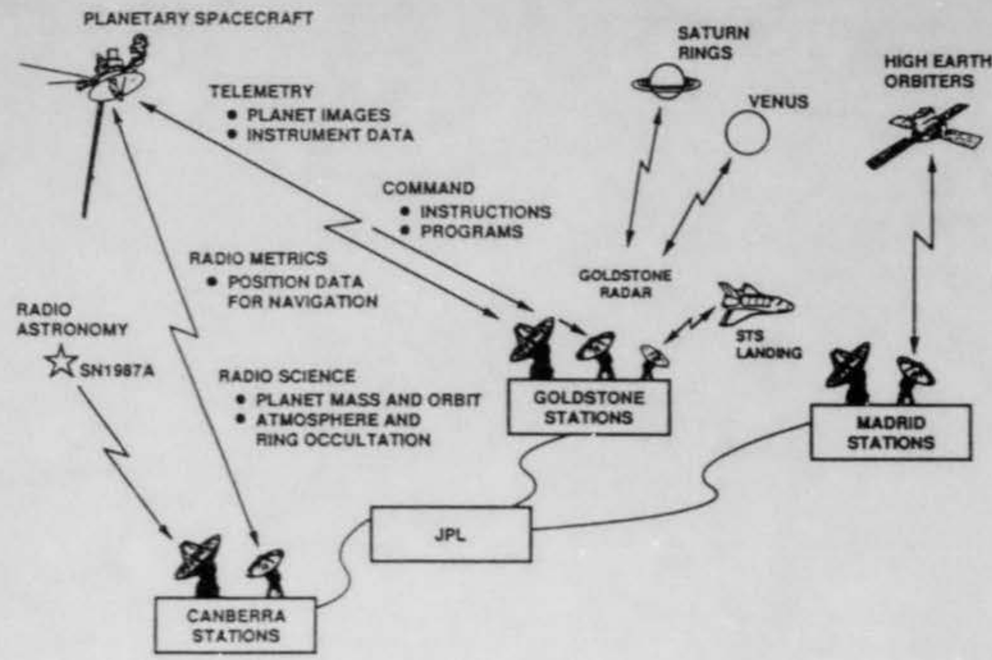
LUNAR COMMUNICATIONS SUPPORT SCENARIO



LUNAR - EARTH TELEMTRY LINK
CONDENSED DESIGN CONTROL TABLE
180 Mb/s DATA RATE AT 30 GHz

Parameters	Design
2 Watt Transmitter Power (dBm)	33.0
Circuit Loss (dB)	-1.0
0.6-meter Antenna Gain (dB)	44.0
Pointing Loss (dB)	-1.0
Space Loss (dB)	-234.0
Atmosph Attenuation (dB)	-2.3
34-meter Ground Antenna Gain (dB)	77.2
Pointing Loss (dB)	-0.4
Noise Spectral Density (dBm/Hz)	-173.9
Data Modulation Loss (dB)	-0.1
Data Rate (dB)	82.5
System Losses (dB)	-1.5
Threshold Eb/No (dB)	0.4
Data Margin (dB)	4.6

DEEP SPACE NETWORK



Cryogenic Cooling Summary

	Status	Flight Experience	Approx. Minimum Achievable Temp.	Practical Maximum Heat Load (W)	Size	Representative Efficiency Wcooling/Winput	Lifetime (representative)	Advantages	Disadvantages
Thermoelectric Coolers	Mature	Many	170K	1	Small	0.001	5 years	Vibrationless, reliable small, lightweight	Cannot cool below 170K, inefficient from 200K-170K
Radiative Coolers	Mature/ Active	Many	70K	0.2	Large	No power required	5 years	Passive, reliable, longlife	May limit mission scenarios, large, may be sensitive to contaminant, low heat loads at cold temperatures
Open Cycle Coolers									
• Liquid	Mature/ Active	Many	1.4K	10	Large	—	1 year*	Flight proven, constant temperature	Limited lifetime, large, may require complex design implementation and testing
• Solid		Many	8K	1	Large	—	2 years*	More compact than liquid, flight proven	
• J-T		Some	4K	20	Large	—	1 year*	Simple, can provide intermittent cooling	
Closed Cycle Coolers									
• Recuperative									
J-T, mechanical	Active	Few	4K†	>10	Moderate	0.010	1 year	Reduces size of open cycle J-T	High input power, compressor lifetime limited, vibrates, sensitive to J-T clogging
J-T, sorption	Develop-mental	None	4K†	>10	Moderate	0.015	5 years	Quiet, compact, can use heat as power source, modular	Developmental, complex system design, sensitive to J-T clogging
• Regenerative									
Stirling	Active/ Testing	Few	15K†	10	Moderate	0.030	5 years	Very efficient, compact	New design in test, vibrates, may require complex interface, may experience wear-out
Other	Develop-mental	Few	Varies	Varies	Moderate to large	0.020 to 0.001	2 weeks to 5 years	Varies according to specific need: heat powered, low pressure, split cycle, etc.	Developmental or need adaptation for spacecraft use, lower efficiency, complex designs

* Limited by amount of cryogen stored
† 60 K typical

Figure 4.1

Table 5.1 Power Generation Summary

	Specific Power (W/kg)	Practical Max Power (W)	Power Density (W/m2)	Power/Unit Module (W)	Schedule Risk Uncertainty	Relative Cost	Estimated Date Available
Conventional Planar Photovoltaic Solar Arrays	45	—	120	—	L	M-L	Current
APSA Arrays- Advanced Photovoltaic Solar Arrays	130	—	130	—	M-L	M-L	late '90s
High Performance Solar Cells	190	—	190	—	M-H	M-H	2005
Modular RTGs	7-8	300-400	—	40-50	M	M	1995
AMTEC RTGs	20	1000	—	—	H-M	H-M	2000
Dynamic Isotope Power System (Dips)	6.5	1000-10,000	—	—	H-M	H-M	1995
Baseline SP-100	25	100 K	—	—	N/A	N/A	mid '90s

H = High
M = Med
L = Low

Table 5.2 Power Management and Distribution Summary

	PMAD Mass (% of System)	PMAD Parts Count	PMAD Power Density (W/cm3)	PMAD Conversion Efficiency (%)	Schedule Risk Uncertainty	Relative Cost	Estimated Date Available
State of the Art (SOA)	25-30	BASELINE	0.061	75-95	—	—	Current
Hybrid Functional Blocks	25%<SOA	50%<SOA	0.244	75-95	L	L	1995
Power Integrated Circuits	40%<SOA	80%<SOA	0.61	75-95	H	M	1996

H = High
M = Med
L = Low

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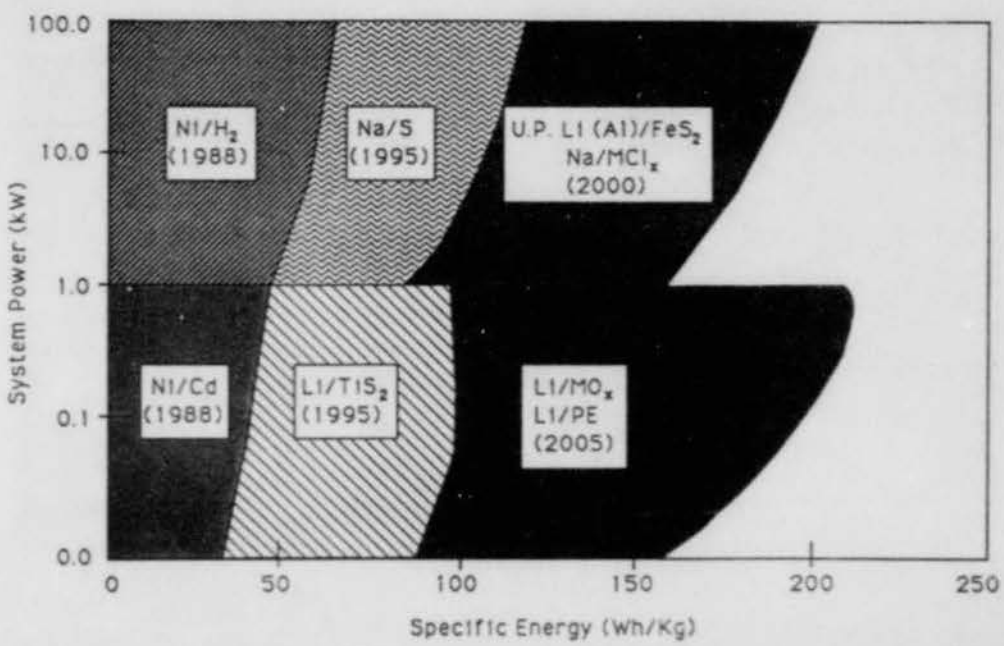
Table 5.3 Power Storage Summary

	Specific Energy (Wh/Kg)	Energy Density/ (Wh/l)	Specific Power (W/Kg)	Operating Temp. (°C)	Cycle Life (80% DOD)	Schedule Risk Uncertainty	Relative Cost	Estimated Availability Date
Ni-Cd	20-30	60-80	330	-10 to 35	>2000	L	L	Current
Ni-H_2	25-35	30-40	270	-10 to 35	>2000	M	M	Current
$LiTiS_2$	70-80	180-200		-10 to 35	>500	M	M	1995
Na-S	60-80	40-60	125	350	>500	N/A	N/A	1995
$LiFeS_2$	100-140		275	300-400	>500	N/A	N/A	2000
Na-$MC1_x$	70-80	40-60	125	250-350	>500	N/A	N/A	2000
Integrated Alkaline electrolyte	80-100	15-20	25-30	80	N/A	N/A	N/A	95-00
Dedicated Alkaline electrolyte	80-100	15-20	25-30	80	N/A	N/A	N/A	95-00
Dedicated Solid Polymer electrolyte	80-100	15-20	25-30	80	N/A	N/A	N/A	95-00
Dual Alkaline electrolyte	120-200	20-40	30-50	80	N/A	N/A	N/A	95-00

H = High
M = Med
L = Low

Advanced Rechargeable Battery Performance Envelopes



ASTROTECH 21:

Section 6: Robotic Servicing of Advanced Science Missions
Issues and Guidelines

The servicing section of the infrastructure handbook provides an in-depth discussion of pertinent issues:

- Practicality of robotic application.
- Cost effectiveness of robotics.
- Transportation issues.
- Spacecraft servicing, assembly, maintenance, refueling, cleaning, instrument changeout.

ASTROTECH 21:

Section 7: Near Earth Radiation Environment

Earth Trapped Radiation
- Inner Zone Electrons
- Outer Zone Electrons
- Energetic Protons

Galactic Cosmic Radiation
- Electrons
- Protons
- Cosmic Rays
- Geomagnetic Effects

Solar Energetic Particle Events
- Protons
- Electrons
- Heavy ions

ASTROTECH 21:

Section 8: Radiation Effects on Electronic Devices

Basic Damage Mechanisms
- Ionization
- Displacement

Integrated Circuits
- Visible Detectors
- IR Detectors
- X & Gamma Ray Detectors
- Optical Components

Hardening Approaches

ASTROTECH 21:

Section 9: Near Earth Orbital Environment

Atomic Oxygen
Vacuum Ultraviolet Radiation
Meteoroids
Orbital Debris
Contamination

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ASTROTECH 21:

Section 10: Lunar Environment

General Characteristics
Stable Platform
Atmosphere
Surface Temperatures
Magnetic Field
Radiation Environment
Micrometeorite Flux
Regolith
Upper Few Hundred Meters of the Moon
Crater Morphologies

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WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

STATUS OF THE HUBBLE SPACE TELESCOPE (HST)

PETER STOCKMAN

SPACE TELESCOPE SCIENCE INSTITUTE
Baltimore, Maryland

March 4, 1991

(Presentation material follows)

SPACE TELESCOPE SCIENCE INSTITUTE

ASTROTECH 21
DECEMBER 12, 1990
P. STOCKMAN

HST STATUS:

THE SPACECRAFT IS PERFORMING REASONABLY WELL WITH THREE EXCEPTIONS:

- SPHERICAL ABERRATION -- 2 MICRON ERROR CENTER TO EDGE 8 WAVES IN INTENDED WAVEFRONT. THESE DATA ARE IN BASIC AGREEMENT WITH THE FOSSIL DATA REPORTED IN THE ALLEN REPORT.
- FINE GUIDANCE SENSORS -- THE EFFECTS OF THIS DEGREE OF SPHERICAL ABERRATION COMBINED WITH SMALL MISALIGNMENTS CREATES PROBLEMS IN THE INTERFEROMETRIC NULLS.
- THE SOLAR ARRAY DISTURBANCES WHICH ARE A COMBINATION OF TWO PROBLEMS: DIFFERENTIAL EXPANSION IN THE BISTEM WHICH EXCITES A 0.1 HZ OSCILLATION, AND A STICK-SLIP JOINT WHICH EXCITES A 0.6 HZ OSCILLATION/DISTURBANCE.

SPACE TELESCOPE SCIENCE INSTITUTE

ASTROTECH 21
DECEMBER 12, 1990
P. STOCKMAN

PLANS FOR IMPROVING HST PERFORMANCE

- SOFTWARE FIX FOR REDUCING THE SOLAR ARRAY OSCILLATIONS. DIFFICULT AND NOT LIKELY TO REMOVE ALL THE DISTURBANCES, PARTICULARLY THOSE AT 0.6 HZ.
- M&R SERVICING MISSION IN SUMMER 1993 TO REPLACE

  -- WF/PC II

  -- SOLAR ARRAYS

  -- TAPE RECORDER

  -- GYROS

  -- COSTAR (PROBABLY)

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SPACE TELESCOPE SCIENCE INSTITUTE

ASTROTECH 21
DECEMBER 12, 1990
P. STOCKMAN

SCIENCE FROM HST

- EVEN ABERRATED IMAGES SHOW A SHARP CUSP WHICH CONTAINS 10-20% OF THE LIGHT. WHILE THE TELESCOPE CANNOT GO AS DEEP (DUE TO THE LIGHT LOSS), IT IS STILL VERY USEFUL FOR OBJECTS BRIGHTER THAN 24TH MAGNITUDE AND MORPHOLOGICAL STUDIES.

  -- SN 1987A/GRAVITATIONAL LENSES

  -- GALACTIC STRUCTURE/AGN CORES

  -- SOLAR SYSTEM STUDIES (SATURN)

  -- AND, OF COURSE, UV SPECTROSCOPY AND IMAGING

SPACE TELESCOPE SCIENCE INSTITUTE

ASTROTECH 21
DECEMBER 12, 1990
P. STOCKMAN

LESSONS FOR HST2

- THE STATE-OF-THE-ART IN SPACECRAFT ENGINEERING IN 1980 WAS QUITE GOOD.
- HST IS CHARACTERIZED BY LOW MARGINS IN POWER AND THERMAL AREAS AND HAS PERFORMED WELL.
- THE DESIGN OF THE PCS SYSTEM AND UNDERSTANDING OF THE DISTURBANCE LEVELS APPEARS TO HAVE BEEN SOUND.
- THE SCIENTIFIC INSTRUMENTS ARE WORKING WELL.
- THE THREE MAJOR PROBLEMS WERE DUE TO:
  - MIRROR ERROR - TECHNICAL ERROR COMPOUNDED WITH AN INCOMPLETE VERIFICATION/TEST PROGRAM.
  - FINE GUIDANCE PROBLEM - UNFORESEEN EFFECT OF AN UNIMAGINABLE ERROR.
  - SOLAR ARRAY - DESIGN/SYSTEM ENGINEERING ERROR COMPOUNDED WITH AN INCOMPLETE VERIFICATION/TEST PROGRAM (THE SOLAR BLANKETS OR BISTEMS WERE NOT TESTED AT FULL SCALE OR NEAR FULL-SCALE).

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SPACE TELESCOPE SCIENCE INSTITUTE	ASTROTECH 21 DECEMBER 12, 1990 P. STOCKMAN

LESSONS:

1. HST'S CURRENT PROBLEMS ARE NOT DUE TO POOR OR INADEQUATE ENGINEERING TECHNOLOGY (IE. AN ASTROTECH 21 STUDY IS NOT NEEDED TO UNDERSTAND OR AVOID THEM IN THE FUTURE). THE TECHNOLOGY WAS IN HAND WHEN HST DEVELOPMENT BEGAN.

2. INDEPENDENT TESTING AND VALIDATION MUST BE AN INTEGRAL PART OF THE DEVELOPMENT. WHILE IT APPEARS TO BE A HIGH COST ITEM, IT PROBABLY LOWERS COST OVERALL AND INCREASES THE UNDERSTANDING/OPERABILITY OF THE SPACECRAFT.

3. CERTAINLY, ACTIVE CONTROL OF THE TELESCOPE OPTICS WITH A RANGE OF ADJUSTMENT EXTENDING TO ACCURACIES GUARANTEED BY INDEPENDENT TESTING IS HIGHLY DESIRABLE. SUCH CONTROL MUST ADEQUATELY CONSIDER MUCH LARGER RANGES OF INITIAL ADJUSTMENT THAN FOR NORMAL OPERATIONS.

4. THE POINTING CONTROL/FIGURE ADJUSTMENT SYSTEM SHOULD HAVE AMPLE MARGIN TO COPE WITH OFF-NOMINAL PERFORMANCE. OTHERWISE, OPTICAL PROBLEMS CAN BE COMPOUNDED OR CAN SEVERELY IMPACT THE POTENTIAL SCIENTIFIC GAINS.

5. ALL POTENTIAL SOURCES OF SPACECRAFT DISTURBANCES MUST BE MEASURED AT SCALES COMPARABLE TO FULL SCALE, PARTICULARLY THERMAL DISTURBANCES.

6. IF HST IS ANY MEASURE, THE INITIAL ADJUSTMENT AND CALIBRATION OF A MULTISEGMENTED MIRROR OR INTERFEROMETER ON-ORBIT WILL BE VERY DIFFICULT. AS MUCH AS POSSIBLE, SUCH INITIAL ADJUSTMENTS SHOULD BE AUTOMATED AND TESTED ON THE GROUND FIRST.

SPACE TELESCOPE SCIENCE INSTITUTE	MARCH 4, 1991 P. STOCKMAN

SCIENCE LESSONS LEARNED

- MAJOR ADVANCES IN IMAGING RESOLUTION HAVE AN IMMEDIATE IMPACT ON ASTRONOMY THROUGH NEWLY DISCOVERED MORPHOLOGIES.

  PRO: VERY LARGE OPTICS SUCH AS THE LUNAR 16M AND VERY LONG BASELINE INTERFEROMETERS.

- IMAGE RECONSTRUCTION/DECONVOLUTION TECHNIQUES FOR DIFFUSE BUT FINE STRUCTURAL OPTICAL PSFS ARE EXTREMELY LIMITED BY THE MODEST SIGNAL TO NOISE ACHIEVED IN MOST OPTICAL SCENES.

  CON: INTERFEROMETERS AND SPARSELY FILLED ARRAYS WILL PRODUCE SIMILAR PSFS AND WILL THUS BE LIMITED IN SENSITIVITY.

- ROBUST SCIENTIFIC RATIONALE IS REQUIRED TO JUSTIFY THE MISSION AND AS TECHNICAL CONTINGENCY.

  - SENSITIVITIES 2.5 MAGNITUDES GREATER THAN OTHER FACILITIES.
  - RESOLUTION 3-5X BETTER THAN OTHER FACILITIES.

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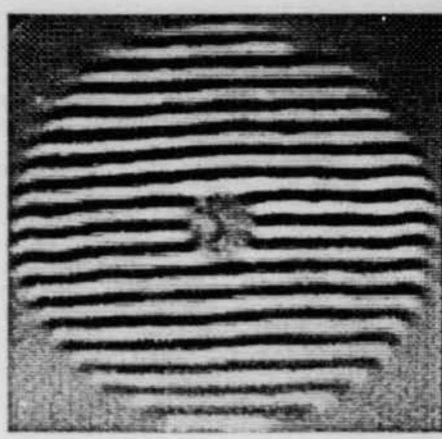
AF 3.5m 10.6 microns



15:28:58 02-26-91 rms surface error 210 nm

Phase Image Halftone

Operator:	Customer:	Part ID:
Title: AF 3.5m 10.6 microns	Phase Shift Technology, Inc.	Wedge: Surface
TIME 15:28:58 / DATE 02-26-91	Phase Analysis Software Version 3.03 (c) 1985-1990	Polarity: +
Terms Subtracted:		

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QUESTIONS:

E. SCHREIER: I should bring up the point we mentioned before, that another category of lessons beyond technology and science is management lessons learned, and I think it's important to keep bringing up pieces of the system - subsystems could be developed more directly by the groups using them - either the instruments themselves or pieces of the ground system tended to work much better than the overall system engineering. And I think in future projects, that has to be brought into mind. You can't keep doing this...

P. STOCKMAN: One of the important points about smaller class telescopes, and particularly in the near-IR or the optical, is that unless they're extremely special purpose, they have a very difficult time competing with the ground. They're less expensive than these larger, next generation space telescope concepts, but with 10 m telescopes on the horizon (on the ground) and the ability to restore much of the image quality on the ground in the near IR, you have to be very careful if you believe you can compete with them in space without going to either comparable apertures or much cooler optics.

R. ANGEL: On the Allen Committee we struggled with what were the technical reasons for what went wrong with the mirror and I think we understand that very well now, but I think the fundamental problem was more one of a social question of how we go about doing high tech on these things. In that case I think the root cause of the mirror failure was that in order to meet schedules, there was a complete separation between the people who actually understood deeply what this was supposed to do and what it should meet and the guys who were making it. So there was a division of the management layer where people responding to problems below didn't talk to people who understood it and the people above who even predicted that this problem would occur, their messages never got through the management layer further down and the reason for that false division was that at that time, it seemed that the only way that schedules could be met would be to close off any further discussion. So one of the relevant things you have to look at, is how you keep this sort of vertical path open. And one of the messages that is really troubling is that prior to making that mirror there was a whole industry set up of companies looking at how to polish mirrors - two or three different optics groups. It was a massive industry looking at how to make the Hubble telescope work and the net result of that confusion of effort was a failure. I think that confusion was sort of horizontal but it went out into all kinds of groups who knew about mirror making. But there wasn't an effort to make a vertical connection, a very strong group which would look from understanding the function of the real optics all the way down through the manufacture. So I see a little bit of danger here in this type of approach which is to identify technologies that users outline on the horizontal level because that didn't help us on Hubble. There were all kinds of money and effort spent on looking at mirror technology and it never came together.

G. ILLINGWORTH: ...but does that solve the problem or is it more the means of actually getting the facility or the optics or whatever it is you need? You need to continue that and maybe you'd end up with a group that goes in there on a periodic basis and looks at the progress at a technical level, but I think the upfront work is valuable. I don't think you want to use that experience to say you don't want to do this upfront work.

A. MEINEL: I would like to say that NASA did have scientific work presented; the company will not share with them things like those interferograms. There is no control whatsoever through the experimental result so you could have any amount of expertise supposedly looking from the outside and not be knowledgeable of the problems.

R. THOMPSON: I do have to take issue with Pete's comment about moderate sized telescopes in the infrared. A moderate sized telescope, anything over 4 meters for example –

P. STOCKMAN: I was talking about uncooled optics –

- would be tremendous because what's limiting us on HST is the thermal emission from the mirror and there's this fantastic minimum in the natural background around 3 microns that could be exploited by a moderate class instrument. You can't reach that from the ground and you can't do it with HST because of its thermal emission. So there's a whole range of things to do in the infrared, even with moderate class, and greatly exceed all the things that you have up there. I guess the other point is what Ethan was just saying on management: all you have to do is go to one HST quarterly meeting where all of the top management are supposed to be there with 300 people in the room. That tells you a lot about where things went wrong. It is management responsibility combined with authority that is really needed, and the right people in the right places with the guts to go in and ask the right questions. It's something we need to look at.

P. DAVIS: ...from a different line of reasoning, when asking that a space telescope would be able to do substantially better than a ground-based telescope, you gave the answers for things that can be done at all on the ground and didn't consider things that cannot be done on the ground like most of the infrared and ultraviolet parts of the spectrum.

G. ILLINGWORTH (?): Yes, I wasn't trying to imply that I was only talking about competition with the ground. I'm also talking about competition with other facilities, whatever facility it might be. You have to have those kinds of an increase to sell the mission. If you run too close to the edge in terms of the capability of the mission compared to competing facilities, you run into a problem - hopefully never as severe as the aberration of HST...

(UNIDENTIFIED): That's quite true and actually it's a great struggle to get out a factor of 2-1/2 to 3 in some ranges for the spectrum and in other ranges of the spectrum, you have an infinite factor.

P. STOCKMAN: Yes, but we are competing, even now, with really superb data we're getting in the ultraviolet. The fact that we're losing something like a factor of 3 to 4 in terms of throughput in the spectrograms leads some people to compare us to IUE. I think we're far superior to IUE, even if the same number of photons go through the aperture because of the improved instruments in the telescope. But clearly whereas we were supposed to be a factor of something like 50 better than IUE, we're now not as competitive as we should have been and that's hurt us.

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THREE CURRENT CONCEPTS FOR A SUCCESSOR TO THE HST

- PROPOSAL FOR A SUCCESSOR TO THE HST
- LUNAR AND HIGH EARTH ORBIT TELESCOPES
- CONCEPTS FOR A PARTIALLY FILLED-APERTURE SPACE TELESCOPE

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PROPOSAL FOR A SUCCESSOR TO THE HST [NEXT GENERATION SPACE TELESCOPE (NGST)]

PIERRE BELY

SPACE TELESCOPE SCIENCE INSTITUTE
Baltimore, Maryland

March 4, 1991

(Presentation material follows)

NGST GOALS

IDEALLY:

- A quantum jump with respect to HST (similar to what HST would have been in 1977 compared to the ground telescopes of the time)
- Examples:
  . a 10 meter space-based
  . a 16 meter on the moon

REALISTICALLY:

Deliver by 2005 the most telescope at a cost comparable to HST's
- use technological advances to improve
  . resolution
  . collecting power
  . wavelength coverage
  . observing efficiency
- increase the share of international participation

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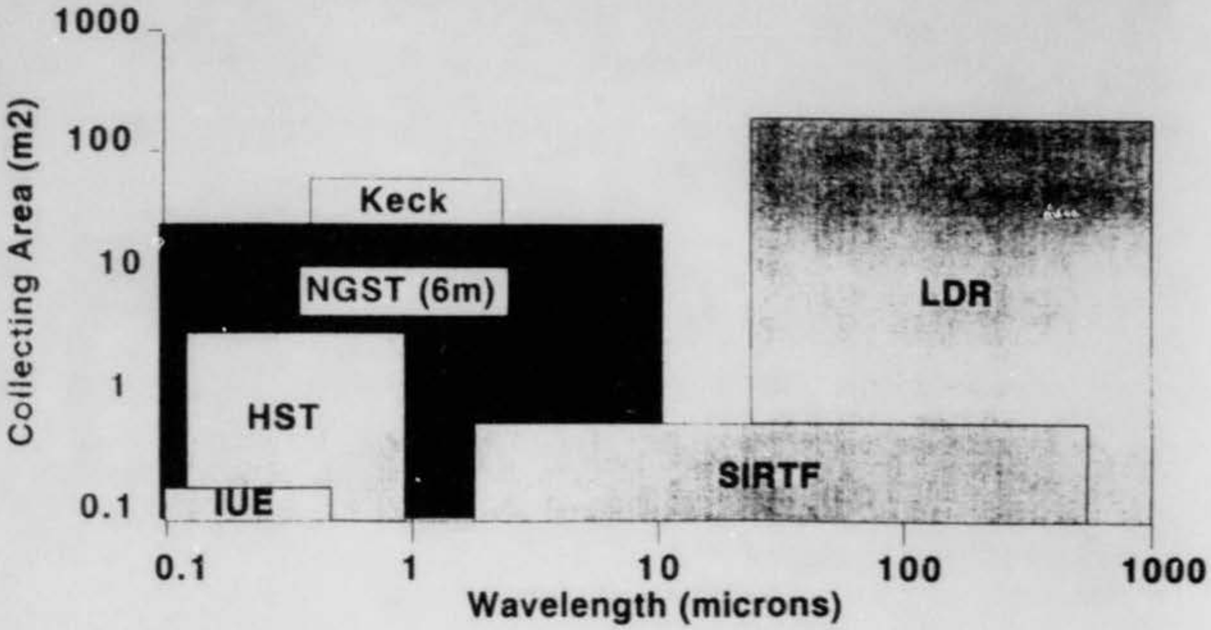
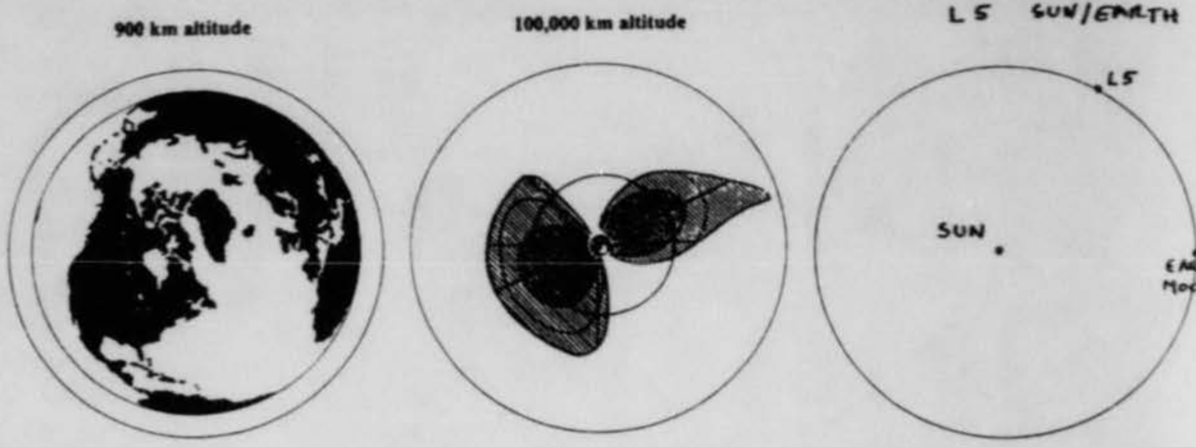
NGST POTENTIAL



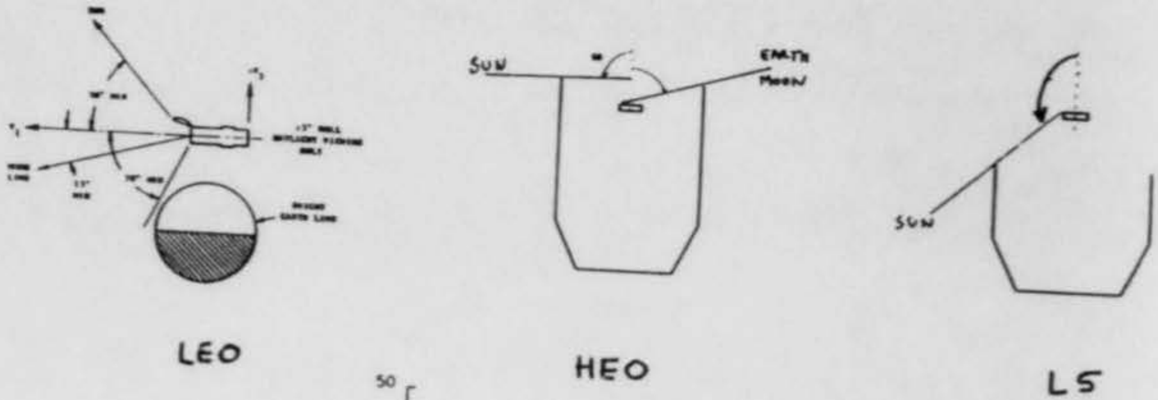
RATIONALE

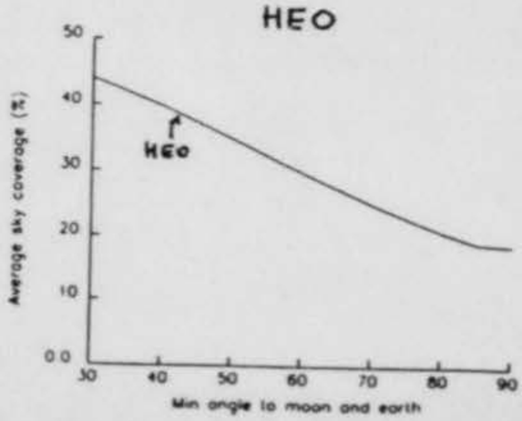
- Select optimal orbit for astronomical observations
  (high observ. efficiency, low thermal input, benign environment)
- Integrated spacecraft/ telescope/scientific instrument design
- Rely mostly on current technology and minimize required development
- 7-10 years lifetime - without on-orbit maintainance
- Minimize moving parts and complex systems

ORBIT



BAFFLING - SKY COVERAGE





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ORBIT

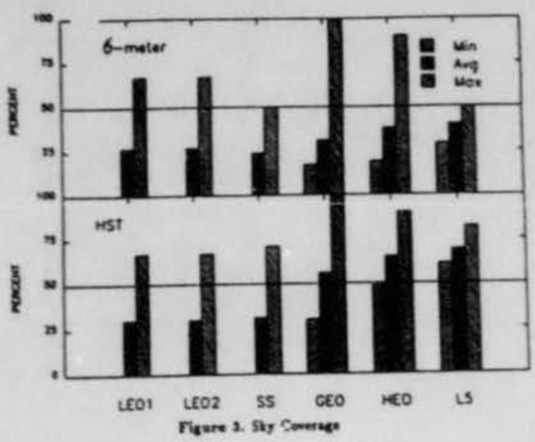
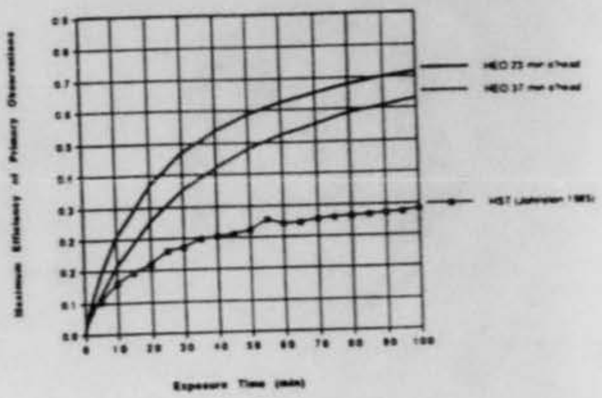
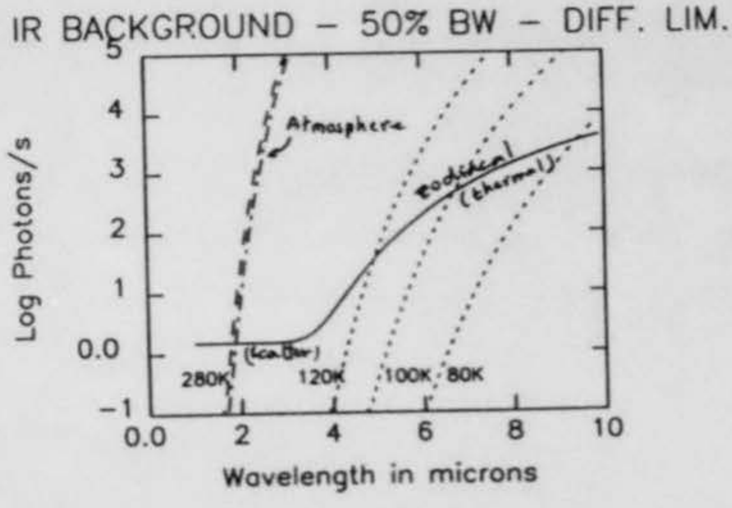


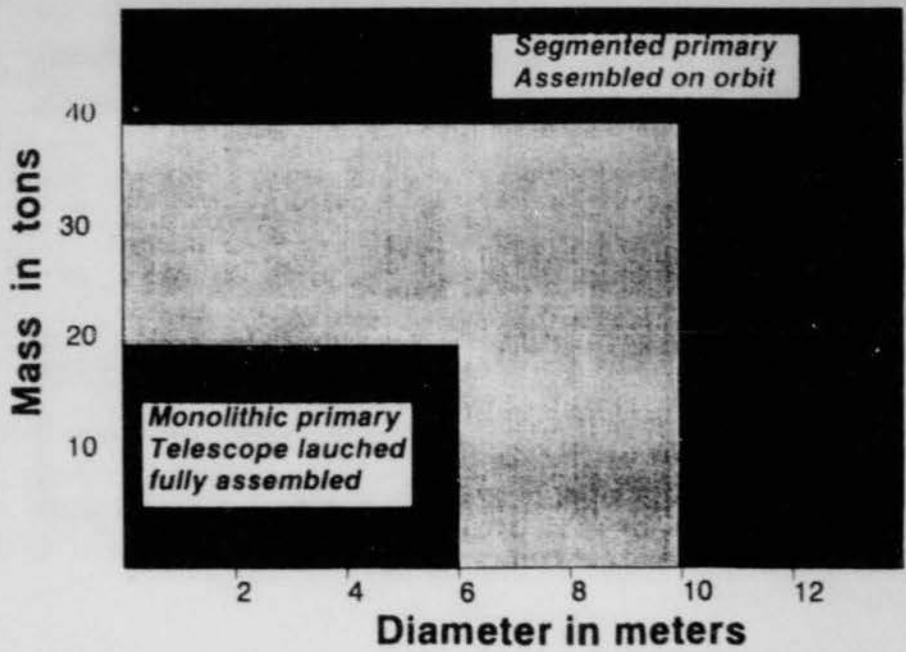
Figure 3. Sky Coverage



IR BACKGROUND



MONOLITHIC VS SEGMENTED PRIMARIES



OPTIMAL FOCAL RATIO

Nyquist criterion: pixel size= $\lambda f/2D = \lambda FD/2D$ $\longrightarrow$ $F=2\ px/\lambda$

Wavelength microns	Resolution mas	Pixel size microns	Optimal F/
1	42	50	100
0.6	25	10	34
0.24	10	5	41
0.12	5	5	83

Use: $\longrightarrow$ $\boxed{F/50}$

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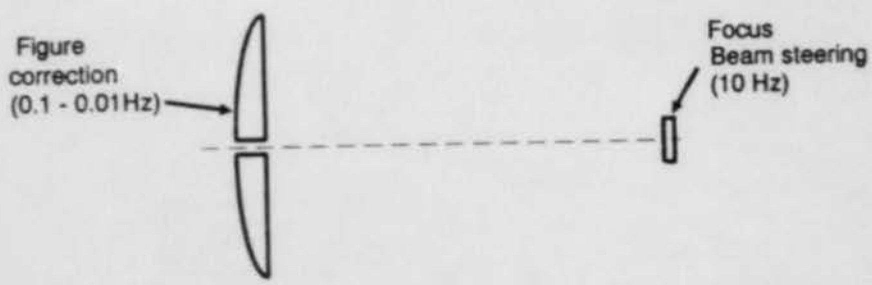
SEGMENTED VS MONOLITHIC PRIMARIES

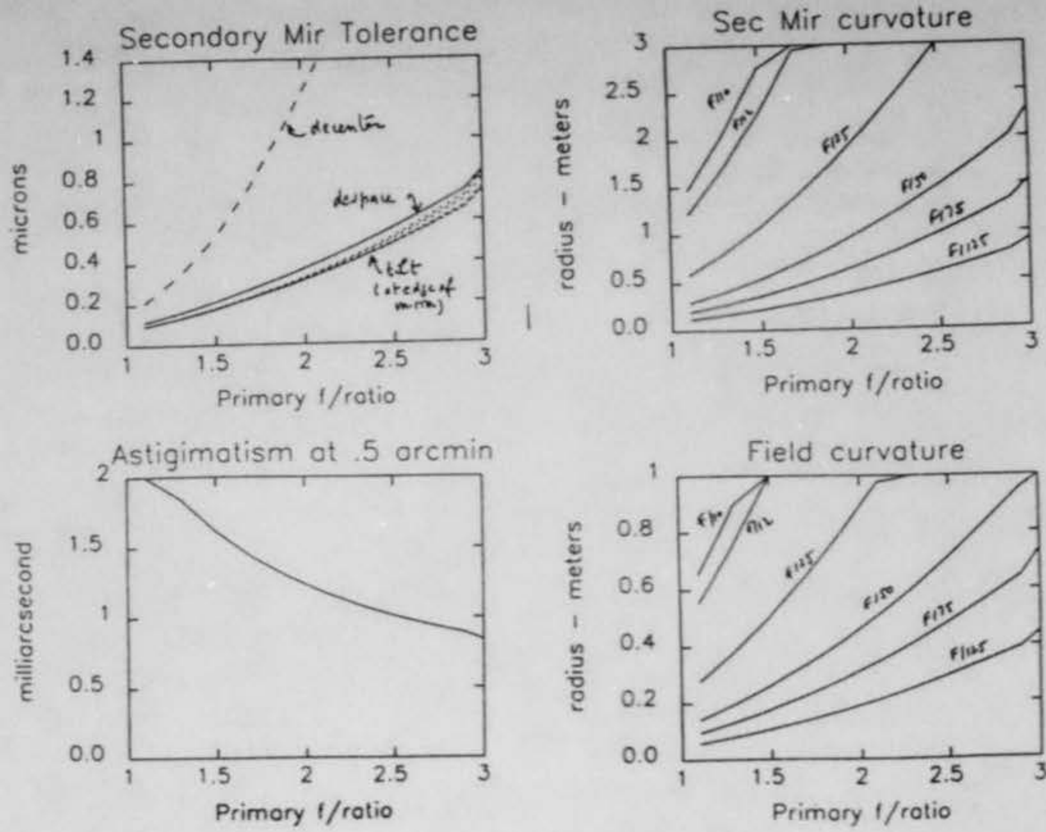
	Pros	*Cons*
Segmented	Allow very large apertures Smaller overall mass	Requires cophasing sensing and metrology Higher IR background Lower reliability Requires launch load protection
Monolithic	Polishing straightforward No cophasing required	Higher overall mass Limited to 8 m apertures

→ Within mass limitations, $\boxed{\text{monolith}}$ is the prime choice for a 6 meter

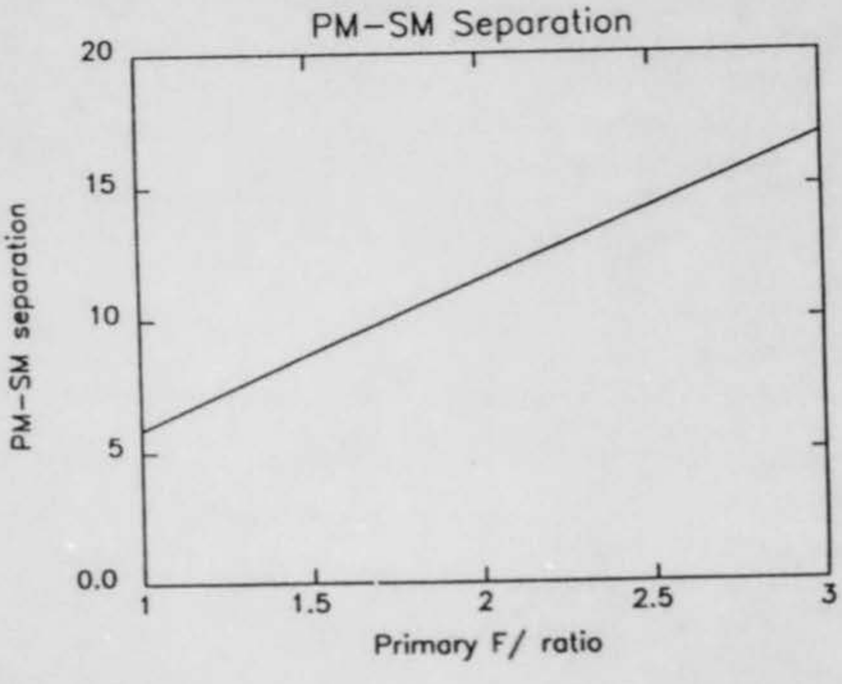
WAVEFRONT CORRECTION

Wavefront Errors	*Origin*	*Bandwidth*	*Sensing*	*Correction*
Tilt - Focus	Pointing errors Thermal	10 Hz 0.1 to 0.01Hz	Guide Star	Active Second mirror + Pointing
Coma **Astigmatism, trefoil** **Spherical**	Figure errors Gravity release Thermal	DC DC 0.1 to 0.01 Hz	Curvature sensing on on 2nd star	Actuators on Primary mirrror
High order aberrations	Polishing	DC	None	None





PRIMARY F/ RATIO



OPTICAL PARAMETERS
(Ritchey-Chretien configuration)

System characteristics:	
Primary mirror diameter	6.000 m
Final Cassegrain focus F/ratio	50.000
Wavelength	0.125 microns
Backfocal distance	1.000 m
Total protected field	4.000 arcmin on sky
Final focal length	300.000 m
Focal plane:	
Focal plane scale	1455.0 micron/arcsec
"	87.0 mm/arcsec
Airy disk diameter	0.010 arcsec
"	15.250 microns
Field curvature (radius)	0.502 m
Astigmatism at 1 arcmin	0.004 arcsec
at 5 arcmin	0.106 arcsec
at 10 arcmin	0.424 arcsec
at 15 arcmin	0.953 arcsec
Mirror parameters:	
Primary mirror f ratio	2.000
Radius curvature of primary mirror	24.000 m
Primary mirror conic constant	-1.000
Primary-Secondary separation	11.500 m
Radius curvature of secondary mirror	1.042 m
Secondary mirror clear diameter (zero field)	0.250 m
Secondary mirror conic constant	-1.177
Secondary mirror tolerances:	
Tilt	0.537 arcsec
Decenter	1.301 microns
Despace with refocussing	7.794 microns
Despace w/o refocussing	0.399 microns
Baffles:	
Upper baffle distance from primary apex	10.686 m
Upper baffle diameter	0.669 m
Lower baffle distance from primary apex	6.425 m
Lower baffle diameter	0.298 m

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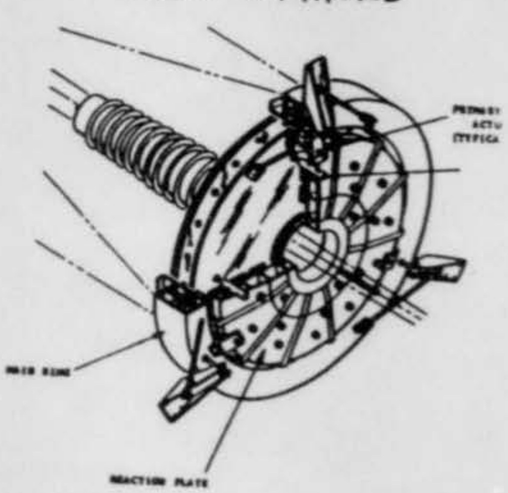
MOMENT VS. FORCE ACTUATORS

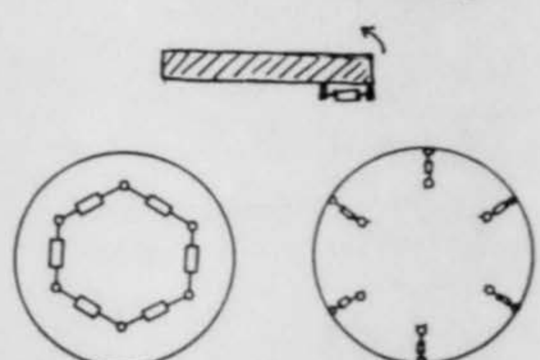
Table 1. A Generic Comparison between Moment and Piston Actuation Approaches

Characteristic	Actuation Approach	
	Moment	Piston
• Line of action	Perpendicular to optical axis, or parallel to surface	Parallel to optical axis, or normal to optical surface
• Reaction structure	Not required	Required
• Kinematic mount	Yes	No
• Coarse/fine control	Uncoupled (using separate actuators)	Coupled (using dual-mode actuators)
• Coupling of reaction/support structure distortion with mirror	No	Yes
• Weight	Less	More
• Actuator connectivity	Series	Parallel
• Dynamic range of DM	Variable	Fixed
• DM resonant frequency	Less	More
• Actuator density	Less	More
• Influence function	Global	Global (for Force actuators) Pseudo-zonal (Disp. actuators)
• Control system matrix	Coupled	Coupled (for Force actuators) Pseudo-diagonal (Disp. act.)

FORCE ACTUATORS



MOMENT ACTUATORS



TANGENTIAL RADIAL

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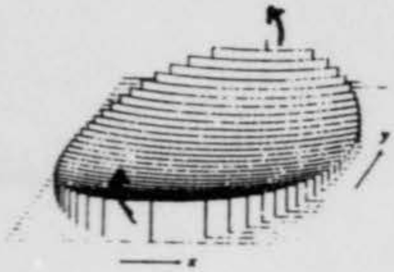
FIGURE CORRECTION

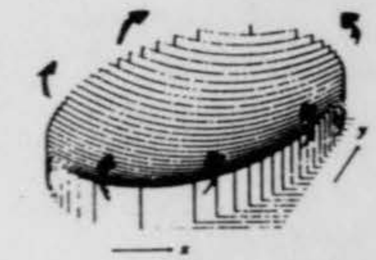
Zernike Polynomials for zero obscuration

	$Z_1 = 1\theta$	Constant
	$Z_2 = 2r\cos\theta = 2x$	X-tilt
	$Z_3 = 2r\sin\theta = 2y$	Y-tilt
2nd	$Z_4 = \sqrt{3}(2r^2 - 1)$	Focus
2nd	$Z_5 = \sqrt{6}r^2\cos 2\theta$	0° Astigmatism
2nd	$Z_6 = \sqrt{6}r^2\sin 2\theta$	45° Astigmatism
3rd	$Z_7 = \sqrt{8}(3r^3 - 2r)\cos\theta$	x-coma
3rd	$Z_8 = \sqrt{8}(3r^3 - 2r)\sin\theta$	y-coma
3rd	$Z_9 = \sqrt{8}\, r^3\cos 3\theta$	x-clover
3rd	$Z_{10} = \sqrt{8}\, r^3\sin 3\theta$	y-clover
	$Z_{11} = \sqrt{5}(6r^4 - 6r^2 + 1)$	3rd order spherical
	$Z_{12} = \sqrt{10}(4r^4 - 3r^2)\cos 2\theta$	Sphere astigmatism
	$Z_{13} = \sqrt{10}\,(4r^4 - 3r^2)\sin 2\theta$	Sphere astigmatism
	$Z_{14} = \sqrt{10}\, r^4\cos 4\theta$	Ashtray
	$Z_{15} = \sqrt{10}\, r^4\sin 4\theta$	Ashtray

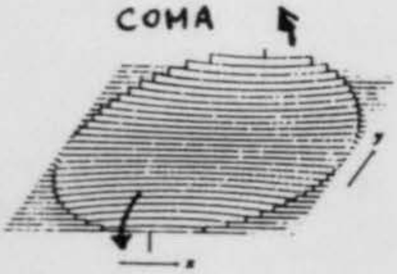
ASTIGMATISM



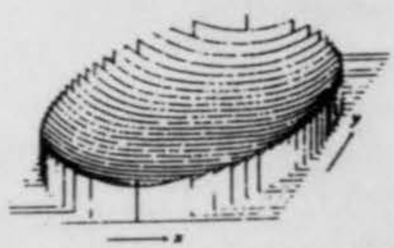
FOCUS



COMA



SPHERICAL



GUIDING

GUIDE STAR (PITCH / YAW)

Integration time 1/10 sec. (HEO quieter than LEO)

HST magnitude 14 over 25 ms.

Area:		Integration time:		Better throughput:			
$(6/2.4)^2$	x	(100 / 25)	x	(2)	=	50	i.e., 4.2 magnitudes

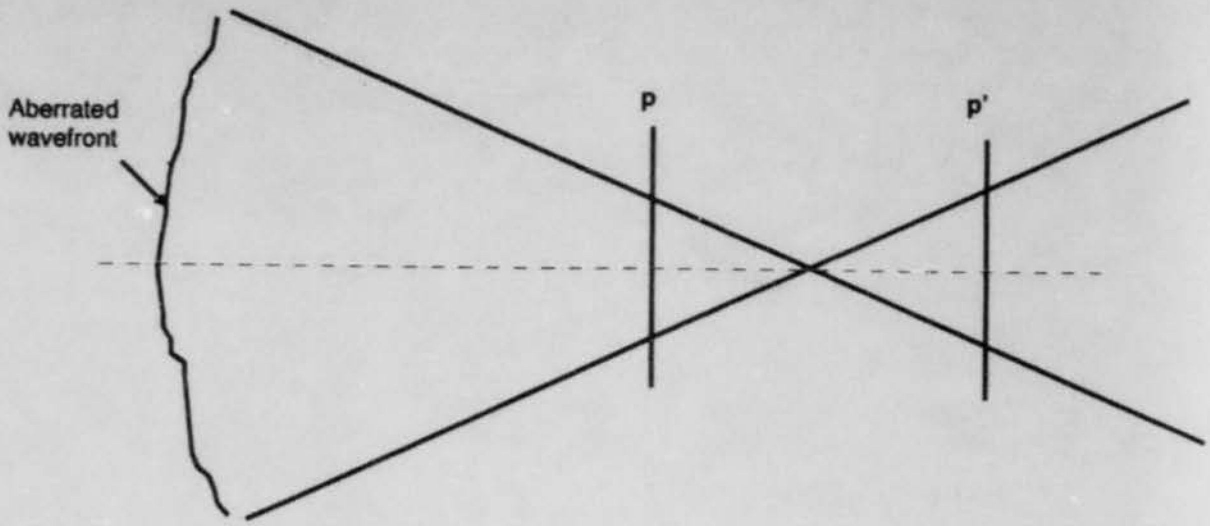
=> can guide on mag 18.

At galactic pole: 827 stars with magnitude 18 or less per square degree

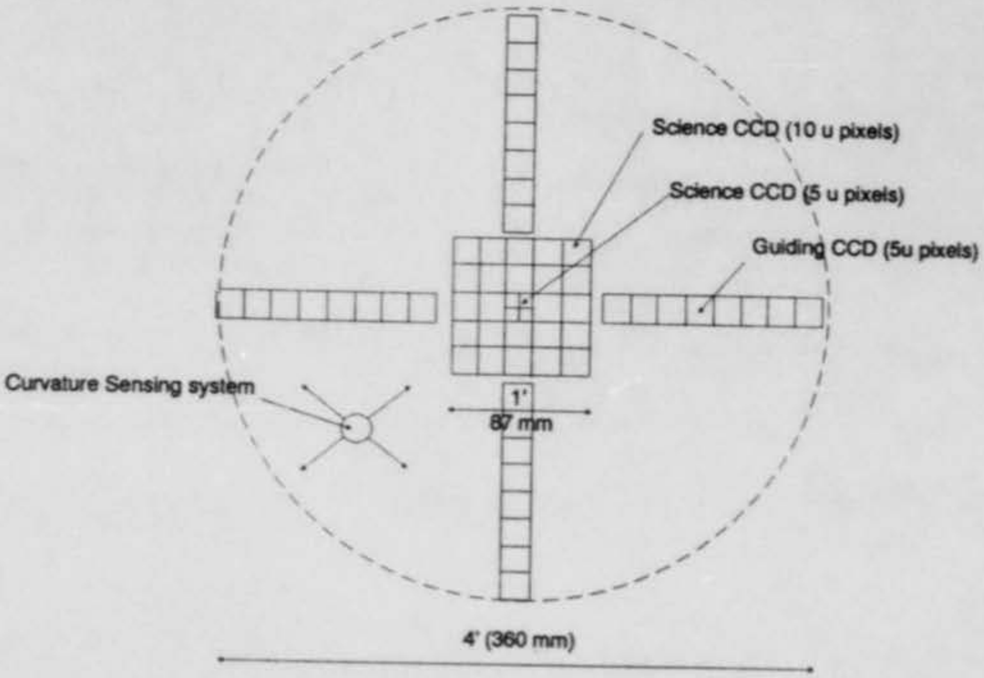
Need ~ 10 square arcminutes

i.e., Field = 2' in radius.

CURVATURE SENSING



FOCAL PLANE



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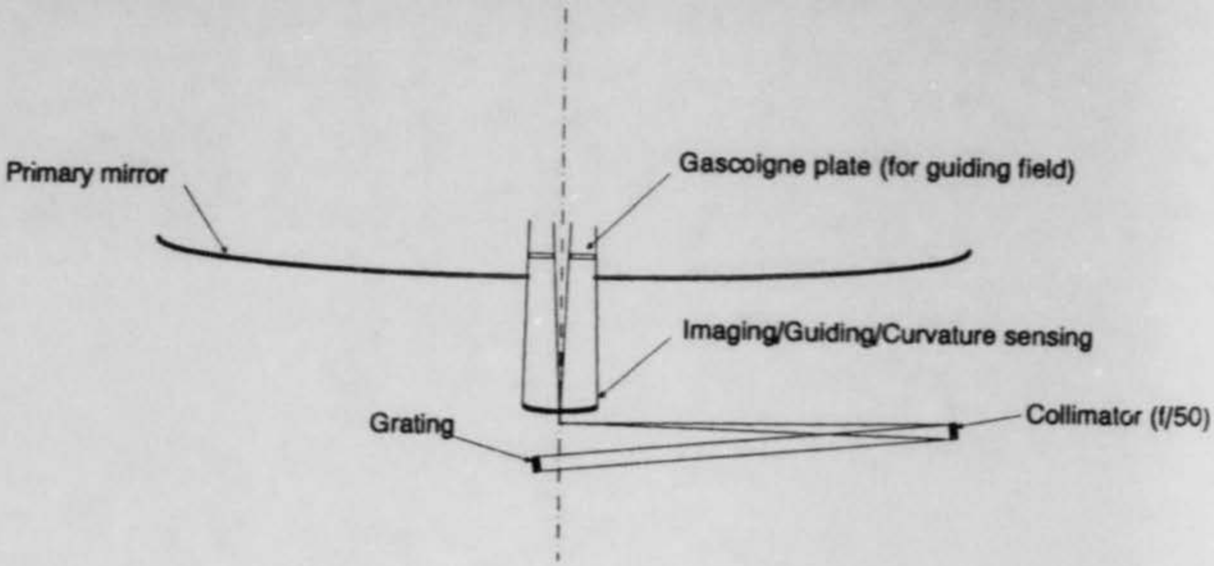
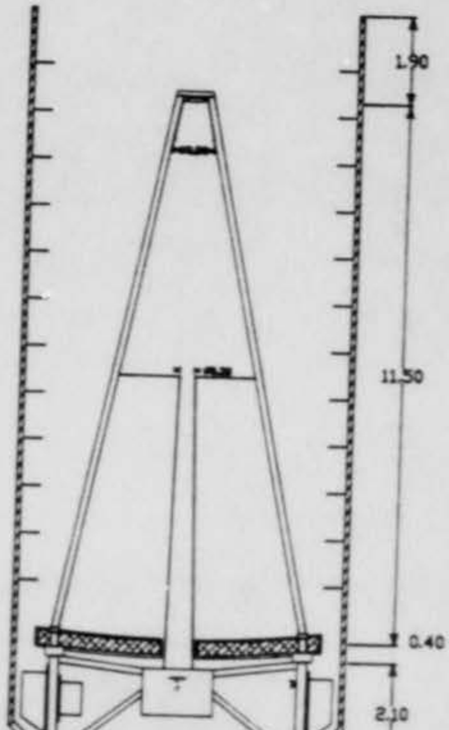
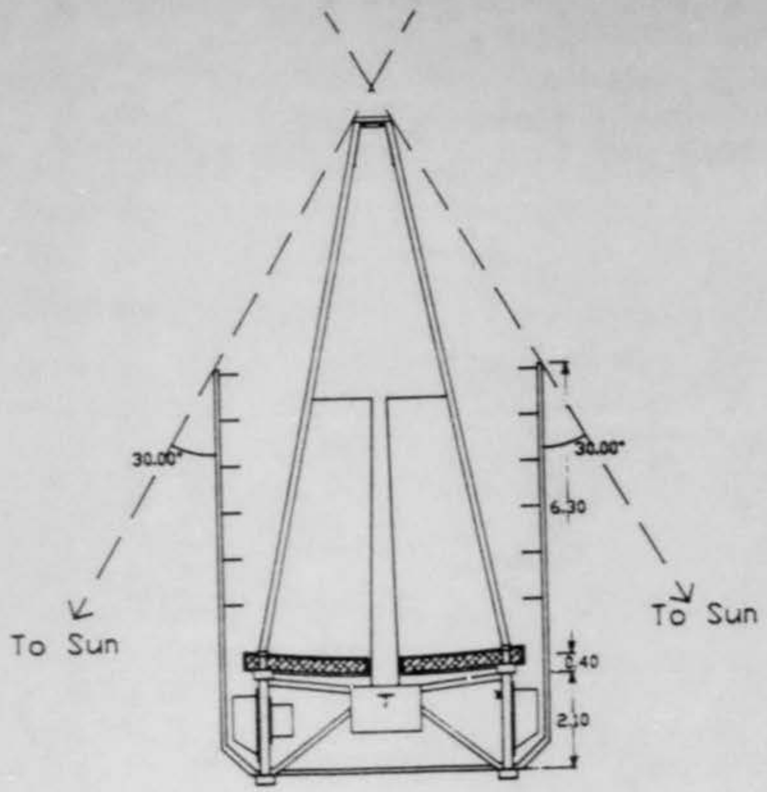
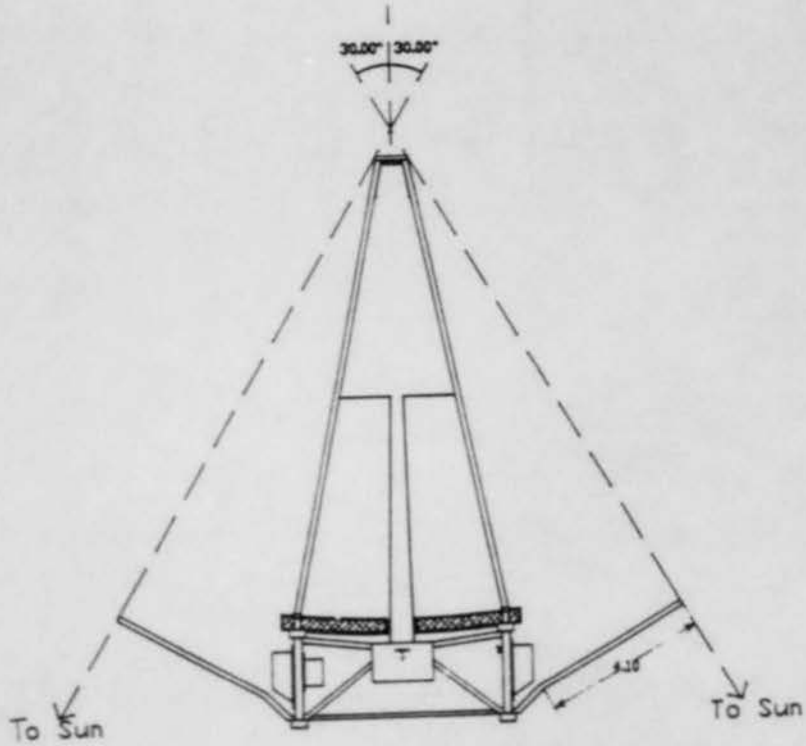
FOCAL PLANE



Six Meter Space Telescope




30.00°
30.00°
6.30
0.40
2.10
To Sun
To Sun


30.00°
30.00°
To Sun
To Sun

PRELIMINARY MASS ESTIMATE (tons)

	HST	6MST
Primary mirror[1] and figure control system	1.4	5.0
Sec mirror assembly, baffle and truss	0.3	0.6
Focal plane structure and central baffle	1.0	1.0
External shield and spacecraft structure	3.6	4.0
Science Instruments and Guiding system	2.0	1.5
Pointing control system [2]	0.5	1.0
Data management and communication	0.4	0.6
Power system	1.3	1.0 [3]
Thermal system	0.3	0.3
Crew systems	0.2	
Total	11.0	15.0

Notes:

(1) Lightweighting ratio: HST 75%, 6mST:85%

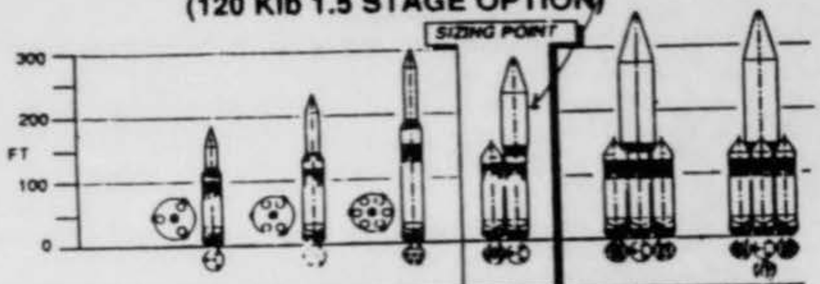
(2) Inertia: 31000/76000 kgm2 for HST; 85000/110000 kgm2 for 6mST

(3) No batteries for 6mST (400 kg for HST)

ADVANCED LAUNCH SYSTEM

FAMILY OF VEHICLES
(120 Klb 1.5 STAGE OPTION)

D≈10m
H≈26m



	ALS-C4	ALS-C5	ALS-C7	ALS-L	ALS-L2	ALS-L3
PAYLOAD 28.5° (KLB)	22	42	82	120 — 60t	224	318
PAYLOAD 90° (KLB)	14	27	58	81 — 40t	181	261
GLOW (MLB)	1.24	1.65	2.47	3.49	5.31	7.09
CORE SUSTAINER (580KLB)	1	1	1	3	3	3
CORE BOOSTER (580KLB)	3	4	6	-	-	-
BOOSTER (580KLB)	-	-	-	7	2 X 7	3 X 7
RELIABILITY	.996	.994	.990	[illegible]	.994	.990
NRECURRING $M	46.0	49.5	55.2	70.3	87.0	100.3
RECURRING $/Lb	2,113	1,184	674	[illegible]	[illegible]	318

NEED AN UPPER STAGE FOR HEO

CAPACITY TO HEO : 20 to 30 tons (?)

4

KEY TECHNICAL ISSUES

1. Demonstrate feasibility of a 6-meter class monolithic mirror of diffraction limited quality at 100 K
2. Demonstrate feasibility of passive 100 K temperature operation
3. Demonstrate compatibility of a 6-meter class observatory in high orbit with ALS capability
4. Validate primary mirror figure control system (moment actuators)
5. Validate proposed wavefront sensing system (curvature sensing)
6. Validate beam steering concept (control/structure interaction)

QUESTIONS:

G. ILLINGWORTH: What was the number of actuators [needed for mirror figure control]?

P. BELY: Ideally in theory you have ten terms to correct so that's the number you need.

J. BURNS: Clearly you have a number of important advantages in going up to a higher orbit, but there is one important disadvantage and that has to do with receiving the full brunt of cosmic rays. How will you deal with that when it comes to your sensitive images with CCDs?

P. BELY: We feel maybe there is a need to choose a shield..., otherwise you have to suffer the showers from the shielding. So you need a detector system that can discriminate between the photons and cosmic rays.

J. BURNS(?): How would you do that because you have a flood of these cosmic rays coming down on the chip?

G. ILLINGWORTH: That's one of the key questions, but it is an issue that's been around. It does need further discussion.

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WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

LUNAR AND HIGH EARTH ORBIT TELESCOPES

MAX NEIN AND BILLY DAVIS

MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

March 4, 1991

(Presentation material follows)

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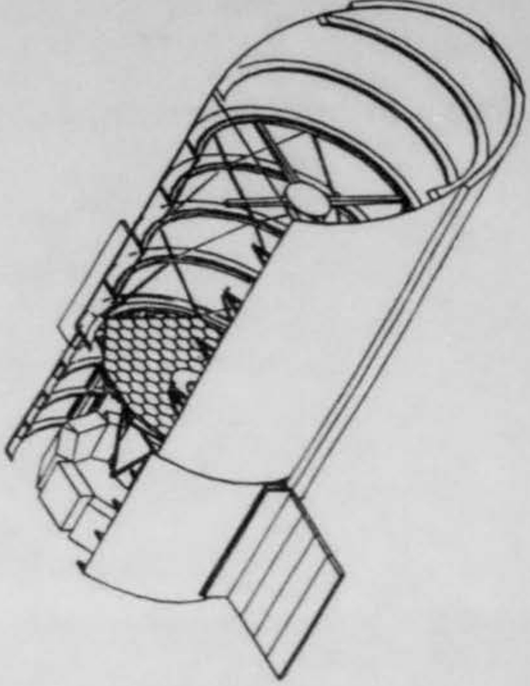
VOL 4

The High Earth Orbit Telescope



HEOT REQUIREMENTS FROM ILLINGWORTH AND BELY

1. APERTURE	6M
2. SPECTRAL COVERAGE	0.12 TO 10 MICROMETER
3. DIFFRACTION LIMITED AT ALL WAVELENGTHS	1/40 WAVE
4. OPERATIONAL TEMPERATURE	80 TO 100 K PASSIVE COOLING
5. ANGULAR RESOLUTION (UV)	5 MAS
6. FINE GUIDANCE FIELD	6' BY TWO FIELD STARS
7. TRACKING ACCURACY W/BEAM STEERING	0.5 MAS
8. PRIMARY FOCAL RATIO	f/1.4 (50 TO 300 FINAL)
9. PRIMARY AND SECONDARY OPTICS	FUSED SILICA OR ZERODUR, SEGMENTED
10. POWER	5 KW W/BODY MOUNTED ARRAYS (2.5 W ?)
11. BRIGHT OBJECT AVOIDANCE	SUN: 90 DEG (59 ?) MOON: 30 DEG (25 ?) BRIGHT EARTH: 90 DEG (59 ?)
12. INSTRUMENTS	CAMERA: HST WFPC UV/VIS SPECT: HST 2ND GEN STIS IR SPECT/CAMERA: LIKE NICMOS, 10 K
13. MASS GOAL	25-30 KLB
14. DATA ACQUISITION RATE	5 TO 10 MBPS (2 MBPS ?)
15. ORBIT	100,000 KM HIGH EARTH

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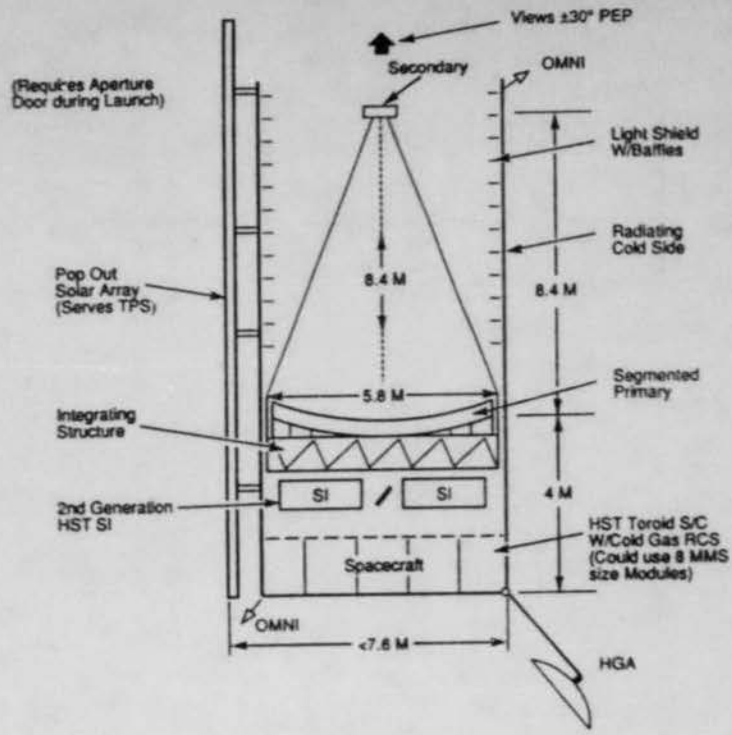
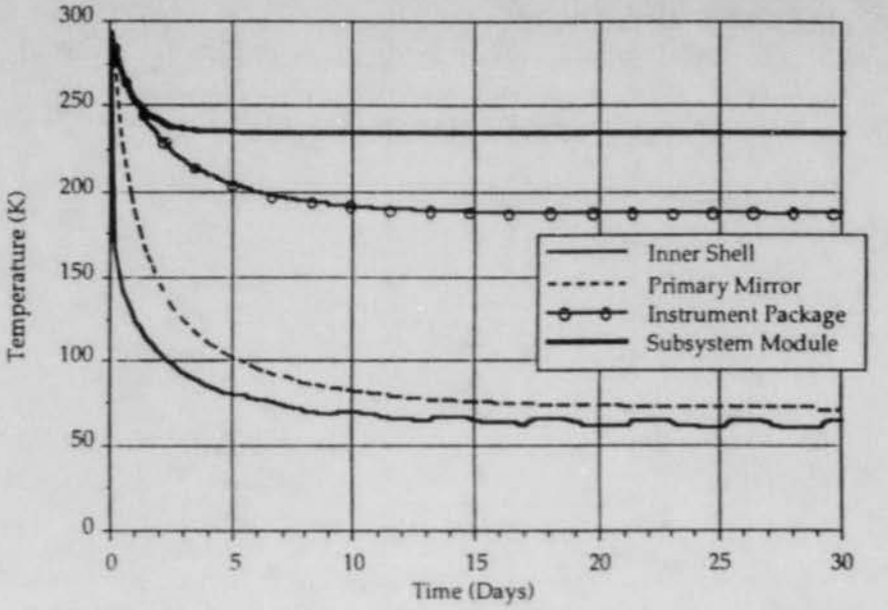
6M HEO Telescope (HEOT) Concept



CONFIGURATION DRIVERS

* MUST FIT WITHIN A 7.6 M (25') INSIDE DIAMETER PAYLOAD FAIRING
  - ASSUME INLINE HLLV WITH THIRD STAGE
* DESIGN TO VIEW WITHIN A 60 DEGREE BELT THAT IS PERPENDICULAR TO THE SUN LINE
  - ONE SIDE IS ALWAYS SUNWARD
  - THE OTHER SIDE VIEWS DEEP SPACE
  - THE SPACECRAFT END VIEWS DEEP SPACE
  - SHOULD BE ABLE TO OCCASIONALLY VIEW ANTI SUNWARD
* SHOULD MAKE LENGTH AS SHORT AS POSSIBLE
  - LOWER PRINCIPAL INERTIAS
  - MINIMIZES ENVIRONMENTAL TORQUES
  - BETTER CONTROLLABILITY/MANEUVERABILITY
* BODY FIXED SOLAR ARRAYS FOR POWER AND A SUN SHADE
* THE TELESCOPE AND OPTICS SHOULD BE KEPT AS COLD AS POSSIBLE (80 TO 100 K)
  - USE SUN SHADE AND INSULATION ON THE SUNWARD SIDE
  - RADIATE HEAT TO DEEP SPACE SIDE
* SHOULD BALANCE SURFACE AREA WITH CG TO MINIMIZE SOLAR RADIATION TORQUES
* ARRANGE SUBSYSTEMS IN A RING AT THE BASE OF THE TELESCOPE
  - PACKAGE IN BOXES SIMILIAR TO SIRTF
  - SPACECRAFT STRUCTURE MUST CARRY LAUNCH LOADS
* USE HST SI AND MOUNTING SI MOUNTING STRUCTURE AS STRAWMAN
  - SI ARE INSIDE OF SPACECRAFT RING
  - THE DETECTOR OF ONE SI MUST BE MAINTAINED AT 10 K

HEOT Thermal Analysis
Results - Transient Analysis



After 30 days mirror is at about 70K

No cyclic variation in mirror temperature observed

Instrument & subsystem electronics should have smaller radiators than modelled

HEOT Thermal Analysis
Conclusions & Comments

Conclusions

- Primary mirror temperatures of 70 to 80 K seem achievable by passive means
- Secondary mirror temperatures should be even lower
- Temperature variations of 3 to 5 K are possible across the primary mirror
- Radiator area or optical properties should be adjusted to provide a warmer environment for electronics

Final Comments

- Conduction between shells & sunshade, and instruments/subsystems & mirror support structure should be minimized.
- Anti-solar viewing may impact instrument cooling & will increase optics temperatures unless radiators are relocated & additional shades are provided
- Increased heat load on mirror due to actuators will result in increased temperatures
- Cryogenic cooler technology advances will be required to develop a space-qualified cooler for the 2 - 10 K temperature range

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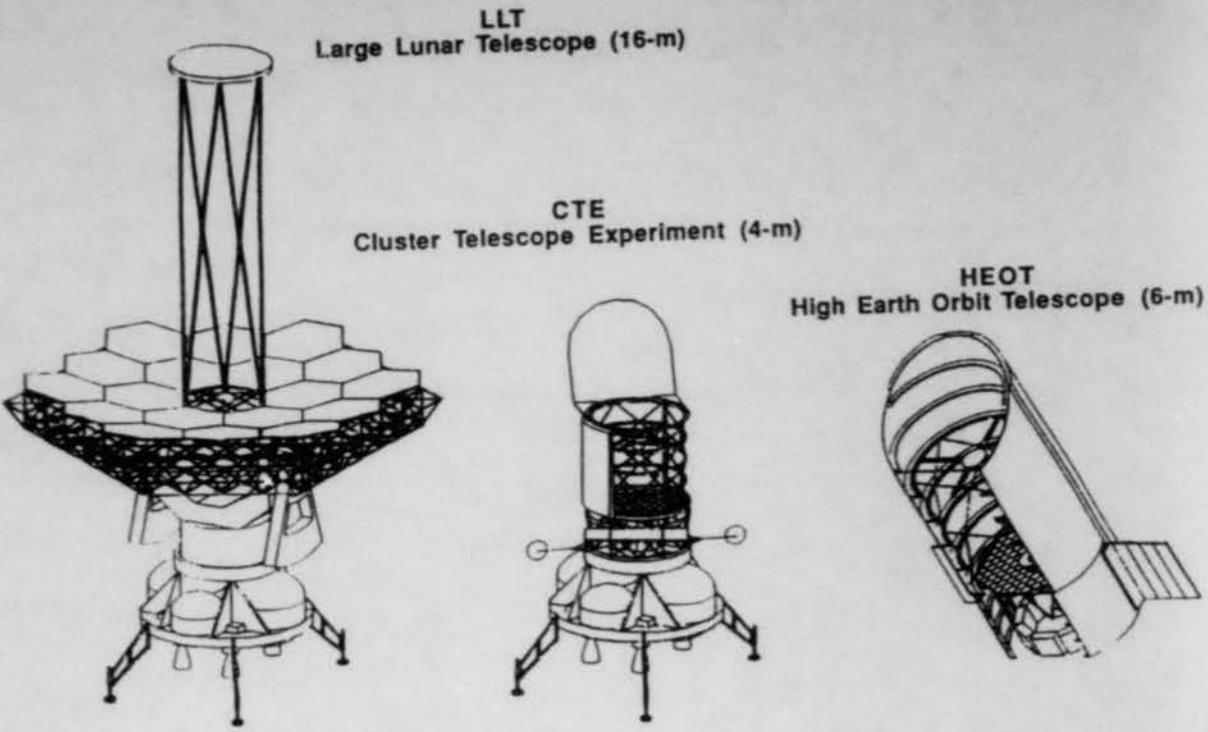
LUNAR AND HIGH EARTH ORBIT TELESCOPES



12\11\90:BGD

SEVERAL LLT DESIGN DRIVERS

1. TELESCOPE ARCHITECTURE (WHAT DOES IT LOOK LIKE?)
   - OPTICAL DESIGN/SEGMENTED PRIMARY/MATERIALS SELECTION
   - STRAWMAN INSTRUMENTS/NUMBER/CHARACTERISTICS
   - ALIGNMENT, DIMENSIONAL CONTROL AND ADAPTIVE OPTICS
   - PRECURSOR OPTIONS FOR EARLY SCIENCE

2. MISSION DESIGN DRIVERS (ARE THERE ANY SPECIAL CONSIDERATIONS?)
   - UNDERGROUND INSTRUMENTS FOR COSMIC RAY SHIELDING
   - PROBLEMS IN DIGGING, FILLING AND MOVING REGOLITH
   - SUN, LUNAR LIMB AND EARTH SHINE AVOIDANCE

3. SITE SELECTION (WHERE SHOULD WE PUT IT?)
   - NEAR SIDE, FAR SIDE OR POLE? NEAR OUTPOST FOR MEN UTILIZATION
   - CLOSE ENOUGH TO USE OUTPOST RESOURCES
   - FAR ENOUGH TO MINIMIZE CONTAMINATION

4. CONTAMINATION AND ENVIRONMENTAL CONTROL (HOW DO WE PROTECT IT?)
   - DUST FROM LUNAR OUTPOST ACTIVITIES/LUNAR LANDINGS
   - MICROMETEOROID AND STRAY LIGHT PROTECTION
   - TEMPERATURE CONTROL AND PROTECTIVE COVER DESIGN

5. TRANSPORTATION TO THE MOON (HOW DO WE GET IT THERE?)
   - LAUNCH, SPACE AND LANDING SYSTEMS REQUIRED
   - USE OF PROPOSED SEI ARCHITECTURE/COST PER LB ON THE MOON
   - MODULARITY FOR LAUNCH TO LEO, PREASSEMBLY AT SSF AND LUNAR LANDING

6. ASSEMBLY/CONSTRUCTION ON THE MOON (CAN THE PIECES BE PUT TOGETHER?)
   - SITE PREPARATION AND FOUNDATION ESTABLISHMENT
   - EQUIPMENT, TOOLS AND MATERIALS NEEDED
   - USE OF MAN AND TIME FOR ASSEMBLY

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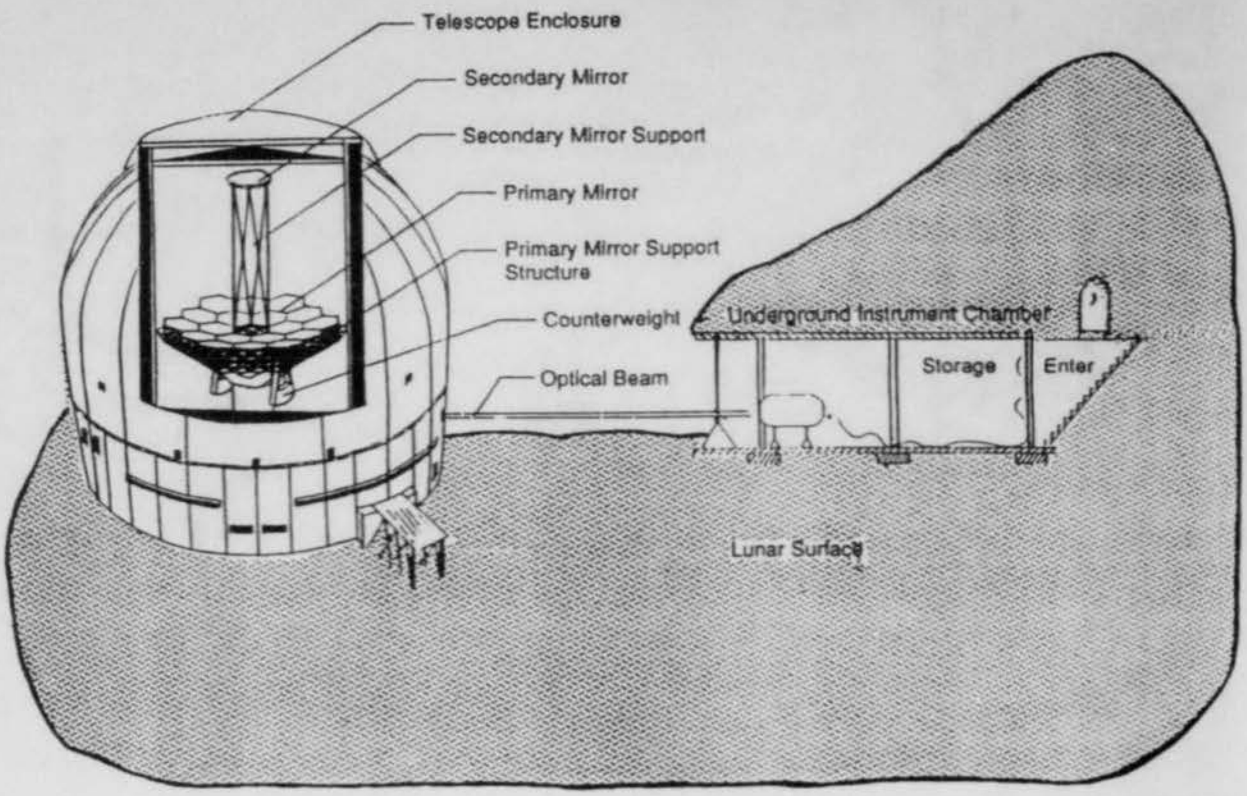
16 m Lunar Telescope Facility



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Large Lunar Telescope (LLT)

INSTRUMENT GUIDELINES AND REQUIREMENTS
(Ref. Illingworth and Bely)

- **Telescope:**

UV/Visible/IR Bandwidth:	0.1 to 10 µm
Field of View:	20 arcsec (UV); 2 arcmin(Vis/IR)
Resolution:	20 nrad (0.25µm) to 250 nrad (3µm dark zodiacal window)
Temperture:	Telescope < 100 K; Instruments 4 K to 270 K
Detectors:	Mosaic for diffr. lim. imaging and spectroscopy

- **Instruments:**

Operations:	Multiplexed Operation of Imagers and Spectrographs
Special Instrument:	On axis wide field imager with cont. access to focal plane
Data Rate:	2.5 MBPS
Background Noise:	Shielding of detectors against cosmic rays

- **General:**

Observations:	Interrupted during lunar day
Time on target:	Viewing time ranges from hours to days
Maintenance:	Access to instruments
Day time operation:	Straylight and temperature control

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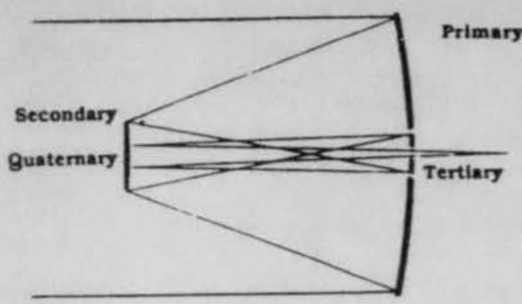
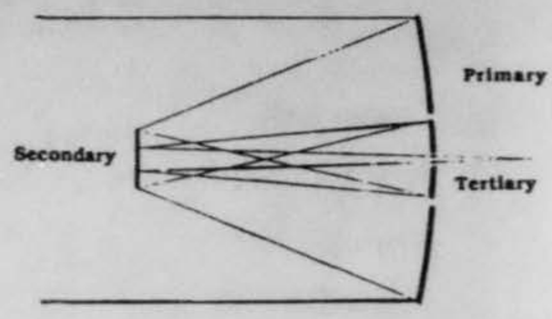
Telescope Optical Configurations



Spherical Primary Four- Mirror Telescope

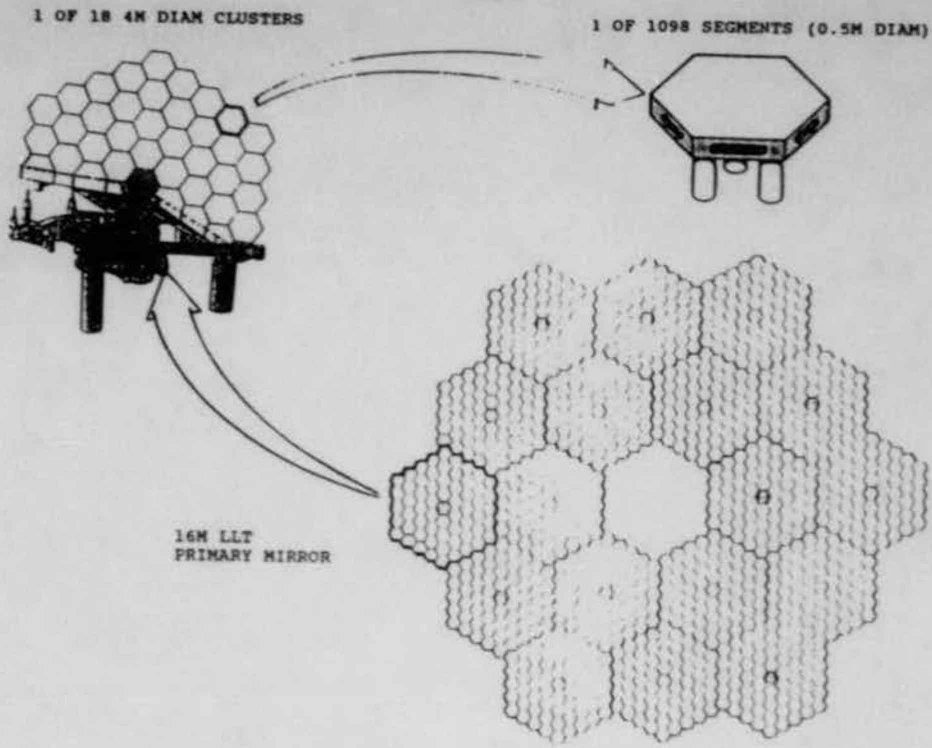


Four- Reflection Three- Mirror Telescope

Basic Telescope Parameters

Primary Diameter (m)	4	6	16
Secondary Dia. (m)	0.85(1.0)	1.25(1.5)	3.4(4.0)
Tertiary Dia. (m)	1.1(0.68)	1.64(1.1)	3.4(2.8)
Separation: (m)			
Pri.-Sec.	4	6	16
Sec.- Ter.	4	6	16
Backfocal dist.	5.33	8	-30 (coudè)
Diff.lim. Resol.(μrad) @ λ = 0.5 μm	0.15	0.1	0.038

SEGMENTS, CLUSTERS AND 16M LLT PRIMARY MIRROR



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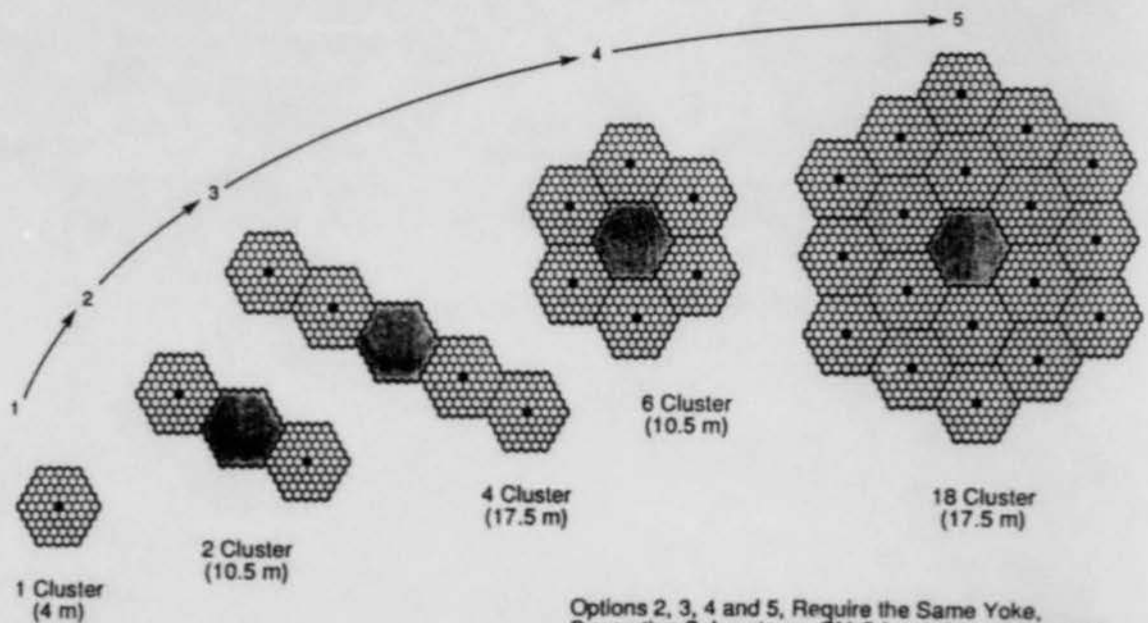
LLT PRECURSOR OPTIONS



Options 2, 3, 4 and 5, Require the Same Yoke, Supporting Subsystems, SH-C Launch, and Assembly Techniques. Option 1 Can Serve as a Test Bed for the Cluster and Lunar Environmental Effects.

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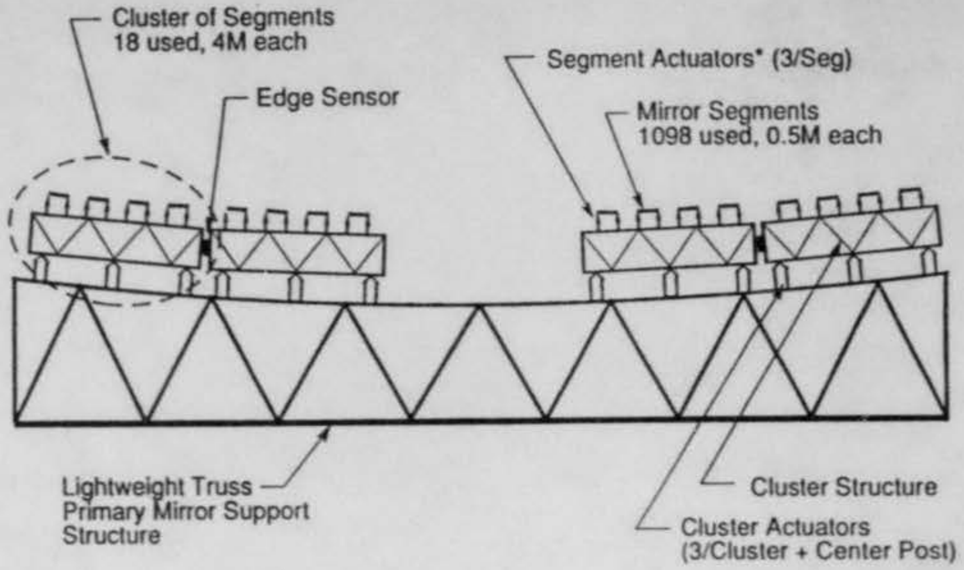
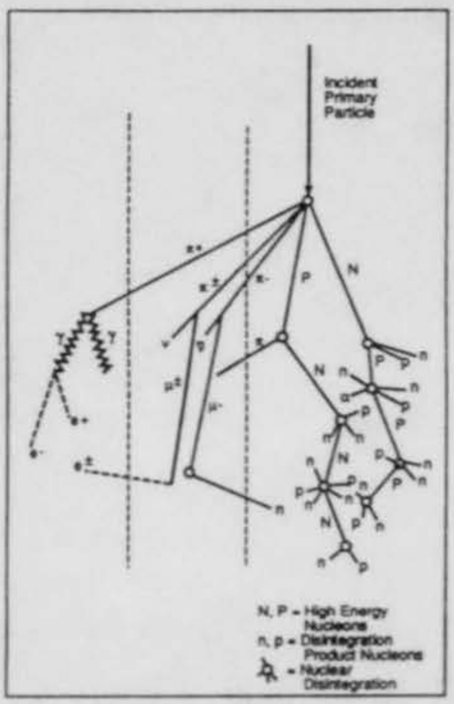
16M LLT Primary Mirror Concept

(Each Cluster Contains 61 Segments)



*Edge Sensors for Segments not illustrated

Cosmic Ray Effects on CCD Photodetectors



Background Noise

- Galactic Cosmic Ray (GCR) strikes material surrounding CCD photodetector
  - Secondary particle cascade results
  - Many particles strike CCD producing noise
- Primary GCR strikes CCD creating noise
- Noise is significant during the long integrations needed for faint object Detection

Long-Term Operation

- Heavy energetic GCR nuclei interact with detector
  - Displacement of atoms in structure
  - Degradation of detector performance

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Preliminary Recommendation

In the absence of detailed calculations it is a consensus that . . .

- Operation in unshielded Lunar environment would produce an inhibiting background for faint object detection
- Five meters of regolith is sufficient to reduce flux to LEO norm
- Should calculations indicate reduced shielding requirements, LLT design is simplified

Cosmic Ray Impact on CTE and HEOT

CTE

- Will experience same environment as Large Lunar Telescope (LLT)
- Will not have benefit of regolith shielding for noise attenuation
- Can serve as a "testbed" for cosmic ray noise assessment and alternative mitigation techniques

HEOT

- Orbit is outside Earth's magnetospheric shield against cosmic rays
- Does not benefit from 2x shielding available on the lunar surface
- Will not have shielding for noise attenuation
  - Would require 0.88m-thick lead shield

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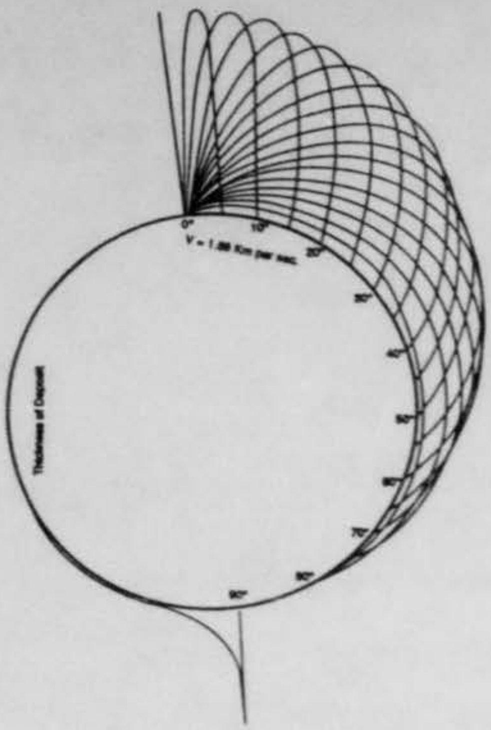
Lunar Dust Contamination



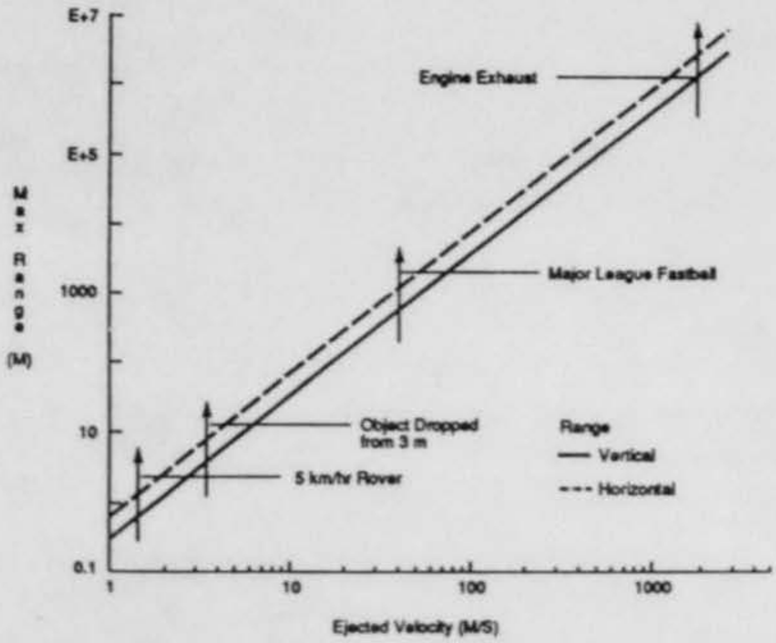
Dust Environment

- The moon is covered with dust in layers from a few cm to a meter in depth
- Rocket exhausts and human activities eject dust particles with ballistic trajectories
- Low Lunar gravity gives ballistic dust extensive range
- No atmosphere present to retard dust motion

Dust Effects on LLT

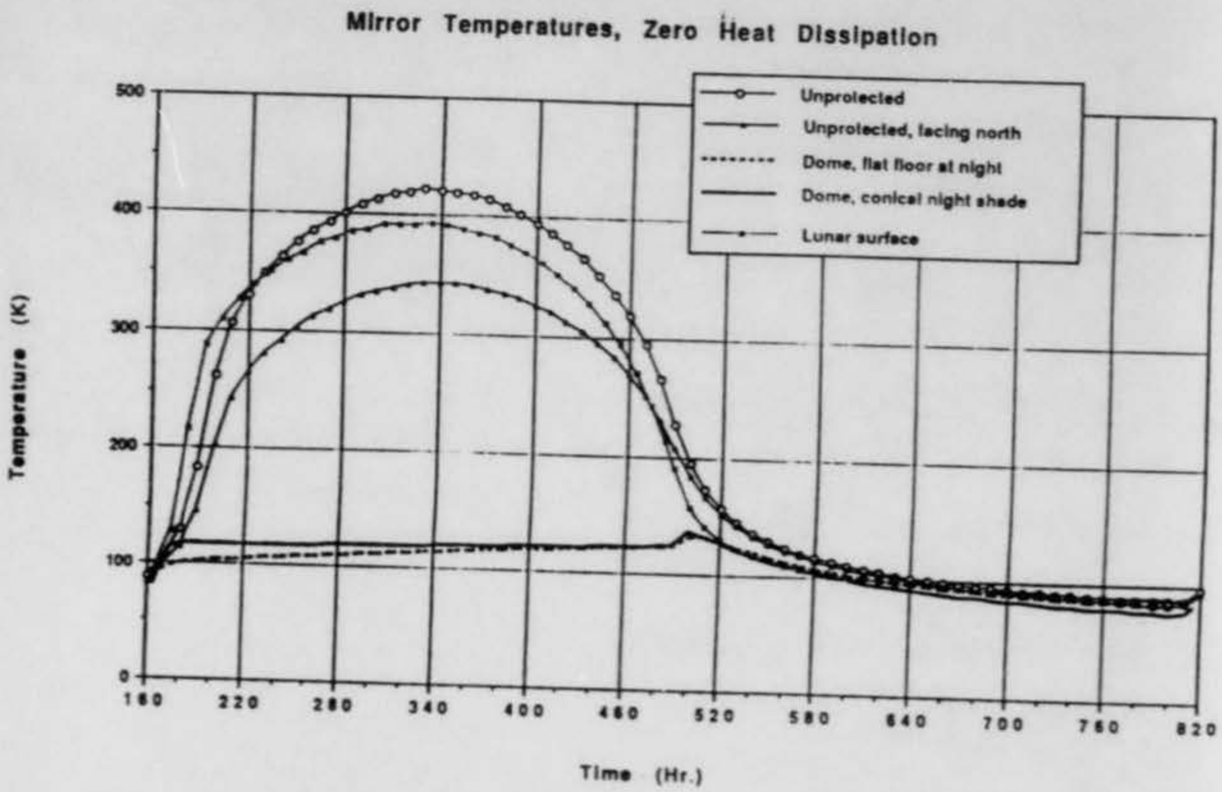
- Obscuration of telescope optics
- Damage to telescope mirrors (scratching)

Dust Mitigation

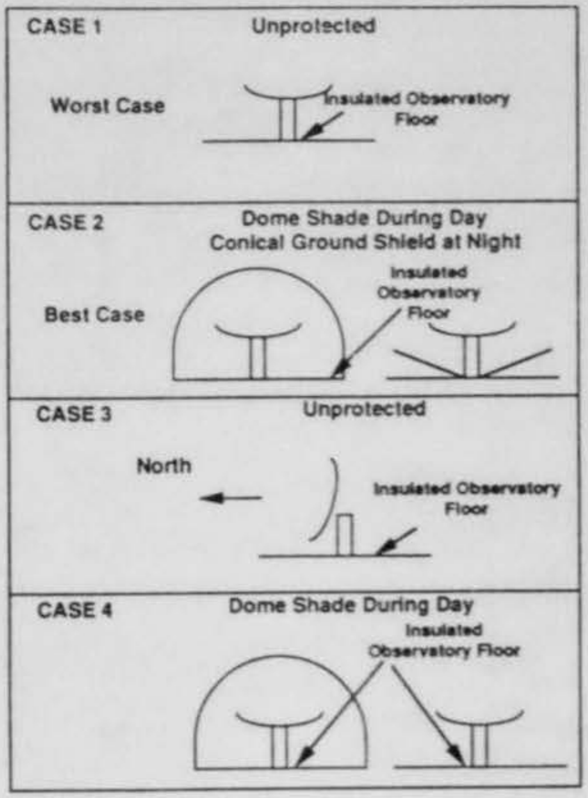


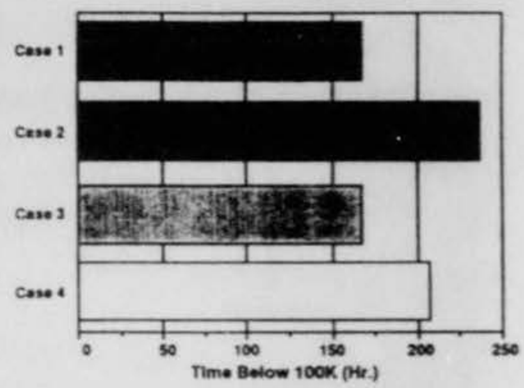
- Locate LLT at least 10Km from human outpost
- Cover Telescope during rocket lift-off and descent
  - Landings and launches occur infrequently
- Thermal shield can also serve as a dust cover
- Dust disturbed by engine exhaust will remain aloft for less than one hour

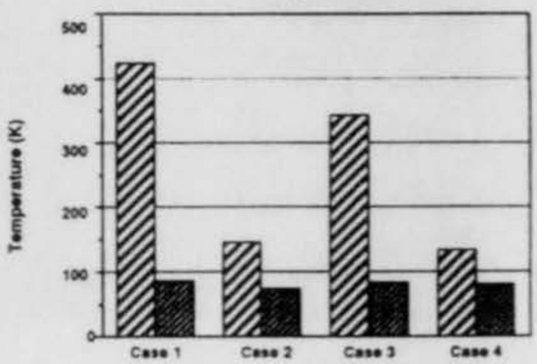
Large Lunar Telescope Thermal Analysis
Summary of Mirror Temperatures



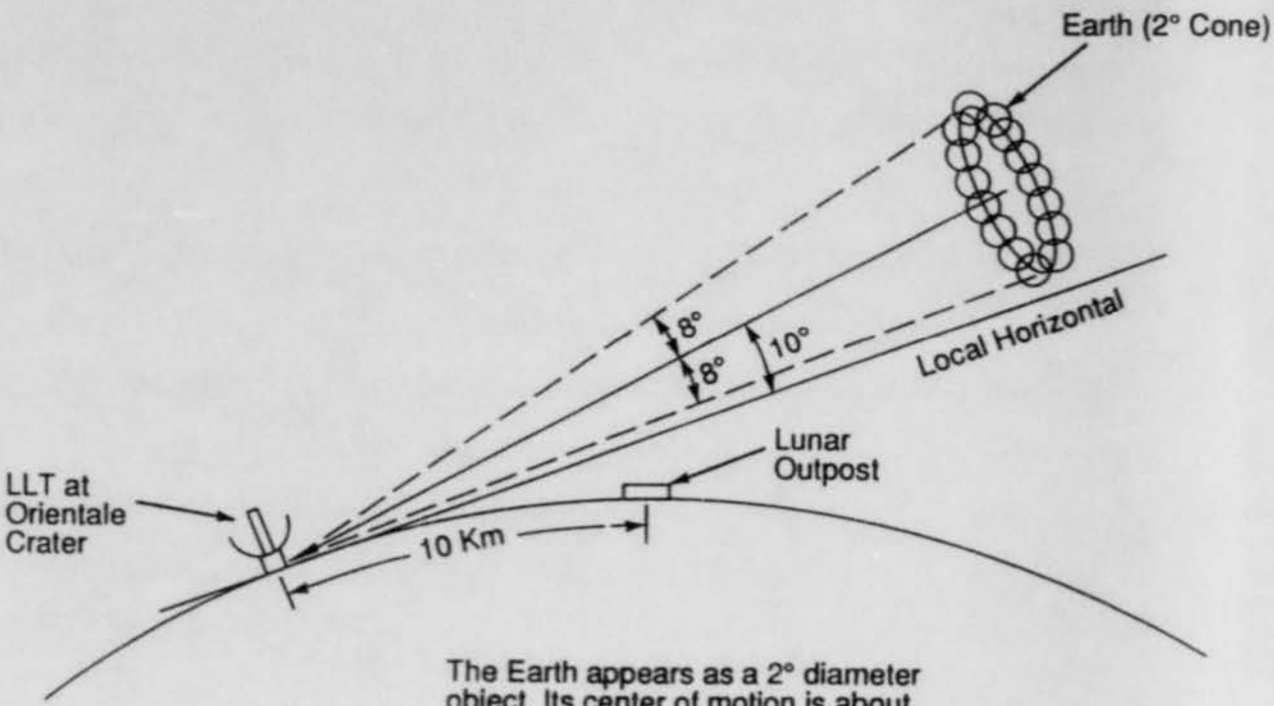
**Large Lunar Telescope Thermal Analysis
Summary of Results**







LLT Orientale Crater Location

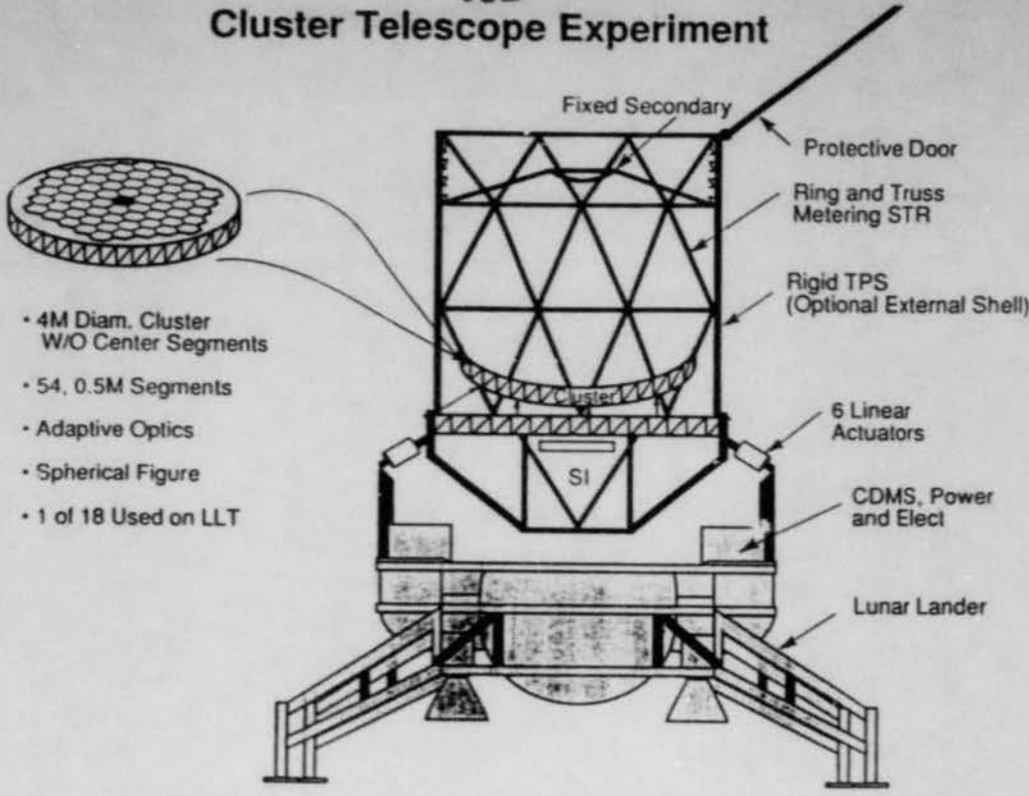


The Earth appears as a 2° diameter object. Its center of motion is about 10° above the lunar horizon. Its movement is confined to an approximate 8° conical area. The Earth makes one circuit around the region in one month.

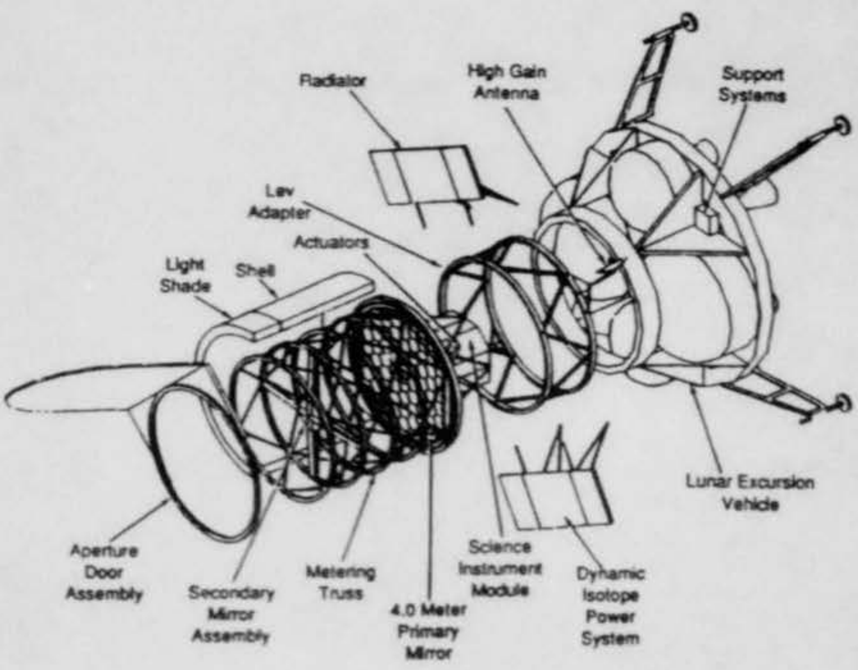
KEY DECISIONS

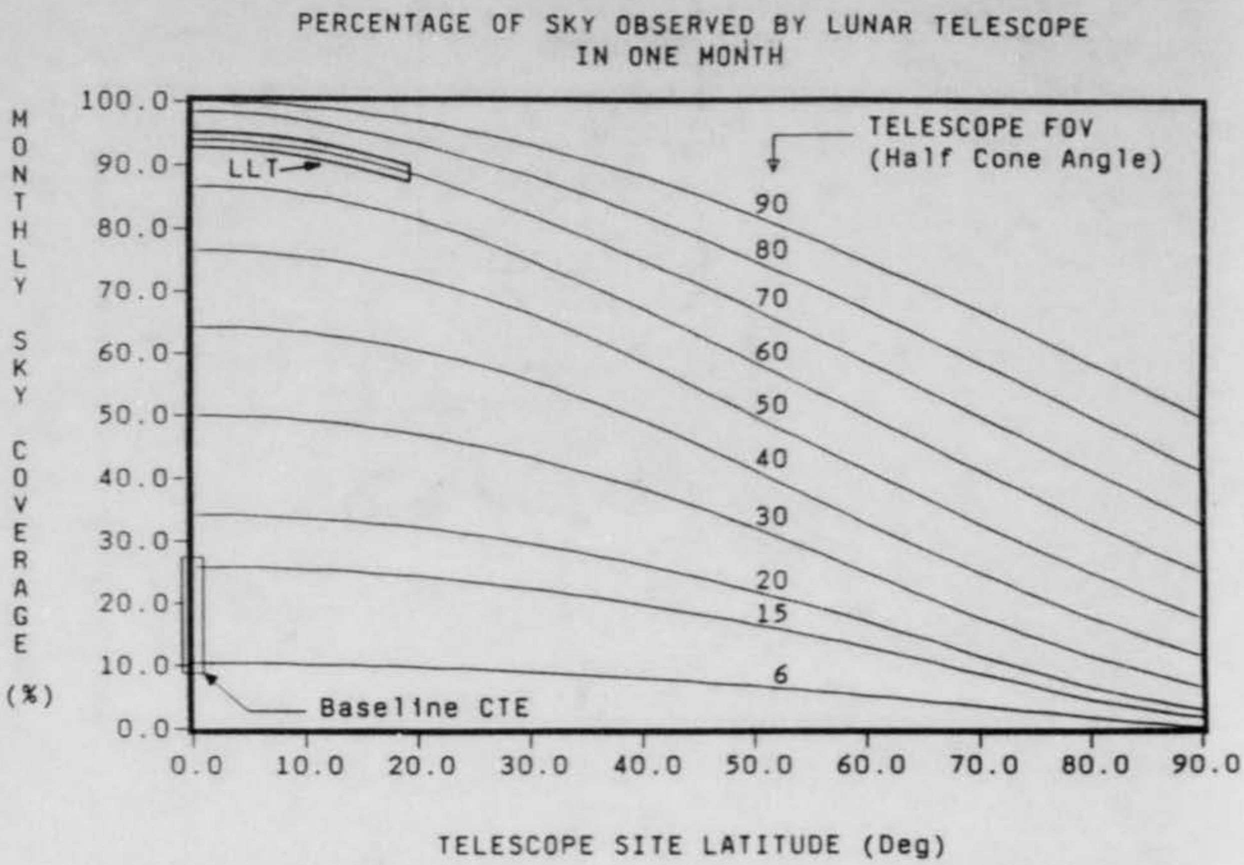
ISSUE	OPTIONS	SELECTION
1. PRIMARY MIRROR SIZE	4 TO 16 METER DIAM.	16M TO DETECT PLANETS AND ELEMENTS TO SUPPORT LIFE
2. TYPE PRIMARY MIRROR	MONOLITHIC; HONEYCOMB; THIN FLEXIBLE; SEGMENTED	SEGMENTED FOR LIGHTWEIGTH AND PACKAGING
3. TYPE SEGMENTS	HONEYCOMB; THIN GLASS; MOLDED	MOLDED/FIRED SIC SUBSTRATE POLISHED TO 1/40 WAVE (KAMAN)
4. SEGMENT SIZE	4M TO 10CM DIAM HEXA'	50CM SEGMENTS PACKAGED INTO 4M DIAM CLUSTERS
5. PRIMARY MIRROR FIGURE	HYPERBOLOIDAL; SPHERICAL	SPHERICAL PERMITS ALL ELEMENTS TO BE IDENTICAL (KORSCH)
6. AREAL DENSITY	10 TO 200 KG/M^2	ASSUMED 30 KG/M^2 (KAMAN) FOR COMPLETE CLUSTER
7. TELESCOPE ARCHITECTURE	NUMBER OF REFLECTIONS	SECONDARY/QUATERNARY COMBINATION WITH TERTIARY O/C IN PRIMARY
8. COSMIC RAD. PROTECTION	MAN-MADE SHIELDING VS BURYING INSTRUMENTS	COVER SI UNDER 5M OR MORE OF REGOLITH (COUDE' OPTICS)
9. LOCATION OF SI	UNDER TEL VS TO ONE SIDE	SIDE LOCATION. EASIER TO TUNNEL OR COVER THAN TO DIG HOLE
10. TYPE OF INSTRUMENTS	KECK, HST OR SIRTF TYPE SI TO COVER IR/VIS/UV	FIVE GENERIC SI. USE HST TYPE REPLACEABLE MODULES
11. POINTING MECHANISMS	AZ-EL YOKE; EQUATORIAL; HEXAPOD	AZ-EL YOKE UNDER TELESCOPE PERMITS PRECURSOR
12. SECONDARY SUPPORT	GEOMETRY OF METERING STR.	CENTRAL SUPPORT: ACCOMMODATEDS PRECUSOR W/O FULL OPTICS
13. TELESCOPE LOCATION	NEAR SIDE; FAR SIDE; POLE	ORIENTALE CRATER AT 85 DEG W. LONG. ON THE EQUATOR (LOWMAN)
14. OUTPOST RESOURCES VS SELF CONTAINED SUBSYSTEMS	DISTANCE FROM OUTPOST: 1, 10, 100, 1000 KM?	10KM PERMITS USE OF OUTPOST RESOURCES, MAN AND POWER
15. OPERATIONS CENTER	OUTPOST VS EARTH	EARTH BASED SOC
16. TELEMETRY LINK	OUTPOST VS EARTH	DIRECT EARTH COMMUNICATIONS
17. VIEWING	DAY/NIGHT VS NIGHT ONLY	NIGHT ONLY. HIGH DAY TEMP'-- IR IMPOSSIBLE. (STR DIMENSIONS)
18. THERMAL PROTECTION	LIGHTSHADE; DOME; SHED; ETC	TBD. MUST PROTECT FROM DAY TEMPERATURE EXTREMES
19. METEOROID PROTECTION	SHIELDING; DOME; INSULATION	NOT REQUIRED. OPTICS DEGRADATION ACCEPTABLE
20. DUST PROTECTION	DISTANCE FROM OUTPOST; PROTECTIVE COVER	DUST COVER REQUIRED DURING LANDINGS
21. MODULARITY	LARGE VS SMALL	LARGE TO MINIMIZE TIME FOR ASY'
22. ASSEMBLY	MANUAL; ROBOTICS; AUTOMATIC	MAN AND SURFACE SYSTEMS
23. PREASSEMBLY	SSF; LEO NODE; LUNAR	SSF PREASSEMBLY INTO LTV/LEV
24. ETO LAUNCH	SH-C VS GROWTH HLLV	SH-C' LAUNCH TO SSF. NEED 25 FT DIAM SHROUD
25. LLO TO MOON TRANS'	MARS VS LUNAR VEHICLE	LEV ASSUMED AT 33t PAYLOAD

Cluster Telescope Experiment



Cluster Telescope Experiment




PERCENTAGE OF SKY OBSERVED BY LUNAR TELESCOPE
IN ONE MONTH
MONTHLY SKY COVERAGE (%)
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
LLT
TELESCOPE FOV
(Half Cone Angle)
90
80
70
60
50
40
30
20
15
6
Baseline CTE
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
TELESCOPE SITE LATITUDE (Deg)

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WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

CONCEPTS FOR A PARTIALLY FILLED-APERTURE OPTICAL SPACE TELESCOPE

DAVE MEIER (for STEVE SYNNOTT)
JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California

March 4, 1991

(Presentation material follows)

JPL **PARTIALLY FILLED APERTURES**

RATIONALE

WHY DISCUSS A STUDY OF PARTIALLY FILLED APERTURES AT A CONFERENCE ON FILLED APERTURES?

- CERTAIN PARTIALLY FILLED APERTURES CAN SAMPLE THE ENTIRE (U,V)-PLANE: THEY OBTAIN THE SAME IMAGING INFORMATION AS A FILLED APERTURE

- WITH FEW EXCEPTIONS, THE TECHNOLOGY INVESTIGATED BY THE JPL STUDY ON PARTIALLY FILLED APERTURES IS APPLICABLE TO FILLED:

  - DEPLOYMENT(?)
  - PHASING
  - THERMAL CONTROL
  - VIBRATIONAL CONTROL
  - POINTING

JPL **PARTIALLY FILLED APERTURES**

THE NASA ASTROTECH 21 PROGRAM: TECHNOLOGY FOR OPTICAL INTERFEROMETERS IN SPACE

- SINGLE-SPACECRAFT FREE FLYERS -- S. SYNNOTT
- MULTIPLE-SPACECRAFT, LONG BASELINE INTERFEROMETERS -- D. JONES
- LUNAR-BASED, LONG BASELINE INTERFEROMETERS -- M. SHAO

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JPL PARTIALLY FILLED APERTURES

SINGLE-STRUCTURE SPACE OPTICAL INTERFEROMETER DESIGN TEAM

S. SYNNOTT, Team Leader

- **STRUCTURAL STABILITY**
  - SHORT TERM
    - PASSIVE (VIBRATIONAL ANALYSIS) -- J. HEDGEPETH
    - KNOWLEDGE (METROLOGY) -- M. SHAO, E. TUBBS
    - ACTIVE (DAMPING) -- J. FANSON, W. LAYMAN, M. SAN MARTIN
  - MID TERM
    - THERMAL (BLANKETING) -- R. MIYAKE, Y. WON
    - MATERIALS (CTE) -- P. DARDZINSKI, R. FREELAND
  - LONG TERM
    - MATERIALS (DESORPTION) -- P. McELROY
- **OPTICS AND INSTRUMENTATION**
  - OPTICS -- E. HOCHBERG, N. PAGE, A. VAUGHAN
  - DETECTORS -- S. PRAVDO
  - SPECTROSCOPY -- A. VAUGHN
- **SCIENCE RETURN**
  - IMAGING SIMULATIONS -- P. DUMONT, D. JONES, D. MEIER
  - SCIENCE ASSESSMENT -- D. MEIER

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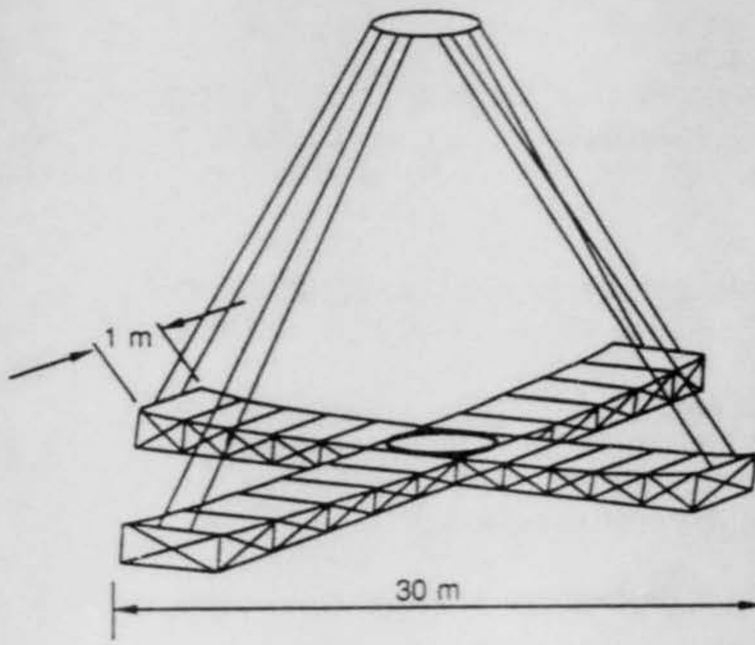
IMAGING SCIENCE

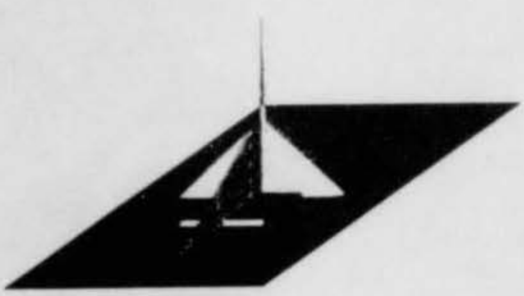
A "STRAW-MAN" MISSION: THE FILLED MILLS CROSS

ATTRIBUTES:

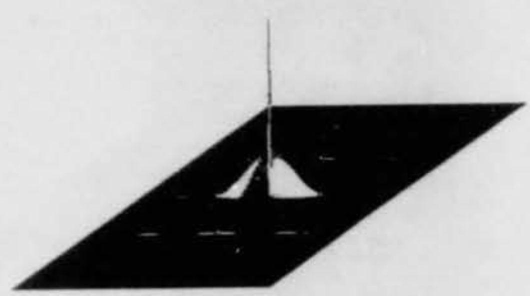
- 4 SEGMENTED, PARABOLIC ARMS, 1m x 15m EACH
- TOTAL COLLECTING AREA: $60m^2 \approx 8.7m$ MIRROR



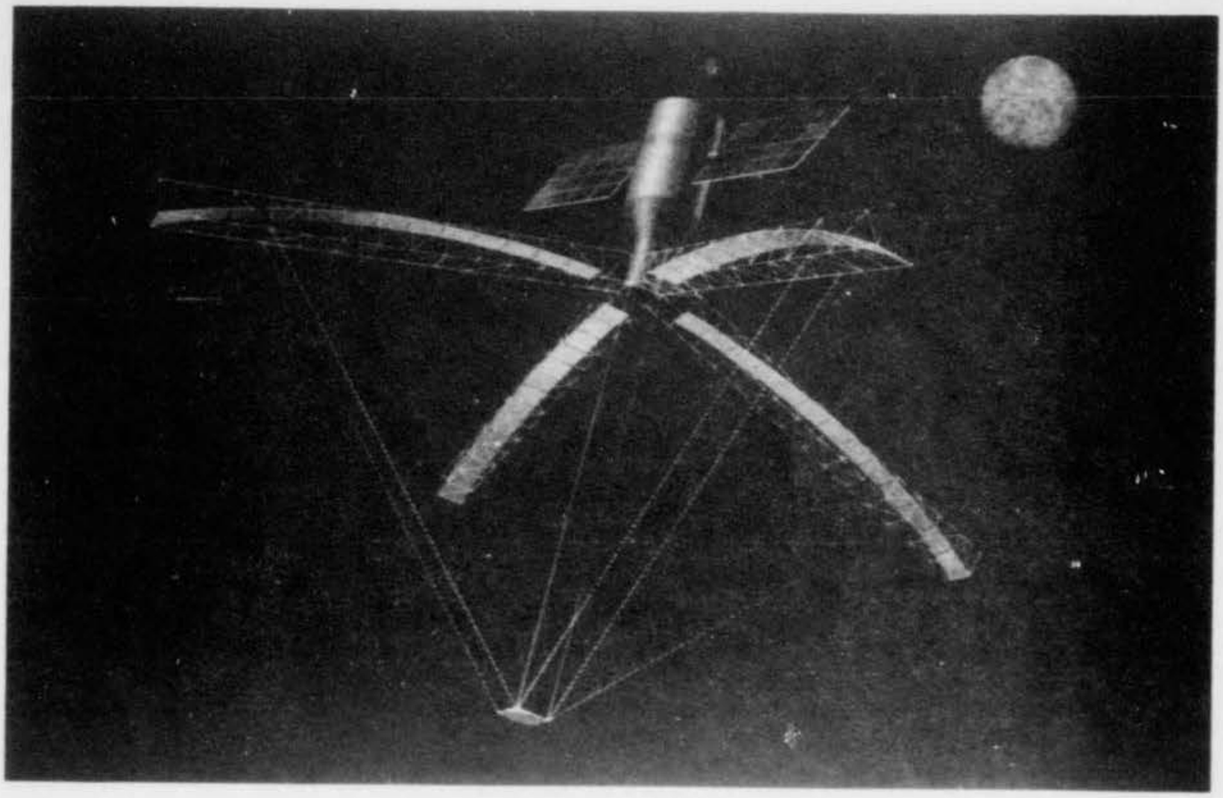
SNAPSHOT (u,v)-COVERAGE



SNAPSHOT DIRTY BEAM



ARTIST'S CONCEPT OF FIZEAU FILLED-ARM TELESCOPE (FFT)



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JPL PARTIALLY FILLED APERTURES

IMAGING SIMULATION SOFTWARE

- **EFFECTS TAKEN INTO ACCOUNT**
  - STUDIED IMAGE PLANE BEAM RECOMBINATION ONTO CCDs ONLY
  - ASSUMED LIGHT IS MONOCHROMATIC
  - INCLUDED *EXPLICIT* NOISE/ERROR SOURCES
    - PHOTON STATISTICAL (SHOT) NOISE (POISSONIAN)
    - THERMAL BACKGROUND NOISE (10^{-3} CT S^{-1} $PIXEL^{-1}$; POISSONIAN)
    - CCD READOUT NOISE (1 CT $READ^{-1}$; GAUSSIAN)
    - CCD QUANTUM EFFICIENCY (50%)
  - MODELLED *IMPLICIT* ERRORS BY SIMULATING INCOMPLETE (u,v)-COVERAGE
    - PHOTON STATISTICAL (SHOT) NOISE IN SIDELOBES
    - INTERPOLATION ERRORS IN THE (u,v)-PLANE

- **POST-PROCESSING TECHNIQUES USED**
  - REJECTION OF POWER IN SPATIAL FREQUENCIES NOT SAMPLED
  - SUBTRACTION OF NOISE FLOOR
  - DECONVOLUTION WITH POINT SPREAD FUNCTION (DIRTY BEAM) USING "CLEAN" OR "MAXIMUM ENTROPY" TECHNIQUES

- **EFFECTS NOT MODELLED FOR THE FILLED MILLS CROSS**
  - PUPIL PLANE BEAM RECOMBINATION
  - DETECTION USING PHOTON COUNTERS
  - PHASE ERRORS
  - POLYCHROMATIC EFFECTS (FINITE BANDWIDTH)

JPL **PARTIALLY FILLED APERTURES**

IMAGING CAPABILITIES OF THE 30m FFT: COMPLEX SOURCE SIMULATION RESULTS

- **COMPLEX SOURCE PROPERTIES**
  - DEVISED FOR ORBITING VLBI (QUASAT) STUDIES
  - CENTRAL COMPACT FEATURES (CORES, JETS; ~ 5% OF TOTAL FLUX)
  - EXTENDED EMISSION (LOBES, EMISSION LINE REGIONS; ~0.5% OF TOTAL FLUX)
  - POINT SOURCES (MASERS, BRIGHT STARS, GLOB CLUSTERS; 0.1% OF TOTAL FLUX)
  - SIZE CHOSEN 0".1 x 0".3, TYPICAL OF NARROW LINE REGION OF QUASARS

- **FIRST FIGURE**
  - ORIGINAL SOURCE (3 mas RESOLUTION)
  - SUM OF 8 ROTATED DIRTY SNAPSHOTS WITH FFT -- 10^3 ct s^{-1} m^{-2}
  - CLEANED IMAGE USING 8 ROTATIONS WITH FMC (8 mas RESOLUTION)
  - IMAGE OF <u>8 METER MIRROR</u> (SAME COLLECTING AREA AND INTEGRATION)

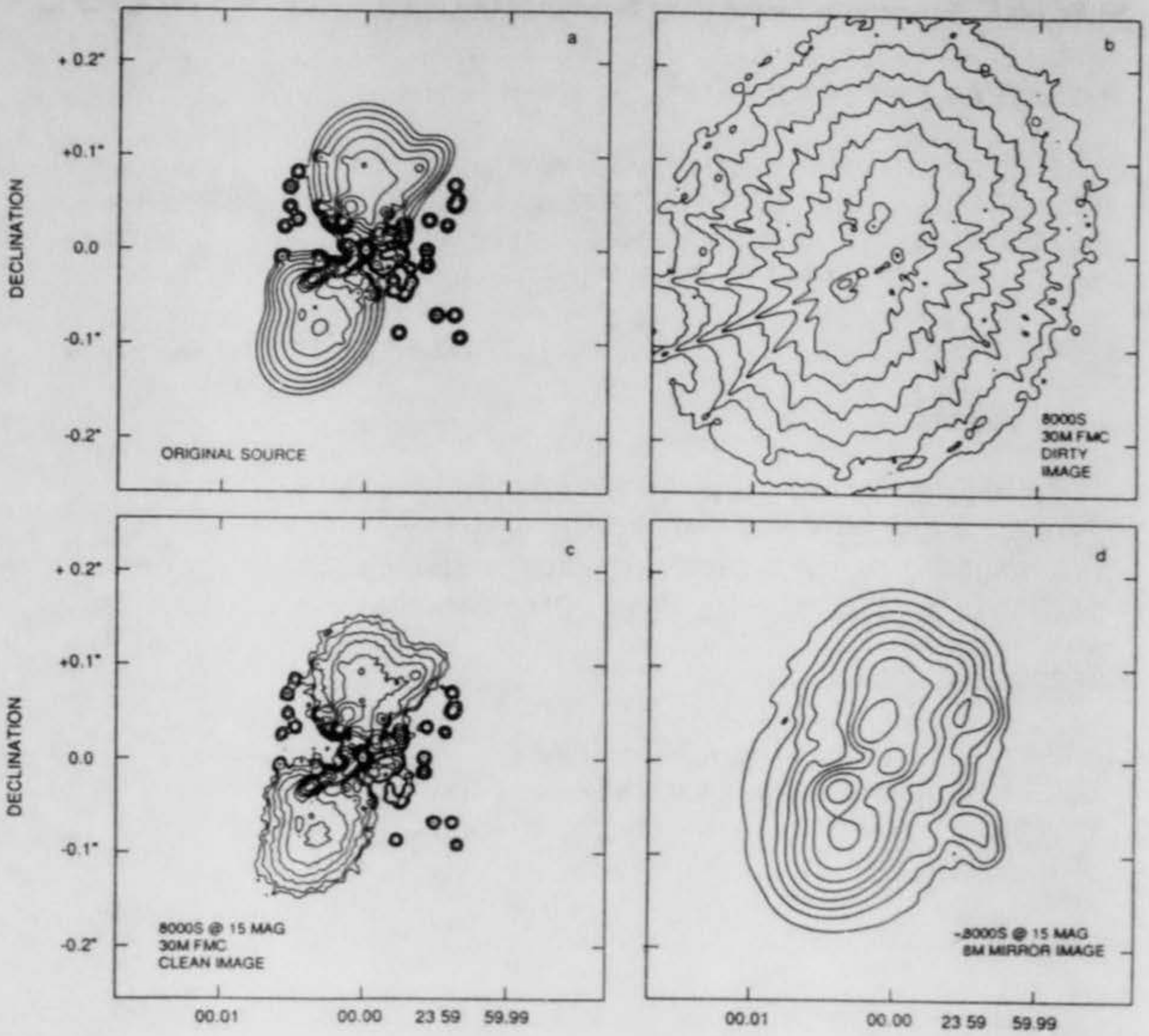
- **SECOND FIGURE**
  - ORIGINAL SOURCE (3 mas RESOLUTION)
  - CLEANED SNAPSHOT IMAGE WITH FFT -- 10^3 ct s^{-1} m^{-2}
  - CLEANED IMAGE USING 8 ROTATIONS WITH FFT -- 10 ct s^{-1} m^{-2}
  - IMAGE WITH <u>HST</u> -- 10 ct s^{-1} m^{-2}

- **RESULTS**
  - RMS NOISE FAR FROM SOURCE (THERMAL BACKGROUND + READOUT) OF 4×10^{-3} $N^{-1/2}$ ct s^{-1} m^{-2} beam^{-1} (4σ DETECTION LIMIT OF 27 mag beam^{-1} WITH 100Å BANDWIDTH)
  - DYNAMIC RANGE FOR POINT SOURCES:

    $\sim 0.1\ \boldsymbol{N}^{1/2}\ \mathrm{N}$ $\quad \boldsymbol{N} > 5 \times 10^5$

    $\sim 0.1\ \boldsymbol{N}^{1/2}\ \mathrm{N}^{1/2}$ $\quad \boldsymbol{N} < 5 \times 10^5$

    WHERE $\boldsymbol{N}$ = TOTAL ct snapshot^{-1} AND N = # snapshots


DECLINATION
+ 0.2"
+0.1"
0.0
-0.1"
-0.2"
a
ORIGINAL SOURCE
b
8000S
30M FMC
DIRTY
IMAGE
c
8000S @ 15 MAG
30M FMC
CLEAN IMAGE
d
-8000S @ 15 MAG
8M MIRROR IMAGE
00.01
00.00
23 59
59.99

JPL PARTIALLY FILLED APERTURES

IMAGING CAPABILITIES OF THE 30m FFT: IMAGE PLANE SIMULATION RESULTS

THE FOLLOWING PROPERTIES WERE MEASURED FROM MANY SIMULATIONS OF POINT AND COMPLEX SOURCES USING THE FIZEAU FILLED-ARM TELESCOPE INTERFEROMETER:

IMAGE PROPERTY	SNAPSHOT IMAGE	"FULL" SYNTHESIS IMAGE (7-8 ROTATED SNAPSHOTS)
DYNAMIC RANGE NEAR BRIGHT OBJECTS ($m_V \sim 15$)	700 : 1	5000 : 1
RMS NOISE FAR FROM SOURCE ($ct\ s^{-1}\ m^{-2}\ beam^{-1}$)	0.004	0.0015
DETECTION LIMIT OF FAINT OBJECTS ~ 4σ (mag $beam^{-1}$ @5000Å OVER 100Å BANDWIDTH)	27	27.5

CONCLUSIONS:

- GLASS MIRROR SEGMENTS ARE BETTER UTILIZED IN A FILLED-ARM INTERFEROMETER THAN IN A CIRCULAR MIRROR OF EQUAL AREA
- FILLED MILLS CROSS PROVIDES GOOD COMPROMISE BETWEEN HIGH RESOLUTION AND FAINT OBJECT DETECTION
- PUPIL PLANE BEAM RECOMBINATION SHOULD GIVE <u>BETTER</u> SIGNAL-TO-NOISE, <u>WORSE</u> DYNAMIC RANGE

JPL

PARTIALLY FILLED APERTURES

SUMMARY CAPABILITIES OF THE 30m FIZEAU FILLED-ARM TELESCOPE

- **IMAGE PLANE BEAM RECOMBINATION RESULTS**
  - DYNAMIC RANGES OF AT LEAST FEW THOUSAND
  - RMS NOISE: 10^{-3} ct s^{-1} m^{-2} $beam^{-1}$
  - 4σ DETECTION LIMIT ~27th MAGNITUDE (100Å BANDWIDTH)

- **SOLAR SYSTEM**
  - ENOUGH PHOTONS SO THAT BLURRING IS NOT A FACTOR
  - ALL OUTER PLANETS, INCLUDING PLUTO, ASTEROIDS AND MOONS IMAGEABLE

- **STELLAR ASTRONOMY**
  - REASONABLE IMAGES (5-10 beams) OF RED SUPERGIANTS AND O/B WINDS
  - CRUDE IMAGES (< 5 beams) OF NEAREST FEW GIANTS AND DWARFS

- **NOVAE:** BEAUTIFUL, DETAILED IMAGES OF EXPANDING EMISSION LINE NEBULA > 10 DAYS AFTER EXPLOSION

- **SUPERNOVAE**
  - LIGHT ECHOES IMAGEABLE AFTER 1.5 YR (VERY WEAK: S/N ~ 1)
  - REMNANT IMAGEABLE AFTER 50 YR (S.B. NOT YET DETERMINED)

- **10^8 M_o BLACK HOLES IN GALAXY CENTERS:** JUST POSSIBLE (S/N ~ 10)

- **ACTIVE GALACTIC NUCLEI AND QUASARS**
  - NARROW LINE REGION IMAGEABLE IN GREAT DETAIL(100 beams)
  - INNER NLR / OUTER BROAD LINE REGION POSSIBLE WITH CRUDE IMAGE (< 5 beams)

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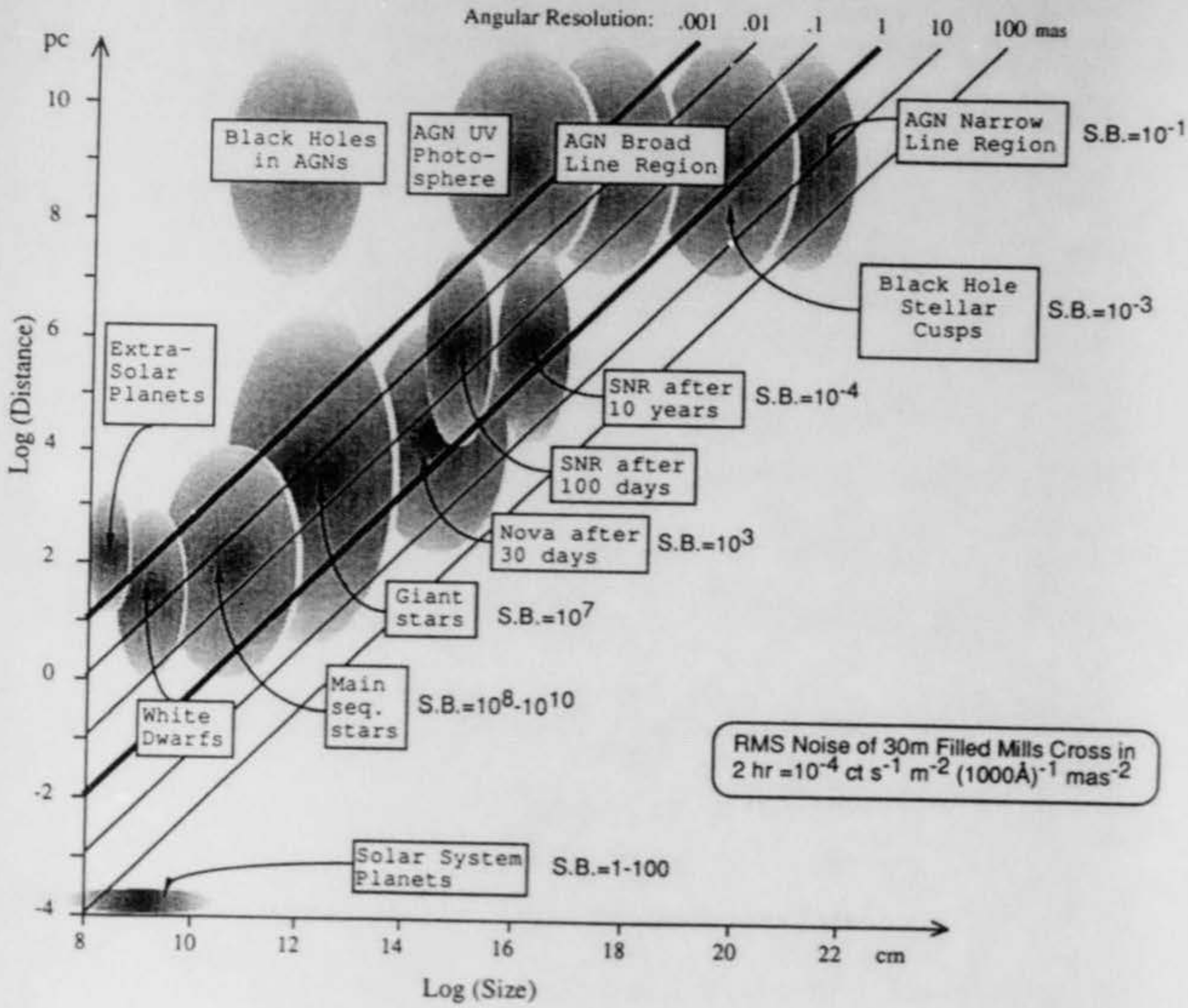


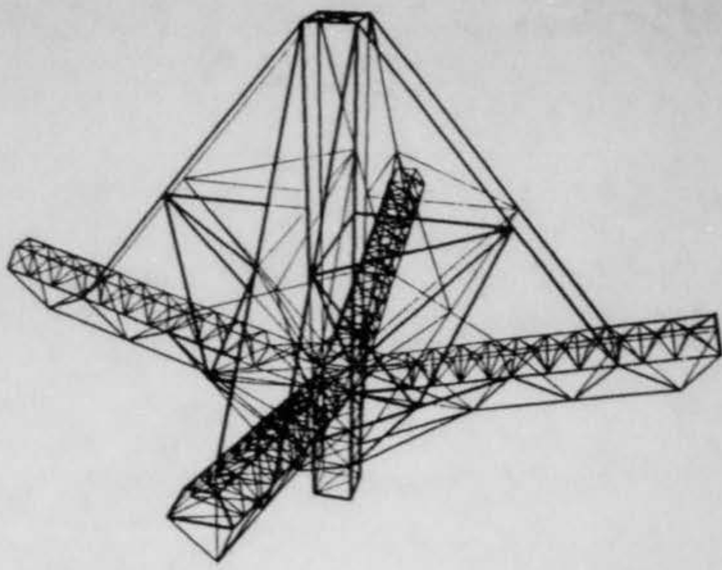
Angular Resolution: .001 .01 .1 1 10 100 mas
pc
Log (Distance)
Log (Size)
cm
Black Holes in AGNs
AGN UV Photo-sphere
AGN Broad Line Region
AGN Narrow Line Region
S.B.=10-1
Black Hole Stellar Cusps
S.B.=10-3
Extra-Solar Planets
SNR after 10 years
S.B.=10-4
SNR after 100 days
Nova after 30 days
S.B.=103
Giant stars
S.B.=107
Main seq. stars
S.B.=108-1010
White Dwarfs
RMS Noise of 30m Filled Mills Cross in 2 hr =10-4 ct s-1 m-2 (1000Å)-1 mas-2
Solar System Planets
S.B.=1-100

JPL PARTIALLY FILLED APERTURES

SCIENCE POSSIBLE AND NOT POSSIBLE WITH PARTIALLY FILLED APERTURES

- SCIENCE POSSIBLE WITH A PARTIALLY FILLED APERTURE
  - HIGHER RESOLUTION IMAGING THAN A FILLED APERTURE OF THE SAME WEIGHT AND UNDEPLOYED SIZE
  - FULL IMAGING DOWN TO SURFACE BRIGHTNESS OF 27 MAG BEAM^{-1}
    - ALL FEATURES OF BRIGHT, COMPLEX SOURCES
    - HIGH SURFACE BRIGHTNESS FEATURES OF FAINT SOURCES
  - IMAGING SPECTROSCOPY (?)
- SCIENCE NOT DONE WELL BY PARTIALLY FILLED APERTURES: "LIGHT-BUCKET" TASKS
  - VERY ACCURATE PHOTOMETRY
  - IMAGING OF VERY FAINT SURFACE BRIGHTNESS FEATURES OF COMPLEX FAINT SOURCES
  - SPECTROSCOPY OF FAINT POINT SOURCES
  - DETECTION OF VERY FAINT SOURCES (> 27 MAG)

LARGE OPTICAL REFLECTING INTERFEROMETER



JPL PARTIALLY FILLED APERTURES

STRUCTURAL DESIGN RESULTS FOR THE FFT

- HIGHLY RELIABLE, FULLY DEPLOYABLE 25-30m APERTURE CAN FIT IN SHUTTLE BAY
- DEPLOYMENT ERRORS ARE FEW TENS OF μm OR BETTER, CORRECTABLE TO A FEW μm
- LOW FREQUENCY ACTUATORS ARE NEEDED ON PANELS TO CORRECT OPTICAL PATH TO < ~10nm
- MASS ~ 6000kg (1/2 HUBBLE) WITH LIGHTWEIGHT (10-20 kg m^{-2}) MIRROR SEGMENTS
  - ⇒ TELESCOPE CAN BE PUT INTO HIGH (1000 km) ORBIT
- MASS IF FILLED WOULD BE 12,000kg + >>5000kg STRUCTURE
  - ⇒ MASS > 20,000kg
  - ⇒ NEITHER WEIGHT NOR SIZE CAN FIT INTO ONE SHUTTLE OR TITAN LAUNCH
  - ⇒ FILLED APERTURE MUST BE ASSEMBLED IN LOW EARTH ORBIT

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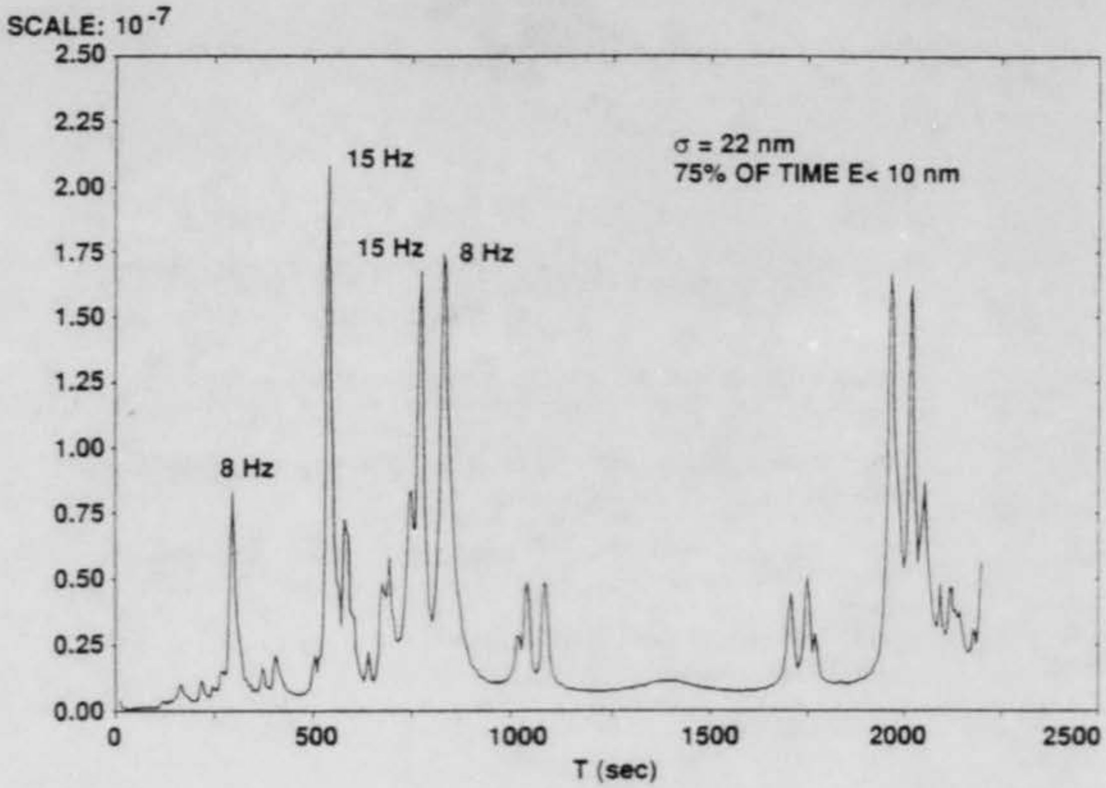
PARTIALLY FILLED APERTURES

DISTURBANCE ANALYSIS RESULTS FOR THE FFT

- MAIN SOURCE OF VIBRATION IS THE REACTION WHEEL SYSTEM
- WORST CASE SCENARIO: A 2000 sec PORTION OF A 400km ORBIT SHOWS <10 nm VIBRATIONS 75% OF THE TIME



- CAN INCREASE VIBRATION-FREE TIME BY
  - PASSIVE DAMPING AT OPTICAL PANELS
  - ACTIVE DISTURBANCE SUPPRESSION AT THE SOURCE (WISH TO AVOID HIGH FREQUENCY ACTUATORS AT PANELS)

JPL PARTIALLY FILLED APERTURES

THERMAL ANALYSIS RESULTS FOR THE FFT

- ASSUMPTIONS:
  - GRAPHITE-EPOXY TRUSS; CTE = 10^{-7} K^{-1}
  - INTERIOR TUBES AND EXTERIOR STRUCTURE WRAPPED WITH MULTI-LAYER INSULATION BLANKETING
  - ANALYZED A SLEW FROM 15° TO 25° SUN ANGLE
- RESULTS
  - THERMAL CHANGES < 0.05 K IN 1000 sec OBSERVATION

    ⇒ 75 nm DEFORMATION
  - CAN BE COMPENSATED BY
    - LOW FREQUENCY ACTUATORS (0.02 Hz)
    - OR LOWER CTE MATERIALS

TECHNOLOGIES REQUIRED FOR FFT

- HIGHLY RELIABLE DEPLOYMENT CONCEPTS/MECHANISMS/LAB DEMOS
- LIGHTWEIGHT (20 kg/sq m or less) MIRROR SEGMENTS
- LIGHTWEIGHT COMPOSITE STRUCTURE WITH CTE OF 0.01 PPM
- DETAILED LASER METROLOGY DESIGN AND LABORATORY DEMONSTRATIONS OF FIGURE MEASUREMENT AND CONTROL ACCURACY
- LABORATORY MEAUSREMENTS OF NANOMETER LEVEL BEHAVIOR OF STRUCTURES AND MATERIALS
- LABORATORY MEASUREMENTS OF DISTURBANCE SOURCES

QUESTIONS:

(UNIDENTIFIED): How wide is the central peak [of the point spread function] then?

D. MEIER: It's the same width that you expect from a 30 meter mirror which is a few milliarcseconds...

J. NELSON: Was that also processed with CLEAN?

D. MEIER: Yes.

R. THOMPSON: A couple of questions that are related. The recovery of the resolution depends heavily on obtaining good signal to noise and you had an enormous figure in your viewgraph -- I'm not sure I understood, something like 10^3 photons per square meter per second?

D. MEIER: That's right.

R. THOMPSON: How did you calculate that? It seems like the scattered light would certainly be much higher than that. The second question is can this be looked at for infrared use and is there a way to reduce the emissive background? I guess the first one was how did you get that noise number?

D. MEIER: Well, the 10^3 photons per square meter per second is just what you get from a magnitude 15 quasar, and the noise number was obtained by running through the simulations and then looking at the images that resulted and looking at an RMS –

R. THOMPSON: Did you put the zodiacal background noise into that?

D. MEIER: Yes, we did.

D. JONES: I thought the noise was per beam area, so it's essentially per square milliarcsecond and it's down by about 10^6 over the count you'd get per square arcsecond.

R. THOMPSON: So it's for one second and it's in the optical. Which part of the spectrum, the optical or...?

D. MEIER: These are at 500 nm. In fact the simulation of the narrow line region was done in the 5,007 Angstrom line of [O III].

(UNIDENTIFIED): It's the small beam size that he uses.

R. THOMPSON: What about the infrared use, is there any ... to consider that at all?

D. MEIER: Not in the way that you suggested. We didn't look at cooled optics. We looked at imaging at some other wavelengths, but we did not look at infrared imaging.

D. TENERELLI: Two things, one is on that one chart that you showed. That's what we tried to do on Hubble space telescope, develop a control system that was operated at less than 10 Hertz. And you don't see those higher disturbances in the system. As a matter of fact in developing a control system operating less than a Hertz ... you're always down in very small effects on the optics of the telescope as far as jitter causing disturbances within the primary and secondary area. So I'm saying that if you design your control system so it's operating at low frequencies, then you don't see the high frequency disturbances.

D. MEIER: I think I agree with you, except I don't know what frequency these pieces are ...

D. TENERELLI: The other point I wanted to emphasize was the item on the vibration from reaction wheels. That telescope doesn't have the thermal effects and the thermal spectrals ought to be very significant, probably more significant than the effects from the reaction wheels.

D. MEIER: Yes, but they're of a much lower frequency, that is if you have actuators on the spacecraft.

D. TENERELLI: They may be of much lower frequency, but they will affect your optical performance much more significantly because you will be distorting the optical surfaces, depending on how those disturbances are transmitted to the rest of that structure, because what can happen in one location can be carried along the optical surfaces. We found that out in one of these telescope studies.

D. MEIER: First of all the optical surface is in small segments or panels and the transmission would undoubtedly be through the structure and not through the panels themselves.

(UNIDENTIFIED): Yes that's right.

D. MEIER: So the distortion of the panels is assumed to be minimal.

(UNIDENTIFIED): ... in addition to the distortion of the panels.

D. MEIER: Yes, now the distortion of the structure itself, they looked at in great detail. I'm sorry I can't describe in more detail how they did it. I know that there was a finite element study done. They looked at many different nodes in the system and assumed it was wrapping in multilayer insulation and looked at the slew angles from the side. Now to the extent that they did that correctly and they determined what the variation was in the spacecraft I am told that it is possible to correct that at the panels with low frequency actuators. Unfortunately I can't comment to that in more detail because I didn't do the study myself.

(UNIDENTIFIED): Was that correction to the 10 nanometer level?

D. MEIER: Yes.

R. ANGEL: Let us make one general point which is that I share Pete's pessimism about having beams which are not filled. Consider a 25% filled aperture. You pay two prices: One is a loss of aperture ... four to one. You have 16 times less light and only 1/16th of the light you do get goes into a diffraction limited path. So compared to the filled aperture, you're down by 256 in signal and you're down by 16 in background so you have a lousy signal to background. So before we get carried away with these things, I think you're right into the present space telescope analysis situation. It's a difficult thing plus the inability to baffle against stray light. It's a very big price.

D. MEIER: I want to speak to that. First of all, you're correct. There are a couple of things: First of all the point spread function itself, unlike the space telescope, would be determined prior to launch and one would know in great detail...

R. ANGEL: ... not knowing what it is, just having it.

D. MEIER: Well, part of the limitation is in fact knowing what it is. I agree that also having it and deconvolution does affect the signal to noise ratio and as I said earlier, I don't want to imply that unfilled apertures can do the same kind of science. In fact, I want to imply that they can do a different kind of science than filled apertures. They're optimized not for making very detailed images of galaxies, but for looking at much higher resolution structure than you could ever look at with a spacecraft of similar size and weight and cost. So again one has to trade off: do you want angular resolution 10 times greater than what you have with a significant loss of signal to noise or do you want that extra signal to noise but not nearly as high an angular resolution? And I really think they are not necessarily mutually exclusive, in fact I think they –

G. ILLINGWORTH: I think your comments parallel a level of discussion over the last couple of years of the relationship of interferometers to filled-aperture telescopes. And I think that a consensus has really developed that there are whole areas that filled apertures will not touch, and interferometers are going to be needed. So it's a complementary area...

J. CUTTS: I believe that this cross configuration sort of represents a compromise...

(UNIDENTIFIED): They imply mutual compromises. I think this one may turn out to be the worst in some sense.

J. CUTTS: I'm not defending it.

G. ILLINGWORTH: I understand. I think it's good to analyze the different approaches and to look at what science program you can carry out ... You get into the small scale structures and we're looking at pretty big interferometers that really touch on the science - bigger than the 30 meter baseline. We actually really should move on unfortunately. It's an interesting and complex subject.

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WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

KECK TELESCOPE ACTIVE CONTROL AND ION POLISHING

JERRY NELSON

KECK OBSERVATORY
Kamuela, Hawaii

March 4, 1991

(Presentation material follows)

Summary of Active Control System
12 January 1991

Characteristics		Image Blur arcseconds 1-dim rms
Sensors		
number	24	
range	±2mm	
sampling rate	100Hz	
first filter	30Hz	
digital filter	0.2Hz	
least count	4.0nm	
Actuators		
number	27	
range	1.1mm	
step size	4.0nm	
update rate	2Hz	
Performance		
Sensors		
electrical noise (rms)	1nm	0.002
segment vibration (rms)	15nm	0.021
sensor residual filtered (rms)	11nm	0.016
Actuators		
actuator residual (rms)	18nm	0.013
Star stacking		
time to star stack	< 10 minutes	
accuracy of star stack		≤ 0.05
Temporal Stability		
time: 10 minutes		≤ 0.10
time: 5 days		≤ 0.10
Elevation Angle Stability		
uncorrected variation with elevation angle (85° to 40°)		± 1.0
smoothness with elevation angle (rms deviation from straight line)		≤ 0.10
Atmospheric Seeing Variations		
centroid errors (1.0 s integration)		~ 0.10

Figure 8

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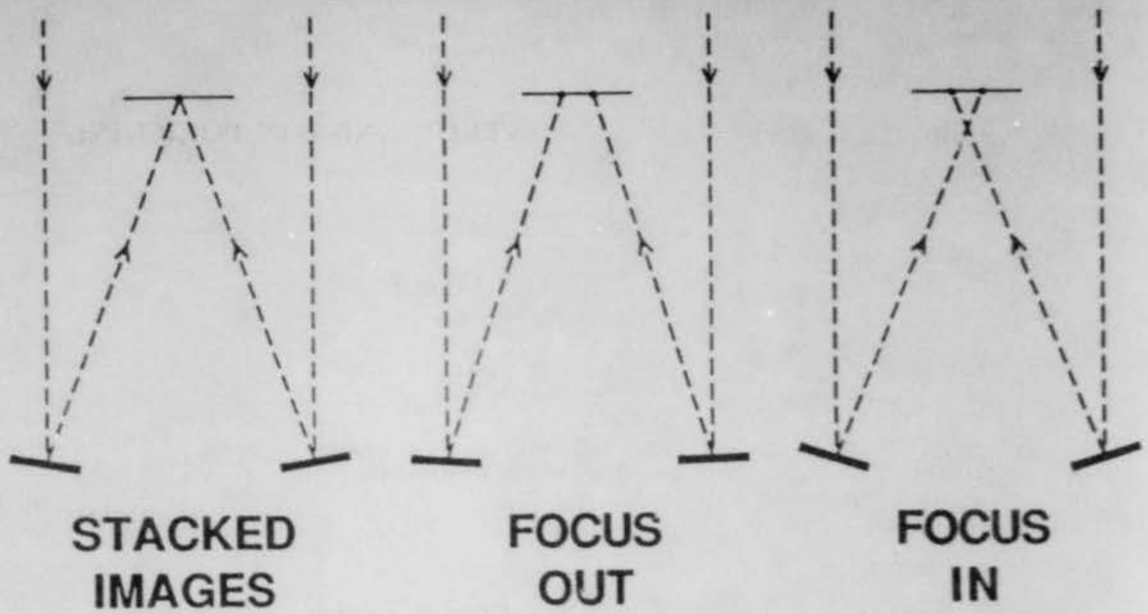
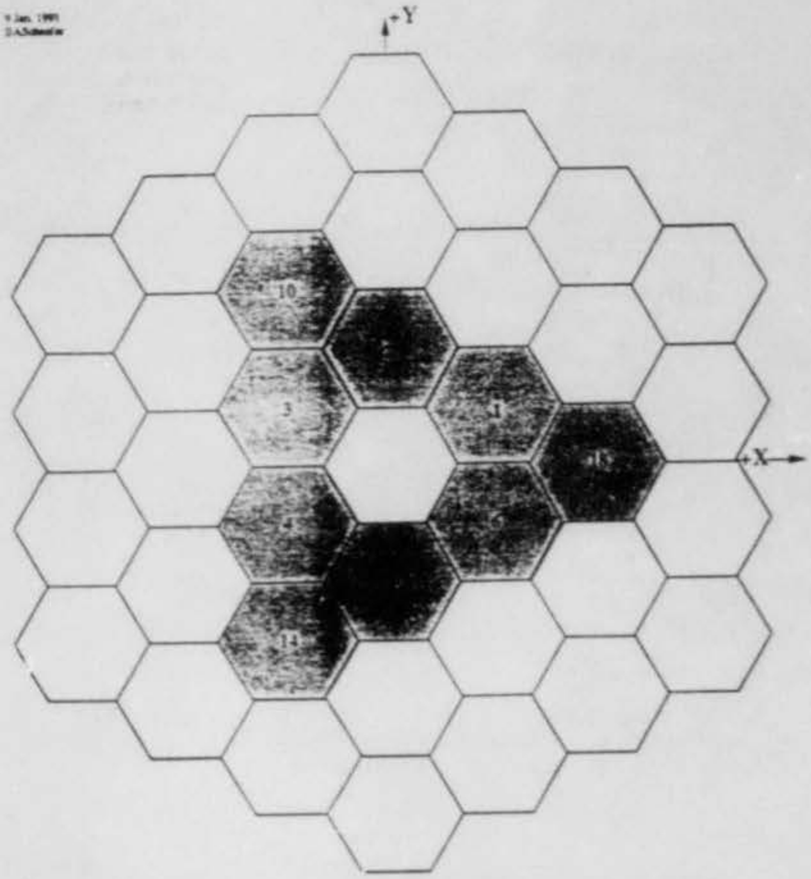
STAR STACKING





Keck First Light Segments

Ion Polishing (Ion Beam Figuring)
4 March 1991

Basic Process

- collide energetic atom with work surface to evaporate surface material
- single atoms with energy 10^2 to 10^4 eV heat surface roughly 10-100 atoms deep and occasionally a surface atom evaporates
- energetic atoms created by accelerating ion beam then neutralizing
- efficiency is low in that only about one surface atom is removed for each incident ion at 1 keV energy.
- surface heating can be substantial (>100 °C)

Typical parameters

- Kaufman ion sources exist with throat diameters in 1-10cm range
- typical ion material is Argon (inert gases)
- moderate distance from gun throat the beam becomes Gaussian with σ = throat radius
- ion energies of 1400 eV typical
- beam currents of 100 mA available (5cm gun) or 140 Watts
- removal rates of 5×10^8 μm^3 per minute achieved with above parameters.
- surface heating depends on beam power and dwell time of source surface heating (50°C to 300°C common)

Advantages

- high accuracy of removal: error should be <10%
- no edge effects on optic since process is atomic not macroscopic
- process independent of shape of mirror for same reason
- process insensitive to mirror thickness or thickness variations as opposed to mechanical polishing which relies on pressure

Limitations

- the process does not polish the mirror so it must already be polished and adequately smooth on scale of ion beam
- relatively low removal rate: $4.6 \times 10^8\ \mu m^3/min$ or $28 nm/m^2/hr$ for 5cm beam limits one to fairly small corrections ($\leq 1\mu m$)
- spatial resolution limited by size of gun. Smaller guns may take longer to cover a surface or produce more heating.
- thermal sensitivity of some materials, in particular glass-ceramics may limit removal rate (require $\Delta T < 100°C$)

Availability

- Standard equipment needed
  - vacuum chamber
  - ion source (Kaufman)
  - translational stage for ion source
  - software to predict source dwell times from surface errors.
- Commercial firms in the business:
  - Kodak has a 2.5m capacity machine working
  - Itek plans to build a 2m capacity machine by end of 1991
  - others?

Experience with Keck Mirrors

- we decided to ion polish the worst of our mirrors (SN09) at Kodak (segment a 1.8m hexagon)
- 1st ion polish:
  216 hours of ion polishing
  total volume of $4 \times 10^{12}\ \mu m^3$ removal desired
  results: mirror warped from overheating
  two grooves in surface
  one ridge in surface
  initial rms = $0.672\mu m$
  final rms = $0.276\mu m$
- 2nd ion polish:
  38.5 hours of ion polishing
  total volume of $1 \times 10^{12}\ \mu m^3$ removal desired
  results: mirror warping from heating negligible
  ridge gone
  grooves greatly improved
  final rms = $0.090\mu m$ (close to surface uncertainties due to support)
- We plan to ion polish more mirrors

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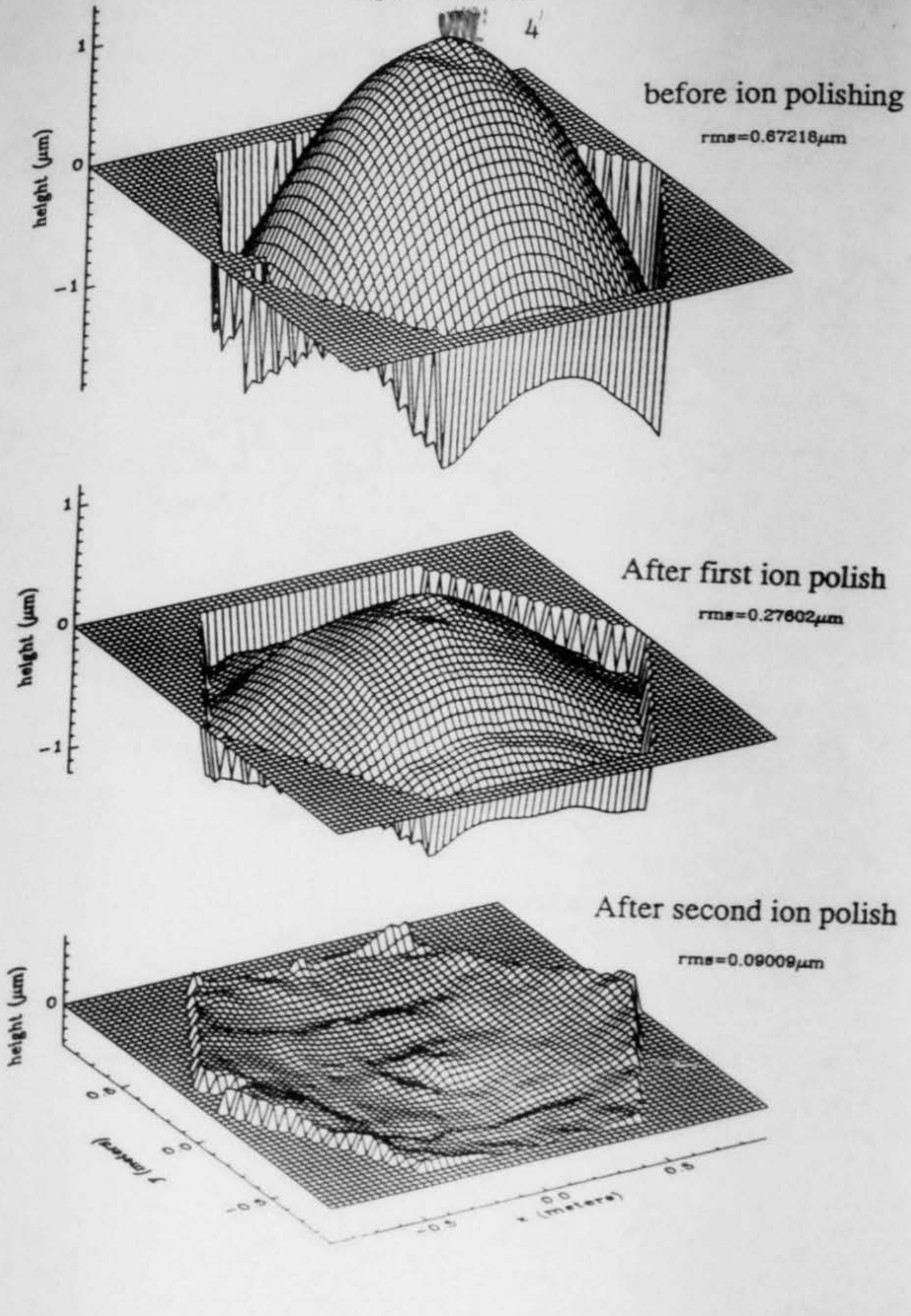
Segment SN09



QUESTIONS:

(UNIDENTIFIED): Jerry, have you measured the repeatability of those actuators? [refers to the actuators used to position the segments of the Keck telescope primary mirror]

J. NELSON: There are lots of laboratory tests which suggest that they are repeatable to 4 nm. That is, the RMS noise is compatible with the digitization you expect from 4 nanometer moves. So they're quite smooth and because they're digitized at that level, of course, they can't tell you how they were below that.

(UNIDENTIFIED): Jerry, when you say that the stacking accuracy depended on the atmospheric seeing, do you mean just the external seeing or dome seeing?

J. NELSON: We don't have any indications of any dome seeing. It may very well be there, but whatever the sources there are, whatever the seeing is, it limits your ability to measure the centroid. You have to integrate longer and longer to get more and more accuracy. We were doing 10 second integrations and that just limits the accuracy to which you can measure the centroid. If you have more patience, you can do better, of course, but it takes integration time. Typically our seeing conditions were much better than an arcsecond, but I can't tell you whether that was locally induced or upper atmosphere. My guess is it's upper atmosphere, but we don't know - speculation.

(UNIDENTIFIED): Unintelligible question. (Regarding wind loadings.)

J. NELSON: Our control system surely is sensitive to wind gusts. As a practical matter on the dozen lights that we were observing, we never saw any problems associated with wind. We didn't see anything at all that indicated there were any problems; that may just be an indication that the wind velocities were very small on those nights. We didn't even measure the wind, so I can't go back and reconstruct what they were. But on the basis of a dozen nights, we saw nothing at all so that's at least encouraging although utterly non-informative.

STRESSED-LAP POLISHING

ROGER ANGEL

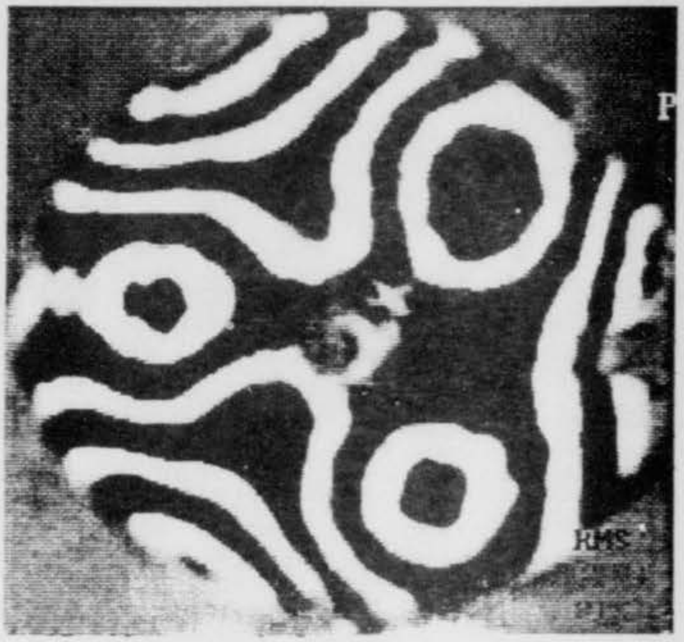
STEWARD OBSERVATORY
Tucson, Arizona

March 4, 1991

(Presentation material follows)

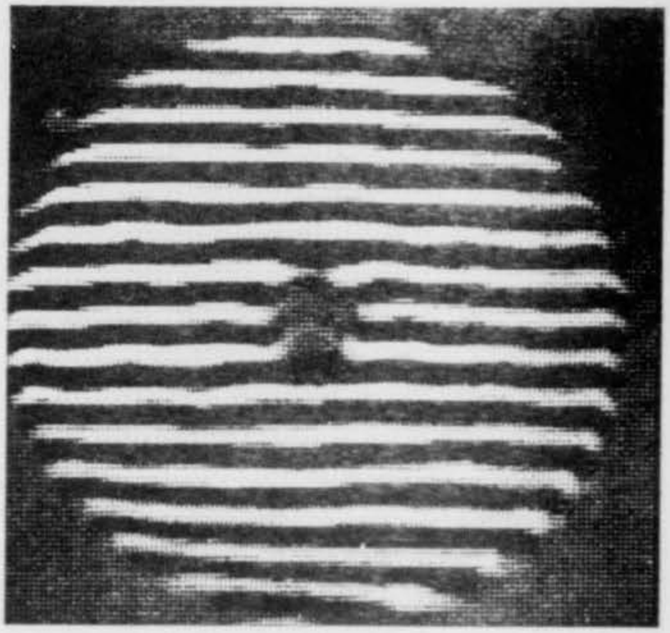
The figures show the improvement in surface accuracy on a 3.5-meter mirror polished with the stressed-lap technique at the University of Arizona.

3.5-m f/1.5 9-μm **abrasive grinding**



January 8, 1991 (start of grinding):

peak-valley surface error	19.7 μm
rms surface error	4.2 μm



January 31, 1991 (end of grinding):

peak-valley surface error	2.5 μm
rms surface error	0.33 μm

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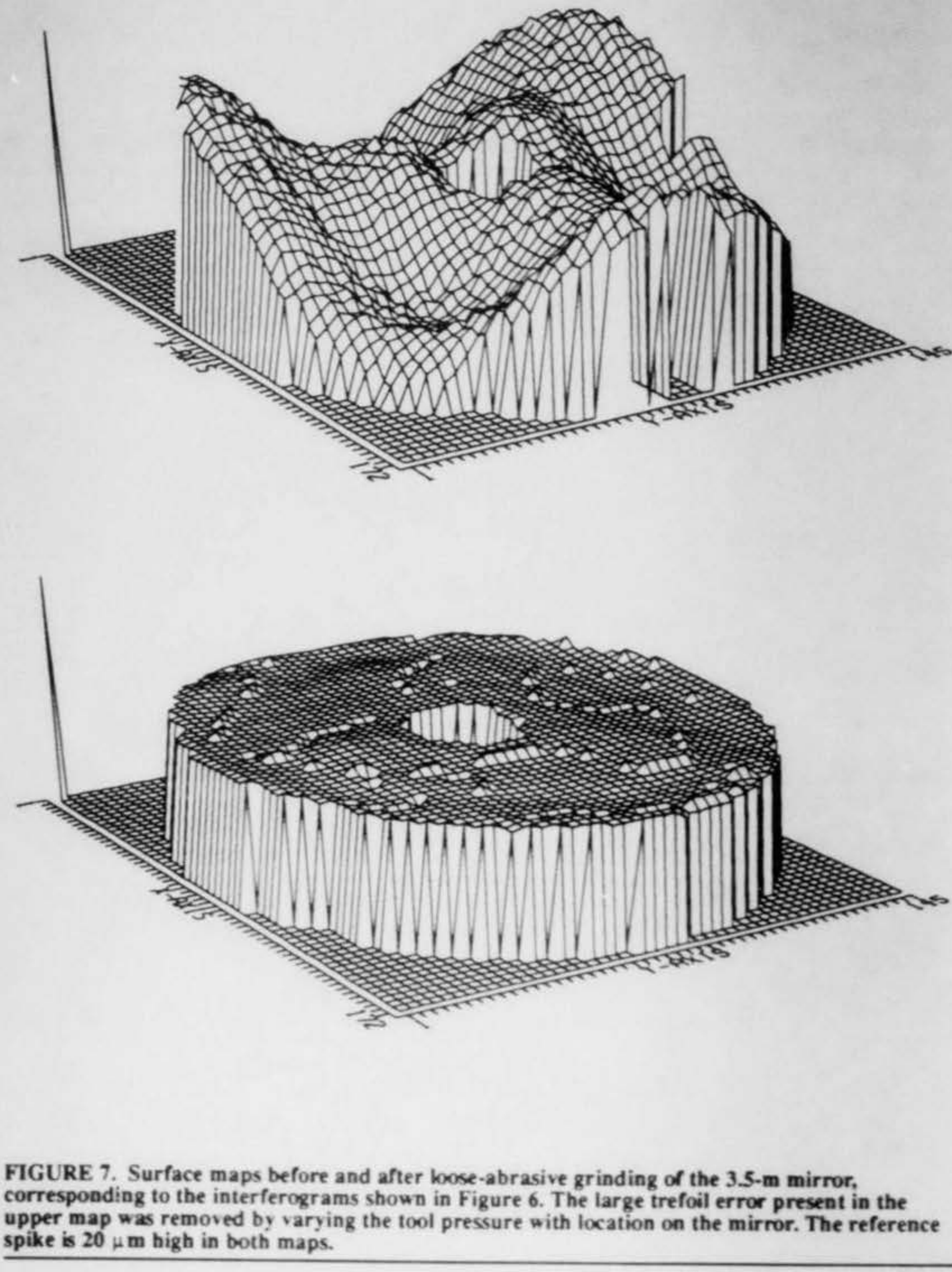

FIGURE 7. Surface maps before and after loose-abrasive grinding of the 3.5-m mirror, corresponding to the interferograms shown in Figure 6. The large trefoil error present in the upper map was removed by varying the tool pressure with location on the mirror. The reference spike is 20 μm high in both maps.

QUESTIONS:

D. MACCHETTO: I'd like to know whether you measured the surface accuracy for the ... system mirrors.

R. ANGEL: We have a resolution of 200 pixels across the surface in the direct phase maps. Now the interferograms I showed were not what we really use to measure the surface. We do direct phase measuring interferometry which takes a series of interferograms ..., so that's done with a resolution of 200 pixels across the surface and we haven't done measurements of smaller spacings than that.

P. SWANSON: Roger Angel was kind enough to give me a tour of this facility last summer and it is indeed very impressive.

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WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

THIN MIRRORS AND ACTIVE OPTICS FOR THE ESO NEW TECHNOLOGY TELESCOPE

RAY WILSON, EUROPEAN SOUTHERN OBSERVATORY

March 4, 1991

(No presentation material available at the time of this printing)

QUESTIONS:

P. DAVIS: If the image analysis could be put up there, is that based on observation of a star or on an introduced signal from a laser?

R. WILSON: No, it's fundamental to the system that it is an actual star measured in the field and normally this is just the guide star which is borrowed. At the moment we have a mirror flicking between the two; soon we shall have a beam splitter or a dichroic where you can observe them both using ...

(UNIDENTIFIED): What magnitude do you require then for the kind of analysis you need?

R. WILSON: Well, some of my colleagues think that we can go to magnitude 14; I think it's more like 13-1/2 in fact. This I think is fully adequate because we have a somewhat larger search field in the space telescope.

B. MARTIN: ... having to correct for deformation you get by the wind?

R. WILSON: Yeah, that's a very good question. It is not certain whether there will be sufficient shielding to prevent that and since we're not certain, we're expecting that we will have to do some corrections. The frequency band pass for doing that has not been fully determined and this is a much more difficult area than what I've been showing with the NTT [New Technology Telescope] because you've got overlap with the band pass of the atmosphere.

B. WOODGATE: How fast can your image analysis be performed?

R. WILSON: We fundamentally integrate for 30 seconds to be sure we're integrating out the external seeing. If the seeing is very good, you might get away with 10 seconds, but we use 30 seconds. Of course we don't have problems with lack of photons compared with 10 seconds. So the actual response time of the whole system, in other words, the whole sequence: image analysis, correction, and a further ... image analysis with the recent speed ups that we've done will be of the order of 5 minutes. This is in fact a certain problem because the NTT has proved to be so efficient that our integration time is much shorter than we had expected. So this is one of the reasons why it is a very good question and we would like to speed it up more, but it would need a faster computer system to get closer than that.

P. STOCKMAN: I want to ask in your analysis, you must take logs night to night of what your adjustments are ..., have you analyzed them and do you understand them: are they primarily due to the changes in temperature in the dome, or what?

R. WILSON: That's very true, Peter. We have a log which is an abbreviated version of that optics output sheet, in fact, which tells you the most basic information and this is going to be amplified with more temperature information from sensors. In fact at the moment, it doesn't require all that much analysis because by far the most important effect always is focus. In other words, we're having to get automated because the focus varies more rapidly and this is one of the problems that has to be solved this year. Once we've got to that stage, this analysis you refer to will become much more refined and I think that probably for a time we shall find that it's limited by tracking.

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WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

LOW MASS MIRRORS FOR LARGE SPACE OPTICS

JERROLD ZIMMERMAN, ITEK

March 4, 1991

(No presentation material available at the time of this printing)

QUESTIONS:

D. TENERELLI: Two millimeters you said [refers to thickness of mirror face plate]. How much thinner could you have gone and how do you evaluate the heavy stress concentration you used?

J. ZIMMERMAN: We machined down to about 3 times that, and we've done a lot of testing and we actually look at the stress at the joint as a function of the feeds and speeds on the machining and found that that's kind of safe; for that particular piece that was the safe answer. We had a lot of experimental results, and then when you acid melt to get it down to that thickness, there's no grinding stress left. You completely clean up any of the subsurface cracks from the hard diamond grinding and, in fact, you get a beautiful fillet down between the rib and faceplate. Most of these dimensions were the result of break testing on samples.

B. DAVIS: How lightweight is lightweight...?

J. ZIMMERMAN: Most of our designs are better than 90 percent, which is almost a meaningless number because it's 90 percent compared to a solid and what do you start with? But basically, the other part of the answer is yes, all of these mirrors except for that flat which I showed you are active mirrors. That flat was 94 percent lightweight and it was completely passive because of the way it was used. Most of the primary mirrors that we looked at recently in this lightweight regime are designed and ought to be active mirrors.

M. KRIM: To what extent have any of these larger mirrors been followed by low frequency vibration or static testing?

J. ZIMMERMAN: I can tell you that the flat mirror was centrifuged at 19 Gs with the mounts, and that there have been frequency measurements made. I just don't know exactly what they are. I will say that on the LAMP especially, it met the requirements of that program and I will say also that everything behaves pretty much the way you would expect it to if you looked at a good ___ model. There were no surprises when we put it together.

P. SWANSON: An editorial comment: The weight is so important - it costs very nearly $100,000 per kilogram to put it in geosynchronous orbit, but there's also another very important thing. We have costing people that try very hard to tell you how much space hardware is going to cost and you know it's expensive. But the one single thing that correlates best with cost is weight and the implication of that is that a pound of cast iron ingots and a pound of high technology electronics cost about the same when you space qualify it, because the cost is not in the hardware, it's the paperwork and inspections, the procedures, the marching army that goes along with it. So in fact if you take a mirror and you could cut the weight by a factor of 5, you could cut the cost by a factor of 5 as well when you go into space with it. And it seems hard to believe but in fact it is true.

R. THOMPSON: It can't be true. I'm sorry, I mean if you take the mirror and you have to do more work on it to make it lightweight, it can't cost less –

P. SWANSON: It seems bizarre, but it is true.

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TELESCOPE TECHNOLOGIES: STRUCTURES AND CONTROL SYSTEMS

- JPL CONTROL STRUCTURES INTERACTION TECHNOLOGIES
- ACTIVE MIRRORS
- HST POINTING CONTROL SYSTEM

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WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

JPL CONTROL STRUCTURES INTERACTION TECHNOLOGY

ROBERT A. LASKIN

JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California

March 4, 1991

(Presentation material follows)

Control Structures Interaction (CSI) Technology for Precision Optical Structure

The Vibrational Stability Challenge of Large Optical Space Missions: High performance space optical systems typically have total light path-length stability goals on the order of $\lambda/50$ (≈ 12 nm visible, ≈ 2 nm ultraviolet) . Because the total path length stability budget must be allocated among several contributors, a reasonable stability goal for any one of the system's optical elements is in the neighborhood of $\lambda/200$ (≈ 3 nm visible, ≈ 0.5 nm ultraviolet).

Structural vibrations, even on very quiet spacecraft, are typically larger than the desired 'nanometers' goal. (Consider that only four millionths of a "g" vibration level at 10 Hz is ± 100 nanometers of motion.) Analysis of large optical structures indicates that between a few-hundred and a few-thousand nanometers of dynamic motion are caused by noise from even the extremely quiet Hubble Space Telescope reaction control wheels (RCW's) operated at less than 50% of their design spin rate (higher rate gives greater disturbance). Beyond RCW's, other disturbance sources, such as tape recorders, pointing drive mechanisms, control moment gyros, etc, have not yet been evaluated but they are likely to induce vibration levels at least as severe as the HST RCW's.

Vibrational Stability With Conventional Structures and Mechanisms Technology: Using conventional spacecraft technology it is conceivable that a large optical space mission could be accomplished, but only if extremely restrictive operational limits and design limits were placed on: 1) allowable pointing directions [restricted solar heat load location], 2) science data gathering and data return to earth [no tape recorder usage (?), no antenna pointing mechanism operation (?)], 3) maneuvering rates [slow slew dynamics, low RCW speed], 4) machinery bearing and gear smoothness, 5) machinery balance, 6) etc. The stability requirements of even such a constrained design, would press conventional structure, mechanism, and control capabilities to the limit. There would be little technology margin to cover typical flight project performance problems, and there may be inadequate NASA confidence in mission success to obtain funding for such a project.

Vibrational Stability With Control Structures Interaction (CSI) Quieting Technology:
CSI technology is currently being developed to quiet large space optics, reduce stringent design/operation constraints, and raise NASA planners' confidence in mission success. This technology achieves quieting to the nanometer-level by inserting progressive layers of passive and active structure/optical control into otherwise conventional spacecraft hardware. Each CSI layer (disturbance isolation, structural quieting, optical motion compensation) reduces critical motions by one to two orders of magnitude, ultimately enabling end-to-end quieting factors of 1,000 to 10,000.

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NASA CSI Technology Development Responsibilities: CSI technology is being cooperatively developed at three NASA centers, LaRC, JPL, and MSFC. JPL's CSI application is directed specifically at quieting the micro-precision structures of large space optical systems.

Status of JPL CSI Technology Development: JPL's new precision structural actuator design has been built, and a Honeywell heavy-viscous damper (D-Strut) has been adapted for precision structure control. Both have been tested, with excellent and repeatable behavior at the tens-of-nanometer level. A micro-precision component tester has been built which will in the summer of '90 characterize the force/displacement behavior of full-sized flight joints, struts, actuators, and materials at the mili-pound and nanometer level. In order to characterize micro-disturbance outputs of typical spacecraft machinery (tape recorders, reaction control wheels, actuators, etc.) a new JPL micro-disturbance measurement facility has also been made available to the CSI effort. And, in order to support testing of new layered CSI control designs, the CSI team has built and installed a high speed digital real-time control computer in the JPL Test Bed facility.

In parallel with component hardware, new integrated structure/control design methods have been in development, and preliminary results from these methods have been used to design control systems for the JPL Precision Truss Test Bed. Of the several "layers" of quieting being developed, initial testing has focused on a single layer of "all-active" structural quieting. Tests with this layer have demonstrated excellent quieting (factor-of-thirty), and even greater single layer performance is expected in the coming months, using mixed "passive/active" structural quieting. (Addition of newly available heavy passive damping directly increases quieting. More important, it increases the stability margin which synergisticly permits aggressive active control to give even greater quieting.)

The first tests of the *multi-layered* CSI micro-precision quieting approach will begin in the fall of '90 with the advent of JPL's new "Phase B" testing. After Phase B testing demonstrates extreme quieting with multi-layered CSI control, three major demonstrations will remain, they are:

1) Demonstrating feasibility of spacecraft attitude-control in conjunction with CSI micro-precision quieting.
2) Demonstrating "end-to-end fringe tracking" with a CSI-quieted structure/optical system that is attitude-controlled (free floating), and tracking a simulated stellar target.
3) Demonstrating the above on a test article near to flight article size (to allay scale factor concerns).

NASA's CSI plan includes an advanced JPL "Phase 1 Test Bed" for conduct of the three major demonstrations, but this test bed has been delayed, and could be dropped, due to NASA CSI budget reduction. Reinstatement of the JPL Phase 1 Test Bed is critical to acceptance of the micro-precision CSI technology needed on NASA Large Optical Space and Lunar Missions.

JPL CSI Technology: Summary Description

The JPL Control Structure Interaction (CSI) task is a focused technology effort, in intellectual partnership with the Langley Research Center, and the Marshall Space Flight Center. NASA's CSI Program is managed from the Office of Aeronautics and Exploration Technology (OAET) by the Materials and Structures division. OAET is specifically focusing CSI technology to enable or enhance classes of missions which are supported by the Office of Space Science and Applications (OSSA). OAET and OSSA are actively coordinating to assure direct applicability of the CSI effort to future missions.

The NASA CSI program is developing technology to support high performance control/structure systems designs. Because the controllers for "CSI systems" have frequency responses beyond many of their "controlled plant" structural resonances, the systems can exhibit (exciting) interactions between the structure and control subsystems.

Flight experience is teaching the Control and the Structure design communities that successful CSI system design requires cooperative trade offs between the control subsystem and structure/configuration, throughout the design phase. These interdisciplinary trade offs are extremely difficult to conduct with the existing design methodologies, and design/analysis tools.

JPL is coordinating with LaRC, and MSFC in building core CSI technology common to all CSI efforts. Upon this core, JPL is building the special capability to create Micro-Precision Controlled Structures (μ-PCS) by developing new integrated design methodologies, new active structure actuators, controllers, and usage strategies, and new ground validation test techniques. The readiness of Micro-Precision Controlled Structure for flight projects will be demonstrated via analytical simulations, ground tests and corroborating flight tests.

JPL's CSI technology specialty of Micro-Precision Controlled Structure will make it practical to fly missions with Large Optical Systems, and Large Precision Microwave Antenna Systems. *New classes of missions*, enabled by JPL μ-PCS technology, will include large (20 to 100m) optical interferometers. *Greatly enhanced classes of missions*, enabled by blending JPL and LaRC CSI specialties, will include free flying or Geoplatform-mounted very large telescopes, and precision microwave or radar antennas.

An initial JPL effort has developed a CSI μ-PCS design for a spaceborn optical interferometer, the Focus Mission Interferometer (FMI). Stepping through a CSI μ-PCS system design to meet the FMI's challenging sub-micron accuracy requirements, has built a strong technology team and focused their efforts on the portions of μ-PCS technology most needing improvement. The team is intensively developing new active structure actuators and controllers, and is testing these in a multi-layered CSI quieting architecture on a test structure.

The major objectives of the JPL CSI effort are to: 1) develop the Micro-Precision Controlled Structure technology which enables advanced Large Optical and Large Precision Antenna missions, and 2) validate μ-PCS technology by corroborating analysis with ground and flight tests.

JPL's CSI effort includes:

- Development of a "Focus Mission" structure/control/optics design for the application of μ-PCS CSI technology.
- Establishment of CSI performance requirements, based on satisfying the "Focus Mission" and generic other needs.
- Development of methodologies and tools for combined synthesis, analysis, and simulation of control/structure systems.
- Development of a precision test bed to:
  - Evaluate evolving μ-PCS CSI methods and hardware (including "active structure" actuators, controllers & usage strategies).
  - Develop and validate new test techniques.
  - Validate performance predictions made by CSI analysis, and simulation tools.
- Development of proposed flight experiments, to validate μ-PCS CSI methods and hardware.
- Support of the CSI Guest Investigator program, with emphasis on μ-PCS CSI experiments to be done on the JPL test bed, and/or at the Guest Investigator's facility.

COMMENT AT END OF PRESENTATION:

R. LASKIN: I guess the other point I'd like to make ..... is kind of a philosophical point: I think in the past NASA has had something of a strange approach to technology. They tend to emphasize the so-called enabling technologies very much and not emphasize what they call enhancing technologies quite as much. And I think what you see in the commercial world is that technology makes things cheaper. Obviously the computer history is a case in point. If you develop advanced technology not just to enable you to do things that you couldn't otherwise have done, but to enable you to do these things much more efficiently at lower cost, I think that maps back into the margin argument: if you build significant margins into things up front by using advanced technologies rather than pushing your old technologies to the breaking point, then you're going to save cost because you're not going to run into, in the middle of the design, a critical thing that pops up that you hadn't anticipated. Now you're going to try to eke 20 percent or a factor of 2 out of something that only wants to give 20 percent. So, just a bit of my own philosophy.

QUESTION:

P. BELY: I think you have a perfect optics system, ... So where is the trade-off?

R. LASKIN: That's a good question. First of all one of the problems that you get into when you extend the bandwidth of articulation systems is that they can interact in an unstable way with the rest of the structure. There have been instances of that occurring in space and even on the ground. So we're looking into that issue. If you articulate something very tiny like a secondary or tertiary mirror, you're much less apt to run into that than if you articulate something reasonably massive like say a segment of a primary mirror. You can interact unstably with the structure if you push the bandwidth. Furthermore you tend to be limited by your sensor bandwidths. I think that in fact these things work synergistically together and what you get into is a case where if you add a factor of 10 passive damping, that allows your active optical control to work much more robustly. So you approach the thing with considerable margin and you don't get into trouble as you go down the road. The passive dampers are bandwidth unlimited. They go right out and I think we feel it's important to have passive elements in the system for just that reason. Right now on the PZT systems I think we're operating closed loop at 100 Hertz sampling... We are in the process of looking at the closely spaced mode issue. What happens there is when you work with very high Q systems, very lightly damped systems, you try to identify what the modes are so that you have a good model of them so you can do very high gain control. Closely spaced modes really hurt you badly because you can't identify the model. If on the other hand, you add damping so that you get passively up to about 1 to 10 percent damping, you're much less sensitive to your knowledge of modeling and you can do a lot better in the face of closely spaced modes.

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4

WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

ACTIVE MIRRORS

MICHAEL KRIM

HUGHES DANBURY
Danbury, Connecticut

March 4, 1991

(Presentation material follows)

D-8541

VOL 4

ACTIVE MIRRORS

CONTROLS / STRUCTURES / <u>CREDIBILITY</u>

M. KRIM

<u>NOT HERE TO REPLOW OLD GROUND</u>

- ABUNDANT CONCEPTS AND ARCHITECTURES EXIST
- SYSTEMS AND COMPONENTS OPERATING IN THE LABORATIES
- ALL ARE REPORTED IN THE LITERATURE
- MOST COULD BE MADE TO WORK, TO SOME DEGREE

<u>BUT WILL THEY PERFORM IN A "REAL-WORLD" ENVIRONMENT -- AND HOW TO PROVE IT!!</u>

- MULTI-BODY, 500 ANGSTROM POSITION STABILITY OVER 10+ METER STRUCTURAL PATH LENGTHS
- IN PRESENCE OF MECHANICAL NOISE, JOINTS, MICRO-DYNAMICE, COMPUTATIONAL CONSTRAINTS
- NEED TO PROVE CONCEPT "...IN THE LARGE", UNDERSCORED BY HST, ASTRO, ...

<u>MOVE BEYOND GRANITE SURFACE PLATES</u>

- PSR IS GOOD STEP
- SOLICIT BROAD CONTRIBUTOR AND SUPPORT BASE
- AIM TOWARDS A FLYING BREADBOARD
- WITH ADEQUATE PRECURSOR PROGRAM
- PLAN AND COMMITMENT IS KEY

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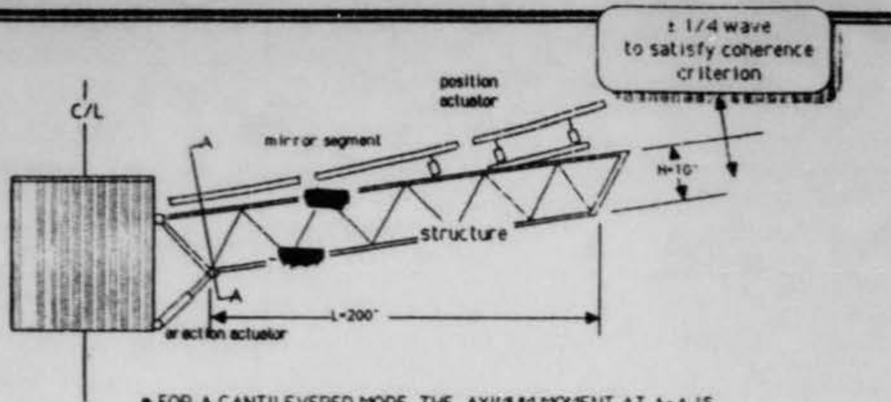
VOL 4

0.04 psi CAN BE FATAL TO A SEGMENTED PRIMARY MIRROR



- FOR A CANTILEVERED MODE, THE MAXIMUM MOMENT AT A-A IS

$$M = 3EI\Delta/L$$

WHERE Δ IS THE TIP DISPLACEMENT

- THE RADIUS OF CURVATURE CORRESPONDING TO THIS IS

$$R = EI/M = L\ /3\Delta$$

- THE STRAIN IN THE BEAM CORRESPONDING TO THIS CURVATURE IS

$$e = h/2R$$

AND THE STRESS IS THAT QUANTITY MULTIPLIED BY THE MODULUS OF ELASTICITY

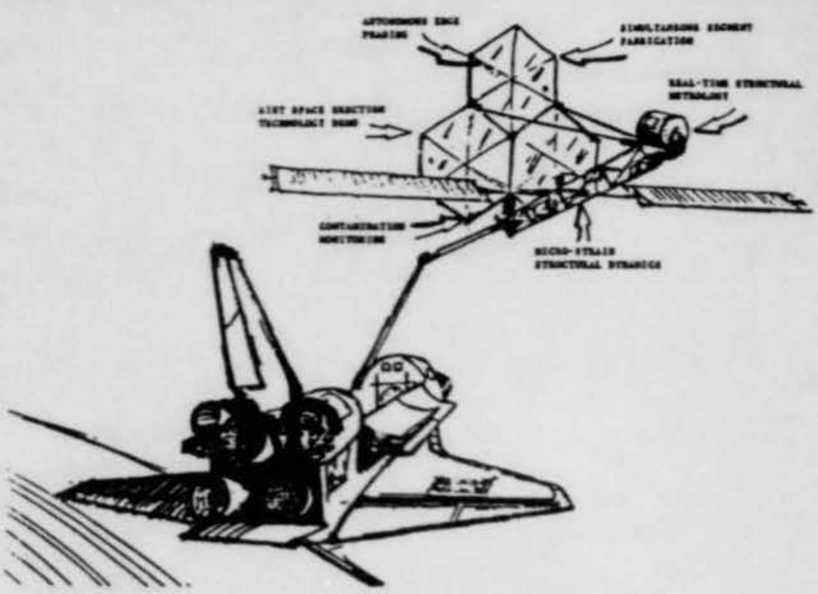
$$s = Eh/2R$$

- FOR Δ = 6 E-06 inches, h = 10 inches, L = 200 inches, and E = 15 E+06 psi,

- THE STRESS AT SECTION 'A-A' WILL BE ONLY 0.036 psi !!!

AIST

PERKIN-ELMER
Space Science Division



NEAR TERM SPACE DEMONSTRATION OF CRITICAL ENABLING TECHNOLOGIES. The drawing shows the integrated space demonstration of a precision optical mirror with matched curvature mirror segments, space vehicle compatible assembly technology of an optical system, real-time structural metrology and control, and structural design technology for precision optical systems. Industry is supporting this program.

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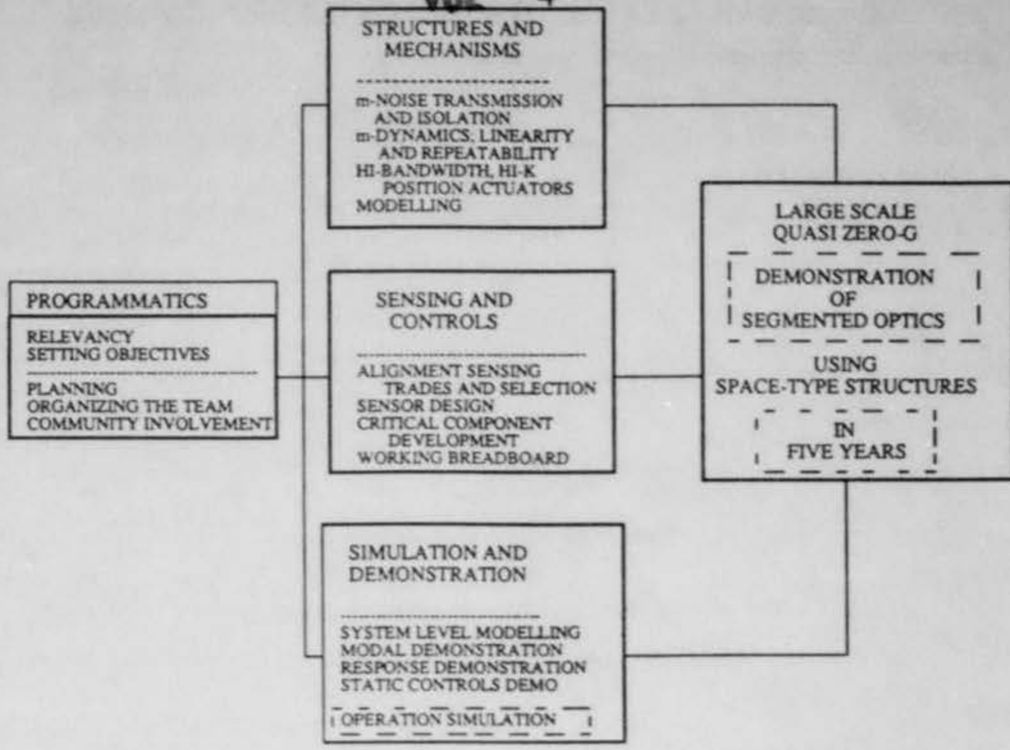
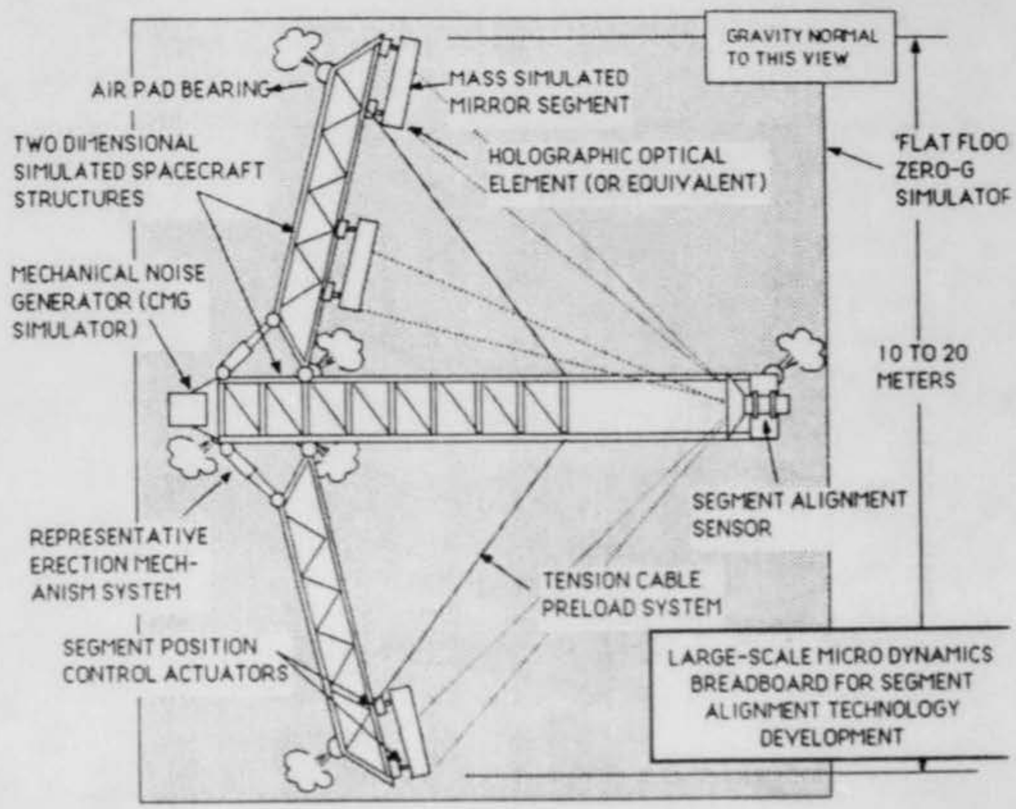


STRUCTURES AND MECHANISMS
m-NOISE TRANSMISSION AND ISOLATION
m-DYNAMICS: LINEARITY AND REPEATABILITY
HI-BANDWIDTH, HI-K POSITION ACTUATORS
MODELLING
PROGRAMMATICS
RELEVANCY
SETTING OBJECTIVES
PLANNING
ORGANIZING THE TEAM
COMMUNITY INVOLVEMENT
SENSING AND CONTROLS
ALIGNMENT SENSING TRADES AND SELECTION
SENSOR DESIGN
CRITICAL COMPONENT DEVELOPMENT
WORKING BREADBOARD
LARGE SCALE QUASI ZERO-G
DEMONSTRATION OF SEGMENTED OPTICS
USING SPACE-TYPE STRUCTURES
IN FIVE YEARS
SIMULATION AND DEMONSTRATION
SYSTEM LEVEL MODELLING
MODAL DEMONSTRATION
RESPONSE DEMONSTRATION
STATIC CONTROLS DEMO
OPERATION SIMULATION



GRAVITY NORMAL TO THIS VIEW
AIR PAD BEARING
MASS SIMULATED MIRROR SEGMENT
TWO DIMENSIONAL SIMULATED SPACECRAFT STRUCTURES
HOLOGRAPHIC OPTICAL ELEMENT (OR EQUIVALENT)
'FLAT FLOO ZERO-G SIMULATOF
MECHANICAL NOISE GENERATOR (CMG SIMULATOR)
10 TO 20 METERS
SEGMENT ALIGNMENT SENSOR
REPRESENTATIVE ERECTION MECH-ANISM SYSTEM
TENSION CABLE PRELOAD SYSTEM
SEGMENT POSITION CONTROL ACTUATORS
LARGE-SCALE MICRO DYNAMICS BREADBOARD FOR SEGMENT ALIGNMENT TECHNOLOGY DEVELOPMENT

QUESTIONS:

J. R. VYCE: I would just like to make the comment that over the decades we've seen all kinds of problems being pushed ahead in the sense that many of the problems were circumvented by emerging technology. One of the patterns that I see coming on today is that, by the time anyone flys a next generation space telescope, it's almost certain to allow the use of a continuous primary mirror. You should not take the position not to fly it. There was reference to a 10 meter shroud, and a really heavy lift vehicle. I just wonder whether deployment where you have segmentation is really going to be a very important factor.

M. KRIM: I prefaced the remarks with the fact that I was going to talk only about segmented systems. I wasn't quite sure what the results of this workshop would be in terms of whether you predicate a system on the existence of a proposed 10 meter shroud or the largest shroud that I found in the inventory, the 4.6 meter shroud used on the Ariane.

J. R. VYCE: I'm not challenging what you did at all –

M. KRIM: No, I understand. I only talked about segmented systems. I guess the experience I've had every time I've had the opportunity to work on an optical systems with my hands, as opposed to on paper, is that nothing seems to stand still. It's very hard getting good fringes...

D. TENERELLI: We're talking about the shuttle having testbed missions, and of course getting into flight with this probably would be unwarranted from a cost standpoint. That's for a piggyback; as far as piggyback missions are concerned, you could build a structure. It doesn't necessarily have to be as large perhaps as what some people are envisioning for this, but you could verify some of these concepts. So somehow something like that should be pursued, as far as piggybacking on the shuttle.

M. KRIM: They flew a mission years ago where they built this large boom, a tubular framework that went out for 20 or 30 meters –

(UNIDENTIFIED): No, it was a tower, it was a rectangular tower –

(UNIDENTIFIED): – 20 or 30 or 40 meters long that they put all together with their little hands and then they took it all apart again and put it back in the bay.

(UNIDENTIFIED): I'm talking about actively controlling the structure.

(UNIDENTIFIED): Well they haven't built that but they do fly missions to do experiments like this demonstration.

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WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

VOL 4

HST POINTING CONTROL SYSTEMS

GARY BEALS

LOCKHEED
Palo Alto, California

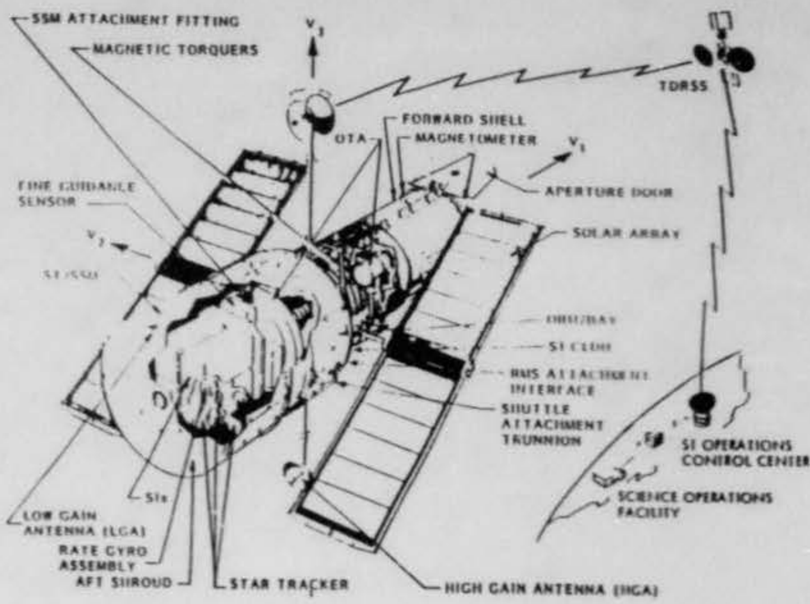
March 4, 1991

(Presentation material follows)

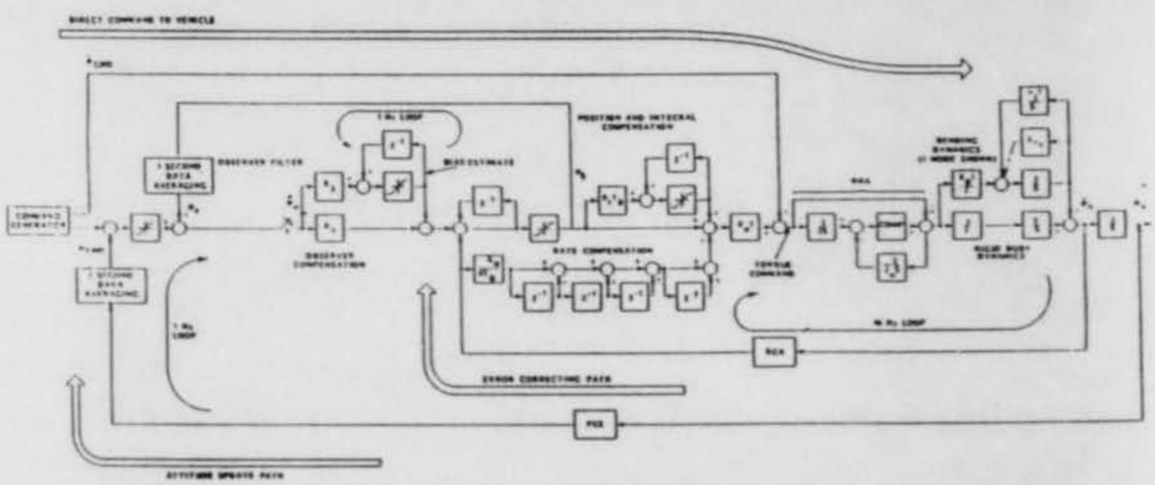
D-8541

VOL 4

HUBBLE SPACE TELESCOPE SYSTEM



POINTING CONTROL SYSTEM



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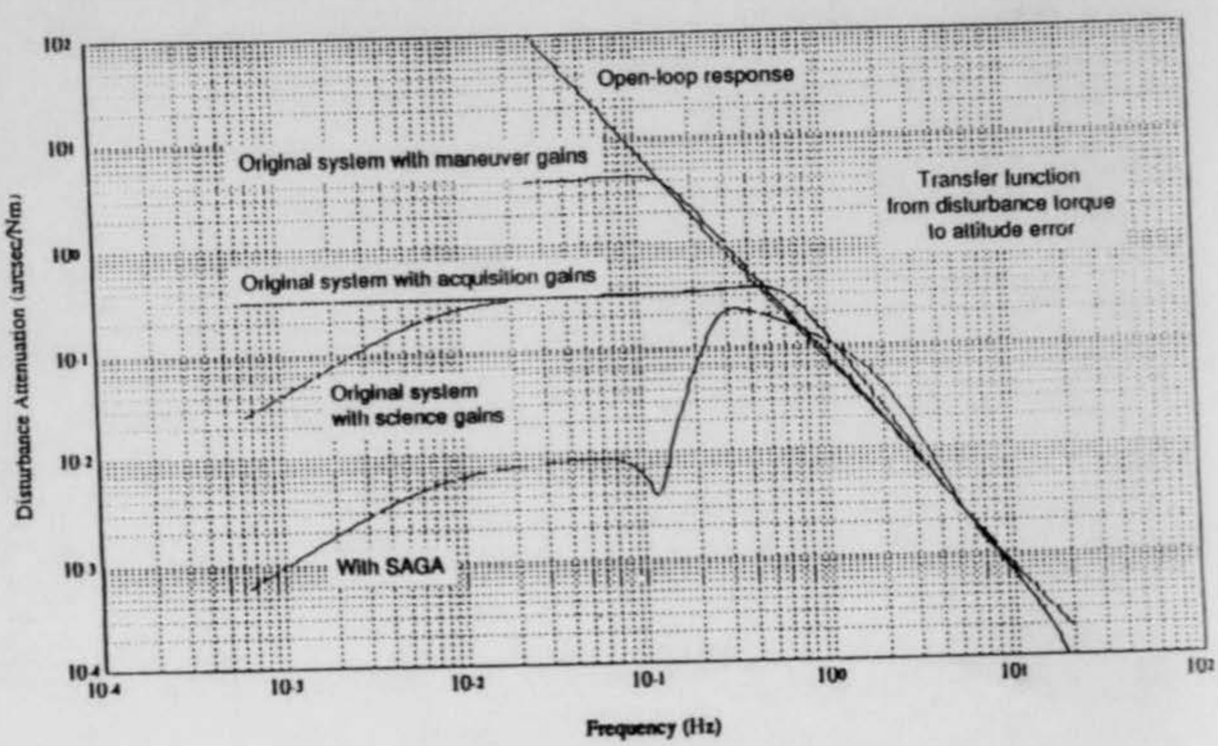
VOL 4

Disturbance Rejection for Various PCS Configurations



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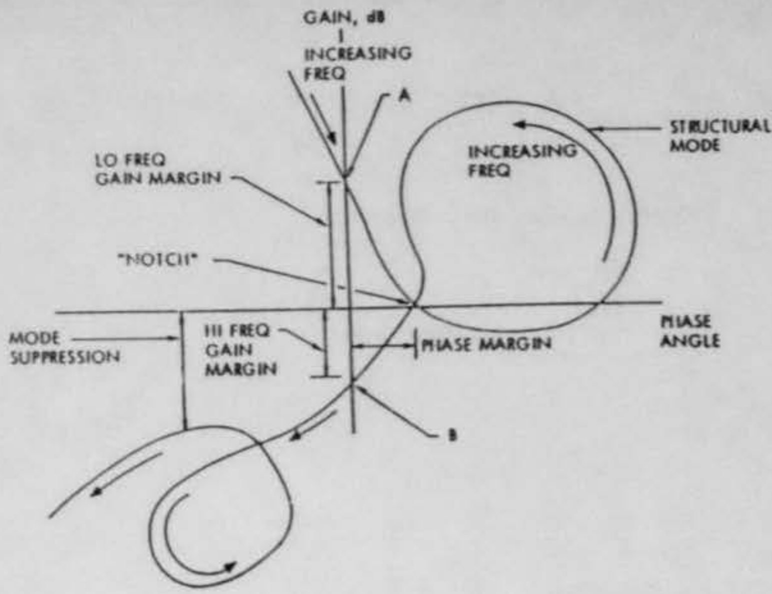
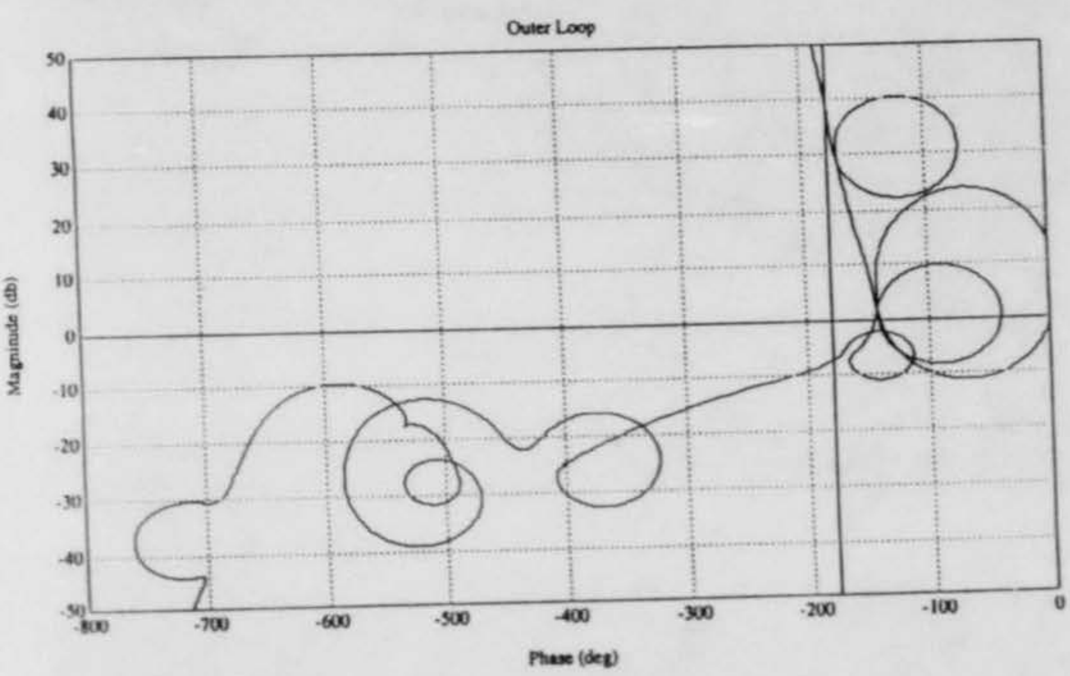
VOL 4

Typical Nichols Plot Showing Stability Margin Definitions



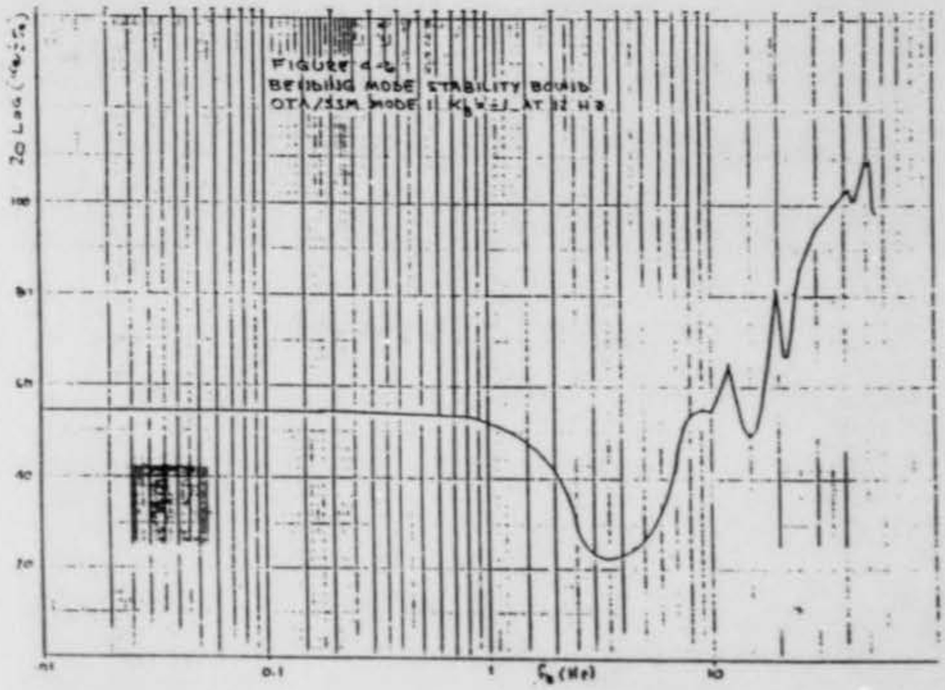
Nichols Plot of the HST V3 Axis



Significant Bending Modes about the V3 Axis

Description	Frequency (Hz)	Modal Gain K_B
Solar array	0.110	0.025
Solar array	0.600	0.079
Solar array	1.079	0.029
Solar array	2.508	0.013
	10.834	0.104
	12.133	-0.320
	13.201	-0.110
	14.068	-0.217
	14.285	-1.516
	15.264	0.170

Bending Mode Stability Bound for the V3 Axis



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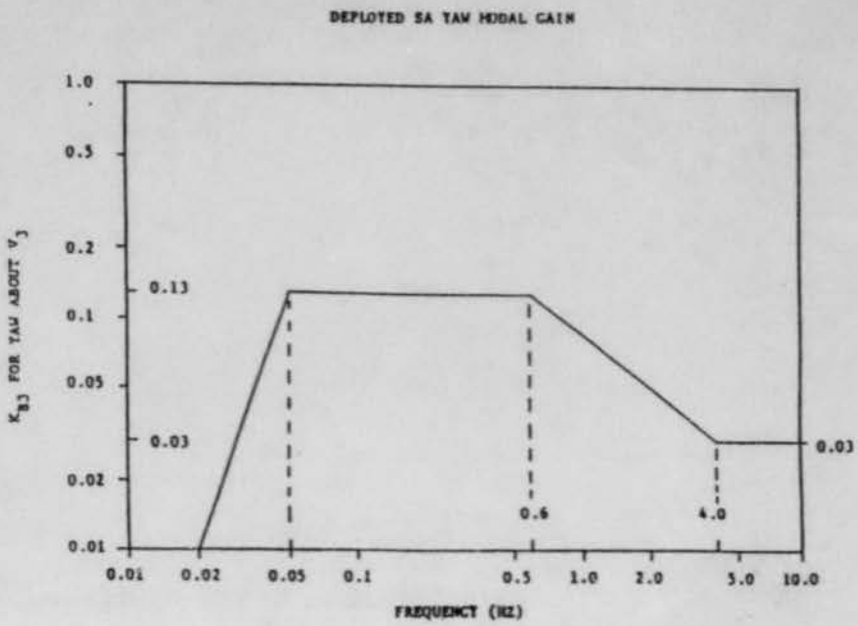
VOL 4

Bending Mode Envelope for the Solar Array



PARAMETER	HST	NGST
Accuracy	10 mas	10 mas
Stability	7 mas	1 mas
Weight	11 tons	~ some
Orbit	LEO	HEO
On-orbit service	Yes	No

QUESTIONS:

R. THOMPSON: Could you put your first handwritten graph up because as we look at that particular set of assumptions, you wonder if we're heading down the right track at all, especially the one that says no on-orbit servicing. And that means there's no new instruments for that telescope and if it's a one-shot telescope with a lot of money, perhaps that's not the way to do it. Understanding that there are spatial resolutions and things you want, you can ask if maybe a series of identical, let's say, 6 meter telescopes with individual instrumentation, all sort of lined up to go for specific purposes, might be better. One might be cryogenic, one might be just for spectroscopy or something else. This might be a better way to save money. These are production line types of telescopes. And I don't know that we've ever considered it, but when you really think of spending all of the money that we might spend for such a large telescope, this may be the bridge between now and the time that we really do have a lunar base where you'd have a different way to look at it.

G. BEALS: Let me just think of the problems. I think that's a very good observation. Unfortunately in our groups we don't have a systems panel and I think we're seeing the need for a systems panel to look at these overriding issues. If you have a 100,000 kilometer orbiter in that sense in the near future, it's going to be impossible to service. The astronauts simply cannot go that high. And telerobotics is not of such sophistication where it could really do much servicing at that altitude. On the other hand, your idea of having several of them, maybe not necessarily at a 100,000 kilometer level, maybe at several levels... Then when they wore out, you destruct them.

P. SWANSON: Also allows you to make changes –

G. ILLINGWORTH: There's certainly a significant level of rationality in that argument. But politically it's something that you'd never be able to sell. Having one of something that was closely similar to the rest of them would essentially kill off the rest, given the cost. In the minds of the folks that are funding these things - and I think Congress in a sense - they're looking at this and saying: Here's astronomers out there wanting the world. We'll give them one and that's it.

R. THOMPSON: I think if we keep that attitude ourselves, they will also keep it. But also I think what has happened to HST perhaps has changed attitudes even since we had the first of these conferences, and it may be that if we look at it as a rational program, for example in one sense if you look at the DOD type of missions, that's what they do and when you look at a long-term commitment over a long time, this may be a way to go. I'm just throwing it out there for consideration.

P. SWANSON: There's an awful lot of dogma within NASA and people seem to believe this and feel it can't be changed. But if you come up with an absolutely compelling argument to save money and get more science in the long run, NASA can change. They've done it before. It's not easy to change them, but they can change.

(UNIDENTIFIED): Either way it's not a big impact to the control system designers.

(UNIDENTIFIED): If we can get nearly rigid appendages, then you eliminate a lot of the complexity that was discussed in the previous presentation.

J. CROCKER: We're doing better currently on stability ... to 7 milliarcseconds. Do you have an estimate for how much of that is separable into being in low earth orbit or is it in panels and appendages? Can you just enter a guess?

G. BEALS: I think the primary driver right now on performance as we've seen is the terminators. The solar array disturbance just swamps out everything else and because of that we've spent most of our time quantifying that and not going further down in the error budget trying to understand the other error sources.

P. DAVIS: What are those ___ gains, what do you mean by that?

G. BEALS: These are the gains we get when we're actually ready to take science, and so as the space telescope goes from one target to the next, it has to slew from one position to the next in the maneuver gains. When the rate gets below a certain level, we go to the acquisition gains at which point the fine guidance sensors are looking out for their guide stars, they're locking onto them. Once they're locked and we're ready to go to science, we switch into these gains.

P. DAVIS: So you mean they're using fine guidance?

G. BEALS: That's correct.

P. BELY: I think you mentioned earlier that one of the assumptions here is that we're using the same stiffness for NGST as for HST. What will be the effect of that?

G. BEALS: I'm guessing based on your presentation you were talking about a longer tube.

P. BELY: __ about twice as long as HST, but the main modes will be lower, about 30 Hertz.

G. BEALS: If you move the modes down then you're well within the bandwidth of the control system. In fact, you could probably roll them off better than if they're around the bandwidth. What we're finding right now is that the PCS has a bandwidth of about 0.6 Hertz and it turns out that's where one of the solar array disturbances is and it's really tough to control the mode close to the bandwidth. So if you can get well within the bandwidth or well outside, it's not a stability problem.

G. BEALS: One other issue that raises is that when you're at a high altitude like that, I didn't mention the momentum management system Space Telescope had, but we rely on the Earth's magnetic field for damping and for dumping momentum from the reaction wheels. You obviously don't have that available at high altitudes, so there would have to be an alternate scheme for momentum dumping whether it's cold gas or whatever.

R. ANGEL: Lets come back to Roger Thompson's point. I think we're sort of conditioned to think of universal optical-infrared telescopes in the range from the ultraviolet through the near infrared. That's because on the ground seeing limits you always to pretty much the same resolution. In space there's a big difference between 2,000 angstroms and 2 microns. There's a factor of 10. Radio astronomers would never consider making a universal radio telescope because at every factor of 10 you completely change the way you do it. So the argument for making more than one telescope, I find very compelling. If you make a telescope that's diffraction limited at 2 microns and works at 100 Kelvin, it's a totally different animal from one that's diffraction limited at 2,000 Angstroms. It doesn't need to be cooled. And if you put them together, you're going to pay a very significant price for that. So we should think very hard about this issue before we say we want to get into that sort of stuff.

G. BEALS: We'd like to sort of start with 6 telescopes, although some slightly different.

R. ANGEL: It may now be six but these are not slightly different. They have a major, major difference.

G. BEALS: That's a very good point, Roger.

B. WOODGATE: I just want to follow up on Roger's point – there's a very specific issue that comes up. If you run this thing at 100 Kelvin through the IR and you also want to work in the ultraviolet, it's likely to collect some contaminants on it. Then they don't work in the ultraviolet because contaminants are being absorbed on it. So if you want to run a CCD in ultraviolet, it's the same problem as trying to run cold mirrors in the ultraviolet and you just may not be able to do it. There's too much stuff around. So you may have to separate them.

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TELESCOPE TECHNOLOGIES: DETECTORS AND INSTRUMENTS

- ASTROTECH 21 SENSOR TECHNOLOGY WORKSHOP SUMMARY
- CCD AND PHOTOEMISSIVE DETECTORS
- IR DETECTOR TECHNOLOGY

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WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

VOL 4

ASTROTECH 21 SENSOR TECHNOLOGY WORKSHOP SUMMARY

BARBARA A. WILSON

JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California

March 4, 1991

(Presentation material follows)

D-8541

VOL 4

ASTROTECH 21
Detector Technology Requirements
0.1 μm - 10 μm

Presentation To Large Filled Aperture Telescope Workshop

3/4/91

B. Wilson

Chair, Astrotech 21 Sensor Technology Workshop

OUTLINE

1. Overview of Sensor Technology Workshop
2. Summary of UV - Visible - MWIR Findings

BAW 3-4-91 - #1

ASTROTECH 21 SENSOR TECHNOLOGY WORKSHOP

Astrotech 21
Sensor Technology Workshop

SCOPE

SIX TECHNOLOGY AREAS:

1. X-RAY, GAMMA RAY
2. UV-VISIBLE-NEAR IR
3. DIRECT IR
4. HETERODYNE SUBMM-RADIO
5. SENSOR READOUT
6. SENSOR COOLER

BAW 3-4-91 - #2

ASTROTECH 21 SENSOR TECHNOLOGY WORKSHOP

Astrotech 21 Sensor Technology Workshop

CHARTER

ASSEMBLE TEAMS OF EXPERTS CHARGED TO:

1. IDENTIFY DETECTOR REQUIREMENTS FOR AT21 MISSION SET
2. DETERMINE NEED FOR TECHNOLOGY ADVANCES
3. RECOMMEND TECHNOLOGY DEVELOPMENT PLAN

BAW 3/4/91 - #3

ASTROTECH 21 SENSOR TECHNOLOGY WORKSHOP

Large Filled Aperture Telescopes:

RELEVANT PANELS

UV-Vis-Near IR	0.01-2.5 μm (0.1 - 2.4 μm)	**Gethyn Timothy**, M. Blouke, D. Bredthauer, J. Janesick, R. Kimble, T.-H. Lee, M. Lesser, O. Siegmund, G. Weckler.
Direct IR	2.5 - 200 μm (2.5 - 10 μm)	**Craig McCreight**, R. Bharat, R. Capps, W. Forrest, A. Hoffman, R. McMurray, M. Reine, P. Richards, D. Smith, E. Young.
Readout	All wavelengths (0.1 - 10 μm)	**Eric Fossum**, J. Carson, W. Kleinhans, W. Kosonocky, L. Kozlowski, A. Peczalski, A. Silver, H. Spieler, J. Woolaway.

BAW 3-4-91 - #4

RECOMMENDATIONS
0.1 - 0.3 μm

Si CCD

Parameter	Exists	Required	Technology Advance Required
Solar blindness	None	E-4	New materials, filters
Quantum efficiency	10%	> 50%	Device design, new materials
Format size	2K x 2K	4K x 4K	Lithography, materials
Read rate	20 μs/pixel	< 4 μs/pixel	Device design
Read noise	5 e rms	< 1 e rms	Read averaging
Rad. insensitive	Counts	Discriminates	Dual detector anticoincidence
Rad. survival	Problems	15 year life	Device design

BAW 3/4/91 - #5

ASTROTECH 21 SENSOR TECHNOLOGY WORKSHOP

RECOMMENDATIONS
0.1 - 0.3 μm

EMISSIVE PHOTOCATHODE / MICROCHANNEL PLATE

Parameter	Exists	Required	Technology Advance Required
Solar blindness	None	≥ E-4	New photocathode materials
QE	< 50%	≥ 50%	Device design, new materials
Format size	2K x 2K	≥ 4K x 4K	Lithography, semiconductors
Channel diameter	10 μm round	6 μm square	Lithography, semiconductors
Dark count	< 0.3 ct/cm2/s	< 0.01 ct/cm2/s	
Read rate	1E6 ct/s	>> 1E7 ct/s	
Rad. insensitive	None	Discriminates	
Rad. survival		≥ 15 year life	Device design

BAW 3/4/91 - #6

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ASTROTECH 21 SENSOR TECHNOLOGY WORKSHOP

RECOMMENDATIONS
0.1 - 0.3 μm

3D DETECTORS:
2D IMAGING WITH ENERGY RESOLUTION

Parameter	Exists	Required	Technology Advance Required
Solar blindness		≥ E-4	New technology, filters
Quantum efficiency		≥ 50%	New technology
Energy resolution		E/ΔE > 10	New technology
Format size		≥ 1K x 1K	New technology
Rad. insensitive		Discriminates	Automatic with E resolution
Rad. survival		≥ 15 year life	

BAW 3/4/91 - #7

ASTROTECH 21 SENSOR TECHNOLOGY WORKSHOP

RECOMMENDATIONS
0.3 - 0.9 μm

Si CCD

Parameter	Exists	Required	Technology Advance Required
Quantum efficiency	> 60%	> 80%	Retain in new options
Dynamic range	2E5	≥1E6	Device design
Format size	2K x 2K	8K x 8K	Lithography, materials
Read rate	20 μs/pixel	< 1 μs/pixel	Device design
Read noise	5 e rms	< 1 e rms	Read averaging
Rad. insensitive	Counts	Discriminates	Dual detector anticoincidence
Rad. survival	Problems	≥ 15 year life	Device design

BAW 3/4/91 - #8

ASTROTECH 21 SENSOR TECHNOLOGY WORKSHOP

RECOMMENDATIONS
0.9 - 2.5 μm

Si CCD/CID, Intrinsic Photovoltaic Detectors

Parameter	Exists	Required	Technology Advance Required
Quantum efficiency	> 50%	> 50%	Retain in new options
Format size	0.5K x 0.5K	8K x 8K	Lithography, materials
Read rate	20 μs/pixel	< 1 μs/pixel	Device design
Read noise	5 e rms	< 1 e rms	Read averaging
Rad. insensitive	>1 ct/hit	≤ 1 ct/hit	Device design
Rad. survival		≥ 15 year life	New materials, structures

BAW 3/4/91 - #9

ASTROTECH 21 SENSOR TECHNOLOGY WORKSHOP

RECOMMENDATIONS
2.5 - 10 μm

Intrinsic Photovoltaic, Quantum Well, Superlattice Detectors

Parameter	Exists	Required	Technology Advance Required
Quantum efficiency	> 50%	> 50%	New materials, structures
Format size	0.5K x 0.5K	8K x 8K	Lithography, materials
Read rate	20 μs/pixel	< 1 μs/pixel	Device design
Read noise	5 e rms	< 1 e rms	Read averaging
Rad. insensitive	>1 ct/hit	≤ 1 ct/hit	Device design
Rad. survival		≥ 15 year life	New materials, structures

BAW 3/4/91 - #10

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ASTROTECH 21 SENSOR TECHNOLOGY WORKSHOP

KEY TECHNOLOGY ISSUES

Wavelength	Key Tehnology Issues	Technology Advance Required
0.1 - 0.3 µm	Solar blindness, high quantum efficiency, large format, low read noise, rad hardness.	New CCD & photocathode mats, filters, semiconductor MCPs, MCP readout, 3D detectors.
0.3 - 0.9 µm	Large format, low read noise, rad hardness.	Si CCD design, Anticoincidence
0.9 - 2.5 µm	large format, low read noise, rad hardness.	Hybrid CID, new PV materials, bandgap engineered devices.
2.5 - 10 µm	Large format, low read noise, rad hardness.	New PV materials, bandgap engineered devices.

BAW 3/4/91 - #11

IR DETECTORS FOR NGST: REQUIREMENTS

- Large format, good uniformity
- High sensitivity and dynamic range
- Low read noise and high read rate
- 60 - 80 K operating temperature
- Cosmic ray discrimination / fast recovery
- Cosmic ray survivability

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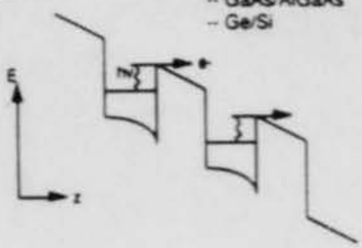
IR DETECTORS FOR NGST: EMERGING TECHNOLOGIES

Technology	Potential Advantages and Disadvantages	State of Development
GaAs QWIP (AT&T, etc)	Large arrays, good uniformity, compatible MUX. In-plane light detection.	Large arrays produced, good uniformity.
Si, GaAs HIP (JPL, LL)	Large arrays, good uniformity, compatible MUX. Quantum efficiency may be limited.	First arrays fabricated, good uniformity.
III-V SLSL (CIT, Hughes, Sandia, JPL)	High sensitivity, III-V process technology, low dark current. Materials uncertainties.	First discrete devices fabricated, needs more materials development.

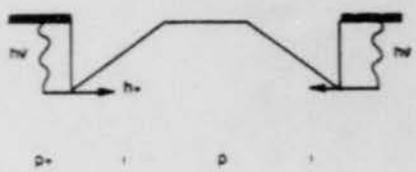
JPL

NEW LWIR DETECTOR OPTIONS

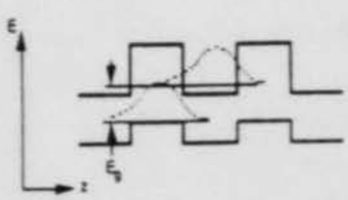
AT&T* Multiple Quantum Well Detectors
-- GaAs/AlGaAs
-- Ge/Si



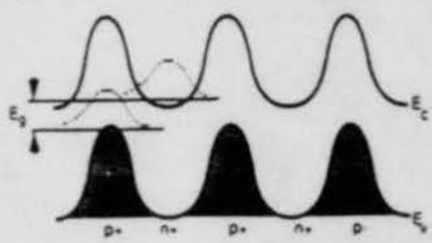
JPL Internal Photoemission Detectors
-- Heterojunctions: GaAs/AlGaAs and Ge/Si
-- Si Homojunctions



SNL* Strained Layer Superlattices
(type II heterojunction with strain)



JPL InAs or InSb Doping Superlattice



* JPL and University participation

QUESTIONS:

R. THOMPSON: You have a column called requirements. How were they put together, how were they determined to be requirements as opposed to desires in some cases?

B. WILSON: The desires were often even higher. The desires went to an even higher range. That's a good question as far as how one decided on a number that you're going to list as a requirement. I think there's not a very good, hard answer for that. It wasn't in a very clear cut manner; the idea was to take things that were listed as desired for the missions in terms of the background that exists on the different missions set for Astrotech 21. To rule out the things that were just totally out of the question and to back off to something that looked like it might be feasible and could be considered as a goal for a requirement

J. CUTTS: Yes I would like to respond to that also. I think part of the answer is that it is still possible within even say the proceedings from this workshop - insofar as they list things that are requirements or desired capabilities - that can still be folded in. It's not in finished form yet.

B. DAVIS: The read rate of 1 microsecond per pixel, is that how long it takes to read one out or how often are they read out, or how many bits per pixel ___?

B. WILSON: Actually that's a good point, it really should be specified in terms of bits per pixel too which can certainly make a difference, and I don't believe that was provided and I don't know which number they were aiming at in that particular case. You fill a ten thousand by ten thousand array with little packages of charge and each one has to be read out to say how much charge did that pixel see. So you have to multiply that time by the total number of pixels to get the full frame rate.

B. DAVIS: The frame rate is the requirement here, not the pixels?

B. WILSON: Yes.

L. ROBINSON: What they really meant by microseconds was a million pixels per second.

B. WILSON: Yes, that's correct. It was written to be on the order of a sixty second full-frame readout. In order to compare different technologies with different pixel counts, I turned that back into a per pixel read time But yes, if you are doing parallel readout, then the net time will not be the multiple of this time and the number of pixels.

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CCD AND PHOTOEMISSIVE DETECTORS

BRUCE WOODGATE

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

March 4, 1991

(Presentation material follows)

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SCIENTIFIC CCD
STATE-OF-THE-ART SPECIFICATIONS

FORMAT SIZE:

4096 X 4096 PIXELS POSSIBLE (4 CHIPS/4 INCH WAFER EMPLOYING 7.5 MICRON PIXELS)

2048 X 2048 PIXELS POSSIBLE (4 CHIPS/4 INCH WAFER EMPLOYING 15 MICRON PIXELS)

1024 X 1024 CONSERVATIVE... 15-20% IMAGER YIELD (9 CHIPS/4 INCH WAFER)

3 SIDE BUTTING POSSIBLE WITH A 2 PIXEL GAP

PIXEL SIZE:

MAXIMUM 52 MICRONS (3-PHASE)

MINIMUM 7.5 MICRONS (3-PHASE)

READ NOISE:

4-5 ELECTRONS RMS (SINGLE SAMPLING AT 6 MICRO-SEC)

< 1 ELECTRON RMS (32 SAMPLES USING "SKIPPER" TECHNOLOGY)

ON-CHIP AMPLIFIER SENSITIVITY:

2-4 MICRO-VOLTS/ELECTRON

CHARGE TRANSFER EFFICIENCY:

> 0.999999 AT -70C (> 10,000 ELECTRON POINT SOURCE)

BULK STATE LIMITED (I.E., CTE DEPENDENT ON QUALITY OF SILICON MATERIAL)

DARK CURRENT (REFERRED TO ROOM TEMP, 15 MICRON EPITAXIAL):

1 NANO-AMP/CM^2 NONINVERTED

0.1-0.2 NANO-AMP/CM^2 PARTIALLY INVERTED

0.01-0.02 NANO-AMP/CM^2 TOTALLY INVERTED (MPP OPERATION)

SCIENTIFIC CCD
STATE-OF-THE-ART SPECIFICATIONS

FULL WELL CAPACITY (18 MICRON PIXEL):

325,000 ELECTRONS (PARTIALLY INVERVED)

125,000 ELECTRONS (MPP)

PIXEL-TO-PIXEL NONUNIFORMITY:

2-3% (NONINVERTED)

1% (MPP OR PARTIALLY INVERTED)

NONLINEARITY:

< 1% (18 MICRON PIXEL; 1 MICRO-VOLT/ELECTRON)

QUANTUM EFFICIENCY (10 MICRON EPITAXIAL):

BACKSIDE ILLUMINATION (QE-PINNED, UV FLOODED)

2000 A = 0.2
4000 A = 0.5
6000 A = 0.6
9000 A = 0.3

FRONTSIDE ILLUMINATED (1500 A THREE-PHASE POLY GATES)

2000 A = 0.0
4000 A = 0.08
6000 A = 0.45
9000 A = 0.2

FRONTSIDE: OPEN PINNED PHASE (OPP 3-3-12) (1500 A TWO-PHASE POLY GATES)

2000 A = 0.18
4000 A = 0.3
6000 A = 0.55
9000 A = 0.3

SCIENTIFIC CCD
STATE-OF-THE-ART SPECIFICATIONS

HIGH ENERGY RADIATION TOLERANCE BEFORE CTE DEGRADES:

1 KRAD... ELECTRONS

25 RADS... PROTONS

VIDEO DUMP TIME CONSTANT:

< 50 NANO-SEC (5 PF LOAD CAPACITANCE)

FRONTSIDE MTF:

0.6 BETWEEN 2000-6000 A

> 0.45 BETWEEN 6000-9000 A (10 MICRON EPITAXIAL)

MISCELLANEOUS FEATURES:

NO RESIDUAL IMAGE

NO QUANTUM EFFICIENCY HYSTERISIS (QEH)

1 FRAME ERASURE FROM A TOTALLY SATURATED CONDITION

MAXIMUM CCD BIAS = 20 VOLTS

MINIMUM LINE TRANSFER TIME 5 MICRO-SECS (1023 X 1024 18-MICRON PIXEL)

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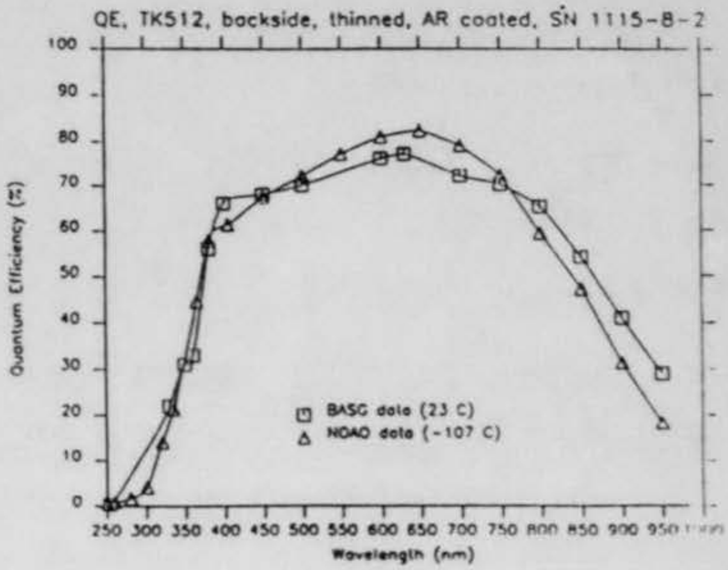
Tektronix

QUANTUM EFFICIENCY 512² CCD AR COATING

STIS



PHOTOEMISSIVE DETECTORS

ADVANTAGES

- VISIBLE-BLIND UV DETECTORS
- HIGH TIME RESOLUTION
- LOW SENSITIVITY TO COSMIC RAYS
  - AND COULD USE ANTI-COINCIDENCE
- RADIATION-HARD

DISADVANTAGES

- QE IN VISIBLE LOWER THAN CCDs
- LIMITED UPPER COUNTING RATE DUE TO USE OF MICROCHANNELPLATE INTENSIFIER

TYPES

- PHOTON COUNTERS, CAN BE TIME TAGGED
  - MAMA
  - WEDGE AND STRIP
  - DELAY LINE
  - RESISTIVE
  - CODACON
- PHOTON COUNTER OR ANALOG - INTENSIFIED CCD

MAMA PROGRESS

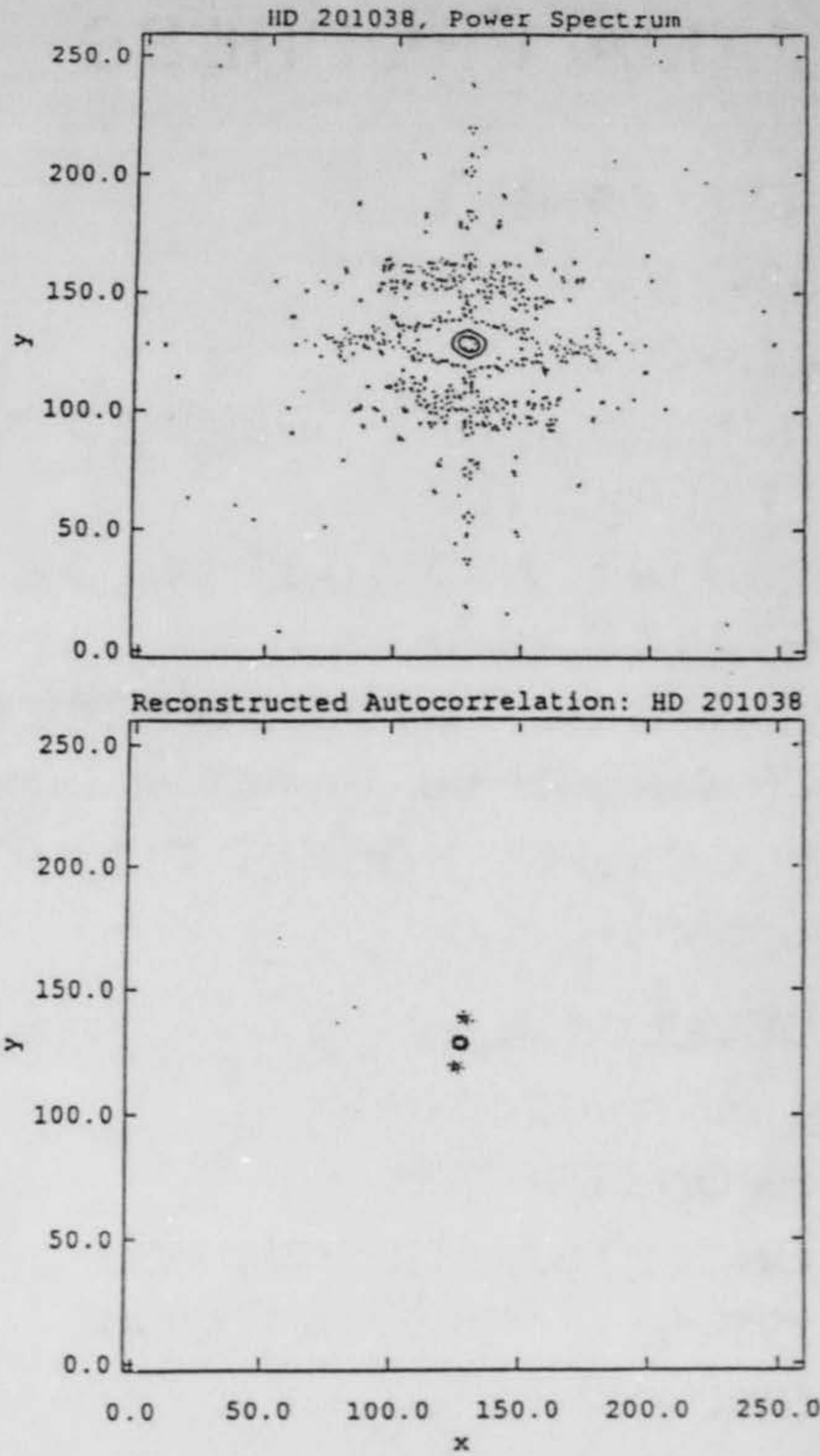
STIS DEVELOPMENT

- 1024x1024 BUILT
- 2048x2048
  - ANODE ARRAY DESIGNED AND IN FABRICATION
  - HEADER AND TUBE ~~IN DETAILED DESIGN~~ BUILT
  - FIRST DETECTOR ~~SCHEDULED FOR MARCH 90~~ OPERATING IN VACUUM CHAMBER
- SUCCESSFUL ROCKET FLIGHT (A. SMITH)

FUSE DEVELOPMENT

- 14 micron 240x960 DEMONSTRATED
- CONCEPTUAL DESIGN FOR 8192x512 ARRAY AROUND ROWLAND CIRCLE

SPECKLE IMAGE RECONSTRUCTION



DATA FROM THE ESO MAMA DETECTOR

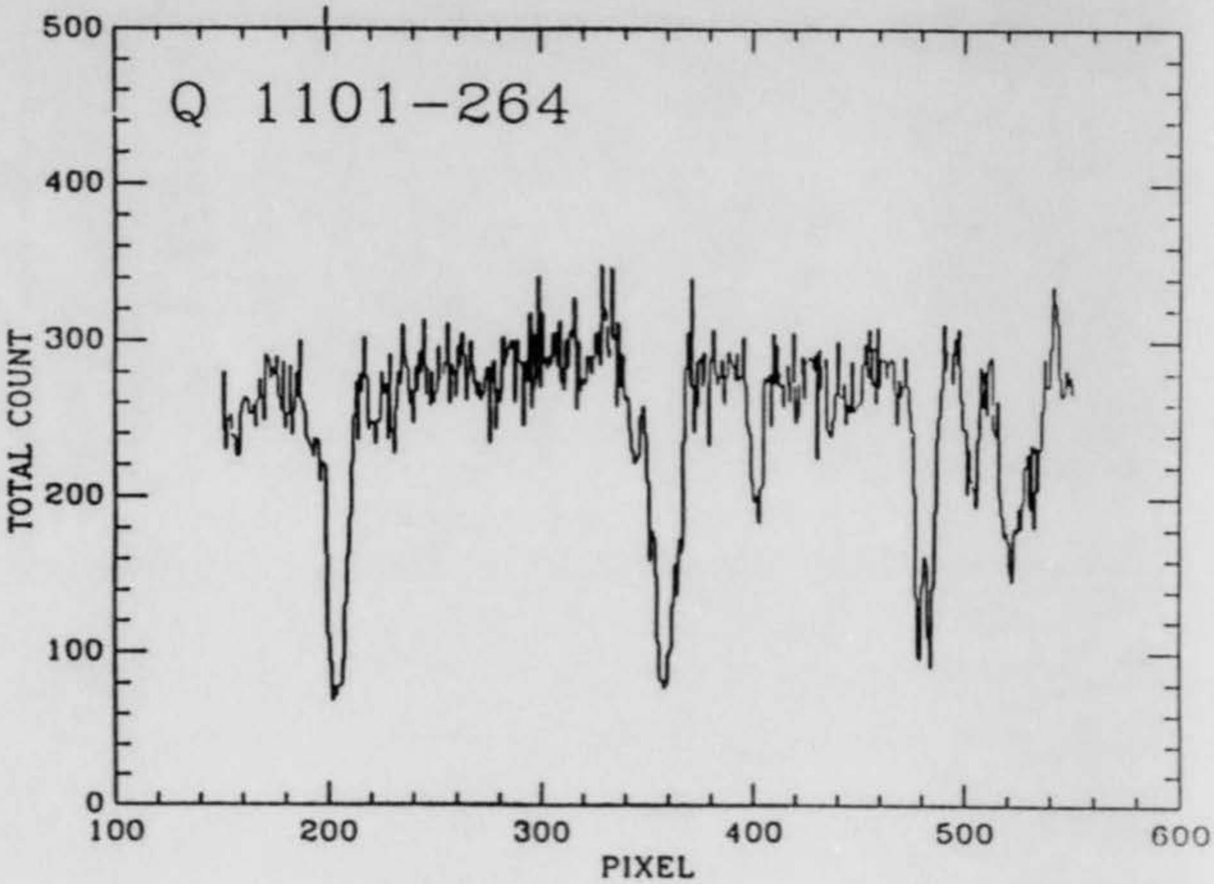


Figure 4: *A portion of the extracted spectrum of the quasar 1101-264. The scattered light background between the orders has been removed. This results in good scaling of the strong absorption lines.*

COSMIC RAY RATES

ENVIRONMENT	FLUX (CM**-2 S**-1)	MAX EXPOSURE TIME TO CLEAN IDEAL IMAGE BY VETO OF 2 (MIN) #
EARTH SURFACE	0.01	46
LOW EARTH ORBIT	0.1	4.6
HIGH EARTH ORBIT	2	0.25
LUNAR SURFACE	1	0.5
20 METERS BELOW LUNAR SURFACE	0.01	46
		# TIME FOR 0.05% OF A 2048x2048 ARRAY OF 21x21 MICRON PIXELS TO BE FILLED

REMOVAL OF COSMIC RAY HITS FROM CCD IMAGES

NUMBER OF IMAGES	1	2	3	4	5
PROBABILITY OF A HIT IN EACH PIXEL, p	2.5**-7	.0005	.0063	.022	.048
MAX INTEGRATION TIME TO ELIMINATE HITS BY VETO AT: #					
EARTH SURFACE (0.01 CM**-2 S**-1)	5.7 s	46 m (1.5 h tot)	10 h (30 h tot)	--	--
LEO (HST) (0.1 CM**-2 S**-1)	0.57 s	4.6 m (9.3 m tot)	1 h (3 h tot)	--	--
HEO (10 METER) (2 CM**-2 S**-1)	0.03 s	14 s (28 s tot)	3 m (9 m tot)	10 m (40 m tot)	22 m (1.9 h tot)
EFFECTIVE READOUT NOISE (STIS TECHNOLOGY) (EL'S)	2.7	3.8	4.7	5.4	6.0
COUNTS REQUIRED FOR S/N = 5 DETECTION	31	35	39	42	45
EXPOSURE FACTOR INCREASE FOR SAME S/N	1.0	1.13	1.26	1.35	1.45

FOR A 2048x2048 DETECTOR WITH 21x21 MICRON PIXELS, 4 PIXELS/HIT (TO ALLOW FOR SUB-PIXEL REGISTRATION

CAVEATS: APPLIES TO LOW DENSITY OF HITS, BLANK FIELDS. PROBLEMS WITH HIGH DENSITY OF HITS, IMAGE STRUCTURE SLOPES, SUB-PIXEL REGISTRATION, NOT MUCH USED IN RAF EVEN WITH p=.0005

DETECTORS ABOVE EARTH'S MAGNETIC SHIELD - GEOSYNCHRONOUS AND ABOVE

LUNAR

- FOR VISIBLE: CCDs BURIED UNDER 20 meters OF LUNAR ROCK - LIMITS COSMIC RAY RATE TO THAT ON EARTH SURFACE
  - EXTEND TO UV WITH DEVELOPMENT OF VISIBLE REJECTING FILTER
- FOR UV: PHOTOEMISSIVE ARRAY DETECTORS, HIGH COUNT RATE CAPABILITY FOR CAMERAS

NON-LUNAR

- FOR VISIBLE: POSSIBLY USE CCDs, REJECTING COSMIC RAY HITS WITH MULTIPLE IMAGE VETOs
  - (BUT WE MUST SIMULATE THIS)
- FOR UV AND VISIBLE: PHOTOEMISSIVE ARRAY DETECTORS, HIGH COUNT RATE CAPABILITY FOR CAMERAS

GENERAL

- LARGER FORMAT, HIGHER QE, LESS EXPENSIVE
- POSSIBILITY OF 3D (X,Y,E) DETECTORS - e.g. USING SUPERCONDUCTING OR OTHER VERY LOW TEMPERATURE SENSORS (MICRO-EV)

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DETECTOR RECOMMENDATIONS

CCDs

- LARGER FORMATS - monolithic and mosaic, multiple outputs
- RADIATION HARDENING - especially for CTE, trap dynamics, time scales and temperatures
- UV FILTERS - visible blind, alkali metals, polarization, tandem gratings
- QE IMPROVEMENTS - temperature variations?
- COSMIC RAY REJECTION
  - for high orbits
  - study methods
  - combine images, lower readout noise, eg skipper or JFET
- CONTAMINATION CONTROL (ESP. COLD & UV)
- SMALL PIXELS

GENERAL

- HIGH COUNT RATE PHOTOEMISSIVE DETECTORS
  - ICCDs: low gain MCP, or 2-D digicon, or oblique; but must remove cosmic rays
  - discrete dynode MCP
  - separate charge replacement and secondary emitting materials
- CURVED FOCAL PLANES
- PHOTOEMISSIVE QE IMPROVEMENTS
- PIXEL SIZE CHOICE
- SPACE QUALIFIED, LESS EXPENSIVE
- XYE DETECTORS
  - measure energy of UV/vis/IR photon by ultra-low noise proportional detection
  - drastically low thermal noise, very cold
  - superconducting sensors
  - solid state photomultiplier
  - other?

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WORKSHOP PROCEEDINGS:
TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

VOL 4

IR DETECTOR TECHNOLOGY STATUS

CRAIG McCREIGHT

AMES RESEARCH CENTER
Mountain View, California

March 4, 1991

(Presentation material follows)

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ASTROTECH 21
SUBMILLIMETER ASTROPHYSICS PROGRAM

DIRECT DETECTOR SYSTEMS MISSION INHERITANCE

MISSION	DETECTOR TYPE: INTRINSIC	EXTRINSIC SILICON	EXTRINSIC GERMANIUM	BOLOMETERS	INTEGRATED ARRAYS	COMMENTS
IRAS		✓	✓			DISCRETE DETECTORS, WITH JFET TIAs
COBE	✓ (InSb)	✓ (Si:As IBC)	✓	✓ (1.5K)		"
SIRTF	✓ (InSb) OR HgCdTe)	✓	✓ (Ge IBC, or Ge STRESSED)	✓ (0.1K)	✓	MULTIPLEXED READOUT; INTEGRATING Si FET READOUTS

9-7

DIRECT DETECTORS: 1990 STATE OF THE ART

READ NOISE	$\leq$ 50 E^-
QUANTUM EFFICIENCY	~ 40% SI AND GE ~ 90% INTRINSICS
DARK CURRENT	< 10E^- /S
ARRAY FORMATS (λ<30 μM)	256 x 256 ~~128 x 128, WITH 256 x 256 NOT FAR OFF~~ (DEMONSTRATED IN HgCdTe)
READOUT TYPE	SWITCHED SI FET, MULTIPLEXED READOUT
UNIFORMITY	~ 5%
WELL CAPACITY	1 - 10 x 10^6 E^-

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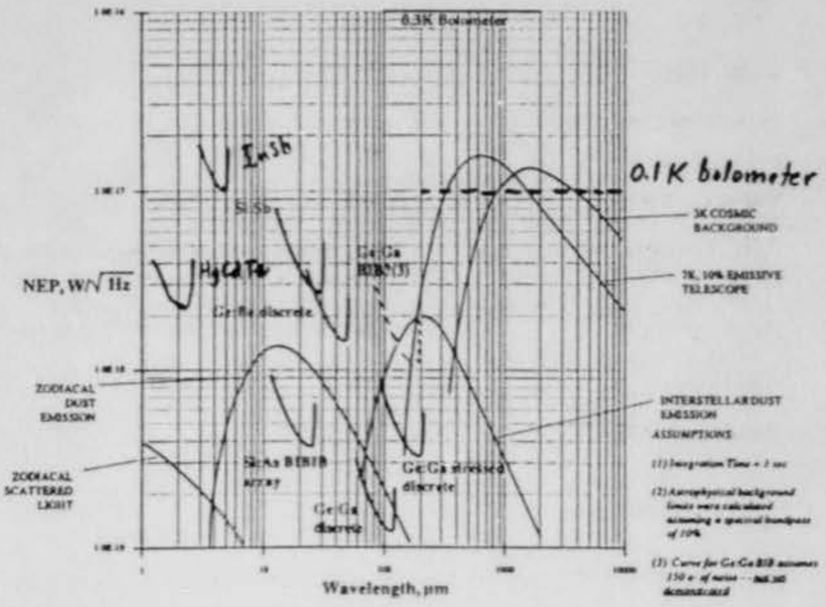
SIRTF DETECTOR DEVELOPMENT SENSITIVITY



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JPL

SIRTF Detector Development Activities

Status Date: 10/17/90

	Detector Material	Multiplexer and Packaging	Development Responsibility	Characterization Responsibility	Test Verification Responsibility	Cutoff Wavelength
1 D	SBRC InSb PV	CRC 228 58x62	IRAC (UR)	IRAC/IRS (UR)		5.3
2 B	SBRC InSb PV	CRC 463 256x256	IRAC (UR)	IRAC/IRS (UR)		
3 A	CE InSb PV	VO 256x256	JPL/ARC	UR/Various		
4 A	SBRC InSb PV	VO 256x256	IRAC (UR)	IRAC (UR)		
5 A	RI HgCdTe PV	VO 256x256	IRS Proposed Test			5
6 D	RI Si:As IBC	RI 10x50	IRS (Cornell)	IRS (Cornell)	IRAC (ARC)	28
7 D	Hughes Si:As IBC	CRC 228 58x62	IRAC (ARC)	IRAC (ARC)		
8 B	RI Si:As IBC	VO 128x128	IRS (Cornell)	IRS (Cornell)		
9 A	Hughes Si:As IBC	CRC 463 128X128	IRAC (ARC)	IRAC (ARC)		
10 A	RI Si:Sb IBC		IRS (Cornell)	IRS (Cornell)		34
11 B	Ge:Be PC		MIPS (LBL)	MIPS (UA)		50
12 B	Ge:Ga PC		MIPS (LBL)	MIPS (UA)		120
13 B	Ge:Ga Stress PC		MIPS (LBL)	MIPS (UA)		250
14 B	Ge:Ga Stress PC		IRS/MIPS	IRS (UR)		
15 A	Ge:Ga IBC		JPL/IRS/MIPS	JPL/IRS/MIPS	IRS/MIPS (UR/UA)	
16 A	Ge:B IBC		MIPS (LBL)	MIPS (LBL)		
17 D	Silicon Bolometer		GSFC	GSFC	MIPS (UA)	1200
18 D	Germanium Bolo.		MIPS (UCB)	MIPS (UCB)		
19 B		AE 152	MIPS (UA)	MIPS (UA)	IRS (UR)	
20 B		Thermal Isolator (1)	MIPS (UA)	MIPS (UA)		
21 D		VO CMOS Cryo FET	JPL/ARC	Low		
22 D		VO 1x32	JPL/ARC	MIPS (UA)		
23 D		VO 128x128	JPL/ARC	ARC/CORNELL/JPL		
24 D		VO 256x256	JPL/ARC	UR/ARC/JPL		
25 D		Thermal Isolator (2)	GSFC	IRAC(GSFC)		
26 D		Thermal Isolator (3)	Low	IRAC(ARC)	IRS(Cornell)	
27 A		Low Temp 256x256	SBRC	IRAC (UR)		
28 A		TAB	MIPS(UA)	MIPS(UA)		
29 B		Planar Package	MIPS(UA)	MIPS(UA)		
30 B		Light Concentrator	MIPS(UA)	MIPS(UA)		
31 B		Stress PC Package	MIPS(UA)	MIPS(UA)	IRS(UR)	

A - Alternate Technologies B - Baseline Technology D - Developmental Activity

Fig. 1. Direct IR Detector Technology Needs

	Near IR (1 - 5 μm)	Mid IR (5 - 10/20 μm)	Far IR (30 - 200 μm)	Far IR (200 - 1000 μm)
Materials	PV: InSb, HgCdTe. Bandgap engineered. Photon Counting (Superlattice or SSPM). Etc.	Si:x IBC. HgCdTe. Photon Counting. Bandgap Engineered. Etc.	Ge:x IBC. Bolometers (semi- & superconducting). Bandgap engineered. Ge:x PC detectors. Etc.	Bolometers (semi- & superconducting). Narrow-bandgap semiconductors. SIS direct detectors. Etc.
Readouts	Low-noise, low dark current, low dissipation, rad hard	⇒	⇒	⇒
Formats Requested in Mission Set	$(1000 - 3000)^2$ $(20{,}000)^2$ $(1000)^2$	$(20{,}000)^2$ $(1000)^2$	$(10)^2$ $(32 - 100)^2$	$(10)^2$ $(32 - 100)^2$
Yrs 'til Needed in Mission Set	3, 4, 6, 13, 16	13, 15, 16	5, 15, 15	5, 15

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Fig. 2. Overall Recommendations for IR Detector Development

- ❑ *Low-Temperature Readout Electronics*
  - *-Low Array Read Noise (1 e-)*
    - *•Si CMOS (<<20 K, and >20 K)*
    - *•non-Si FETs*
  - *-2 K, Low-bias Circuits*
  - *-Bolometers*
  - *-Photon Counting Detectors*
- ❑ Large-Format IR Arrays
  - -≤ 30 μm
  - -Ge Arrays (Photoconductors, BIBs)
  - -Array-compatible Bolometer Concepts
- ❑ Photon Counting Detectors
  - -Si:As SSPM
  - -Novel Near-IR Concepts (Superlattice?)
- ❑ Higher-Temperature 10 μm Detectors
  - -HgCdTe (~30 K)
  - -Bandgap Engineered Materials
- ❑ Ge BIB Detectors (epi technology)
- ❑ Improved Si:Sb BIB Detectors
- ❑ Adapt SIRTF Technology for Higher Backgrounds
- ❑ Critical Mass Problem (esp. at long-λ)

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Fig. 3. Readout Electronics

State of the Art	Key Components/ Desired Level	Promising Technologies	Pros	Cons	Recommend for Support?	Missions
Si MOS array <20 K ~50 e⁻	<<20 K Si FETs 1 e⁻	Si MOS	Si maturity	Radiation, onset of freezeout	✔ (for highest sensitivity arrays)	LB, SMMM?
Si MOS discrete >20 K ~4 e⁻	>20 K Si FETs 1 e⁻	Si MOS	Si maturity	Radiation, onset of freezeout	✔ (for higher-background arrays)	MB
GaAs JFET 4 K ~60 e⁻	non-Si FETs 1 e⁻	GaAs or Ge or InSb or ?	Harder to radiation than Si	Immature	✔ (for longer term arrays)	LB post-SIRTF, others
Si JFETs for bolometers (40 K) few nV/√Hz	Bolometer readout and multiplexer	Isolated Si? GaAs? Superconducting devices?			✔ (support best idea) (For bolometer arrays)	SMMM, LDR, MB, LB
	Stable-bias circuits (few mV)	MOS TIA, other innovative concepts	Si maturity	Power dissipation (?)	✔ (long-λ Ge arrays)	LB, MB, SMMM
					Total Cost: large. Limited by: $	

Fig. 4. Large-Format Arrays

State of the Art	Key Components/ Desired Level	Promising Technologies	Pros	Cons	Recommend for Support?	Missions
1-5 µm: $(256)^2$ to $(512)^2$	$\geq(1000)^2$ arrays for < 20 µm	Hybrid (In bump) arrays with Si MOS readouts	Si maturity	Radiation, onset of freezeout	✔ Cost: moderate. Limited by: $	MB
		Monolithic arrays	No thermal mismatch	Processing	-	•
5-20 µm: nearly $(128)^2$		Non-Si readouts	Some rad hard	Maturity	✔ Cost: moderate. Limited by: $	•
	>30 µm Ge:x arrays	Stacked Si MOS. Cascode or source-follower circuits	Si maturity SIRTF experience	Desire very low temp operation.	✔ Cost: small. Limited by: ideas	LB, MB, SMMM
30-120 µm: 3 x 32		Planar Si readouts for Ge BIB		Desire very low temp operation.	-	•
	Array-Compatible Bolometer Concepts	Superconducting Concepts (Transition Edge, Kinetic Inductance, Tunnel Junction, etc.)	SQUID amplifier advancements	Still at idea stage	✔ (fund best idea) Cost: small. Limited by: ideas	•
120-200 µm: 5 x 5		Si bolometer arrays	AXAF experience	FET coupling	✔ Cost: small. Limited by: ideas	•
>200 µm Bolometers: 8 x 8						

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Fig. 5. Photon Counting Detectors

State of the Art	Key Components/ Desired Level	Promising Technologies	Pros	Cons	Recommend for Support?	Missions
Si:As Solid State Photomultiplier (SSPM) ~8 - 28 µm QE ~30% T < 8 K	1-5 µm Photon Counters & Readouts	Small-bandgap superlattice (III-V, II-VI)	Higher operating temperature? Lower leakage?	Unproven	✔ Cost: moderate. Limited by: ideas	LB
		Improved Si:As SSPM for <5 µm	Demonstrated at longer λ	Unproven	✔ Cost: moderate. Limited by: ideas	*
	5-28 (→36?) µm SSPM	Si:As (or Si:Sb?) SSPM & hybrid readout	Detectors demonstrated	Readout undemonstrated	✔ Cost: moderate. Limited by: ideas (SSPM readout by $)	*
	>30 µm SSPM?	Ge:Ga SSPM?	Wider spectral coverage	Ge BIB not yet mature	-	*

Fig. 6. Higher-Temperature 10 µm Detectors

State of the Art	Key Components/ Desired Level	Promising Technologies	Pros	Cons	Recommend for Support?	Missions
"High Background" 10 µm HgCdTe T: 40 - 60 K	Low-leakage Intrinsic (or "intrinsic-like") Detector Arrays T: ~30 K	10 µm HgCdTe	Large technology base	Untried at these temperatures	✔ Cost: moderate. Limited by: $	MB
Si:As IBC (= BIB) Detectors T: ~12 K		Small bandgap superlattice (III-V)	Higher temperature? Lower leakage?	Very developmental	✔ Cost: small to moderate. Limited by: $	*
Quantum Well Detectors T: TBD		Quantum well devices	Tailorable cutoff wavelength	Low T; low QE; non-normal incidence	-	*

Fig. 9. Adapt SIRTF Technology for Higher Backgrounds (or Higher Detector Temperatures)

State of the Art	Key Components/ Desired Level	Promising Technologies	Pros	Cons	Recommend for Support?	Missions
10 K InSb arrays $(256)^2$	⇒	⇒	Initial development well underway. Labs and expertise developed.	Key people too busy on SIRTF?	✔ (Support a study and test activity)	Most all
4 K Si:As IBC arrays 10 x 50 & 58 x 62	⇒	⇒	Project development discipline			
2 K Ge:Ga arrays 3 x 32	⇒	⇒				
1.5 K Ge:Ga BIB discrete	⇒	⇒				
0.1 K bolometers	⇒	⇒				
4 K readouts	⇒	⇒				
⇑ Technologies optimized for low-backgrounds		⇑ Same "tools" optimized for 10^n times higher backgrounds (n = 3,4,5,?)			⇑ Total Cost: moderate. Limited by: $	

QUESTIONS:

D. TENERELLI: I have a general question. If you look at all the programs, how much money is being spent by NASA on developing detectors?

M. KAPLAN: By NASA, that's an important type of qualification. I would quickly guess the order of magnitude to be a few million dollars per year -- two, three or so million dollars a year. Most of that money is coming through the SIRTF detector program. I don't know the numbers associated with HST, but I think that's probably about the right order of magnitude.

P. STOCKMAN: The question I had was, Barbara mentioned that this group considered coolers as something they wanted to make some statements about. But I don't recall if either she or Bruce went any further. What was the group's feeling about the state of the art in terms of closed cycle coolers?

B. WOODGATE: Just to clarify, there was a panel of 10 experts, separate from our panel really, to discuss that and present recommendations. Let me take a crack at what they said. There's been a massive investment on the part of the defense community that has been on the one hand agonizingly slow in producing results and yet on the other hand impressive performances are beginning to be demonstrated. I think the general word from that panel would be that one could assume with reasonable confidence that these systems would be practical. The long life coolers down to even 10 Kelvin are probably going to happen. NASA support will be needed to deal with specific issues that we can't count on getting inheritance on.

II. FINAL PLENARY SESSION

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SUMMARY OF NASA ASTROPHYSICS DIVISION PLANS

M. KAPLAN

NASA HEADQUARTERS
Washington, D.C.

March 4, 1991

(Presentation material follows)

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NASA

Astrophysics Division New Initiatives Strategy: 1992 - 2000

Astrophysics Division

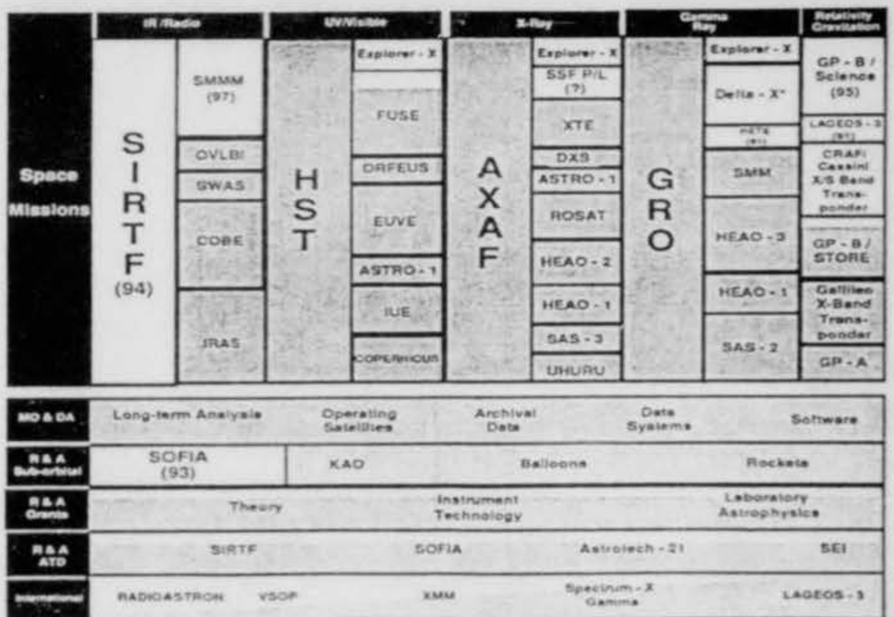
	Repricing of Ongoing Program	Major & Moderate Missions	Small Missions	Research Base Enhancements	Space Exploration Initiative	Space Station Freedom Utilization (?)
1993	Gravity Probe - B / STORE		Explorer Augmentation	SOFIA / R & A Grants Enhancement	Advanced Technology Development Enhancement	XBSS / LAMAR
1994	Explorer (Delta -class)	SIRTF				
1995	International Programs	Gravity Probe - B / Science				
1996			Explorer Augmentation	R & A ATD Enhancement		
1997		Sub-millimeter Moderate Mission			Lunar Transit Telescope	OSI
1998				R & A Grants Enhancement		EXOSS
1999		Optical Interferometer Mission	Explorer Augmentation		Lunar Very Low Frequency Radio Array	SSSF
2000						

Nuclear Astrophysics Explorer (NAE) assumed to be an Explorer-class mission

NASA

Baseline Astrophysics Plan: 1992 - 2000

Astrophysics Division



*NAE is a leading candidate

QUESTIONS:

B. WADA(?): I think it's reasonable to talk in the context of HLV-sized shrouds, but also to look at the impact if we're forced back to something smaller. ... 10 to 13 meters is what I see for HLV. The telescope itself, we talked about an 8 meter scale. 8 meters is my preferred number, 6 meters is what I think folks have concentrated on because it's a little more easily accommodated within some of the envelopes. But scientifically I would love to see us push towards 8 meters.

M. KAPLAN(?): I think we need to discuss an 8 meter telescope. It can be 7 meters, 8 meters or 9. But look at it two ways. In one you'd need automatic deployment, alignment, and all of that. In the other case one might get away with building the whole thing on ground.

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REPORTS BY WORKING GROUP CHAIRPERSONS

- OPTICS WORKING GROUP
- STRUCTURES WORKING GROUP
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- LUNAR-SPECIFIC ISSUES WORKING GROUP
- ORBITAL-SPECIFIC ISSUES WORKING GROUP

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REPORT OF THE OPTICS WORKING GROUP

R. Angel

Steward Observatory
Tucson, Arizona

Working group members: J. Breckinridge, D. Diner, H. Epps, D. Fisher, C. Gilbreath, T. Glavich, S. Hinman, E. Hochberg, D. Korsch, R. Locke, B. Martin, A. Meinel, M. Meinel, J. Miller, and R. Wilson

What did galaxies look like as they formed after the big bang? What goes on close to the giant black holes at the center of galaxies, the powerhouses of quasars? Do nearby stars have planets like the sun's?

We know that in principle space telescopes to answer these questions can be built, if they are big enough, cold enough and accurate enough. What should they look like in practice, and what does it take to build them?

The placing of any new major telescope in space is a human undertaking on a grand scale. Its design, if it is to be built at all, must be exceedingly efficient. Such efficiency can be achieved by an evolutionary process of refinement of the goals and the design and technology, with vigorous debate and research by the astronomy community.

The work of this panel is part of this process, identifying technology investigations that are needed as part of the refining process.

Introduction

Two general considerations of performance threaded our discussions. One is the question of versatility in terms of wavelength that can be accommodated in one telescope. The other is the weight placed on filled aperture, as opposed to dilute or interferometric arrays. The third general aspect was the value of heavy lift vehicles.

No matter what the wavelength, the bigger the telescope operating at the diffraction limit, the higher the resolution. The cost and difficulty of manufacture increases with the higher surface accuracy needed at shorter wavelengths. The situation is analogous to that for ground based radio telescopes, which operate in the diffraction limit over a wavelength range of more than 3 decades. Any one telescope is usually used at wavelengths close to its limit set by surface accuracy, leaving to less accurate and less expensive instruments the longer wavelengths where they are perfectly satisfactory.

Large space telescopes are needed to cover four decades of wavelength, from around 90nm, the limit from hydrogen absorption and normal incidence reflection, to 1 mm, where ground based instruments are uncompromised by the atmosphere. This broad band falls naturally into three domains on thermal grounds. From 90 to around 1800 nm, thermal emission by the telescope at room temperature is negligible. A high accuracy mirror, coated for highest ultraviolet reflectivity and protected against contamination is needed in this range. From 1.8 to 10 microns wavelength, passive cooling to 80K of a low emissivity silver coated mirror brings a telescope to reach the natural background limit set by zodiacal background. From 10 to 1000 microns, there is a need for both cryogenically cooled telescopes and for very large apertures that are more emissive but with higher spatial resolution. NASA mission planning currently has clearly distinguished the need for two specialized telescopes in the third domain, (SIRTF and small sub-mm telescope). Our group sees the differences in the first two domains as very large, and urges that the trade off of using two separately optimized telescopes should be seriously considered. While most large ground based telescopes are used over most of two decades from 0.3 to 30 microns, this is because cooling is not possible, and atmospheric turbulence sets similar angular resolution (and hence surface accuracy requirements) across the whole band.

The second general consideration concerns the value of filled aperture. The panel considered the proposed deployable Mills cross concept for a rigid but unfilled aperture. The feeling is that high signal to noise realized by a filled aperture should not be sacrificed unless there is a very compelling scientific need for the somewhat higher spatial resolution. For galaxies at the diffraction limit the signal to background noise (from zodiacal background light) is weak, even for filled apertures, and is independent of size. Any dilution which takes energy from the main beam is damaging. Thus, the Hubble telescope in its present condition has a beam profile not unlike that of a dilute aperture telescope, putting some 15% of its energy into a diffraction limited main beam. Even with this modest dilution, optical imaging of galaxies is very poor.

The extremely tight tolerances for large diffraction limited optical systems favor launching preassembled systems in the largest launch vehicles. There is a huge gain if a 6 or 8 meter aperture telescope can be checked out on the ground, and then put up in one piece. Automated fine alignments will still be needed, but the large job is done.

The above general considerations underlay our detailed discussions of technical aspects set out below.

Surface accuracy requirements

To be sure to realize the advantage of filled aperture, we take as a tolerance for the mirror surface figure that it alone should give no more than a 10% reduction in Strehl ratio. This leads to a spec of lambda/40, i.e. 2.2 nm rms at 90 nm wavelength, 50 nm rms for 2 micron wavelength and so on. Planet searches which use techniques to reduce aperture diffraction need still lower errors, down to lambda/1000 on a large scale to allow apodization at close to the diffraction core. This is 1 nm for 1 micron wavelength, and 10 nm for 10 microns. Small scale structure also needs to be carefully controlled, so that at 1 arc second radius the scattered light is no more than the Airy pattern intensity.

Several factors contribute to the primary mirror error. These are thermal distortion, manufacturing error, testing error, imperfect gravity release. For a telescope that is to reach overall accuracies of 1-2 nm, each of these errors must be controlled to 1/2 to 1 nm. Such requirements represent a considerable advance over the Hubble telescope mirror, which reached an rms compared to the incorrect reference of about 6 nm rms. Realization of the higher specs in a mirror that is 6-8 meters diameter and operating at 80 K will be difficult, and requires technology advances in each of the areas above. The working group spent most of its time grappling with this very challenging problem. For large mirrors with more relaxed specs, more attention can be paid to issues such as very light weight and deployment.

Optical Design

There are many complex trade offs to be made early on that involve the scientific goals and the optical design. Mirror size, field size, primary focal ratio, final focal ratio, number of mirrors, tolerable aberrations, operating temperature, pupil stops, IR chopping, wavelength range, deployment issues, spacecraft pointing vs optical beam steering, pupil wavefront correction on orbit are all factors that can only be optimized as part of a system. It is essential to have strong and repeated interactions between astronomers, optical designers and vehicle people to find optimum solutions. There must be no false assumptions that drive the design unnecessarily, and no forgotten issues.

Aspects of this complex area that caught the attention of the panel were:

* Requirements for image stabilization and wavefront correction at secondary, tertiary mirrors.

* impact on design of lunar/HEO location. Design of coude focus deep under lunar regolith, for CCD shielding. Design aspects to facilitate HEO delivery or erection on the lunar surface. Trade off of primary focal ratio-tube length and spacecraft size/inertia, field of view.

* design optimized for non-cooled telescope for uv-optical at GEO

* design and optimization of optics for passive wide field lunar transit telescope.

Materials

Mirror substrates must maintain the correct shape over some range of tolerance in temperature. Low coefficient at the operating temperature, and good homogeneity on small spatial scales where actuators cannot correct are both important. Thus if the operating temperature tolerance is 1K, and the thickness is 30 cm, a 10^{-9} variation in coefficient gives a bump of 0.3 nm. The mirror must withstand repeated cycling from room temperature to operating temperature with no hysteresis.

Glasses that are nearly pure fused silica are obvious candidates. ULE is silica doped with titania to have zero coefficient at room temperature. By using less titania or switching to boron dopant, the coefficient can be made zero at any colder temperature. Research is needed to verify the homogeneity that can be realized in new compositions. Alternatives to silica may be possible, particularly for mirrors with less demanding accuracy of 10 nm or worse. The limitations to stability and surface finish in non glassy materials needs to be understood if they are to be considered viable alternatives.

If lightweighted monoliths are to be used in large sizes of 6 to 8 meters, then manufacturing techniques that give low enough weight need to be developed. Frit bonding glasses with the right extended thermal range may be needed. 90% lightweighting of honeycomb sandwich is readily achievable on smaller scales, and in a silica 8 meter blank, 30 cm thick, would give a mass of 3.3 metric tons. This should be within the lift capability of a vehicle large enough to accommodate an 8 m telescope. Methods to provide protection from the launch vibration environment need to be worked out. Another issue is to devise honeycomb structures or supports for a thin facesheet that provide adequate support for the surface under polishing (smoothing) forces.

Form of mirror substrate

The choice of mirror substrate is critically dependent on launch vehicle. If the mirror is too big to be delivered in one piece, the only solution to build it in segments which deploy or are assembled in space. If a large enough vehicle is available, then it is possible to use a monolithic mirror. There are other key choices to be made. The substrate piece or pieces may be intrinsically stiff, like the honeycomb glass of the Hubble telescope, or may be a thin sheet that derives its shape from a back-up structure. Active on-orbit correction of the mirror figure may be accomplished by force control or position control.

Results from the manufacture of 8 to 10 meter ground based telescopes will provide valuable practical tests of different technologies to an accuracy of around 30 nm. The masses of these mirrors, 14 tons of glass for both the Keck 10 meter and Arizona 8.4 meter mirrors, are higher than needed for space, but not by large factors if HLVs are available.

The panel supports the concept of a 1 ton, 4 meter technology demonstration mirror, made of honeycomb glass appropriate for 80K operation, and polished and tested to 1 nm accuracy by the methods described below.

Surfacing process

Four steps can be identified in the surfacing process for large primary mirrors. These are: numerically controlled generating (machining); loose abrasive lapping; pitch lap smoothing or polishing; deterministic figuring. We envisage that all figuring operations would be carried out at room temperature, but that metrology at the operating temperature would establish the shape change on cooling, and would be used extensively in the final figuring and verification stages. The present state of different techniques and their size limits and accuracies is shown in figure 1. There is good reason to hope that advances in these methods and in testing and flotation will allow the surfacing of even an 8 meter mirror to be taken to 2 nm tolerance.

A sequence for manufacturing combining powerful newly developed techniques and applicable to monolithic or segmented primary mirrors as well as secondary mirrors is as follows:

* Numerically controlled generation to about 1 micron rms
* Fine abrasive lapping with a stressed lap, with 10.6 micron metrology to 300 nm rms
* Stressed lap polishing with HeNe metrology to remove subsurface damage and gives very smooth surface on small scales. Overall accuracy 30 nm rms.
* Ion figuring to 1 nm rms. This is unexplored territory. Metrology, thermal release on cooling and gravity release are critical factors (see below).

Testing and wavefront sensing

Testing of 8 meter mirrors during fabrication to an accuracy of better than 1 nm, or lambda/1000 at 633 nm test wavelength, is a challenge that goes well beyond the state of the art. Advances are needed that involve shorter wavelengths, improved algorithms and hardware for phase shifting interferometry, high spatial resolution over the mirror, vibration control or rejection, accurate thermal control of the mirror at the operating temperature, large vacuum chambers, exquisitely accurate null lenses.

Absolute metrology at this sub-nm level will present a severe challenge. For monolithic primaries, null lens tolerances need to be controlled to an order of magnitude higher tolerance than achieved by current state of the art. If a segmented primary is to be built, methods to obtain absolute metrology of off-axis segments to sub-nm level must be developed.

Testing on orbit would be carried out with wavefront sensors operating down to 100 nm wavelength and could involve shearing interferometry for small scale errors, and neural net analysis of focal plane images for large scale errors.

Coating and contamination

At present no coating exists that optimizes performance simultaneously in the vacuum ultraviolet and in the thermal infrared. High reflectivity in the UV is obtained with overcoated aluminum. Telescope designs with more than two mirrors place a premium on the highest UV reflectivity. Low emissivity in the IR requires gold or silver. Research may find a universal coating, though this seems unlikely.

High reflectivity in the vacuum ultraviolet can be destroyed by contamination at very low levels. It will be very difficult to avoid contamination if the mirror surface is cold, and there is any significant outgassing of the spacecraft. This issue needs urgent resolution. If contamination of a cold mirror is inevitable, then a universal UV-IR telescope is not possible.

SUMMARY TABLE

Technology Area	Current State of the Art	New Requirements
Mirror surface accuracy	6 nm rms	0.5-1.0 nm rms
Mirror and substrate materials	10^{-9} CTE at 300K	10^{-9} CTE at ~80 K
Optical testing	$\lambda/100$ at 633 nm over 2.5 m diameter	$\lambda/1000$ at 633 nm over 6-8 m diameter
Optical coatings	No universal UV-IR coatings are available	Need to determine if contamination of cold mirrors is inevitable

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REPORT OF THE STRUCTURES WORKING GROUP

B. Wada and D. Rapp

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California

Working group members: D. Coulter, M. Krim, E.J. Roschke, and G. Sarver

Introduction

The goal of the Structures Working Group was to establish a list of the 4-6 highest priority technology requirements for a hypothetical, but representative future filled aperture mission. The members of the Working Group included specialists in the technology fields: structures, materials and temperature control.

Mission Set

The main emphasis in this workshop was on a hypothetical future mission that would serve both as a Next Generation Space Telescope in the visible (and possibly the UV), as well as a powerful IR telescope. The key system parameters for this filled aperture space mission are:

- Diameter 8 meters, segmented
- Launch vehicle shroud diameter = 4-8 meters
- Orbit is 100,000 km or greater
- Mirror temperature = 100 K (passive)

Two parameters which are strongly interacting, and which are difficult to fix exactly, are the areal density of the primary mirror, and the surface figure RMS error. Depending on the range of applications of the telescope, the surface figure RMS requirement could vary significantly. It is desirable to operate this telescope in the near UV, in which case an RMS of < 0.01 micron for the primary mirror would be needed. However, it is recognized that there are two distinct approaches for the primary mirror materials, based on composites or glass (or glass-ceramics). Composites have the possibility of achieving areal densities of 15-20 kg/m^2. However, it appears extremely unlikely that a mirror based on composites could achieve an RMS of 0.01 micron. In fact, it will be difficult to produce a mirror based on composites with an RMS of 0.03 micron, the minimum needed for measurements in the visible. Segmented glass mirrors can almost surely be made with a room temperature RMS of 0.03 micron, and possibly 0.01 micron, but these are expected to have areal densities in the range 50-100 kg/m^2. Furthermore, the ability of these mirrors to retain their accuracy at 100 K is not fully understood. In these early stages of planning, it is difficult to determine whether it would be more important to use a lightweight structure and give up the hope of UV measurements, or to insist on retaining the capability for UV measurements, and accept the higher mass that is required. Therefore, one cannot simply state the requirements for areal density and surface RMS of the primary mirror.

A partly filled aperture telescope was also briefly considered. The technology requirements for such a system are similar to those of the filled aperture segmented telescope described above, except that it would require a boom type structure approximately 30 m long.

A lunar based mission was considered briefly with the characteristics:

- Diameter = 8-16 m
- Temperature range = 80 K to 380 K.
- The telescope can be enclosed
- Surface accuracy = approximately 0.01 micron RMS for the total system.

It appeared that the technology requirements for space may be more challenging than those for lunar based missions. Generally, many of the extensive technologies developed for terrestrial ground based telescopes are applicable for the lunar based telescopes. Therefore, this study concentrated on the technology needs for space missions.

It should be emphasized above all other needs, that since the required diameter of the telescope exceeds the diameter of the shroud of presently available launch vehicles, there will be a critical need for a credible assembly scenario in space, based on either an erectable, deployable or hybrid approach, unless a very large diameter heavy lift launch vehicle is developed and made ready in time.

Technology Recommendations

In priority order, the technology needs are:

Priority	Technology(ies)
1	Assurance of On-orbit Structural Performance Improved Ground Test Validation Adaptive (Active) Structures
2	Modeling Validation of Large Precision Structures Materials and Coatings for Dimensionally Stable Structures
3	Deployable and Erectable Structures Containing Segmented Mirrors
4	Integrated Multi-function Adaptive Structural Elements

(1) Assurance of On-orbit Structural Performance (Priority 1)

Ground testing, in conjunction with good analytical prediction methods, has been used effectively over the past 30 years to detect unforeseen problems in space structures. This has provided an assurance, in advance of launch, that a spacecraft structure will perform as required. In recent years, space structures have become more complex and have required higher precision, making it much more difficult (and expensive) to carry out effective ground test validation. As a result, there has been a tendency to bypass some critical ground tests. Unfortunately, this has resulted in problems such as significant excitations in the Hubble Space Telescope due to the solar arrays, oscillations in the antenna boom on the Ulysses, and significant problems in opening the Galileo high gain antenna. Recent analysis indicates that current design and ground test approaches are not adequate to validate the on-orbit structural performance of large precision structures due to the perturbing effects of the earth's gravitational field. Considering the accurate demands placed on structures for the missions under consideration here, together with the uncertainties of the analytical predictions of structures vibrating in the sub-micron range, it appears necessary to either develop new approaches for ground testing, or develop approaches for on-orbit adaptation, in order to make these missions feasible. Thus, there are two alternative approaches for achieving assurance of on-orbit structural performance: *improved ground test validation procedures, and use of adaptive structures.*

Actually, the two technologies are highly interactive because as one introduces more and more on-orbit adaptive capability into a structure, this relaxes the requirements on ground test validation because ground test validation only needs to assure that the structure will remain within the dynamic range of the adaptive system when it is placed in orbit. This will generally require considerably less precision than if the structure were not adaptive.

New design approaches must be developed, which can either be validated by ground test, or for which ground test requirements can be relaxed by adaptation in space.

Adaptive Structures provide flexibility in setting geometric or structural characteristics on-orbit to compensate for unknown variations that may not be predictable from ground testing. Changes in the structure in its operational environment are induced through sensors, actuators and controllers which may be integrated into the structure itself. Additional reliability can be introduced by adding redundant active members that are available to compensate when failures occur. The requires that one initially performs a system identification of the structure in its operational environment and then adjusts the structure in space to meet its requirements. The approach can be used to relax the ground test requirements by an order of magnitude (or more) and to use ground tests merely to assure that the on-orbit structural parameters will be within the dynamic range of the adaptive structure.

Ground tests that negate the effects of gravity, such as two dimensional systems on a two dimensional air bearing table may significantly improve the capability of ground testing. Flight tests with adequate instrumentation will be required to establish the validity of such new tools and approaches.

(2) **Modeling Validation of Large Precision Structures** (Priority 2)

Whereas the mathematical model of most space structures designed and flown to date could be validated through ground test, it will be considerably more difficult to do this for the kinds of large precision structures required by the missions under consideration herein. Thus the designer will be forced to rely upon the mathematical model for the design of the structure without empirical corroboration.

Current finite element mathematical prediction tools are based upon structures which are subjected to comparably high loads and stresses. Test and flight data taken over 30 years, were invaluable in obtaining confidence on the accuracy of the predictive capabilities of these methods.

However, almost no experimental data exist on non-monolithic precision structures vibrating in the sub-micron displacement range. The mathematical prediction tools developed for large displacement motions are being tested tentatively to see if they can predict submicron displacement characteristics. However the extremely tight tolerance requirements, combined with low stress levels induced by the space environment, raise the possibility that non-linearities, such as joint free-play will introduce significant non-linearities into the dynamics of the structure at these levels. These non-linearities cannot be detected during the ground test since the gravitational loads mask their presence and are not of significance at higher amplitudes of vibration. Some recent experimentation shows that structures with loose joints respond "chaotically", namely the structural response is random when subjected to deterministic inputs. If such basic characteristics are not properly predicted, then control systems designed to control modal responses will fail when the response is random.

The prediction and control of accurate thermal gradients in the structure will be important to maintaining precision. Similarly, very little data are available on the thermal characteristics of structures where small dimensions are of interest, especially in joint gaps. Ground test data are not adequate since gravity preloads the joints and the potential influence of joint gaps cannot be detected.

The development of improved methods for predicting sub-micron displacements in precision structures will enable future missions by reducing the risk associated with designing large precision structures through analysis.

(3) **Materials and Coatings for Dimensionally Stable Structures** (Priority 2)

To attain the required performance at reasonable cost and with an acceptable level of risk, a passive structure must be built as stable as possible and include active control elements to correct for non-ideal performance. The structure must be lightweight and stable over mission lifetimes under the applicable mechanical, thermal and environmental loads. Current space structure concepts based on existing materials and designs are characterized generally as too heavy, small to moderate in size, having inadequate precision, limited stability and poor thermal control.

In the area of structural materials, approaches should include (1) development of advanced composites with high stiffness, high thermal conductivity, environmental stability and low CTE (< 0.1 ppm/K) and (2) development of novel structural ceramics that are durable, homogeneous, have low CTEs (< 0.01 ppm/K) and show low thermal hysteresis (< 0.001 ppm/K). One novel idea involves fabrication of an "optical assembly" including mirrors and support structure from a single material (graphite/epoxy or silicon carbide, for example).

For advanced actuator materials, the approach should be aimed at developing tailored piezoelectric, electrostrictive, magnetostrictive or other active materials for low power, high throw actuators that operate efficiently at 100 K or below with low hysteresis, and low power dissipation.

In the area of advanced thermal control materials, we should focus on development of materials for thermal control surfaces that have tailorable, programmable or actively controllable thermo-optical properties (transmission, emissivity, absorptivity and reflectivity) to allow thermal control over extended structures to about 1 K. One novel idea involves active thermal blankets with electrochromic coatings whose relevant properties could be controlled (even in flight) by varying the voltage across the blanket.

(4) **Deployable and Erectable Structures Containing Segmented Mirrors** (Priority 3)

The fundamental requirement here is to develop the capability to utilize precision structures containing segmented reflectors, when the launch vehicle shroud diameter is smaller than the diameter of the primary mirror. There are three options: deployable, erectable and hybrid structures. Because the plan for the Space Station involves erection on orbit by astronauts, almost all NASA funds have been directed toward assembly on-orbit. Only token funding has been provided to research and development for deployable structures. Deployable structures tend to be more complex and introduce potentially other adverse characteristics such as loose joints, and more parts. However, erectable structures require extensive astronaut participation, but astronauts may not be as capable as had once been hoped for.

Research is required to develop deployable large precision space structures or improved methods for assembly on-orbit. Both ground and flight test development programs are required.

(5) **Integrated Multi-Purpose Structural Elements** (Priority 4)

Traditional space structures provided "rigid" frameworks for pointing or orientation through separate control systems. Utilities, such as electric power lines and connecting lines to thermal sensors, were added externally.

With the expected development of major space observatories of the future, the demands for precision support structures, coupled with the need to decrease the weight of reflectors, leads to the expectation that active and adaptive structures will be employed extensively. Sensitivity of structural dimensions to thermal variations will require that more extensive and precise thermal monitoring and control will be needed.

The extensive network of electrical lines required to provide power and control logic to active members could make such systems very complex, heavy, and failure-prone. It would therefore seem important to develop techniques for imbedding power, logic and sensing lines and actuators into structural members, whether they are truss elements, or individual reflectors in a segmented reflector system. This seems to be especially feasible with composite materials. Modular elements would couple and form continuous transmission lines for utilities. Ultimately, some degree of local control could be developed so that the huge array of sensors, actuators and heaters need not be connected back to one "brain" in the spacecraft computer system.

For example, instead of cementing moment actuators to the back of a composite reflector panel, with a "rats nest" of wires connected to the actuators, one might envisage a layer of actuators co-cured into the rear face sheet, with wiring fed down through the support structure.

SUMMARY TABLE

Technology Area	Current State of the Art	New Requirements
Ground test validation and use of adaptive structures	Predict on-orbit structure motion at >> micron level	Insure that dynamic range of adaptive structure not exceeded
Modelling of large precision structures	Finite element codes for >> micron motions	Sub-micron modeling of non-monolithic large structures
Materials and coatings for dimensionally stable structures	Composite materials with CTE < 0.1 ppm/K	CTE < 0.01 ppm/K, thermal hysteresis < 0.001 ppm/K
Deployable/erectable structures containing segmented mirrors	Astronaut assembly of non-precision structures	Improved deployment of large structures with multiple joints
Integrated multi-function adaptive structural elements	-----	High throw actuators operating at < 100K with low hysteresis

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REPORT OF THE DETECTORS WORKING GROUP

R. Thompson

Steward Observatory
Tucson, Arizona

Working group members: S. Collins, P. Hintzen, C. McCreight, L. Robinson, H. Schember, B. Wilson, B. Woodgate

Technology Recommendations
(Not in Order of Priority)

1. Develop a UV sensitive, visible-blind, high dynamic range detector system for UV imaging

   i. Emissive photo cathodes
   ii. Enhanced readout rates
   iii. Contamination control

2. Enhance IR read-noise and dark current performance, particularly in the cosmologically important 3 um spectral region

   i. Deep surveys, H/o, omega/o
   ii. High resolution spectroscopy

3. Extend CCD performance to shorter and longer wavelengths

   i. UV-thinning enhancements, other methods
   ii. IR germanium - ?

4. Increase the number of pixels of all array detectors

   i. Larger monoliths
   ii. Mosaics
   iii. Conforming to the focal plane

5. Improve cosmic ray rejection and rad hardness in the visible and IR detectors

6. Improve the performance of fiber optics in the UV <--> IR region

   i. Transmission in UV and IR
   ii. f/# preservation
   iii. Mechanical toughness

7. Preserve the technical ability and production capability for specialized detector systems

   i. High sensitivity CCDs
   ii. High performance IR detectors

8. Develop low vibration, long-life coolers for ~10K and ~60K detector temperatures

9. Program funding should support the ground based observational testing of detector systems

10. Consider the trade offs between multiple focused mission telescopes and single general purpose telescopes

SUMMARY TABLE

Technology Area	Current State of the Art	New Requirements
CCD arrays	4096 x 4096 in visible	Radiation hard, extended long & short wavelength coverage
UV detectors	Photocathodes	High sensitivity and dynamic range, visible blind
IR detectors	Small near-IR arrays	Reduce read noise and dark current, esp. near 3 μm. Improve radiation hardness
Detector cooling	Stored cryogens	Low vibration, long life coolers for 10 K and 60 K

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REPORT OF THE SENSING AND CONTROL WORKING GROUP

D. Tenerelli

Lockheed
Palto Alto, California

Working group members: J. Lesh, M. Levine, J. Rather, G. Sevaston, P. Swanson, M. Tarenghi, and E. Tubbs

Technology Recommendations

There were four key recommendations that resulted from the Panel deliberations, namely to evaluate the following: (l) Temperature range requirements for the UV-IR Telescope; (2) Ground test limitations; (3) Operational efficiency desired; and (4) Potential advantages of A-Focal Telescope Configurations. All four are discussed below .

(1) Evaluate the temperature range requirements for UV-IR telescope:

The temperature range that each subsystem will have to sustain could very well be the deciding issue relative to satisfying all the scientific requirements with one telescope. A careful evaluation will have to be made, and the results could very well show that two telescopes will be needed. Our Panel was quite concerned about the temperature requirements; however, results of detailed thermal analysis will be needed to support our fears.

(2) Evaluate limitations of ground system testing:

Large appendages, Solar Arrays, High Gain Antennae, and Aperture Doors such as used on HST are rarely dynamically tested (they were not on HST). These appendage with their low fundamental dynamic modes often drive the design of the Pointing Control System (PCS) . Everything is based on analysis, and if a mistake is made it may be handled in the following ways:

(a) Design a PCS system with bandwidth characteristics similar to HST and take the risk that analysis will suffice. If problems were to result during the orbital phase, hope that the PCS can be modified by changing the gains or that operationally you will be able to work around the problem.

(b) Design a PCS similar to HST, however, extend the bandwidth to 2.5 Hz (HST is about 0.6 Hz), and the gyro's ability to accommodate this will have to be investigated.

(c) Go to a more sophisticated, high frequency (min 10 Hz) PCS, which interacts with the optical system so that the PCS immediately stabilizes the image and science operations can continue essentially uninterrupted.

(3) Evaluate operational efficiency:

The pointing control system for the Hubble Space Telescope (HST) completes a 90° maneuver slew in 14 minutes. Acquisition of the guide stars requires additional time. The Design Reference

Mission (DRS) for HST was based on 11 slews (≅ 55° in 10 minutes). This amounts to roughly two hours a day that otherwise could be used for science observations.

More advanced PCS's (compared to HST) can slew vehicles in seconds, and, in addition, interact directly with the optical system to correct the image when arriving at the new object. These PCS's are more costly; however if increased scientific utility of the telescope is required then these types of systems must be evaluated.

One more point should be made on this subject and it relates to one of the scientific operational goals of the Space Infrared Telescope Facility (SIRTF) . In their latest Requirements Document, SIRTF would like to visit 100 targets in a 24-hour period. In order to achieve this, in all likelihood, a PCS will be needed that can slew to targets within seconds, and interact with the Optical System to stabilize the image when arriving at each new target.

(4) **Evaluate the A-focal telescope configuration:**

Patents (e.g. D. Korsch's in 1975) for A-Focal Telescope configurations appeared in the early to mid-1970's. Since then certain off-shoots have been developed which seem to improve upon the original patents.

An A-Focal Telescope design that the panel chairman (D. J. Tenerelli) is currently evaluating provides the basic advantage of shortening the overall length of the telescope by 15 percent. For the sake of this discussion presume that the thickness of the members comprising the structural system for a Ritchey-Chretien Telescope and a comparable A-Focal Telescope are the same, i.e. we do not optimize the A-Focal telescope's structural makeup.

By reducing the telescope's length by 15 inches the fundamental dynamic modes (e.g. scissor modes) increase in value. This will help the Pointing Control Subsystem and the Structures and Mechanisms Subsystem. The weight and moments of inertia of the vehicle will be reduced. This helps the Pointing Control and Structural Subsystems, and the Launch Vehicle System -- allowing delivery of the telescope to a higher orbit. Furthermore, the Pointing Control Subsystem (PCS) is aided by potentially reducing the coupling that can occur between the fundamental vehicle dynamic mode and the bandwidth of the control system.

By having the advantage mentioned above the PCS may be able to use smaller torque actuators (e.g. Reaction Wheel Assemblies). If this happens, the power to operate the RWA's will be less and the mass will be less. This in turn will probably help the thermal control system since the heater power required to keep the RWA above a minimum temperature will be less. This also helps the Electrical Power System since the power requirements on the Solar Array (SA) will be less. There may be some other smaller advantages with this because the SA will be smaller in size meaning less weight, smaller mass moments of inertia, and dynamically may have certain modal advantages.

For some A-Focal Telescopes subassembly testing may be easier. For certain A-Focal Telescope designing, an unaberrated image is available to all the scientific instruments (versus the design we had on Hubble Space Telescope where only one of the five instruments receives an unaberrated image) . The very important result from the discussion above is that the program cost will very likely be less for an A-Focal Telescope when comparing it to a Ritchey-Chretien System. For the large aperture filled telescopes discussed at the workshop, it is recommended that A-Focal Telescopes be evaluated.

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<u>SUMMARY TABLE</u>

Technology Area	Current State of the Art	New Requirements
Pointing control system	0.6 Hz bandwidth Slew rate ~6 deg/min (HST)	> 10 Hz, interacting with optical system. Slew rate > 20 degrees/minute

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WORKING GROUP REPORT: LUNAR-SPECIFIC ISSUES

J. Burns

New Mexico State University
Las Cruces, New Mexico

Working group members: K.-M. Chua, B. Davis, J. McGraw, M. Nein, and K. Nishioka

Unique Features of the Moon

In considering the technology drivers for the construction of a Large Lunar Telescope (LLT), our working group began by reviewing the unique features of the Moon. They include:

(1) **The Surface** - With a solid surface available, the LLT will be designed in a fundamentally different fashion than free-flying telescopes; the LLT will more resemble the Keck telescope than the HST in construction, pointing, and operation. (a) The LLT will be anchored to the surface of the Moon which raises interesting questions concerning the foundation design since the lunar regolith is far different than the Earth's upper crust (***e.g.***, no bedrock). The surface will be useful as a sink for vibrational noise, which is not available for free flyers. Extremely important technology issues that must be addressed include site preparation and excavation – issues that NASA has not previously dealt with in the space program. Digging and trenching in a high vacuum, dusty, and 1/6g gravity environment are substantially different tasks from that on Earth and will possibly require new techniques and equipment. Careful thought must be given to site selection and interaction of this site with other activities (*e.g.*, vehicle launches, mining, habitats) around a lunar base. (b) The lunar regolith is a very effective shield for cosmic rays. A coudé room approximately 5-m below the surface would have a cosmic ray flux equivalent to that of low Earth orbit (LEO). This advantage may be crucial for CCD detectors and other sensitive electronics. (c) Dust is a potential problem but the magnitude of this problem is unknown at present. It was demonstrated during Apollo that regions near launching/landing sites were exposed to substantial dust contamination including sand-blasting of paint surfaces and attenuation of optical surfaces. In addition, the anhydrous and fine grained nature of the dust coupled with the intense solar photon flux produces substantial charging of the dust grains. This leads to dust levitation, particularly at dawn, and dust creep from bright to dark areas of the surface. Thus, research into dust control and mitigation techniques, and studies of the effects of dust on mechanical components are required. (d) Finally, new approaches will be needed for assembly, testing, and retrofitting of components for the LLT on the lunar surface. Again, because of the substantial differences in environments between the Earth and the Moon, new techniques/approaches will likely need to be developed.

(2) **Gravity** - The gravity of the Moon is about 17% that of the Earth. This will

produce some gravity loading on the telescope superstructure and optics (absent for Earth-orbit), yet these strains will be far less than on Earth. In principle, one can construct structures on the Moon that are 5-6 times larger than on Earth with similar amounts of gravity loading. The fact that the Moon has some gravity will allow us to use adaptations of Earth-based pointing and control systems which are far simpler and better understood than that required for free flyers such as HST. Similarly, a telescope mount like that of terrestrial telescopes can be adapted to the lunar surface. Furthermore, it has been demonstrated that the lunar gravity greatly simplifies construction tasks in comparison to LEO so we expect that more complex structures can be assembled on the Moon.

(3) **Thermal Cycling** - The lunar surface experiences approximately two weeks of daylight ($\approx$385 K) and two weeks of darkness ($\approx$100 K). This thermal loading is quite different from that in LEO or HEO. During the lunar day, the sun angle varies with time thus producing nonuniform heating of telescope surfaces. This is unlike HEO where a free-flyer will likely have one side facing the Sun and another facing cold space so that the spacecraft will achieve thermal equilibrium. The variation in heating on the lunar surface requires extra attention to be given to the choice of telescope construction materials, to variable outgassing from the superstructure, and to the possible use of a movable sunshade. Also, energy generation and storage is a consideration. With the long lunar night, battery storage alone of solar energy may be insufficient with current or projected technology. Thus, the LLT may have to be sited close enough (*i.e.*, 10 km) to a (nuclear) power station for continuous telescope operation. Finally, an advantage of the lunar surface is the longer integration times that will be available under the darkest sky conditions.

(4) **Natural Lunar Resources** - Unlike Earth orbit, the Moon possesses an abundance of natural resources including aluminum, ceramics, and glass. Some simple processing of the regolith (including using it for shielding as noted above) could greatly reduce the transport costs of an LLT from Earth. Other natural resources include permanently shadowed regions in polar craters with equilibrium temperatures as low as 60-70 K. These craters could provide important continuous passive cryogenic cooling for infrared telescopes. Finally, the lunar far-side with a sky free of both the Earth and the Sun at least half of each month would have the darkest possible sky in the inner solar system.

Technology Recommendations

We believe that with the above unique features and the establishment of a permanent lunar infrastructure (including regular transportation and technical servicing), science from the Moon will be cheaper, faster, and better than any other location in the near-Earth environment. With this in mind, our working group makes the following recommendations for further technology studies:

(1) Since the Moon rotates about 28 times more slowly than the Earth, the LLT telescope drive system will have to be considerably more accurate than any tele-

scope on Earth. This is compounded by the longer integration times and the much higher diffraction limited resolution (0.01-0.001 arcsec) imaging that will be possible. New approaches to the drive mechanism may be required to achieve the necessary stability in light of the $\approx 300K$ temperature variations and the dust problem (*e.g.*, sealed and self-lubricating bearings?).

(2) Landing vehicles will need to be developed for depositing prefabricated telescopes or telescope components on the lunar surface. Astronomers should work closely with vehicle designers in an effort to construct a "generic" soft lander that can be used for transporting a variety of cargo to the Moon. Standard interfaces should be designed so as to reduce costs and permit cost-sharing of this development. Unlike most other lunar payloads, astronomical telescopes will be volume rather than mass limited. This should be considered in the vehicle design.

(3) In the area of detectors, we advocate that further studies of shielding of CCDs by the lunar regolith should be vigorously pursued. Cosmic ray transport codes should be run for the lunar soil to determine both the effectiveness and the equivalent mass/depth of regolith needed to shield CCDs to an acceptable level. The long term effects of secondary radiation must also be studied. At the same time, we recommend that anticoincidence capabilities for these detectors must be developed; this will be useful for CCDs on the ground, in Earth orbit, and on the Moon. It is not clear to us if the considerable heat source represented by the Moon will limit IR observations to $\leq 30\mu m$; if so, development of far-IR detectors for lunar-based astronomy is not as important as for HEO. We also wish to note that the detectors for the Moon will require less redundancy than in HEO because of the accessibility to these detectors by trained lunar astronaut-technicians; overall lunar telescopes can tolerate more failures and, therefore, more risky technology than inaccessible HEO telescopes. Finally, we urge the development of wide field of view detectors as a priority.

(4) Because of the still relatively harsh conditions on the Moon, automation, telepresence, and robotics must be applied to the construction, operations, and maintenance of lunar-based telescopes to reduce hazards to and time spent by human astronauts at the observatories.

(5) Stiff, stable, and light-weight telescope superstructures with low coefficients of thermal expansion must be developed.

(6) The LLT will likely use a segmented mirror design similar to the Keck telescope. The size, number, and emplacement of the segments require study. The adaptive optics for a 16-m class telescope must be agile. The metrology must be part of the optics design.

(7) Dust control and mitigation must be pursued actively. First, the magnitude of the problem must be defined. This can be done with both numerical and laboratory experiments. In the lab, lunar simulant can be placed in vacuum chambers and irradiated with uv light and high energy particles to simulate solar radiation. Such tests can be used to study the physics of dust levitation and mobility. Second, in-situ measurements on the Moon must be performed as part of early lunar base

activities. Precise observations of dust movement are needed. Components from previous Apollo and Surveyor missions should be recovered and analyzed for effects due to dust and solar radiation. Third, new techniques for dealing with the dust especially around the optics and mechanical components of the telescope must be developed.

(8) Some kind of telescope enclosure will likely be necessary to reduce the effects of dust, for thermal protection, and to reduce micrometeorite exposure. The enclosure must be light-weight and easily retractable. Additional buildings will be necessary near the telescope to house construction and maintenance crews.

(9) Substantial new technologies may be needed for lunar soil mechanics and regolith engineering. *We emphasize that telescope construction and engineering techniques used on the Earth will not be straight-forwardly translated to the Moon because of the substantial differences in atmospheric and soil conditions.* Consideration of excavation on a high vacuum, low gravity surface including sizing/controlling blasting is needed. Soil replacement and densification, especially for shielding, will be necessary. The foundations for the telescopes on the Moon will be fundamentally different. Studies are needed of the basic behavior of lunar soil under static and dynamic loads, and repeated thermal cycles. Soil-structure interaction and disturbance issues (*e.g.*, control system feedbacks, transients, damping) need to be validated in the lunar environment.

A Scenario for Lunar-Based Observatory Technology Development

With the above recommendations for new technology studies, our group envisions a multiphase scenario leading to the emplacement of an LLT on the Moon. The steps include:

(1) We strongly recommend the development and emplacement of a 3-4 m Lunar Transit Telescope (LTT) early on or even before the commencement of lunar base activities. This has the considerable attraction of excellent science with a relatively simple, easily deployable telescope that takes advantage of the unique properties of the Moon. In addition, this LTT serves as a crucial testbed of the above engineering and environmental issues.

(2) In the very earliest stages of a lunar outpost, astronauts must gather important environment information. This should include revisiting and careful inspections of Surveyor and Apollo spacecraft to ascertain degradation caused by dust, micrometeoroids, secondary impacts, and uv radiation.

(3) Careful site selection for an LLT should be made including considerations of proximity to the lunar base.

(4) Finally, incremental construction and operation of the LLT should proceed possibly along the same lines as the Keck telescope using segmented mirror technology.

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SUMMARY TABLE

Technology Area	Current State of the Art	New Requirements
Telescope drive system	~ 0.1 arcsec pointing for ground-based telescopes	~ 0.001 arcsec pointing; withstand dust exposure
Thermal variations	$\Delta T < 100$ K in Earth orbit	$\Delta T \sim 300$ K on Moon: structure/pointing problems
Lunar landing vehicles	Not presently available	Consider volume limited, not mass limited, payloads
Detectors (UV, visible, and near/mid IR)	Radiation shielded CCDs	Anticoincidence CCDs; lunar regolith shielding of CCDs; larger array sizes
Dust control and mitigation	Magnitude of problem not well defined	Laboratory measurements of dust levitation/mobility
Telescope enclosure	-----	Light weight, retractable enclosure for thermal, dust, & micrometeorite protection
Lunar soil-structure interaction	-----	Construction techniques and response of lunar soil to both static and dynamic loads need to be studied
Power generation	Solar cells, fuel cells, batteries, RTGs	Continuous power during the 2-week lunar nights

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WORKING GROUP REPORT: ORBITAL-SPECIFIC ISSUES

P. Stockman

Space Telescope Science Institute
Baltimore, Maryland

Working group members: B. Collins, A. DeCou, S. Durrance, D. Machetto, and H. Thronson

During the general sessions of the workshop, several speakers outlined technical and scientific approaches to future orbiting UV-Optical-Near-IR observatories. The working group on Orbiting Missions considered these different approaches in more detail in an attempt to find common technological themes for the Astrotech 21 initiative. In addition, we identified major differences in the relative technological maturity of these potential missions. It is worthwhile stating at the outset that all these approaches could benefit substantially from better definition of the mission objectives and more consideration of the focal plane instrumentation.

Three Mission Scenarios

The working group examined three mission scenarios, which are described briefly below:

(1) Pierre Bely described an observatory built around a 6-8m monolithic-primary, passively cooled telescope. The optical design is essentially a classical Ritchey-Chretian two-mirror system, with the focal length chosen to provide 10-20 micron resolution elements in the focal plane. The mirror would be lightweighted to 85-90%, and the figure controlled by mechanical moments over modest time scales (10 seconds - 1 minute), using an offset guide star and a wavefront sensor. To permit adequate pointing performance, it might be desirable to use an active/tilting secondary mirror with frequency response in the 1-10Hz bandpass and controlled from an offset star in the focal plane. In order to achieve the low optical emissivity in the near infrared, the mirrors and the telescope cavity would be passively cooled to approximately 100K. This requirement, the higher operating efficiency, and the dramatically lower aerotorques argue that the observatory should be deployed at relatively high orbits (preferably beyond geosynchronous orbit) For purposes of the study, the Advanced Launch System (ALS) was assumed.

(2) Billy Davis described a study done by MSFC on a similarly sized orbiting telescope based upon a segment of the MSFC 16m lunar telescope and the Space Transfer Vehicle to achieve high earth orbit. The MSFC study uses the HST science payload for study purposes and obtains a total weight somewhat less than the monolith value of 15 tons. The most significant difference between the two observatories is the use of segmented mirrors and active figure control in the MSFC study. The MSFC design is based upon the Keck Telescope, and the choice reflects a similar concern over weight and the maturity of

manufacturing lightweighted monoliths of the required accuracy. One of the consequences of the choice of segments is more active control of the primary mirror and possibly a 4-mirror optical system to permit adequate wavefront correction at an intermediate pupil.

(3) David Meier described the Filled Arm Fizeau Telescope (FFT) or a Mills Cross interferometer of 30m diameter. This design is an outgrowth of the JPL interferometer studies and represents an intermediate step between a filled aperture telescope and an interferometer with a low filling factor. Like the filled-aperture telescopes, the FFT's optimum deployment might be in high earth orbit. Unlike the filled-aperture telescopes, the FFT is designed to deploy to its full diameter after launch; and the launch configuration is consistent with the Shuttle C shroud diameter. The Mills Cross design creates an image point spread function (PSF) which also resembles a cross. While only a small fraction of the light is concentrated in the central core of the PSF, much of the remaining light is spread into very narrow "arms" of approximately 0.2 arcsec length and 0.007 arcsec angular width. This image is better defined than than the image from the current HST or more open interferometers. The results, as shown by extensive simulations, are better faint object sensitivity than an interferometer and superior resolution than a smaller diameter monolith/segmented mirror design. Further design and mission studies would be required before it was clear that this design is the correct path for a successor to HST. Obvious missing design elements are adequate light baffling and the ability to work with passive cooling to reduce emissivity in the mid infrared

Common Elements

The three proposed designs embraced several common elements and assumptions. Since these have important implications for the Astrotech 21 initiative, these are summarized in this section:

(1) **Wavelength Coverage:** All three designs assume that the observatory would operate from the MgF cutoff (114 nm) to the near-IR (> 1000 nm). The two filled aperture telescopes had a primary goal to be background limited by the zodiacal scattering and emission out to wavelengths 6-8 microns. These goals and assumptions affect the quality and manufacture of the optical surfaces, the preferred deployment altitude, and the scientific instruments. In particular, the requirement for UV coverage argues for simple two-mirror systems or for the development of new broadband coatings.

(2) **Operating Altitude:** All three designs incorporate larger diameter optics than HST and have more stringent pointing requirements (approx. 0.001-0.002 arcsec RMS). Thus, consideration of aerotorques and a desire for a more stable thermal environment make a very strong case for deployment and operation in HEO or beyond. Direct line-of-sight communications also becomes feasible with HEO as well as a simplified science mission operation (lower ground system costs and complexity.) The working group felt strongly that the development of an advanced launch capability, with a large shroud diameter (8-10m), was a critical NASA element for the development of advanced space telescopes. Such systems have been considered for the Mars mission.

(3) **Science Instruments:** All three observatories share the 114-1000 nm bandpass and emphasize the need for sensitive, large array detector formats. The technologies for these arrays appear to be almost in-hand, although more consideration for cosmic ray identification and rejection is needed. The two filled-aperture designs, which exploit the 1-8 micron region, will require advances in IR array performance and size to be limited by the zodiacal light in imaging and have adequate sensitivity in for moderate resolution spectroscopy in this regime. In this regard, the IR detectors must be operated in such a way to permit adequate cosmic ray rejection.

Evaluation of the Mission Scenario Maturity

The working group categorized the three design missions in terms of the maturity of the required technologies as defined in the workshop. The following key was used:

A: New technology or capability which is essential to the scientific success of the mission. A long-term development (5 years or more) development program would be required.

B: A currently evolving technology or capability which is essential to success of the mission. A short-term development (2-5 years) followed by a brassboard would be required before a mission could go to Phase A/B.

C: Either an existing technology or capability or one in which satisfactory progress is currently being made to support a Phase A/B study.

S: An area which requires more study before the technological status is clear. Generally, these were areas where certain critical elements had not been addressed in the workshop.

The following table indicates the working group's evaluation.

	MISSION:		
Technology	6-8m Monolith	6-8m Segmented	Mills Cross(FFT)
Optics	B	B+	B/S
Structures	B/S	A-	A/S
Detectors	B	B	B-
Sensing&Control	B	A	A
Infrastructure	A	A	B
Notes:	1,2,3,4,5	1,3,4,5,6,7,8	3,6,9,10,11,12

1) Desired surface accuracy at 100K should be demonstrated in a large lightweighted mirror.
2) The interaction between the spacecraft and the optical assembly must be studied, including active tip/tilt of the secondary.
3) High performance IR arrays required, techniques must be developed to deal with cosmic ray background.
4) Wavefront sensing techniques must be demonstrated, actuators with sub-micron level adjustments must run at 100K.
5) An advanced, heavy-lift launch vehicle must be developed to provide deployment in high earth orbit.
6) New materials for lightweight segments should be studied.
7) New composite structures and joints must be developed to support the active mirror assembly.
8) Segment sensing at the required sensitivity (10nm RMS) must be developed and operated at 100K and 10 Hz.
9) Deployment accuracies to 1 micron accuracies of CSI. Low CTE materials must be developed for structural members.
10) Sub-milliarcsec pointing accuracy and similar wavefront accuracy using CSI/laser metrology must be developed and proven using an on-orbit testbed.
11) Complex structural and pointing control interactions will require extensive simulation.
12) Effective baffling must be studied, including the effects of scattered light and thermal emission.

Technology Recommendations

The working group recommended that the following technologies be developed or demonstrated as part of the Astrotech 21 program:

(1) Demonstrate that the optical elements can be passively cooled low enough for near IR observations (i.e. 100K).

(2) Demonstrate that large lightweighted mirrors (6-8 monoliths or segments) of diffraction-limited surface accuracy can be fabricated for operation in a 100K environment.

(3) Validate the techniques which currently appear the most appropriate for wavefront sensing (i.e., curvature sensing)

(4) Validate and possibly develop active optics actuators with sub-micron accuracy to be operated in a 100K environment.

(5) Demonstrate that the interaction of the active optics elements (segmented primary and tip/tilt secondary) with a traditional structure and attitude control system is

compatible with the required sub-milliarcsecond pointing stability. If not, these missions may require active structures (to increase their effective stiffness.)

(6) Develop high performance IR arrays to be used in a high cosmic ray background.

(7) Demonstrate techniques for the rejection of cosmic rays with CCD-type arrays.

(8) Demonstrate that the mass and size of the proposed filled aperture missions is compatible with the launching capability to HEO currently envisaged for the next decade.

(9) Demonstrate that deployable diluted aperture concepts are compatible with long term stability and high pointing accuracy. Validate concept using an on-orbit testbed.

SUMMARY TABLE

Technology Area	Current State of the Art	New Requirements
Optics	HST mirror	Surface accuracy testing at 100 K
Active optics	Ground based	Active tip/tilt of secondary; actuators with sub-micron steps at 100 K
Segmented mirror	Ground based, slow control	Segment sensing: 10 nm rms at 10 Hz bandwidth & 100 K
Detectors	CCDs, IR arrays	Cosmic ray rejection
Telescope pointing	7 mas rms	1-2 mas rms
Large diameter shroud for heavy launch vehicle	~ 5 meters	~ 10 meters

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PANEL DISCUSSION

PANEL MEMBERS:
ROGER ANGEL (Steward Observatory)
JIM CUTTS (Jet Propulsion Laboratory)
GARTH ILLINGWORTH (Lick Observatory)
MIKE KAPLAN (NASA Headquarters)
MAX NEIN (Marshall Space Flight Center)
PETER STOCKMAN (Space Telescope Science Institute)
DOMENICK TENERELLI (Lockheed)
RODGER THOMPSON (Steward Observatory)
BEN WADA (Jet Propulsion Laboratory)

G. ILLINGWORTH: I've made up two headings, one I call Top Ten Issues and the other I call Top Ten Technology Demonstrations. Maybe we could place these here and fill them out. Just to get things started, I wrote down a couple of things which came out at various points during the workshop. This question of monolithic versus segmented mirrors and then the question of the number of telescopes. But I think at this stage of the discussion we could range over most any of the areas that we've heard about and we may not get to fill all of these out. We have heard the chair presentations and so on, so we can work this together. We'd certainly like to get some input and to see what the issues are that concern people the most in the areas that you feel we need emphasis in. And so I would welcome any comments from anybody with regard to this. If you like we could start out on one of these and maybe just for a starting point, I'll take the second one. We're speaking about telescopes which are very broadband and basically do everything from UV through to IR and it's clear that this poses some challenging technical constraints on the system. Maybe it makes them impractical. And so then we thought about this split where we might do a UV telescope plus an IR telescope, but it's not clear that this a reasonable thing to do. If there are comments from anybody about this, I would be willing to hear them spend a few minutes discussing this.

D. TENERELLI: Would you explain that again? I see UV plus IR.

G. ILLINGWORTH: We could make two telescopes.

R. ANGEL: Actually, is it two, is it one, or is it three, because one of the panels suggested three?

G. ILLINGWORTH: I think from a matter of practicality ... Roger said he could stop at the two level, so I don't know about three telescopes.

P. STOCKMAN: Excuse me, before you get down, what happened to the submillimeter wavelength region here? You said there are a number of programs of technology development, some of which are scheduled for new starts at the end of the decade, which aren't really being considered either –

G. ILLINGWORTH: There was an implicit assumption in this. NGST assumes its a UV-visible-IR telescope and basically we are dealing with this wavelength range, even though the title didn't include that. So, its large filled aperture telescopes in this sort of tenth to ten micron range. I'll now sit down because I want interaction between the panel members.

R. ANGEL: I guess, just two things. One is, what is the temperature range that the various control systems, structures, and damping systems have to operate over? If you're talking about a narrow range, then it makes a significant difference whether you have one or two telescopes. It also is significant for the power requirements, because if you're talking about narrow ranges of temperature control with maybe large heater systems required - that's a paradox you have here. If I allow wide variation in the temperature, then I probably minimize my power requirements. And what does that mean? It gets to the size of the solar array. Then, if I have a smaller array –

J. NELSON (?): Well, maybe I can answer this fairly quickly, then we'll see what anybody else has to say. The baseline view, I think, has been that we are going to a low temperature operation and we will continue to operate at that point. If for any reason, it has to sit through wide temperature fluctuations, then it's probably impractical to make a usable telescope at a different temperature, one that has high optical performance. So on the Moon, for example, the view developed that it was a nighttime observatory only and in the day you basically protect it. For the high earth orbit one, the view has always been that you bring it to your operating temperature and that's basically in the vicinity of 100°K, whatever we can reach. Lower if possible. But, in fact, the operating range would be quite small. Now, this point was brought up by the other group, but I think my gut reaction is that it adds an incredible level of complexity to the thermal and structural control systems and so unless we are driven to that for some reason, I would much prefer to stay in the regime of a single temperature operation. The numbers that we've worked in ground-based telescopes, the temperature change is 30° C and the delta output is 10^{-8}. You get about a tenth of an arcsecond image, so even when we're thinking about the infrared, the temperature range can't be more than 30°C. So if you let it vary by a factor of 20°K from 80° to 100° you're increasing your background by almost two orders of magnitude. And so stability is going to be very important for operation in that regime. I don't think a UV-optical telescope can survive temperature variations because of figure changes or an infrared telescope can survive temperature variations because of fluctuating background, so they are both going to have to have a control system that establishes the optical elements that are seen by the detectors at a constant temperature. This means some active thermal control, I would think. We just can't let it passively assume any temperature it will do. We have to help it to maintain a constant temperature.

R. ANGEL: There are two things. If we want to control the temperature, let us say to +/-2°C, whatever temperature you are going to establish as your nominal temperature, then that defines the power requirement. That power requirement then is one of the factors that sizes your array. If I increase that range of temperatures that I am allowing the telescope to operate at, then I reduce my power requirements, which means that I get a smaller array, which means then I probably have less of a concern about potential disturbances from an appendage system. So now you see you've isolated on a very key parameter and that is the temperature range, because now it also can change the type of control system you would need if you have, let's say, segmented optics.

J. NELSON: I must say, first though, one of the assumptions going in to this is we would try to use body panels wherever possible, if it turned out to be practical. It needs to be addressed at a technical level to see whether that is practical, given the pointing and so on, but if you can do that, we do get away from a lot of the disturbance problems with the appendages.

G. ILLINGWORTH: The solar arrays?

(UNIDENTIFIED): Yeah, from the solar arrays.

R. THOMPSON: ___ are you going to use body panels?

G. ILLINGWORTH(?): Yes.

M. KAPLAN: What does that mean?

G. ILLINGWORTH: It means that the solar panels are mounted on the side of the spacecraft and so you keep that side of the spacecraft pointed to the sun, so there will be a hot side and a cold side. Then you use the other side as your radiating side.

M. KAPLAN: If it were, for instance, sure that an 8-meter mirror would be no better in the UV than a 3-meter mirror, say, then clearly you might actually do better in terms of resolution in the UV with a smaller mirror and of course you get a UV dedicated mission in similarly high orbit. Even for a somewhat smaller aperture, you might actually get more science, because you could optimize for the UV and it wouldn't be sharing its time. And influencing the Hubble space telescope now is the science management business, sharing our time between ultraviolet spectroscopy, optical imaging and so forth. There is very little parallel science going on and basically each of the instruments gets shared. Everyone gets their slice of the pie.

(UNIDENTIFIED): On the optics side the assumption is then if we are going to run a UV telescope it would be UV diffraction limited.

M. KAPLAN: Right, what I mean, is that if it were decided for some reason, looking into the technology, that that was not feasible –

(UNIDENTIFIED): But on the ground we work all the time with a hard image quality limit independent of aperture, yet many of us want to build big telescopes on the ground and more than one of them. But they are all general purpose. We've been unsuccessful in saying that this is going to be an 8-meter telescope to work from atmospheric cutoff to 1/2 a micron, period, or this is going to work from 2 microns long only. We don't do that. So I think we have lots of examples where we've decided for one reason or another that our telescopes must be general purpose, and you just accept what you can get for image quality. So this will be diffraction limited at 300 nanometers and short of that, you just take the image quality that you can get. It's not diffraction limited.

(UNIDENTIFIED): This will be polished 20 years after the Hubble mirror was polished, right? There is no reason not to make it diffraction limited.

M. KAPLAN: Obviously, if the wavelength at which you're diffraction limited drives every part of the system, everybody hurts to be sure that you make that wavelength and pain converts into money and you may not be able to afford ...

G. ILLINGWORTH: Perhaps it would be useful to separate out the technical issues between the infrared and the UV telescope. If you have an infrared telescope, you want it passively or actively cooled down to this temperature which means that you are going to have to decouple thermally the optical structure from the outside body of the telescope. That is a very important structural situation and if you didn't have to do that, you would not build the telescope the same way. Also, you are going to have to figure a mirror at essentially room temperature and then operate it at a temperature which is at least 100 or 200 degrees below that and maintain accuracy. You may be able to do that actively, but I think in terms of the tolerances you are talking about in the UV, it is very difficult to do that. Also for the infrared you will want to coat it with something like gold which is a very different coating than you would use in the ultraviolet. On the other hand, you're not as concerned about microcontaminants as you are in the UV. Now if you just go to a UV telescope, you do not have to thermally decouple the optical structure from the main structure of the telescope.

(UNIDENTIFIED): Why do you say that?

(UNIDENTIFIED): If you are going to maintain it at room temperature, like HST, then you don't have to worry about that big thermal mismatch.

G. ILLINGWORTH: There is a scientific point that has come up quite often about the value of having wideband systems. We really do need information at a wide range of different wavelengths and the question is do you want the spatial resolution as well over that range? It is not something we can do from the ground. The logical extension of that is that you push to the UV as well. Now, that may not be the optimum thing to do from a technical point of view, but my concern is that you run the risk when you split these things apart that it ultimately turns into two sequential projects, which is not good. On Mike's charts, you'd have NGST1 and NGST2 ten years farther down the road. They may have started out sitting there together, but when you look at all the other missions in the other wavebands, there's double the number of objects for folks to shoot at, to compete with. So unfortunately while the technical arguments can be quite good, as a going in position I still have a bias or preference for a broadband UV-IR system. But I would welcome other comments on this.

We want to continue the same philosophy that we've had with the great observatory program, in other words of having the ability to look across the spectrum at the same point in time. I think there will be evidence over the next decade that this has been a very good thing. If we make discoveries, then we've seen a piece in one waveband and we see another piece in another waveband. Put the story together and we probably make discoveries that you couldn't have made with any one waveband. We've had several instances of that happening. That will be the science justification when we go to this next generation to have these things in parallel, not sequentially, and that is the point we have to make. The politics that we are talking about is a real consideration, but that is from previous decades of selling these things –

M. NEIN: But, they told us the great observatories were going to be flying together and where is SIRTF? By the time we get SIRTF, HST will be 8 years old.

G. ILLINGWORTH: I understand, but currently if SIRTF goes in as a new start in 94, it will be flying in Hubble's last 5 years. So we will have achieved the goal. The argument we are going to use, pushing it in 94, is that if you let it slip beyond then, then it has has lost its power. That is one of the primary rationales we've got for pushing it. We would have liked to have pushed it as 93 when we started this year, but given the word in the appropriations language last year, which cut all new starts to astronomy by 50% - OSL, SIRTF, and GPB - it's kind of hard to come back the next year and ask for the restart. I was going to raise another point, if we can get back to this, which is why do we do without servicing?

J. NELSON: In high earth orbit?

G. ILLINGWORTH: Right.

R. THOMPSON: You might have more insight than I do, but my impression was that it was impractical to do it on these sort of time scales. If we're looking at the early part of next century, are we going to have access to high earth orbit robotically?

G. ILLINGWORTH: Well the reason I say that is if we don't state that it's a desire for us to have it, we're never going to have it. So if we put our oar in the water and say we'd like it and here's the benefits that it can have, it clearly is good. It might cross the mission up, but probably we think about servicing and we say it would be nice to have this capability of changing out instruments. What it does is it puts NASA in the position, when they go and they ask for these missions, they can project a longer lifetime for the missions. If we're asking for these missions at $3 billion apiece, you're not asking for $3 billion for a five year mission that you've frozen the technology for at a certain point. That was one of the beauties of HST. My point is that even though today we can look at servicing for these missions as risky, we don't have any way of doing it now. We're in the process now of laying out a technology development program; let's put our oar in the water and say we would like to have servicing options for these missions because it would make these missions more compelling. We could fly them longer, we could change out instruments, we could do limited repairs. That's the rationale they need to have an aggressive servicing telerobotic technology program, which may or may not provide what we need in the future, but if we don't say it now, we're not going to get it. One more point: it's not to say that we will service those missions, but if we don't say that we'd like to have the option, we'll never have it.

(UNIDENTIFIED): It could be very expensive to respond to. The HST nearly doubled in cost because of servicing. It was deployed from the shuttle, and it had to be serviced from the shuttle.

M. KAPLAN(?): I hear what you're saying, but if we don't at least mention it as an option now, we're never going to have it. What would we do with HST now if it wasn't serviceable?

(UNIDENTIFIED): If it's going to make the job of selling a big telescope easier. People in Congress are going to ask you: the last one, you screwed up with the optics, but you had the servicing and you were able to fix it. Now you're going to build a telescope that's 3 to 4 times its diameter, it's going to cost more, and you're telling us that you guarantee us you're going to get it right and you're never going to need –

(UNIDENTIFIED): You build it right and you make sure that you build it right. That's the whole point!

J. CUTTS: If I can make a point here, what we need is a study.

(UNIDENTIFIED): Right

J. CUTTS: And I think it's a study –

(UNIDENTIFIED): We're not going to answer that here –

J. CUTTS(?): But it's something we really should seriously undertake. We have been going into this with some prejudices because on the Earth the trade-off between a specialized IR telescope and a visible telescope is not so extreme. When you go to space, the differences, the cost of performance tradeoffs, I think, are much larger and I think that kind of investigation really needs to be done. Maybe we can make that a part of the list of recommendations.

G. ILLINGWORTH: And we should move on, too. We don't want to spend a lot of time on one issue, but Max has been trying to say something for a little while.

M. NEIN: I just wanted to come back to one point. I think segregating the telescopes on the basis of temperature that you achieve or don't want to achieve, ... at least on the lunar surface things cool down so rapidly that even if the telescope is designed to operate at a specific temperature, it will attain 120 degrees anyway whether you want it to or not because of all this radiation out the front and the lunar surface is extremely cold. So it seems to me you have to live with very low temperatures even with a UV telescope.

(UNIDENTIFIED): Yes, you're right.

(UNIDENTIFIED): - for the Moon -

(UNIDENTIFIED): Right, in earth orbit it's different because you've got the Sun -

G. ILLINGWORTH: Yeah, you do have the option of running it hot or cold in orbit. So we have the servicing issue. There's the two separate telescopes where I think I read the consensus being for moving towards two separate telescopes. Is there anybody that has a strong disagreement with that?

J. NELSON: ... the group prejudice is that we probably can't afford it. I think we'll be better off just specifying the shortest wavelength at which it's diffraction limited, and it may require some efforts to find out what that wavelength is and what can we afford. And I don't yet buy the thermal argument. I mean we're not running it at 2° Kelvin. Those things are going work at 100° Kelvin and stabilizing the temperature seems like it's equally important to achieve optical quality as to control the emissivity so you're going to do that for either telescope.

G. ILLINGWORTH: Again I guess that having identified an issue, you might want to start out on a two telescope path at some level, but also keep in mind that you may be forced into one and we want to be in the position to maximize the range with which we utilize one telescope. And so having started out on a path of two, we don't want to be in the position that if it turns out that one looks impractical, you just drop one of them and you're left with the other. You'd like the option to expand the remaining one which means that in the study that deals with this issue, it needs to look at the capabilities of one broadband telescope and the limitations and the tradeoffs. And actually that was an item that's been discussed before as well, in meetings last year.

D. MEIER: I have a question about this issue - are we really talking about two separate telescopes when we say two telescopes? That is, there's different optics? Or are we talking about two instruments on parallel tracks, same optical design, same truss, basically the same but they have different systems attached? There's some cost savings in that latter -

G. ILLINGWORTH: I think that probably is the safer baseline position to go in; one, there's two telescopes where you can draw a list of many of the common elements you have to develop for the structural and support level. The instruments will be different but the basic configuration will be the same. Maybe then you will find at some point you're driven away from that for other reasons.

D. MEIER: It's also possible you will find that maybe one could do the job after all ...

G. ILLINGWORTH: I think this sort of trade-off has never had a serious technical cost study done and it needs it. That was certainly brought up in all the panel discussions last year. This same argument went on at some level and so the end result was that we lack information. We really need people to sit down and go through a serious study and see what the impact is. Then, at least, we're in a better position. If it turns out it's double the cost to do two of them, then you know you're not in a position of really selling it. If there are some cost savings to be made, we may be in a much more advantageous position.

(UNIDENTIFIED): There's perhaps another point of view in which the same question might come up in studying options for SIRTF. At one point one study seriously suggested that the cheapest way to get five years of lifetime might be to launch two telescopes each with 2-1/2 years of lifetime, one after the other.

G. ILLINGWORTH: That argument is probably much less applicable here, but it may be in some regards: If you're thinking about adding new instruments later, you have to consider will it be cheaper to launch a whole new telescope with different instruments than to design a telescope that you can plug new instruments into? Now the argument against that is it's politically dangerous. I tend to not like arguments that this is politically dangerous even if it's scientifically and financially the best thing to do.

M. KAPLAN: I think those considerations need reasonably to come later. You have to keep the HST experience in mind, that's a 1-1/2 to 2 billion dollar telescope depending on who costs it.

The replacement instruments are $100 million instruments. They're pretty small by comparison and we don't factor in launch costs in the usual way business is done. But in fact in terms of what it costs the program, it's a 5 to 10% level.

M. KAPLAN: I was going to ask Harley if the infrared telescope that we're talking about is a super Edison?

H. THRONSON: In part, of course. The primary difference between Edison and this is that we think that some structural differences, more sophisticated, larger area radiators, more shielding and so on can get Edison colder than these kinds of temperatures that you're talking about here.

M. KAPLAN(?): But if we decide on separate infrared instruments, maybe an IR instrument should be aimed at say 5 meters, which will be half an order of magnitude better than SIRTF as far as aperture size.

(UNIDENTIFIED): There are a number of people that I know that if they decided to go to two telescopes, then they would snatch up the infrared telescope. Maybe argue that it should be about half the size of what we're talking about here.

M. KAPLAN(?): So in other words, the infrared instrument may be a 5-meter class as opposed to an 8–meter which could maybe drop the price a little bit.

G. ILLINGWORTH: Maybe, but I think in the interim many of the problems we're dealing with are resolution limited and in the infrared of course, you lose resolution because of the wavelength and it's a big factor. You're up to 3 or 4 microns, looking at factors of 6 from where we typically deal with HST. So we're worse than HST at 3 microns at this low background window on the universe. So diameter is more important for the IR than it is for the UV.

(UNIDENTIFIED): You've been talking from time to time yesterday that each mission wants to be an order of magnitude more sensitive than in the past. Any machine that is going to work at 3 microns, any conceivable mission is going to be orders of magnitude more sensitive than what is going on now. So we've reached the order of magnitude sensitivity improvement already. There's probably less desire in this community, the infrared community, to push for 8 meter, if we can get a 5 meter telescope say, if it's politically feasible to get a 5 meter telescope.

G. ILLINGWORTH: That could well be true, but I think at this stage it's a little premature to be doing that.

J. CUTTS: Can I throw up another one for discussion and that's the development evolution. We hear from the lunar group that the logical next step is essentially a scientific precursor, the transit telescope, followed by this much larger telescope at a later date. We have the goal of an 8-meter class orbital telescope modified by this discussion we've been having. I'm not sure what all that implies, but at least some much larger telescope involving many, many new technologies that haven't previously been demonstrated. I'd like to hear from the group here what their thoughts are on the desirability and need for some kind of precursor to that, maybe more of an engineering precursor perhaps, something that doesn't have to be rationalized as a scientific experiment in its own right, but that gets us to that 8-meter class capability.

R. ANGEL: I'd like to say something, I mean, there are going to be precursors on the ground before we ever get moving at all with this, there's going to half a dozen to ten 8-meter telescopes on the ground, running at a level of performance which is not so very different from what we're talking about. I mean you're going to see diffraction limited, 8-meter images coming from the ground within the next decade so looking at this 10 years hence, it isn't going to seem really such a massive step as it may seem now.

(UNIDENTIFIED): I have a totally different topic.

G. ILLINGWORTH: Maybe we should just see if there are responses to Jim's point before we go off on another topic. Mike, did you have one?

M. KRIM: Yeah, I really think a lot of the technology that we need to develop is going to depend on what kind of launch vehicle we're going to be faced with. I just have this gnawing feeling that sooner or later we're going to build the largest telescope that we can fly prebuilt, preassembled, pretested, for the largest shroud available and it would be I think very instructive and very important to try and get some testament of firmness on what size shroud is going to be available in the 2000 to 2010 era. I hate planning 10-meter telescopes and suddenly find them turn out to be ships in a bottle.

M. KAPLAN: I think you could ask anybody in optical space flight and you'd ask ten people and you may get ten different answers. I think the more important thing is to state that if we want to be able to fly an 8-meter class instrument, then we may very well just conclude that we need a 10-meter shroud, period. That's one of the recommendations that comes up in this workshop. Put that out as a requirement and then let them react to it.

P. STOCKMAN: That certainly was the point of the orbital working group. That was their highest recommendation, this larger shroud, more launching ability. That just makes all of this so much more feasible. If you don't have that, you're into a very advanced technology.

M. KAPLAN: And that has to happen now, because there are studies going on starting right now between NASA and DOD to look at the next generation of launch vehicles. So this recommendation has to come out now.

G. ILLINGWORTH(?): In many ways I think this is probably the best situation since the 70's for actually being on the track to having new launch capabilities. There's a lot of attention that's focused on this. It may dissipate for various reasons, but at this time if we bring together arguments that help support this case, we're doing a service for future HLV capability -

M. KAPLAN(?): If you say we need a 10-meter shroud and we need it by 2005, they're going to love it, because that way they're going to put together a program to have a heavy lift launch vehicle with a 10-meter shroud to put up whatever this thing weighs.

(UNIDENTIFIED): What is needed is commitment from very high up. I can't help but remember what Kennedy said: He wanted to place a man on the Moon and bring him back safely in a decade. He didn't say 20 years or 30 years, he said a decade, in 10 years, and I think we only had in this country an accumulated 15 minutes of human space flight when Kennedy said that.

M. KAPLAN: I think it's a conclusion that all of us came to from the first meeting that we had in September of '89, that the technology exists to put into a space a 10-meter telescope. Now it all depends on the types of features you want to put into that system. That determines whether or not you want to delay it because you want to put in something like image motion compensation using fast steering mirrors and slewing the telescope in seconds versus ten minutes and things like that. But if you wanted to build on essentially the technology of Hubble Space Telescope, you can put in a 6-meter or an 8-meter mirror. You can put one up in 10 years. The way you get the commitment, the way to make this happen, to work, is the Bahcall report. We're going to be anxiously looking at the Bahcall report that comes out on the 19th and we hope to see SIRTF in a recommendation, and SOFIA, and where the next generation space telescope fits in will be important as far as the support that NASA high-level managers can give the project because we have to respond to that report. That report is going to provide us with the goals for building our program over the next decade. It will be very important how these missions that we're talking about here fits into that perspective.

R. THOMPSON: I have to leave in a couple of minutes, so if there's a comment about detectors?

E. SCHREIER: My question is most relevant to that. One of the things that has not been dealt with at all is the data rate and information systems aspect, and I'd request all of the panels in writing up their final reports, to include where you think there should be new technology in the areas of data compression and data transmission. There's been this whole Astrotech activity on information systems with a report on the verge of coming out which tended to be a very large grab bag of different kinds of technology and different ways of doing operations and data systems in space and, in fact, it took a much larger system approach than most of the discussions that we've had in the last two days. However, I think there could be a lot of benefit to giving some priorities to those things, and this mission would be a very good driver. One thing I heard here is large scale modeling and simulation efforts. You all ought to think about that and put them into the report so that we can merge that into the information systems report and try to channel that piece of Astrotech in the right direction.

G. ILLINGWORTH: Let me ask you, where do high performance radiation hardened microprocessors fall in all this? Is that dealt with in information systems or ?

E. SCHREIER: Yeah, there were recommendations in there, but -

J. CUTTS: That right. There were five areas; high speed processors was one of them and there was consideration given to processors for supporting both the sensors and also this business of active control, figure control.

(UNIDENTIFIED): So it's there -

J. CUTTS: Sort of a place holder for that in the plan. What's maybe lacking is how severe are the demands that will be placed on those processors.

E. SCHREIER: Garth, you're going to have massively parallel architectures long before this telescope ever flys, so the computer requirements are not going to appear the same as they do to us now.

H. EPPS: You may not have massively parallel processors in space before this flies. You say you're going to need them.

E. SCHREIER(?): They'll certainly exist . Whether you'll want to put them in space, I think will be up to you but they exist right now as a matter of fact.

(UNIDENTIFIED): The problem is very hardened systems and -

(UNIDENTIFIED): Well, the military, of course, is interested in that -

(UNIDENTIFIED): Yes, I think you're right.

(UNIDENTIFIED): They're pouring a lot of money into that.

G. ILLINGWORTH(?): There might be a certain technology that's already been developed that might be available, and that's probably something that should be looked into. There has been a lot of work done in this area.

J. CUTTS: Let me make one observation: We keep trying to get bigger and bigger telescopes. Eventually we're going to go to a telescope where there is not going to be a launch vehicle big enough to launch this thing. And that may happen sooner, it may happen later. So at some point we need to start investigating the technology necessary for putting a segmented telescope together in space. And if you say, we're not going to have segmented now, and you're presuming a launch vehicle capability, what you're saying is it's going to be the largest launch vehicle we have.

P. STOCKMAN: The evolution, to some extent is in two parts. One is segmented and the other is deployable and you can't have segmented without a deployable system. It may be that even if you could launch a 10-meter telescope, you'd probably want that segmented.

J. NELSON: On the ground, in general, 8 meters is taken as somewhere around the limit for single filled apertures. In the case of the VLT and Columbus, the direction then is to go with the interferometric systems beyond that, so your premise that you're sometime going to go to segmented systems is not necessarily true. We may find that the evolution goes beyond that into array-type systems.

J. CUTTS(?): Does that apply in space?

J. NELSON(?): On the ground, it's simply that the scientific value of going to a bigger single aperture is not all that great compared to making array systems.

R. ANGEL: Definitely some debate about that point.

M. KAPLAN: Given we're assuming an 8-meter glass telescope, and assuming that we do have a launch vehicle envelope that will accommodate that, there are two options: segmented and a monolithic mirror. I think it would be useful for this group to consider what differences there are between those approaches, relative to the differences that exist for ground-based implementations. Presumably there's tradeoffs when you look at these two approaches on the ground. Perhaps there are some of the same tradeoffs, but perhaps there are some different issues that come up if you want to use these approaches in space. I'd be interested if there are any comments on that.

R. ANGEL: I'd like to come back to the optical design. I think we should have as a goal in some of these architect studies that at the end of them, we would be ready to undertake a vigorous, vast program to make the telescope. It gives a sense of focus to what you want to look at. So I think one of the outputs at the end of this study is that we know exactly what the telescope looks like. As part of this program we ought to try and put all the complex trades in. The optical design has a way of focusing your attention on what all these trades are. Until you look at them all, you can't make the optical design, so if one of the outputs of this program in a few years was a design where a lot of thinking has gone on, all the tradeoffs are made, that would put us in a very good spot. More generally, we had some discussion last night about the idea of clearing out the proposed technologies. The result of the Astrotech program should be that at the end of it we're ready to go with a 6 or 8 year program that will get the whole thing done and finished without unknown technology developments. I found that gave me a real good sense of focus as to what this list of things should be. And one thing is advanced optical design, with every trade, every consideration put into it.

P. STOCKMAN(?): The question came up by Jim of what would be a demonstration. What's a demonstration of this facility that might be useful in terms of thinking about Astrotech 21? I believe the optics panel made a specific recommendation in terms of looking for the appropriate ULE material and trying to manufacture some reasonable size mirror to requirements that are similar to what we are looking at now, and I think it's entirely appropriate that that sort of thing be considered as a demonstration step. Whether you do something from this, whether you turn it into the spacecraft is another thing, but optics and the ability to make high precision optics appropriate for use at low temperature is not a done deal even though it's not obvious that there should be a problem. That's a test program where I can really see an enormous amount of value. You could even have a cryogenic chamber and let the temperature move up and down and see what the inhomogeneities do to the optical shape and learn a lot in that process.

(UNIDENTIFIED): I would rather see even more than two telescopes because I feel there are huge economies. Nearly everything you spend money on is learning how to do it and that making another one hardly cost anything even though the companies will try to charge you a lot. Keck II will try and charge you the same as Keck I, but in fact the repeats don't cost you nearly as much as the original development.

(UNIDENTIFIED): The argument for going towards throw away, I feel, is very strong.

(UNIDENTIFIED): We have to see some realistic studies. I think I see some nodding around the room.

(UNIDENTIFIED): I'd just like to mention about the multiple telescope concept, what we have found in some of the work is that there are some considerable cost savings. Now where you see some of the cost savings are the electronics. If the electronics are very similar from vehicle to vehicle, then most of the problems that you have with designing and fabricating and testing a black box is on that first vehicle. Systems level tests ... you've gone through all the problems on the first vehicle, and you're able to definitely go through systems level tests in a much more efficient manner.

(UNIDENTIFIED): I can certainly believe that.

M. KAPLAN: We're at a point in our program philosophy where the decade of the 90's is going to be, we believe, the decade of the moderate missions. Now the moderate missions may be missions that were half a billion dollars which may grow into a billion dollars by the time we're finished, but the philosophy is that this is the decade of the moderate missions. Politics seem to dictate that. Although there may be a lot of shared experience that might benefit us from the submillimeter moderate mission fitting into this concept, the risk is that the submillimeter moderate mission people develop jealousy, they may be wary of having their mission branded as the precursor next generation space telescope. So there's that perception that this is no longer a moderate mission. It's a perception problem.

END OF WORKSHOP

APPENDIX

- WORKSHOP WORKING GROUPS AND MEMBERS
- LIST OF PARTICIPANTS

WORKSHOP ON TECHNOLOGIES FOR
LARGE FILLED-APERTURE TELESCOPES IN SPACE

WORKSHOP WORKING GROUPS AND MEMBERS

1. OPTICS	R. Angel (Chair), J. Breckinridge, D. Diner, H.Epps, D. Fisher, C. Gilbreath, T. Glavich, S. Hinman, E. Hochberg, D. Korsch, R. Locke, B. Martin, A. Meinel, M. Meinel, J. Miller, and R. Wilson
2. STRUCTURES	D. Coulter, M. Krim, D. Rapp, E.J. Roschke, G. Sarver, and B. Wada (Chair)
3. DETECTORS	S. Collins, P. Hintzen, C. McCreight, L. Robinson, H. Schember, R. Thompson (Chair), B. Wilson, and B. Woodgate
4. SENSING AND CONTROL	J. Lesh, M. Levine, J. Rather, G. Sevaston, P. Swanson, M. Tarenghi, D. Tenerelli (Chair), and E. Tubbs
5. LUNAR-SPECIFIC ISSUES	J. Burns (Chair), K.-M. Chua, B. Davis, J. McGraw, M. Nein, and K. Nishioka
6. ORBITAL-SPECIFIC ISSUES	B. Collins, A. DeCou, S. Durrance, D. Machetto, P. Stockman (Chair), and H. Thronson
AT LARGE:	J. Ayon, J. Cutts, P. Davis, J. Fordyce, D. Jones, M. Kaplan, D. Lawson, A. Pappano

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WORKSHOP ON TECHNOLOGIES FOR LARGE FILLED-APERTURE TELESCOPES IN SPACE

Pasadena, California, March 4–5, 1991

LIST OF PARTICIPANTS

Roger Angel	Steward Observatory
Juan Ayon	Jet Propulsion Laboratory
Gary Beals	Lockheed
Pierre Bely	Space Telescope Science Institute
Peter Bender	Joint Institute for Laboratory Astrophysics
Jim Breckinridge	Jet Propulsion Laboratory
Jack Burns	New Mexico State University
Chris Burrows	Space Telescope Science Institute/ European Space Agency
Richard Capps	Jet Propulsion Laboratory
Koon-Meng Chua	University of New Mexico
Stewart Collins	Jet Propulsion Laboratory
Dan Coulter	Jet Propulsion Laboratory
James Crocker	Space Telescope Science Institute
Jim Cutts	Jet Propulsion Laboratory
Bill Davis	Marshall Space Flight Center
Paul Davis	Ames Research Center
Anthony DeCou	University of Northern Arizona
Dave Diner	Jet Propulsion Laboratory
S. Durrance	John Hopkins University
Harland Epps	Lick Observatory
James Fanson	Jet Propulsion Laboratory
Dave Fisher	University of California at Santa Cruz
Jess Fordyce	Jet Propulsion Laboratory
Charmaine Gilbreath	Naval Research Laboratory
Tom Glavich	Jet Propulsion Laboratory
Stephen Hinman	Kodak
P. Hintzen	Goddard Space Flight Center
Eric Hochberg	Jet Propulsion Laboratory
Garth Illingworth	Lick Observatory
Stewart Johnson	BDM International
Dayton Jones	Jet Propulsion Laboratory
Mike Kaplan	NASA Headquarters
Richard Key	Jet Propulsion Laboratory
Isabella Kierk	Jet Propulsion Laboratory
Dietrich Korsch	Korsch Optics
Michael Krim	Hughes Danbury
Robert Laskin	Jet Propulsion Laboratory
D. Lawson	NASA Headquarters
Jim Lesh	Jet Propulsion Laboratory
Martin Levine	Jet Propulsion Laboratory
Robert Locke	Kodak
Duccio Macchetto	Space Telescope Science Institute
Buddy Martin	Steward Observatory
Craig McCreight	Ames Research Center
John McGraw	Steward Observatory
David Meier	Jet Propulsion Laboratory
Aden Meinel	Jet Propulsion Laboratory
Marjorie Meinel	Jet Propulsion Laboratory
Ramsey Melugin	Ames Research Center
Joe Miller	Lick Observatory
Max Nein	Marshall Space Flight Center
Jerry Nelson	Keck Observatory
K. Nishioka	Jet Propulsion Laboratory
Alfred Pappano	Jet Propulsion Laboratory
Georgene Peralta	Jet Propulsion Laboratory
Don Rapp	Jet Propulsion Laboratory
J. Rather	NASA Headquarters
Lloyd Robinson	Lick Observatory
E. J. Roschke	Jet Propulsion Laboratory
George Sarver	Ames Research Center
Helene Schember	Jet Propulsion Laboratory
Ethan Schreier	Space Telescope Science Institute
George Sevaston	Jet Propulsion Laboratory
Mike Shao	Jet Propulsion Laboratory
Peter Stockman	Space Telescope Science Institute
Paul Swanson	Jet Propulsion Laboratory
Massimo Tarenghi	European Southern Observatory, Garching
Domenick Tenerelli	Lockheed
Richard Terrile	Jet Propulsion Laboratory
Rodger Thompson	Steward Observatory
Harley Thronson	University of Wyoming
Christopher Thyen	University of Minnesota
Eldred Tubbs	Jet Propulsion Laboratory
J. Richard Vyce	Itek
Ben Wada	Jet Propulsion Laboratory
Barbara Wilson	Jet Propulsion Laboratory
Ray Wilson	European Southern Observatory, Garching
Bruce Woodgate	Goddard Space Flight Center
Jerrold Zimmerman	Itek

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