By

Leonard H. Solomon

17 October 1996

Optical System Design for the Next Generation Space Telescope

Final Report

SV96-011
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Optical System Design for the Next Generation Space Telescope

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and

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Both SOlVisions and ORA wish to thank the remainder of the NASA IP for their continued support and interaction, and we especially appreciate the efforts of Max Wenn and James Billbro.

A 15-30% stretch of the stake-of-the-art (STK) for an 8-in primary to be acceptable, though rational, while a weight goal of 10-12Kg/m² is about

SITON for an 8-in primary to be acceptable, though rational, while a weight goal of 10-12Kg/m² is about

Much remains to be done, of course, but these initial looks show the cost goal to both cost and weight. Much remains to be done, of course, but these initial looks show the cost goal

upon the earlier briefing in the areas of thermo-optics, material, and system natural frequency, some of these areas.

The ORA section of this report expands

NASA use on April 15, 1996, addressing some of these areas. The ORA section of this report expands

optics, material science, and parametric cost/weight modeling, a brief data package was provided for

optical modeling and tolerancing using CODE V and LIGHTTOOLS, through to opto-mechanics, team.

Much of the ORA work is based on proprietary data, and spans disciplines ranging from classical

development supporting the NGST are included.

Our recommendation for technology

implementation for high performance operation in space. Our recommendations for technology

leapfrog design, and on deployable primary mirror technology, especially suited to their system

program sponsored by the government, SOlVisions has provided data in this report on deployable

deployable reflector topics and demonstration hardware. Based on that work, much of it done on-look

over the past few years SOlVisions and ORA have each worked on a very broad range of

NGST OPTICAL SYSTEM STUDY

NGST

NGST
Optical Design Considerations
can meet all criteria.

- IPT Baseline - Nearly-centered Three-mirror Reflected Design

Provision for light baffling

Location for test steering mirror for image motion control

Wavefront control

Acceptable scale image of primary at a (flat) deformable mirror for

At focal plane instrumentation (spectrometer, photometer, etc.)

Adequate focal length to provide spatially resolved images

An NGST optical design should provide:

Optical Design Considerations

NGST
We strongly recommend the use of a filled aperture system.

contrast between target objects and sky background. non-imaging instruments, whose observing efficiency is degraded by the lack of for azimuthally varying cases, the situation is even more pronounced in the use of predicted high resolution based on the aperture. For low aperture fill factor, especially in reconstructions, the image to obtain the information concerning with the low MTF and increase for any achievable sensor Signal to Noise ratio (SNR). Great difficulty although a large aperture can yield high ultimate resolution, a low fill factor leads to utility of various forms of filled and unfilled aperture for remote sensing. In general, previous studies, some for classified system applications, have evaluated the relative

Configuration Choice

NEST
Signal to noise from the imaging device does not allow straightforward image reconstruction with achievable untilled apertures, even the C0lay-6 and C0lay-9 forms, untilled aperture configurations.

Due to their monotonic, relatively high MTF response, configurations for imaging and especially for energy detection devices (photometers and spectrometers) are annular or untilled apertures, analytically and experimentally, that the most useful primary mirror.

Various studies of large untilled apertures have determined both configuration choices.
Aperture Breakpoints
and place mechanism to assemble
of outer panels of 4-m scale, requires pick-
• Can achieve up to 20 meters with double row

system based on 4-m mirror panels
• 1.1-1.2 meters is size limit for simply-deployed
based on weight and volume for 3-4 m mirrors
• 4 meters is packaging limit for Alpas shroud

Facilities Limit
using lightweighted glass facetsheets
• 4 meters is composite mirror size limit

Conventional polishing to 8 meters
• Existing CGS facility limit is ~4 meters,
2.5 meters is facility limit for ion figuring,

Mirror blanks - Facilities Limit
• 1-2 meters is current limit for Be and SiC

Aperture breakpoints - Near Term Technology
System Considerations

NGST
Detachable Mirror

Telescope Technology Limitations

NGST
Technology Limits on Telescope
Deformable Mirror

Critical Issues

Actuator Spacing/Stroke/Influence Function
Low temperature DM operation

Impact on System Design

Actuator spacing affects minimum size of pupil mirror, based on scale of residual WFE to be corrected, for a given actuator count. This could limit choice of focal ratio. Current baseline configuration would require 3.5 mm actuator spacing.

If 30K operation of DM cannot be provided, existing technology would require heating the DM, or direct correction of primary mirror panels, to provide correction of WFE.

Existing Technology

Stroke of ~4μm is produced by existing combination of device parameters, including actuator spacing of 7 mm. Other parameters include actuator diameter and length, facesheet thickness, voltage, etc. To achieve 4mm stroke with closer spaced actuators will require engineering development of materials and processes.

Electrostrictive material used for actuators is limited in low temperature response, demonstration required for 30 K operation.
Technological Issues

Low Temperature Mirrors
Major cost driver. If facility and test are feasible at all.

• Full primary mirror and system test at operational temperature will be

Fabrication errors removed at ~290K.
Facility and test process significant issues

• Mirror segments must be tested at operational temperature, but any

Fabrication and Test

• Operational temperature
  Calibrated operation of actuators (mirror segment or pupil mirror) at
  CTE match between substrate and facesheet over temperature range

• and operational temperatures
  CTE and CTE uniformity of facesheet for 250K difference between fabrication

Material Selection

Major Drivers

Technology Issues

Low Temperature Mirrors

NIST
For other programs, and for possible low-risk design approaches for NSTL, made and demonstrated in the early 1980s. These form the backdrop for later development with Near-IR sensor operation, with a 10-m aperture. The specific data design equipment performance goal for the High Altitude Large Optical (HALO) program was consistent with other government funding, and this chart shows some of the results of that work. Composite, segmented large mirrors have been developed for several purposes under ARPA.
Composite Primary Mirrors

NGST
Technology Improvements
Composite Mirrors
WE at completion met speciﬁcation, suitable for NGST needs.
These 17-mm thick segments not high weight due to system application.
LOS Demonstration: Surface fabrication of center and outer 4-m segments of 16+ m deployable mirror.

Legacy to NGST - Demonstration of Initial Mirror Phasing, Independent Control, System Operation using external reference source, long-term phasing stability, and update capability.

Substrate: Designed for very high resonant frequency, and to serve as support for other system elements.

Changes not necessarily applicable to NGST.

Mass/Area Reduction - modest at best.

Face-sheet: 0.014 μm, high-frequency pattern equilibrium triangles with 200 nm sides.

NOTE: Overall system not designed to minimize weight, therefore many features unsuitable for NGST.

Edge pattern same as remainder of Face-sheet. Stiffness equivalent to 17 mm thick solid metals.
Wall and face-sheet thickness increased to 4 mm, but variation reduced to ±2.5 mm.

FOR ALOT and other programs - (late 1980s-1994)

Technology Enhancements
Historical Composite Mirror

NGST
In the HALO program, the successful final telescope performance demonstration was done at 100K. The actuators which in turn support and control the operational shape of the facet sheet face sheets. The substrate was designed to be stiff and lightweight and to accommodate chemical milling techniques used to achieve thin, precisely dimensioned walls and mirrors. The facet sheets were of a "pocketed" construction, with both hard machining and semi-monocoque graphite-epoxy substrate needed in passing, but their physical design has not changed much from HALO to the most recent designs for composite mirrors. The easy-to-use, yet focal point of the sketch, the lightweight glass facet sheet shown, is schematically shown, based on the HALO-derived composite mirror configuration.
was molybdeum disulfide grease
for 77K-gallium HAlO actuators
Low temperature lubricant used

• Including redundancy ~ 0.45 kg

• Weight of ALOT dual range unit

• Weight of HAlO device ~ 0.24 kg

• Large stroke with high precision
attachment point to provide
ALOT used PMN stack at glass

• Actuator attachment for ALOT

• Note indicates placement of
for HAlO configuration
Actuator and placement shown

Actuator Schematic Configuration
Composite Mirror

NGST

Solutions
Based on the HALO, ALOT, LOS and other programs, the composite mirror design configuration is extrapolated here for application to NGST. This chart shows both glass and SiC face-sheets applied to the design, with their different stiffneses leading to a difference in spatial distribution of the actuator supports. While the weight predictions are not definitive, requiring further validation from structural model analyses, they should be representative of a low-risk design.
Future Composite Mirrors
Improved Composite Mirrors
<table>
<thead>
<tr>
<th>Material</th>
<th>Substrate:</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR-epoxy</td>
<td>0.1 m deep</td>
</tr>
<tr>
<td>GR-Cyanate</td>
<td>no change</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass/Area (kg/sq m)</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current COI contact</td>
<td>0</td>
</tr>
<tr>
<td>Current COI contact</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Actuators:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replace by springs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass/Area (kg/sq m)</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>(30 Hz Vert., &gt;100 Hz lateral)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Facile sheet:</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Existing)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component/Technology</th>
<th>HALO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overview: Apply only improvements producing significant weight reductions</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Further Potential Weight Reductions</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Improved Composite Mirrors</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>NGST-A</th>
<th>NGST-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>HALO</td>
<td>HALO</td>
</tr>
</tbody>
</table>
facility improvement each of the others would probably be acceptable as well.

prove at these mass-area ratios and sizes. Although with some development and/or
that could do the work, only Computer Controlled Optical Surfacing (CCOS) has been
operation, which requires closely matched focal lengths. Of the available processes
shop procedure, especially for segments that must be close-packed and phased in
Suttering of odd-shaped mirror segments of 3-10 m aperture is not an ordinary optical

Primary Mirror Segment Surfacing

NEST
facilities available to 4 x 6 meters capacity

- CCOs has demonstrated all requirements, though not all at once;

Replication

CCOs - special lap control

Ion Figuring

Conventionally loose abrasive operation, post cutting

Potentially available surfacing techniques

Mirror surface material: Fused Silica, SiC, Be (HIB) or other metal

cryo temperature operation

- finished to very edge of lightweight face-sheet surface

8 - 12 A surface roughness or better, no residual print-through

precisely matched to 1.25 figure (local length) on segments

0.03 μm RMS or better surface error

Aspheric surface, several hundred μ from nearest sphere

Results Required:

Primary Mirror Segment Surfacing

NEST
Contingent risk: assessed that the large, segmented lightweight mirror represents a problem of relevancy during which this specific requirement was addressed. Based on this history, it is unclear whether the mirror assembly and references one or more prior programs (performed at JPL) and this chart shows a tabulation of the attributes or features required for the NGST segments.

Composite Mirrors - Glass Facet Sheet
Primary Mirror Technology Base
NGST
Corocycle of mirror assembly
Surface Roughness (10 - 15\textmu m)
Larger SIC fabrication (1.1 x 0.9 m)
Edge phasing (absolute)
Matched figure (radius)
Ultra L/W facet sheet
Full surface figured (25mm to edge)
T/1.5 or faster
Surface quality
4-m size (Facet sheet, substrate)
Segment Fab (Non-circular shape)
Attribute/feature
Composite Mirrors - Glass Facet sheet
Primary Mirror Technology Base
NGST
Wavefront Control System

Partition of Functions
maintaining proper alignment of the optical surfaces. Alignment-induced WFE should normally be controlled by actively part of the primary mirror structure. By use of a pupil mirror, should the actuator weight not be required as in the HALO, LAMP, and ALOT demonstration, where weight is a critical issue, lighter system weight may be achieved using both approaches. In the HALO, LAMP, and ALOT demonstration, environmental correction has been experimentally demonstrated at either the mirror surface or at a pupil mirror, whichever is more convenient. Such correction is no longer permissible when environmental effects or residual fabrication errors may be corrected by environmental correction. Wavefront errors caused by pupil wavefront error control. Wavefront errors caused by pupil wavefront error control.

Development of demonstration programs as HALO, LAMP, and ALOT has already been demonstrated for segmented mirrors in such development, beyond that already required. On the other hand, panel development would require an additional element of technology. To achieve this control at the primary mirror, panels themselves. To achieve this control at the primary mirror, (e.g., several waves height difference in one spatial frequency cell), panel phasing control should take place in one spatial frequency cell. Due to the large potential local slope imposed in a deformable pupil mirror, if this function were done at an image of panel phasing.

Partition of Functions

NCSST
Line of Sight Control

Line of Sight Control
allocation of control functions, rather than new technology development. A challenging engineering task, whose solution depends on proper design and implementation of LOS control, is for NGST.

**General note:** Design and implementation of LOS control for NGST.

- Distributed system control architecture
- Fast steering mirrors
- Secondary mirror fine pointing control
- Active damping of structural elements
- Passive and active isolation of disturbance sources

**Technology Available**

- Use of active LOS control measures
- (particularly secondary mirror support)
- Improving effective stiffness and damping of structure
- Isolation of disturbance sources

**Issues in LOS Stabilization**

- CMS, Coolers, Sunshield/Solar Panel Clocking, etc.
- On-board equipment and component response dynamics
- slew dynamics

**Sources of LOS Disturbance**

**Line of Sight Control**
in turn directly uses tolerances, weights, and cost.

allowable WFE (for a given F-number, pixel size, and S/N or energetic energy/FE). This allowable WFE

effect of diffraction takes over and the energy in a pixel fails off due to the increased spot size. This type

impact of WFE becomes less important as we are measuring our error with a larger „outer“ until the

selected and an F-number chosen, based on factors including packaging and tolerance sensitivity. Some of

This figure shows some of the parameters involved. In this case we assume our pixel size has been

operation (1), accounting for the influence of tolerances as part of the process.

WFE can do this by varying both F-number (F = focal length for a given aperture size) and wavelength of

effectively use the energy it collects, we wish to confine our Any disk diameter to fall within a pixel.

Let's assume that we wish to distinguish a 1 m „small“ object. We first estimate the aperture

understand how the science objectives of the mission can drive both weight and cost. One specific

We have begun work on parametric modeling of various performance measures. This helps us

NGST OPTICAL SYSTEM ENGINEERING TRADES

NGST
Balancing against cost (by item) -
- Establish explicable tolerances and degrees of freedom (adjustments)
- On launch date
- Pixel sizes will evolve over time so run for expected state of the art/base.

Eventually Diffraction Governs

\[ \frac{\lambda}{\Delta} \geq \text{WFE Effects} \]

Jitter
- Residual Defocus
- Residual / Higher Order Wavefront Error

Determine how performance varies as a function of wavelength for

Performance parameters are in WORK
while simultaneously lowering both weight and cost to ~25% of their initial values. The placement and type of adaptive controls in some of our prior work we were able to hold performance and approach to complete technical achievement and establish cost and weight optimal for both design form and schedule and team size. We have used this WFE and natural frequency (F N) driven parametric scheduling and/or team size. We have used this WFE and natural frequency (F N) driven parametric scheduling and/or team size. We have used this WFE and natural frequency (F N) driven parametric scheduling and/or team size. We have used this WFE and natural frequency (F N) driven parametric scheduling and/or team size.

hidden factors and proactively design-to-cost rather than accept self-fulfilling prophecies based on maintenance performance but reduce weight and/or cost. This type of analysis helps us understand/estimate specific tolerance of interest means to cost and weight, we can then revise or reparation the error to

We have found that by taking detailed error budgets and translating each error term into what the

**Cost & Weight Modeling Are Key Parallel Efforts**
- Revise / Reapportion - Hold Performance But Design to Cost
- Understand / Ease “Hidden” Costs
- Work Break-Point Parameters-Avoid Self Fulfilling Prophecies
  - Natural Frequency ($F_N$)
  - Residual RMS Wavefront Error (RMS WFE)
- Specific Attention to Design Form and Adaptive Aspects
- Provide Cost & Weight Data = Compare Technical Alternatives
- Objectives:

Cost & Weight Modeling Are Key Parallel Efforts
and weight vary over material type and as a function of both WPE and natural frequency. Hardware end-items of interest. Tables, such as the one shown, would be constructed to show how cost evolves, bottom-up estimates for cost and weight can be made for the specific components and sub-systems such as actuators, sensors, and residual structural frequencies. Finally, as the design iteration between lower level error budget terms such as structural/interconnect/motor/encoder deflection (as related to lower level error budget terms) expand to allow generic costs and weights to be refined. Eventually, the cost and weight evolve, specific structure and support structure materials are chosen, and our data method, and our active control arrangement. These early models also often rely heavily on historical models. Even so, the system is set to top-down criteria such as diameter, F number, wavefront error, phase error. When we evaluate the error budgets and their relationships to cost and weight, we work on both a
**Cost & Weight Modeling Are Key Parallel Efforts**

<table>
<thead>
<tr>
<th>Approach</th>
<th>Top Down</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Both &quot;Top-Down&quot; &amp; &quot;Bottom-Up&quot; Methods are used</td>
</tr>
</tbody>
</table>

**From first principles**

- Functionally, by Hardware End-item

**Bottom-Up:**

- Facesheet TH. vs # of Actuators
- Thermo-Optical (T/O) Errors Allowed
- Interellular Deflection (Ion Pol/"O" P/ thick surface)
- Mat-BE, Ni, SiC, Glass, G/E, Metal Matrix Composite

**Deployed Form:** Active/Passive control

Over configuration variables

Based on historical data

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Several weight and technology terms

were among the largest radio telescopes. Allowable WPE is the most important factor in this heavily
surveyed in developing these ORA-proprietary relationships from large optical telescopes through 1X to

1.9X 1X to 1.9X, F. Further, cost to the way the deployed primary is

WPE(b) and (1/FN)= where C = X(WPE b)

have also been found to be in various technology factors that relate to material type, design (wider)

in which lies to manufacturing risk. Cost (WPE), hours to make a specific optic (c.

Highness) post-acquisition action for expected thermal loadings and as constrained by allowable WPE's,

and cost increases proportionally to overall weight, and that weight in turn lies to (the-diameter)², face-sheet

However, if we fit a many-armed equation with a simple overall relationship, we find that

decomposition of these relationships are much more complex (c. The higher can mean increased cost for various

factors into these components. One component lies to system weight. At lower levels of system

Some of the factors which relate to cost and weight are shown here. We have broken the various

TOP DOWN COSTS TO WEIGHT (AFN) WPE, & SEGMENTATION

NGST
WFE DRIVES WEIGHT AND TECHNOLOGY BASED COST TERMS

- Diameter: m
  - 10m - 100m
  - 1.2

- motel:
  - 1% per Km

- Weight:
  - Scale Factors
  - Configuration Variables

- COST = WEIGHT x TECHNOLOGY x SEGMENTATION

- SEGMENTATION
  - Scale Factors

- TECHNOLOGY
  - Scale Factors

- WEIGHT
  - Scale Factors

- TOP DOWN COSTS FILE TO WEIGHT & SEGMENTATION

- WEIGHT

NIST
benefit from downstream actuation.

position and section/counter section geometry to produce a robust design of lowest possible cost (this is likely to

along each curve, but costs and weight vary. Our first job will be to choose the appropriate actuator

need lower actuator per segment for thinner effective mirror facesheets. Here RMS WFE is constant all

In the lower right we have plotted some generic curves for an annular primary mirror where we

vendor costs and overheaded and on deployment and packaging issues.

smaller downstream mirror lower cost still higher and allows us to set the sizes more directly based on

variation isolation, but at higher net cost than 3-layer construction. Of course, due to construction on a

which shifts optimum size to smaller diameters. 5-layer construction can achieve higher levels of

with a set of dual-range actuators. This makes structure costs even more important in 5-layer construction,

for phase corrections) while in 3-layer construction a single reaction/support structure is employed (alone

In 5-layer construction there is both a reaction structure for actuators and a lower support structure

segment size increases. This trend gives rise to an optimum segment size.

stiffness by increasing support depth by a cubit, couple the cost of the reaction structure to rise as

reaction structure diameters rise, we lose support stiffness by (segment diameter). If we buy back this

recession segment size climbs, overall mirror recession polishing costs drop. However, as recession

In the lower left figure we see how our models can be used to help set an optimum size. As

material, beryllium.

siliconized, reaction bonded, CVD or replicated loan versions of SC, ceramic matrix composite

ULF fused silica is shown; other data exist for alternative materials, such as

fabrication factors and thresholds in establishering costs, some of these are shown in the upper right figure. Here

left of the chart, those will be discussed further in subsequent charts. We also evaluate a wide range of

Our models allow evaluation of various materials. A set of merit functions is shown in the upper

COMPARISONS

FORM'S MODELS TREAT KEY FACTORS ALLOW COMPARISONS
This helps set best segment diameter to hold stiffness (D/TH) relation constant; as facet sheet diameter increases, its cost drops, but reaction structure must deepen. This too consistent WFE, but costs vary. Curves of consistent WFE, all loadings checked.

Facet sheet vs. No. of actuators

Material Fatigue Factors

O.R.A.'s Models Treat Key Factors / Allow Comparisons

Material Fatigue Factors
order scoring of RMS WFE

- dividing material properties and to construct material merit functions which directly lead to a simple first-order segment bow between supports (note that $h = h + H$). These kinds of equations help us see what are the details and how between supports (not even simply supported) facessheet and give overall minor

- The equations shown are for a free or even simply-supported facessheet and give overall minor deformations.

- Details are also critical in assessing net deformations. World factors such as substrate thermal expansion coefficient differentials (inhomogeneity) and mounting different factors are more important during transient operation than at steady-state. Additionally, real-world factors also depend on various material properties (more on this later in upcoming charts) where somewhat members thereby equilibrating locally varying axial temperature gradients. Of course these gradients exchange through the core pockets are more nearly equivalent to conduction through facessheet web.

- It is possible to tune the lightweight mirror's core emissivities and absorptivities such that radiative exchanges through the core pockets are more nearly equivalent to conduction through facessheet web.

- This chart shows the effects of an input heat load (e.g., solar) on a lightweighted mirror facessheet.

THERM-OPTICAL (T/O) DISTORTIONS CAN BE A WEAK DRIVER
### Thermo-Optical (T/O) Distortions Can Be A WTF Driver

**NGST**
### Additional Factors Include Scatter, Schedule, Cost

<table>
<thead>
<tr>
<th>p (psi)</th>
<th>105/90 (0.18)</th>
<th>(OR 0) Microyield Stress, MPa</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's Modulus (E)</td>
<td>( \frac{p}{(1-\nu^2)} )</td>
<td>(OR) DEFLECTION (SELF-WEIGHT)</td>
<td>6</td>
</tr>
<tr>
<td>Axial Inhomogeneity</td>
<td>0.006 = Axial Strains</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Sag Change</td>
<td>( \frac{\sqrt{2 \times 10^{-13} \times (1-\nu) \times 4 \times 10^8 \times D \times 10^4}}{1-\nu} )</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

**Equations**

**Characteristics**

**Thermo-optical Merit Functions Concluded**

- NGST
On the right we can see the influence of SiC's higher thermal conductivity. Axial temperature gradients are reduced by ~100x.

SIC

Here we have taken some of the material properties noted in the preceding charts and listed the relevant data. Many materials are in evaluation, but only two are shown here for simplicity: LFE and NGST.

High conductivity materials have lower gradient but also have higher expansion & inhomogeneity.
Other materials also available

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Heat (J/kg-K)</td>
<td>1.420</td>
</tr>
<tr>
<td>Thermal Conductivity (W/cm-K)</td>
<td>0.013</td>
</tr>
<tr>
<td>Thermal Expansion (ppm/°C)</td>
<td>3.5</td>
</tr>
<tr>
<td>Young's Modulus (10^6 psi)</td>
<td>96</td>
</tr>
<tr>
<td>Density (lb/in^3)</td>
<td>0.080</td>
</tr>
</tbody>
</table>

But also have higher expansion & inhomogeneity
High conductivity materials have lower gradients,
N.G.T.
Inhomogeneity can be especially important (depending on thermal loadings) as residual surface errors at contact interfaces can contribute heavily to requirements for actuator number and spacing.

Errors in thermal properties can drive steady-state conditions, though there are cross-product influences that can mitigate to a degree by the presence of active control, this is another area where the higher cost and resultant specifications for acceptable thermal control. Since the influence of thermal errors is residually can influence the error budget, material choice, design of the actuator system (range, speed, etc.), responses more slowly to the transient and has lower initial WFE. This comparison shows how solar homogenous, shows lower errors, and merit function No. 3 (varying thermal environment, where LFE is not useful as a metric, shows the difference between merit function No. 1 (steady state) and CIC, it

**SIC vs. LFE as a Generic but Specific Comparison**

**NGST**
ORAM

drive configurations to those offering the lowest possible weight and cost.

They also have high significance for final, on-site system performance. As such, they are design

impedance gradients. Since these terms are defined inside the capability of the control loops,

an intercellular or inter-support/actuator detection, which can be caused by polishing residuals or axial

are discussed to higher spatial frequencies, i.e., those outside the capability of the correction loops. These are referenced

On the right side of the chart we show a blow-down for a passive system isolating terms which the

large - so long as the active control system can "clean-up" the waveform.

We have used some of ORA's existing proprietary cost models to show generally how cost varies

IMPACT OF ACTIVE CONTROL DEPENDENCE IS ASSESSABLE

NCTI
IMPACT OF ACTIVE CONTROL DEPENDENCE IS ASSIMILABLE
These types of analysis should be continued to both refine the models at lower quality levels, refine at higher quality levels (18% variation).

On the right, we have shown the "left-sided", lower (cross-hatched) set of curves (those for ~20-

applicable.

These numbers are generic and depend upon many factors, but are illustrative and WPF quality levels). WPF is lower weights (the WPF varies from ~2x for already casised WPF conditions to ~5x at higher 20Hz) and loose tolerances to 13x/4). We can also see how raising natural frequency requirements (~50Hz to up to 13x (the horizontal axis, x-axis) was our "base" and five first heightened tolerances from x to 13x/4, then

On the left we see how real density can be lowered by ~3.5x by raising net WPF requirements by

PARAMETERS RUN ON BOTH WPF & NATURAL FREQUENCY

NEST
PARAMETRICS RUN ON BOTH WFE & NATURAL FREQUENCY
So, what's the Rom Conclusions(s) today?
SOFTVISIONS

ORA

Face sheet thickness / Actuator spacing
Coating characteristics / Thermal control scheme
Thermo-optical error (Substrate expanse homogeneity/Actuator spacing)
Face sheet thickness / Actuator spacing
Polishing load (>0.2 psi: Ion Polishish, "0" Pressure Polish)
Intercellular delamination / Need for trade off speed for cost ( Preis's Law)
Material gauge / Percent lightweighting (Thin solid face, TBR)
(Diam.) 2.77

Design form, segmentation, WFE, Net reg, (React struct limits BW)

Weight drivers:

- Position actuators - 3.11%
- Gap Electronics - 4.77%
- Act Electronics - 6.16%
- React Supp Struc - 24.39%
- Figure Actuators - 18.37%
- Faciliate - 43.5%

Example shown with 4 meter panels & 3.0 waves PK Surt

Primary minor percent (very configuration dependent):

- Primary ≈ 64% of weight (TBR) and ≈ 79% of cost

Based on Prior Programs

SO WHAT'S THE ROM CONCLUSION(S) TODAY?
Technology costs should be set as the program evolves.

Our preference is to employ and extend reliability low risk technologies, derived from the extensive work done on prior programs which we are familiar. These would include such items as lightweight glass and silicon for the mirror facesheet, graphite-epoxy or carbon material for the composite mirror substrate and Silicon carbide (SiC) for the mirror backplane. Graphite-epoxy or carbon material for the composite mirror substrate and Silicon for the mirror backplane. Graphite-epoxy or carbon material for the composite mirror substrate and Silicon carbide (SiC) for the mirror backplane.

The model 7 is included to support the overall system development by providing a framework for cost control and risk management. It may be used to assess performance of alternative technologies and to compare design optimization. Models may be used to assess performance of alternative technologies and to compare design optimization. Models may be used to assess performance of alternative technologies and to compare design optimization. Models may be used to assess performance of alternative technologies and to compare design optimization. Models may be used to assess performance of alternative technologies and to compare design optimization.

This chart summarizes our recommendations for technology activities that should be pursued in the next 3 years.
<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>1997-2000</td>
<td>1. Mirror Faceheet Material&lt;br&gt;2. Low Temperature Actuators&lt;br&gt;3. Composite Mirror Assembly&lt;br&gt;4. Deformable Pupil Mirror&lt;br&gt;5. System Control Architecture&lt;br&gt;6. Deployment Mechanisms&lt;br&gt;7. System Performance and Cost&lt;br&gt;Modeling Control and Control System Cost&lt;br&gt;Survive Launch, Deploy Within Control Capture Range&lt;br&gt;Error under all disturbances&lt;br&gt;Control Phasing, Pointing, Wawerfront&lt;br&gt;Operate at useful bandwidth to 0.01%&lt;br&gt;Achieve &amp; Hold Phasing, Figure&lt;br&gt;Low Weight&lt;br&gt;Operate for 10 yrs at low power,&lt;br&gt;Good Figure at f/1.25, low mass&lt;br&gt;GFY Time Frame Requirement</td>
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</table>
This report provides considerations and suggested approaches for design of the Optical Telescope Assembly and the segmented primary mirror of a Next Generation Space Telescope (NGST). Based on prior studies and hardware development, we provide data and design information on low-risk materials and hardware configurations most likely to meet low weight, low temperature and long-life requirements of the nominal 8-meter aperture NGST. We also provide preliminary data for cost and performance trades, and recommendations for technology development and demonstration required to support the system design effort.
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