Giant Segmented Mirror Telescope

L. Stepp
Optical Society of Southern California
12 March 2003
Overview

• Introduction:

• Frequently Asked Questions:
  – Why do astronomers need GSMT?
  – What would GSMT look like?
  – Where would you put a 30-m telescope?
  – What are the key challenges for GSMT?
  – How much would a GSMT cost?
  – How long will it take to build GSMT, and what is the current status?
Introduction:
The Current Generation of Large Telescopes
3.5-m Borosilicate Honeycomb Mirror
Cast at Steward Observatory Mirror Lab
WIYN Observatory
Kitt Peak, Arizona

Wisconsin
Indiana
Yale
National Optical Astronomy Observatory
Gemini Observatory
Mauna Kea, Hawai‘i
Gemini Observatory
Cerro Pachon, Chile
Gemini Primary Mirrors

8-m ULE Meniscus Mirror
Cast at Corning
Gemini Primary Mirrors

8-m ULE Meniscus Mirror
Polished at REOSC
Gemini Secondary Mirrors

1-m Zerodur Meniscus Mirror Blanks produced by Schott
Gemini Secondary Mirrors

1-m Zerodur Meniscus Mirror
Polished by Zeiss
In May, 2000, the National Research Council's Astronomy and Astrophysics Survey Committee recommended its highest priority projects for this decade. At the top of the list was the GSMT:

“The Giant Segmented Mirror Telescope (GSMT), the committee’s top ground-based recommendation….is a 30-m-class ground-based telescope that will be a powerful complement to NGST in tracing the evolution of galaxies and the formation of stars and planets.”

“The committee recommends that technology development for GSMT begin immediately and that construction start within the decade. Half the total cost should come from private and/or international partners.”
Astronomy and Astrophysics in the New Millennium

- JWST
- ALMA
- LSST
- GSMT
Why do astronomers need GSMT?
The Birth of Planetary Systems

- Find evidence of forming giant planets by locating tidal gaps
- Determine where, when & how frequently such planets form

Simulation by Geoff Bryden

Sample 1000 PMS stars out to 1kpc

R \sim 10^5 \text{ mid-IR spectroscopy}
Characterize Exo-Planets

- Directly detect exo-planets
- Determine surface gravity; atmospheric structure; composition

$R \sim 1000$ spectroscopy  
Imaging with Extreme AO
The Birth of Large-Scale Structure

- Determine 3-dimensional distribution of galaxies; gas for \( z > 3 \)
- Compare emerging LSS with CMB structure

Densely sample emerging structure

- \( R \approx 3000 \) spectra of \( 10^6 \) galaxies
- \( R \approx 20,000 \) spectra of \( 10^5 \) quasars
The Birth of Galaxies: Witnessing the Process Directly

- Quantify masses; star-formation; chemical composition in pregalactic fragments and young, merged galaxies
The Birth of Galaxies: The Archaeological Record

• Use stellar populations in mature galaxies to diagnose merger history

Diagnose populations with differing metallicities and ages using high precision photometry on MCAO images

30-m telescope with MCAO
Simulation by Knut Olsen
What would GSMT look like?

There have been many design concepts proposed for ELTs
NEXT GENERATION TELESCOPE CONCEPT

THE STEERABLE DISH
National New Technology Telescope

• 16-meter optical-infrared telescope
• MMT type with four 8-meter primary mirrors
The California Extremely Large Telescope
The Overwhelmingly Large Telescope

http://www.eso.org/projects/owl/index_2.html
Top Performance Requirements For GSMT

- Near-diffraction limited performance over ~ 2 arc-minute fields
- High-dynamic-range imaging
- High sensitivity mid-IR spectroscopy
- Enhanced-seeing over ~ 5 arc-minute field
- Wide-field, seeing-limited multi-object spectroscopy
Summary of Optical System

Optical design: Classical Cassegrain
Adaptive Secondary Mirror
Aperture stop at M2

M1 diameter: 30 meters +
M1 focal ratio: f/1
Hex segments: 1.33 m across corners

M2 diameter: 2 meters
M2 focal ratio: f/18.75
Radio Telescope Structural Design

- Lightweight steel truss structure
- M2 supported on tripod structure
- Elevation axis behind M1
  - Span between elevation bearings is less than M1 diameter
  - More direct load path through elevation bearings
  - Allows large Nasmyth platforms without extending beyond M1 width
  - Eliminates need for a large tertiary mirror above the primary
  - Accommodates several fixed-gravity-orientation instrument locations
Point Design Structure
Instrument Locations
MCAO Mode

- Science: Birth of Galaxies: Archaeological Record
- Field diameter: 1-2 arc-minutes
- Multi-Conjugate Adaptive Optics (MCAO)
- Instrument: Near-IR imager
MCAO Mode

- Sodium laser launch telescope
- Adaptive secondary mirror
  - Serves as first correction stage
MCAO Mode

- Sodium laser launch telescope
- Adaptive secondary mirror
  - Serves as first correction stage
- MCAO System
  - Occupies level below M1
  - Relays corrected image to Nasmyth
- Science instrument
  - Rotates about vertical axis to compensate field rotation
Spot diagrams at field center and at radius of one arc minute.

Circles indicate Airy disk diameter for $\lambda = 2.5$ microns.
MCAO System

• System parameters
  – 3 DMs at conjugate ranges of 0, 5, and 10 km
  – 5 sodium laser guide stars at center & corners of 1' square
  – 3 natural guide stars
  – Diameter of DMs 0.5 m
  – Final focal ratio: f/38
  – FOV: 2 arcmin
    • Linear diameter of 2 arcmin field 0.66 m
MCAO-fed Near-IR Imager

- Field of view: 2 arcmin
- Detector: 28,000 x 28,000
  - For critical sampling
- Image scale: 5.5 mm/arcsecond
  - Assumed pixel size: 22 microns
- Preliminary optical design below has FOV 1.44 arcminutes on a side
  - Pupil stop is 39 mm diameter.
  - Images diffraction-limited over field, for $1.2 < \lambda < 2.2$ microns
Enhanced-Seeing Medium Field

- Science: Birth of Galaxies: Direct Spatial Deconstruction
- Field diameter: 5 arc-minutes
- Image stabilized with adaptive secondary mirror
- Instrument: Million-element Integral Field Unit Spectrograph (MEIFU)
Optical Performance
Cassegrain Focus: Medium Field

Spot diagrams at field center and at radius of 2.64 arc minutes.

Circle diameter is 0.5 arcsec
Preliminary Optical Concept

- **Million Element Integral Field Unit**
- 5 x 5 arcmin field of view
- 0.092 x 0.184 arcsec sampling
- 420 - 910 nm full coverage (R~500) in 4 exposures
- R ~ 500 and 1500 (2 pixel)
- 24 spectrographs (8k x 8k detectors)
- ~1.6x10⁹ pixels in cameras

Milestone 1, 15.4.02
Wide-field, Seeing-Limited Spectroscopy

- Science: Birth of Large-Scale Structure
- Field of View: 20 arcmin
- Instrument: Fiber-fed multi-object spectrograph
- Seeing enhanced by image stabilization and low-order AO
Optical Performance
F/18.75 Focus: Wide Field

Spot diagrams at field center and at radius of six arc minutes.

Linear diameter of 12 arcmin field is 1.96 meters
Diameter of 20 arcmin field is 3.27 meters

Circle diameter is 0.5 arcsec.
Multi-Object Multi-Fiber Optical Spectrograph (MOMFOS)

Fiber positioner located at prime focus

Fiber cable ~ 700 fibers

Spectrographs
Multi-Object Multi-Fiber Optical Spectrograph (MOMFOS)
Prime Focus AO System

- Corrects M1 warping and ground-level turbulence
  - Achieves moderate improvement over 20-arcmin FOV

Multiple NGS wavefront sensors

Adaptive mirror conjugate to M1
  - ~1000 actuators

Tip-tilt mirror
Mid-IR Spectroscopy

- Science: Birth of planetary systems
- Diffraction-limited image quality
  - Adaptive secondary mirror
- Instrument at Cassegrain focus
  - Only two warm reflections
## Telescope Emissivity

<table>
<thead>
<tr>
<th>Source</th>
<th>Telescope emissivity (%)</th>
<th>Telescope emissivity (%)</th>
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<tbody>
<tr>
<td></td>
<td>Aluminum coatings</td>
<td>Silver coatings</td>
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<td>M1 coating</td>
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<td>1.3</td>
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<tr>
<td>M2 coating</td>
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<td>M2 obscuration</td>
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<td>Segment joints</td>
<td>0.9</td>
<td>0.9</td>
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<td>M2 support tripod</td>
<td>2.7</td>
<td>2.7</td>
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<td><strong>Total</strong></td>
<td><strong>8.0</strong></td>
<td><strong>6.6</strong></td>
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</table>
Cassegrain Instrument Location
• Three spectrograph modules:
  - 1.5 - 5 \( \mu m \) (near infra-red echelle spectrograph, NiRES)
  - 8 - 14 \( \mu m \)
  - 16 - 20 \( \mu m \) (mid-IR high-dispersion AO-fed spectrograph, MIHDAS)

NiRES
- Spectral resolution: 100,000
- 40 x 200 mm R5 echelle grating
- Instrument volume ~ 1 m\(^3\)
• Three spectrograph modules:
  – 1.5 - 5 \( \mu \text{m} \) (near infra-red echelle spectrograph, NIrES)
  – 8 - 14 \( \mu \text{m} \)
  – 16 - 20 \( \mu \text{m} \) (mid-IR high-dispersion AO-fed spectrograph, MIHDAS)

MIHDAS
  ▪ Spectral resolution: 100,000
  ▪ 150 x 1500 mm R10 echelle grating
  ▪ Instrument volume ~ 16 m\(^3\)
High Dynamic Range Imaging

- Science: **Characterize Exo-Planets**
- Instrument: High-order AO coronagraph
- Cassegrain focus
- Field of View: \( \sim 2 \) arcsec
- Wavelength range: 1-5 \( \mu \text{m} \)
HDR Imaging

- System uses natural guide star
- Adaptive secondary mirror
  - Serves as first correction stage
- Science instrument
  - Fixed relative to telescope
  - Field rotation compensated by rotating detector
High-Order AO Coronagraph
## Summary of GSMT Instrument Concepts

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Wavelength</th>
<th>Image Resolution</th>
<th>Spectral Resolution</th>
<th>FOV</th>
<th>Multiplex</th>
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<tr>
<td>MOMFOS</td>
<td>0.4 - 1 µm</td>
<td>1”</td>
<td>2000 - 20,000</td>
<td>20 arcmin</td>
<td>700</td>
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<tr>
<td>NIRDIF</td>
<td>1 - 2.5 µm</td>
<td>0.1” x 1”</td>
<td>5000 - 10,000</td>
<td>2 arcmin</td>
<td>26</td>
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<tr>
<td>MIHDAS</td>
<td>16 - 20 µm</td>
<td>0.2” (DL)</td>
<td>100,000</td>
<td>1 arcsec</td>
<td>1</td>
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<tr>
<td>NIrES</td>
<td>1 - 5 µm</td>
<td>0.03” (DL)</td>
<td>100,000</td>
<td>0.1 arcsec</td>
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<tr>
<td>MCAO Imager</td>
<td>1 - 2.5 µm</td>
<td>0.03” (DL)</td>
<td>Imager</td>
<td>1.5 - 2 arcmin</td>
<td>1</td>
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<tr>
<td>MEIFU</td>
<td>0.4 - 1 µm</td>
<td>0.1” x 0.18”</td>
<td>500 - 1500</td>
<td>5 arcmin</td>
<td>5,000,000</td>
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<tr>
<td>Coronagraph</td>
<td>1 - 5 µm</td>
<td>0.03” (DL)</td>
<td>Imager</td>
<td>2 arcsec</td>
<td>1</td>
</tr>
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</table>
Some Possible GSMT Enclosure Designs
Mayall, Gemini and GSMT Enclosures

at same scale
McKale Center – Univ of Arizona
GSMT – at same scale
Where would you put a 30-m telescope?
GSMT will be a big investment -- it is imperative it be placed on an outstanding site

- Scientific productivity is proportional to number of clear nights
- Frontier science depends on the best conditions available
- Site choice will significantly effect operational issues and cost
- Site characteristics drive the facility design
  - Wind loading => telescope and dome design
  - Atmospheric properties => adaptive optics (AO) system
Site Selection is a Compromise

Site characteristics affect an observatory in complex ways; any site choice is a compromise among multiple factors:

- Meteorological conditions
- Seismic conditions
- Pollution sources
- Political factors
- Cost
Site Selection is a Staged Process

Because the number of candidate sites is large, and the science requirements are continuing to evolve, the site selection is a staged process:

1. General collection of information
2. Remote sensing studies
3. Selection of most promising candidates
4. CFD modeling of candidates
5. Preliminary testing at multiple sites
6. Intensive testing at 2-3 sites
Information is needed on:

- Cloud cover -- number of clear nights
- Seeing statistics
  - Effects of site topography
  - Turbulence properties as a function of altitude.
- Sky brightness and transparency in the mid-IR
  - Depends on the precipitable water vapor (PWV).
- Wind speed and direction
- Temperature variations
- Pollution
  - Light
  - Aerosols
Important Parameters

- Sky coverage
- Adaptive Optics Issues
  - Height and thickness of sodium layer
  - Wind speed aloft
  - Presence of cirrus
  - Characteristics of ground turbulence layer
- Geological conditions
  - Earthquakes
  - Nearby volcanoes
  - Soil stability
- Logistical factors
  - Accessibility
  - Altitude
  - Distance to:
    - Roads
    - Power lines
    - Medical facilities
- Political issues
  - Host country
  - Ownership issues
    - Mineral rights
    - Funding agencies
What Makes a Great Site?

Conventional wisdom indicates Great Sites fall into two categories:

1. Isolated high mountains on islands in temperate oceans
   - Mauna Kea
   - La Palma

2. Coastal mountains next to a cold ocean current with stable subtropical anticyclone conditions
   - California
   - Baja California
   - Chile
   - Namibia

Continental sites are generally considered to have inferior prospects; HOWEVER, sites like Maidanak in Uzbekistan and Mount Hopkins in Arizona are relatively competitive.
Cloudiness

Coarse Cloudiness Maps are readily available. A few km resolution is accessible.

Source: Surface Meteorology and Solar Energy Data Set (SSE) of NASA's Earth Science Enterprise Program (1x1 degree grid).
Aerosols

Summary of the global oceanic aerosol pattern detected by polar-orbiting satellites between July 1989 and June 1991

Saharan Plume
West African Plume
Arabian Sea Haze

Source: Tropospheric Aerosols Over the Oceans by Rudolf B. Husar and Larry L. Stowe

Marc Sarazin
European Southern Observatory

9/12/01
S.W. USA is going fast…

Baja California still looks pretty dark….

…. But Costa Rica is going too….

http://www.lightpollution.it/dmsp/
Centers of artificial light.
Uncalibrated DMSP-OLS satellite image covering the southern III region (Magellan) and the IVth region (Gemini South, La Silla, SOAR, Tololo).
GIS Input: Seismicity

Peak Ground Acceleration up to 5m/s²: 10% probability of exceedance in 50 years

Source: http://www.seismo.ethz.ch/GSHAP/

Marc Sarazin
European Southern Observatory
9/12/01
Volcan Lascar, normally....
Lascar in 1993...
Remote Sensing Survey of Cloud Cover and PWV

- Survey uses meteorological satellite images
- Long time baseline
- Well-defined methodology provides:
  - Photometric, spectroscopic, unsuitable conditions based on cloud cover
  - Precipitable water vapor column above the sites
- Dispassionate comparison thus possible
- Areas studied:
  - Northern Chile
  - SW USA-Mexico
  - Mauna Kea – Chile comparison
- Finish August 2003
Comparison of Chilean Sites

Fraction

- Transitional
- Clear

Sites:
- Cascasco
- Chaco
- Chascon
- Grande
- Infieles
- Paranal
- Pena
- Quanquero
- Quimal
- Tolar
- Tololo
- Toloncha
- Tronquitos
- Yacas
Computational Fluid Dynamics

- Characterize wind flow to allow pre-selection of sites
  - Wind intensity
  - Turbulence characteristics
  - Down-wind wakes

Las Campanas, Chile
Las Campanas Peak 2
Turbulent Kinetic Energy

500 m
Mines are a problem in Chile – there are two types
Weather Station on Honar
Measuring Turbulence Layers with MASS
Combining MASS + DIMM Results

Free atmosphere seeing steady at ~ 0.25" for 4 nights
What are the key challenges for GSMT?
Challenging Areas For a GSMT

- Secondary mirror
- Primary mirror segments
- Adaptive optics systems
- Science instruments
- Hierarchical control systems

Wind buffeting
Adaptive Secondary Mirror
Technical Challenges

• Fabrication:
  – 2-meter deformable facesheet ~ 3 mm thick
  – Figure must be good to the outer edge
    • Bevel size <1 mm
  – Surface figure accuracy ~ 20 nm RMS with active correction

• Testing:
  – Difficult to test large convex aspheres
  – Figure measurement accuracy ~ 5 nm RMS
  – Facesheet extremely flexible
    • In-process testing should match acceptance test
  – Metrology mount with ~ 2400 actuators

• Adaptive control:
  – Fast focus, tip-tilt
  – Higher order terms
Feasibility Demonstrations: Approaching a 2-m Adaptive Secondary

MMT F/5 Secondary Mirror
1.7-m Diameter

MMT Adaptive Secondary Mirror
0.33-m Diameter

Steward Observatory Mirror Laboratory
Images courtesy Buddy Martin
Adaptive optics systems
Technical Challenges

• Component development
  – Large (> 0.5 m) DMs
  – Large (> 0.5 m) fast tip-tilt mirrors
  – High-power sodium lasers for guide stars
  – Large-format low-noise high-speed detectors
  – Extremely high-order DMs (MEMS technology)

• System development
  – Efficient wavefront reconstruction algorithms
  – Faster processors
  – High speed electronics for real-time control
Science Instruments
Technical Challenges

• Development of larger:
  – Volume phase holographic gratings
  – Windows, filters
  – Cryogenic instruments
  – Image slicers for IFUs
  – Detector arrays
  – Etc.
Primary Mirror Segments
Technical Challenges

• Fabrication challenges
  – Aspheric departures > 200 microns P-V
  – Mechanical dimensions accurate to ~ 0.1 mm
  – Bevel size <1 mm
  – Surface figure accuracy ~ 20 nm RMS
  – Need high-reflectivity, high-durability coatings
  – Production rate of ~ 200 segments / year
  – Large number of different:
    • segment shapes
    • orientations
    • asphericities
Primary Mirror Segments
Technical Challenges

• Testing challenges
  – With respect to the optical test equipment:
    • Segment position must be known to ~ 0.3 mm
    • Segment clocking must be known to ~ 0.1 mrad
  – Figure measurement accuracy ~ 5 nm RMS
  – Radius of curvature repeatability ~ 0.5 mm in 60 m
  – Production rate of ~ 200 segments / year
  – Large number of different:
    • segment shapes
    • orientations
    • asphericities
Primary Mirror Segments
System Challenges

• High speed position control to ~ 10 nm
• Need efficient method for co-alignment / cophasing
• Combine edge-sensor feedback with WFS
Hierarchical Control Systems

• When observing from the surface of a planet, one must deal with disturbances:
  – Gravity
  – Temperature gradients
  – Atmospheric turbulence
  – Wind buffeting

• These enemies of image quality gain strength as the telescope aperture grows:
  – For a given Strehl ratio, the required RMS wavefront is the same as for smaller telescope
  – Demands on corrective systems grow
    • Larger disturbances
    • Higher resolution diffraction limit

• Success of an ELT will depend on active & adaptive systems
Multiple Controls Systems
Systems Overlap in Parameter Space

- Zernike modes
- Bandwidth [Hz]

- LGS MCAO
  - spatial & temporal avg
- AO (M2)
  - spatial avg
- Secondary rigid body
  - spatial avg
- Main Axes
  - spatial & temporal avg
  - temporal avg
  - spatial avg

- aO (M1)
  - spatial avg
  - temporal avg

- Main Axes
- Secondary rigid body
- AO (M2)
- LGS MCAO
The most significant challenge in building an extremely large telescope is to control the cost.
How much would a GSMT cost?
Scaling Laws

$10.6\ M -- 1973$
$33.7\ M -- 1992$
$10m \sim \$400\ M$

$110\ M -- 1992$
$141\ M -- 2002$

$2.5\ B -- 2002$

350\ tonnes \ 270\ tonnes$
# Initial Cost Estimate for GSMT
Excluding Instruments

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost ($K 2002)</th>
<th>%</th>
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<tbody>
<tr>
<td>Primary Mirror</td>
<td>$95,126</td>
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<tr>
<td>Secondary Mirror</td>
<td>$15,360</td>
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<td>Other Optics</td>
<td>$5,299</td>
<td>1.0 %</td>
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<td>Telescope Structure</td>
<td>$34,654</td>
<td>6.2 %</td>
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<tr>
<td>Site Development</td>
<td>$5,000</td>
<td>0.9 %</td>
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<tr>
<td>Enclosure</td>
<td>$50,000</td>
<td>9.0 %</td>
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<tr>
<td>Support Facility</td>
<td>$3,419</td>
<td>0.6 %</td>
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<tr>
<td>Base Facility</td>
<td>$4,000</td>
<td>0.7 %</td>
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<tr>
<td>Co-alignment, co-phasing System</td>
<td>$10,000</td>
<td>1.8 %</td>
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<tr>
<td>Adaptive Optics</td>
<td>$64,858</td>
<td>11.7 %</td>
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<td>Control Systems</td>
<td>$15,000</td>
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<tr>
<td>Program office &amp; engineering</td>
<td>$124,436</td>
<td>15.2 %</td>
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<tr>
<td>Subtotal</td>
<td>$427,152</td>
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<tr>
<td>Contingency on above @ 30%</td>
<td>$128,146</td>
<td>23.1 %</td>
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<td>Telescope capital cost</td>
<td>$555,298</td>
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## Initial Cost Estimate for GSMT Instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Cost ($K 2002)</th>
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<td>MOMFOS</td>
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<td>NIRDIF</td>
<td>$33,402</td>
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<td>NiRcES</td>
<td>$6,942</td>
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<td>MIHDAS</td>
<td>$15,123</td>
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<tr>
<td>MCAO Near-IR Imager</td>
<td>$40,000</td>
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<tr>
<td>MEIFU</td>
<td>$27,960</td>
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<tr>
<td>AO Coronagraph</td>
<td>$16,558</td>
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</table>
Typical yearly expenditures of large observatories:

- Operations: 3% - 6% of construction cost
- Upgrades: 3% - 5% of construction cost
  - New instruments
  - Adaptive optics
  - Etc.

Over ~ 30-year lifetime, = 2 to 3 times construction cost
How long will it take to build GSMT, and what is the current status?
## Proposed GSMT Schedule

### D & D Phase

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<td>Design studies and contracts</td>
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<td>Conceptual Design Review</td>
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<td>7</td>
<td>Segment Fabrication Contract</td>
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<td>Submit Construction Proposal</td>
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<td>First Light -- All Segments</td>
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AURA currently negotiating with Caltech and University of California to join forces to launch the Design and Development Phase of GSMT/CELT

- UC & CIT preparing proposal to private foundation for private half of DDP funding
- NIO preparing proposal to NSF for public half of DDP funding
  - Key aspect: technology development program to benefit ELT projects as well as current telescopes
  - Prospects good for funding approval this year

Collaborative site testing program already initiated
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- Steve Strom
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- Andrei Tokovinin
- Konstantinos Vogiatzis
- Patrick Wallace

Plus many NOAO, Gemini and community scientists working on the GSMT science case

NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation.

Gemini is an international partnership managed by the Association of Universities for Research in Astronomy under a cooperative agreement with the National Science Foundation. Partner countries include the United States, United Kingdom, Canada, Chile, Australia, Argentina, and Brazil.
Information on the NIO design studies is available at:

www.aura-nio.noao.edu

The GSMT Book was recently distributed in CD form in the NOAO and Gemini newsletters.