Space astronomy without barriers –
synthesis of several papers written by many

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Space astronomy without barriers

• Larger aperture space telescopes & instruments are constrained by
  • Limited volume & mass => many complex mechanisms & large # of reflections & small FOV - One launch => risky & expensive

• Tomorrow’s science will require
  • Aperture >20 to 30-m & High transmittance telescopes & instruments

• Cost awareness
  • No need to “throw-away” the investment in the telescope
  • Revisit observatory to upgrade instruments & telescope components

• Need break the cost-curve to give more science per $
  • The 6.5-m JWST costs ~ $9B

• Never happen and “astronomy at the threshold of discovery” is dead!
An Evolvable Space Telescope Requires a Culture Change

- Commit to a long term program to modulate the large cost/year fluctuations
  - Schedule is dictated by budget realities (can accelerate or decelerate)

- Grow the in-space performance over time
  - Design for aperture, resolution, science scope to evolve with time
  - Improve/advance instruments with on-orbit replacement

- Benefits:
  - Much earlier science return
  - On-orbit replacement of instruments and support hardware to adapt to evolving science and technology

Approved for public release; distribution unlimited. NGAS case 15-0157 dated 2/10/14.
In-space assembly of telescope and instruments

• Relieves constraints on mass, volume & structures to improve
  • Pointing & control stability
  • Optical performance - transmittance (increases threshold science)
  • Very high angular resolution

• Investigate architectures for in-space robotic assembly of telescope and instruments
  • Innovative optical designs
  • High transmittance, low polarization, exoplanet science compatible
  • FOV wide & narrow AND spectrometers

• New architecture concepts are needed
  • Telescopes & Instruments
To afford new large aperture space telescopes, we as a community need to discover a way to break the cost-aperture curve.
Evolvable space telescopes and Instruments use previous investments to evolve into new capabilities
Evolvable space telescope optics concept

Prime Focus Instrument Module
5-m long x 3.8-m Dia.

3.93-m flat-flat Hexagonal Mirror

Hexagonal Mirror

Future Secondary Mirror Location

20-m Parabolic Primary Mirror

Primary mirror structure stays in space

Segments replaced

New science Measurements => replace instrument module
• Pie-shaped Instrument Enclosure
  • 90-degree segment of cylindrical module with 1.9-m radius, 4.8-m
• Designed for on-orbit removal and replacement
• Kinematic mount
• Linear removal/replacement
Advantages to prime focus

- Prime focus architectures for large space telescopes: reduce surfaces to save cost – Breckinridge & Lillie SPIE - 9904-173

  - Reduce # of surfaces
    - Less surface scatter & absorption
    - Increases SNR in UV & visible
    - Decreases cost: fewer mechanical parts to design, build, align and hold to optical tolerances
    - Baffle architectures simpler – reduce mass
    - Lower cumulative polarization aberrations

  - Off axis prime focus
    - Improved image quality over wide FOV
Assume a 10 meter telescope can be built for $3B. What is the cost to recover the losses caused by reflections?

<table>
<thead>
<tr>
<th># of normal incidence reflections to detector</th>
<th>Tau for R=0.95</th>
<th>Increase the d = 10m diameter to maintain SNR in m</th>
<th>New $ cost assuming cost=d^2.0</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.95</td>
<td>10.3</td>
<td>3.2</td>
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<td>0.81</td>
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<td>8</td>
<td>0.66</td>
<td>12.3</td>
<td>4.5</td>
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<tr>
<td>12</td>
<td>0.54</td>
<td>13.6</td>
<td>5.6</td>
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<td>16</td>
<td>0.44</td>
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<tr>
<td>28</td>
<td>0.24</td>
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<td>12.6</td>
</tr>
</tbody>
</table>

Package today’s instruments => > 8 reflections

Eight reflections cost > $1B

Minimize reflections & Maximize reflectivity

Minimize internal polarization aberrations
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Goal</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>Telescope Aperture</td>
<td>&gt; 10 m</td>
<td>&gt; 16 m</td>
<td>~HDST concept</td>
</tr>
<tr>
<td>Stage 1</td>
<td>3 segment</td>
<td>~ 4 x 12 m</td>
<td>Three hexagonal segments</td>
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<tr>
<td>Stage 2</td>
<td>Filled Aperture</td>
<td>12 m</td>
<td>Twelve hexagonal segments</td>
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<tr>
<td>Stage 3</td>
<td>Filled Aperture</td>
<td>20 m</td>
<td>Eighteen hexagonal segments</td>
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<tr>
<td>Wavelength</td>
<td>100-2400 nm</td>
<td>90-8000 nm</td>
<td>UVOIR, MIR under evaluation</td>
</tr>
<tr>
<td>Field of View</td>
<td>5 to 8 arcmin</td>
<td>30 arcmin</td>
<td>Wide field VNIR imaging</td>
</tr>
<tr>
<td>Diffraction Limit</td>
<td>500 nm</td>
<td>250 nm</td>
<td>Enhanced UV/Optical</td>
</tr>
<tr>
<td>Primary Segment Size</td>
<td>2.4 m</td>
<td>3.93 m</td>
<td>flat to flat</td>
</tr>
<tr>
<td>Primary Mirror Temp</td>
<td>&lt; 200 K</td>
<td>150 K</td>
<td>Minimize heater power</td>
</tr>
<tr>
<td>Design Lifetime</td>
<td>15 years</td>
<td>&gt;30 years</td>
<td>On-orbit assembly and servicing</td>
</tr>
</tbody>
</table>
The primary mirror

Nicolas Lee, Paul Backes, Joel Burdick, Sergio Pellegrino et. al.
Architecture for in-space robotic assembly of a modular space telescope, JATIS (2) 2016

Launch the mirror structure separately and assemble in space
Modular Demonstration of an Evolvable Space Telescope (MoDEST)

The Evolvable Space Telescope

• This Northrop Grumman Evolvable Space Telescope (EST) concept study was initiated in 2014

• Concept science goals were taken from various community studies (e.g. AURA HDST Report)

• Architecture is a staged, in-space assembled, concept that began small and grew in stages to achieve a > 14 meter segmented telescope
The Evolvable Space Telescope

• **Stage 1** is a medium sized (equivalent to a 4 or 6 m telescope) partially filled aperture, launched as a fully functional astronomical telescope complete with instruments.

• **Stage 2** is launched some years later and augmented the Stage 1 telescope with additional mirror segments, instruments, and additional support systems, growing the Stage 1 telescope into a larger (8 – 12 meter) filled aperture.

• **Stage 3** Augment the existing Stage 2 telescope with more mirror segments to achieve a 14 – 20 meter aperture with new, enhanced, instruments and additional support systems.

• **Stage 4** is a sustained Stage 3, refurbishing or enhancing the now existing large Space Observatory as needed to enable a multi-decade useful lifetime.
Instrument volume barriers gone!

• Minimize # of reflections
  • Maximum power to the focal plane

• Threshold science @ minimum cost
  • Each optical mirror absorbs 3%
  • To hold the threshold science constant => Increase aperture to collect more light to compensate for absorption
  • For a $3B space telescope each instrument mirror costs about $100M+

• New way to think about instruments
  • Minimize mirror count
  • Think of deploying instrument optics
Minimum # of optical surface coronagraph

Scale = 1.5 inches per meter

- Six mirror system provides > 60% transmittance
- M3 and M4 are 128 x 128 actuator Xinetics DMs
- 512 x 512 pixel EMCCD photon counting detector with 16 μ pixels
- Inner Working angle of 83 mas and Outer Working Angle of 1320 mas at 400 nm
- Enhanced Silver or Al MgF2 mirror coatings for 400 to 950 or 250 to 950 nm bandpass
- 10 arc second Field of View for Exoplanets, 106 arc second FOV for general Astrophysics
- Focal Ratios ≥ 4 minimize polarization effects to maximize image quality for >10⁻⁹ contrast

FROM: Lillie
Autonomous Adaptive Reconfigurable Space Telescope (AAReST)

• Caltech student driven small sat based on cubesat technology

• Space technologies
  • Wafer mirror adaptive optics
  • Formation flying reconfigurable telescope pupil

• Demonstrate technology that is focused on assembling a segmented primary mirrors in space
Concept of Operations for Caltech AAReST
Team lead: Professor Pellegrino, Caltech Aero

- Turn on, verify satellite components
- Stabilize attitude, temperature

- Deploy boom in two stages:
  1. Boom segments unfold
  2. Camera is released
- Uncage deformable mirrors
AAReST Concept of Operations

• Telescope points to a bright reference star
• Calibrate:
  • Segment tip/tilt/piston
  • Deformable mirror surface figure
• Camera provides feedback for segment calibration
Concept of Operations

- MirrorSats release from CoreSat (one at a time)
- Fly out ~1 m
- Re-dock into “wide” configuration
Conclusion

• Many studies on servicing and assembly in space
• Many applications to next large aperture telescopes & instruments
• No resources being expended to study how these technologies will benefit astrophysics and exoplanet science
• What can we do to change that?
Back-up