Large Space Apertures: Kick-off Workshop

State of the Art: Active and Adaptive Optics

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Acknowledgement

This paper was first presented at the 2008 SPIE Astronomical Instruments Symposium, Marseille, France:

Active Optics for a 16-Meter Advanced Technology Large Aperture Space Telescope (ATLAS-T16)


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The Ares-V cargo launch vehicle offers the possibility of a truly large space telescope in the 2020 time-frame
- 8.8 m diameter by 18.7 m long shroud
- 55,600 kg to L2 orbit

ATLAST Study objective is to create a technology plan leading to development of a new flagship mission for NASA
- Study team led by ST ScI (Marc Postman), with participation from 4 NASA Centers, 4 Universities, and 2 system contractors (Ball and NG)

Two concepts are being pursued:
- 16 m aperture, deployed telescope with a segmented Primary Mirror (PM)
- 8 m aperture, monolithic, non-deployed telescope (H.P. Stahl, this meeting)

This paper considers the special technical challenges of the 16-m system
Wavefront Sensing and Control Baseline

Opics and optical controls:
- Segmented primary
  - Deforming actuators
  - Rigid-Body actuators
- Deployed secondary
  - Rigid-Body actuators

Instruments and WF sensors:
- High-dynamic range imager
- Visible imager
  - Phase Retrieval Camera
  - Dispersed-Fringe Sensor
- Spectrometer
- UV imager
- Shack-Hartmann Camera

Spacecraft System:
- Attitude Control
- Command and telemetry

Metrology System:
- Laser Truss
- Edge sensors?
- IRU

On-board processor:
- Optical State Estimator
- WF Controller
- Pointing Controller

- Wavefront Sensing uses Imaging and Shack-Hartmann cameras and Laser Metrology to measure WF errors
- Wavefront Control uses the deformable/moveable PM segments to keep WF error small for diffraction limited image quality
- Line-of-Sight Pointing Sensing and Control will use a Fast Steering Mirror driven from Metrology and/or Guide Star error signals to limit jitter
Exoplanet imaging is perhaps the most demanding task for an ATLAS-T16 telescope

WF performance required will depend on implementation
– Does the Planet Imaging (PI) instrument provide a second layer of control?
– Is an external occulter to be used?

LOS pointing performance for PI is similarly extreme

Target telescope WF performance for good general astrophysics performance
– Use a PI instrument with active WFC, or with an external occulter
  • Telescope static WFE < 10-40 nm RMS
  • Telescope WFE stability < 5-20 nm RMS
ATLAST-16 will require lightweight, actively controlled optics such as Active Hybrid Mirrors (AHMs)

AHMs combine a cast SiC substrate with integrated ceramic actuators, with a Nanolaminate facesheet

- Nanolaminate facesheet is a multi-layer metallic foil grown by sputter deposition on a precision mandrel
- AHMs are fabricated by replication for minimum cost and manufacturing time
- AHM technologies are a joint development of NG Xinetics, LLNL and JPL
WF Control and Metrology Baseline

- Initial WF Sensing and Control establishes the metrology set-point
  - Star observations for WFS&C during commissioning, and 1/day after that
    - Full-spectrum for segment phasing
    - Full field for Telescope alignment

- Segment thermal control keeps segment figure constant

- Metrology keeps alignments constant, compensating for thermal deformation of the supporting structures

- Metrology technology options:
  - Laser Truss *Provides full observability of Telescope alignment errors*
  - Edge / Gap Sensors
  - Full-time WF sensing
At the conceptual level, a Laser Distance Gauge (LDG) is a “yardstick,” with “inchmarks” provided by the interference fringes of the laser beam

- Changes in the distance $d$ between the Beam Launcher (BL) and the Corner Cube (CC) are measured as phase shifts between input and output beams
  - Intrinsic accuracy is better than 1 nm
  - We “count fringes” to track large changes in $d$
  - A 2-color mode provides a large “absolute mode”

- We can keep the BL and CC the same distance apart, by position feedback control of the BL and/or CC to keep $d$ constant
  - LDG runs at high BW (nominally 1 kHz)

- A SIM Mission-derived technology application funded by JPL R&TD
A 2-Dimensional LT Example

- This 2-D example illustrates use of LDG measurements to estimate rotational as well as translational DOFs between bodies
  1. Nominal geometry. There are 3 relative DOFs – \( x \) and \( z \) translation, and \( \theta \) rotation
  2. Changes in LDG measurements due to a \( z \) translation:
     \[
     \delta_1 = dz; \quad \delta_2 = \cos(\alpha)dz; \quad \delta_3 = dz;
     \]
  3. Changes in LDG measurements due to an \( x \) translation:
     \[
     \delta_1 = 0; \quad \delta_2 = \sin(\alpha)dx; \quad \delta_3 = 0;
     \]
  4. Changes in LDG measurements due to a \( \theta \) rotation:
     \[
     \delta_1 = r_1 \theta; \quad \delta_2 = r_2 \sin(\alpha)\theta; \quad \delta_3 = r_3 \theta;
     \]

- The measurement in matrix form
  \[
  \delta = \begin{bmatrix}
  \delta_1 \\
  \delta_2 \\
  \delta_3 
  \end{bmatrix} = \begin{bmatrix}
  0 & 1 & r_1 \\
  \sin(\alpha) & \cos(\alpha) & r_2 \sin(\alpha) \\
  0 & 1 & r_3
  \end{bmatrix} \begin{bmatrix}
  dx \\
  dz \\
  \theta
  \end{bmatrix} = Cx
  \]

- A simple state estimator
  \[
  x = C^{-1} \delta
  \]

- Feedback control based on the \( \delta \) measurements can keep the truss aligned
The Full 3-Dimensional Laser Truss

- The same approach is extended for the full 3-D LT
  - 6 LDGs per segment measure all relative RB DOFs in the entire OTA
    - All PM segments, the SM, FF, TM and OBA
  - The IRS is attached to the OBA, providing measurements of 6 more absolute DOFs wrt inertial space

- Same measurement equation: \( \delta = Cx \)
  - Sensitivities computed from model kinematics

- Measurement is invertible: \( x = C^{-1} \delta \) is full rank

- Optical State Estimator uses a Kalman Filter to estimate the RB state
  - Balances measurement vs. prior knowledge for optimal estimate
  - Predicts WF and Boresight from state estimate

- Feedback control using RB actuators and optimal control laws keeps performance in spec
  - Integrated model will be used to evaluate performance
Major elements include

- Wavefront Sensing and Control
- Laser Truss Active Alignment: active WF compensation and LOS pointing control
- Segment Thermal Control to stabilize optical figure
- Isolation and Damping to attenuate vibration disturbances

Chief disturbances include

- Time-varying heat load from sun
- S/C vibration, dominated by ACS
- Static errors, including fabrication errors
Initial WFS&C

- Wavefront Sensing & Control sets segment figure and alignment
  - Initially, and then periodically during ops
  - Update frequency will depend on figure and Laser Truss drift rates

OPTICS

- Wavefront
- WFS&C
- Boresight Cal
- Initial WFS&C
- Wavefront Sensing & Control sets segment figure and alignment
- Initially, and then periodically during ops
- Update frequency will depend on figure and Laser Truss drift rates
WF Sensing and Control

WF Initialization & Updates

ATLAST Deployment

SM Focus Sweep

Segment ID

Segment Search (if needed)

Segment Focusing

SHC Coarse Phasing

DFS Coarse Phasing

PRC Fine Phasing

Multifield Fine Phasing

Wavefront Maintenance w/ Extended Scene SHC

First light, showing segment images

Segment images following segment-image array

Segment images following SHC mirror figure correction

PSF following coarse phasing

Diffraction limited PSF

WF Maintenance

Challenges

- Large initial WF error after segment deployment
- Small final WF required for system performance

Solutions

- Initialization: Use a suite of WFSC algorithms to bring down WF error
- Maintenance: Use Laser Metrology and low-BW WF sensing to keep WF error in spec
- Updates: Repeat WFSC periodically to limit Laser Metrology error growth

Chart borrowed from JWST – Scott Acton/Ball
Coarse Phasing: Dispersed Fringe Sensing

- Dispersed-Fringe Sensing (DFS) uses a dispersive element (a grism) in an imaging camera to spread spot images into linear spectra.

- DFS uses segment steering to select segment combinations for control.

- “Dispersed Hartmann Sensing” (DHS) is DFS with prisms that select edge patches only.
  - JWST approach

- Wavelength variation along the spectrum modulates fixed path differences between segments to create interference fringes:
  - Bright peak where $\lambda$ is coherent with $\delta L$
  - Dark null where $\lambda$ is out of phase with $\delta L$

- Period of fringe gives absolute piston displacement.
- Slope of dark bands gives the sign.

Dispersed-Fringe Sensing enables the absolute phasing of the segments to within 1 wave.
Example: Keck DFS Experiment 2

- Two DHS devices were used in the second Keck experiment
  - 0° and 60° grism orientations
  - 10 edges sampled in each image
- Combination provides enough information to reconstruct piston of 18 segments
  - Tilts constrained
Phase Retrieval WFS

- **Image-based Phase Retrieval WFS offers**
  - High accuracy
  - High resolution
  - Can be performed in any camera, any field point
  - Minimum of non-common optics

- **Bumps on a mirror surface shift the focus of patches of the beam**
- These show up as bright spots on one side of focus and dark spots on the other
- The pupil and defocussed images are related by Fourier transforms
- Iterative processing of multiple defocussed images correlates the intensity variations in each, derives common WF phase map
Example: Fine-Phasing 36-Hex PM

- Fine Phasing uses MGS Phase Retrieval to estimate WF
- WF control is applied using segment RB and RoC actuators

Post-control WF meets 150 nm objective
WFS Capture Range and Accuracy

**Ball AMSD Mirror at 30K [08-13-2003]**

- **Defocused Data Images**
  - Defocus + 1.6 waves
  - Defocus + 1.9 waves
  - Defocus + 1.6 waves
  - Defocus + 3.6 waves

- **Pupil Image**

- **PRC / Phase Shift IPI Interferometer / Difference**

- **RMS - 2.2 / 2.3 / 0.3 waves at 632.8 nm**

- **Defocused**

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**High Contrast Imaging Testbed**

- The TPF HCIT is intended to demonstrate extremely high contrast coronagraphy for planet hunting
- Requires suppressing scattered light in low and mid spatial frequencies using (in this example) a 32\(^2\) actuator DM
- This chart shows a sequence of WFS&C iterations leading to a WF corrected to \(\lambda/5000\) for spatial frequencies within the DM bandpass

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- **JPL’s High Contrast Imaging Testbed provides a highly stable test environment for WFS&C and Coronagraphy**
  - Demonstrated \(\lambda/5,000\) WFS&C performance
  - Demonstrated 6.4 x 10-10 contrast at the 4\(^{th}\) Airy ring, and 10% bandwidth centered at 800 nm

- **PRC was used to test the 1.3 m-class Advanced Mirror System Demonstrator (AMSD) beryllium mirror, built by Ball Aerospace and tested at the MSFC XRCF facility**

- **Demonstrated >12 waves capture range, with < 8 waves of focus diversity**
Thermal Control Preserves PM Figure

- Wavefront Sensing & Control sets segment figure and alignment
  - Initially, and then periodically during ops
  - Update frequency will depend on figure and Laser Truss drift rates

Segment figure is thermally stabilized
- Passive Athermalization: keeps WFE/°C very low
- Local Segment Thermal Control: PM segment temperatures are kept constant using heaters integrated with segment structure
Laser Truss Keeps All Optics Aligned

- Laser Truss Active Alignment keeps the segmented PM phased and aligned with the rest of the telescope
  - Compensates large structural deformations

- Laser Truss measurements at high BW are processed in a Kalman Filter to estimate the perturbation state of all the optics
- Estimated state is fed back to control WFE at low BW and boresight at high BW
Laser Truss measurements at 100 Hz are processed in a Kalman Filter to estimate the perturbation state of all the optics

- Estimated state is fed back to control WFE (< 1 Hz) and boresight (< 10 Hz)
Laser Truss Pros and Cons

- **Pros**
  - High accuracy – < 1 nm per LDG when Δ angle is small
  - Observes all important RB states – including Primary and Secondary Mirrors, and Optical Bench
  - Low drift – with 1 laser feeding all LDGs, require WFS update once per day
  - Light weight beam launchers
  - No on-segment power dissipation
  - Does not require segments to be close together
  - Does not require any particular gap geometry
  - Works with missing segments (no degradation for the segments that remain)
  - Useful for I&T
  - Degrades gracefully if individual LDGs go out

- **Cons**
  - Requires 12 fibers into each segment for 6 DOF
Notional Metrology Error Budget

- Notional LDG error budget, based on extrapolated SIM and R&T data

<table>
<thead>
<tr>
<th>Component</th>
<th>Error Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pointing error</td>
<td>3nm</td>
</tr>
<tr>
<td>BL internal stability</td>
<td>1nm</td>
</tr>
<tr>
<td>Cyclic error</td>
<td>0.1nm</td>
</tr>
<tr>
<td>Source/fiber error</td>
<td>1nm</td>
</tr>
<tr>
<td>Phase meter electronics</td>
<td>0.3nm</td>
</tr>
<tr>
<td>BL detector noise</td>
<td>0.3nm</td>
</tr>
<tr>
<td>Corner cube stability</td>
<td>2nm</td>
</tr>
</tbody>
</table>

Estimated by comparing to SIM requirements

- This level of performance is much worse than was demonstrated by SIM
- However...
  - Much smaller, lighter-weight components will be needed
  - Long-term laser frequency stability will be required
Conclusion

- Our baseline utilizes developing and realized active optics technologies to provide a plausible development path to diffraction limited performance at 500 nm wavelength for ATLAS-T16

- Planet Imaging will require further active optics technology development
  - Large lightweight segments
  - Smaller, lighter, higher performance LDGs
  - On-board closed-loop extreme WF sensing and control
  - Broad-band coronagraphy