OPTICAL DESIGN OF WFIRST-AFTA WIDE-FIELD INSTRUMENT

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WFIST-AFTA Optical Design

- Wide-Field Infra-Red Survey Telescope - Astrophysics Focused Telescope Assets
- Makes use of unused telescope components from the intelligence community, repurposed to NASA for scientific use.
- Optical Design: 2.36-meter aperture Three Mirror Anastigmat (TMA)
- Constrained and influenced by a combination of existing hardware, design heritage, science interests and volume constraints
COST EFFECTIVE – LOW RISK – MATURE TECHNOLOGIES

Hits 5 of 6 NASA Strategic Goals

#1 Large Mission Priority
WFIRST science

#1 Medium Scale Priority
Exoplanet Imaging

Nobel Prize science

Brings Universe to STEM
Next generation citizen science

Foundation for discovering
Earth-like planets

Complements and enhances JWST science
WFIST-AFTA Optical Design

- Wide-Field Instrument composed of two channels:
  - Wide-Field Channel (WFC) provides ~1/3-square degree of instantaneous field coverage at 0.11 arcsecond pixel scale.
  - WFC Focal plane of 300 million pixels
- Diffraction-limited imaging mode (WFI), operating in six panchromatic bands between 0.6 – 2.0µm, or spectrographic mode (WFS) from 1.3-2.0µm.
- Separate Integral Field Channel (IFC) - Discrete spectral analysis over a ~3”x3” field with 0.15” sampling and R=100 spectral resolution.
Wide-Field Channel Optical Design

- The WFIRST-AFTA TMA optical design is anchored to the repurposed assets’ size and figures.
- Allows for small changes in the conic figure of the Primary Mirror (T1) and minor changes in the curvature and position of the Secondary Mirror (T2).
- Entrance Aperture Plate (EAP) at the intermediate focus passes the WFC’s field into the instrument enclosure.
Wide-Field Channel Optical Design

- Powered mirror within the instrument (M3) works in concert with T1 & T2 to produce a corrected field
- All three powered mirrors are optically co-axial and simple conics
- Two fold mirrors are use for packaging
- Maximum root mean square (RMS) polychromatic wavefront error of 45nm across entire field
  - Half of the 90nm budget (based on 1/13 $\lambda$ @ 1.2$\mu$m)
- Currently in “Cycle 4” design iteration
Focal Plane Array Layout

- 18 individual H4RG-10 detectors, each with 4,088x4,088 10µm active pixels.
- Each sensor is custom shimmed in the array with a tilt and piston to match a field curvature of about 16 meters, allowing a 10% performance gain over a perfectly flat field.
- 6 columns of 3 sensors w/ offset columns
- Columns follow the natural annular curve of an off-axis TMA optimized field.
Pupil / Element Wheel

- At the pupil, located approximately midway between M3 and the FPA, is the cold/Lyot stop and the element wheel.
- Blocks the scatter and emissions form the telescope struts and baffles.
- 8-position Element Wheel: 6 bandpass filters, 1 spectrograph grism assembly, 1 null position.
- All wheel modes are par-focal to no filter.
- The filters are very weak meniscus lenses.
- The grism consists of 3 optical elements; only spherical surfaces on fused silica and two diffracting surfaces on flats. (See presentation by Qian Gong)
Optical Design Considerations

- Constraints of existing hardware (Use “as-is”)
- Hold volume while maintaining large field.
- Pupil clearance to allow for the large element wheel
- M3 distance to allow for mounting
- EAP location which allows for clean baffling of the intermediate focus
- Minimum central obscuration
Imagine this wall of a million galaxies – a 300 megapixel image from a single WFIRST-AFTA pointing -- filling walls of schools and museums and providing a wealth of citizen science.
Target Area for Phase-2
M31 PHAT Survey
HST Andromeda Project
Dalcanton et al. 2012
Phase-2 Observations
M31 PHAT Survey
432 Hubble WFC3/IR pointings
Phase-2 Observations
M31 PHAT Survey

432 Hubble WFC3/IR pointings
2 WFIRST-AFTA pointings
WFIRST Observatory Layout

- WF Instrument
- Coronagraph
- OBA
- AMS
- Instrument Carrier
- HGA (2X)
Telescope Reuse

100% of the existing telescope hardware is being re-used. Electronics and baffles not available and must be replaced.

Existing H/W, reuse
Existing design, remake
New design
TOTAL:

1188 kg
153 kg
254 kg
1595 kg
WFIRST IC/WFI/CGI Layout – Cycle 4

- AMS
- Instrument Carrier
- Coronagraph
- Instrument Rail Guides
- WF Instrument
- FPE (2x), ICDH (2x)

AFTA Instrument Carrier, FPA & WFI design – Cycle 4
- Single wide field channel instrument
- 3 mirrors, 1 powered
- 18 4K x 4K HgCdTe detectors
- 0.11 arc-sec plate scale
- IFU for SNe spectra, single HgCdTe detector
- Single filter wheel
- Grism used for GRS survey
- Thermal control – passive radiator
WFIRST WFI Layout – Cycle 4

IFU

M3 Assembly

Optical Layout v4-2-0

F1 Assembly

F2 Assembly

Element Wheel Assembly (EWA)

FPA
Wide field Instrument Shares Architecture and Heritage with HST/WFC3
Wide-Field Major Subassemblies
18 NIR detectors
0.11 arcsec/pixel  0.28 deg$^2$

Slitless spectroscopy with grism in filter wheel
$R_{\theta} \sim 100$ arcsec/micron

Each square is a H4RG-10
4k x 4k, 10 micron pitch
288 Mpixels total
Design overview
## ATLAST (v4.2.5) Optical Components

<table>
<thead>
<tr>
<th></th>
<th>Radius (mm)</th>
<th>Conic</th>
<th>Aperture (mm)</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM (T1)</td>
<td>5,670.69</td>
<td>-0.97198</td>
<td>C 2,362</td>
<td>Concave</td>
</tr>
<tr>
<td>SM (T2)</td>
<td>1,294.73</td>
<td>-1.69502</td>
<td>C 536</td>
<td>Convex</td>
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<tr>
<td>Fold 1</td>
<td>Flat</td>
<td>0</td>
<td>R 504 x 280</td>
<td></td>
</tr>
<tr>
<td>Mirror 3</td>
<td>1,729.732</td>
<td>-0.56660</td>
<td>R 620 x 500</td>
<td>Concave</td>
</tr>
<tr>
<td>Filter</td>
<td>S1: 1,594.07</td>
<td>0</td>
<td>C 110</td>
<td>Meniscus</td>
</tr>
<tr>
<td>S2: 1,593.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fold 2</td>
<td>Flat</td>
<td>0</td>
<td>C180</td>
<td></td>
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</tbody>
</table>
Instrument ray trace views
Channel Field Layout for AFTA-WFIRST Instruments
As Projected on Sky
[ Cycle 4, v4.2.5 ]

Coronagraph Field (0.4°)

Sunshade (Payload +Y)

60°

37.5°

32.5°

IFU Field (0.14°)

WFI Field (Center 0.617°)
Element Wheel Modes

Wide-Field Imaging Mode
Bandpass Filter
(6 positions)

Wide-Field Spectrograph Mode
Bandpass Filter
(1 position)
Payload CS +y

Optical CS +y

WFI Optical CS +y

Payload CS +x

Optical CS +x

(x-axis bisects the AMS Turtle head)

WFI Optical CS +x

30deg

32deg
Lyot Cold Stop Layout

- Average blockage over field:
  - Telescope Only: 15%
  - Tel plus Lyot Stop: 23%
    - Mask blocks additional 5.1% to 10.6%
Imager Performance

- Comparative Polychromatic Spot Sizes
WFI Error Budget

• Pre-Launch Phase:
  – Each parameter is budgeted for degrees of freedom in both fabrication and alignment
  – Predictions in cooldown and gravity release are accounted for
  – These form compensated/uncompensated totals
  – All I&T methods (alignment tools, Wavefront sensing, etc...) and all adjustable (mechanisms, shims, etc..) are brought to bear for compensation.

• Post-Commissioning
  – Errors in analysis and stabilities form new compensated/uncompensated totals
  – Only adjustable mechanisms are available for compensators
WFI Error Budget (Sample Totals)

- Error Budget Totals are applied to the Linear Optical Model (LOM)
- Wavefront and boresight changes are calculated.
- Totals compared against system budgets.
- Iterative process, refined as I&T methods and tools are refined.
Cycle4 WFI design update

- Outline
- WFI design progress
  - Optics performance: distortion, dispersion
  - Mechanical, thermal, electrical progress examples
  - Error budgeting
  - Risk reduction activities
- Cycle5 trade space
- Update on detector development
- Reminder – details of filter set are pending the telescope temperature vs risk assessment, ongoing
Statistical Results

- 41x41 sampling of across each sensor
- Each group showed distinct trending:

![Design residual wavefront error distribution across field and wavelength](image)
Optical distortion

- Optical distortion assessed
  - ‘Feature’ of TMA optical designs used off field axis
  - Independent of the small field configuration tweaks under consideration for Cycle5, see below
  - Simple function of radial field angle

Square outline: zero distortion;
Filled trapezoids: actual SCA field positions

X: field angle, degrees; Y: Distortion, %
Element #1: Fused silica
  Surface #1: Filter (spherical)
  Surface #2: Diffractive lens (flat)

Element #2: Fused silica
  Surface #1: spherical
  Surface #2: Spherical

Element #3: Fused silica
  Surface #1: Spherical
  Surface #2: Grating (flat)

The filter can be on any spherical surface, but the first surface is smaller, also more perpendicular to the beam.
Integral Field Channel

- A separate channel within the Wide-Field instrument enclosure
- Using an assembly of 21 sets of 0.5 x 10 mm slicer mirrors, pupil mirrors, and output mirrors, a 3”x3.15” field is sliced and re-arranged into a continuous slit.
- This slit is then relayed through a spectrograph (R~100), allowing for the multiplexing spectral analysis of each individual 0.15x0.15” field
WFIRST IFU Design

IFU Mounts

IFU Optical Bench

IFU Enclosure

IFU Assembly v4-2-5

03/28/2014
IFU Design Features

- Uses “current art” for image slicing method
- 21 10mm x 0.5mm slicer mirrors form pupils
- 21 pupil mirrors reimage slices to single 50mm output slit
- 21 slice output field mirrors create telecentric output
- Spectograph used tri-prism for more constant R
- Collimation and focus mirrors reduce to 18mm, fits on single H1RG.
- Telecentric input & output
IFU Layout: Slicer with Relay Mirrors
IFU Layout: Slicer with Relay Mirrors
3”x3.15” field cut into 21 0.5mm slices
Final Image Plane: 21 slices dispersed
Final Images near diffraction-limited

<table>
<thead>
<tr>
<th>Config 1</th>
<th>Config 2</th>
<th>Config 3</th>
<th>Config 4</th>
<th>Config 5</th>
<th>Config 6</th>
<th>Config 7</th>
<th>Config 8</th>
<th>Config 9</th>
</tr>
</thead>
</table>

-0.0004, 0.0000 (deg)

0.0000, 0.0000 (deg)

0.0004, 0.0000 (deg)

Surface: IRA Detector Array

Configuration Matrix Spot Diagram

WFIRST IFU Channel Front End, Unfolded
3/1/2013 Units are μm.
Airy Radius: 22.13 μm
IFU Performance

- Shortest Wavelength (0.6µm)

Surface IMA: Detector Array

Configuration Matrix Spot Diagram

WFIRST Cycle 4 IFU Relay
9/9/2013 Units are µm.
Airy Radius: 215 µm

Scale bar: 1000 Reference: Chief Ray

v4-2-1 08-20-13 D.ZMX
Configuration: All 9
IFU Performance

- Longest Wavelength (2µm)
Stray Light Requirement (Cycle 2&3)

\[
\sum_{\lambda=1.3\ \mu m}^{\lambda=2.0\ \mu m} Zodi_{\text{min}}(\lambda) \times Bandwidth(\lambda)
\]

\[\left(\frac{\text{Watts} \times \text{m}^2}{\text{arcsec}^2}\right)\]

<table>
<thead>
<tr>
<th>Watts</th>
<th>Obscuration</th>
<th>IFOV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{\text{WFIRST-SCA}}^{\text{stray-light}})</td>
<td>(10%)</td>
<td>(10%)</td>
</tr>
<tr>
<td>(0.1 \times 2.269469^{-18} \times \pi \cdot (1.1811)^2 \times (1 - 0.13) \times (0.98)^5 \times (450)^2)</td>
<td>Aperture Area (m²)</td>
<td>Mirror Reflectivity (5 mirrors)</td>
</tr>
<tr>
<td>(= 1.58 \times 10^{-13})</td>
<td>Stray-light / SCA at focus (10% of Zodi-min)</td>
<td></td>
</tr>
</tbody>
</table>

Based on “Cyc1_S-N_Sim_Parameter_Freeze_v5.xls” spreadsheet dated: 1/10/2007

Currently, there is no “official” stray-light requirement for the WFIRST/AFTA, so a tentative “Pass” or “Fail” threshold value of 1.58e-13 Watts/(WFIRST-SCA) is assumed

In simplistic terms, the requirement is for stray light to be <= 10% of Zodi min
Description of PST Calculation (Sunshield)

Sun, earth and moon are modeled as rising above the horizon of the Sunshield.

The values of Irradiance (Power/Area) and Flux (Power) utilized in the irradiance calculations are model and are listed in the appendix.

The source is assumed uniform and collimated (far away).

To produce the proceeding graphs the PM aperture is illuminated at various angles.

The results are read as detector Irradiance vs. Requirement.
Footprint of Beam on Sky

Full Sky View

Field of View as Seen from Detector (31% Obscuration)
Central Obstruction: Standard Cut vs. Sculptured Baffle (30% Central Obscuration)

- Rogue (Out-of-field) rays greatly reduced with Sculpted Baffles
Telescope Baffles

- WFIRST-AFTA’s Telescope baffles will be custom sculpted to match the instrument fields
  - Secondary Mirror Shade
  - Inner Telescope Baffle
  - Primary Mirror edge
  - Entrance Aperture Plate
  - Reduce Rogue Rays

WFIRST-AFTA Stray Light model example
AFTA PST for 31 Percent Obscuration

Detector Irradiance (Watts/mm²)

Angle of Incidence (Degrees)

- Sun 31%
- Earth 31%
- Moon OP 31%
- Moon 0.5P 31%
- Moon 1P 31%
- Moon 1.5P 31%
- Requirement
CURRENT EFFORTS

- Full Bottom-up I&T error allocation for predicted performance
- Expansion of IFU Field to include 6”x6” ‘coarse’ 0.3” sampling field, adjacent to current field
- ... All this in PRE-PHASE-A!
- Launch Date: 2021 - 2024
For More WFIRST Information:

- http://wfirst.gsfc.nasa.gov
  (or just search “WFIRST” in any search engine)

- Science Definition Team Presentations

- Project Reports

- Contact Project Team Members