WFIRST-AFTA
Overview & Technology needs summary
Mirror Technology Conference 2015

Catherine Marx (NASA-GSFC)
Dave Content (NASA-GSFC)
Feng Zhao (JPL/Caltech)
WFIRST was highest ranked large space mission in 2010 Astrophysics Decadal Survey
Re-Use of existing 2.4m telescope enables
- Hubble quality imaging over 100x more sky
- Imaging of exoplanets with $10^{-9}$ contrast with coronagraph

Dark Energy

Exoplanets

Astrophysics

Coronagraph
WFIRST Instruments

Wide-Field Instrument

- Imaging & spectroscopy over 1000s of sq. deg.
- Monitoring of SN and microlensing fields
- 0.7-2.0 μm (imaging), 1.35-1.89 μm (spec.), 0.42-2.0 μm (IFU)
- 0.28 deg² FoV (100x JWST FoV), 9 asec² & 36 asec² (IFU)
- 18 H4RG detectors (288 Mpixels), 2 H1RG detectors (IFU)
- 6 filter imaging, grism + IFU spectroscopy

Coronagraph

- Image and spectra of exoplanets from super-Earths to giants
- Images of debris disks
- 430 – 970 nm (imaging) & 600 – 970 nm (spec.)
- Final contrast of 10⁻⁹ or better
- Exoplanet images from 0.1 to 0.9 arcsec
Executive Summary

- Huge progress on WFIRST over the past two years
- SDT studies & NRC Harrison committee report confirm that WFIRST-AFTA exceeds NWNH requirements in all areas.
- $107M in FY14 & 15 has enabled major steps forward and NRC-Harrison committee recommendations have been addressed (H4RGs, coronagraph, mission design). Planning against $56M in FY16, exact amount depends on appropriations.
- Coronagraph on track, technology development on schedule. Wide Field detector technology development on schedule
- SDT 2014 & 15 studies completed
- Preparatory Science teams selected
- Pasadena conferences held
- Special session at AAS's & IAU
- Science team NRA released
- Industry study RFIs received
- Significant international interest (Canada, ESA, Japan, Korea)
Scientific Objectives

1) Produce NIR sky images and spectra over 1000's of sq deg (J = 27AB imaging, F_line = 10^{-16} erg cm^{-2} sec^{-1})

2) Determine the expansion history of the Universe and the growth history of its largest structures in order to test possible explanations of its apparent accelerating expansion including Dark Energy and modifications to Einstein's gravity.

3) Complete the statistical census of planetary systems in the Galaxy, from the outer habitable zone to free floating planets

4) Directly image giant planets and debris disks from habitable zones to beyond the ice lines and characterize their physical properties.

5) Provide a robust guest observer program utilizing a minimum of 25% of the time over the 6 year baseline mission and 100% in following years.
WFIRST Dark Energy Program

WFIRST–AFTA Probes of Expansion and Growth

- Supernova Distances
- Galaxy BAO Distances
- Weak Lensing Distances

H(z)/(1+z) [km s⁻¹ Mpc⁻¹]

- Acceleration Era
- Deceleration Era
- ±1%

ΛCDM
- w = -0.9
- w = -1.1

- Weak Lensing Growth
- Clusters Growth
- Galaxy RSD Growth

redshift
WFIRST Microlensing for Exoplanets
Completes the Census Begun by Kepler
Combined with space-based transit surveys, WFIRST-AFTA completes the statistical census of planetary systems in the Galaxy.

- 2600 planet detections.
- 370 with Earth mass and below.
- Hundreds of free-floating planets.

WFIRST perfectly complements Kepler, TESS, and PLATO.
Multi-band imaging at high contrast provides for direct detection and preliminary characterization of exoplanets.

Simulated WFIRST-AFTA CGI images of a 30 zodi disk around 47 UMa.

Simulated WFIRST-AFTA coronagraph image of the star 47 Ursa Majoris, showing two directly detected planets.
WFIRST Brings Humanity Closer to Characterizing exo-Earths

- WFIRST-AFTA advances many of the key elements needed for a coronagraph to image an exo-Earth
  - Coronagraph
  - Wavefront sensing & control
  - Detectors
  - Algorithms
#1 Large-Scale Priority - Dark Energy, Exoplanets
#1 Medium-Scale Priority - New Worlds Tech. Development
(prepare for 2020s planet imaging mission)

WFIRST covers many other NWNH science goals

5 Discovery Science Areas
ID & Characterize Nearby Habitable Exoplanets ✔
Time-Domain Astronomy ✔
Astrometry ✔
Epoch of Reionization ✔
Gravitational Wave Astrometry

20 Key Science Questions
Origins (7/7 key areas)
Understanding the Cosmic Order (6/10 key areas)
Frontiers of Knowledge (3/4 key areas)
WFIRST-AFTA Observatory Concept

Key Features

- **Telescope**: 2.4m aperture primary
- **Instruments**
  - Wide Field Imager/Spectrometer & Integral Field Unit
  - Internal Coronagraph with Integral Field Spectrometer
- **Max Data Downlink Rate**: 275 Mbps downlink
- **Data Volume**: 11 Tb/day
- **Orbit**: Sun-Earth L2
- **Launch Vehicle**: Delta IV Heavy
- **Serviceability**: Observatory designed to be robotically serviceable
- **GSFC**: leads mission and I&T, wide field instrument, spacecraft
- **JPL**: leads telescope, coronagraph
Telescope Overview

- 2.4 m, two-mirror telescope provided to NASA. Built by Harris (Kodak/ITT/Exelis).
  - Ultra Low Expansion (ULE®) glass mirrors
  - All composite structure
  - Secondary mirror actuators provide 6 degree of freedom control
  - Additional secondary mirror fine focus actuator
  - Active thermal control of structure
  - Designed for operation at room temperature (293 K) with design minimum temperature of 277 K, OBA design minimum temperature of 216 K
  - Outer barrel includes recloseable doors
  - Passive damping via D-struts at the spacecraft interface
Telescope Assembly

**Outer Barrel Assembly (OBA)**
- Door
- Scarf
- Outer Barrel
- Outer Barrel Extension
- OBA Bipods

**Forward Optics Assembly (FOA)**
- Focus Drive Actuators
- Secondary Mirror (SM)
- SM Support Structure
- SM Baffle
- SM Support Tubes
- Primary Mirror (PM)
- PM Baffle
- Fwd Metering Structure
- Alignment Drive Actuators
- Aft Metering Structure
- FOA Bipods
- Telescope Control Electronics
Wide Field Instrument

Key Features

- Wide field channel for both imaging and spectroscopy
  - 3 mirrors, 1 powered
  - 18 4k x 4k HgCdTe detectors cover 0.76 - 2.0 μm
  - 0.11 arc-sec plate scale
  - Single element wheel for filters and grism
  - Grism used for GRS survey covers 1.35 – 1.89 μm with R = 461λ (~620 – 870)

- IFU channel for SNe spectra, single HgCdTe detector covers 0.6 – 2.0 μm with R between 80-120

- Auxiliary guider for guiding during grism spectroscopy mode
Element wheel includes bandpass filters and a wide field grism; see coatings talk by M. Quijada
Coronagraph Instrument – see also talk by R. Demers

- **Completed design for 2015 SDT Report**
  - Coronagraph met all WFIRST interface constraints
  - Initial end-end simulations indicate that the coronagraph is likely to achieve all performance goals with the current, unmodified telescope
- **Coronagraph cost estimate within expectations**
  - NICMs
  - CATE by Aerospace
- **Currently working on refining design**
  - Improved I&T flow
  - Improved optical throughput (less fold mirrors)

### Performance Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bandpass</strong></td>
<td>430 – 970 nm</td>
</tr>
<tr>
<td><strong>Measured sequentially in 10% and 18% bands</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Inner Working Angle [radial]</strong></td>
<td>100 mas</td>
</tr>
<tr>
<td><strong>at 550nm, 2λ/D driven by WFIRST-AFTA pupil obscurations</strong></td>
<td></td>
</tr>
<tr>
<td><strong>270 mas</strong></td>
<td>1μm</td>
</tr>
<tr>
<td><strong>Outer Working Angle [radial]</strong></td>
<td>0.5 as</td>
</tr>
<tr>
<td><strong>at 550nm, 10λ/D, driven by 48×48 format DM</strong></td>
<td></td>
</tr>
<tr>
<td><strong>0.9 as</strong></td>
<td></td>
</tr>
<tr>
<td><strong>at 1μm (imaging camera)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Detection Limit (Contrast)</strong></td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td><strong>Cold Jupiters; deeper contrast unlikely due to pupil shape &amp; extreme stability requirements.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Spectral Resolution</strong></td>
<td>70</td>
</tr>
<tr>
<td><strong>R = λ/Δλ (IFS)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>IFS Spatial Sampling</strong></td>
<td>17 mas</td>
</tr>
<tr>
<td><strong>3 lenslets per λ/D, better than Nyquist</strong></td>
<td></td>
</tr>
</tbody>
</table>
Coronagraph Development Summary

- Team is making good progress on coronagraph technology program to achieve appropriate TRL by Phase A/B
- Coronagraph design is advanced and detailed, not driving mission complexity
- WFIRST coronagraph addresses key 2010 NWNH technology and science goals
  - WFIRST coronagraph brings wavefront-controlled coronagraphy to flight levels on the path to future Earth finding missions, not just hardware, but algorithms
  - As Kepler and microlensing complete the exoplanet census, the WFIRST coronagraph moves into the era of characterization
WFIRST technology overview

- Technology needs in 2 areas
  - Coronagraph technology: deformable mirrors, exquisite diffraction control using masks & stops, and very low noise Si detectors
    - Next pages for Milestones & TRL timeline, and also see R. Demers talk
  - Wide field instrument, NIR detector technology
    - Progressing steadily towards TRL6

- WFI has significant engineering challenges also:
  - Lightweight cold M3 (tertiary mirror, 170K, ~0.6m)
  - Cold filters, grisms, large fold mirrors
  - Integral field unit – image slicer
  - Cold precision composite structures

- CGI has small but high precision optics also, few nm rms wavefront error class
## Coronagraph Technology Milestones

<table>
<thead>
<tr>
<th>MS #</th>
<th>Milestone</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>First-generation reflective Shaped-Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than $10^{-4}$ and 20 μm pixel size.</td>
<td>7/21/14</td>
</tr>
<tr>
<td>2</td>
<td>Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with narrowband light at 550 nm in a static environment.</td>
<td>9/30/14</td>
</tr>
<tr>
<td>3</td>
<td>First-generation PIAACMC focal plane phase mask with at least 12 concentric rings has been fabricated and characterized; results are consistent with model predictions of $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm.</td>
<td>12/15/14</td>
</tr>
<tr>
<td>4</td>
<td>Hybrid-Lyot Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with narrowband light at 550 nm in a static environment.</td>
<td>2/28/15</td>
</tr>
<tr>
<td>5</td>
<td>Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a static environment.</td>
<td>9/15/15</td>
</tr>
<tr>
<td>6</td>
<td>Low Order Wavefront Sensing and Control subsystem provides pointing jitter sensing better than 0.4 mas and meets pointing and low order wavefront drift control requirements.</td>
<td>9/30/15</td>
</tr>
<tr>
<td>7</td>
<td>Spectrograph detector and read-out electronics are demonstrated to have dark current less than 0.001 e/pix/s and read noise less than 1 e/pix/frame.</td>
<td>8/25/16</td>
</tr>
<tr>
<td>8</td>
<td>PIAACMC coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a static environment; contrast sensitivity to pointing and focus is characterized.</td>
<td>9/30/16</td>
</tr>
<tr>
<td>9</td>
<td>Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.</td>
<td>9/30/16</td>
</tr>
</tbody>
</table>

Excellent progress on technology development
Coronagraph TRL6 timeline

- **Occulting Mask Coronagraph (OMC)** system
- **Deformable Mirror (DM)**
- **Low noise detector (EMCCD)**

**Pre-Phase A**
- 6/16/2014 SPC mask (MS1)
- 9/17/2014 Gen 1 SPC broadband DM (MS2)
- 11/22/2014 Low noise demo
- 2/27/2015 HLC narrowband (MS4)
- 4/30/2015 LWFS demo (MSS)

**Phase A**
- 6/30/2016 WFIRST MCR
- 9/15/2017 WFIRST MDR
- 2/1/2016 Thermal test
- 2/14/2016 IFS delivered
- 9/17/2015 OTA simulator installed
- 9/15/2015 OMC broadband (MSS)
- 9/30/2015 Receive 48x48 DM from Xinetics
- 11/15/2015 Surface gauge Testing complete
- 3/28/2016 Post-environmental performance test Complete (MS7)
- 12/30/2016 Sensor chip assembly (SCA) validated
- 9/20/2017 Low-flux EFC demo
- 2/29/2016 Environmental tests complete
- 11/15/2015 Surface gauge Testing complete
- 6/30/2016 WFIRST MCR
- 9/15/2017 WFIRST MDR

**Environmental tests complete**
- 11/22/2014 Low noise demo
- 2/27/2015 HLC narrowband (MS4)
- 4/30/2015 LWFS demo (MSS)
- 12/2/2015 Radiation test (cold)
- 9/30/2015 OMC broadband (MSS)
- 9/30/2016 OMC broadband, dynamic (MS9)

**Post-processing algorithm verified**
- 3/28/2016 Post-environmental performance test Complete (MS7)
- 12/30/2016 Sensor chip assembly (SCA) validated
- 9/20/2017 Low-flux EFC demo
Over the past two years, increased funding has enabled significant progress in technology maturation as well as additional fidelity in the design reference mission.

WFIRST with the 2.4-m telescope and coronagraph provides an exciting science program, superior to that recommended by NWNH and also advances exoplanet imaging technology (the highest ranked medium-class NWNH recommendation).

Great opportunity for astronomy and astrophysics discoveries. Broad community support for WFIRST.

Key development areas are anchored in a decade of investments in JPL’s High contrast imaging tested (HCIT) and GSFC’s Detector characterization Lab (DCL).

Great progress made in pre-formulation, ready for KDP-A and launch in mid-2020s.
Telescope Reuse Approach

- JPL and the Study Office have worked closely with Harris to understand the telescope hardware.
  - The Observatory design provides an instrument carrier as the prime optical bench for the payload, supporting both the telescope and the instruments, providing substantial structural margin.
  - Set operating temperature at 282K, within heritage hardware design specifications.
    - Continuing to evaluate the feasibility of taking the telescope slightly colder to optimize system design (minimize heater power & improve science performance/margin).
  - Instituted a thorough inheritance audit process to ensure hardware is consistent with the WFIRST application.
    - Includes reviews of original hardware build books and analyses along with new assessments for aging and WFIRST environments.
    - No major issues with planned reuse have emerged to date
- Detailed build plan, schedule, and cost estimate prepared and reviewed as part of Aerospace CATE.
Acronym list