



Design Evolution of the Wide Field Infrared Survey Telescope using Astrophysics Focused Telescope Assets (WFIRST-AFTA) and Lessons Learned

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The authors would like to thank the entire team for their tireless efforts to design, analyze, and push massive amounts of data and analysis through to complete numerous STOP cycles. These analysis included numerous points over long slew periods simulating the worst case or most representative for the CGI and WFI instruments. The responsiveness and collaboration of the entire team to rise up to the schedule challenges, both planned and unexpected, has been remarkable.



Agenda

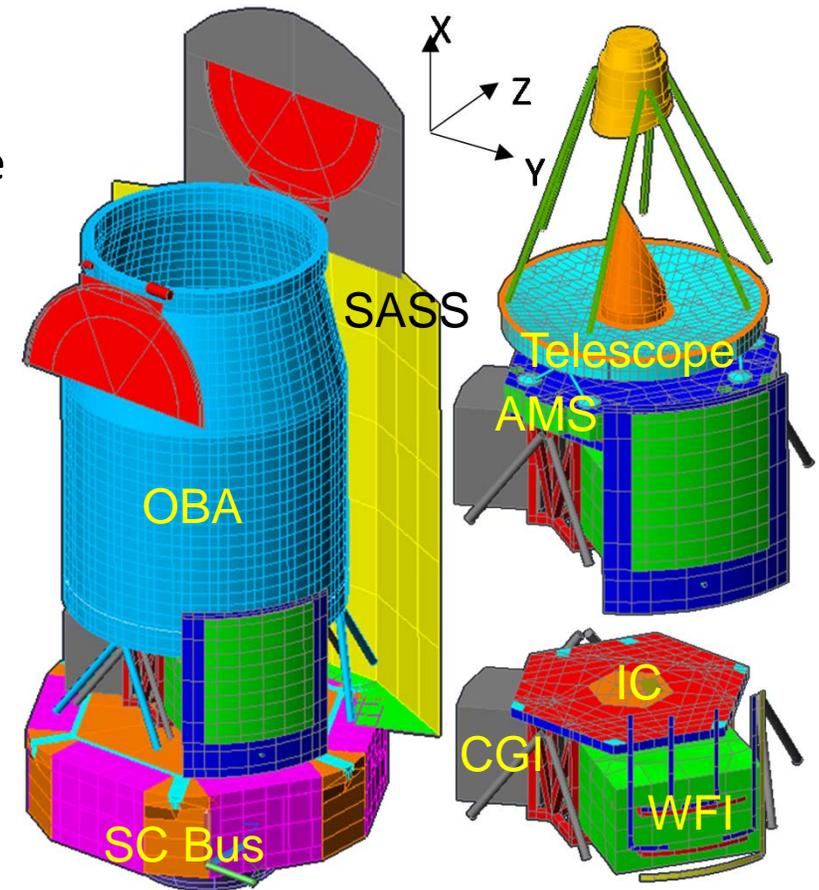
- WFIRST Mission Overview
- Overall Observatory Design
- WFIRST Cycle 3 Design
 - Cycle 3 Lessons Learned
- WFIRST Cycle 4 Design
 - Cycle 4 Lessons Learned
- WFIRST Cycle 5 Design
 - Cycle 5 Lessons Learned
- Conclusions and Moving Forward



- Top Ranked large scale space mission in 2010 New Worlds, New Horizons Decadal Survey for Astronomy and Astrophysics
 - *Measures Dark Energy, Exoplanet Microlensing, and the near InfraRed Sky*
- Includes a 2.4 m *existing* telescope donated from elsewhere in Federal Government
- Includes two baseline instruments supported by Instrument Carrier
 - *Wide Field Instrument (WFI) with 2 channels*
 - IR imaging with 3x6 array of H4RG detectors for a FOV about 100x Hubble's WFC3 Instrument
 - Integrating Field Unit using a slicer and spectrograph to provide individual spectra of each slice
 - *CoronaGraph Instrument (CGI)*
 - Imaging and spectroscopic modes to image exoplanets and debris discs around nearby stars

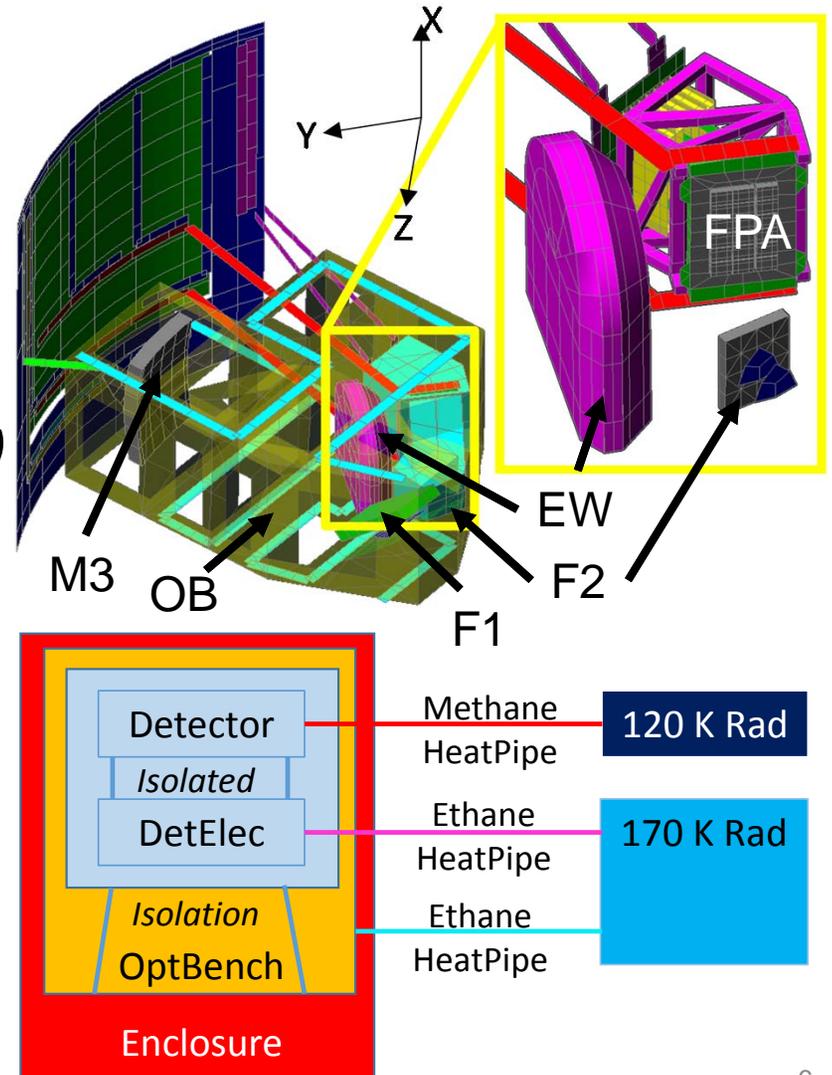


- Geosynchronous orbit
- Utilizes Solar Array/SunShield (SASS) to provide stable thermal environment
- Spacecraft bus (SC Bus) provides power, attitude control, comm., and other spacecraft functions
 - *6 modular, orbit serviceable avionics bays*
- Aft Metering Structure (AMS) supports IC and Telescope. Supported by bipods to SC
 - *Limitations of structural loads and lines of action for existing AMS inserts*
- Instrument Carrier (IC) supports WFI and CGI. Supported by AMS
 - *Instruments are serviceable on orbit*
- Outer Barrel Assembly (OBA) mitigates stray light for telescope. Supported by bipods to SC
- Notionally planned as a joint mission by GSFC (BUS, WFI) and JPL (Telescope, CGI)





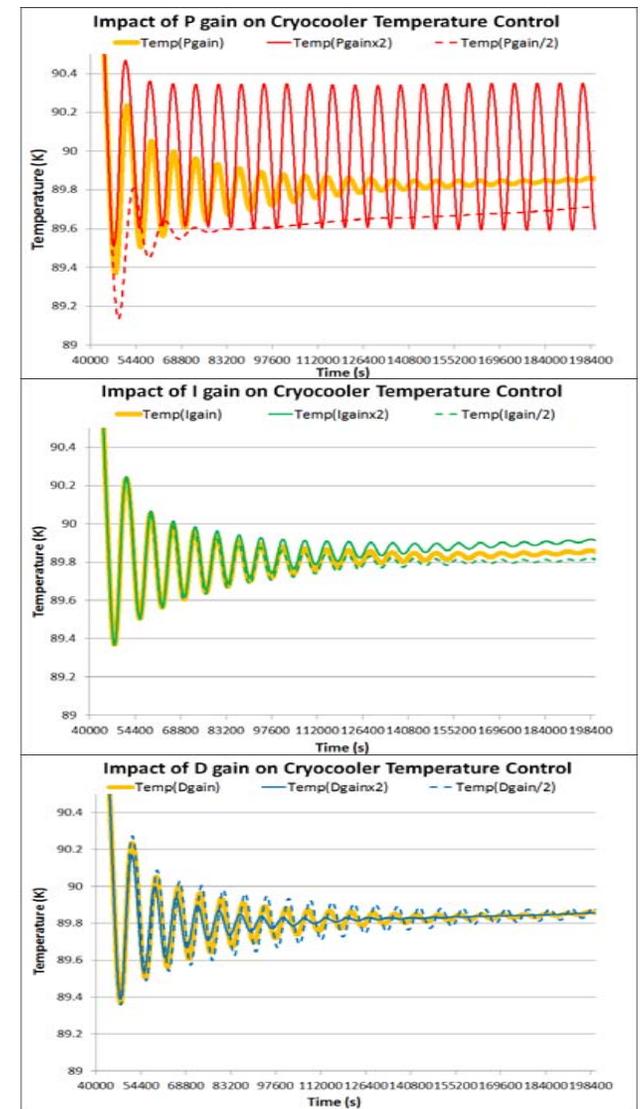
- Two temperature zone, passive thermal design
- Thermally controlled Optical Bench (OB) supports optics, detectors, and element wheel
 - Ethane heatpipes embedded in optical bench connect to radiator. PID heater control to maintain 170 K
 - Incoming light reflects off F1 fold mirror, powered M3 mirror, through Element Wheel (EW), and off F2 fold to Focal Plane Array (FPA)
- Focal Plane Array
 - SiC MOSAIC plate supports 3x6 array of H4RG detectors
 - Methane heatpipes connect to 120 K radiator cool detectors with PID heater control
 - Isolating frame supports MOSAIC plate on one side and Detector Electronics on other
 - Detector Electronics connected to 170 K radiator via Ethane heatpipes
- OB surrounded by Enclosure (Not Shown)



WFIRST Cycle 3 Lesson Learned: *Thermally Modeling a Controller*

- Tight thermal stability requirements for OB and FPA
 - 120 ± 0.01 K over 180 s for FPA, 170 ± 0.5 K for OB
- Thermostatic control not sufficient. Proportional Control in thermal software meets stability but not bulk temperature
 - *PI or PID control needed*
- For PID Control, what Gain values should a thermal analyst use? (not something thermal commonly does)
 - $Power = (P_{GAIN} * E) + (I_{GAIN} * \sum E * dt) + (D_{GAIN} dE/dt)$
 - I_{GAIN} needed to meet bulk temperature requirement
 - P_{GAIN} too high results in oscillations
 - $P_{GAIN} = (Available\ Power) / (T_{Off} - T_{On})$
 - Too small a range results in large P_{GAIN}
 - Larger timesteps in model also can introduce oscillations; decrease P_{GAIN} to compensate. Timesteps in thermal model may not synchronize with actual hardware design

Lesson Learned: For tight temperature control, the inclination to set a small control band may lead to poor performance of a proportional controller. A larger temperature control band will likely improve the stability.



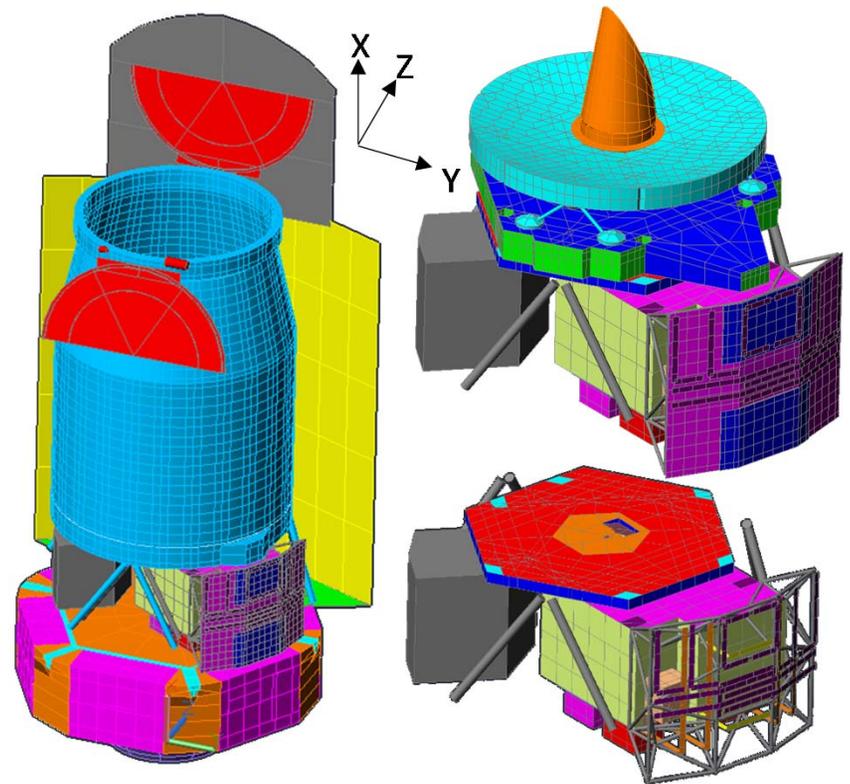


- Team evaluated a new software package designed for optimized Structural Thermal Optical Performance (STOP) Analysis
 - Approach utilized meshing rules and common geometry for thermal and structural model
 - Allows definition of process and specification of meshing rules to use to allow reuse for new designs
 - Potential time savings benefit to reduce time for analysts to develop models
 - However, does require creation of “Analysis CAD” geometry suitable for meshing
- “Analysis CAD” was a new paradigm for the mechanical designer; this kind of geometric simplification is a step often performed intrinsically by the thermal and structural analyst to meet their needs and is often experience based
 - With limited staffing at the time for mechanical design, this placed a significant burden on the primary mechanical designer
 - Had the adverse impact of delaying design evolution from Cycle 3 to 4
 - In the end, WFIRST opted to continue with the present analysis methodologies rather than adopting the new tool to minimize the impact on the design with regards to schedule

Lesson Learned: Efforts to evaluate new tools within the course of normal design work should be performed in parallel by additional personnel if possible to minimize the impact on design evolution.

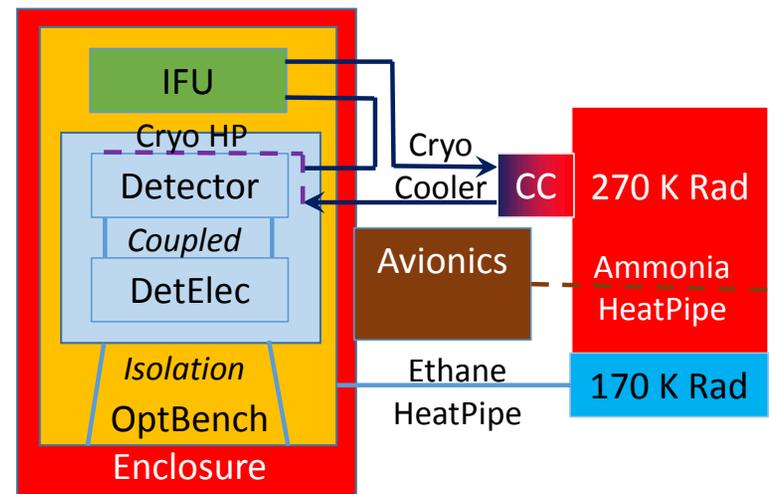
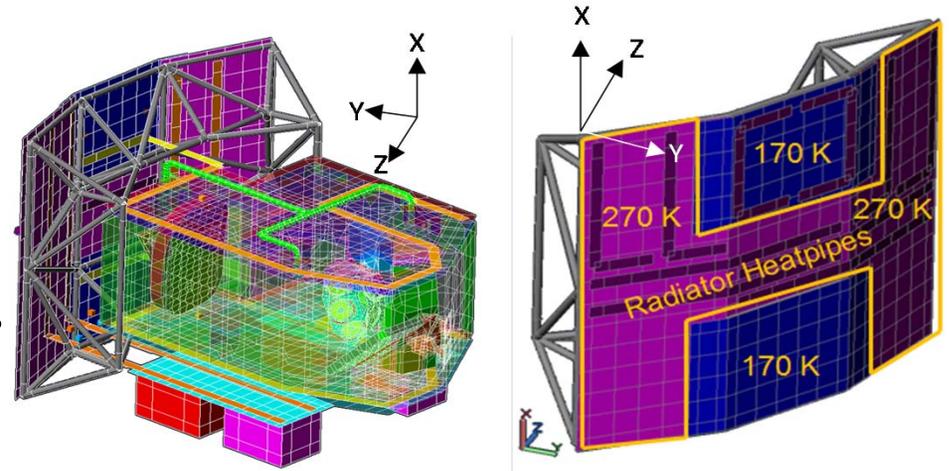


- Instrument Carrier changed from honeycomb top panel with lower frame to just honeycomb top panel.
 - *Latches for instruments moved accordingly. Driven by better structural design for AMS-IC-WFI system*
- Instrument avionics for WFI instrument moved from SC Avionics bay to Instrument
 - *Driven by serviceability and number of wires going across serviceable interface*
 - *Increased mass since Enclosure now needed to accommodate and support instrument side avionics*
 - *Further mass now supported by existing inserts from AMS – constraints of existing hardware still a limitation*





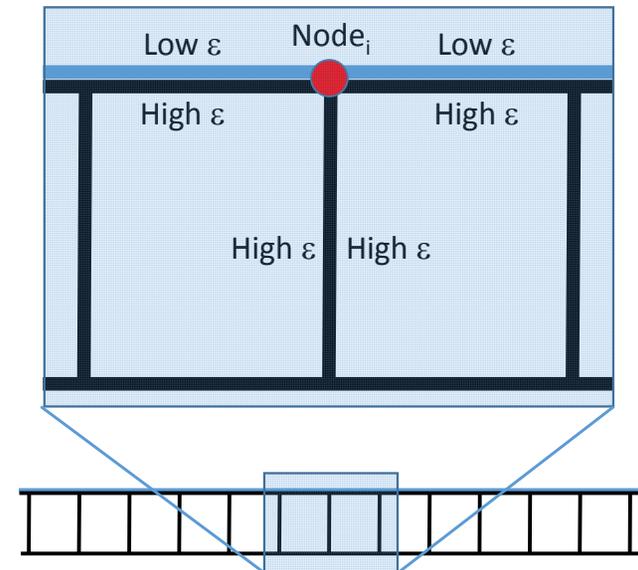
- Detector temperature requirement changed from 120 K to 100 K
 - Active Cryocooler replaced passive radiator
 - Entire FPA assembly including Detector Electronics now cooled. Frame made of high conductivity material. Cryo heatpipe used as transport to heat exchanger
 - Integrating Field Unit channel added
- Instrument avionics for WFI instrument moved from SC Avionics bay to Instrument
 - Driven by serviceability and number of wires going across serviceable interface
 - Increased mass since Enclosure now needed to accommodate and support instrument side avionics
 - Ammonia Heatpipes transported avionics heat to same radiator as Cryocooler
- Top and Bottom Radiators for OB
 - Still uses embedded Ethane Heatpipe





- Evaluation of Cycle 4 predictions revealed that the view of the OBA from the primary mirror was much lower than expected
- Investigations showed that the internal faces of the honeycomb and facesheet surfaces of the primary mirror (PM) were included in both the External and PM Internal radiation enclosures
- For Monte Carlo Ray Trace radiation analyses this is not a problem, unless...
- ...Filtering is used to eliminate negligibly small terms, which is commonly implemented to reduce the runtime of the thermal model
- Software vendors should implement features to allow users to specify critical surfaces exempt from filtering

Lesson Learned: Couplings for the reflective side of critical optical surfaces with both sides active and significantly different optical properties on each side may be eliminated by radiation coupling filtering.



$$\begin{aligned} \Sigma B_{ij} &\approx \textit{Front Surface Top} + \\ &\quad \textit{Front Surface Bottom} + \\ &\quad \textit{Both faces of Ribs} \\ &\approx (4 * A * \textit{Low } \epsilon) + \\ &\quad (4 * A * \textit{High } \epsilon) + \\ &\quad (8 * A * \textit{High } \epsilon). \end{aligned}$$

Front surface accounts for only about 0.8% of emissive capability, which may get filtered



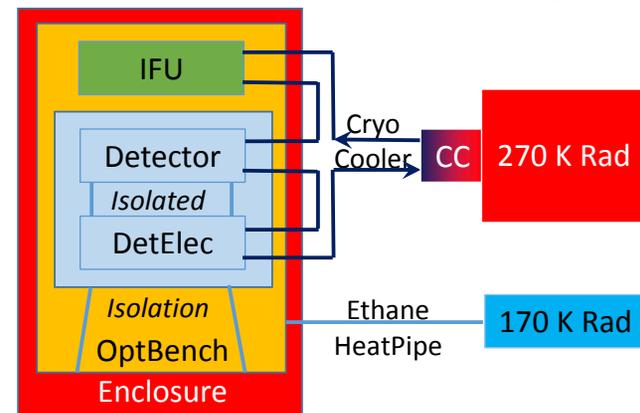
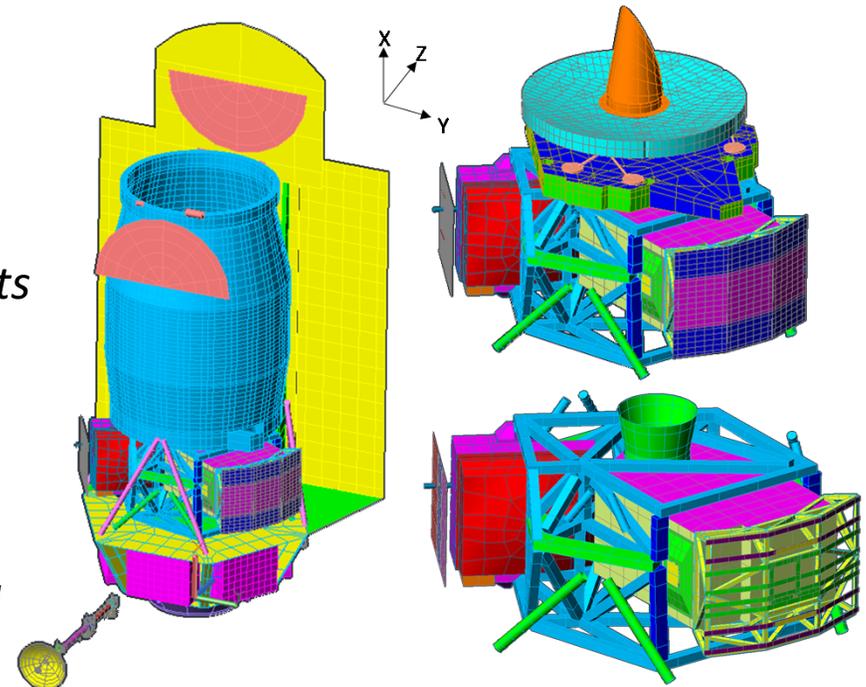
- With the addition of a Reverse Brayton cycle turbomachine cryocooler for the FPA, the coupling to a pumped fluid loop was added into the model
- FLUINT constructs were added to the SINDA model using the FloCAD® module
 - Only the fluid line was included and not the entire cryocooler system
 - No controller was modeled
- Performance curves for the cryocooler were used to estimate the necessary compressor power, electronics power, and mass flow rate to remove the computed heat absorbed by the fluid loop for the desired temperature.
- Initially, both the mass flow rate and initial temperature were used to simulate the flow based on $T_{inlet} = T_{setpoint} - Q / (\dot{m}C_p)$. Setting both \dot{m} and T_{inlet} erroneously resulting in initially cooling the flow near the inlet. The root cause was never fully investigated due to analysis schedule constraints and eventually only the \dot{m} was varied with a constant T_{inlet}
- Future models will include PID control and the compressor FLUINT model

Lesson Learned: In order to predict correct results, it is important to ensure that models account for proper physics and that the analyst fully understands the expected behavior. Furthermore, understanding deficiencies in the model can also help to identify further information needed to improve the predictions

| | | | | | | | | |
|------------|------|------|------|------|------|------|--------|--------|
| Wall Node | ← | ← | ← | ← | ← | ← | Plenum | |
| Fluid Node | ● | ● | ● | ● | ● | ● | ▲ | |
| Wall Temp | 81.5 | 81.4 | 81.3 | 81.2 | 81.1 | | | } TS 1 |
| Fluid Temp | 80.5 | 80.4 | 80.3 | 80.2 | 80.1 | 80.0 | | |
| Wall Temp | 81.5 | 81.4 | 81.3 | 81.2 | 81.1 | | | } TS 2 |
| Fluid Temp | 80.8 | 81.1 | 81.4 | 81.6 | 81.8 | 82.0 | | |
| Wall Temp | 81.7 | 81.6 | 81.5 | 81.8 | 82.1 | | | } TS 3 |
| Fluid Temp | 81.5 | 81.8 | 82.4 | 83.0 | 83.8 | 84.0 | | |



- Major lien against existing AMS loads resolved
 - *New design supports telescope on top using new shorter bipods, removing constraints of existing AMS insert capabilities*
 - *Truss-like structure to support the instruments at the mid-plane*
- Telescope temperature at 282 K
 - *Significant heater power usage*
- Solar arrays now deploy flat
 - *More effective solar array area for increased heater power needs*
- WFI FPA added heat exchanger to cool Detector Electronics downstream from MOSAIC plate
 - *Eliminated need for low TRL cryo heatpipes*
 - *Frame made low conductivity again*
- WFI Avionics moved back to spacecraft module
 - *Significant mass reduction effort*



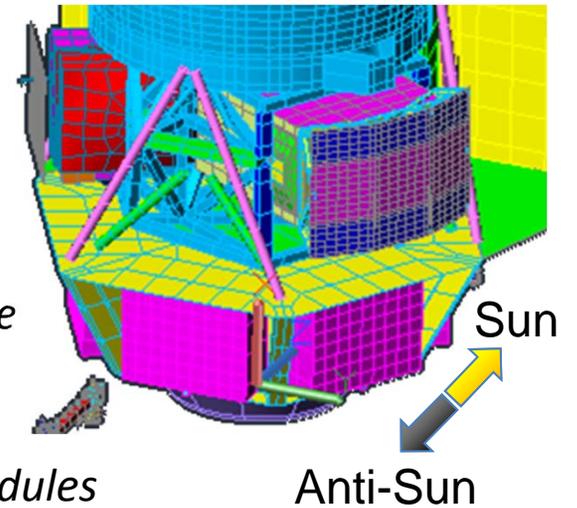


- Limitations of existing AMS for WFIRST needs was a major design driver
 - *Long term issue trying to use existing hardware as designed to meet WFIRST requirements*
- Various options investigated to mitigate these limitations:
 - *Repackaging optics: move F1 and M3 external to instrument volume to reduce mass*
 - *Repackaging avionics and instrument: instrument split into avionics module and optics module while retaining harness connection. Two modules locked together for removal.*
 - *Use of additional existing inserts (over-constraining): additional inserts in AMS “turtle tail” could be used, but not located advantageously*
 - *Re-latching in flight – launch configuration (latched to SC), flight configuration (latched to IC). Flight mechanisms to engage and disengage latches.*
 - *Redesign Instrument Carrier to support telescope and eliminate need for AMS inserts*
- Last option was eventually selected at conclusion of trade studies
 - *Significant efforts and resources were spent through 3 design cycles trying to make existing hardware fit WFIRST’s needs*

Lesson Learned: While use of existing hardware has the appeal of apparent lower cost and schedule impacts, the efforts to accommodate potential limitations of hardware not designed for a specific mission’s needs may result in increased cost, schedule, and complexity elsewhere in the program.



- Another requirement levied on WFIRST is serviceability
 - *What needs to be serviceable and what serviceable means in terms of requirements is not well defined*
- Spacecraft Avionics
 - *With six serviceable bays, only three of them represent effective locations for radiators*
 - *Since each module is structurally and thermally independent, radiator area cannot be shared among avionics in different modules*
 - *Optimization between volume, thermal, and harness could only accommodate packaging and thermal to meet design requirements*
- High wire count across SC to WFI interface
 - *WFI Avionics moved from SC to Instrument for Cycle 4 design: Servicing Implications*
 - *WFI Avionics moved back from Instrument to SC for Cycle 5 design: Mass Implications*
- Significant heater power needs to be provided by servicing vehicle



Lesson Learned: Designing for serviceability should be very clearly defined from the outset, considering many factors such as scope of serviceable components, existing redundancy and reliability, demand from science community for future upgrades, and additional complexity introduced by being serviceable.



Conclusions and Moving Forward

- Conclusions
 - *Design Cycles 3 through 5 have explored the trade and design space prior to formal mission formulation and revealed challenges with respect to reuse of existing hardware and unclear serviceability requirements*
 - *As each design has been thoroughly analyzed through STOP analysis, further refinement of the model has improved the realism and analytical representation of the design*
 - *Risk reduction efforts completed or underway targeting high risk/cost/effort areas*
 - *STOP Analysis software*
 - *Element Wheel and Grism*
 - *Optical Bench Test Demonstrator*
- Cycle 6 Design is underway
 - *Study impact of Earth-Sun Lagrange Point 2 instead of Geosynchronous Orbit*
 - *Trade study for thermally separating Detectors from Detector Electronics cooling paths*
 - *Trade study for possibility of passively cooling detectors at L2*
- Near term schedule (planned)
 - *Internal Concept Review late 2015*
 - *Mission Concept Review mid 2016*
 - *Entry into Phase A in October 2016*



Lessons Learned

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Efforts to evaluate new tools within the course of normal design work should be performed in parallel by additional personnel if possible to minimize the impact on design evolution.

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