UA & UCB-SSL
PEARL IFS DESIGN STUDY

October 23, 2023

Design Study Table of Contents

1. EXECUTIVE SUMMARY

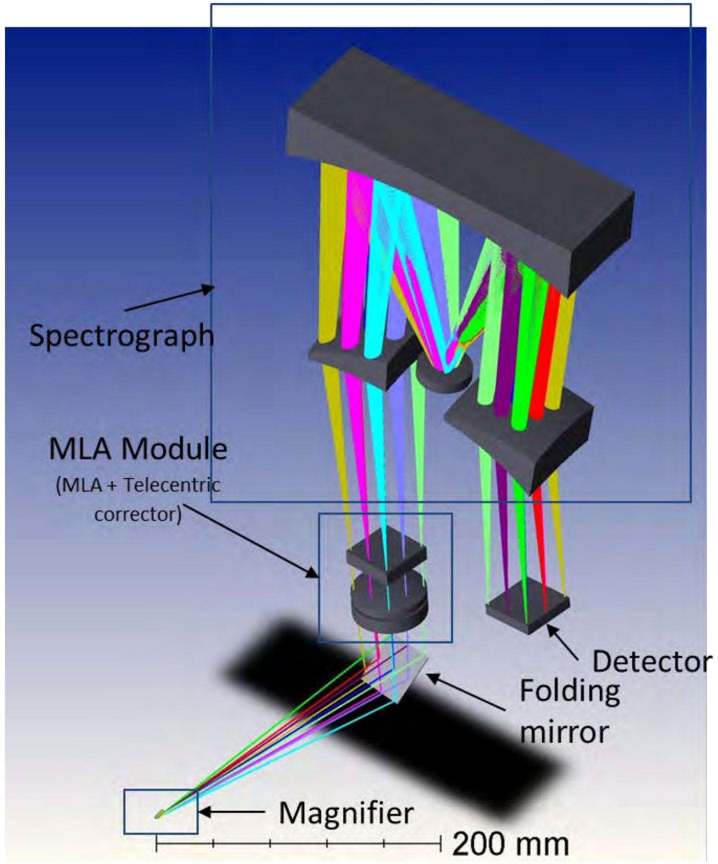
Overview of Pearl IFS Study and what UA and SSL proposed.

The Pearl Project provided University of Arizona (UA) and UC Berkeley – Space Science Lab (SSL) an IFS design that was produced by Laboratoire d'Astrophysique de Marseille (LAM) under a previously commissioned study.

UA-SSL was tasked to produce a design study report to evaluate the LAM design and looked for ways to improve the performance and reduce cost.

The primary deliverable is this Study Report which includes:

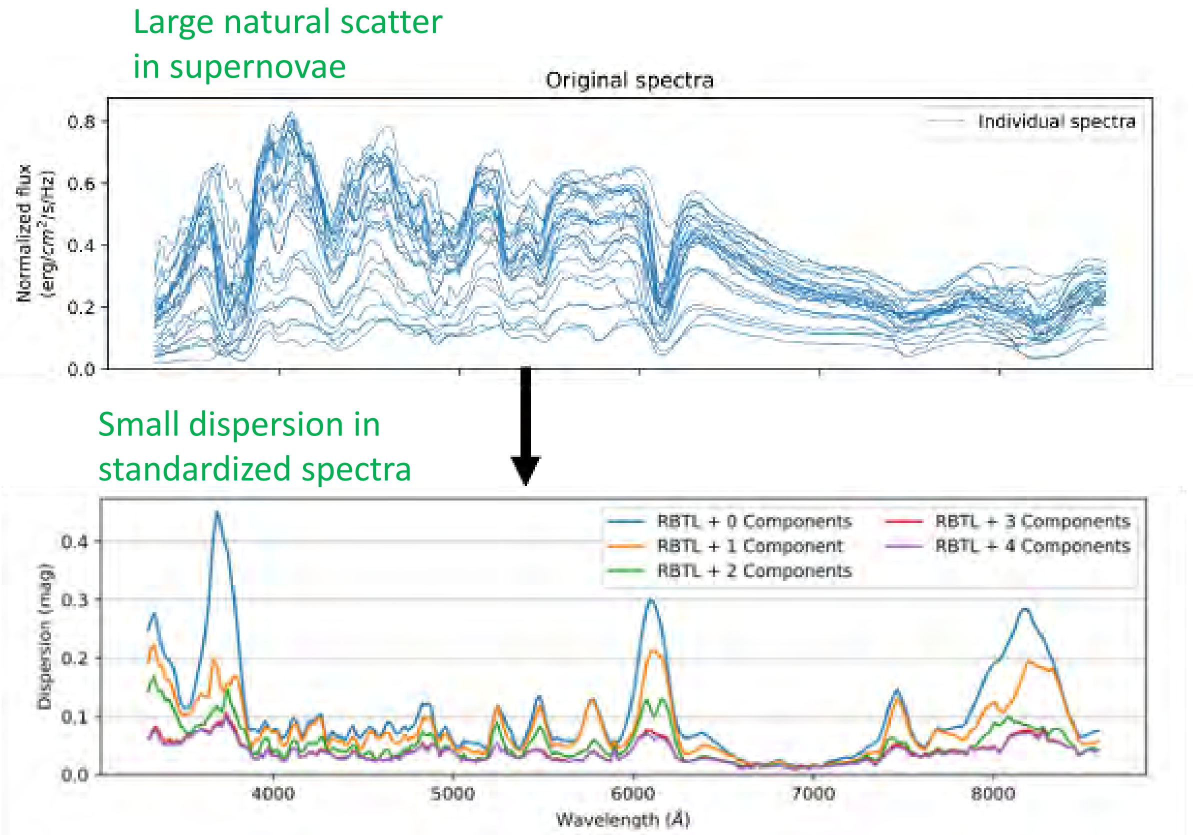
1. A notional IFS design that meets the requirements.
2. An IFS development plan.
   - Management Approach (Program Management, System Engineering, Risk Management)
   - Preliminary Optical and Radiometric Performance Budgets Development
   - Preliminary Integration and Test Plan Development
   - Identification of Key Trades / Descopes / Enhancements
3. Cost and schedule estimates. (Schedule and the costing philosophy is contained here in this package. **Detailed costing will be delivered in a separate package.)**



LAM Spectrograph Design

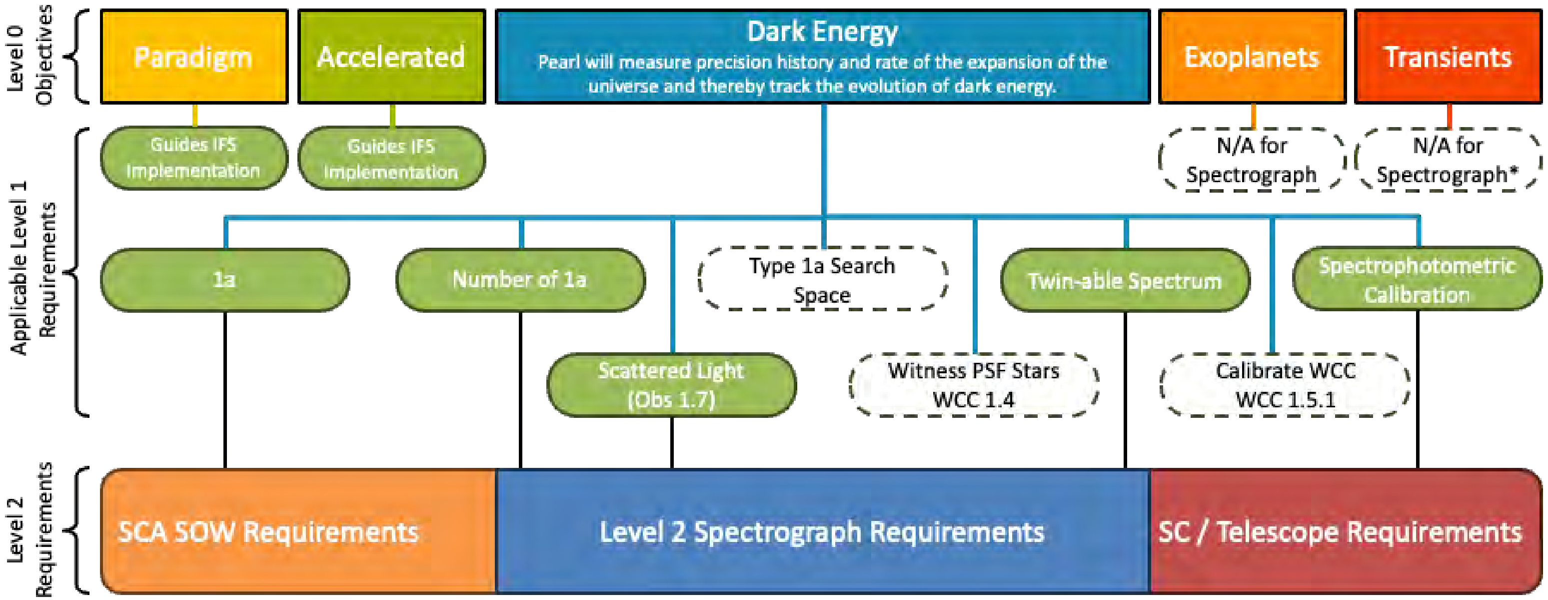
Science Summary

- Spectrograph will observe and measure the spectra of >2500 SN1a targets to better constrain the Dark Energy Equation of State (Science Objective 2)
- Increasing the number of Supernova observations will allow better characterization and classification of SN1a
  - Better characterization of SN1a will reduce error in use of SN1a as standard candles.



Requirements Flowdown

- Comprehensive requirements flowdown and finalization requirement early in the program is key to successful instrument delivery.
- Requirements flowdown process is well underway
    - Identified possible missing L2 Spectrograph requirement
    - Key and Driving Level 3 Requirements outlined.



Compliance Matrix - Summary

ID	Title	Requirement Text	Compliance / CBE	Notes
IFS 2.1	Spectrograph Spectral Bandpass	Simultaneous spectrophotometric measurement over the entire continuous, well calibrated 0.4-1.7µm wavelength band.	Comply	Dependent on detector performance (not under Spectrograph control)
IFS 2.2	Spectrograph Spectral Resolution	Spectral resolution (L /dL) >100 at all wavelengths and spaxels.	Comply (CBE: ~103-280)	Analysis / Design work ongoing to add additional margin
IFS 2.3	Spectrograph Spatial Sampling	Accommodating a range of scale such that the spatial resolution samples a telescope PSF ranging from the diffraction limit (DL) to 6 x DL at 1um, e.g. scales ranging from 0.020 to 0.050 arcsec per spaxel. The scale is expected to be selected in-flight and static thereafter.	Comply (CBE, 3 magnifications 0.020, .030, 0.050 arc, nominal)	Preliminary magnifier design complete.
IFS 2.4	Spectrograph Spaxel Format	Maximize the number of spaxels, with a minimum of 50 x 50 spaxels (for a MLA type design).	In Assessment (CBE 49x45)	Analysis and design work on going to identify correct design within parameter space (focused on spaxel packing design).
IFS 2.5	Spectrograph FOV	IFS shall have a minimum field of view of 1.0 x 1.0 arcsec at the finest sampling scale.	In Assessment (CBE 0.98” x 0.90”)	Analysis and design work on going to identify correct design within parameter space (focused on spaxel packing design).
IFS 2.6	Spectrograph Spaxel Cross-Contamination	Minimize cross contamination between neighboring spaxel’s spectra on the detector to < 2% (TBR), including diffraction.	Expect Compliance	Optical simulations in progress. Early modeling suggests compliance with margin in spectra separation.
IFS 2.7	Spectrograph Nyquist Sampling	Nyquist sampling or better for each spaxel spectral element and cross-dispersion profile at the detector.	Expect Compliance	Optical simulations in progress. Early modeling suggests compliance.

Compliance Matrix - Summary

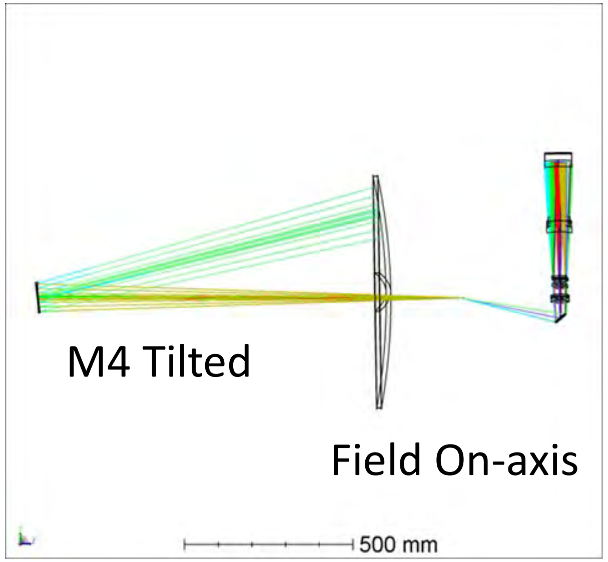
- Compliance against each of the key requirements was assessed for the study
  - Compliance for some requirements still marked as TBD – requirements design analysis that will be completed once design is more mature.
- Spectrograph team expects to be compliant with all requirements
  - No open requirements are showstoppers for implementing the spectrograph design – their CBE assessment is considered work to go.

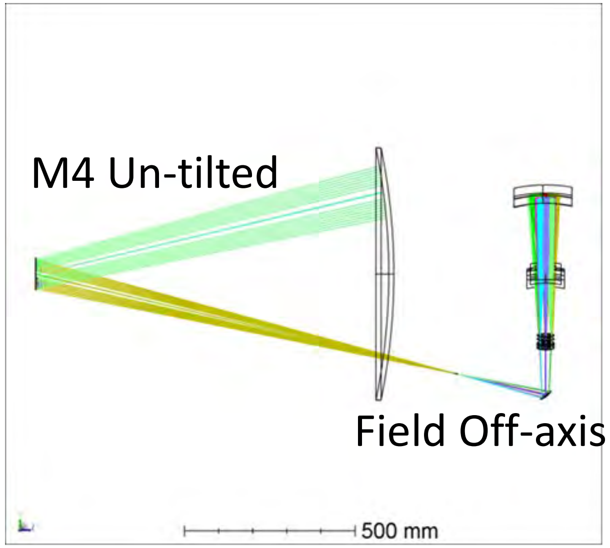
ID	Title	Requirement Text	Compliance	Notes
IFS 2.8	Spectrograph Spatial Stability	Predictably maintain spaxel spectral location within 1/10 pixel and spaxel trace width variation to within 3/10 pixel, given example optical and thermal environment perturbations over > 2h duration (and goal 10h).	TBD	Structural / Thermal Analysis in work.
IFS 2.9	Spectrograph MLA Fill Factor	A fill-factor for IFU focal plane segmentation of > 95% minimum. Goal > 98%.	Comply	Based on vendor discussions and capabilities.
IFS 2.10	Spectrograph Optical Throughput	Total optical throughput of > 50%, and 80% nominal, maximized for L > 1 um.	Comply (~65% min across bandpass)	
IFS 2.11	Spectrograph Thermal Background	Control on thermal background to ensure that on-orbit variations are << detector statistical and systematic errors, e.g. nominally < 0.005 e-/pix/sec; preferably < 0.002 e-/pix/sec.	TBD	Structural / Thermal Analysis in work. STOP and Radiometry analysis to start during flight study phase.
IFS 2.12	Spectrograph Stray Light	Internally scattered light of <1% of the input signal reaching the detector within its effective spectral response range.	TBD	Stray Light analysis in work.
IFS 2.13	Spectrograph Calibration	On-orbit capability for measuring spectral calibration (to L/1000), count rate non-linearity (at several wavelengths) and sensor flat fielding.	TBD	
IFS 2.14	Spectrograph Electronics	Electronic and calibration units are separate and likely distant (~5 m) from the optics bench.	Expect Compliance	Compliance based on heritage electronics and calibration unit designs.

Evaluation of LAM Design and Deficiencies

- During the evaluation we found two major deficiencies:
  - The LAM design did not meet the resolution spec of R>100 (LAM was R = 75) over the 400nm to 1.7 micron bandpass.
  - The LAM design did not use the correct offset position in the telescope focal plane (LAM was on center) and had a 26 deg tilt of the telescope M4 that was not correct (M4 tilt should be 0 deg).
- Those two deficiencies precipitated a new optical design and mechanical layout, which is presented here.

LAM Design



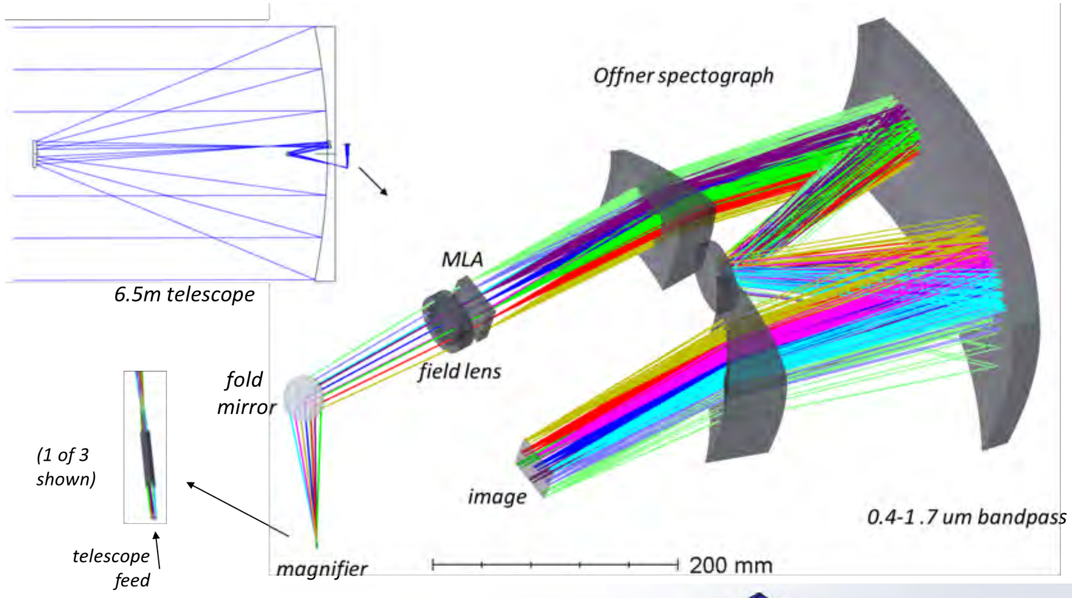


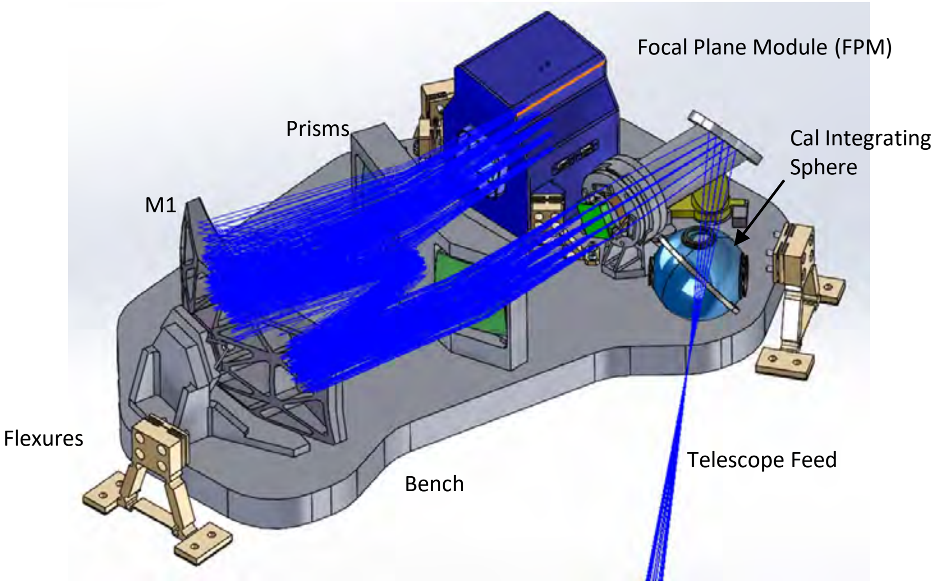
UA-SSL Design

Pearl IFS Design Overview - Optics/Optomechanical

The Pearl Integral Field Spectrograph (IFS) design considered in the present study is:

- An Offner style Spectrograph.
- Utilizies a micro-lenslette array as the Integral Field Unit (IFU) to sample the magnified telescope image.
- Prisms then disperse the light before it is projected on the Teledyne H4RG detector.
- The Offner reflective elements are spherical, reducing cost and fabrication time.
- The bench is aluminum construction with titanium optical mounts.
- Flexures on the interfaces between the bench and Instrument Optical Bench (IOB, not shown) and flexures between the Focal Plane Module (FPM) and bench, reduces strain induced movement due to the temperature differentials between those parts.
- The calibration lamps will be located remotely and then fiber coupled into the Cal Integrating Sphere. A flip in mirror will then be used to select between the telescope or calibration feed.





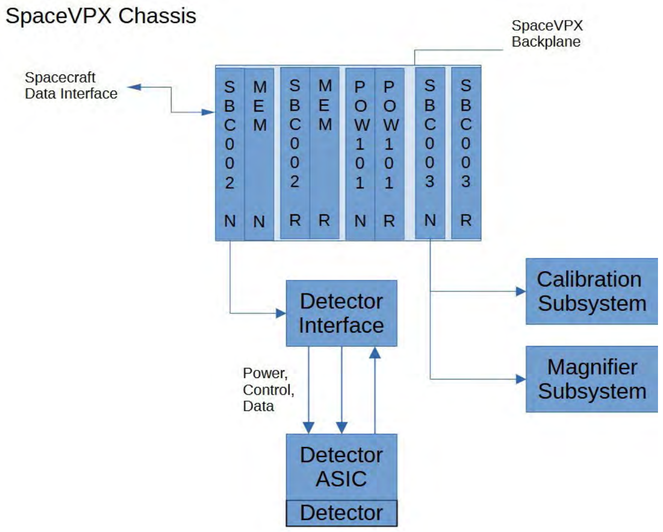
Pearl IFS Design Overview - Electronics/Software

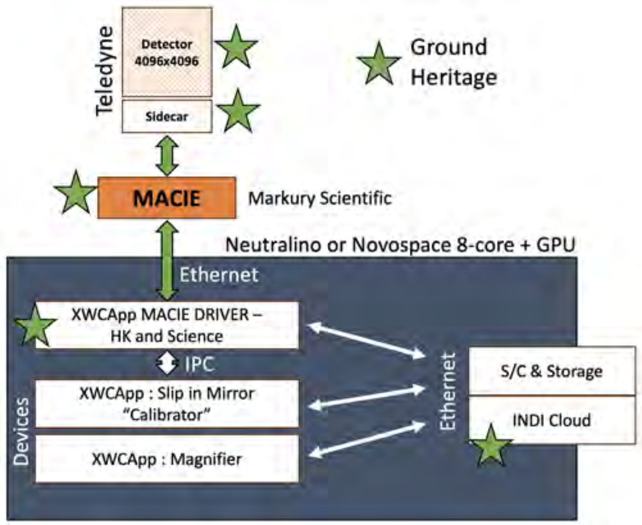
The Pearl Integral Field Spectrograph (IFS) electronics design summary:

- Computing and large heat sources will be mounted away from the IFS,co-located with all the S/C electronics.
- Plan is to have a Space VPX compliant system.
- Two systems are being traded Novo Space and Neutralino.
  - Both companies offer Space VPX complaint backplanes and computing solutions with ARM based processors.
  - The NovoSpace solution is attractive as it has an FPGA that could be used to run the firmware to control the Teledyne ASIC.
  - Neutralino is attractive as it is baselined for the Coronagraph and Wavefront Control and Context Camera (WCC) instruments.
- Both systems can utilize a 1 Gb or 10 Gb data interface.
- Both have capabilities for data storage if needed.
- Power requirements is <80W with a 28V nominal input.

Software design summary:

- Based on software being developed for the Coronagraph and WCC.
- Software uses heritage ground-based astronomy application and ports it for space-based reliability.
- The Sidecar is attached to a MACIE board that provides a network interface to our onboard network.
- Our onboard computer with 8-cores and a GPU will run the INDI-Server software and application that will communicate with the MACIE through a well documented API.
- Data handling will have 3 levels, no compression (raw sci data), lossless compression, cal with science oversight.





Facilities and AI&T Summary

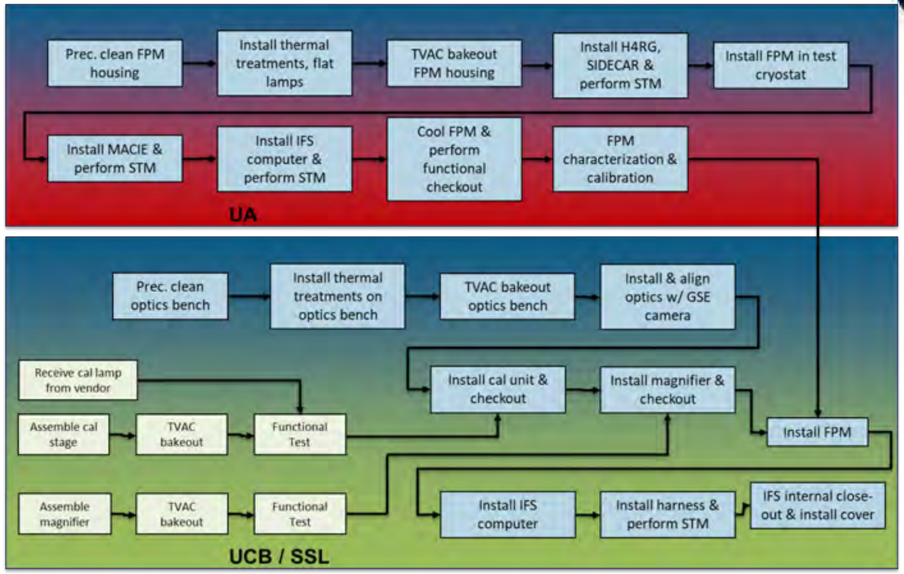
Facilities:

Both UA and SSL have excellent facilities for the mission.

- Ample clean room space and flow benches foir AI&T activities.
- Thermal Vacuum Chambers (TVAC) both large and small for testing the FPMs and larger instrument assemblies.
- Access to vibration tables for component level and full assembly vibe.
- Bottom line we have the facilities and equipment to carry out what we want to do on the IFS.

AI&T

- IFS assembled and aligned at SSL, while FPM work occurs in parallel at UA.
- Develop an instrument alignment plan that allows for late integration of the FPM. Instrument level env. testing will occur ASAP after FPM delivery to SSL.
- We assume that minimal environmental testing is done at the integrated payload and observatory levels.
- Develop EM/qual units for new designs, qualify to proto-flight levels…. Avoid over-testing of the FM instrument!
- Assume there is no CLA cycle that provides realistic loads for the instrument. Team plans to be strategic about where PF level testing occurs.

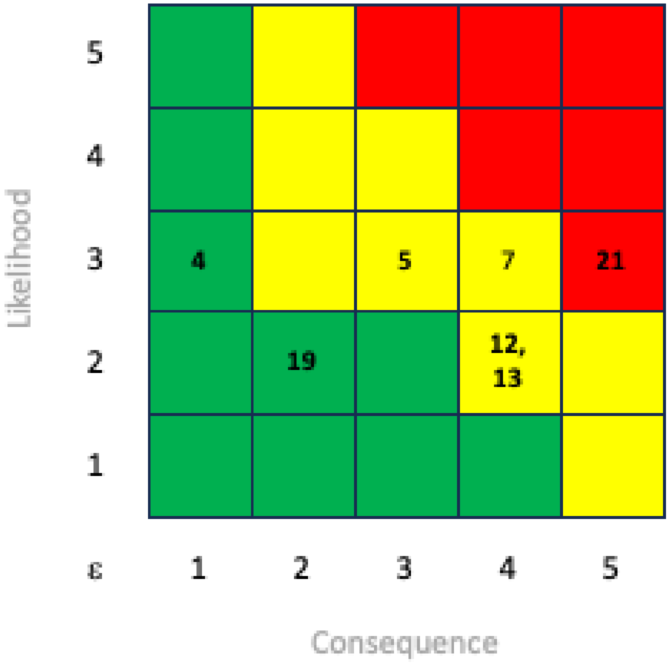


Example test crysostat for H4RG.

SNAP FPM Test chamber in SSL optics lab.

Key Risks Summary

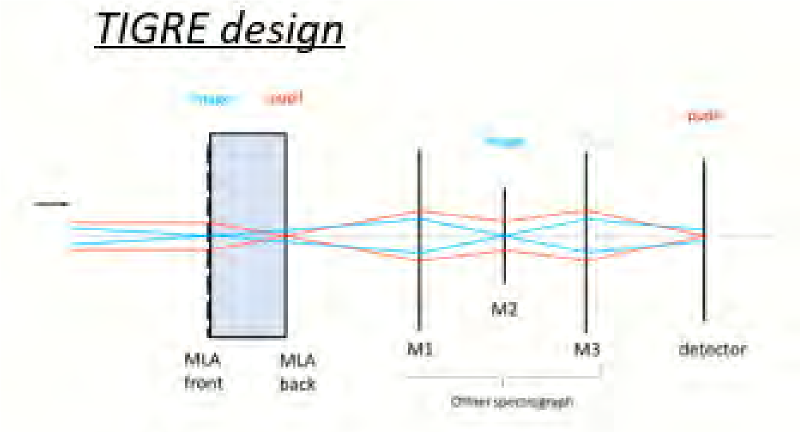
ID*	Risk Title	Full Risk Statement
4	Stray Light Modeling	If the stray light of the spectrograph cannot be accurately modeled due to the complexity of modeling certain optical components, then the stray light of the as-built spectrograph will exceed the stray light requirement and degrade the sensitivity of the spectrograph.
5	Spectrophotometric Calibration Components	If the components of the spectrophotometric calibration budget cannot be measured well enough due to resource limitations (time, money, or people), calibration requirements/allocations which are too stringent, or calibration components not accounted for / misallocated then the spectrograph will not be able to meet the Level 1 Spectrophotometric calibration requirement and ultimately the science goals of the mission.
7	TIS Delivery Date	If the flight model H4RG is delivered after promise date due to unforeseen production delays at Teledyne Imaging Sensors, then then the delivery schedule for the Spectrograph will be delayed.
12	Performance Margins	If the Spectrograph team does not hold and control its own margin and there is insufficient margin in the Level 2 allocations/requirements (sensitivity, resources, etc.) held and controlled at a higher level, then the ability of the Spectrograph team to mitigate any technical deficiencies in the Spectrograph design and/or performance by utilizing margin is reduced and would result in additional schedule and cost to rectify the deficiencies.
13	Unstable Requirements	If changes to the spectrograph design are needed after the start of implementation due to changing or new requirements / interfaces then additional cost, schedule and resources may have to be utilized to implement a new design to meet the updated requirements / interfaces.
19	Streamlined I&T Approach	If a spectrograph subsystem does not meet requirements due to deferred testing until higher-level of assemblies, then cost, schedule, and resources may have to be utilized to update the design to meet the updated requirements or technical margins will have to be utilized to make up for the deficit.
21	New Paradigm	If the Spectrograph has difficult implementing the "New Paradigm" approach due to not sufficient budget/schedule margins, technical challenges in engineering implementation, incorrect balance in management streamlining (etc), then the spectrograph will not be delivered on budget or schedule.

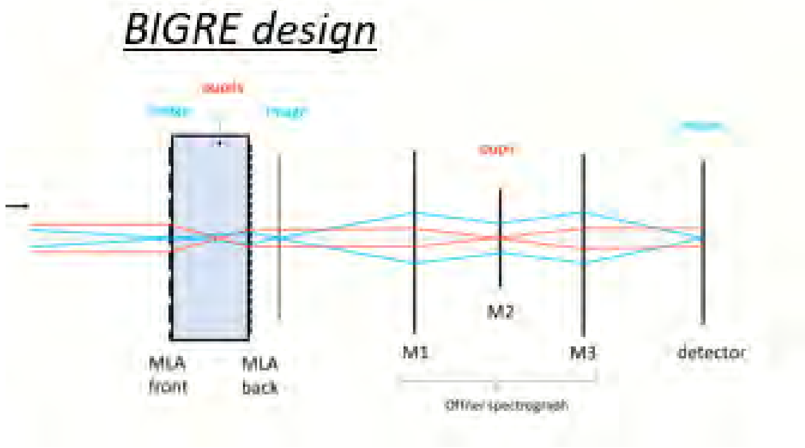


Level	Likelihood	Consequence
1	Remote (<1% chance)	Negligible <1% loss of margin
2	Unlikely (1-10% chance)	Minimal 1-10% loss of margin
3	Possible (11-50% chance)	Moderate 11-50% loss of margin
4	Likely (51-70% chance)	Significant 51-100% loss of margin
5	Highly likely (>70% chance)	Margin Exhausted

Major Trades Summary

- BIGRE vs TIGER Optics Design for the Microlenslette Array (MLA)
  - TIGRE avoids spatial-spectral degeneracy in detector spots, better for spectrophotometric accuracy and the MLA is simpler.
  - BIGRE (current baseline), BIGRE can mask diffraction, and allow denser packing of spectra. It is incompatible with an adjacent-magnifier scheme, drives the use of mechanism for the magnifier.
- Slicer vs MLA Spectrograph Design
  - Open trade, more information will be provided in a later design package.
- Instrument Test / Calibration Campaign
  - Open trade on looking at where we will need testing at the component level versus assembly level testing. Tradeoff here is cost versus risk. Component level testing is more expensive, but with less risk. Continue to look at during design phase.

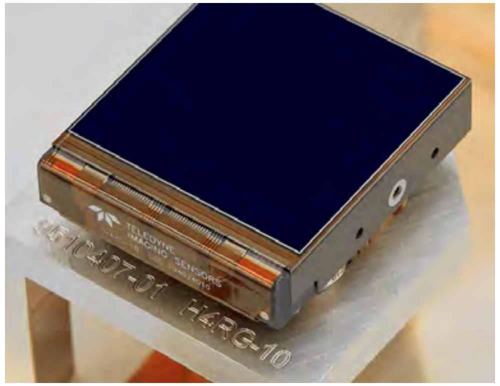




Interface Development Plan - Summary

- Interfaces will be developed in parallel with requirements.
- Comprehensive definition and finalization of interfaces early in the program is key to this new paradigm for instrument delivery
  - Instrument uncertainty will delay finalization of design elements of the Spectrograph and increase schedule and budget risks.
  - Underallocated resources will increase schedule and budget risks due to additional engineering effort needed to mee accommodations.
  - Risk 13 identified to track and mitigate this risk
- Interface development process includes both external and internal interfaces
  - Work with team to identify interfaces throughout the system.
  - For identified interfaces, start defining “what we need” of the interface or match interface with corresponding HW/SW
  - After UA selection, system engineering team will start engaging internal and external teams to definitize all interfaces.
  - Implementing interfaces in design.

Detector - Summary

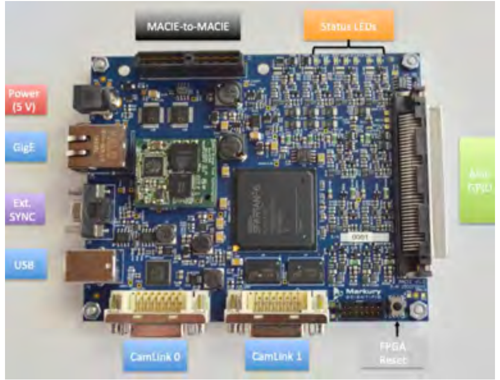


Detector: Teledyne HAWAII-4RG 10-µm pixels (H4RG-10)

- 4096 x 4096 pixels (10 µm pixel size)
- 1.7-µm cut-off
- Expected operating temperature of T~120K
- **Study team has decades of collective experience characterizing and integrating HAWAII arrays, for both ground and space applications (e.g., LBTI, JWST, NEO Surveyor)**

Cold Readout Electronics: Teledyne SIDECAR ASIC

- Provides clocks, biases, and register configuration to H4RG
- 32 amplifiers for simultaneous digitization of output signals
- Provide pixel clock speed of 200 kHz (t_{frame} ~ 3.0 sec)
- **UArizona detector scientists tuned and optimized JWST NIRCam SIDECARs for low noise operations, and those in LBTI LMIRcam and SHARK-NIR for high-speed pixel clocking**



Warm Controller: MACIE board by Markury Scientific (Markus Loose)

- Communication interface to SIDECAR
- Gigabit network communications
- Mature and easy to use C/C++ API library on Linux-based systems
- **Due to ease of use, robustness against errors, and flexibility in operations, the MACIE controller has become a favorite for ground-based instrument scientists**

Detector Test Plan - Summary

Identify and prioritize primary contributors from detector and electronics to the radiometric error budget.
These priority tiers are notional and subject to change based on discussions with science team.

Tier 1

- Read noise detector map (ie., per pixel)
- Total noise for 180-sec integration ramps
- 1/f noise contributions per readout channel
- Dark current map at 120K
- Flat field map (pixel-to-pixel variations, crosshatching structure)
- Linearity corrections per pixel
- Operability and defects (RC pixels, dead pixels, hot pixels, etc)
- Persistence maps at 120K as a function of fluence levels & dwell times

SIDECAR ASIC Optimization

- Tune detector control bias for low noise
- Measure preamp noise at 100kHz and 200kHz pixel rate
- Digitize SCA’s dynamic range within linear response of preamp DAC
- Minimize reference instability
- Adjust digitization timing to minimize smearing of pixel analog signal

Tier 2

- Interpixel capacitance (IPC)
- Conversion Gain (e^-/DN)
- Well depths
- Reciprocity failure
- Charge diffusion / pixel crosstalk
- Brighter-fatter effect
- Charge migration from saturated pixels

Tier 3

- Dark current maps as function of temperature
- Flat field maps as a function of wavelengths
- Quantum yield versus wavelength
- Diffusion as a function of wavelength
- Persistence as a function of temperature
- Burn-in “inverse persistence”
- Electronic crosstalk

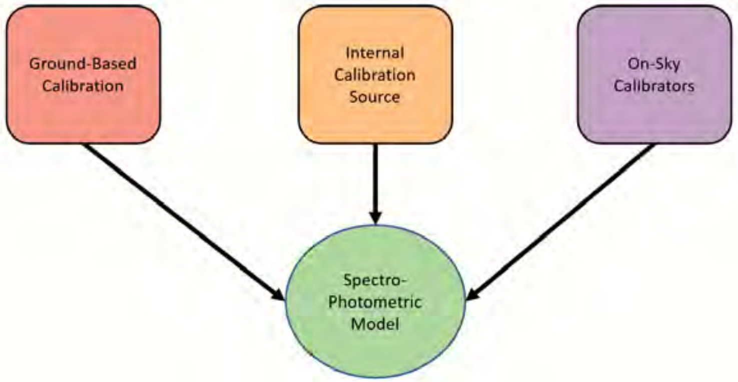
Calibration and On Orbit Checkout - Summary

Calibration

- The calibration starts with the ground calibrations of the detectors and internal calibration unit components. Then, the fully integrated system is calibrated with a telescope simulator and internal calibration unit
- The wavelength, spectrophotometric and spaxel mapping model, as well as raw data are archived for comparison on-orbit
- Initial estimates of the contributions of random and systematic noise in the system (e.g read out noise and non-linearities in the detector) will be assessed to update the calibration budget
- The internal calibration source is then used to shift the spectro-photometric calibration model on-orbit, as well as routinely assess stability, the systematic noise and allow that noise to be removed from the science data when it is processed.
- The on-sky calibrations, on known astronomical sources, will be used to update the flux model as well as assess
- systematics in the overall telescope.
- All these calibration techniques improve the quality of the science data.

On Orbit Checkout

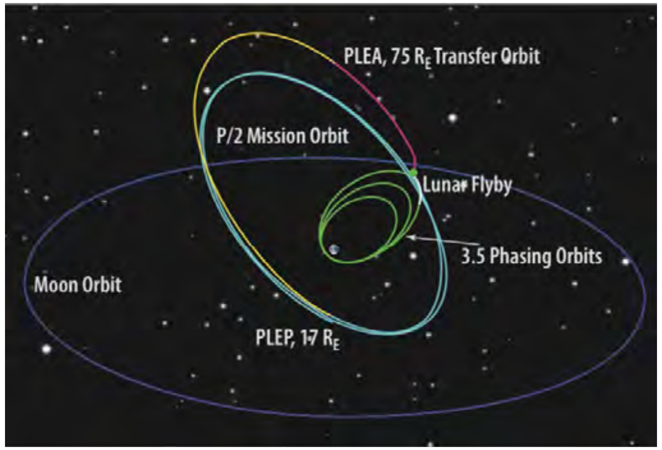
- Involves a number steps to check the systems overall health and performance once on orbit.
- The first is to power on the system and go through the calibration steps, make sure we can
- point and how well we are aligned with the rest of the telescope.
- Do all the actuators respond, has there been any change in the system during launch,
- how much does the calibration function change between the ground, internal
- and on-sky calibrations, what is the quality of the PSF is the image stable, etc.
- The full plan will be developed as we proceed with the flight system phase.



High Level Concept of Operations – Summary

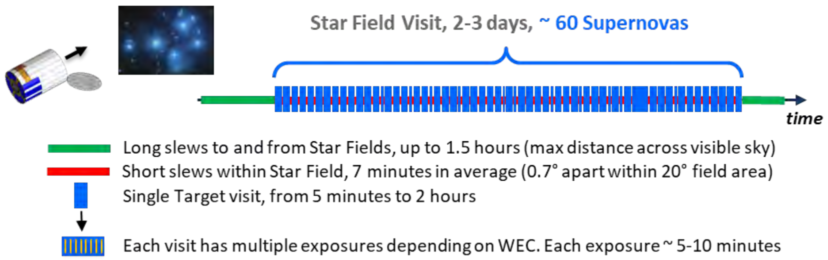
- Pearl orbit
  - High-Earth TESS-like orbit
  - 13.7-day orbital period
  - 2:1 resonance with the Moon
    - Pearl orbits Earth twice for every time the Moon orbits once
  - Enables long observation arcs
  - Low radiation environment

- Mission ConOps
  - Uplink observing sequence (typically every ~5 days, special targets ~1 day)
  - Downlink quicklook data (~every day)
  - Downlink all data 4TB stored in S/C memory during dedicated telecom passes (once / orbit)
  - Mission ConOps levies minimal requirements on Spectrograph



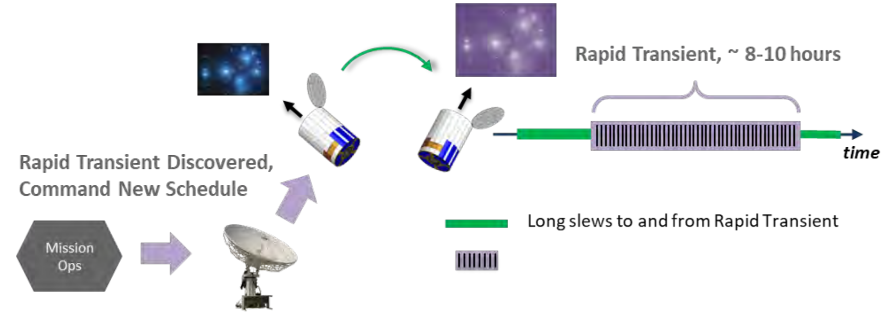
Slow Transients

- Supernova Fields, Exoplanets, Solar System Objects, Public Science Requests
- Observations can be scheduled 1-2 weeks in advance



Rapid Transients

- Gravitational waves, neutrino bursts, fast radio bursts, gamma ray bursts
- Once discovered, rapid transient is localized by wide-field-ground base telescopes before STP can be commanded



Single point-and-stare with multiple exposures

Top Level Team Organization - Summary

- IFS Project Team led by PM
  - Responsible for overall project performance on cost, schedule and performance of final product.
  - Primary POC for project.
  - Responsible for procuring and managing external vendors
- Technical Team led by Lead Engineer
  - Responsible for coordination and allocation of resources for the technical team.
  - Responsible for technical direction of external vendors.
- IFS Instrument Scientist
  - Responsible interface to the Project Science Team.
  - Gives direction to Lead and Systems Engineers on science requirements.
- Lead Systems Engineer
  - Responsible for assuring technical requirements are tracked and met, tracking technical trades and risks.

Program Management Philosophy - Summary

Tailor ground-based instrument management style to achieve a low-cost space instrument.

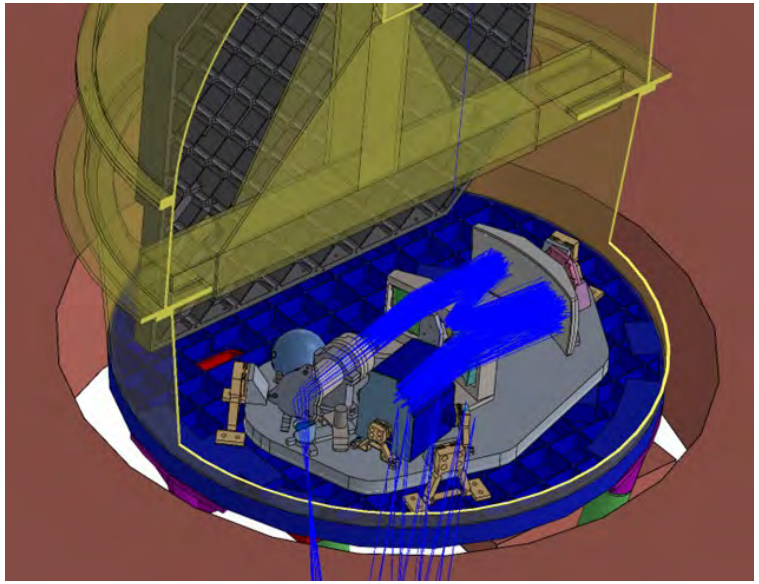
- Small focused teams for Systems, Optomechanical, Electronics, AI&T, and Software.
- Tailor Reviews
  - Minimal formal external reviews (SRR, PDR, CDR, etc.), <u>only those that the customer wants.</u>
  - Use tabletop reviews with SMEs, pushes progress and keeps team headed in the right direction (successful for Pearl Telescope and ESC/WCC).
- Use the synergy with the other Instruments and Telescope Teams to our advantage.
- Communications
  - Due to geographical diversity (only 1 time zone between Tucson and SSL) use Teams & Slack to keep communications timely.
  - Regular f2f meetings for the groups. Plan less frequent f2f for entire team.
- Minimize documentation
  - Only the required procedures and reports to document the work (final optical & mechanical design, thermal analysis, AI&T plan/results, etc.)
- Configuration control only final design documentation/drawings. Changes require cognizant engineer, SE and PM approval.
  - SOEDMS and SharePoint for repositories and document share.
- No Safety & Mission Assurance (SMA) effort will be applied to the effort. We will experienced engineers and technicians using their best practices to deliver quality product (only way to deliver the IFS at the price point).
- Issue tracking with be performed in GitLab.

Program Management Schedule & Costing - Summary

- Schedule
  - Use MS Project
  - Detail WBS to Level 3 using bottom-up approach with input from discipline leads.
  - Iterate on task duration and resource allocation to ensure delivery early in 2026.
  - Forms baseline schedule for Flight System Phase.
  - Re-assess and update task progress on a weekly basis to catch issues early.
- Costing
  - Study Basis of Estimates
    - Excel spreadsheet containing labor rates and estimated hours.
    - Where practical, get ROMs from vendors on major hardware. Use costs from similar recent projects and/or engineering experience in case we are unable to get firm estimates during the study period.
    - Both institutions have extensive capabilities so we will perform cost trades between the institutions to get best price for engineering/fabrication/AI&T tasks.
  - Monthly Risk Management Assessment to form robust risk register and to inform the Project of cost and schedule liens as well as any opportunities.
  - Track costs monthly based on actuals/projections to minimize chance of overruns.
  - Update ROM costing as firm quotes become available.

Development Plan - Summary

- The development plan is to continue with smaller based internal reviews during the Flight Study Phase. We will use table-top reviews with SMEs to inform our design choices.
- Early in the design phase we will start our Long Lead procurements, specifically the development of the MACIE firmware porting to the Zync FPGA.
- After finalizing the reviews, we will start to receive quotes on nominal lead items and move into fabrication.
- The FPM work will proceed in parallel at UA while the other components are built and tested at SSL.
  - FPA work will start with the MACIE boards we have available as we wait for ported firmware.
  - Testing on the engineering FPA will occur as EDU detector arrives. The engineering FPM will be built up and then shipped to SSL once the FDU arrives for form/fit/function.
  - In parallel the flight FPM will be tested and characterized at UA before shipping to SSL for final integration.
- Final integration and testing will then be performed at SSL culminating with final delivery to UA for final integration into the instrument package.
- The team will support the integration and final alignment in the telescope as needed. The post delivery support is beyond the scope of this study.



IFS integrated in Instrument Package

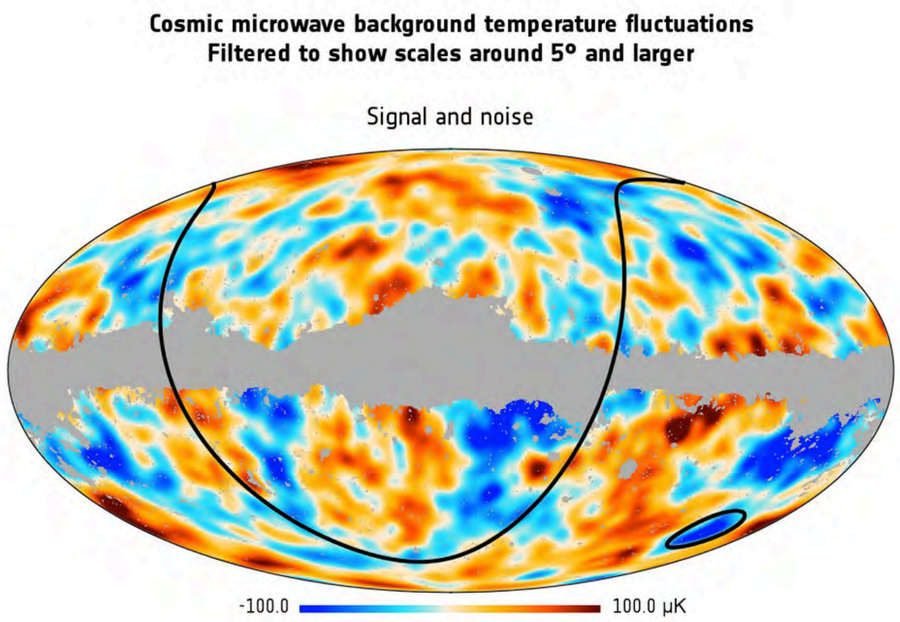
2. SCIENCE, SYSTEMS APPROACH, TOP LEVEL REQUIREMENTS AND SCIENCE REQUIREMENTS FLOW DOWN

Science, Systems approach, Top Level Requirements and Science Requirements Flow Down (Outline)

- Science Overview
- Systems Engineering Approach
- Top Level Requirements
- Science flow down
- Compliance Table

Driving Science Goal

- 69% of the Present-Day Universe is Dark Energy
- What is the equation of state of Dark Energy?
  – Characterize the expansion rate of the Universe
    - Use Type Ia SNe Calibrate-able Candles



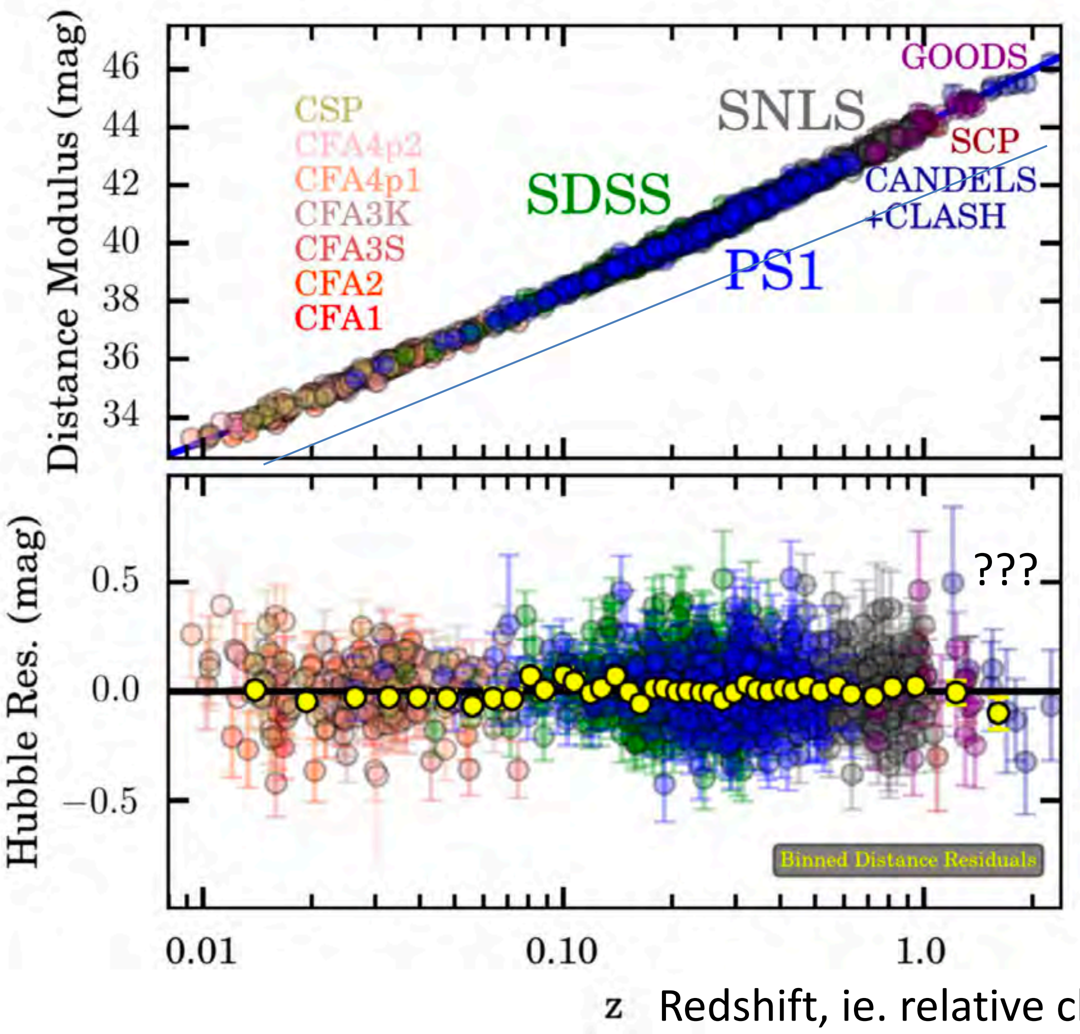
Eg. Planck Collab et al. 2018

https://sci.esa.int/web/planck/-/61397-the-cmb-temperature-on-large-angular-scales

Look at SNe Ia back in time for deviations from w=-1

Distance, According to Measured Flux

Residuals from Best-Fit Cosmology (consistent with w=-1)

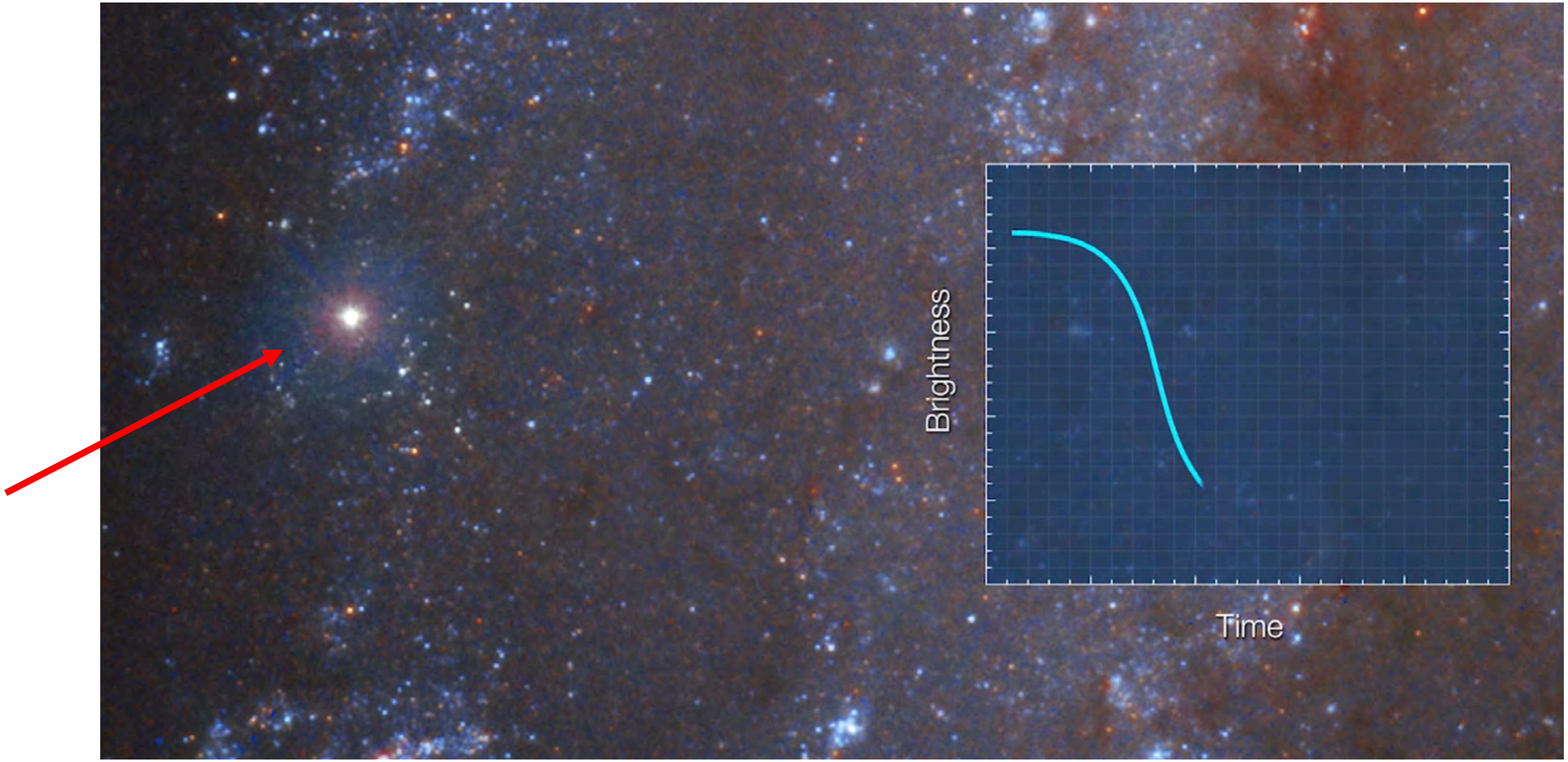


New techniques and observations can decrease scatter

Redshift, ie. relative change in scale of the Universe

Scolnic et al. 2018

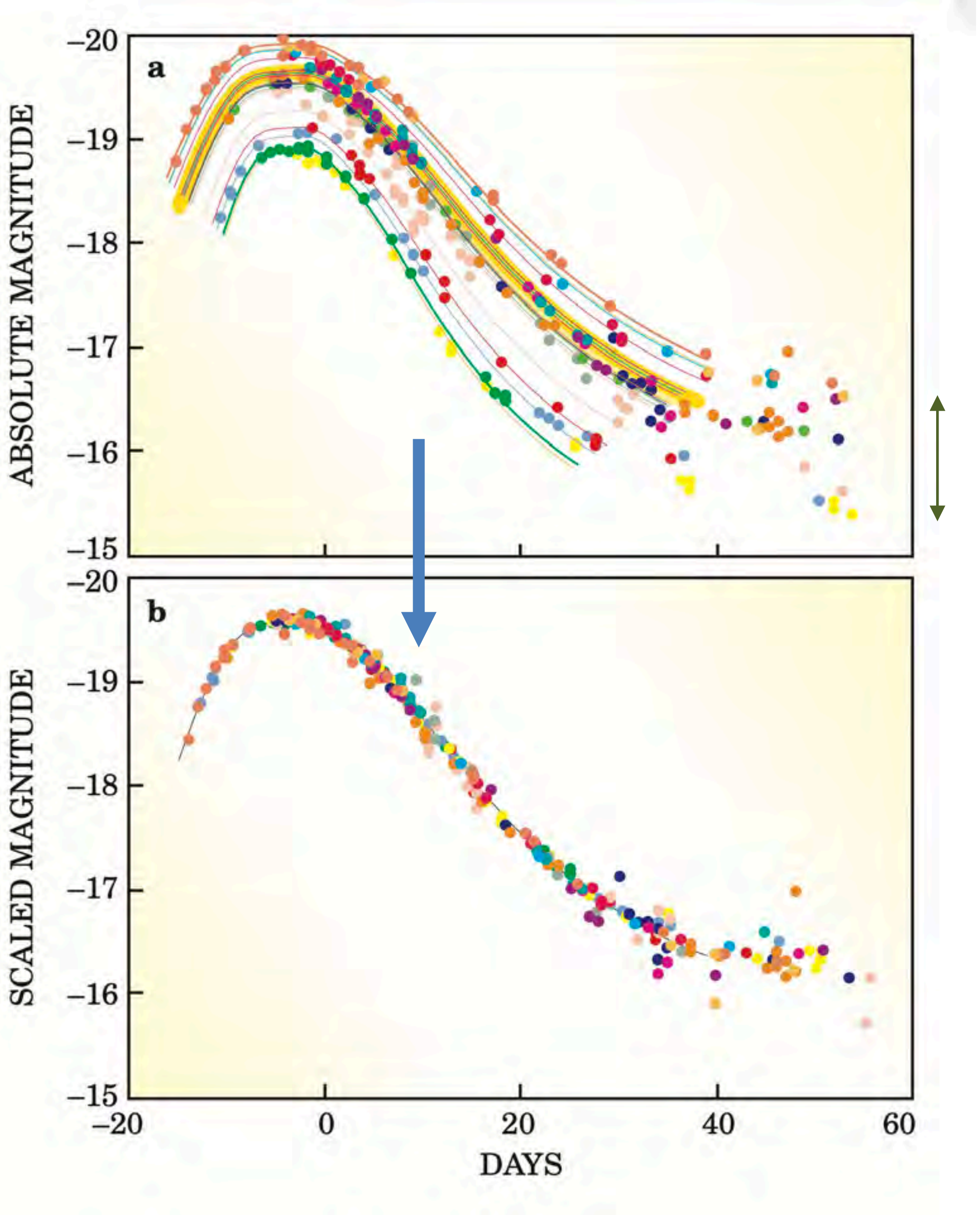
Type Ia Supernovae – Standardizable Candles



NGC 2525, SN 2018gv, esahubble.org

Type Ia Supernovae – Standardizable Candles

Standardization by the Rate of Fading Colors Decreases the Scatter (Phillips 1993)

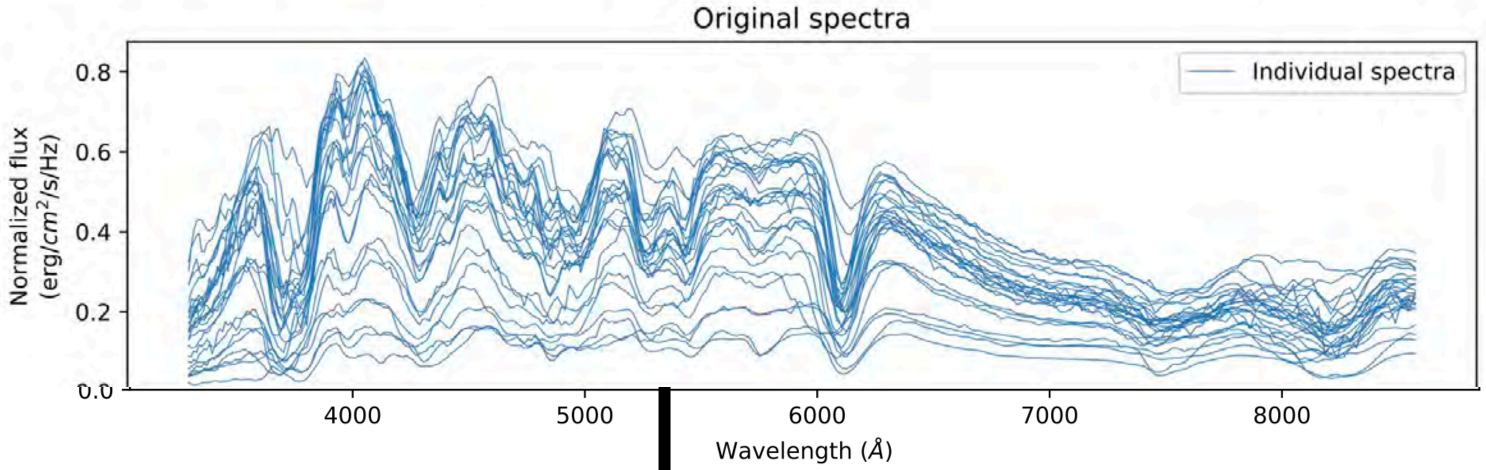


SNe Ia are similar, but have intrinsic scatter

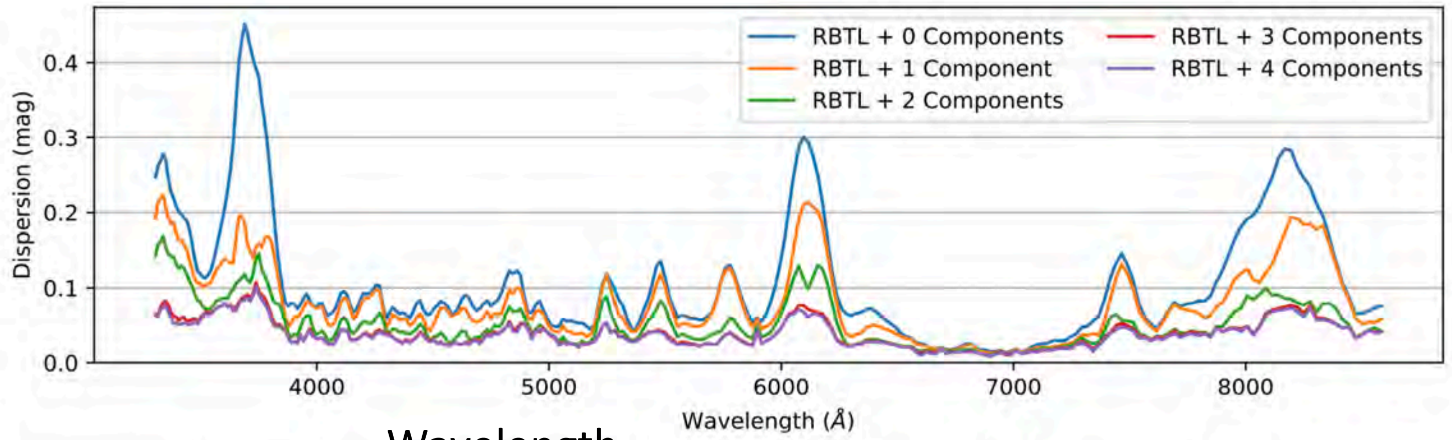
Perlmutter 2003

State of the Art SNe Ia Standardization: Twins Embedding

- Provides the lowest scatter in SN Ie Luminosity



Large natural scatter in supernovae

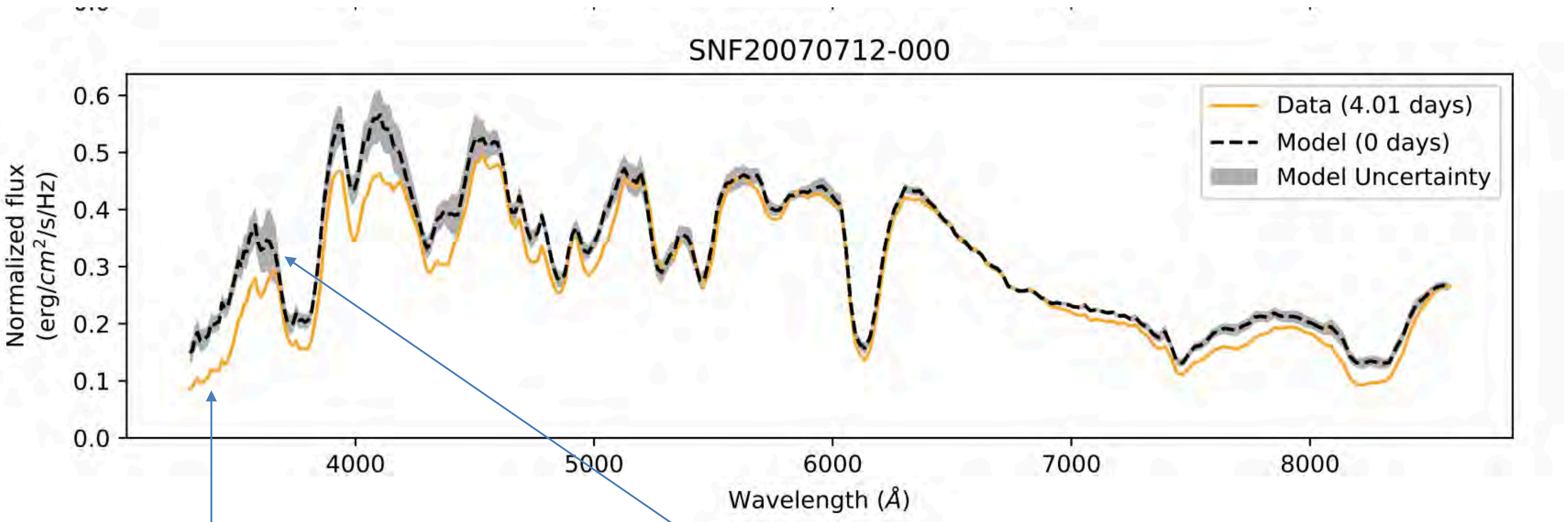


Small dispersion in standardized spectra

Wavelength

Boone et al. 2021a, Boone et al. 2021b

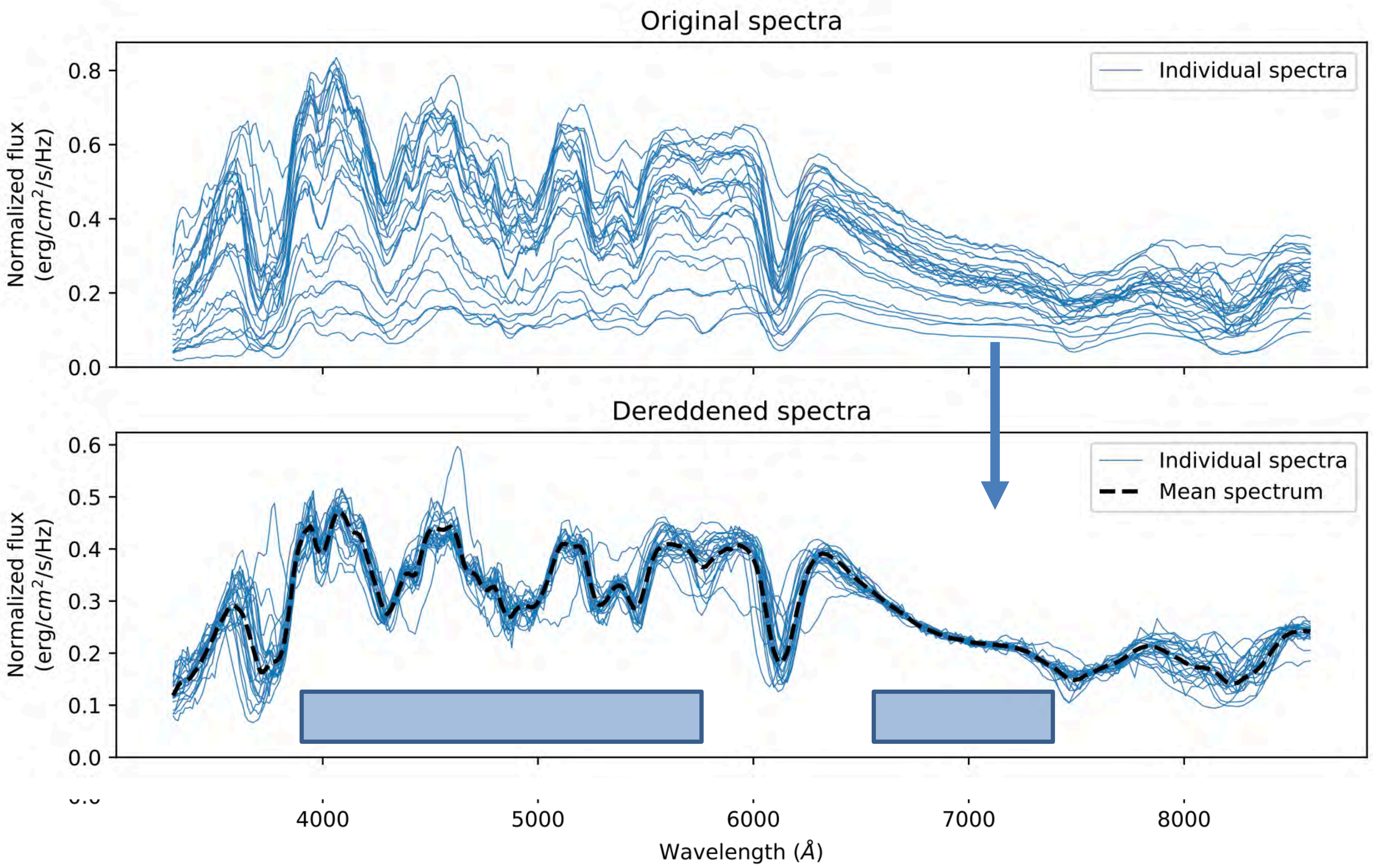
Step 1: Estimate the Spectrum at Maximum Light



Data from 4.01 days is back-tracked to **Maximum Light Spectrum**

Boone et al. 2021a, Boone et al. 2021b

Step 2: De-Redden The Spectra

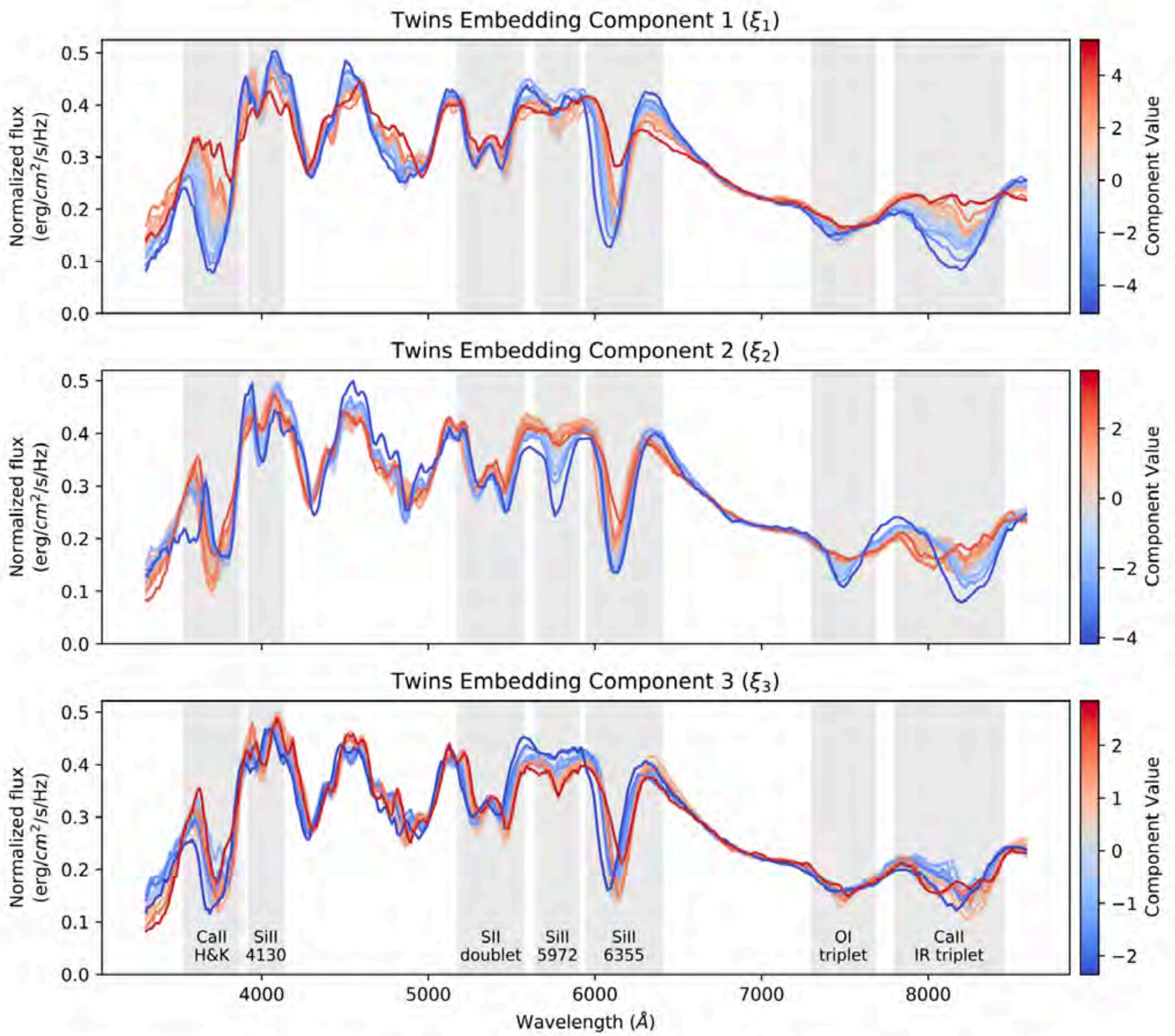


"Read-between the lines" Extinction modeling

Weight key wavelengths of low intrinsic dispersion:

- Mostly 660 nm to 720 nm
- Also, 390 nm to 590 nm

Step 3: Apply the Nonlinear Parametric Model



Manifold Learning:

- Reduce the dimensionality
- 3 Nonlinear Components to parameterize the SNe
- Uses A Sequence of "Twins"

System Engineering Approach

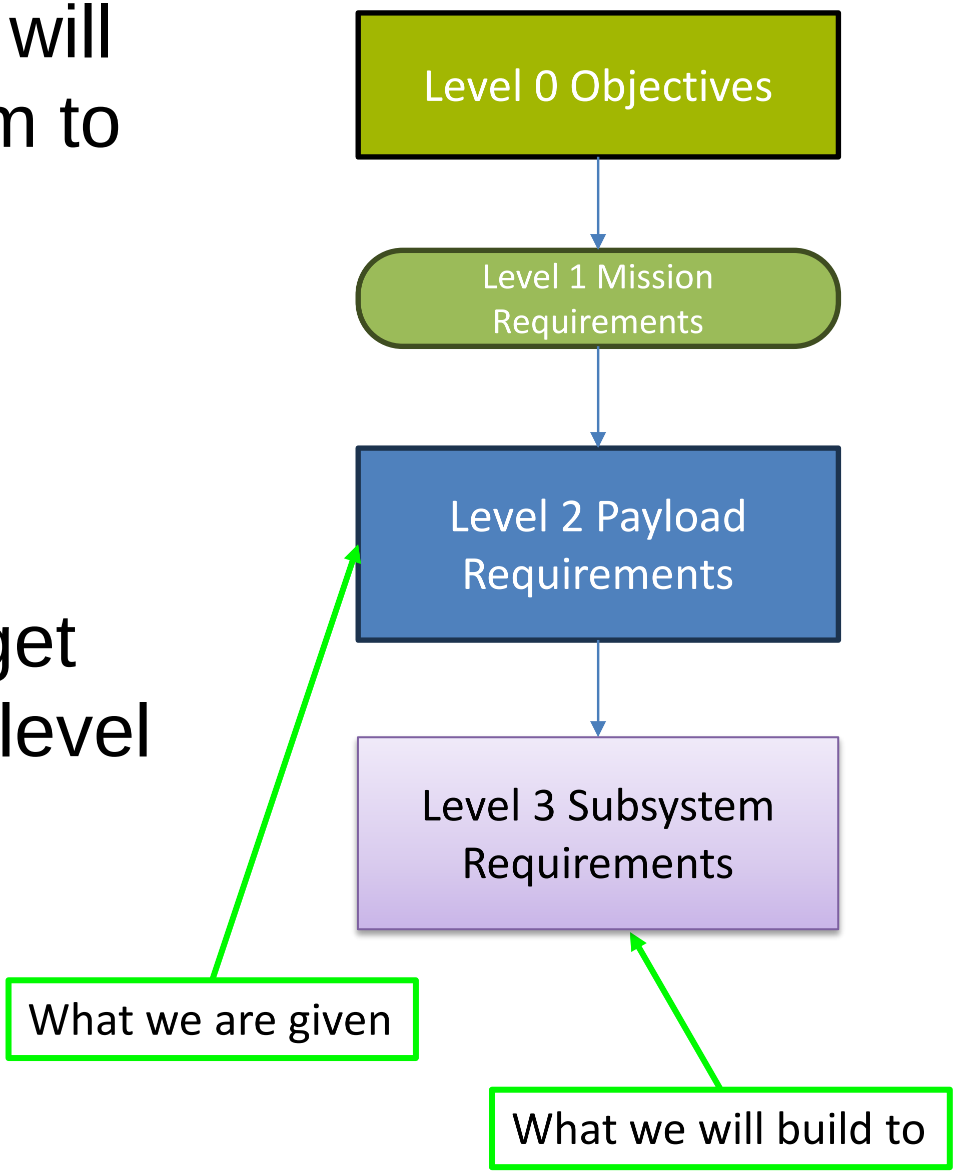
- Spectrograph Team acknowledges a strong system engineering effort is essential to the successfully spectrograph delivery using the “new paradigm” approach.
  - Strong system engineering management will allow engineering team to focus on technical work.
  - Strong system engineering coordination with project team allows for technical issues / risks to be identified and mitigated early.
- Tailor a Spaceflight engineering approach to meet customer needs
  - Will work with sponsor to understand must-haves, good-to-haves, and don’t needs
- Streamline requirements process
  - Identify and focus on key/driving requirements
  - Ensure we have large margins at top level to allow flexibility
- Comprehensive use of analysis and models to help inform development progress and requirements compliance
- Minimize process requirements on the team
  - Will rely on best-practices (rather than formal verification) for many processes to reduce associated overheads
  - Will use study phase to identify processes falling under this category
  - Streamline engineering change process (see PM slides)
- Minimize documentation generation
  - Generation of only key documents
  - Streamline configuration management process (see PM slides)

Requirements Finalization

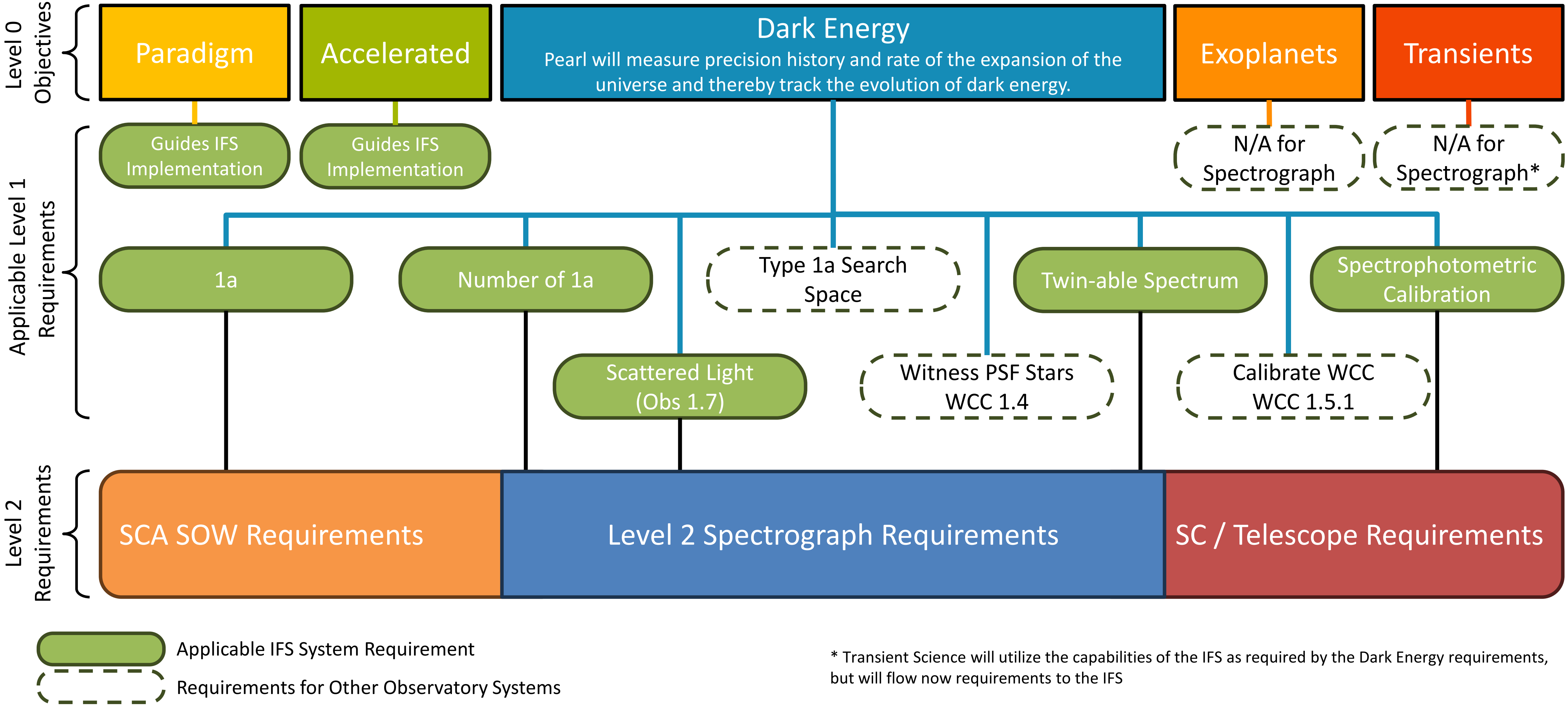
- Comprehensive requirements flowdown and finalization requirement early in the program is key this new paradigm for instrument delivery.
  - Requirements creep will increase schedule and budget risk
  - Overspecified requirements will increase schedule and budget risk
  - Risk 13 identified to track and mitigate this risk
- Ad-hoc requirements flowdown exercise completed to identify any missing or overspecified requirements for L2 Spectrograph
  - Understanding relationship between science goals and engineering requirements also important for implementation.
  - L1→L2 Requirements flowdown included in this package
    - Possible missing requirements identified for discussion
  - L2->L3 Requirements flowdown included in this package
    - Key requirements identified

Requirements Development Process

- At start of implementation phase, team will start work with project and science team to finalize requirements
- Level 3 requirements for individual subsystems will be developed and negotiated with subsystem teams.
- Spectrograph team will hold review to get agreement from all parties on finalized level 2 and level 3 requirements.



Flowdown – Level 0 → Level 2



* Transient Science will utilize the capabilities of the IFS as required by the Dark Energy requirements, but will flow now requirements to the IFS

Spectrograph Level 2 Requirements

- Provided by PEARL sponsor team

ID	Title	Requirement Text
IFS 2.1	Spectrograph Spectral Bandpass	Simultaneous spectrophotometric measurement over the entire continuous, well calibrated 0.4-1.7µm wavelength band.
IFS 2.2	Spectrograph Spectral Resolution	Spectral resolution (L /dL) >100 at all wavelengths and spaxels.
IFS 2.3	Spectrograph Spatial Sampling	Accommodating a range of scale such that the spatial resolution samples a telescope PSF ranging from the diffraction limit (DL) to 6 x DL at 1um, e.g. scales ranging from 0.020 to 0.050 arcsec per spaxel. The scale is expected to be selected in-flight and static thereafter.
IFS 2.4	Spectrograph Spaxel Format	Maximize the number of spaxels, with a minimum of 50 x 50 spaxels (for a MLA type design).
IFS 2.5	Spectrograph FOV	IFS shall have a minimum field of view of 1.0 x 1.0 arcsec at the finest sampling scale.
IFS 2.6	Spectrograph Spaxel Cross-Contamination	Minimize cross contamination between neighboring spaxel's spectra on the detector to < 2% (TBR), including diffraction.
IFS 2.7	Spectrograph Nyquist Sampling	Nyquist sampling or better for each spaxel spectral element and cross-dispersion profile at the detector.
IFS 2.8	Spectrograph Spatial Stability	Predictably maintain spaxel spectral location within 1/10 pixel and spaxel trace width variation to within 3/10 pixel, given example optical and thermal environment perturbations over > 2h duration (and goal 10h).
IFS 2.9	Spectrograph MLA Fill Factor	A fill-factor for IFU focal plane segmentation of > 95% minimum. Goal > 98%.
IFS 2.10	Spectrograph Optical Throughput	Total optical throughput of > 50%, and 80% nominal, maximized for L > 1 um.
IFS 2.11	Spectrograph Thermal Background	Control on thermal background to ensure that on-orbit variations are << detector statistical and systematic errors, e.g. nominally < 0.005 e-/pix/sec; preferably < 0.002 e-/pix/sec.
IFS 2.12	Spectrograph Stray Light	Internally scattered light of <1% of the input signal reaching the detector within its effective spectral response range.
IFS 2.13	Spectrograph Calibration	On-orbit capability for measuring spectral calibration (to L/1000), count rate non-linearity (at several wavelengths) and sensor flat fielding.
IFS 2.14	Spectrograph Electronics	Electronic and calibration units are separate and likely distant (~5 m) from the optics bench.
IFS 2.15	Spectrograph Resource Allocations	Mass and volume are only minor constraints. As guidance, one base-line design had a 65cm cube with a mass of less than 100kg.

Detector “Requirements”

- Detector Requirements extracted from SOW provided to Teledyne Imaging Sensors (SOW for H4RG program - v July 28 2023 - DRAFT.pdf)

ID	Title	Requirement Text	
H4RG 1	Total Noise	Median total noise of all pixels shall be < 9 e- 95% of all pixels shall have total noise < 11 e- assuming 180sec ramps at pixel clock rate below.	Median total noise of all pixels shall be < 7.1 e- 95% of all pixels shall have total noise < 8.3 e- assuming 180sec ramps at pixel clock rate below.
H4RG 2	QE	Median QE over all pixels shall be > 25% at 800 nm > 50% at 1230 nm < 5% above 1850nm	Median QE over all pixels shall be > 40% at 400-900 nm > 70% at 900-1700 nm
H4RG 3	Dark Current	Median dark current over all pixels shall be < 0.004 e-/pix/sec 90% of all pixels shall have dark current < 0.005 e-/pix/sec At 120K: Median dark current over all pixels shall be < 0.05 e-/pix/sec 95% of all pixels shall have dark current < 0.5 e-/pix/sec	Median dark current over all pixels shall be < 0.005 e-/pix/sec at 120K
H4RG 4	Full Well	95% of all pixels shall have full well > 80000 electrons.	
H4RG 5	Persistence	Median persistence level 10 min after exposure to 50 Ke +/- 20% shall be < 1 e-/pix/sec .	
H4RG 6	Operable Pixels	> 95% of pixels shall be operable, defined as: connected QE @800nm > 25% dark current < 0.01 e-/pix/sec at 95K total noise < 15 e- full well > 80000 electrons	> 99% of pixels shall be operable in the central 8 channels
H4RG 7	H4RG	<Implied Requirement> The detector shall be a 4096x4096, 10um pixel format.	

Key Notes:

H4RG operated in 120K (unless stated otherwise) 32output mode, 200kpix/s/output, buffered mode

Total noise uses ~180s ramps per H4RG operating parameters

Sensor Chip Electronics @ 135K

Flowdown – 1a Requirement

- IFS Requirement
- Detector SOW Requirement
- Telescope / SC Requirement

1a
The Observatory shall perform visible-to-near-infrared pixelized spectrographic observations of a Type Ia supernova (SN) at z=1.5 from rest- frame B through I band with S/N > 10 per resolution element (in the restframe B band for an AB-mag=25) .

Scattered Light
The observatory shall control scattered light to less than 1x (TBR) the solar system zodiacal light background (22.1 mag/sq arcsec TBR at V band) at each of the instrument focal planes (TBR)

Key Interface Requirements

- Telescope Throughput
- Observatory ConOps
- Telescope IQ

Level 2 IFS Requirements

- Detector QE H4RG 2
- Detector Well Depth H4RG 4
- Spectral Resolution IFS 2.2
- Thermal Bkgd. IFS 2.11
- MLA Fill Factor IFS 2.9
- Spaxel X-Contam. IFS 2.6
- Detector Noise H4RG 1
- Spaxel Format IFS 2.4
- Spectral Bandpass IFS 2.1
- Optical Throughput IFS 2.10
- Detector I_Dark H4RG 3
- Stray Light IFS 2.12

Missing Requirements

- Exposure Time
- Detector ConOps

Notes:

- Need to define a continuum object for SNR (otherwise low flux spectral bands and distant objects will have lower flux) – need to estimate sensitivity number based on Level 2 requirements. Does mag-=25 refer to the SN1a or something else?
- Observatory Conops is number of exposures coadded per observation and data processing scheme (all done by SDS)
- Detector cutoff is not commiserate with the redshift requirement in the L1 requirement

Flowdown – 1a Requirement

- Interpret this as the key requirement defining sensitivity and spectral requirements used for deriving capabilities of Spectrograph
  - L2 flowdown forms the radiometric sensitivity budget (to achieve the SNR > 10 requirement)
  - L1 scattered light requirement also flows into this requirement as element of noise term of sensitivity budget
  - Note: While we understand the intent is to flow down the components of the sensitivty budget as individual requirement, it would still be good to understand the instrument sensitivity derived from this requirement to better understand development risks for the spectrograph.
- Possible Missing Requirements
  - Exposure Time: Need a requirement on exposure time (or range of exposure times) to be used for radiometric sensitivity tracking and for FW requirements flowdown.
    - Possible Requirement: *The Spectrograph shall accommodate a exposure time of between 30 sec [TBD] and 300 sec [TBD] per ramp.*
    - Note: “Exposure” means one command set of images (ie ramp) from the Spectrograph. It is up to the Spacecraft and
  - ConOps: Need a requirement on the number of frames per exposure time
    - Possible Requirement: The Spectrograph shall accommodate a exposure ramp with up to 32 [TBC] frames (sample up the ramp, assuming 3 second frames) evenly spaced
- Note: Detector cutoff does not support observations over with the redshift range specified in the L1 requirement

Flowdown – Twin-able Spectrum

- IFS Requirement
- Detector SOW Requirement
- Telescope / SC Requirement

Twin-able Spectrum

Low-resolution (R = 100 at =1 um) spectra of SNe Ia shall be obtained at z=2.0 from rest-frame B through I bands, with sufficient signal-to-noise (S/N > 10 per resolution element) in the restframe B band for an AB-mag=25 and host-galaxy rejection via 0.02 arcsec sampling (TBR) of the field out to 1 arcsecond (TBR).

Scattered Light

The observatory shall control scattered light to less than 1x (TBR) the solar system zodiacal light background (22.1 mag/sq arcsec TBR at V band) at each of the instrument focal planes (TBR)

Key Interface Requirements

- Telescope Sky Scale
- Telescope FOV
- Telescope Pointing

Level 2 IFS Requirements

- Pixel Size H4RG 7
- Spatial Sampling IFS 2.3
- Num. Pixels H4RG 7
- Spaxel Format IFS 2.4
- Spectral Resolution IFS 2.2
- Nyquist Sampling IFS 2.7
- Instrument FOV IFS 2.5

Missing Requirements

- Inst. FOV Plate Scale

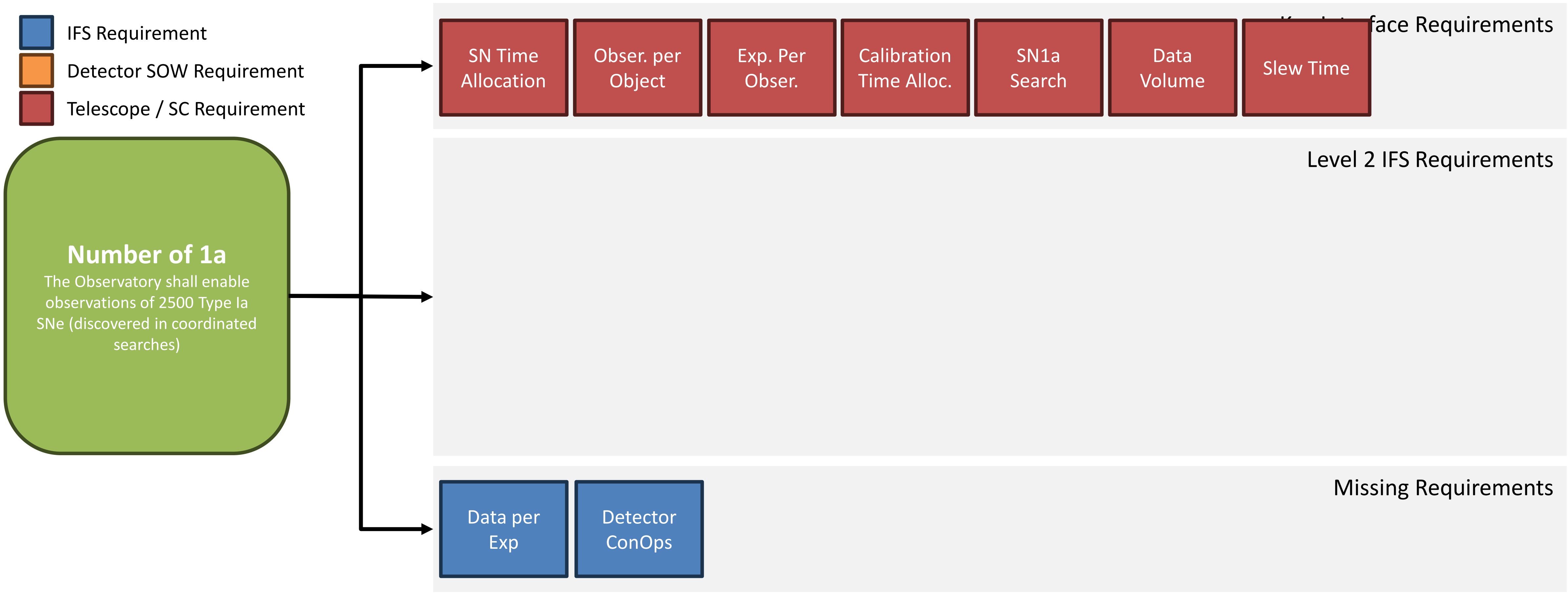
Notes:

- Level 2 SNR requirements coalesce as sensitivity requirement since Signal part of SNR is not well defined by Level 1 requirement
- How much SNR needed for good host-galaxy rejection?
- 0.02” sampling will depend on plate scale over FOV (does Spatial Sampling requirement apply over the entire FOV?)
- 1” Host Galaxy observation depends on FOV and Telescope pointing (Instrument Req = 1”, no allocation to pointing)
- Detector cutoff is not commiserate with the redshift requirement in the L1 requirement; redshift in this requirement is different in other L1 requirements.

Flowdown – 1a Requirement

- Interpret this as the requirement for the spectral / spatial resolution and what needs to be observed in each observation (SN and host galaxy)
  - 0.02 arcsecond sampling and 1.0 arcsecond FOV defines MLA format and FOV.
    - Is this requirement that each Spaxel samples at least 0.02” or at most 0.02”?
  - Note: Assume 0.02” sampling requirement in a “nominal” requirement since
  - Note: Radiometric sensitivity requirement components
- Possible Missing Requirements
  - Instrument FOV Plate Scaling: Needed since Spaxel Format (50x50) and FOV requirement do not allow for variation in design or manufacturing tolerances.
    - Possible Requirement: *The Spectrograph shall have a per spaxel FOV of better than 0.02”*
- Note: Detector cutoff does not support observations over with the redshift range specified in the L1 requirement

Flowdown – Spectrograph Flowdown



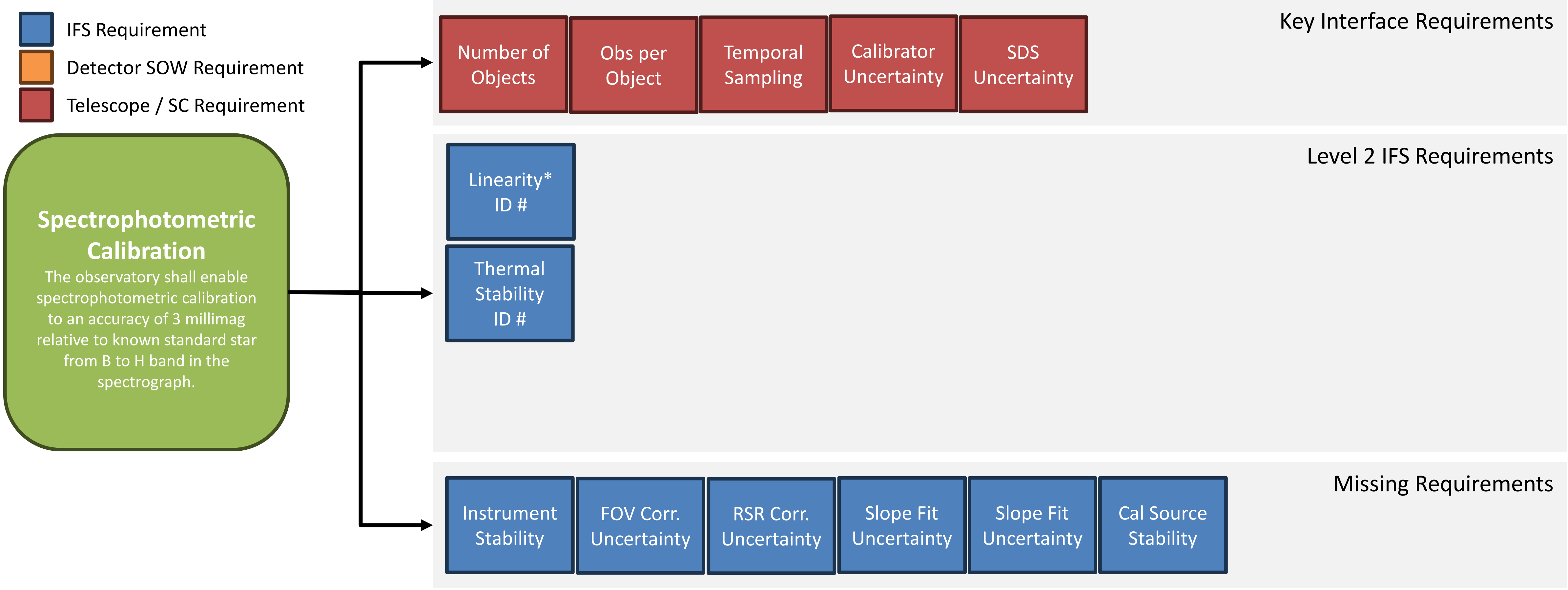
Notes:

- SN Time allocation is the observation time allocated to the spectrograph and excludes time allocated for other instruments, overhead time,
- Assume exposure is acquisition unit of the Instrument. S/C or SDS will combine exposures into observations
- Assume integration time has some requirement on overheads associated with detector conops

Flowdown – Number of 1a

- This requirement defines the number of objects needed to be observed do not have any direct flowdown to Spectrograph requirements.
  - Missing requirements noted that may have impact on time allocated for SN1a observations listed here for consideration
  - Data per Exposure: Data volume from spectrograph my drive allocation for downlink time (which may drive allocation for SN1a observing time). A requirement on data per exposure would drive on-board data processing, compression or detector ConOps
  - Detector ConOps: As part of ConOps development, Spectrograph team can report observing efficiency of chosen detector conops

Flowdown – Spectrophotometric Calibration



Notes:

- Instrument stability includes: dark current stability, bias frame stability, flat field response stability, and stray light stability
  - Stray light stability also includes changes in stray light as function of pointing
- FOV Correction uncertainty includes uncertainty
- *Linearity requirement is only on on-orbit capability to measure; does not address stability or accuracy of linearity measurement used for calibration

Flowdown – Spectrophotometric Calibration

- This is the requirement that defines the calibration requirement for the resulting SN1a data (includes both the calibration and the calibration of the Spectrograph).
  - Note: While we understand the intent is to flow down the components of the calibration budget budget as individual requirements, it would still be good to understand the instrument calibration requirement derived from this requirement to better understand development risks for the spectrograph.
- Possible missing requirements
  - Compone
    - Spectrograph team is assuming project is flowing requirements on different components of calibration (much like sensitivity) rather than a calibration accuracy requirement.
    - See calibration section for initial list of calibration components

Flowdown – "General Requirements"

- A set of "general" L1 requirements flow down from the L0 Paradigm" and "Accelerated" requirements and NASA standards adopted by the project
  - List of "General Requirements" applicable to Spectrograph seem reasonable; will be flowed down
- Key Risk Classification used as guiding principal:
  - The Pearl project is a commercial space mission and does not have a formal Risk Classification. The "Class D" risk classification defined in NASA NPR 8705.4A may be used a guideline. The project will establish a formal Risk Management process to track and disposition risks and mitigations. Identified Single-Point-Failures (SPF) in critical systems shall be mitigated through documented validation testing, including environmental and radiation assurance testing, or shown to result in a graceful system degradation.
- Assume additional interface documents / requirements will be provided at start of implementation phase.

- Relevant "General Requirements" to the Spectrograph

Title	Requirement Text
Chassis Return Current	Structure or shields shall not be used for the primary circuit current return path. A dedicated conductor shall be included to provide the current return path with the smallest loop area possible. In no case shall a signal generate more than 1 milliamp of chassis current, with a design goal of zero chassis current.
Bonding, Electrostatic Discharge	All conducting items, which are subject to charge generating mechanisms, shall have a mechanically secure electrical bond path to vehicle structure. The resistance across the connection shall be 1.0 ohm or less (Class S).
Surface Conductivity	All conductive coatings, including those used to treat dielectric surfaces, shall be electrically bonded to the vehicle structure with a DC resistance of less than 10E5 ohms.
Dissimilar Materials	The use of dissimilar metals in the intended environment should consider galvanic corrosion, wear properties, galling, vacuum welding, etc. The spacecraft will be maintained in climate-controlled, indoor, non-condensing environments (Environmental Class 6), therefore, the requirements of NASA-STD-6012 are a guideline only.
Outgassing	Nonmetallic materials shall be tested to ASTM-E595, with acceptance criteria of ≤0.1% collected volatile condensable materials (CVCM) and ≤1.0% total mass loss (TML).
EEE Parts Derating	The Spacecraft shall use EEE-INST-002 "EEE Parts Selection, Qualification, and Derating" as a guideline for EEE parts selection and derating.
Parts and Materials Traceability	A Certification of Conformance (C of C) shall be obtained for all procured flight parts and materials, including EEE parts. Materials used in the fabrication of flight structures shall be identified as to specific alloy and heat treatment and certified by a C of C from the supplier. EEE parts, including COTS items, shall be identified by manufacturer and P/N, and a C of C shall be obtained.
Lead-Free EEE Parts	Due to the prohibition of pure-tin and risk of whisker growth, all lead-free (RoHS) parts and electronics boards shall demonstrate a mitigation strategy such as conformal coating, solder dip or reflow. The mitigation plan shall be approved by the project. An existing Lead-Free Control Plan (LFCP) such as GEIA-STD-0005-2 may be proposed.
EEE Parts Selection	Grade 4 EEE parts as defined by NASA-STD-8739.10 are acceptable. Grade 4 EEE parts typically meet vendor standards for self-defined or commercial market place reliability criteria, but have not been independently verified. Grade 4 EEE parts can also be referred to as COTS. Traceability to manufacturing lot or testing data may not be available. A Certificate of Conformance to a vendor part number and specification is required for traceability.
Soldering Process Control	Soldering shall be performed with an IPC J-STD-001 approved process. Certification of the J-STD-001 process and operator shall be provided for all flight hardware. The NASA requirement for the J-STD-001(S) Space Addendum is not imposed by the project.
Electronic Assembly Quality	Flight PWBs and board assemblies shall be manufactured and inspected to the applicable IPC Class 3 requirements. Operators shall be trained and certified to the IPC standards. Applicable standards are IPC 600-A and IPC-A-610, board and assembly inspection, IPC-6012, qualification specification for PWBs, and IPC-A-620 for crimped and soldered cable harnesses. The "Space Addendum" requirements are not imposed by the project.

Spectrograph Level 2 Compliance

- Provided by PEARL sponsor team

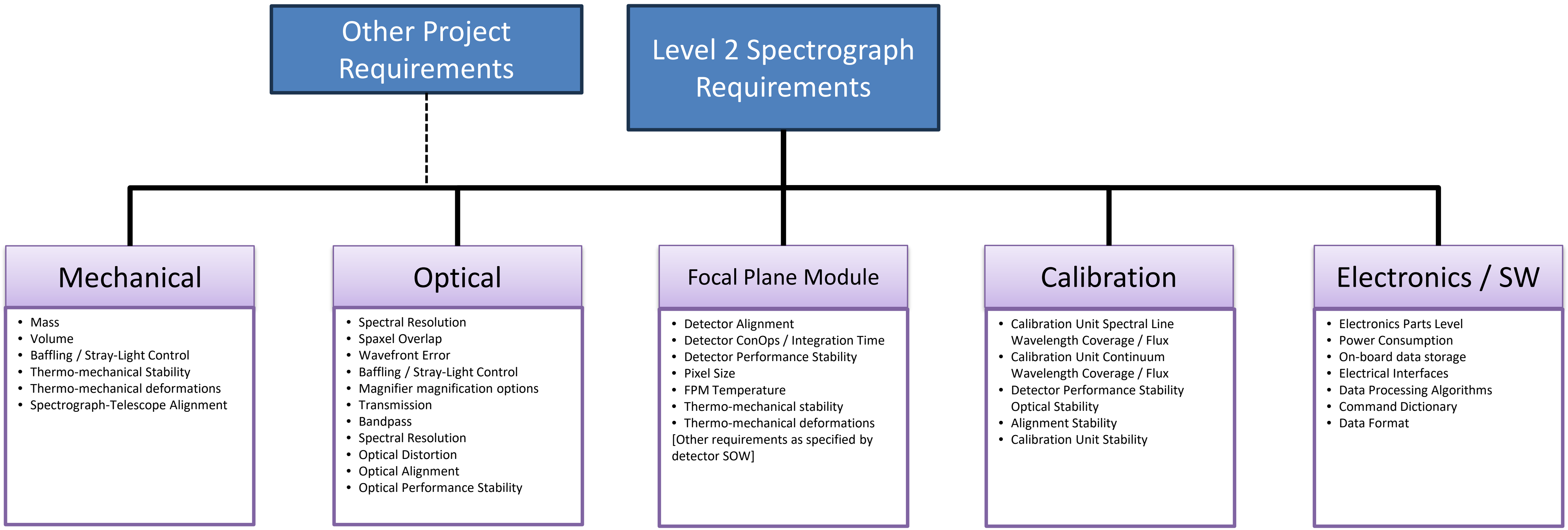
ID	Title	Requirement Text
IFS 2.1	Spectrograph Spectral Bandpass	Simultaneous spectrophotometric measurement over the entire continuous, well calibrated 0.4-1.7µm wavelength band.
IFS 2.2	Spectrograph Spectral Resolution	Spectral resolution (L /dL) >100 at all wavelengths and spaxels.
IFS 2.3	Spectrograph Spatial Sampling	Accommodating a range of scale such that the spatial resolution samples a telescope PSF ranging from the diffraction limit (DL) to 6 x DL at 1um, e.g. scales ranging from 0.020 to 0.050 arcsec per spaxel. The scale is expected to be selected in-flight and static thereafter.
IFS 2.4	Spectrograph Spaxel Format	Maximize the number of spaxels, with a minimum of 50 x 50 spaxels (for a MLA type design).
IFS 2.5	Spectrograph FOV	IFS shall have a minimum field of view of 1.0 x 1.0 arcsec at the finest sampling scale.
IFS 2.6	Spectrograph Spaxel Cross-Contamination	Minimize cross contamination between neighboring spaxel's spectra on the detector to < 2% (TBR), including diffraction.
IFS 2.7	Spectrograph Nyquist Sampling	Nyquist sampling or better for each spaxel spectral element and cross-dispersion profile at the detector.
IFS 2.8	Spectrograph Spatial Stability	Predictably maintain spaxel spectral location within 1/10 pixel and spaxel trace width variation to within 3/10 pixel, given example optical and thermal environment perturbations over > 2h duration (and goal 10h).
IFS 2.9	Spectrograph MLA Fill Factor	A fill-factor for IFU focal plane segmentation of > 95% minimum. Goal > 98%.
IFS 2.10	Spectrograph Optical Throughput	Total optical throughput of > 50%, and 80% nominal, maximized for L > 1 um.
IFS 2.11	Spectrograph Thermal Background	Control on thermal background to ensure that on-orbit variations are << detector statistical and systematic errors, e.g. nominally < 0.005 e-/pix/sec; preferably < 0.002 e-/pix/sec.
IFS 2.12	Spectrograph Stray Light	Internally scattered light of <1% of the input signal reaching the detector within its effective spectral response range.
IFS 2.13	Spectrograph Calibration	On-orbit capability for measuring spectral calibration (to L/1000), count rate non-linearity (at several wavelengths) and sensor flat fielding.
IFS 2.14	Spectrograph Electronics	Electronic and calibration units are separate and likely distant (~5 m) from the optics bench.
IFS 2.15	Spectrograph Resource Allocations	Mass and volume are only minor constraints. As guidance, one base-line design had a 65cm cube with a mass of less than 100kg.

Level 3 Requirements

- Level 3 requirements / allocations will be developed for each Spectrograph subsystem during implementation
  - Full text and allocations will be generated early in the implementation phase to allow for formal subsystem development to begin.
  - Key / Driving requirement identified (by title only) in following chart.
- Once requirements finalized, SE team will continuously monitor subsystem performance to assess any possible adjustments to the requirements
  - To prevent requirements creep, changes to requirements will be reactive to subsystem design (as opposed to flowing down to subsystems forcing changes)

Requirements Flowdown – Subsystem Flowdown

- Key and Driving Level 3 requirements have been identified for the spectrograph subsystems



Conclusions

- Requirements flowdown and finalization is key to successful delivery of Spectrograph.
  - Primary focus for system engineering team at start of implementation.
  - Requirements flowdown is well understood by Spectrograph team .
- Path to completing work-to-go is well defined once Spectrograph enters implementation.
  - Will plan for near term (~months) meeting to finalize requirements
    - Science team will be key to this activity.
  - Generation of formal level 3 requirements to begin after start of implementation.

Requirements Compliance

- Compliance against each of the key requirements was assessed for the study
  - Compliance for some requirements still marked as TBD – requirements design analysis that will be completed once design is more mature.
- Spectrograph team expects to be compliant with all requirements
  - No open requirements are showstoppers for implementing the spectrograph design – their CBE assessment is considered work to go.

Spectrograph Level 2 Requirements

ID	Title	Requirement Text	Compliance / CBE	Notes
IFS 2.1	Spectrograph Spectral Bandpass	Simultaneous spectrophotometric measurement over the entire continuous, well calibrated 0.4-1.7µm wavelength band.	Comply	Dependent on detector performance (not under Spectrograph control)
IFS 2.2	Spectrograph Spectral Resolution	Spectral resolution (L /dL) >100 at all wavelengths and spaxels.	Comply (CBE: ~103-280)	Analysis / Design work ongoing to add additional margin
IFS 2.3	Spectrograph Spatial Sampling	Accommodating a range of scale such that the spatial resolution samples a telescope PSF ranging from the diffraction limit (DL) to 6 x DL at 1um, e.g. scales ranging from 0.020 to 0.050 arcsec per spaxel. The scale is expected to be selected in-flight and static thereafter.	Comply (CBE, 3 magnifications 0.020, .030, 0.050 arc, nominal)	Preliminary magnifier design complete.
IFS 2.4	Spectrograph Spaxel Format	Maximize the number of spaxels, with a minimum of 50 x 50 spaxels (for a MLA type design).	In Assessment (CBE 49x45)	Analysis and design work on going to identify correct design within parameter space (focused on spaxel packing design).
IFS 2.5	Spectrograph FOV	IFS shall have a minimum field of view of 1.0 x 1.0 arcsec at the finest sampling scale.	In Assessment (CBE 0.98” x 0.90”)	Analysis and design work on going to identify correct design within parameter space (focused on spaxel packing design).
IFS 2.6	Spectrograph Spaxel Cross-Contamination	Minimize cross contamination between neighboring spaxel’s spectra on the detector to < 2% (TBR), including diffraction.	Expect Compliance	Optical simulations in progress. Early modeling suggests compliance with margin in spectra separation.
IFS 2.7	Spectrograph Nyquist Sampling	Nyquist sampling or better for each spaxel spectral element and cross-dispersion profile at the detector.	Expect Compliance	Optical simulations in progress. Early modeling suggests compliance.

Spectrograph Level 2 Requirements

ID	Title	Requirement Text	Compliance	Notes
IFS 2.8	Spectrograph Spatial Stability	Predictably maintain spaxel spectral location within 1/10 pixel and spaxel trace width variation to within 3/10 pixel, given example optical and thermal environment perturbations over > 2h duration (and goal 10h).	TBD	Structural / Thermal Analysis in work.
IFS 2.9	Spectrograph MLA Fill Factor	A fill-factor for IFU focal plane segmentation of > 95% minimum. Goal > 98%.	Comply	Based on vendor discussions and capabilities.
IFS 2.10	Spectrograph Optical Throughput	Total optical throughput of > 50%, and 80% nominal, maximized for L > 1 um.	Comply (~65% min across bandpass)	
IFS 2.11	Spectrograph Thermal Background	Control on thermal background to ensure that on-orbit variations are << detector statistical and systematic errors, e.g. nominally < 0.005 e-/pix/sec; preferably < 0.002 e-/pix/sec.	TBD	Structural / Thermal Analysis in work. STOP and Radiometry analysis to start during flight study phase.
IFS 2.12	Spectrograph Stray Light	Internally scattered light of <1% of the input signal reaching the detector within its effective spectral response range.	TBD	Stray Light analysis in work.
IFS 2.13	Spectrograph Calibration	On-orbit capability for measuring spectral calibration (to L/1000), count rate non-linearity (at several wavelengths) and sensor flat fielding.	TBD	
IFS 2.14	Spectrograph Electronics	Electronic and calibration units are separate and likely distant (~5 m) from the optics bench.	Expect Compliance	Compliance based on heritage electronics and calibration unit designs.

3. OPTICAL DESIGN/PERFORMANCE

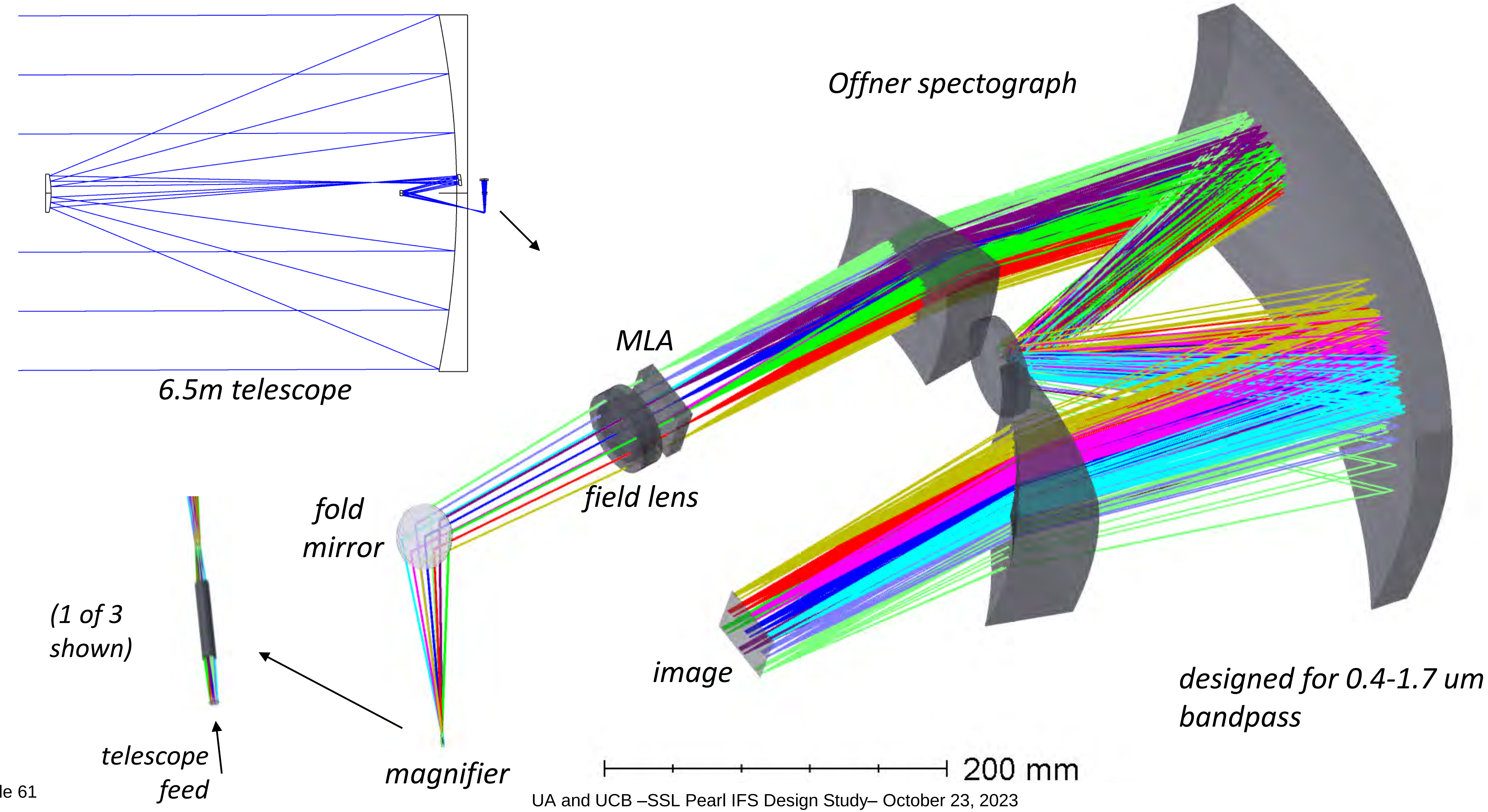
Optical Design and Performance (Outline)

- Status
- Baseline Design
- Baseline Performance
- Summary/Future Work

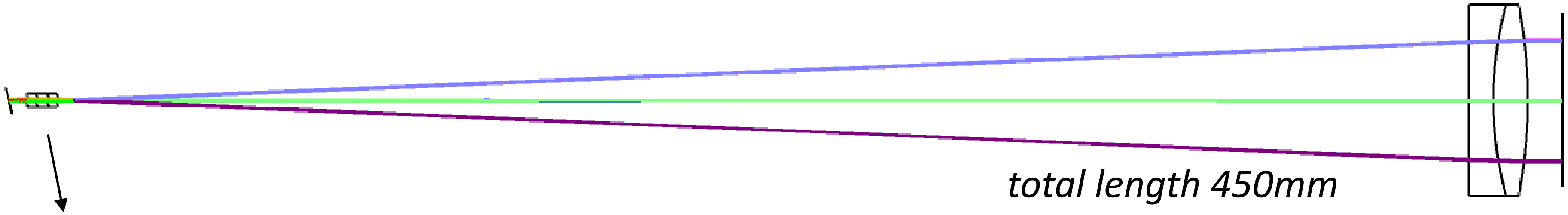
Optical Design Status

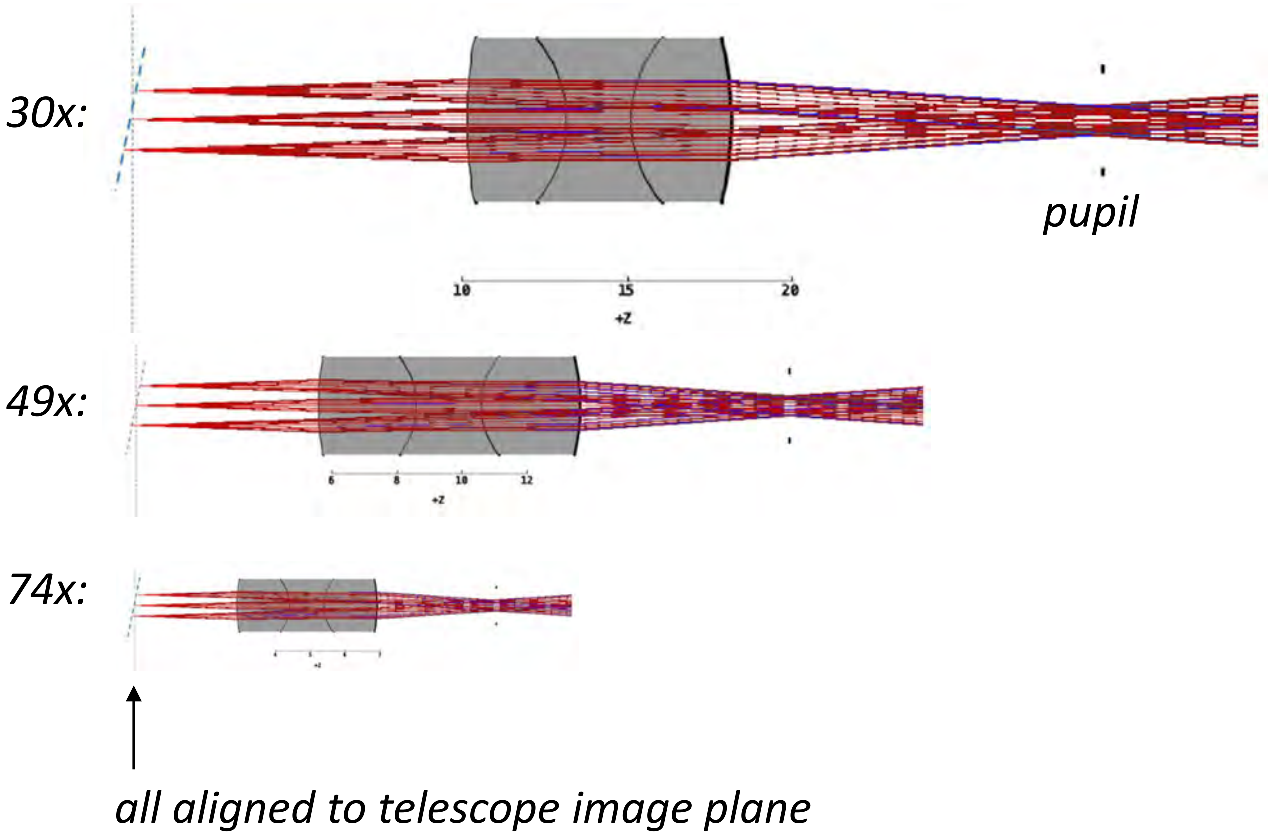
- Initial optical design based on LAM point design
  - some updates to meet L2 requirements and package in instrument volume
- Trading slicer- and MLA-based IFU options
  - MLA option more mature
  - slicer development work in progress: working with ORKID-2 design, and contracted with HiSpectal independently
  - slicer option will be presented in separate Nov 6 report

Optical design overview (MLA-based)



Magnifiers



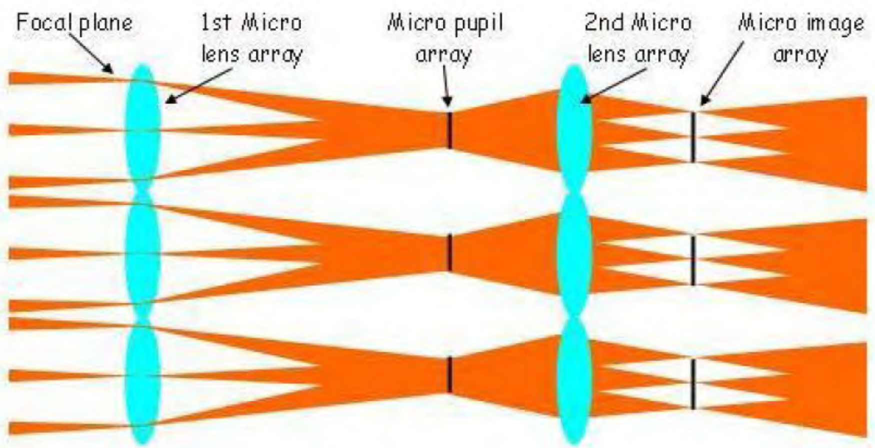


- Apochromatic triplet lens and field-flattening doublet
- 30x, 49x, 74x versions of triplet, mounted in swapping mechanism
- All triplet versions use same catalog glasses: S-PHM53, N-KZFS11, N-BAF52
- All spherical surfaces
- Simple axially-symmetric design low risk to manufacture
- Spot sizes << diffraction limit
- Accessible pupil for cold stop
- Throughput 90-95%

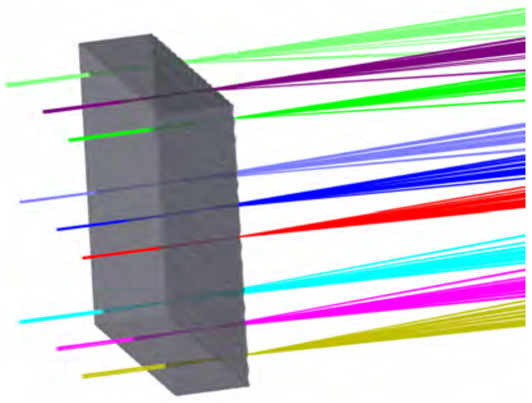
- Closed trades during study:
  - selected transmissive design over reflective design, likely easier fabrication, lower risk, and pupil more accessible
  - selected swapping mechanism over 3 fixed lenslets, more consistent with BIGRE MLA, and simpler calibration

MLA IFU

- IFU microlens array (MLA) samples the magnified telescope image, rearranges field, and sends to spectrograph for dispersion
- uses BIGRE-type MLA: compresses light entering each lenslet into 2D array of spots
  - spots are demagnified images of flux at lenslet entrances; pupil is maintained, see e.g. Giro 2008, Antichi 2018
  - chose BIGRE design over TIGER design in trade, but open to change in next phase if analysis shows advantage
- samples telescope image at 20, 30, 50 arcsec per lenslet (1.0, 1.5, 2.5 deg FOV)
- 51 x 51 spherical lenslets, square apertures, 700um pitch, lenslets both sides (different radii)
- 40mm square fused silica substrate
- 95% fill factor required to minimize scattered light: achievable by Jenoptik

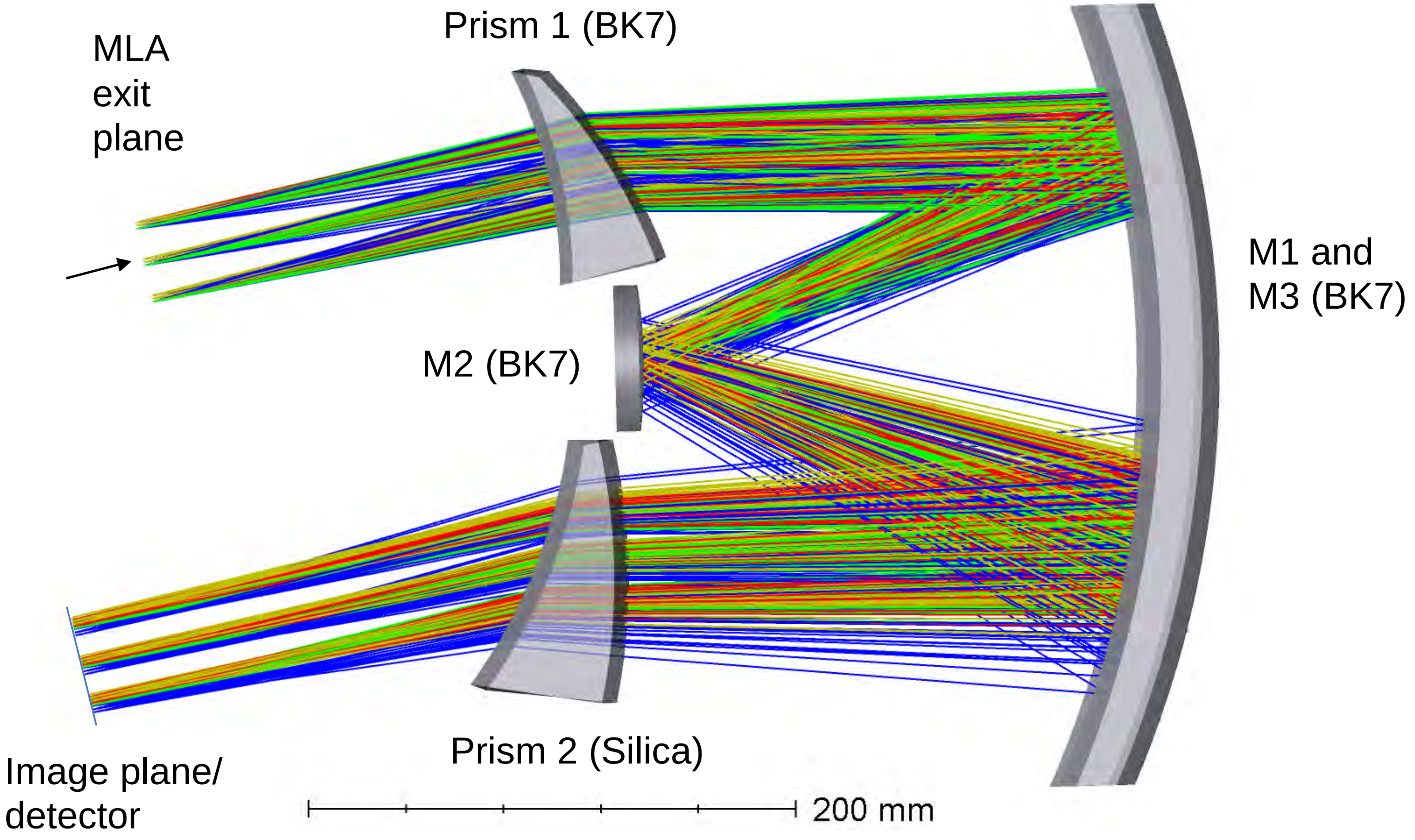


Giro 2008



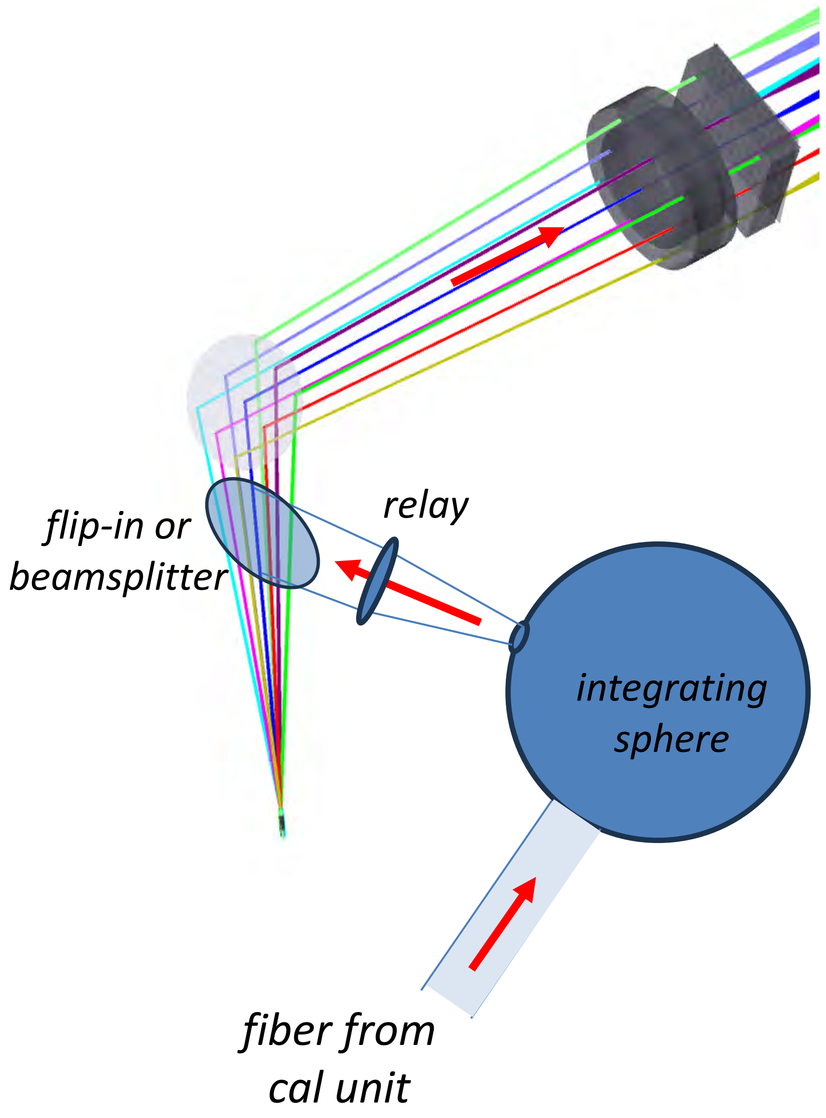
Spectrograph relay

- Offner spectrograph design, e.g. Lobb 1997
- all spherical optics
- designed F/8 to allow diffraction; geometric rays only f/16
- magnification ~1x
- 31 x 34 mm entrance FOV
- largest optic M1/M3, 320 x 170mm



Calibration path

- Calibration light from devoted flux sources can be inserted into optical path
- Calibration unit away from main bench contains necessary flux sources
- fiber cable carries light from cal unit to integrating sphere on cold spectrometer bench
- relay optics transfer the flux from the sphere exit port
  - creates correct f/# and entrance pupil
  - preliminary design is a single COTS lens, Thorlabs #LA1433, 1” diam, 150mm EFL
- a flip-in mirror or 90/10 beamsplitter (TBD) folds the calibration light into the main optical path



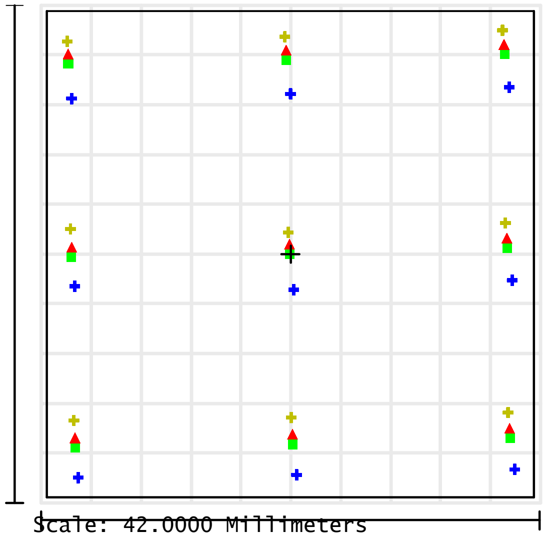
Performance

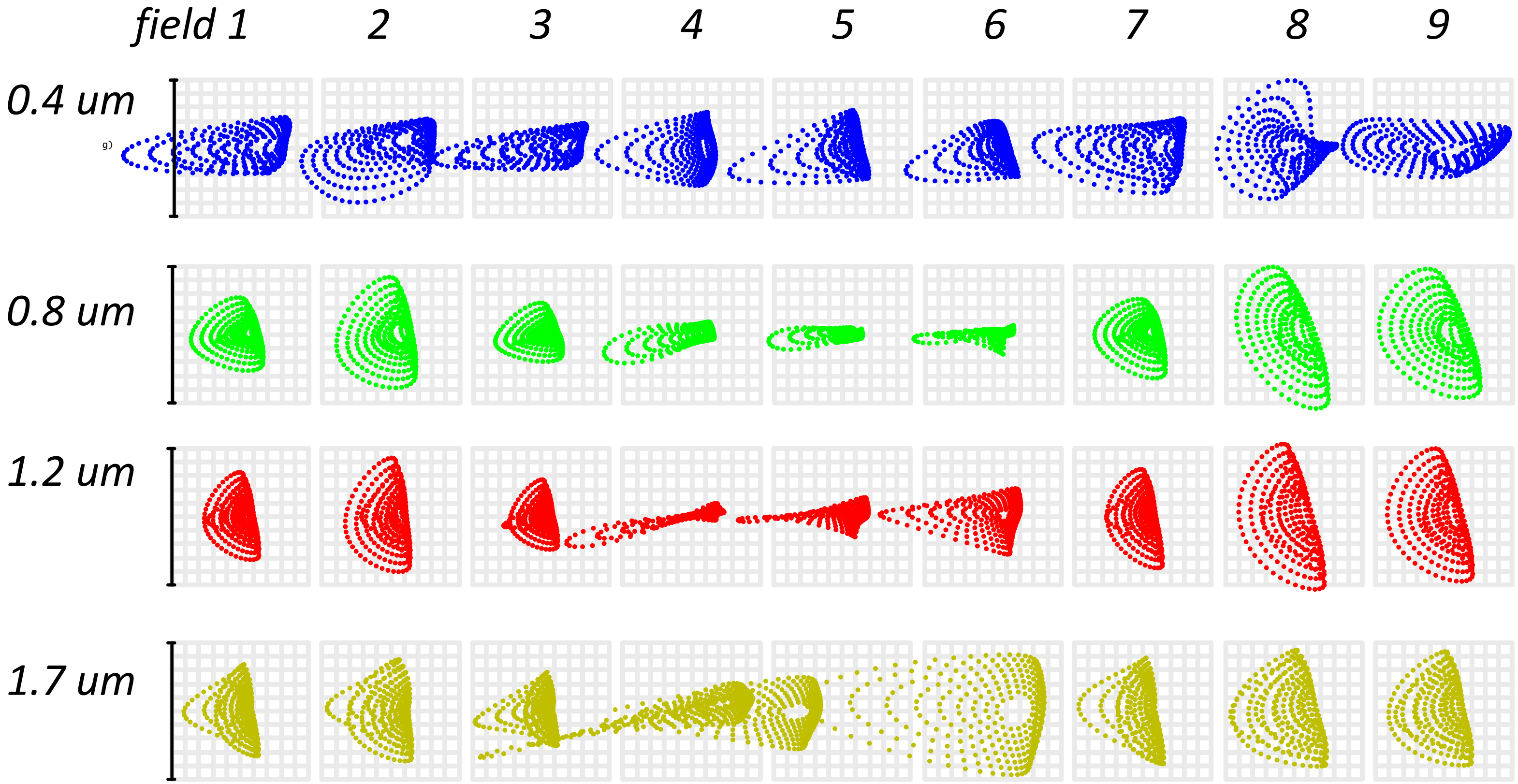
Descibed further on next slides:

- Geometric spot sizes on detector
  - 10 um average (18 um max) rms diam over FOV and 0.4-1.7um bandpass
  - fits within 2x2 pixels on detector
- Diffraction contributes to spot size and shape
- Resolution > 100 across entire bandpass
  - min is 102 at ~1.0um, max is 280 at ~0.4um
- Throughput: 72% average over bandpass
- Number of spectra on detector = 45 x 49
- Initial ghost analysis shows no significant ghosts

See section 3. Top Level Requirements/Science for compliance matrix

Spot sizes on detector





box width: 20 um = 2 detector pixels

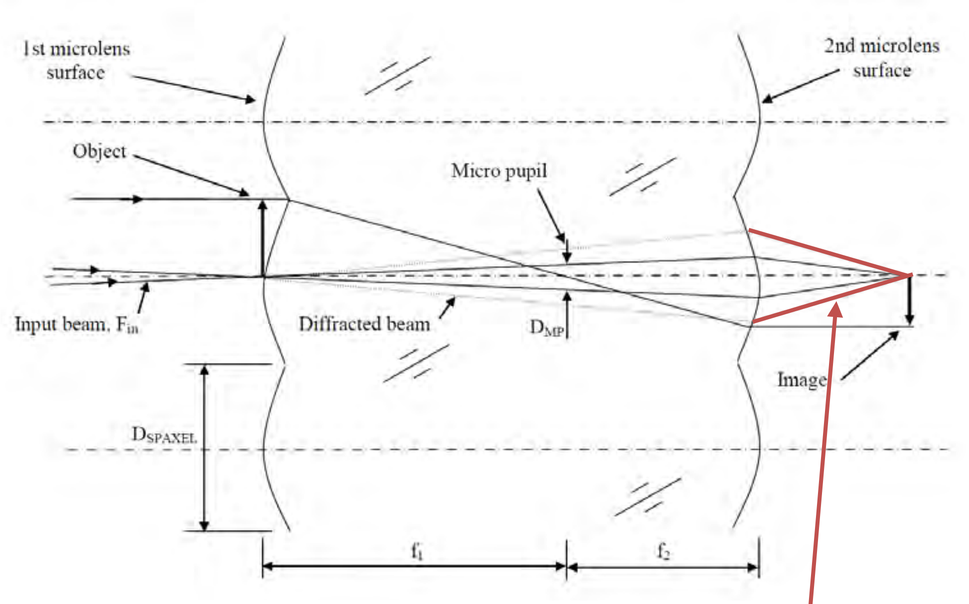
Geometric (aberration) spot sizes on detector

- 10 um rms diam averaged over FOV and bandpass
- 18 um rms diam max over FOV and bandpass

Geometric spot sizes likely do not drive size of spots, may be dominated instead by image of the lenslet aperture and diffraction

Diffraction

- Diffraction effects are significant and must be considered in the IFS design and performance
- Spectrograph f/# must be designed fast enough to accept diffracted light from MLA, or else flux is lost
  - diffraction from the BIGRE MLA lenslet aperture causes spectrograph effective f/# to vary with wavelength
  - significant energy is in diffraction "rings", and light loss depends on how many rings are captured by spectrograph
  - initial calculation suggests 17% light loss at 1.7um for f/8 spectrograph
- Effect drives the spectrograph design f/# to be larger, which introduces more aberrations – must achieve balance
- Clipping the diffraction f/# in the spectrograph also introduces additional diffraction that spreads spots on detector
- Issue is being actively studied



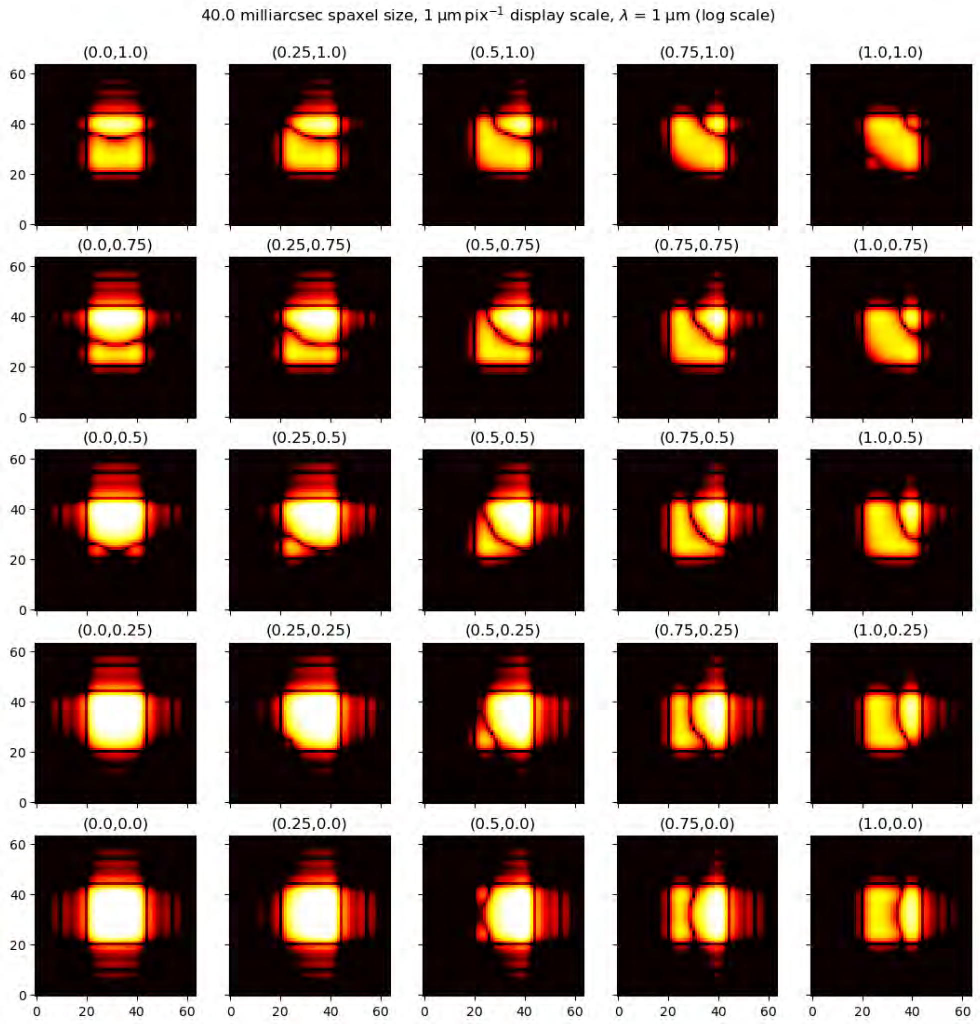
Antichi 2018

Wavelength (um)	0.4	0.55	0.8	1	1.7
F/#	22	18	14	12	8

from LAM 2022: LAM and UA/SSL spectrographs designed to accept f/8, although geometric f/# only f/16

Detector Spot Instability

- Position of the Telescope PSF will vary on the MLA lenslet apertures
- Since the BIGRE MLA design reimages the lenslet apertures directly onto the detector (i.e. spatial-spectral degeneracy), then this variation causes spot shape and magnitude changes at the detector
- These changes cause a centroid error, and therefore a spectrophometry error, i.e. instability that degrades spectrophotometric accuracy
- Spots on detector are also affected by spectrograph aberrations and diffraction (see previous slide)
- Issue is being actively studied



log plot; units in microns; 20um = 2 det pixel

Example of diffraction spots modeled using Python code

<u>40mas/lenslet</u>, at <u>1.0um</u>, for various positions of DL telescope PSF landing on a lenslet

Spots shown at MLA output; similar to expected at detector, but missing spectrograph aberrations and diffraction

Resolution

Δλ	1300 nm	
H4RG-10	4096	4096 pixels
pixel pitch	10 um	
dispersion per pixel	0.32 nm	
slit size	20 um	
pixel slit projection	2	

On-axis field

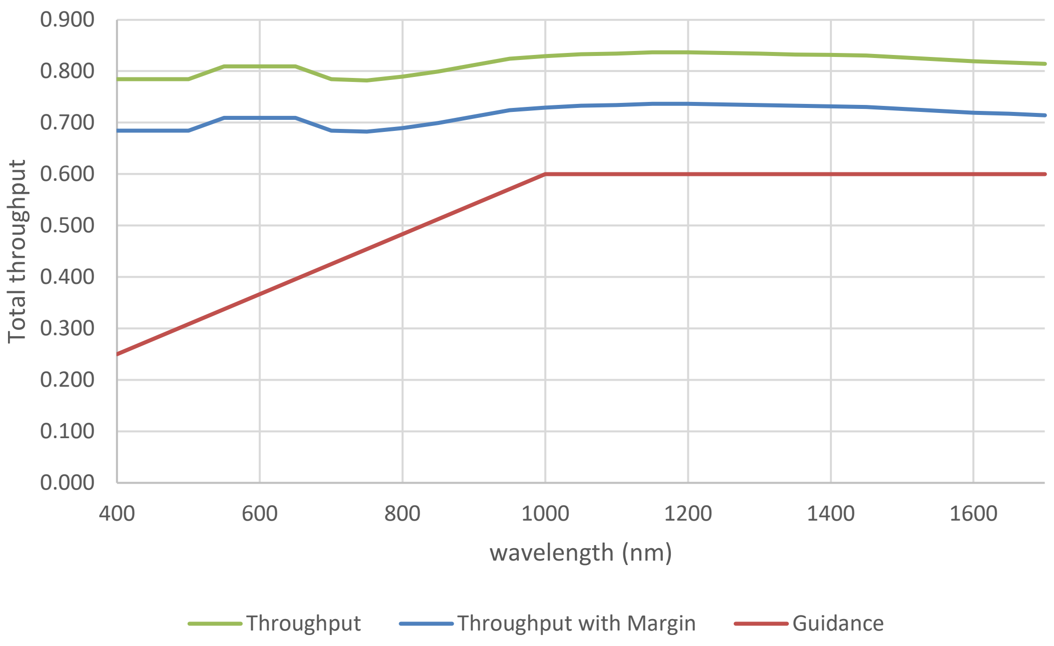
	F1					
Waveleng	X	Y	Shift	Dispersion	Δλ	R
um	mm	mm	mm	um/nm	nm	
0.4	0.281031686	-3.053036300				
0.5	0.153051550	-1.659363866	1.399536269	13.995363	1.429045	280
0.6	0.081483377	-0.899923887	0.762804749	7.628047	2.621903	191
0.7	0.035489164	-0.417924578	0.484188808	4.841888	4.13062	145
0.8	0.002404537	-0.074122935	0.345389869	3.453899	5.790558	121
0.9	-0.023715715	0.195513413	0.270898556	2.708986	7.382837	108
1.0	-0.045969810	0.423927820	0.229495939	2.294959	8.714751	103
1.1	-0.066107262	0.629539005	0.206594958	2.065950	9.680778	103
1.2	-0.085181841	0.823336821	0.194734262	1.947343	10.27041	107
1.3	-0.103863759	1.012235740	0.189820483	1.898205	10.53627	114
1.4	-0.122600360	1.200786080	0.189478999	1.894790	10.55526	123
1.5	-0.141704008	1.392102930	0.192268267	1.922683	10.40213	135
1.6	-0.161402683	1.588396855	0.197279859	1.972799	10.13788	148
1.7	-0.181870464	1.791290446	0.203923367	2.039234	9.807606	163

- Resolution = 103 to 280 across 0.4-1.7um bandpass, assuming Nyquist sampling
- Requirement is >100 minimum
- High resolutions at bandpass ends are due to nonlinear dispersion in the prism glass
- May consider increasing design resolution to 120 minimum to allow margin for blur contributors

Throughput

- Optical Throughput Budget
  - Multiplies reflectance/transmittance of all surfaces
  - for preliminary estimate, assumes reasonable, well-performing coatings:
    - reflective coatings are protected-Ag coatings from Viavi
    - antireflection coatings 98.5%
  - includes 10% margin
- Estimate meets program L2 requirement (July 2023) and program guideline (August 2023)
  - doesn't include sensor or telescope
  - note guideline based on LAM estimate plus margin; LAM estimate assumed catalog AR coatings and protected-Ag coatings

program guideline:



Also L2 requirement: Total optical throughput of > 50%, and 80% nominal, maximized for wavelength > 1 um.

Number of spaxels

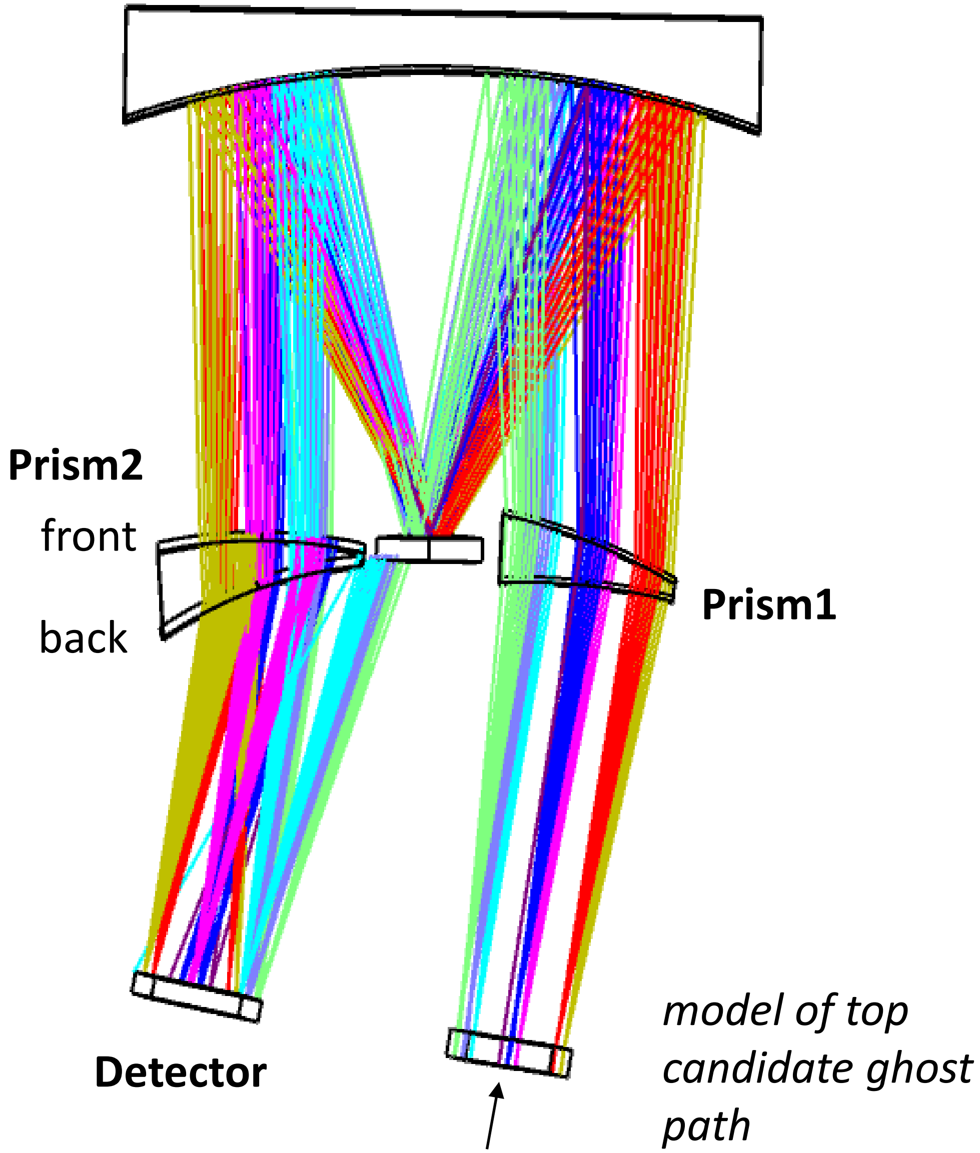
- LAM design fit 51 x 51 spectra (spaxels) onto the H4RG detector, vs requirement of >50x50
- LAM minimum resolution across bandpass was 80, vs requirement of >100
- UA/SSL design scales up the LAM Offner spectrograph to achieve resolution >100 minimum, but longer spectra means 49 x 45 spectra fit on detector
  - likewise, minimum FOV for finest scale (20 mas/spaxel) is therefore 0.98x0.90”, vs >1x1” FOV
- The original LAM packing of spectra allows significant space between spectra
  - significant space is needed to keep any cross-contamination between adjacent spectra < 1% goal
  - amount of cross-contamination has not been modeled, and depends on many factors driving the width of the spectra (abberations, diffraction, geometric image of lenslet sample) that are still not well-characterized
- Further redesign is needed to meet the requirements of both number of spaxels and resolution
  - we believe there is a good chance that we can take advantage of the significant space between spectra, and pack them slightly more densely, while still meeting cross-contamination requirement

Stray Light Control

- Stray light control is critical in our mission that requires low background noise (high SNR)
- Aim to follow best practices for stray light control, instead of relying on extensive analysis
- Best practices: “move it or block it or paint/coat it or clean it”
  - put masks at accessible pupils and image planes
  - baffle edges of optics (scatter sources)
  - paint visible surfaces black as much as possible
  - low roughness optical surfaces
  - good contamination control
- Consider thermal emission, since thermal background is issue within our bandpass
  - bench temperature and cold stops are main knobs to turn
- Assess stray light with increasing fidelity of analysis
  - start with first-order calculations, and targeted analysis
  - full analysis requires more mature optomech design, and will be done in a later phase
- Began stray light analysis in study phase
  - analyzed scatter from MLA dead area between lenslets: stray light at detector only 1e-6 of science spectra, likely insignficant
  - ghost analysis (next slide)

Ghost Analysis

- Performed initial ghost analysis, looking for potential ghost paths arising in the Offner spectrometer
  - also analyzed ghosts in the lens doublet before the MLA, but MLA strongly diverts rays; the analysis will need more attention
- Analyzed 10 double-bounce paths, with conservative assumptions for surface reflectivities
- Identified several candidate ghost paths; top candidate is path between the detector and Prism #2 front surface
  - irradiance (power/area) is ~1e-7 of science spectra, likely insignificant
- Next confirm cross-contamination is negligible; if need be, reoptimize Offner relay to remove ghost path



Summary/Future Work

- Conceptual design meets most requirements
- We believe that there are no showstoppers to meeting all requirements, given further development
  - we have identified paths forward to close all requirements
- Alternate slicer-based optical design (TBD) may address the requirements differently

- Work in next phase:
  - close all L2 requirements, i.e. >50x50 spaxels
  - mature diffraction analysis and effects on performance
  - improve margin on resolution requirement
  - optical tolerance analysis
  - mature stray light analysis, incl thermal emission
  - mature calibration path optics
  - mature throughput estimate

4. MECHANICAL DESIGN/THERMAL ANALYSIS

Mechanical Design/Thermal Analysis (Outline)

- LAM layout vs new layout
- LAM Performance vs new performance (Modal)
- Areas of future investigation

Mechanical and Thermal Requirements (**LAM Design**)

Mass Budget (LAM)

Cold mass (in the Telescope focal plane): **42.7kg**

Warm Electronics: **10.8kg**

Harness: **2.6kg**

system Margin**: 5.6kg**

Thermal

Cold mass (in the Bench 50W @ 215K
Sensor 5W @ 120K
Control & Calibration Units TBC W @ 300K

Optical sensitivity

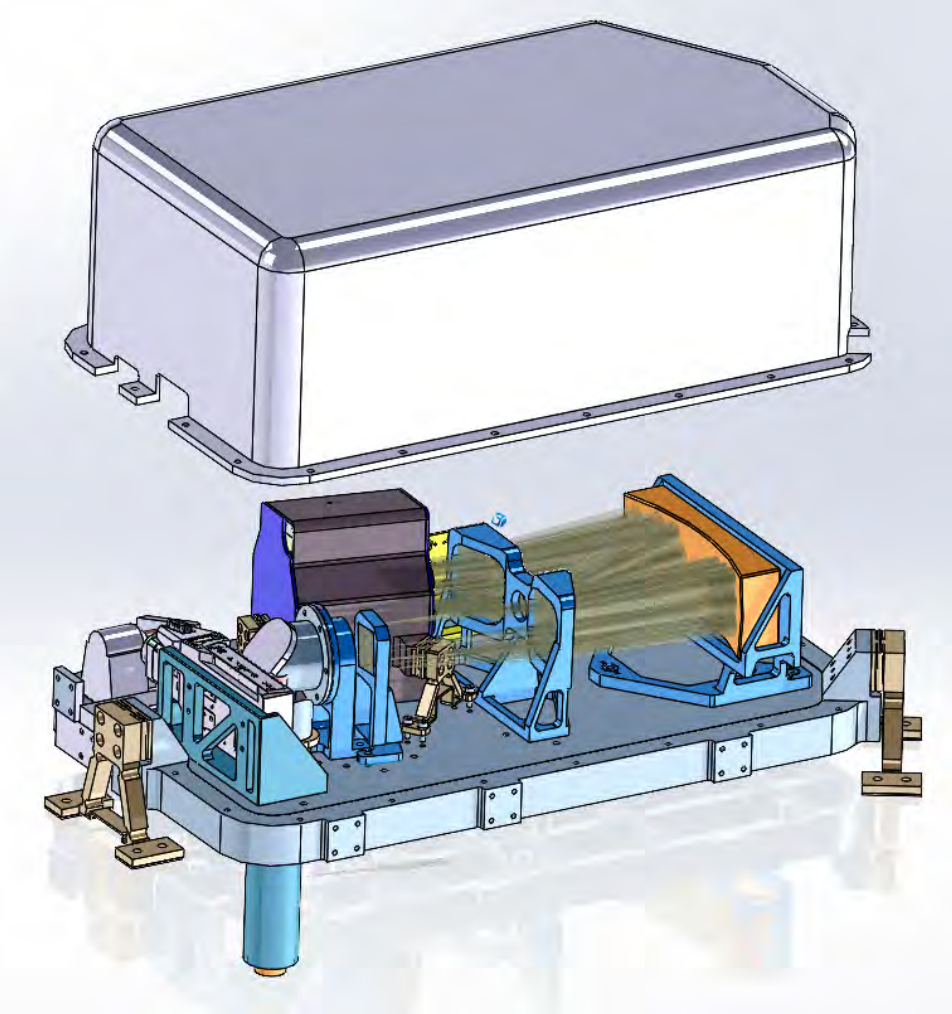
Most Critical assemblies:

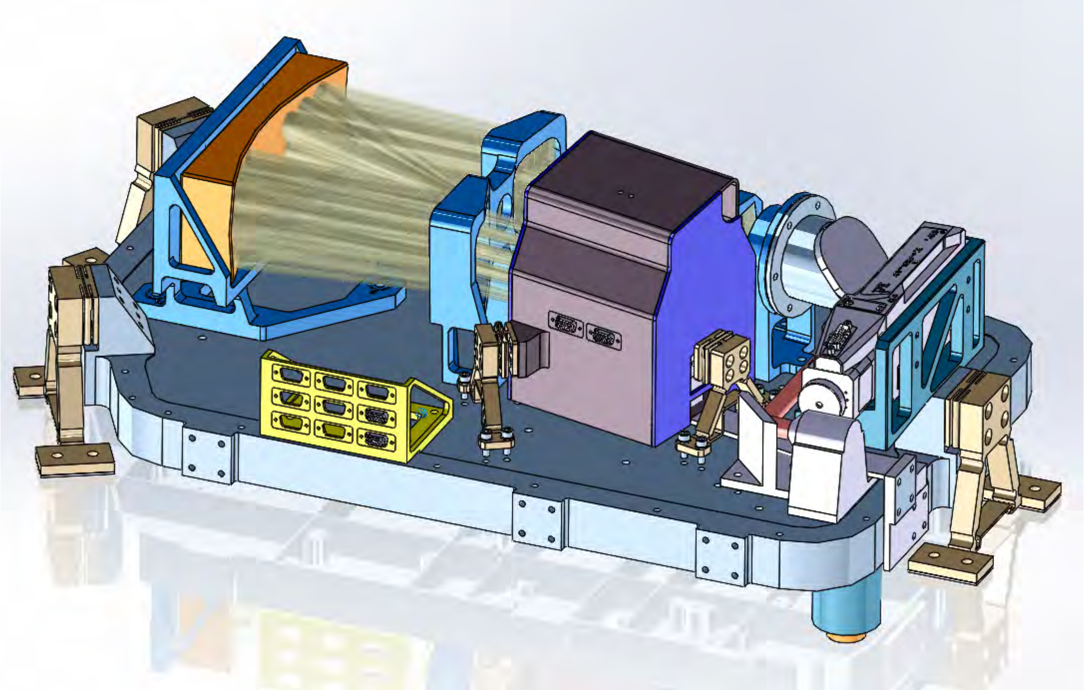
- Instrument to telescope focus= +/-40µm;
  (tip/tilt: +/- 10arcmin)
- Magnifier:
  - Individual surfaces centering +/-100µm
  - Assembly centering= +/- 40µm
- M2:
  - Centering= +/-100µm
- Detector:
  - Flatness= +/-30µm
  - Focus= +/-30µm
  - Tip-tilt= +/-0.1°

Others:

Centering: +/-1mm
Focus: +/- 1mm
Tilt/Wedge: +/-1°

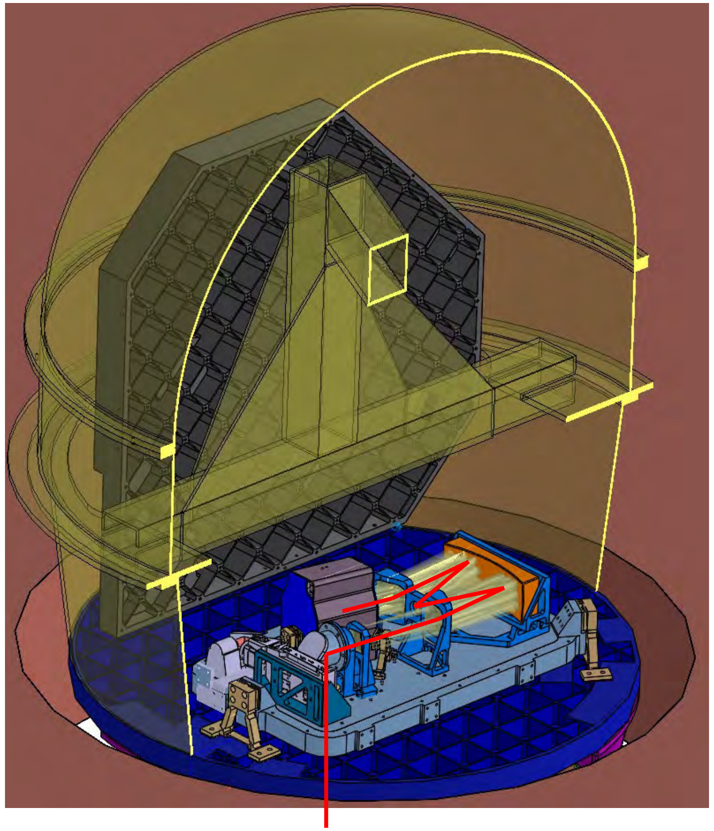
LAM Design Overview

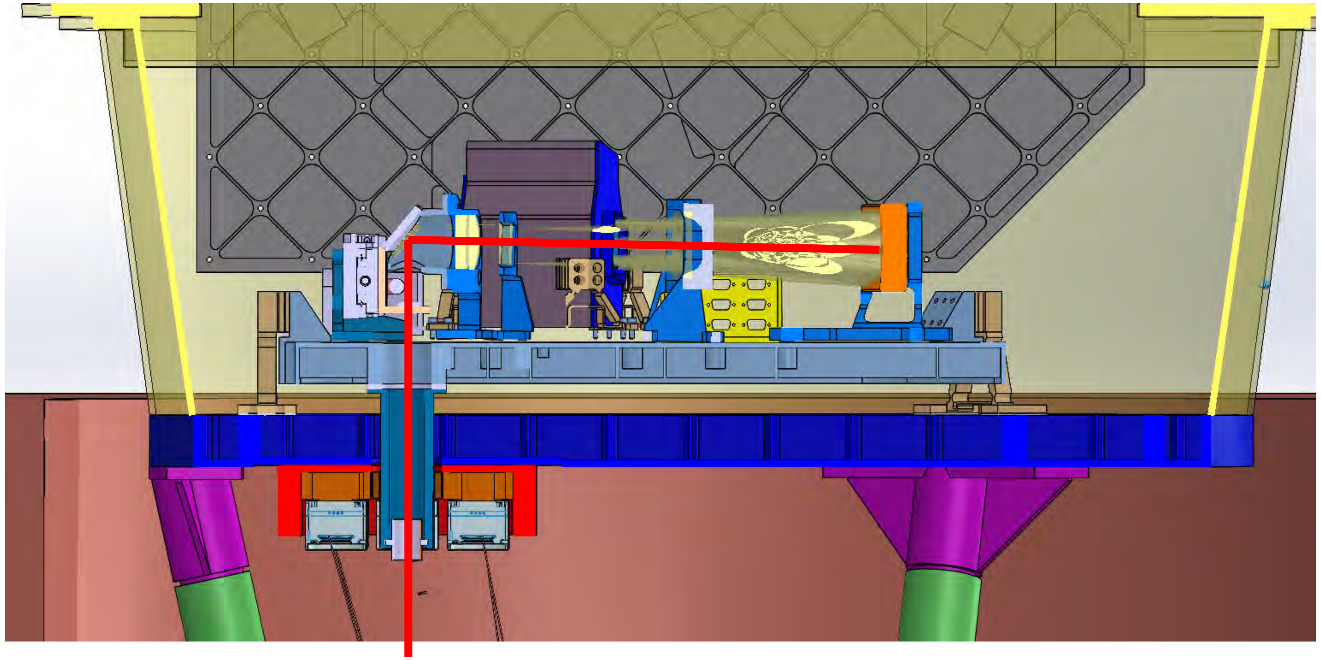




- Lightweighted aluminum bench supported by titanium flexures
- Optical mounts mix of notional/conceptual
- Reflective magnifier assumed
- Linear stage mechanism to insert calibrator pickoff mirror

LAM Design Packaging in Telescope



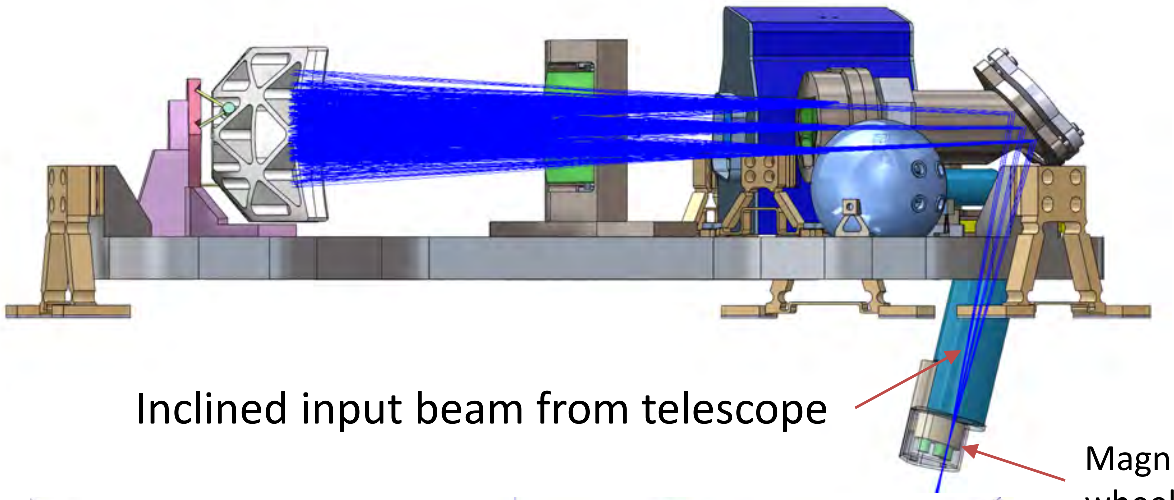


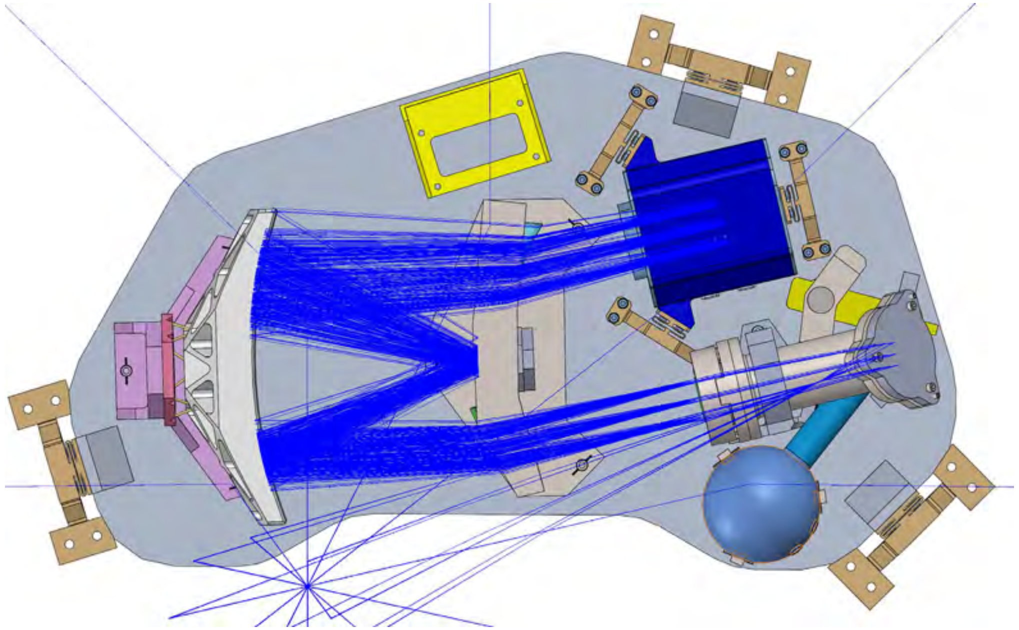
- LAM packaging concept assumed input beam parallel to optical axis which is **not compatible** with telescope optical design

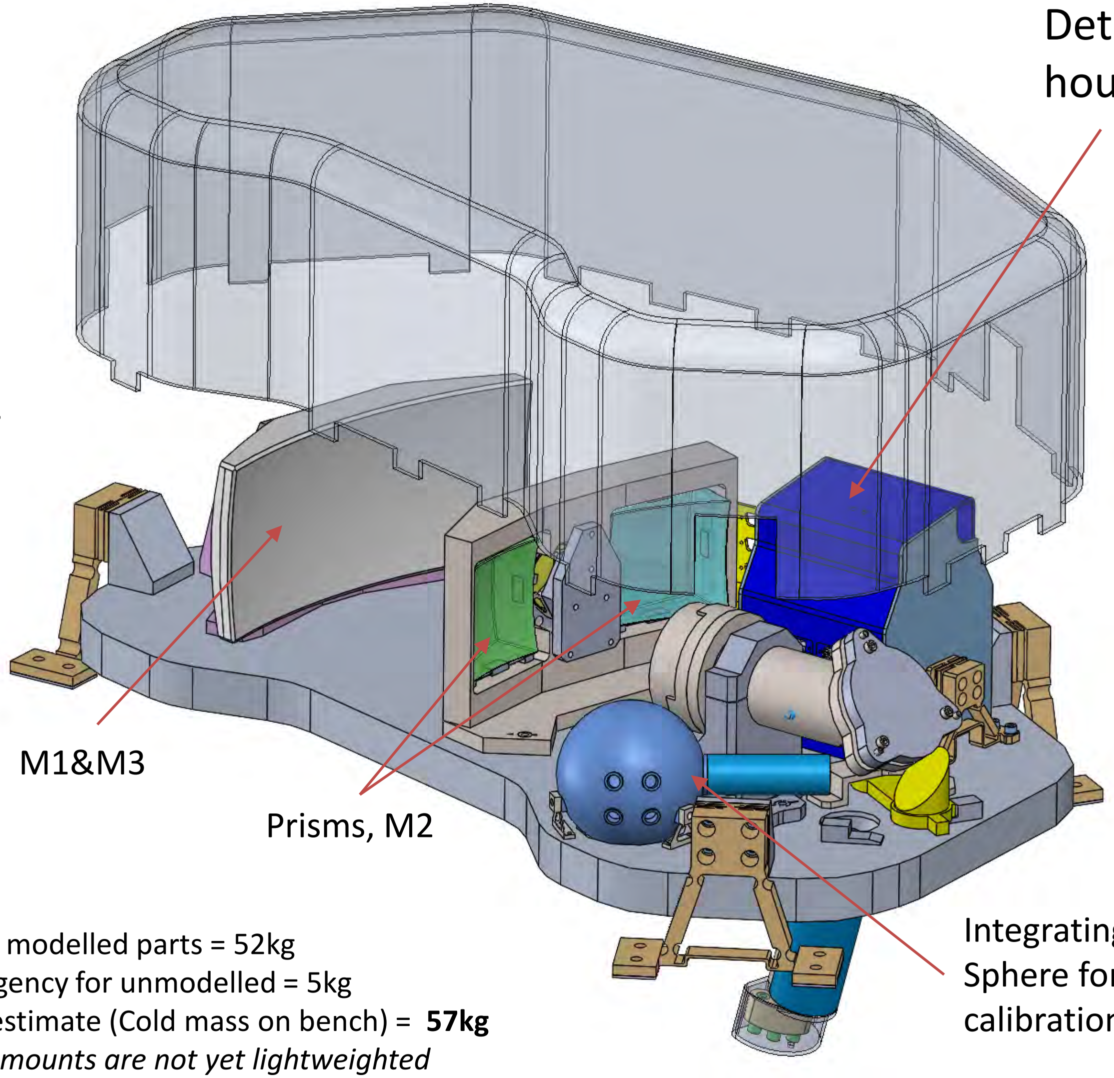
Other Issues identified with LAM design

- Did not meet resolution Spec
- Position and orientation of input beam in focal plane of WCC was not correct
- Optomechanical Mounts are very notional

New SSL/UA concept details

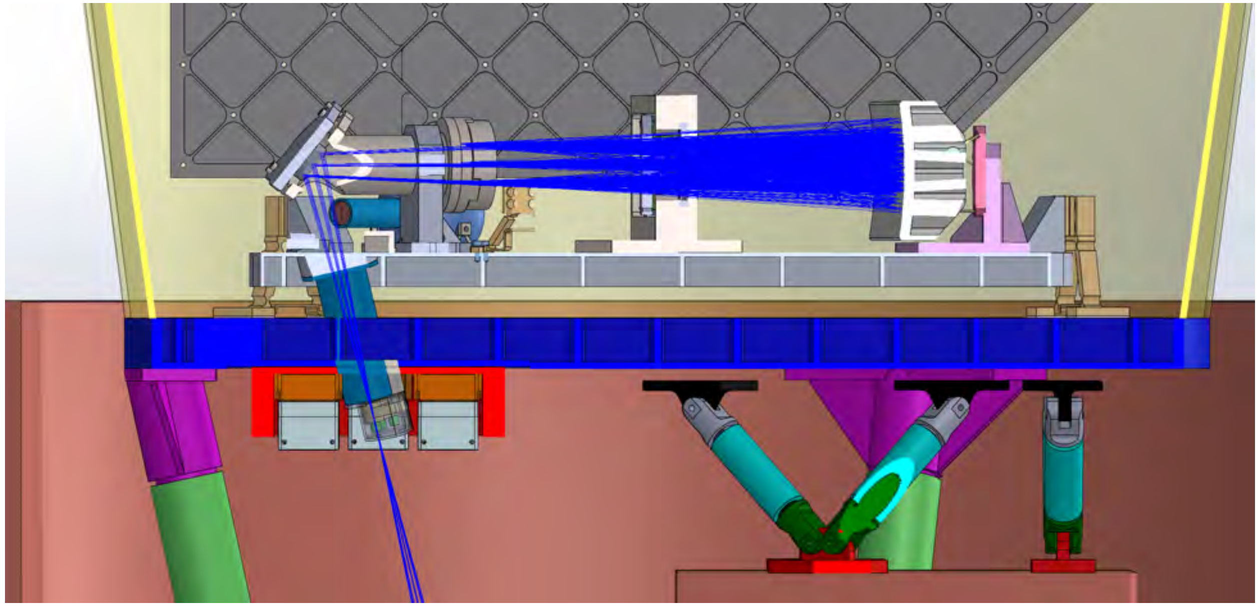


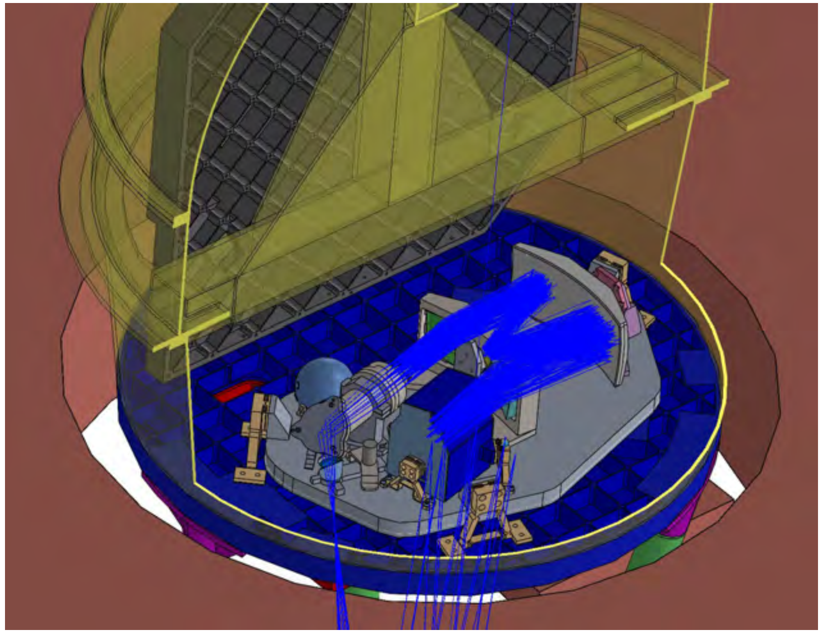


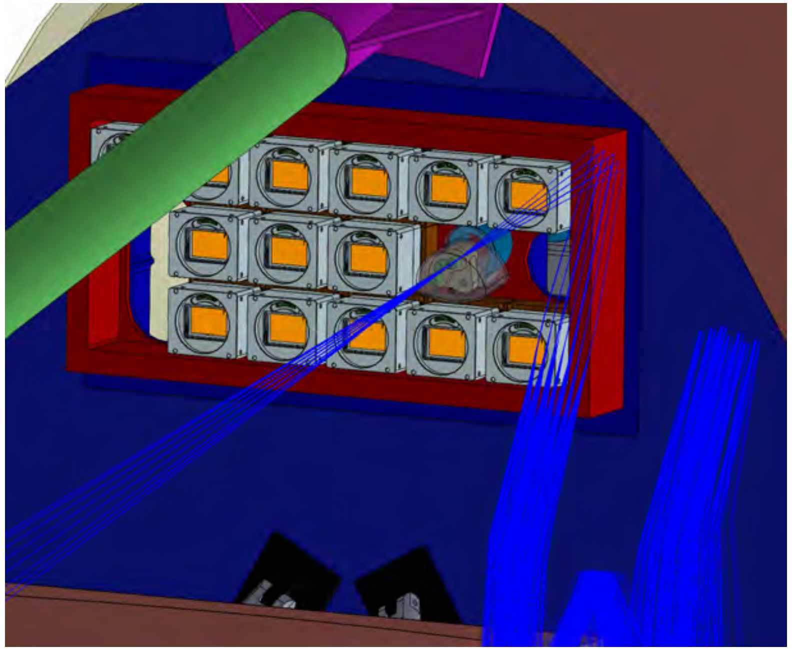


Est. mass of modelled parts = 52kg
10% Contingency for unmodelled = 5kg
Total mass estimate (Cold mass on bench) = **57kg**
Note – new mounts are not yet lightweighted

New SSL/UA concept Telescope packaging

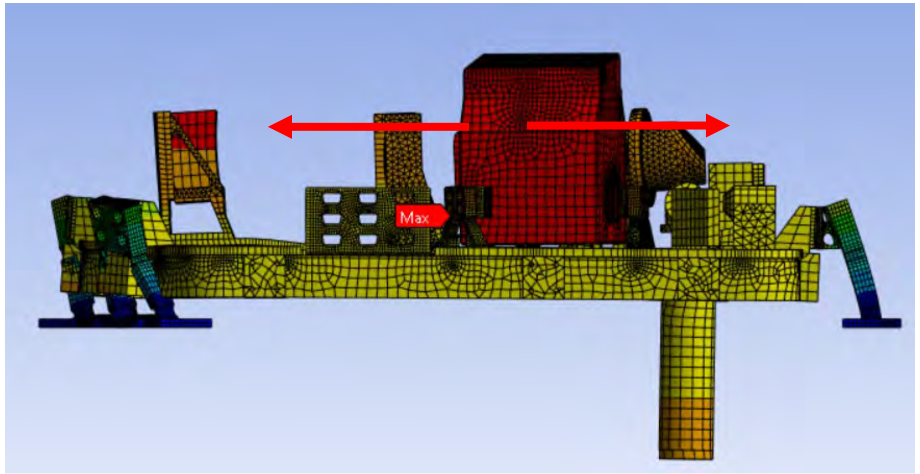




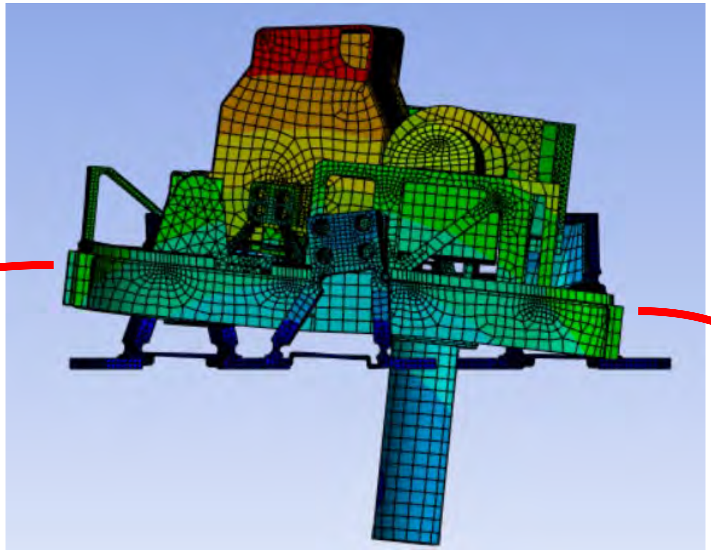


- IFS Optics realigned to telescope optics
- Using transmissive magnifier to avoid incoming beam divergence
- Now using off-axis WCC field, compatible with other instrument packaging
- IFU optics mirrored, to bring detector closer to outer enclosure (for shorter thermal connections)
- Replaced calibrator linear stage with simpler rotation arm
- IFS Bench footprint adapted to new volume restrictions

Preliminary Modal Analysis (**LAM**)

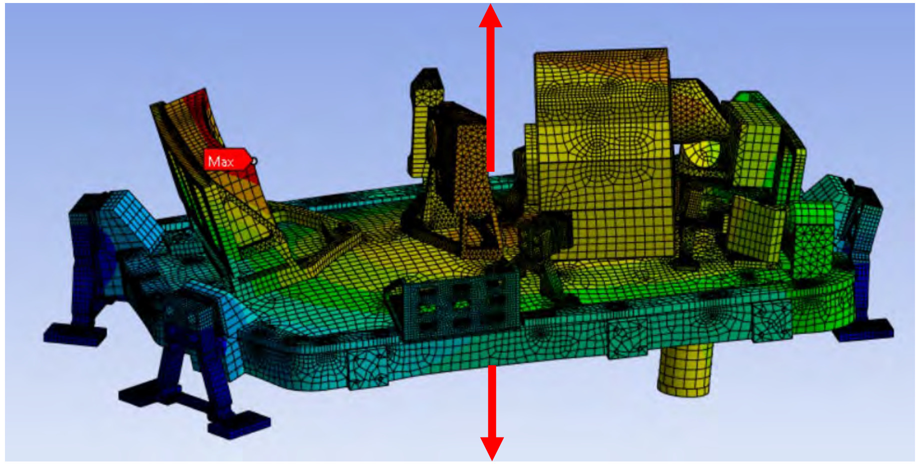


1st mode – 72 Hz

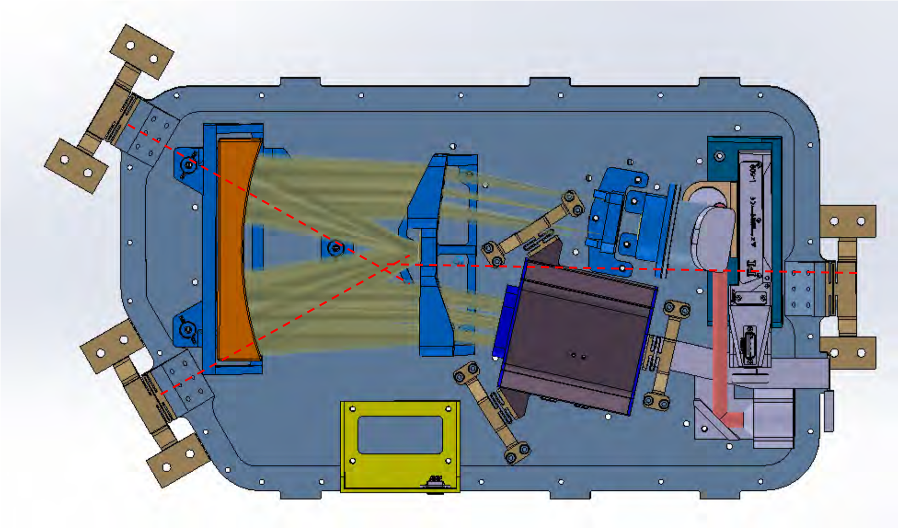


3rd mode – 110 Hz

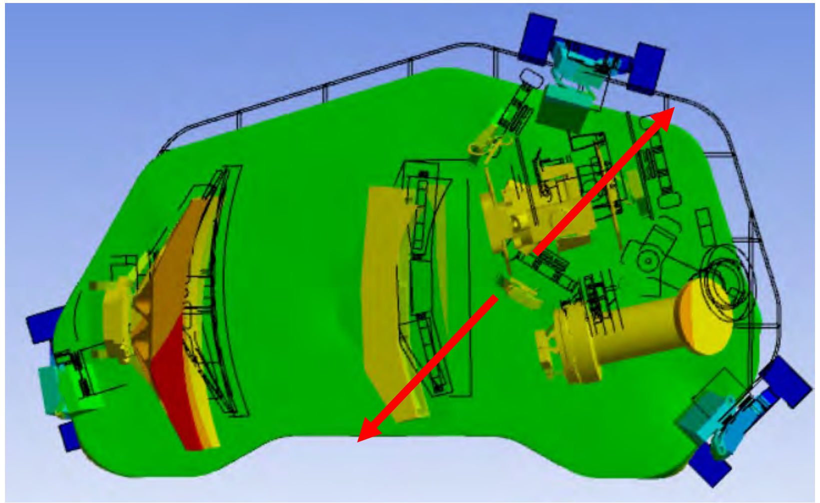
	Mode	Frequency [Hz]
1	1.	71.624126
2	2.	106.0157
3	3.	109.95065
4	4.	117.44045
5	5.	138.79664
6	6.	148.70693



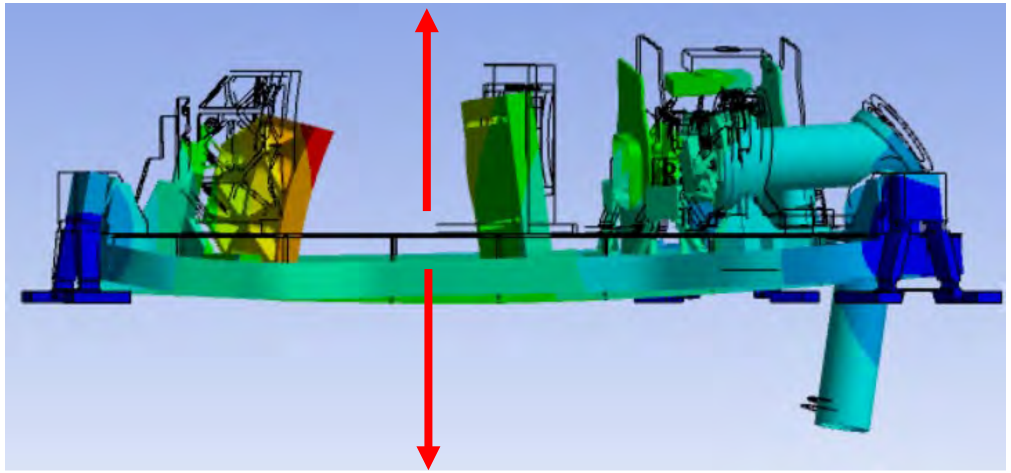
3rd mode – 106 Hz



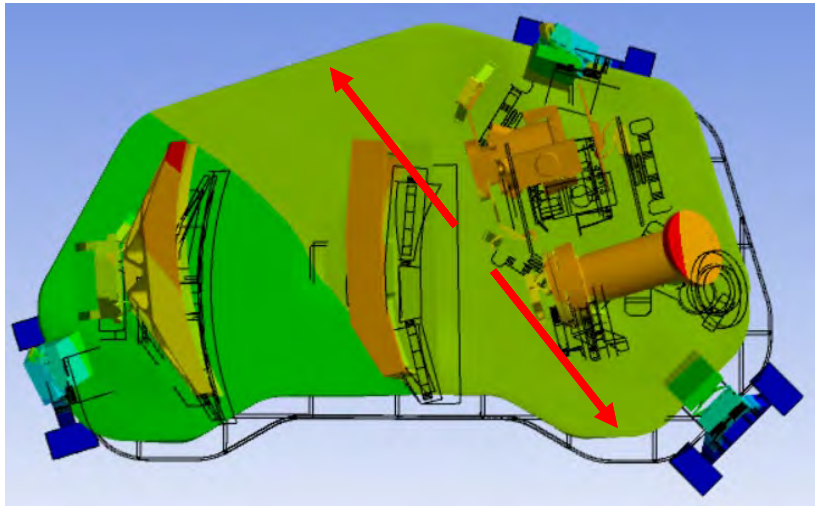
Preliminary Modal Analysis (**UA/SSL**)



1st mode – 77 Hz



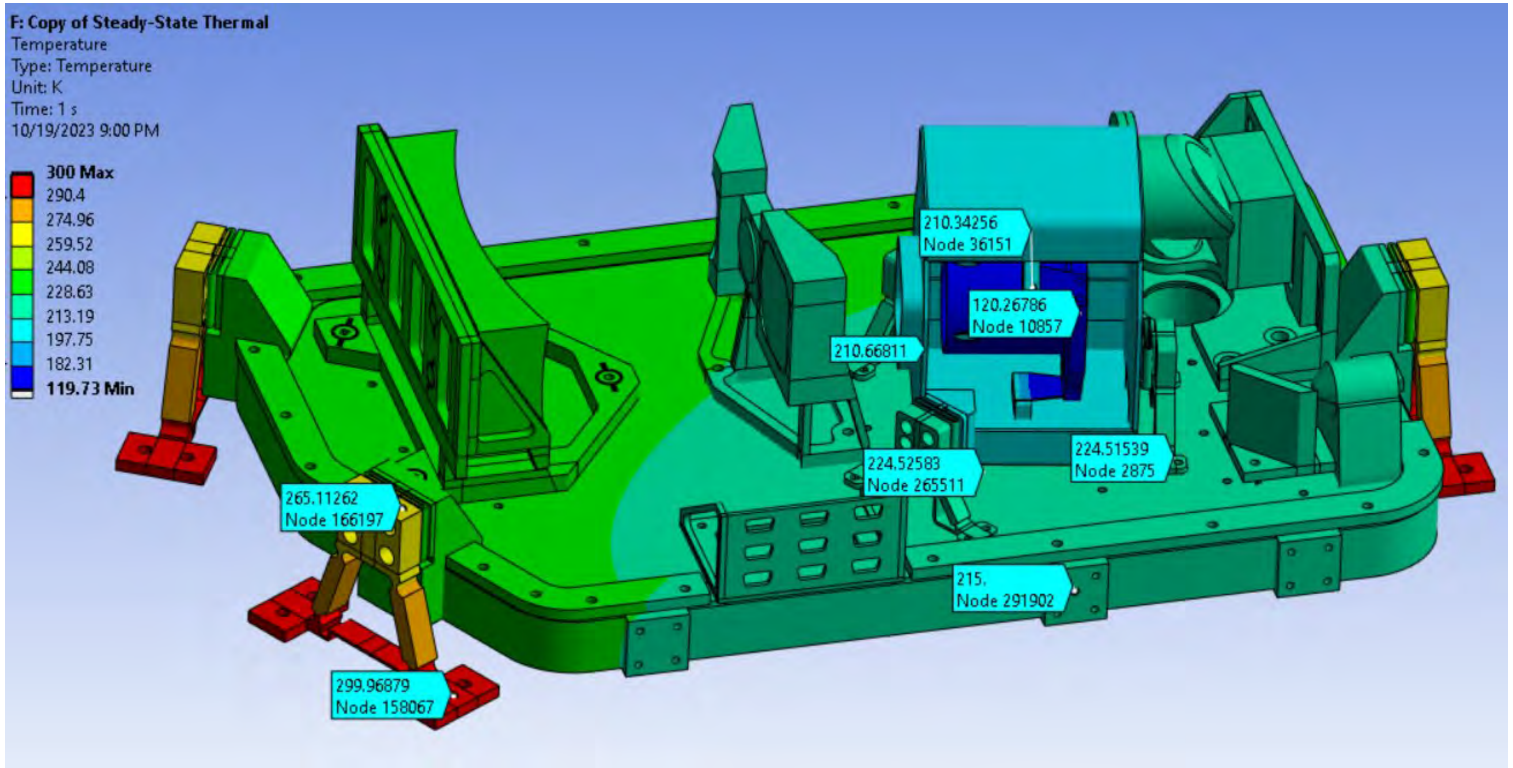
3rd mode – 88 Hz



2nd mode – 79 Hz

Mode	☑ Frequency [Hz]
1.	76.80255
2.	79.024889
3.	87.674453
4.	113.08175
5.	122.93772
6.	125.73827

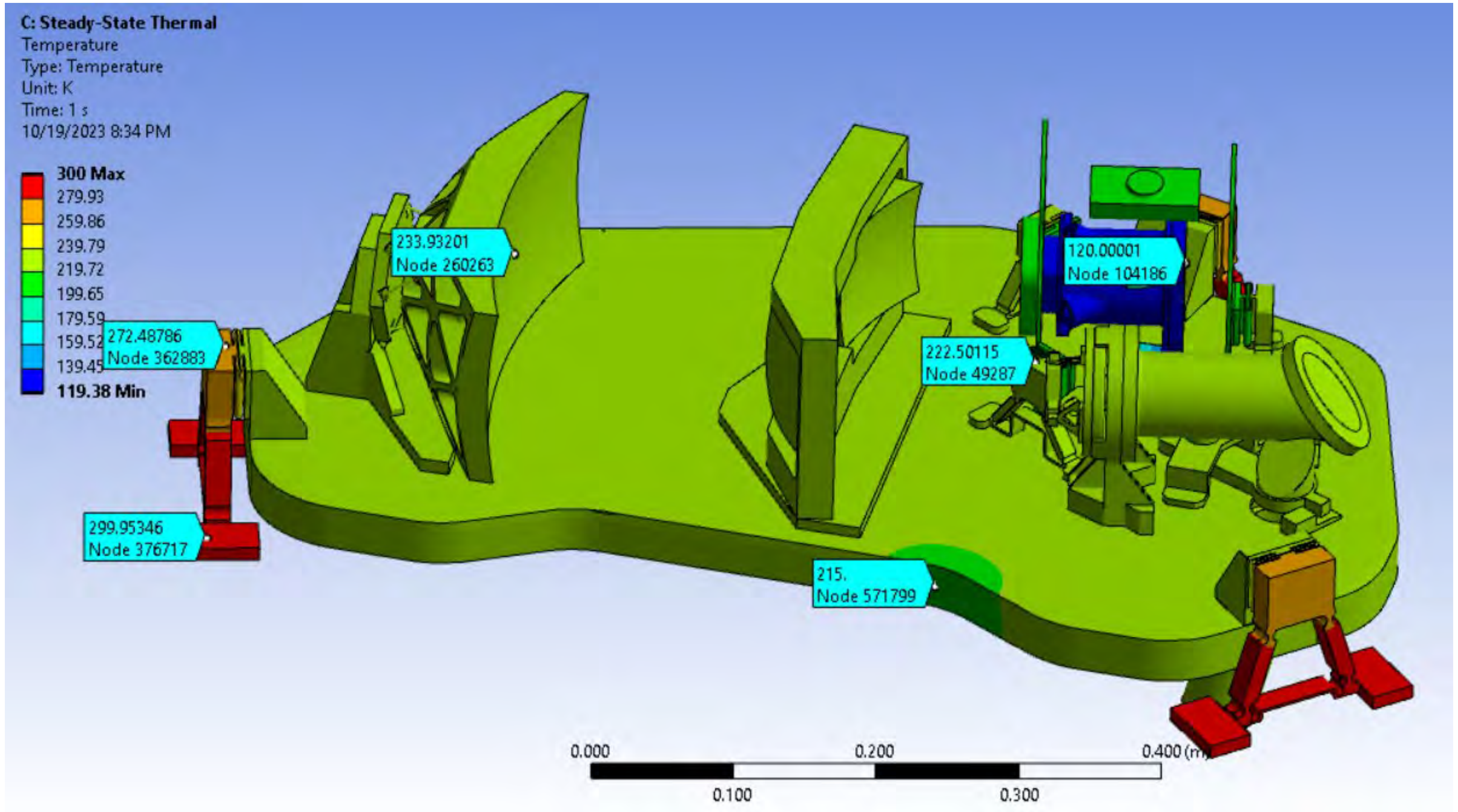
Preliminary Thermal Analysis (**LAM**)



Boundary Condition	Thermal load
Spacecraft Interface 300K	2 W
Detector temp 120K	-2 W
Bench Temp 215K	-21 W

- Detector load not included
- Includes radiative loads from 300K instrument enclosure

Preliminary Thermal Analysis (**UA/SSL**)

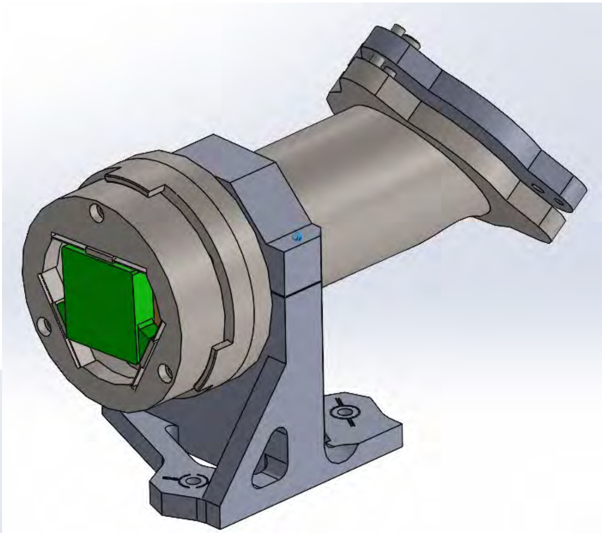


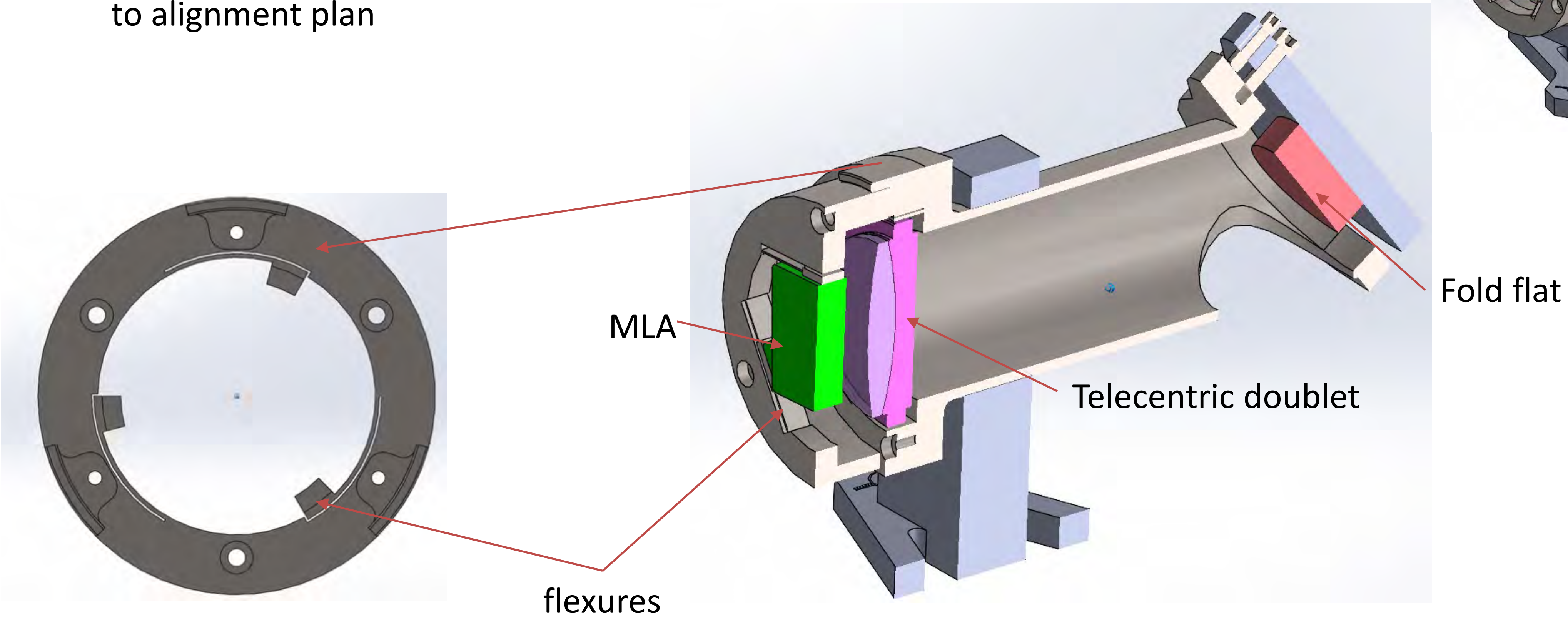
Boundary Condition	Thermal load
Spacecraft Interface 300K	2 W
Detector temp 120K	-2 W
Bench Temp 215K	-22 W

- Detector load not included
- Includes radiative loads from 300K instrument enclosure

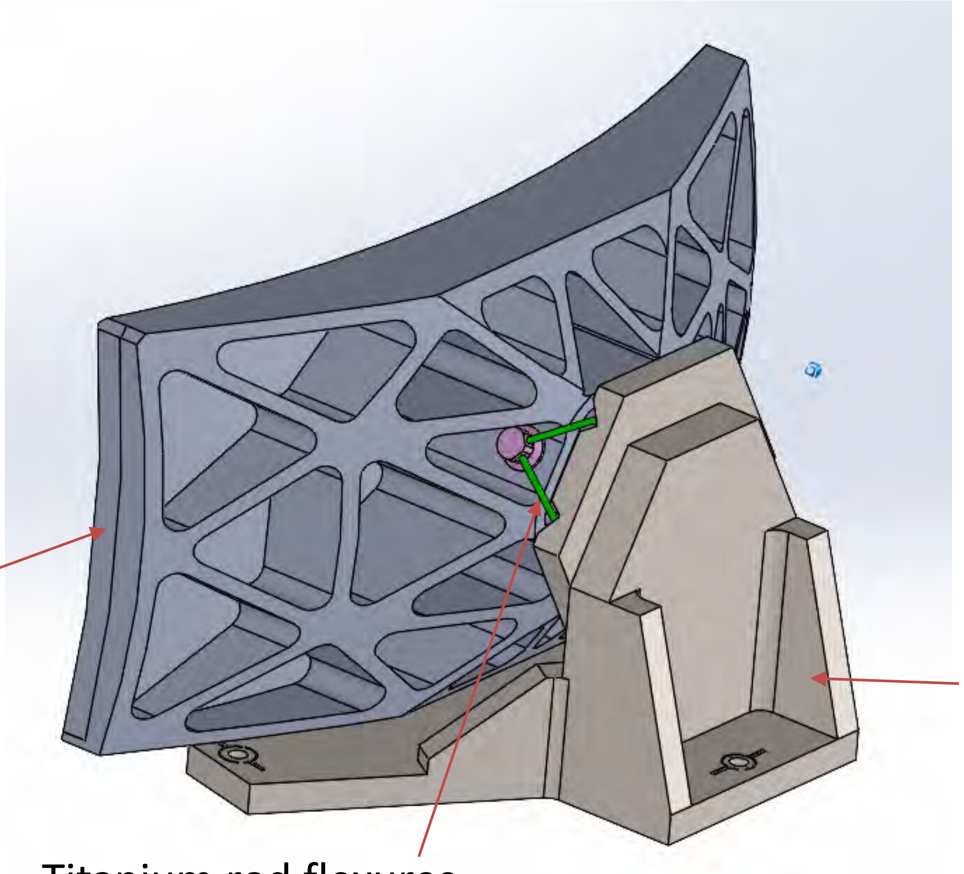
Optomechanical Mount Concepts

- Single assembly supports MLA, telecentric doublet, and fold mirror
- Integral slots in base of mount allow for radial expansion/contraction due to differential CTE between aluminum bench and titanium mount
- Optics are bonded to individual mounts using integrally machined (wire-EDM'ed) flexure elements. Alignment of optics defined by machining, verified according to alignment plan





Optomechanical Mount Concepts



Similar lightweighted mirror with titanium bipods and invar pads has SSL flight heritage

Lightweighted Zerodur M1/M3 optic

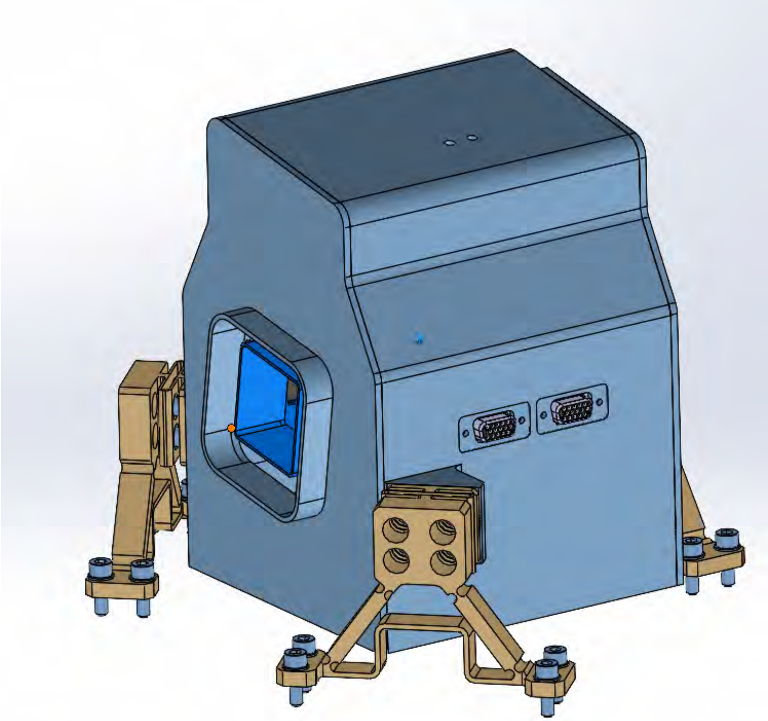
Titanium mount brackets will incorporate adjustment screws to allow alignment according to alignment plan, expansion slots for attachment to aluminum base

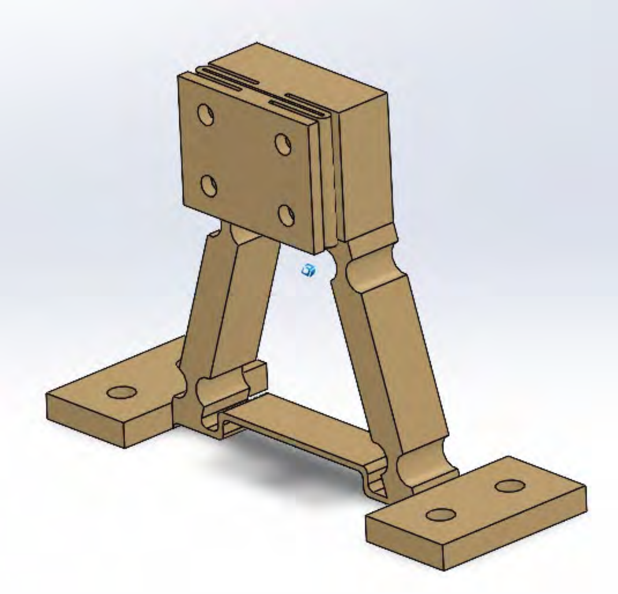
Lightweighting of brackets still TBD

Titanium rod flexures
3x bipod configuration with
Invar bond pads

Optomechanical Mount Concepts

Still baselining LAM design of base flexures and detector housing, to be re-evaluated during Flight System phase

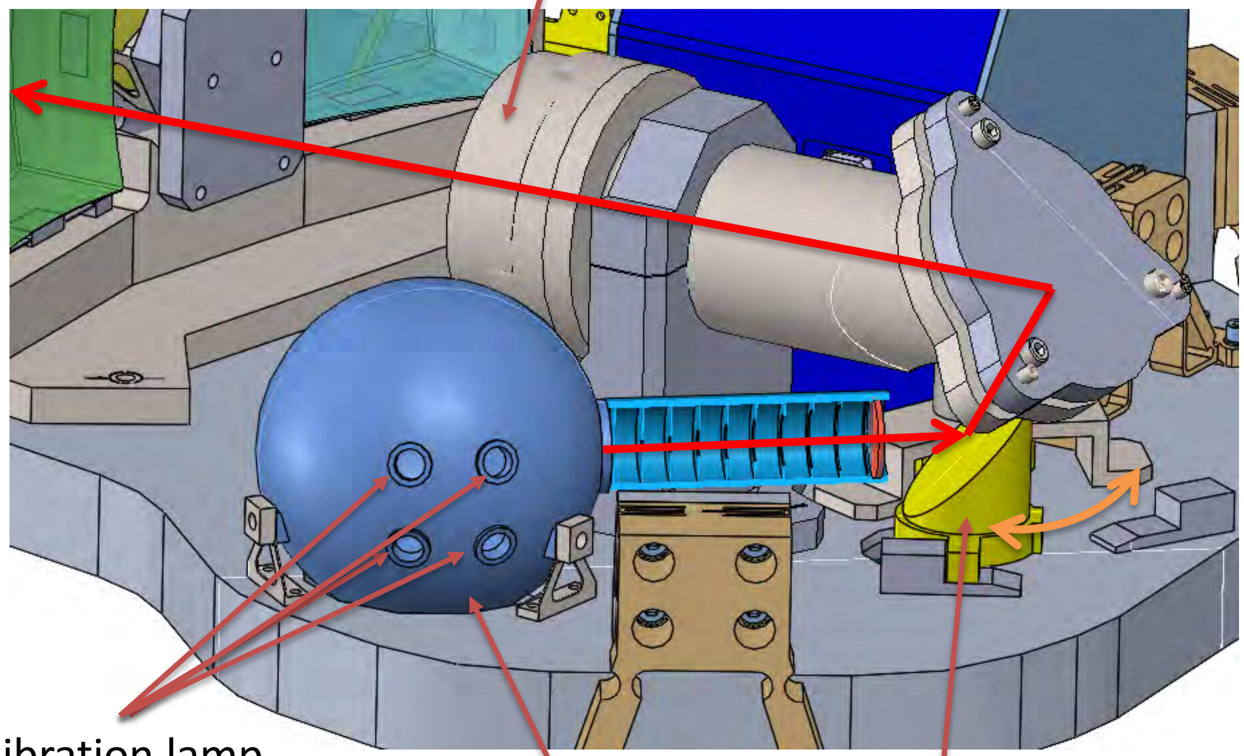




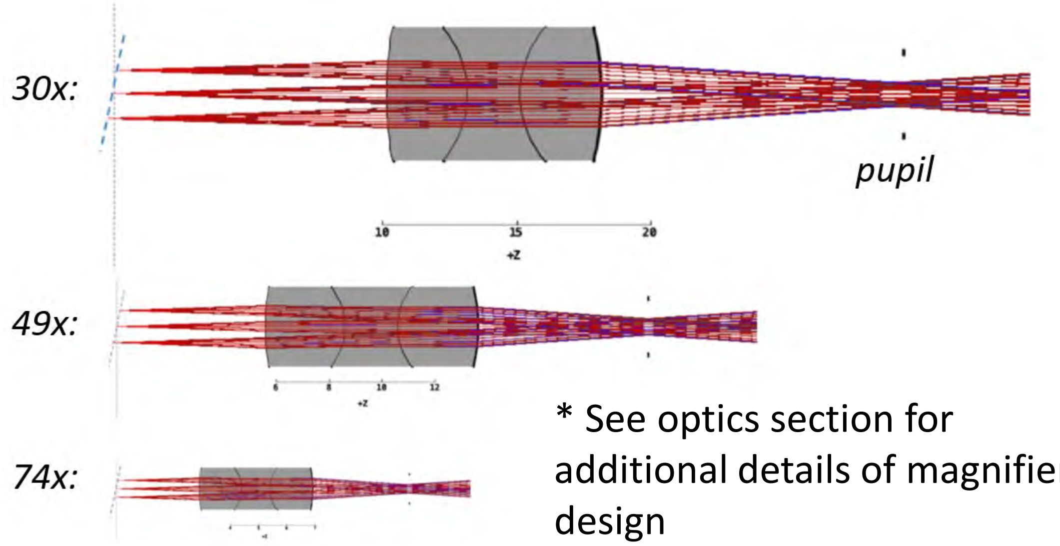
Calibration Mechanism Mechanical Concept

Calibrator

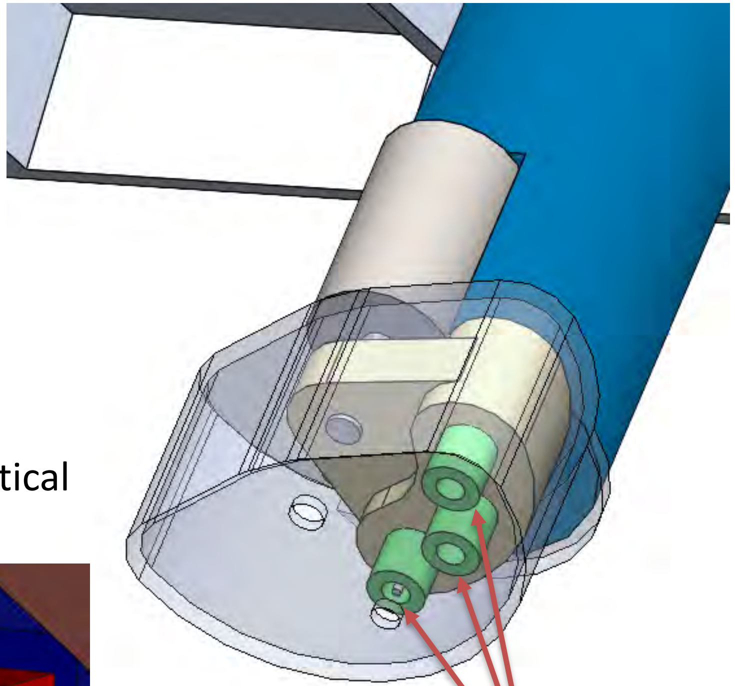
- Flip-in pickoff mirror sends light from integration sphere through MLA to detector
- Alternative to mirror would be beam splitter to avoid mechanism
- Calibration lamps off-bench with fibers feeding sphere



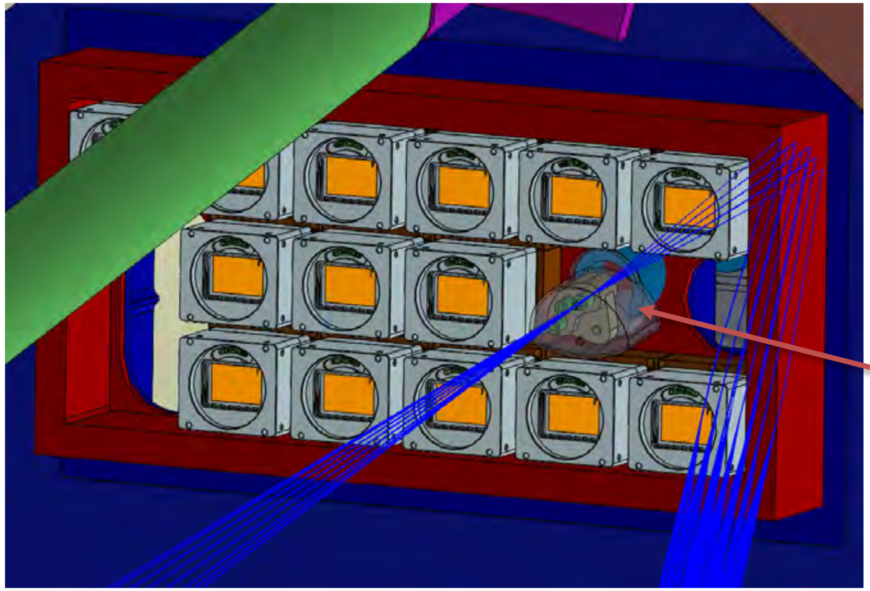
Magnifier Mechanism Concept



* See optics section for additional details of magnifier optical design



Selection of 3 magnifiers



Mechanism fits within single WCC port

- Magnifier mechanism mounts to tube, cantilevered off of IFS bench
- Mechanism to be wrapped in MLI to thermally isolate from warm WCC detectors
- Provides accessible pupil for cold stop

Areas of future study

- Continued maturation of optomechanical mounts
- Material selection trade (mounts, reflective optics)
- STOP analysis – mechanical stability vs. optical tolerancing
- Refinement of thermal loading analysis to inform spacecraft cooling requirements

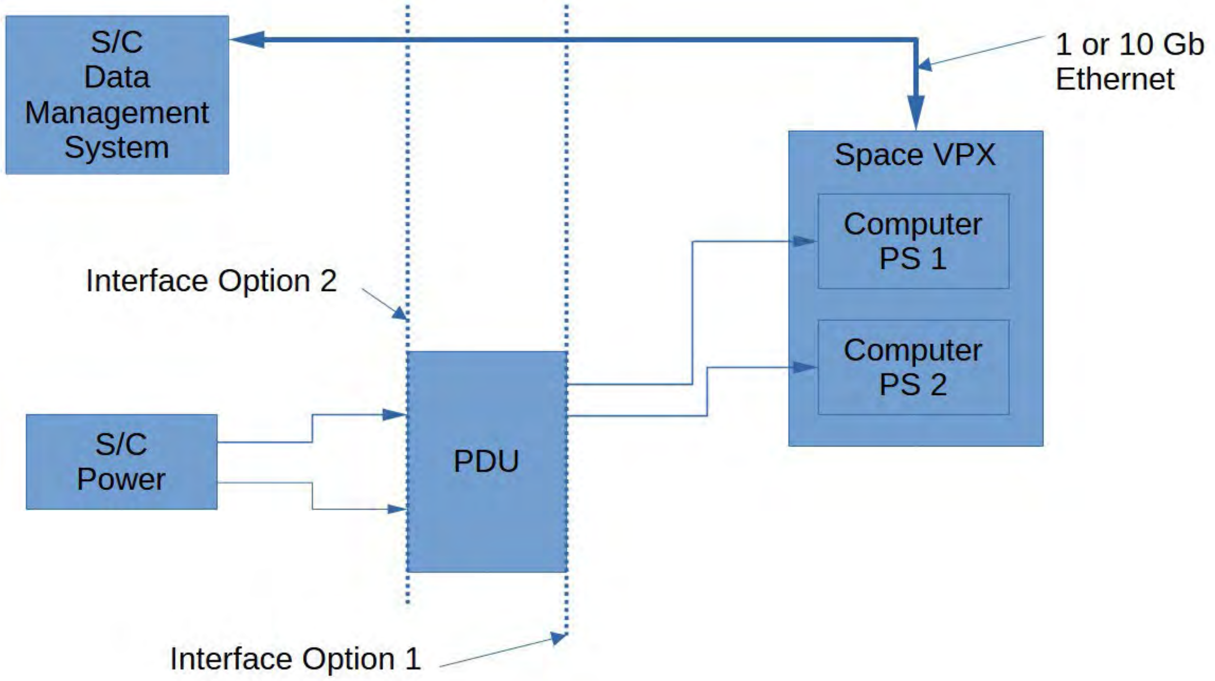
5. COMPUTING AND ELECTRONICS DESIGN

Computing and Electronics Design (Outline)

- Spacecraft Interface
- Electrical System Computing System
- Detector Interface
- Calibration and Motion Control Interfaces

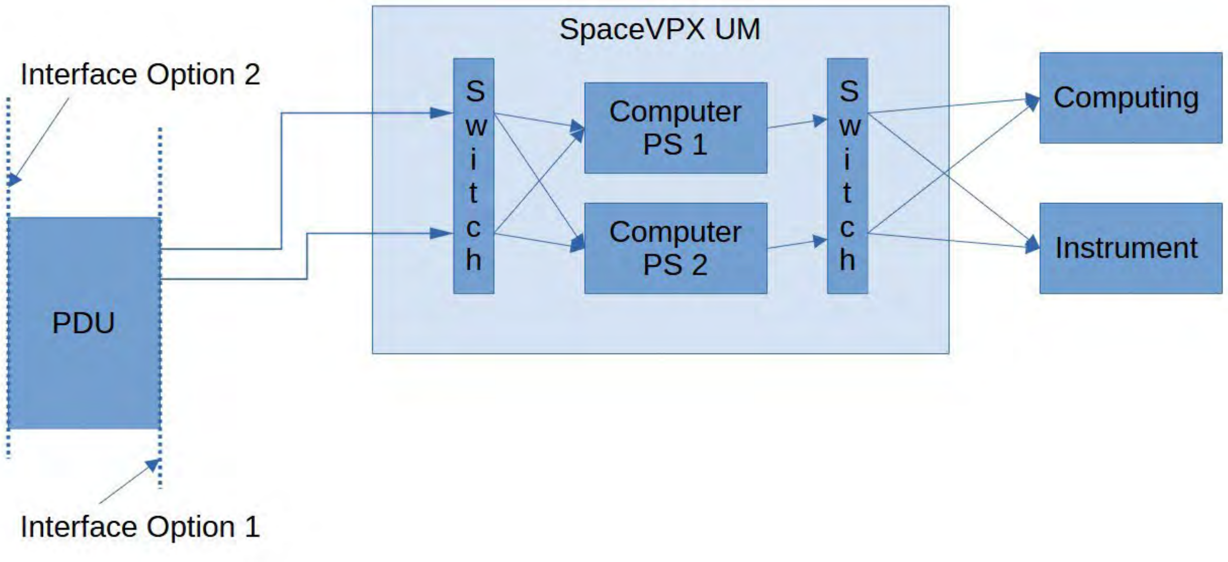
Spacecraft Interface

- Details still TBD, depending on S/C vendor selected
- Electrical
  - 28V nominal input
  - ~80W conservative power estimate power
- Data Interface
  - Ethernet, 1 Gb or 10 Gb
- Power interface option 1 or 2 depending on S/C vendor



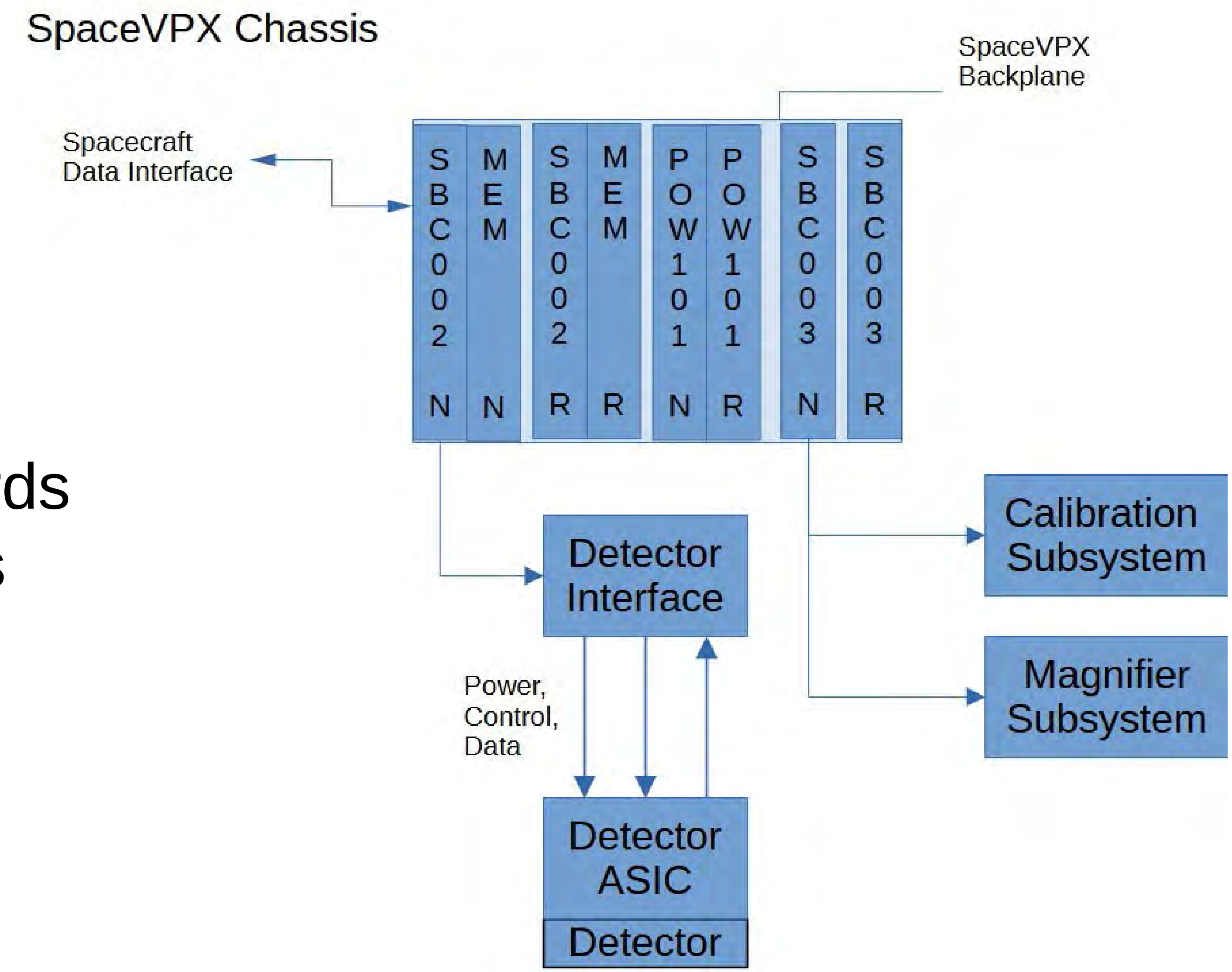
Power Supply

- Spectrograph Electrical Requirements
  - 28V nominal input
  - <80W roughly estimated power
    - <40 W for SpaceVPX Computer
    - 10W for detector and interface
    - <30W calibration system and motors
- SpaceVPX Chassis UM Manages redundant input and output of power supplies to subsystems
  - Detector analog power supplies provided by detector interface



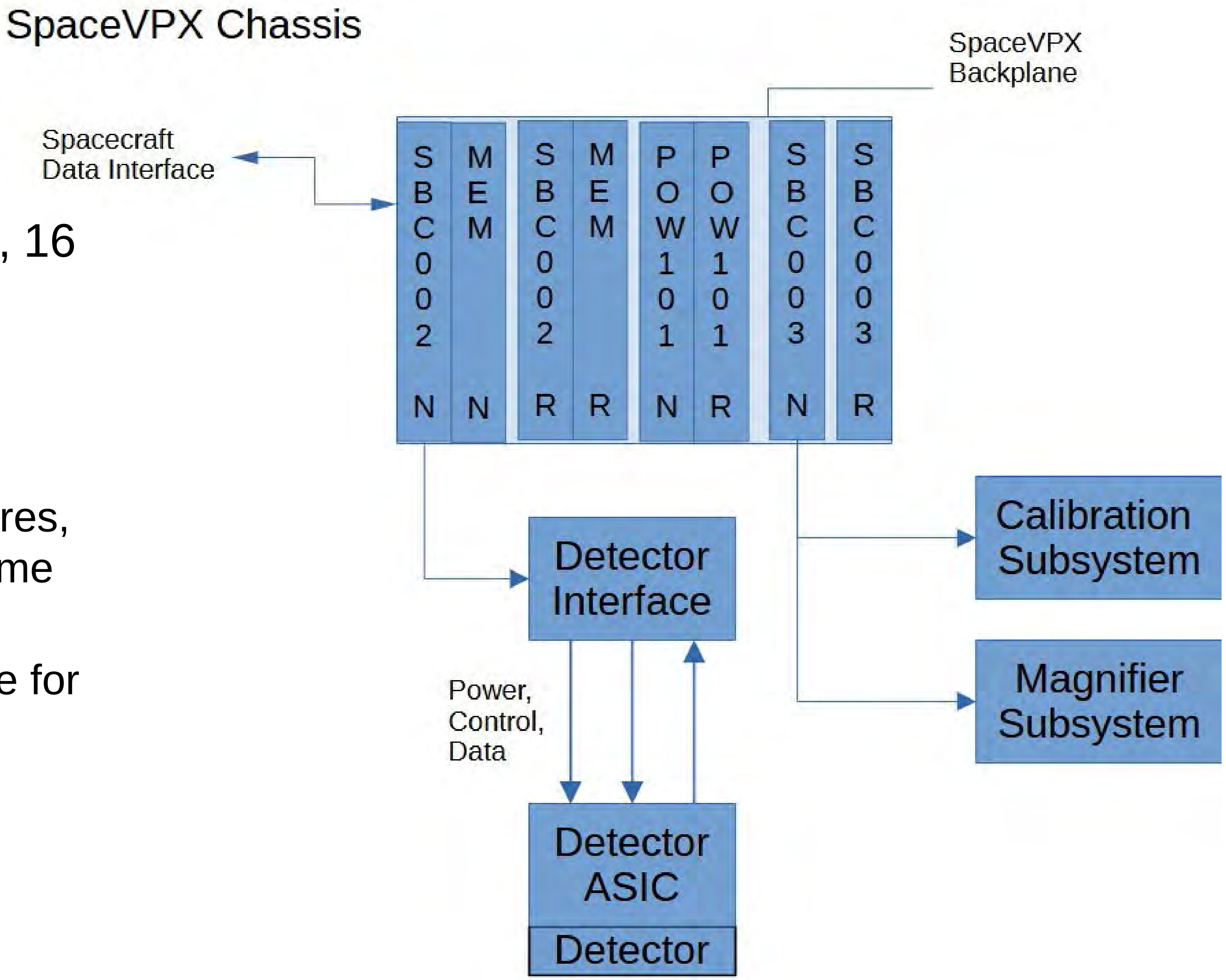
Computing Subsystem

- Redundant power supply
- Redundant CPUs
- Redundant 500 GB non-volatile memory modules
- All interfaces on FMC boards and integrated front panels on VPX chassis



Computing Subsystem

- SpaceVPX Architecture
- Two CPU Options
  - Neutralino SBC, NSV-201
    - 8 core ARM, GPU on board, 16 GB DRAM
  - Novo Space
    - SBC002
      - Xilinx Zynq with 4 ARM cores, plus dual core ARM real-time processor
      - Large unused FPGA space for custom interfaces
      - FMC interface site
    - SBC003
      - Fusion-2 SOC
      - FMC interface site



Detector Interface

- Uses Teledyne Sidecar ASIC
- Two options for Sidecar interface
  - MACIE board possibly modified/depopulated for space use
    - Provides power supplies to sidecar
    - Provides control and data interface via LVDS to sidecar
    - Provides Gigabit Ethernet data stream to host
  - Custom FMC interface or VPX interface using Novo Space FPGA space for control, custom power supply circuits. Would use existing MACIE FPGA firmware or new development

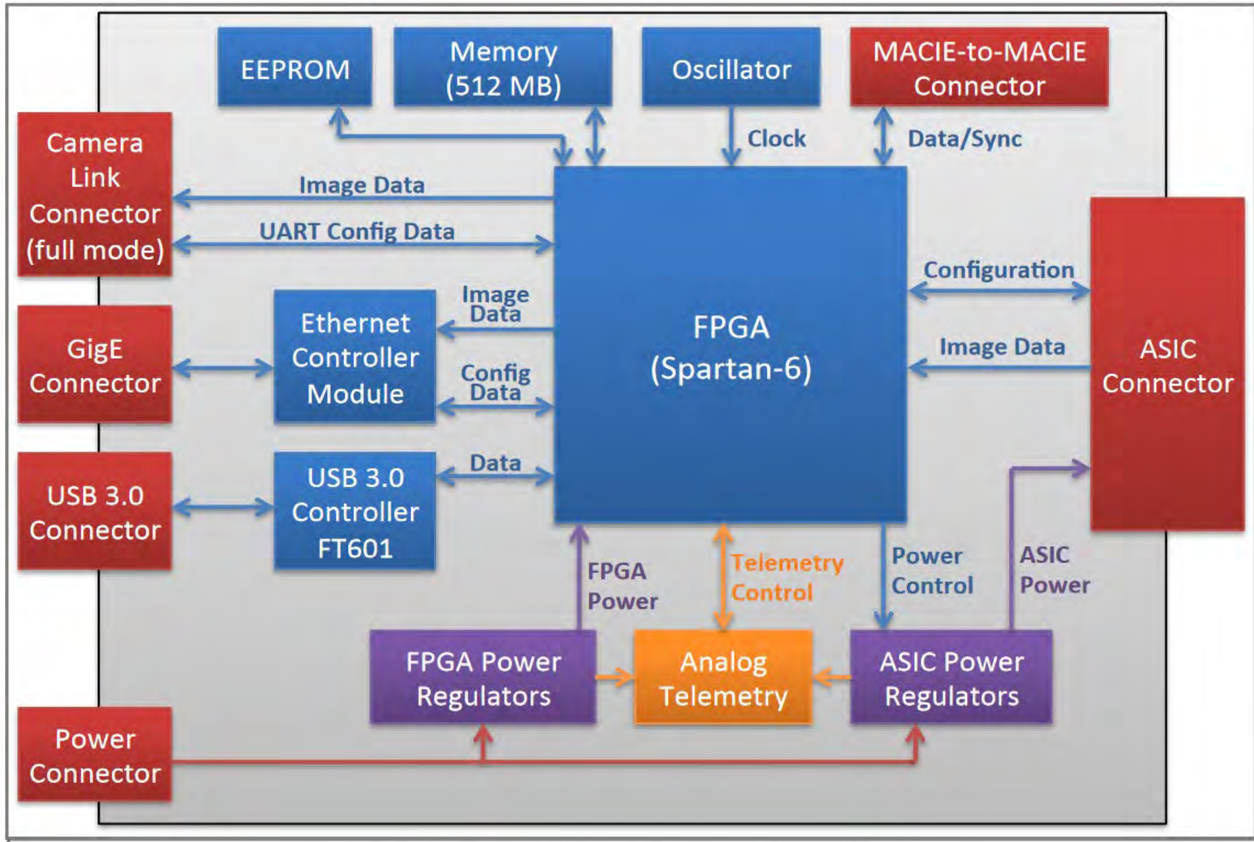


Figure 1: *MACIE Block Diagram*

Calibration Subsystem Control

- Light sources
- Selector mirror
  - Heritage stepper motor driver from SSL/CDA
  - Heritage stepper motor from SSL/CDA
- Controlled by front panel interface on SBC computers (Novo Space design)

Magnifier Control

- Magnification Selector motor
  - Heritage stepper motor driver from SSL/CDA
  - Heritage stepper motor from SSL/CDA
- Controlled by front panel interface on SBC computers (Novo Space design)

Preliminary Computing ICD

Connector	Connector type	Connector pin	Signal bundle	Interface signal index	Interface type	Interface type pin	Connected to
F00100AV - J4	A117704-001	01	Calibration Unit – Fold Mirror Motor	0	H-Bridge Driver	OUT_1	BOTH
F00100AV - J4	A117704-001	02	Calibration Unit – Fold Mirror Motor	0	H-Bridge Driver	OUT_2	BOTH
F00100AV - J5	A117704-001	01	Detector Temp Sensor	0	Analog	AG	BOTH
F00100AV - J5	A117704-001	02	Detector Temp Sensor	1	Analog	AG	BOTH
F00100AV - J5	A117704-001	03	SIDECAR Temp Sensor	0	Analog	AG	BOTH
F00100AV - J5	A117704-001	04	Magnifier Stepper Motor Temp Sensor	0	Analog	AG	BOTH
F00100AV - J5	A117704-001	05	Cal Fold Mirror Motor Temp Sensor	0	Analog	AG	BOTH
F00100AV - J5	A117704-001	06	Cal Source Temp Sensor	0	Analog	AG	BOTH
F00100AV - J5	A117704-001	07	Cal Source Temp Sensor	1	Analog	AG	BOTH
F00100AV - J5	A117704-001	08	Cal Source Temp Sensor	2	Analog	AG	BOTH
F00100AV - J5	A117704-001	09	MACIE Temp Sensor	0	Analog	AG	BOTH
F00100AV - J5	A117704-001	10	Instrument Electronics Temp Sensor	0	Analog	AG	BOTH
F00100AV - J5	A117704-001	11	Instrument Electronics Temp Sensor	1	Analog	AG	BOTH
F00100AV - J5	A117704-001	12	Instrument Electronics Temp Sensor	2	Analog	AG	BOTH
F00100AV - J5	A117704-001	13	Instrument Electronics Temp Sensor	3	Analog	AG	BOTH
F00100AV - J5	A117704-001	14	Instrument Electronics Temp Sensor	4	Analog	AG	BOTH
F00100AV - J5	A117704-001	15	Optics Bench Temp Sensor	0	Analog	AG	BOTH

Preliminary Computing ICD

F00100AV - J5	A117704-001	16	Optics Bench Temp Sensor	1	Analog	AG	BOTH
F00100AV - J5	A117704-001	17	Optics Bench Temp Sensor	2	Analog	AG	BOTH
F00100AV - J5	A117704-001	18	Optics Bench Temp Sensor	3	Analog	AG	BOTH
F00100AV - J5	A117704-001	19	Optics Bench Temp Sensor	4	Analog	AG	BOTH
F00100AV - J5	A117704-001	20	Optics Bench Temp Sensor	5	Analog	AG	BOTH
F00100AV - J5	A117704-001	21	Optics Bench Temp Sensor	6	Analog	AG	BOTH
F00100AV - J5	A117704-001	22	Optics Bench Temp Sensor	7	Analog	AG	BOTH
F00100AV - J5	A117704-001	23	Optics Bench Temp Sensor	8	Analog	AG	BOTH
F00100AV - J5	A117704-001	66	S/C I/O Interface	0	SPACEWIRE	DI_P	BOTH
F00100AV - J5	A117704-001	65	S/C I/O Interface	0	SPACEWIRE	DI_N	BOTH
F00100AV - J5	A117704-001	70	S/C I/O Interface	0	SPACEWIRE	SI_P	BOTH
F00100AV - J5	A117704-001	69	S/C I/O Interface	0	SPACEWIRE	SI_N	BOTH
F00100AV - J5	A117704-001	68	S/C I/O Interface	0	SPACEWIRE	DO_P	BOTH
F00100AV - J5	A117704-001	67	S/C I/O Interface	0	SPACEWIRE	DO_N	BOTH
F00100AV - J5	A117704-001	72	S/C I/O Interface	0	SPACEWIRE	SO_P	BOTH
F00100AV - J5	A117704-001	71	S/C I/O Interface	0	SPACEWIRE	SO_N	BOTH
F00100AV - J4	A117704-001	93	Instrument Heartbeat Discrete (?)	0	LVCMOS	NEW_PIN	BOTH
F00100AV - J4	A117704-001	97	Instrument Reset Discrete	0	LVCMOS	NEW_PIN	BOTH
F00100AV - J5	A117704-001	92	S/C Time Sync	0	LVCMOS	NEW_PIN	BOTH
F00100AV - J5	A117704-001	24	Survival Thermal Hardware?	0	Analog	AG	BOTH
F00100AV - J4	A117704-001	04	Magnifier Stepper Motor I/O	0	H-Bridge Driver	OUT_1	NOMINAL

Preliminary Computing ICD

F00100AV - J4	A117704-001	03	Magnifier Stepper Motor I/O	0	H-Bridge Driver	OUT_2	NOMINAL
F00100AV - J4	A117704-001	05	Magnifier Stepper Motor Position Transducer	0	H-Bridge Driver	OUT_1	REDUNDANT
F00100AV - J4	A117704-001	06	Magnifier Stepper Motor Position Transducer	0	H-Bridge Driver	OUT_2	REDUNDANT
F00100AV - J6	A118151-001	40	Detector Control Heater	0	RS485_HALF_DUPLEX	D_N	BOTH
F00100AV - J6	A118151-001	37	Detector Control Heater	0	RS485_HALF_DUPLEX	D_P	BOTH
F00100AV - J6	A118151-001	11	Detector Control Heater	1	RS485_HALF_DUPLEX	D_N	BOTH
F00100AV - J6	A118151-001	12	Detector Control Heater	1	RS485_HALF_DUPLEX	D_P	BOTH
F00100AV - J6	A118151-001	15	SIDECAR Control Heater	0	RS485_HALF_DUPLEX	D_N	BOTH
F00100AV - J6	A118151-001	16	SIDECAR Control Heater	0	RS485_HALF_DUPLEX	D_P	BOTH
F00100AV - J6	A118151-001	19	Magnifier Stepper Motor Survival Heater	0	RS485_HALF_DUPLEX	D_N	BOTH
F00100AV - J6	A118151-001	20	Magnifier Stepper Motor Survival Heater	0	RS485_HALF_DUPLEX	D_P	BOTH
F00100AV - J6	A118151-001	23	Cal Fold Mirror Motor Survival Heater	0	RS485_HALF_DUPLEX	D_N	BOTH
F00100AV - J6	A118151-001	24	Cal Fold Mirror Motor Survival Heater	0	RS485_HALF_DUPLEX	D_P	BOTH
F00100AV - J6	A118151-001	25	Cal Source Control / Survival Heater	0	RS485_HALF_DUPLEX	D_N	BOTH
F00100AV - J6	A118151-001	26	Cal Source Control / Survival Heater	0	RS485_HALF_DUPLEX	D_P	BOTH
F00100AV - J6	A118151-001	29	Cal Source Control / Survival Heater	1	RS485_HALF_DUPLEX	D_N	BOTH
F00100AV - J6	A118151-001	30	Cal Source Control / Survival Heater	1	RS485_HALF_DUPLEX	D_P	BOTH
F00100AV - J6	A118151-001	33	Cal Source Control / Survival Heater	2	RS485_HALF_DUPLEX	D_N	BOTH
F00100AV - J6	A118151-001	34	Cal Source Control / Survival Heater	2	RS485_HALF_DUPLEX	D_P	BOTH
POW101AV (N) - FRONT_POWER	A118405-001_Power	01	S/C Power Interface	0	Power_Isolated	POWER_IN	BOTH
POW101AV (N) - FRONT_POWER	A118405-001_Power	03	S/C Power Interface	0	Power_Isolated	POWER_RET	BOTH

Preliminary Computing ICD

POW101AV (R) - FRONT_POWER	A118405-001_Power	01	S/C Power Interface	1	Power_Isolated	POWER_IN	BOTH
POW101AV (R) - FRONT_POWER	A118405-001_Power	03	S/C Power Interface	1	Power_Isolated	POWER_RET	BOTH
F00104AV - J1	A117704-001	01	Detector I/O	0	ETH_10GBase-T	A_P	BOTH
F00104AV - J1	A117704-001	02	Detector I/O	0	ETH_10GBase-T	A_N	BOTH
F00104AV - J1	A117704-001	03	Detector I/O	0	ETH_10GBase-T	B_P	BOTH
F00104AV - J1	A117704-001	04	Detector I/O	0	ETH_10GBase-T	B_N	BOTH
F00104AV - J1	A117704-001	05	Detector I/O	0	ETH_10GBase-T	C_P	BOTH
F00104AV - J1	A117704-001	06	Detector I/O	0	ETH_10GBase-T	C_N	BOTH
F00104AV - J1	A117704-001	07	Detector I/O	0	ETH_10GBase-T	D_P	BOTH
F00104AV - J1	A117704-001	08	Detector I/O	0	ETH_10GBase-T	D_N	BOTH

7. RISKS AND TRADES

Risks and Trades (Outline)

- Risk assessment and risk management strategy, including mitigation approaches.
- Summary of open design trades and potential impacts/opportunities.

Risk Management

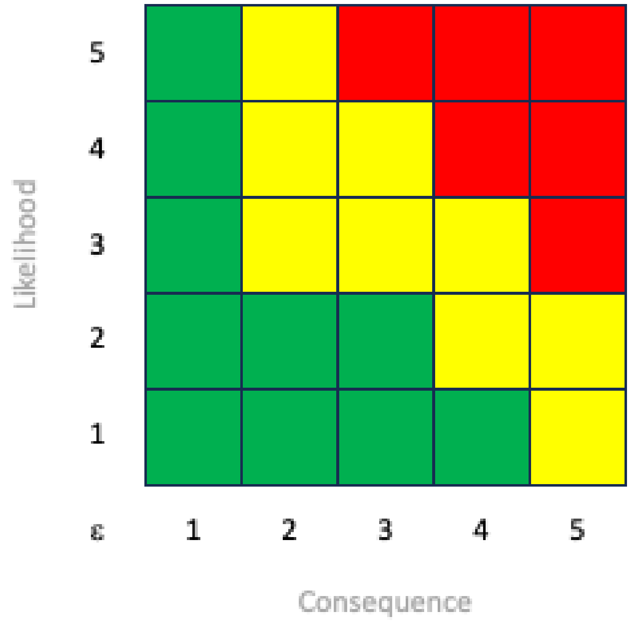
- Risks are important tool to identify and communicate items that my impact spectrograph cost / schedule / technical
  - Intention is for spectrograph team and project to work together to ensure risks aren't realized
  - Constrained Spectrograph budget/schedule means risks will have to be monitored carefully to ensure successfully delivery.
  - Many risks are tied to ability to meet "New Paradigm" approach and should be communicated with project.
- Risks and mitigations will be presented regularly with project
  - Spectrograph team will provide estimates for mitigations.
  - Spectrograph team and project will confer together to decide on implementation of any mitigations.

Risk Management Approach

- Adopt a tailored Risk-Informed Decision Making and Continuous Risk Management strategy based on NASA SP-2011-3422.
- Utilize a “reduced paperwork, reduce meeting” risk approach
  - Similar to other tailored management strategies for the spectrograph project
  - SE and PM will monitor technical work for risks and regularly poll technical teams for risks.
  - Have targeted meetings with technical teams to assess identified risks, identify and implement mitigations, update risks.
- Maintain and track risk list with assessed impacts
  - Risk list will be used by management and SE to manage and implement mitigations
  - List of worries will also be monitored to ensure they don’t evolve into risks.
- Full Risk List provided as Risk_Notebook_20231017.xlsx

Risk Impacts

- The Spectrograph team will adopt a standard 5x5 "stoplight" approach for assessing impact of the risk.
- Each risk will be assigned a likelihood and consequence which will be reassessed regularly.

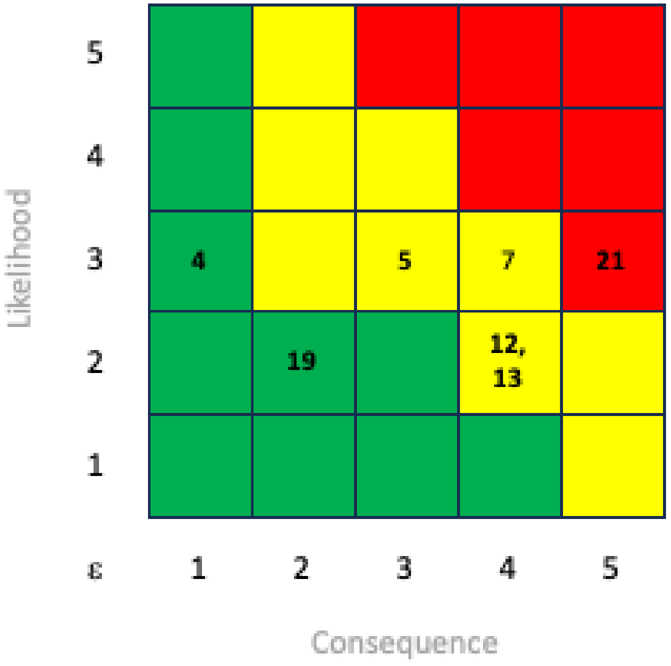


Level	Likelihood	Consequence (Implementation Risk)			Consequence (Mission Risk)
	Likelihood of Occurrence	Cost (impact on cost reserve)	Schedule (impact on schedule margin)	Technical (impact on technical margins)	Mission (impact on science margins)
1	Remote (<1% chance)	<1% loss of reserve	<1% impact to schedule margin	<1% impact to technical margin	Meets L1s; small reduction in science margin
2	Unlikely (1-10% chance)	1-10% loss of reserve	1-10% impact to schedule margin	1-10% impact to technical margin	Meets L1s; significant reduction in science margin
3	Possible (11-50% chance)	11-50% loss of reserve	11-50% impact to schedule margin	11-50% impact to technical margin	Meets L1s; all science margin consumed
4	Likely (51-70% chance)	51-100% loss of reserve	50-100% impact to schedule margin	50-100% impact to technical margin	Does not meet L1s; but some/low quality science data is returned
5	Highly likely (>70% chance)	Budget reserves exhausted	Delay of Delivery	Cannot meet requirement(s)	Does not meet L1s; no science data returned

Key Risks

ID*	Risk Title	Full Risk Statement
4	Stray Light Modeling	If the stray light of the spectrograph cannot be accurately modeled due to the complexity of modeling certain optical components, then the stray light of the as-built spectrograph will exceed the stray light requirement and degrade the sensitivity of the spectrograph.
5	Spectrophotometric Calibration Components	If the components of the spectrophotometric calibration budget cannot be measured well enough due to resource limitations (time, money, or people), calibration requirements/allocations which are too stringent, or calibration components not accounted for / misallocated then the spectrograph will not be able to meet the Level 1 Spectrophotometric calibration requirement and ultimately the science goals of the mission.
7	TIS Delivery Date	If the flight model H4RG is delivered after promise date due to unforeseen production delays at Teledyne Imaging Sensors, then then the delivery schedule for the Spectrograph will be delayed.
12	Performance Margins	If the Spectrograph team does not hold and control its own margin and there is insufficient margin in the Level 2 allocations/requirements (sensitivity, resources, etc.) held and controlled at a higher level, then the ability of the Spectrograph team to mitigate any technical deficiencies in the Spectrograph design and/or performance by utilizing margin is reduced and would result in additional schedule and cost to rectify the deficiencies.
13	Unstable Requirements	If changes to the spectrograph design are needed after the start of implementation due to changing or new requirements / interfaces then additional cost, schedule and resources may have to be utilized to implement a new design to meet the updated requirements / interfaces.
19	Streamlined I&T Approach	If a spectrograph subsystem does not meet requirements due to deferred testing until higher-level of assemblies, then cost, schedule, and resources may have to be utilized to update the design to meet the updated requirements or technical margins will have to be utilized to make up for the deficit.
21	New Paradigm	If the Spectrograph has difficult implementing the "New Paradigm" approach due to not sufficient budget/schedule margins, technical challenges in engineering implementation, incorrect balance in management streamlining (etc), then the spectrograph will not be delivered on budget or schedule.

*Note: Risks listed in numerical ID order, not listed in order of importance or severity



Level	Likelihood	Consequence
1	Remote (<1% chance)	Negligible <1% loss of margin
2	Unlikely (1-10% chance)	Minimal 1-10% loss of margin
3	Possible (11-50% chance)	Moderate 11-50% loss of margin
4	Likely (51-70% chance)	Significant 51-100% loss of margin
5	Highly likely (>70% chance)	Margin Exhausted

Key Risks - Details

ID	Risk Title	Full Risk Statement	L	C	Mitigations
4	Stray Light Modeling	If the stray light of the spectrograph cannot be accurately modeled due to the complexity of modeling certain optical components then the stray light of the as-built spectrograph will exceed the stray light requirement and degrade the sensitivity of the spectrograph.	3	1	• Include additional allocations in performance budgets. • Allocate additional resources to stray light modeling • Adopt best practices stray light mitigation (baffling, black paint, etc)
5	Spectrophotometric Calibration Components	If the components of the spectrophotometric calibration budget cannot be measured well enough due to resource limitations (time, money, or people), calibration requirements/allocations which are too stringent, or calibration components not accounted for / misallocated then the spectrograph will not be able to meet the Level 1 Spectrophotometric calibration requirement and ultimately the science goals of the mission.	3	3	• Establish working group between Spectrograph team and Science team to develop calibration budget • Work with science and project teams to establish and freeze calibration requirements flowdown early in implementation
7	TIS Delivery Date	If the flight model H4RG is delivered after promise date due to unforeseen production delays at Teledyne Imaging Sensors then then the delivery schedule for the Spectrograph will be delayed.	3	4	• Perform early testing and I&T work with EM detectors • Work with project team on other mitigations (contracted owned by project team) • Identify H4RG-10s available from other projects / institutions for early development use.

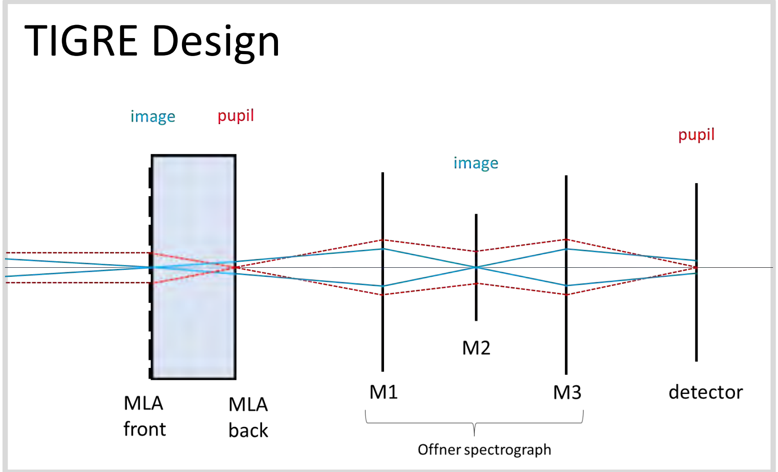
Key Risks - Details

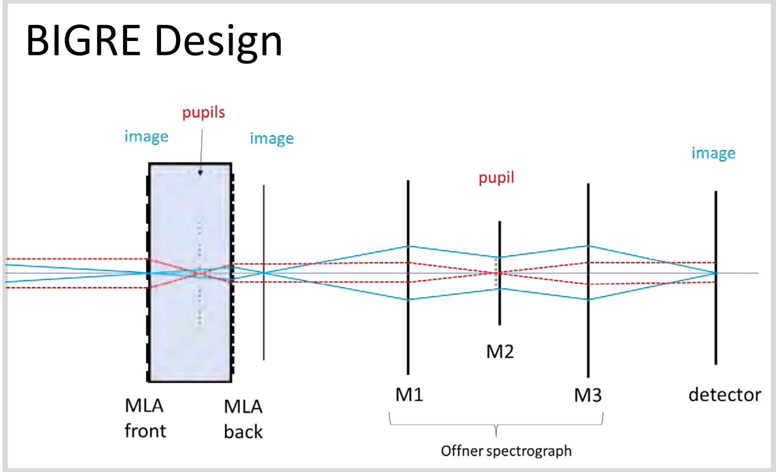
ID	Risk Title	Full Risk Statement	L	C	Mitigations
12	Performance Margins	If the Spectrograph team does not hold and control its own margin and there is insufficient margin in the Level 2 allocations/requirements (sensitivity, resources, etc.) held and controlled at a higher level, then the ability of the Spectrograph team to mitigate any technical deficiencies in the Spectrograph design and/or performance by utilizing margin is reduced and would result in additional schedule and cost to rectify the deficiencies.	2	4	• Ensure requirements are written with sufficient allocated margin to different levels and plan for how margin is deployed • Active management of margins by SE team and understanding of sensitivity of margin to performance changes. • Develop models and sensitivity studies to understand impact of changing CBEs versus performance to understand their magnitudes.
13	Unstable Requirements	If changes to the spectrograph design are needed after the start of implementation due to changing or new requirements / interfaces then additional cost, schedule and resources may have to be utilized to implement a new design to meet the updated requirements / interfaces.	2	4	• Finalize requirements and interfaces as early as possible. • Identify possible high risk requirements /interfaces and ensure adequate margin is allocated.
19	Streamlined I&T Approach	If a spectrograph subsystem does not meet requirements due to deferred testing until higher-level of assemblies then cost, schedule, and resources may have to be utilized to update the design to meet the updated requirements or technical margins will have to be utilized to make up for the deficit.	2	2	• Perform additional performance modeling to assess performance prior to instrument I&T • Identify high risk components and allocation additional resources for early testing.
21	New Paradigm	If the Spectrograph has difficulty implementing the "New Paradigm" approach due to insufficient budget/schedule margins, technical challenges in engineering implementation, incorrect balance in management streamlining (etc), then the spectrograph will not be delivered within budget or schedule.	3	5	•Establish minimum "threshold" mission capabilities with Project. Lessons learned can be applied to next build. •Increase the amount of schedule and budget margin available •When doing trade study selection, bias decision process towards options with cost/schedule savings. •Monitor, manage, and reduce "scope creep"

Trade Studies

- Trade studies are an important tool to ensure sure successful delivery of the Spectrograph under the new paradigm of spaceflight development projects
  - Trade studies are conducted to help the team understand the tradeoffs that may impact final cost, schedule and technical of the delivered Spectrograph
  - Trade studies may also present opportunities for enhancement options for the Spectrograph design that may provide outsized gains in technical performance.
- Intent is for transparency with project team and inclusion in the decision making process, if desired.
  - Trade studies meant to engage sponsor and include them as part of decision making process
- Trade study process will continue through development
- Key trade studies presented as part of the study report.
  - Emphasis on balancing technical performance with need for a low cost, quick delivery instrument

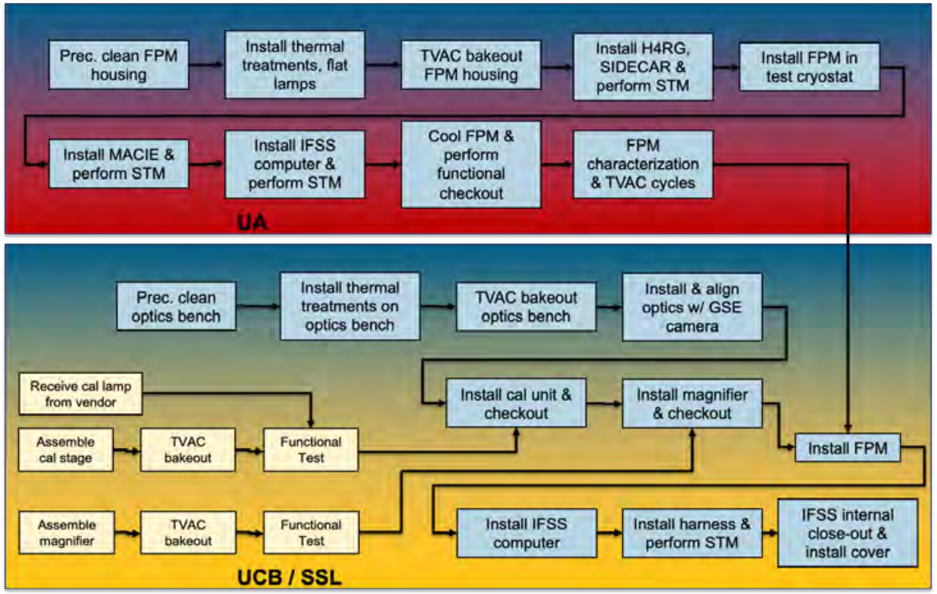
BIGRE vs TIGRE





- Optical Performance Trade
  - BIGRE and TIGRE design offers different approaches to the MLA configuration for the spectrograph.
- Option 1: TIGRE – Single-side MLA Design
  - TIGRE avoids spatial-spectral degeneracy in detector spots, better for spectrophotometric accuracy
  - Single-side MLA presents simpler component
- Option 2: BIGRE – Double-side MLA Design (current baseline)
  - BIGRE can mask diffraction, and allow denser packing of spectra
  - Incompatible with adjacent-magnifier scheme, drives use of mechanism
- Trade Completed: BIGRE chosen based on performance
  - Trade could be reopened, if needed, if design process necessitates.

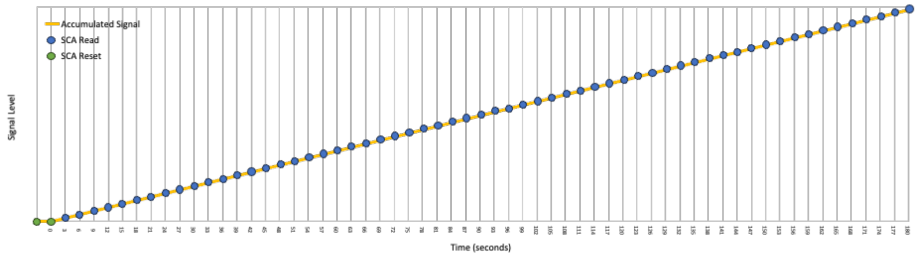
Component/Subsystem/System Testing



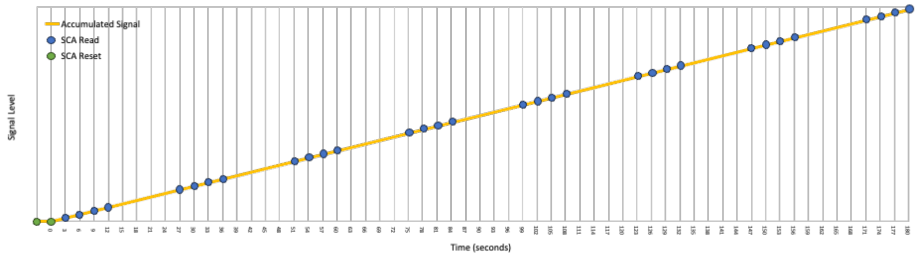
- Cost/Schedule vs Performance/Reliability Risk Trade
  - Decision on amount of component level performance tests and flight qualification screening versus deferring testing to higher level or skipping testing
  - Decided on a part to part basis
- Option 1: Waive Component-level Testing
  - Components are procured ”off the shelf” and integrated into higher level assemblies without qualification or lot testing.
  - Heritage of parts will always be considered during part selection
  - This would be evaluated on a part-to-part basis based on cost, schedule, and risk.
  - Would save ~$100K-$2M and ~1-6mon schedule; depending on which parts forgo testing
- Option 2: ”NASA Class D” component testing (Baseline)
  - Electronic components and mechanism undergoing workmanship env. testing at the vendor and qualification programs for new UA/SSL designs.
- Next Steps: Identify list of components this trade applies to and acquire quotes for costs/schedule; evaluate parts list with project.

On-Board Compression and Data Processing

All Raw Data Downlinked

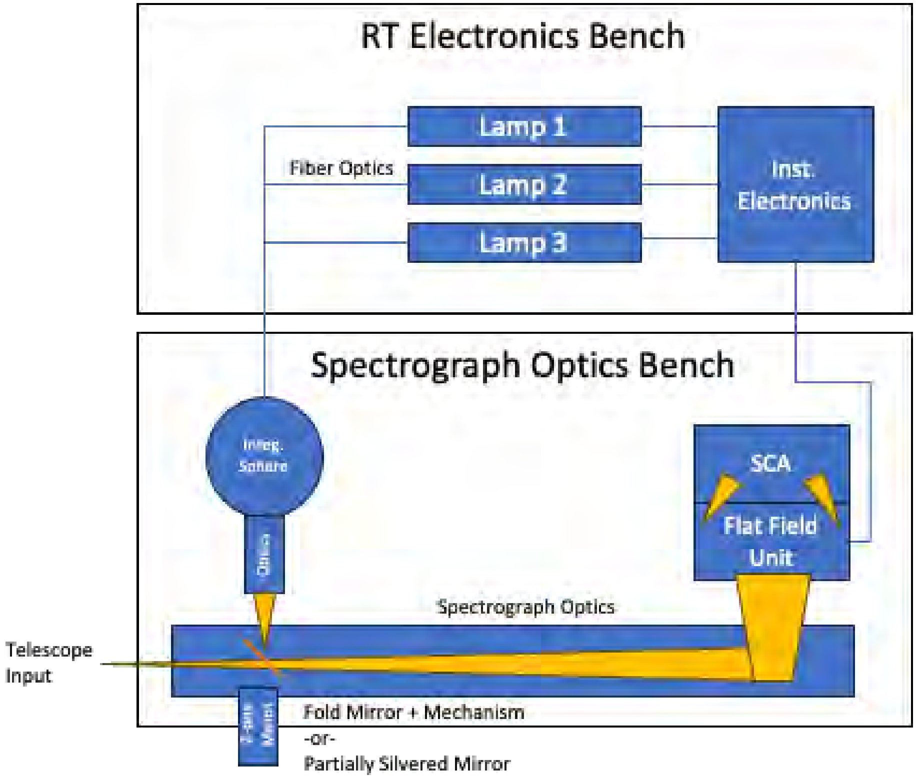


JWST-like Group Acquisition and Coadding



- Resource vs Performance Risk Trade
  - Decision on what data processing / compression capabilities to be included on Spectrograph Instrument Electronics.
  - Data processing would reduce the overall data volume generated by the Spectrograph but may reduce the fidelity of the downlinked science data
- Option 1: Downlink Raw Data Only
  - Requirement to downlink all the raw data would drive requirements on spacecraft on-board data storage and Spacecraft-Ground link rates / Time required for downlink passes.
  - Total Data Volume per Day (estimated): 150Gbits/day
- Option 2: Process / Compress Science Data
  - Implement data processing or data compression for science data prior to transfer to spacecraft for storage.
  - Could reduce data volume up to 4X (estimate, would depend on detector ConOps or compression chosen)
  - Would add up to $50K to implement data processing and/or compression
- Recommendation: Include capability for basic data processing of science data. Need to establish requirements and impact on science calibration prior to deciding implementation

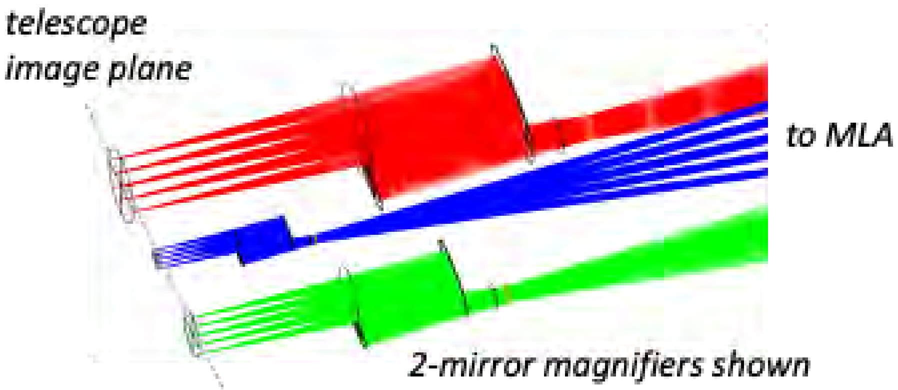
In-Situ Calibration Unit



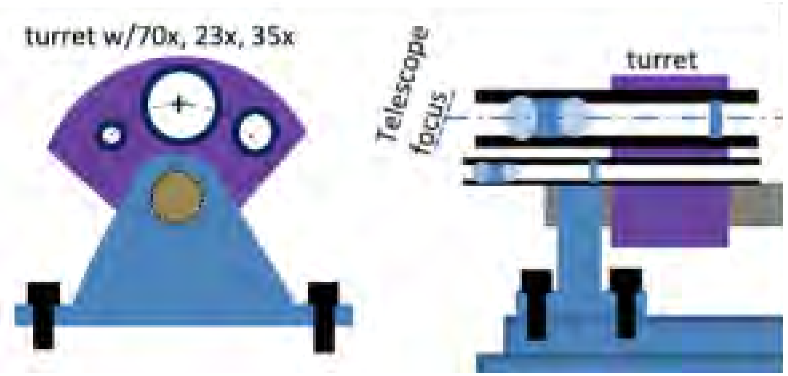
- Cost vs Performance Risk Trade
  - Decision to include in-situ calibration unit (with arc lamps, continuum lamps, and flat field lamps) for in-orbit calibration use.
- Option 1: Include In-Situ Calibration unit (current baseline)
  - Requirement to downlink all the raw data would drive requirements on spacecraft on-board data storage and Spacecraft-Ground link rates / Time required for downlink passes.
  - Cost would include calibration lamps, integrating sphere, and support hardware plus design, integration, and test time)
  - Also need to consider use of silvered mirror (possible contamination in calibration images) or fold mirror mechanism (adds additional mechanism)
- Option 2: No In-Situ Calibration unit
  - Spectrograph will depend on data acquired during ground calibration (flats, darks, linearity, etc) and astronomical calibrator objects.
  - This may reduce the spectrophotometric calibration accuracy of the science data.
  - Removal of Calibration Unit would save ~$1M and up to a month of I&T time.
- Path Forward: Complete development of spectrophotometric calibration budget to understand impact of on-orbit calibration only. Complete detailed costing of Calibration Unit components.

Magnifier Design

Fixed magnifiers (+ telescope pointing)



Magnifier Swapping mechanism



- Optical Design vs Design Complexity
  - Inclusion of mechanism to change input magnification of Spectrograph
- Option 1: Magnifier Mechanism
  - Magnifier tube with 3 positions (30X, 49X, 74X); mechanism moves magnifier tube into position to chose magnification
  - Compatible with baseline BIGRE design
  - Costs include mechanism and magnifier components
- Option 2: No In-Situ Calibration unit
  - 3 different optical paths as input into Spectrograph; magnification chosen based on input path.
  - Additional design/alignment complexity for multiple optical paths; costs of optical components
  - Up to additional $50K cost and 1 month for additional I&T time.
- Trade Completed: Magnifier Mechanism using refractive elements (Option 1)
  - Selected due to compatibility with baseline BIGRE design

8. ICD DEVELOPMENT

ICD Development (Outline)

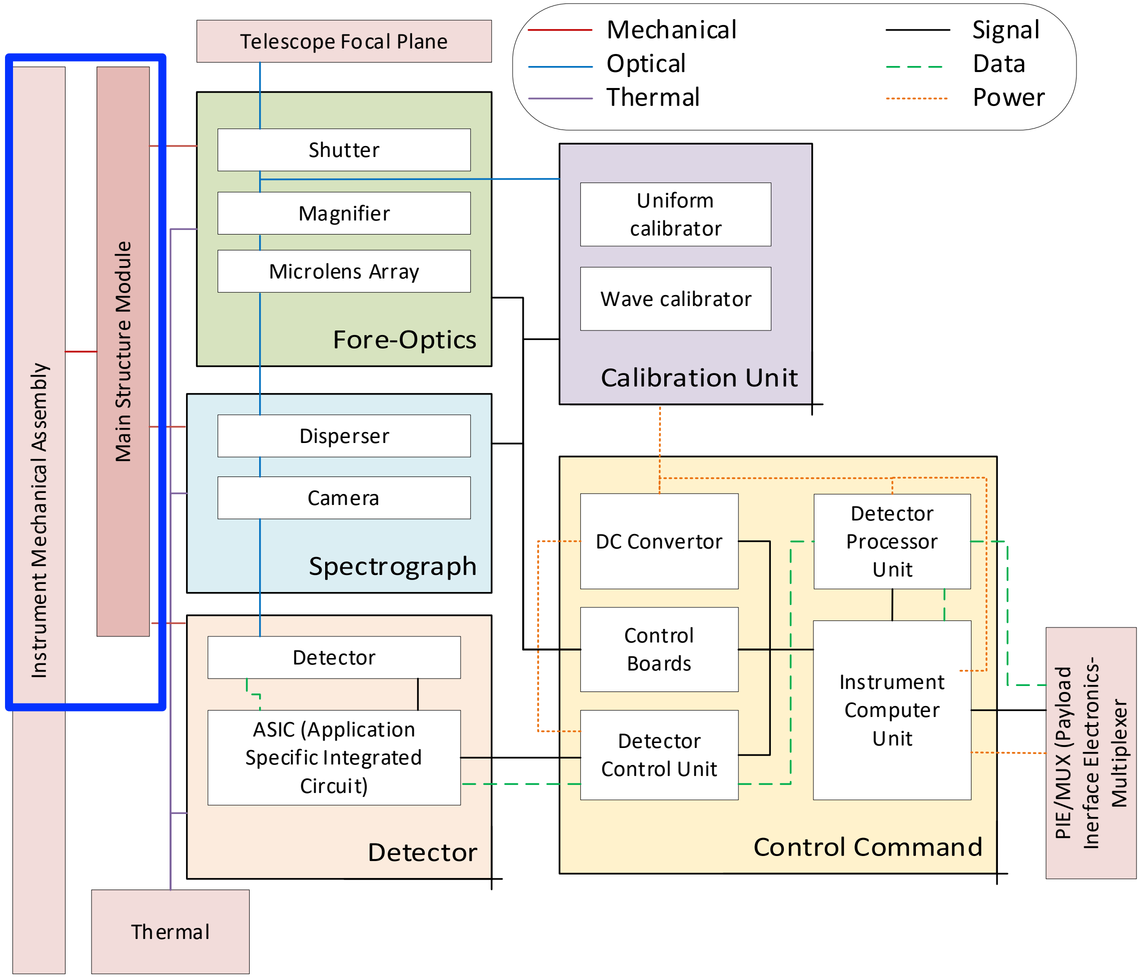
- Interface development plan
- Key interfaces with top level targets.

Interface Development Plan

- Interfaces will be developed in parallel with requirements.
- Comprehensive definition and finalization of interfaces early in the program is key to this new paradigm for instrument delivery
  - Instrument uncertainty will delay finalization of design elements of the Spectrograph and increase schedule and budget risks.
  - Undefined interfaces will increase schedule and budget risks due to additional engineering effort needed to mee accommodations.
  - Risk 13 identified to track and mitigate this risk
- Interface development process includes both external and internal interfaces
  - Work with team to identify interfaces throughout the system.
  - For identified interfaces, start defining “what we need” of the interface or match interface with corresponding HW/SW
  - After UA selection, system engineering team will start engaging internal and external teams to definitize all interfaces.
  - Implementing interfaces in design.

Key Interfaces – Spectrograph Mechanical

- Interface between the Spectrograph and the Payload / Spacecraft
  - Spectrograph Enclosure interface with Payload Optics Bench
  - Instrument Electronics Enclosure interface with Spacecraft Bus
    - Will eventually be separate ICD; including here for simplicity
  - Cabling routing will also need to be accounted for.
- External, Mechanical Interface

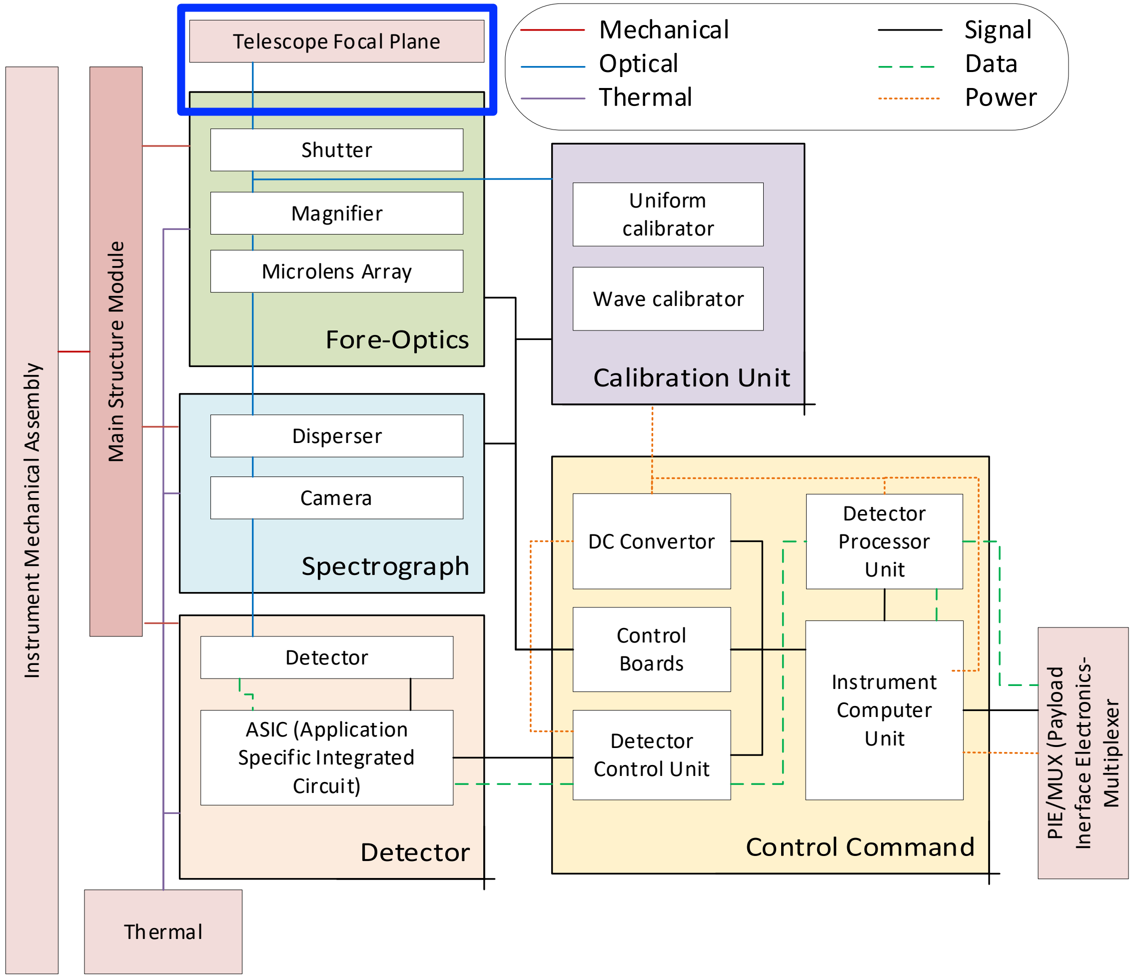


Key Interfaces – Spectrograph Mechanical

Interface	Description	Interface Type	Status
Spectrograph Footprint Allocation / Interface	Footprint on the payload bench from the Spectrograph and mechanical attachment interface	Mechanical	Initial Spectrograph footprint and strut locations defined based on Spectrograph initial design and current Payload Optical Bench design.
Spectrograph Volume Allocation	Allowable volume / shape of Spectrograph outer dimensions	Mechanical	Initial Spectrograph volume defined based on Spectrograph initial design and current Payload Optical Bench design.
Spectrograph Mass Allocation	Mass allocation of the Spectrograph Optical Bench	Resource Allocation	~45kg based on initial design (not including electronics); 100kg allocation based on Requirement 2.15
Spectrograph Optical Interface	Location / Properties of Optical Input to Telescope	Mechanical	Initial Spectrograph design based on curent optics bench design with WFC and input apertures accounted for
Payload Optical Bench Disturbance Profile	Disturbance / Jitter properties of Payload Optical Bench at the Spectrograph mechanical mounting interface	Mechanical / Dynamics	Needs input from project.
Payload Optical Bench Dynamics Profile	Vibration and other loads at the interface between the Payload Optical Bench and Spectrograph	Mechanical / Dynamics	Assuming NASA GEVS
Instrument Electronics Footprint and Volume	Footprint and Volume on the Spacecraft Bus allocated for the Spectrograph instrument electronics	Mechanical	Need inputs from Project
Instrument Electronics Mass Allocation	Mass allocation of the Instrument Electronics	Resource Allocation	Part of 100Kg allocation
Spacecraft Electronics Bench Dynamics Profile	Vibration and other loads at the interface between the Spacecraft Electronics and Spectrograph	Mechanical / Dynamics	Assuming NASA GEVS

Key Interfaces – Telescope

- Interface between Telescope and Spectrograph
  - Optical input to spectrograph from Telescope (jitter included here)
    - Establishes PSF / Image Quality properties for Spectrograph input.
- External; Optical Interface

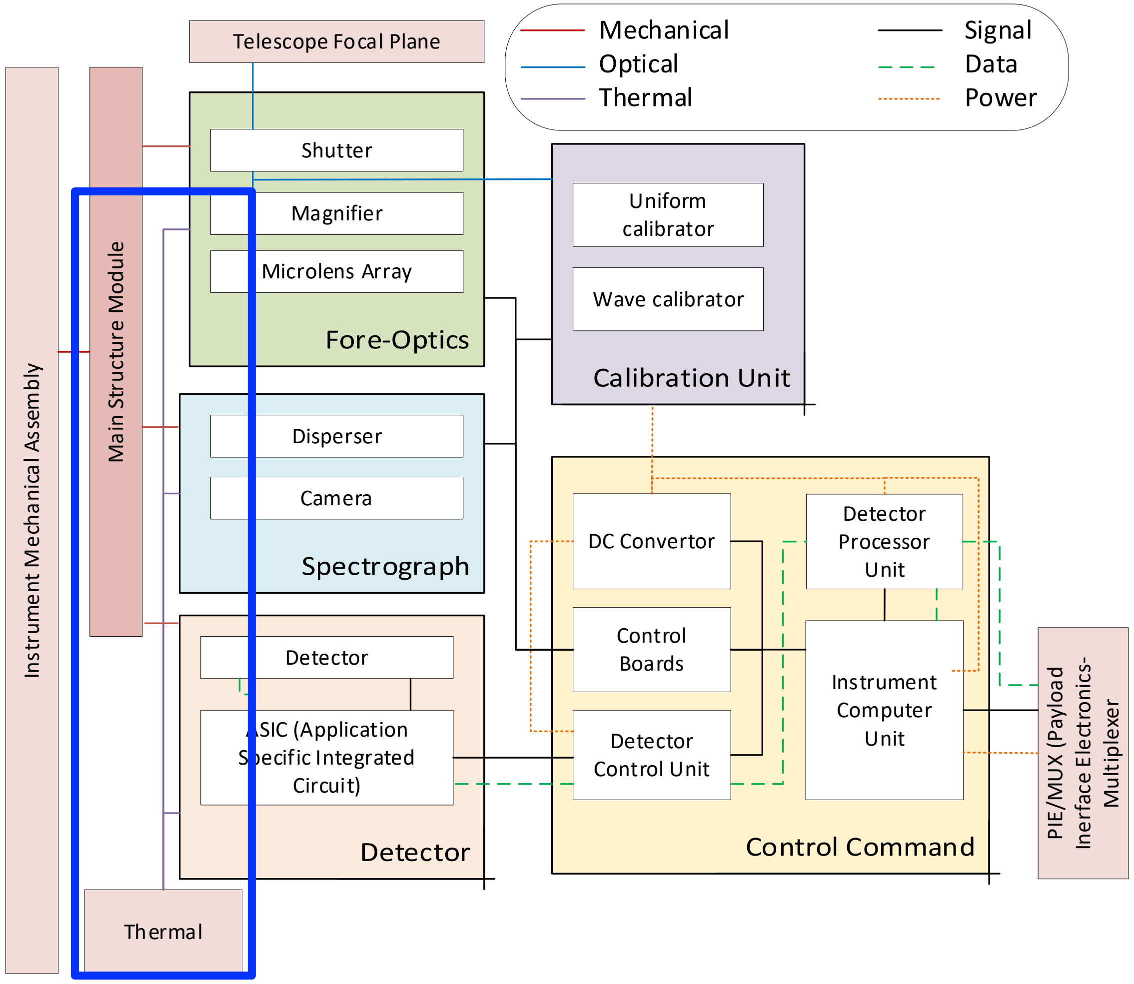


Key Interfaces – Telescope

Interface	Description	Interface Type	Status
Telescope PSF	PSF shape / properties of the optical input at the spectrograph entrance provided by the Telescope	Optical	Needs input from project.
Telescope RSR	Spectral response of the optical input at the spectrograph entrance provided by the Telescope.	Optical	Needs input from project.
Telescope / Spacecraft Jitter	Jitter profile of the Telescope / spacecraft relative to the spectrograph entrance as it relates to optical performance	Optical / Mechanical	Needs input from project. Jitter from Telescope / Spacecraft needs to be limited in order to ensure Spectrograph performance.
Telescope Stray Light	Stray light / Thermal Background from Telescope incident on entrance aperture of Spectrograph. Stray light / Thermal Background from Spectrograph incident on other instruments.	Optical	Needs input. Stray light and thermal background from Telescope needs to be limited in order to ensure Spectrograph performance.

Key Interfaces – Thermal

- Interface between the Spacecraft Thermal System and Spectrograph
  - Thermal Straps to Optical Bench
    - Establishes temperature and heat load requirements of Spectrograph
    - Establishes mechanical interface with thermal strap
  - Thermal Straps to Focal Plane Module
    - Establishes temperature, power dissipation, and heat load requirements for Detector
    - Establishes mechanical interface with thermal strap
- External, Thermal Interface

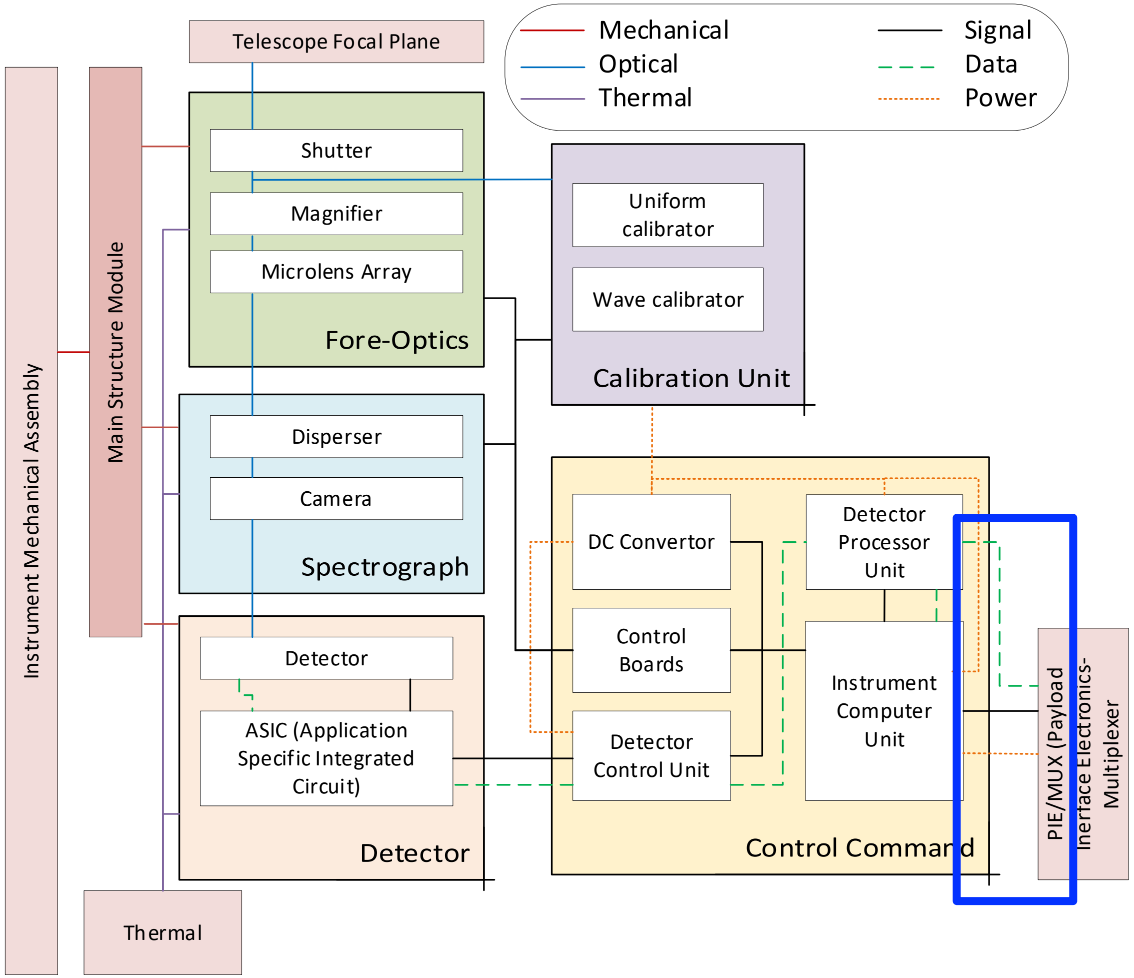


Key Interfaces – Thermal

Interface	Description	Interface Type	Status
Payload Optical Bench Temperature	Temperature (and temperature gradient) of the payload optical bench mechanical interface	Thermal	Needs Input from Project
Payload Optical Bench Thermal Environment	Temperature / Thermal Radiation environment of the payload optical bench	Thermal	Needs input from Project
Spacecraft Spectrograph Thermal Strap Mechanical Interface	Location of thermal straps; thermal strap interface pattern; thermal strap temperature. Need a separate thermal interface between Spectrograph Optical Bench and Focal Plane Module	Mechanical	Bolt pattern and location for Spectrograph optical bench thermal strap assumed in initial spectrograph design.
Spacecraft Spectrograph Thermal Strap Thermal Interface	Temperature of thermal strap; heat capacity of cooling system. Need a separate thermal interface between Spectrograph Optical Bench and Focal Plane Module	Thermal	Bolt pattern and location for Spectrograph optical bench thermal strap assumed in initial spectrograph design.
Spacecraft Spectrograph Thermal Strap Disturbance Profile	Disturbance profile transmitted through thermal straps from active cooler (if present).	Mechanical / Dynamics	Need to define.
Spacecraft Focal Plane Module Thermal Strap Mechanical Interface	Location of thermal straps; thermal strap interface pattern; thermal strap temperature. Need a separate thermal interface between Spectrograph Optical Bench and Focal Plane Module	Mechanical	Bolt pattern and location for Focal Plane Module thermal strap assumed in initial spectrograph design.
Spacecraft Focal Plane Module Thermal Strap Thermal Interface	Temperature of thermal strap; heat capacity of cooling system. Need a separate thermal interface between Spectrograph Optical Bench and Focal Plane Module	Thermal	Bolt pattern and location for Focal Plane Module thermal strap assumed in initial spectrograph design.
Spacecraft Focal Plane Module Thermal Strap Disturbance Profile	Disturbance profile transmitted through thermal straps from active cooler (if present)	Mechanical / Dynamics	Need to define.

Key Interfaces – Spacecraft Electronics

- Interface between the Spacecraft Electronics and Spectrograph Instrument Electronics
  - Command Interface between SC and Instrument Electronics
    - Command Dictionary
  - Data Interface
    - Data volume accommodation in spacecraft for science and HK data – may also define data processing requirements for Instrument electronics
    - Also includes clocks and various signals between SC and Instrument Electronics
    - Survival heater / temperature sensors.
  - Primary Power
- External; Electronics Interface
  - Data, Power, Command Interface

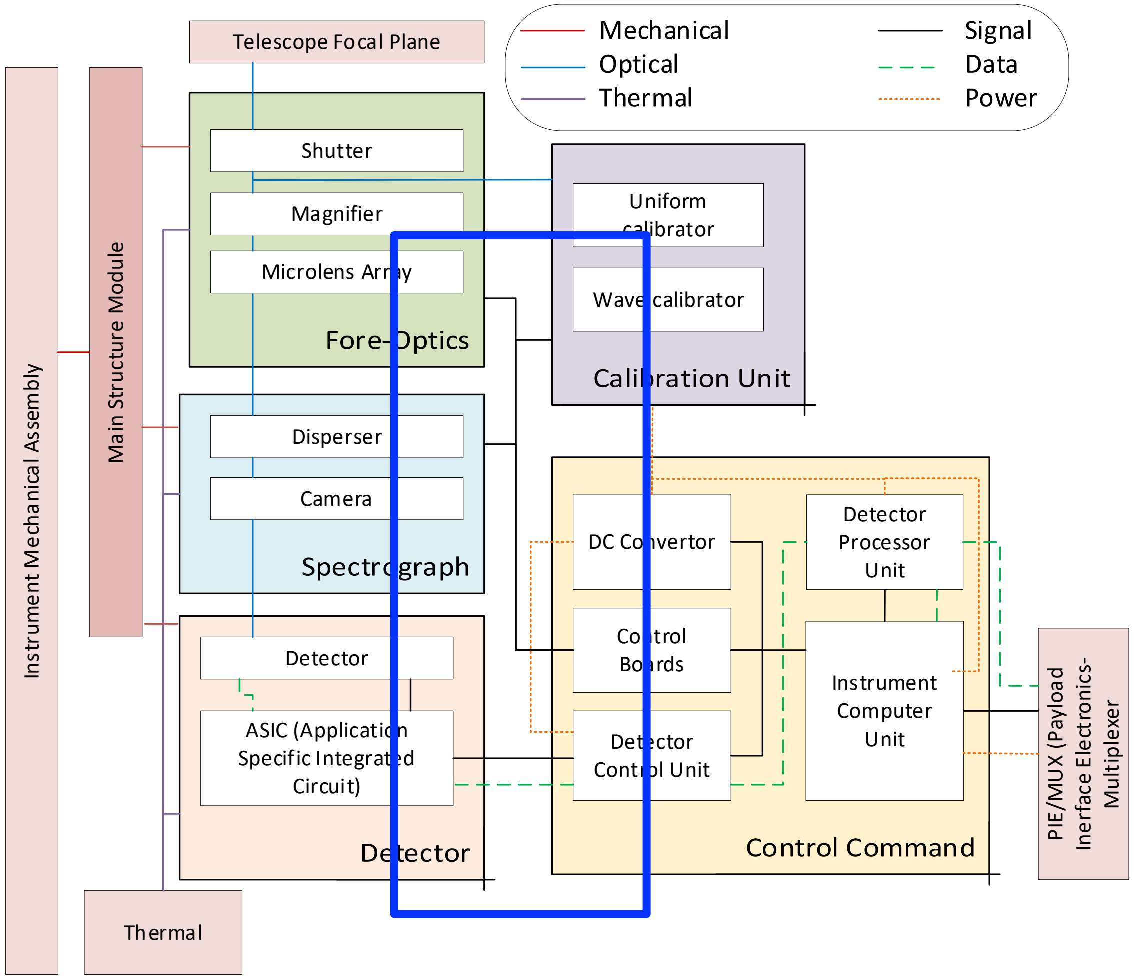


Key Interfaces – Spacecraft Electronics

Interface	Description	Interface Type	Status
Instrument Electronics Primary Power	Primary Power provided by the Spacecraft to the Instrument Electronics. Includes inrush profile and other characteristics	Electrical - Power	Assume 28V; ~80W estimate
Instrument Electronics Primary Power Connector	Connector for primary power	Electrical - Mechanical	Needs to be defined
Instrument Electronics – Spacecraft Data Format	Data Definitions – Volumes, format, packetization, Telemetry, etc	Electrical - Data	Preliminary. Some preliminary information about data format has been defined as part of development process with electronics team, but needs to be finalized.
Instrument Electronics – Spacecraft Datalink Protocol	Data Link Protocol	Electrical - Data	Preliminary. FTP via Ethernet 1000 Base-T
Instrument Electronics – Spacecraft Datalink Connector	Data Link Connector	Electrical - Mechanical	Needs to be defined.
Instrument Electronics – Spacecraft Command Dictionary	Command Dictionary for the Spectrograph / Instrument Electronics	Electrical – Data	Needs to be defined.
Instrument Electronics – Spacecraft Discrete Signal List	List of discrete signals between the Spacecraft and Instrument electronics (PPS, clock, etc)	Electrical – Thermal Hardware	Needs to be defined.
Spacecraft Survival Temperature Hardware	Survival Temperature Sensors and Heaters for key Spectrograph hardware. Survival temperature hardware is controlled solely by the Spacecraft	Electrical – Thermal Hardware	Needs to be defined. Expect passthrough for PRTs.
Spacecraft Survival Temperature Hardware	Survival Temperature Sensors and Heaters for key Spectrograph hardware. Survival temperature hardware is controlled solely by the Spacecraft	Electrical – Thermal Hardware	Needs to be defined. Expect passthrough for resistive heaters.

Key Interfaces – Instrument Electrical

- Instrument Electronics → Spectrograph Subsystems
  - Subsystem Power
    - Spectrograph Mechanisms
    - Calibration Unit
    - Detector + ASIC
  - Subsystem Data Interfaces
    - Detector + ASIC data volume to electronics
    - Cable length between Detector + ASIC also important
    - Spectrograph Temperature Sensors and Heater control
- Internal; Electrical Interface
  - Data, Power, Command



Key Interfaces – Internal Electrical

Interface	Description	Interface Type	Status
Spectrograph Electronics to Detector	Power, Clock, Command, I/O interface between instrument electronics and detector signal chain.	Electrical	Detector, Detector Electronics, and MACIE ICDs exist from manufacturer
Spectrograph Electronics to Calibration Unit	Power, Clock, Command, I/O interface between instrument electronics and calibration unit (lamp sources, motor, etc)	Electrical	Preliminary based on heritage from other projects. Resonance identified as possible vendor.
Spectrograph Electronics to Magnifier Motor	Power, Clock, Command, I/O interface between instrument electronics and magnifier	Electrical	Preliminary based on heritage motors. CDA identified as possible vendor.
Spectrograph Temperature Sensors	Temperature sensors throughout spectrograph	Electrical	Need to define; various Cernox and PRT temperature sensors
Spectrograph Control Heaters	Control Heater for detector and SIDECAR	Electrical	Need to define; standard resistive heaters
Spectrograph Decontamination Heaters	Decontamination Heaters for detector and optics (as needed)	Electrical	Need to define; standard resistive heaters

Conclusion

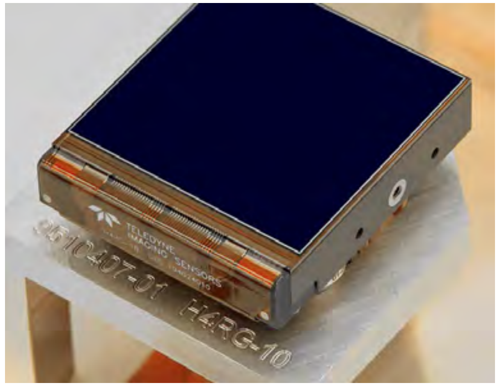
- Interface development and finalization is key to successful delivery of Spectrograph.
  - Primary focus for system engineering team at start of implementation.
  - Internal and External interface are both important
  - Interface flowdown is well understood by Spectrograph team.
- Path to completing work-to-go is well defined once Spectrograph enters implementation.
  - Will plan for near term (~months) meeting to finalize interface.
    - Spacecraft and telescope teams will be key to this activity.
  - Generation of interface control document and requirements to begin after start of implementation.

9. DETECTOR

Detector (Outline)

- Detector overview
- Controller
- Detector ConOPS
- Test Plan
- Detector Facilities
- Required support hardware

Detector Overview

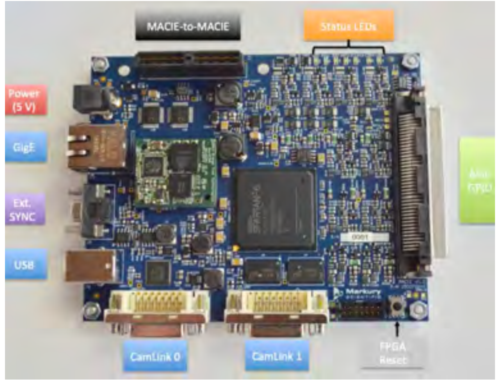


Detector: Teledyne HAWAII-4RG 10-µm pixels (H4RG-10)

- 4096 x 4096 pixels (10 µm pixel size)
- 1.7-µm cut-off
- Expected operating temperature of T~120K
- **Study team has decades of collective experience characterizing and integrating HAWAII arrays, for both ground and space applications (e.g., LBTI, JWST, NEO Surveyor)**

Cold Readout Electronics: Teledyne SIDECAR ASIC

- Provides clocks, biases, and register configuration to H4RG
- 32 amplifiers for simultaneous digitization of output signals
- Provide pixel clock speed of 200 kHz (t_{frame} ~ 3.0 sec)
- **UArizona detector scientists tuned and optimized JWST NIRCam SIDECARs for low noise operations, and those in LBTI LMIRcam and SHARK-NIR for high-speed pixel clocking**

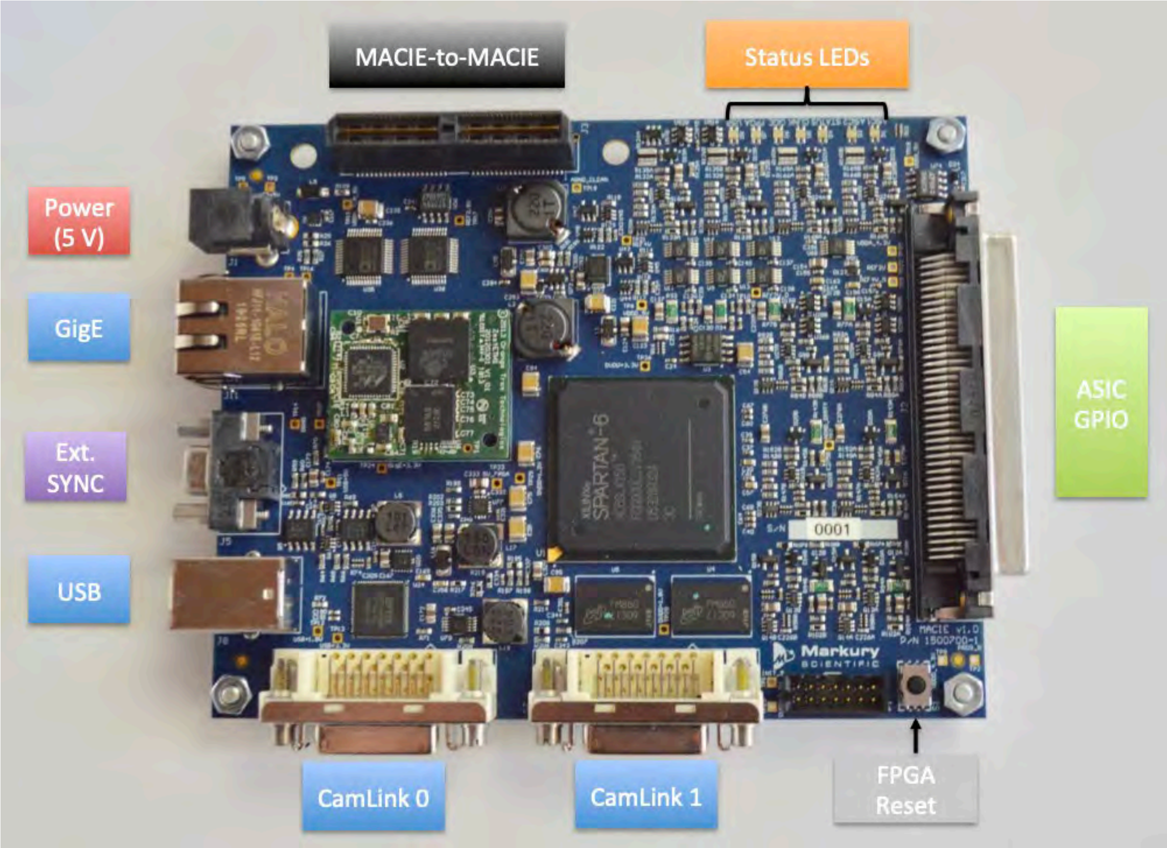


Warm Controller: MACIE board by Markury Scientific (Markus Loose)

- Communication interface to SIDECAR
- Gigabit network communications
- Mature and easy to use C/C++ API library on Linux-based systems
- **Due to ease of use, robustness against errors, and flexibility in operations, the MACIE controller has become a favorite for ground-based instrument scientists**

MACIE Controller

- **M**ulti-purpose **A**SIC **C**ontrol & **I**nterface **E**lectronics
- Hardware Features
  - Xilinx Spartan-6 FPGA
  - 512 MB of onboard buffer memory
  - **GigE**, USB 3.0, and CamLink interface
  - Housekeeping telemetry for ASIC
- Software Features
  - Linux-based API library
    - Not yet compliant for ARM processors
    - Software port to be provided by Markury Scientific
  - Heritage for team (LBTI LMIRcam & SHARK-NIR as well as NEO Surveyor GSE)
- Risks: Limited testing as flight hardware
  - Vibe tests at LLNL indicate high launch survivability
  - Need to perform radiation testing on COTS
- Three options that impact cost and schedule
  1. Use COTS product (cheap and fast; ~$25k); custom firmware; port API library from x86 to ARM
  2. Custom space version (industrial, latch-up protection, MDMs); 3-4x more expensive, longer dev cycle
  3. Power supply board with Zynq FPGA; 3-4x more expensive, longer dev cycle
- Prefer customized solution with industrial components and only required features



Detector ConOps

H4RG-10

- 4096 x 4096 pixels; 32 outputs (128 pixels per row)
- Pixel-by-pixel reset and read at a rate of 200 kpix/s/output = 5 µs/pixel
- Timing
  - Row Time (128 pixels * 5 µs/pixel): 640 µs (assume 720 µs to include overhead, based on previous flight programs)
  - Frame Time (4096 rows * 720 µs): 2.949 s; assume **3 sec** for simplicity
- Data / Frame: (4096 x 4096 pixels * 16bits / pixel): 256 Mbit / frame (assuming 1 Mbit = 1024 x 1024 bits)
  - Max data rate is therefore ~85 Mbps; MACIE ethernet supplies 1 Gbps of bandwidth

Project ConOps requirements

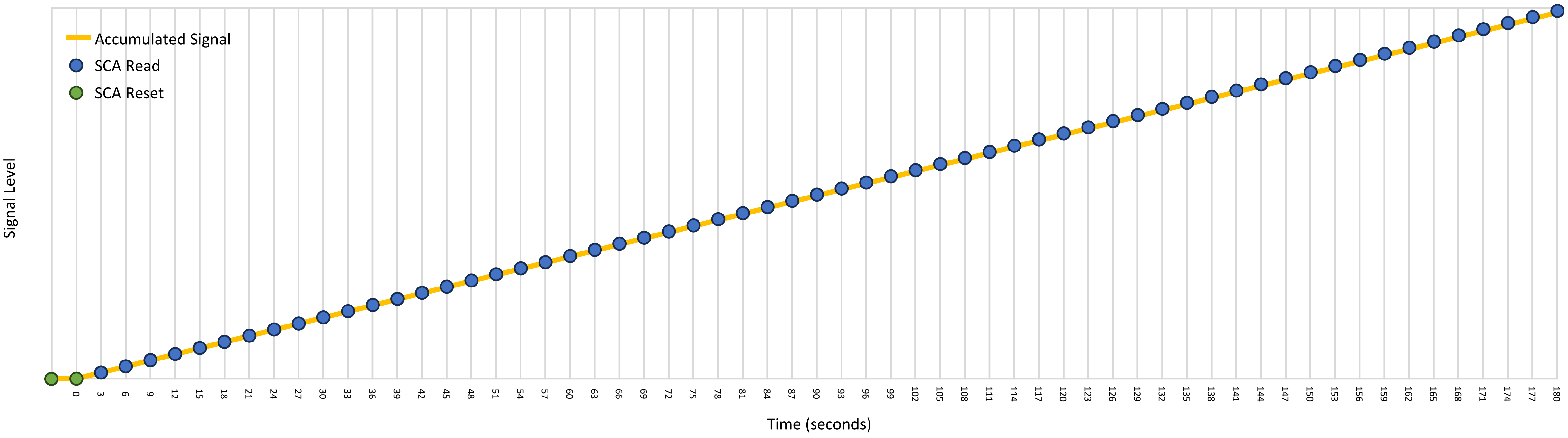
- Sample Up The Ramp (SUTR) reset at the start of the frame and non-destructive samples as detector integrates
- Variable integration time based on object flux
- Fixed 32 frames per integration

Notes

- Frame Timing: Diagrams are illustrative only. Exact timing may change once we design H4RG clocking scheme.
- Data Volume: Data volume coming from SIDECAR, does not include telemetry. Does not assume how much data is processed on board, transferred to SC electronics, or how much is downlinked.
- Nominal Data Processing: “Standard” way of processing data (may differ depending on requirements). Processing may happen in instrument electronics or on the ground. Ground is preferred for reprocessing as calibration files improve.

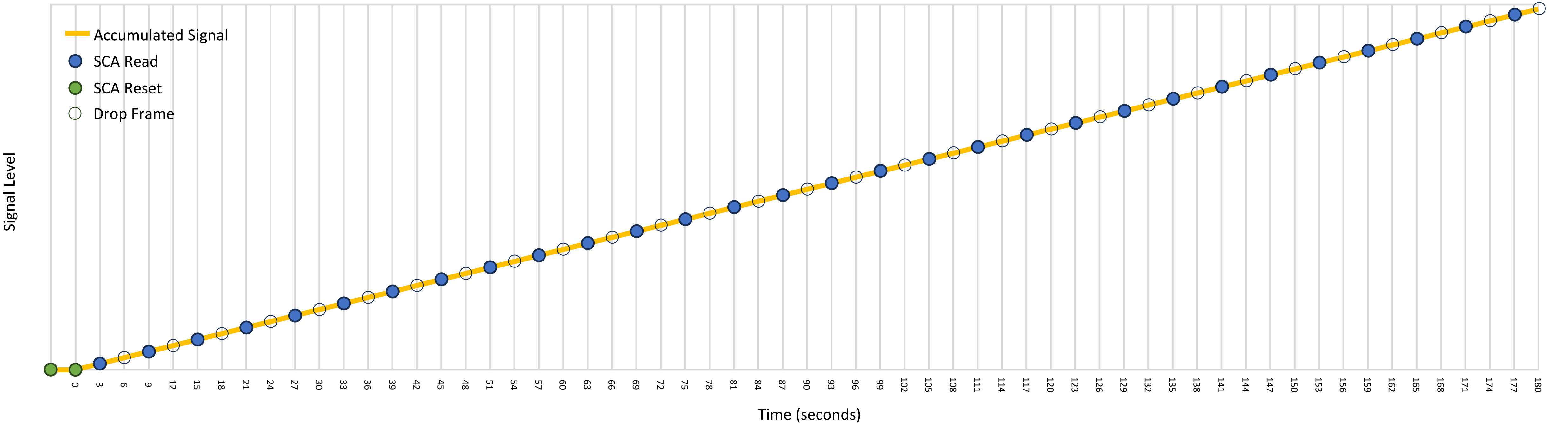
Detector ConOps: Full SUTR

- Detector array sampling every 3 sec
  - Number of Frames: 60 frames
  - Data Volume: 15 Gbit
- Nominal Data Processing: Per Pixel Slope fit across all 60 samples
- Ground testing will operate in this format to maximize SNR
- Note: Preferred mode for flight if onboard disk space allows
  - Compression and coadding due to communications bandwidth limitations can then occur in software



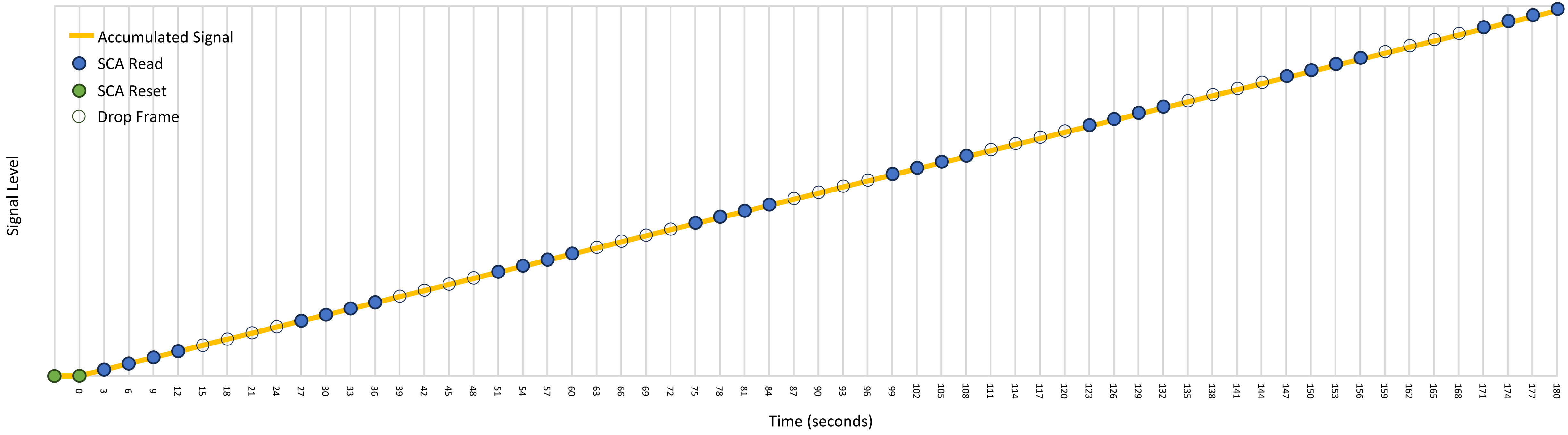
Detector ConOps: Evenly Sampled

- Select some frame time (e.g., 189s) and sample evenly 32 times
  - Number of Frames: 32 frames
  - Data Volume: 8 Gbit (assuming dropped frames are not saved)
- Nominal Data Processing: Per Pixel Slope fit across all 32 samples
- Example: 63 total frames with 32 Read frames and 31 Drop frames evenly spaces
  - Note: only 30 of 32 samples show in figure for simplicity
  - Last sample would occur at t = 189 sec



Detector ConOps: Grouped Sampled

- Sample detector every 3 s in N groups of M frames evenly spaced across integration
  - Number of Frames: 32 frames
  - Data Volume: 8 Gbit (assuming dropped frames are not saved)
- Nominal Data Processing: Average frames in each group and fit slope across results
  - Similar to JWST NIRCam readout patterns (https://jwst-docs.stsci.edu/jwst-near-infrared-camera/nircam-instrumentation/nircam-detector-overview/nircam-detector-readout-patterns)
- Example: 8 groups of 4 Read frames with 4 Drop frames in between
  - Photon collection time = 180 sec
  - Effective integration time (for slope fit) is $t_{eff} = t_{group\_last} - t_{group\_first} = 175.5 - 7.5 = 168$ sec



Detector Test Plan

Detector tests and calibration occurs at different stages of assembly

1. Initial testing performed at TIS (read noise, QE, dark current, full well, persistence, operability)
2. Detector-level characterization and initial tuning occur in focal plane module (FPM) assembly with H4RG, SIDECAR, and Flex cable enclosed within test cryostat at UArizona
3. IFS level tests are performed with the FPM integrated into the IFS and would also measure instrumental properties (e.g., relative spectral response, wavelength solution, etc) using built-in Cal unit

Four versions of detector hardware

- **Ground-like SIDECAR**, **ROIC**, **Engineering**, and **Flight**
- Nominally build and refine testing, characterization, tuning procedures, and software at different stages of hardware delivery

Major Risks

- Long lead times drive instrument I&T schedule
- Limited spares in case of ESD event, S&H mishaps, poor quality / not meeting requirements, etc

Mitigation Strategies

- Optimize tasks around delivery schedule, utilizing internal spare (MACIE, SIDECAR) and loaned (H4RG) hardware
- Create tiered priority list of detector characterization tasks
- Consider **Engineering** hardware as flight candidates

Deliverable		**Quantity**	**Delivery Date AAO (Dec 1 start)**
ROIC Package (TIS)			
	Eng or Ground SIDECAR ASIC	1	+ 9 mo
	Test firmware	1	+ 9 mo
	Packaged H4RG-10 ROIC	2	+ 15 mo
	Detector handling tool	2	+ 15 mo
Engineering Module (TIS)			
	Engineering H4RG-10	1	+ 18 mo
	Engineering SIDECAR ASIC	1	+ 18 mo
Flight Module (TIS)			
	Flight H4RG	1-2	+ 19 / 22 mo
	Flight SIDECAR ASIC	1	+ 19 mo
MACIE Package (Markury)			
	Standard COTS MACIE	1	+3 mo
	Custom Controller	1	+12 mo

Detector Test Plan

Preliminary Schedule

- *t<9 mo:* Utilize existing spare **Steward property** (MACIE, SIDECAR, and ASIC firmware) and **loaned H4RG-10** for early software development, firmware tests, and demonstration of detector readout.
- *t>9 mo:* Swap in **EM SIDECAR and test firmware**.
- *t>15 mo:* Perform end-to-end electrical and communications tests using **packaged bare ROIC** along with custom **Markury controller**.
- *t>18 mo:* Test harnesses, interfaces, and flight mounting scheme in IFS focal plane module (FPM) after delivery of a **flight-like EM SIDECAR and H4RG**.
  - Use **EM H4RG & SIDECAR** to develop and refine detector testing procedures and tuning operations in test cryostat while awaiting delivery of flight hardware.
- *t>19 mo:* Integrate **Engineering module** into IFS while **flight H4RG and ASIC** are assembled onto flight FPM and characterized in test cryostat
- Integrate **flight hardware** into IFS assembly after detector level tests.

Deliverable		**Quantity**	**Delivery Date AAO (Dec 1 start)**
ROIC Package (TIS)			
	Eng or Ground SIDECAR ASIC	1	+ 9 mo
	Test firmware	1	+ 9 mo
	Packaged H4RG-10 ROIC	2	+ 15 mo
	Detector handling tool	2	+ 15 mo
Engineering Module (TIS)			
	Engineering H4RG-10	1	+ 18 mo
	Engineering SIDECAR ASIC	1	+ 18 mo
Flight Module (TIS)			
	Flight H4RG	1-2	+ 19 / 22 mo
	Flight SIDECAR ASIC	1	+ 19 mo
ASIC Controller Package (Markury)			
	Standard COTS MACIE	1	+3 mo
	Custom Controller	1	+12 mo

Detector Test Plan

Detector tests and calibration occurs at different stages of assembly

Test	TIS Testing	Detector Testing	IFS Testing	Notes
Amplifier Linearity	X	X	O	Assume this means SCE + SCA linearity
Detector Capacitance Gain	X	X		
Detector Noise (full map)	X	X	X	H4RG characterization at detector level; measure noise with flight electronics at IFS level
Dark Current (full map, over temperature)	X (at 95K and 120K)	X (110K to 150K)	X	”Dark Testing” at IFS level also includes characterization of stray light and background
Flat Field (full map, over wavelength)	X	X	O	Requires a flat field source, such as integrating sphere
QE	X			Leverage TIS QE to reduce need for calibrated light source
Relative Spectral Response		O	X	IFS level includes optics, etc
Bright Fatter Effect		O	X	Need point source; could possibly do at detector level
Interpixel Capacitance	X	X		Single pixel resets; specialized firmware from Markus Loose
Charge Diffusion		X		Derived from CR Hits in dark data
Trailing Pixel Effect		X		Derived from hot pixels signals elevating subsequent pixel signal
Electronic Crosstalk		X		Window resets
Operable / Bad Pixel Map	X	X	X	Derived primarily from darks and flats
Persistence	X	X		Need to include shutter if doing at detector level
Burn-in		O		”inverse persistence”
Full Well Capacity	X	X	O	

Note: X means test is performed; O means low fidelity version of the test can be performed if needed.

Detector Test Plan

Identify and prioritize primary contributors from detector and electronics to the radiometric error budget.
These priority tiers are notional and subject to change based on discussions with science team.

Tier 1

- Read noise detector map (ie., per pixel)
- Total noise for 180-sec integration ramps
- 1/f noise contributions per readout channel
- Dark current map at 120K
- Flat field map (pixel-to-pixel variations, crosshatching structure)
- Linearity corrections per pixel
- Operability and defects (RC pixels, dead pixels, hot pixels, etc)
- Persistence maps at 120K as a function of fluence levels & dwell times

SIDECAR ASIC Optimization

- Tune detector control bias for low noise
- Measure preamp noise at 100kHz and 200kHz pixel rate
- Digitize SCA's dynamic range within linear response of preamp DAC
- Minimize reference instability
- Adjust digitization timing to minimize smearing of pixel analog signal

Tier 2

- Interpixel capacitance (IPC)
- Conversion Gain (e^-/DN)
- Well depths
- Reciprocity failure
- Charge diffusion / pixel crosstalk
- Brighter-fatter effect
- Charge migration from saturated pixels

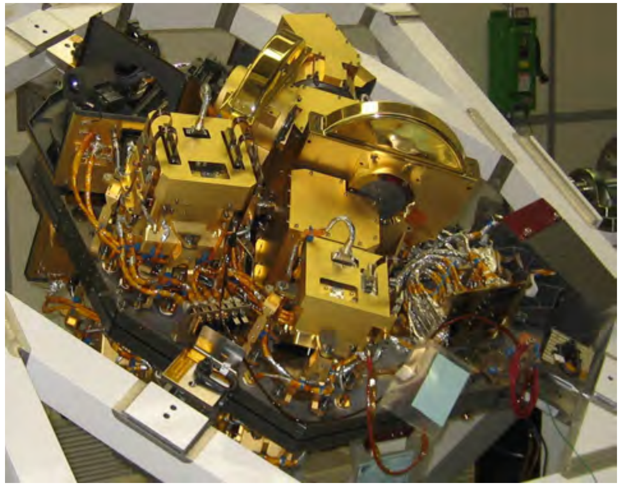
Tier 3

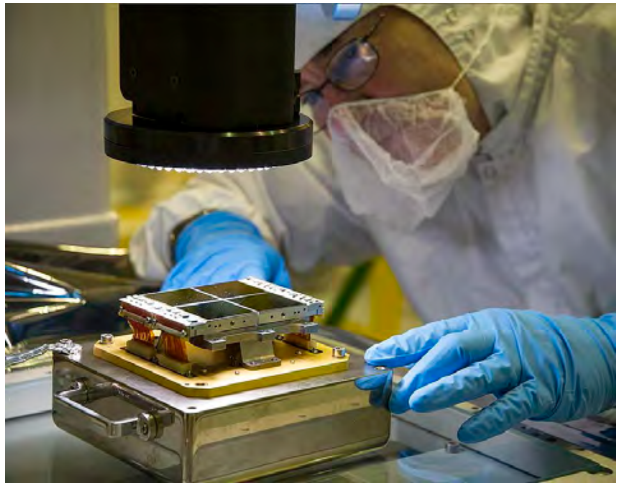
- Dark current maps as function of temperature
- Flat field maps as a function of wavelengths
- Quantum yield versus wavelength
- Diffusion as a function of wavelength
- Persistence as a function of temperature
- Burn-in "inverse persistence"
- Electronic crosstalk

Detector Test Facilities

AZ Infrared Detector Lab

- Equipment, and technical staff for the handling, testing, characterizing, and packaging of detectors.
- Well-equipped detector laboratory established to characterize Spitzer MIPS arrays and JWST NIRCam's HAWAII-2RGs.
- Class 10,000 cleanroom with a Class 100,000 anti-chamber and HEPA filtration system.

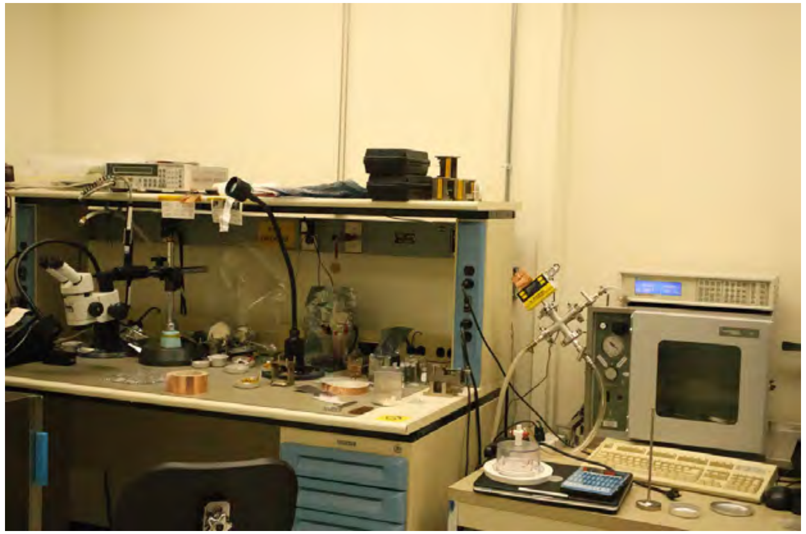




Applied Research Building

- Brand-new state-of-the-art facility built to support space flight missions
- Houses Pearl Coronagraph Instrument and Imaging Technology Laboratory (ITL)
- Exploring opportunity to consolidate AZ Infrared Detector Lab in this space

Detector Test Facilities



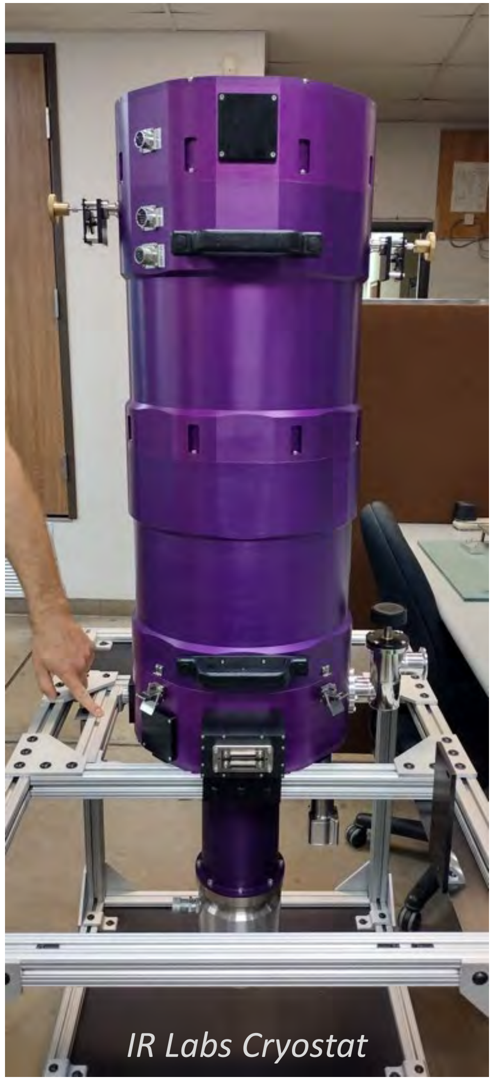
AZ Infrared Detector Lab

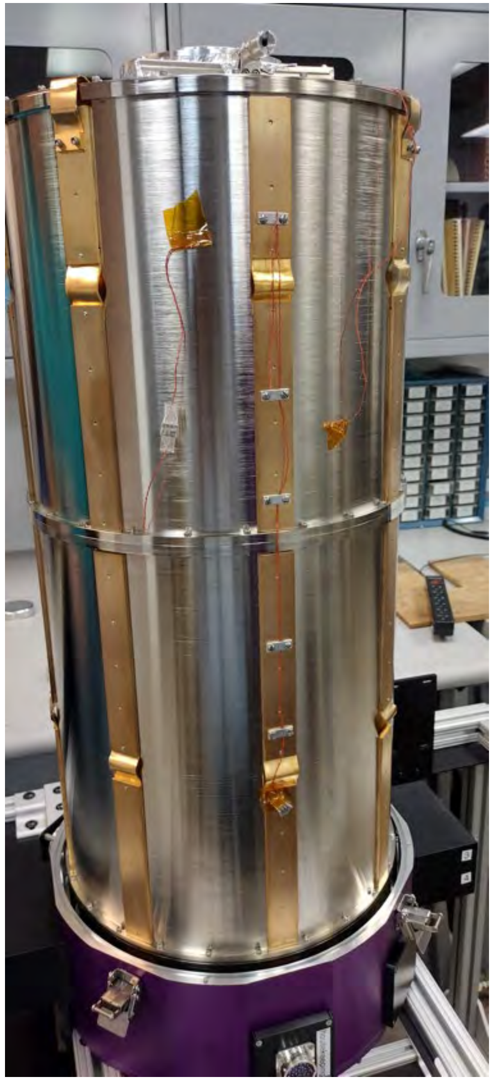
- Class 10,000 cleanroom
- Class 100,000 antechamber
- Cryostat for detector-level testing
  - Dark current measurements
  - LEDs for flood-illuminated flats
- Freezers for SCA storage
- Bake-out chamber
- ESD work bench and laminar flow bench (not pictured) for safe and clean assembly of detector components

Required Support Hardware

Critical hardware to perform detector-level tests, characterization and preliminary calibration

- SCA Test Dewar (IR Labs)
- Cryo Shutter (Uniblitz, IR Labs)
- Integrating sphere (Sierra Lobo)
- Monochromator (Newport)
- SCE-to-MACIE GSE cabling
- Bench power supplies (Keysight)
- Miscellaneous lab equipment and supplies


IR Labs Cryostat



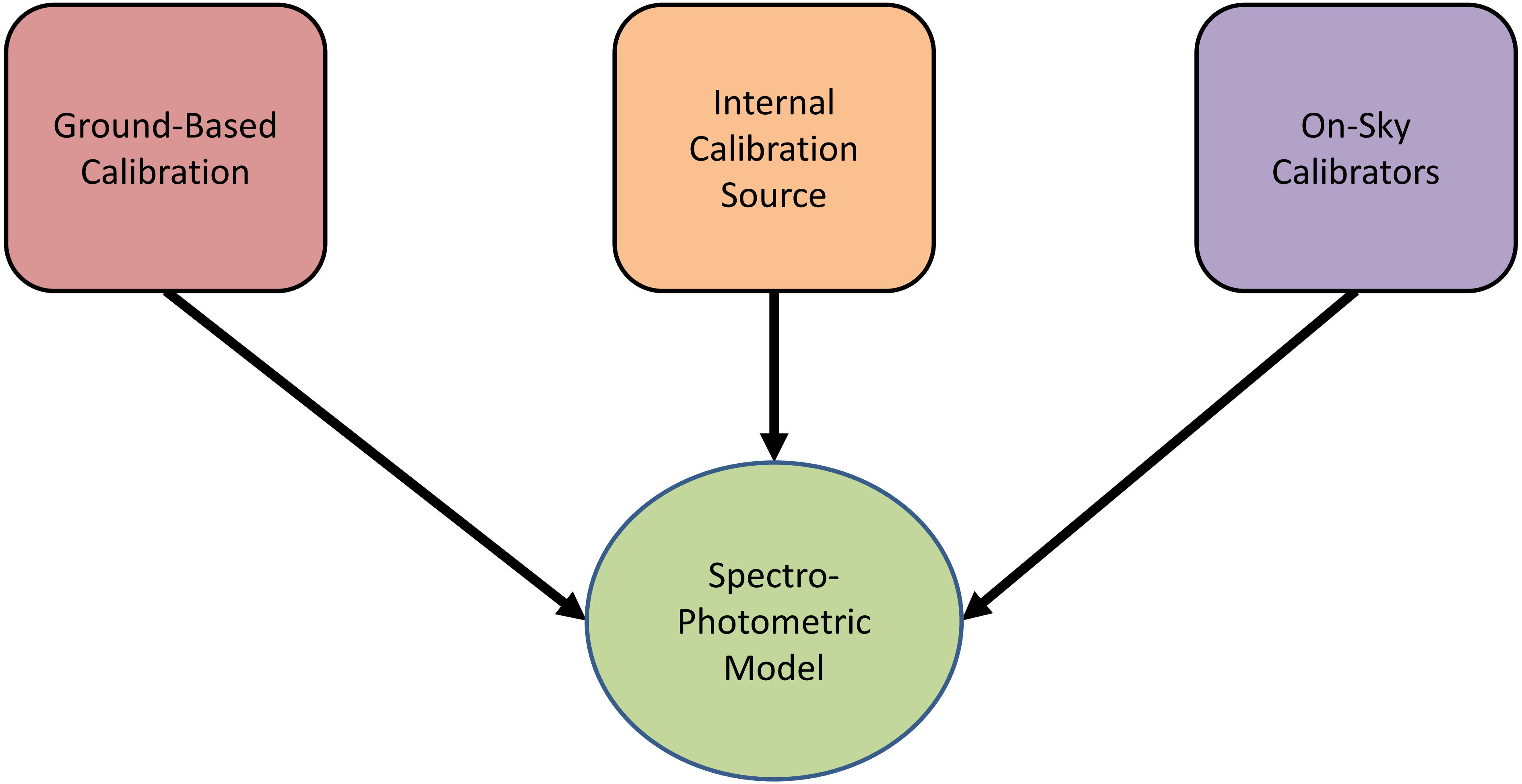
10. CALIBRATION APPROACH AND ON-ORBIT CHECKOUT

Calibration Approach and On-orbit checkout (Outline)

- Calibration Approach
- Techniques
- Noise and Mitigation
- On-orbit checkout

CALIBRATION APPROACH

Calibration Approach



Some of the Calibrations to be Done

- Flat fields
  - Detector pixel relative response
  - Wavelength-dependent crosshatching
  - Instrument-Throughput with MLA & disperser
- Non-linearities
  - Different flux levels
  - Point source vs flood illuminated
  - Brighter-Fatter
- Wavelength calibration
  - Ground arc lamps
  - Internal Fabry-Perot
  - Compact planetary nebulae during flight
- Dark Current
  - Ground-based
  - Updated with Sky Measurements or with calibration fold mirror
  - Cosmic ray occurrence
- Flux calibration
  - Internal Continuum lamp to characterize changes
  - White dwarf and solar analog calibrators
- Point source characterization
  - IPC / pixel crosstalk
  - Charge diffusion
- Persistence
  - Capture and release timescales
- Astrometric
  - Instrument orientation
  - Field distortion

- Component/Subsystem level testing – First Measure How the Items Work on their Own
  - Detector:
    - Pixel-to-pixel flat field, crosshatching (only the detector), non-linearity, flood illuminated
    - Characterize: 1/f noise, dark current, persistence
  - Cal Unit:
    - Assess Function
    - Fabry Perot filters

Calibration Sequence – Part 2

- Integrated Components
  - Detector:
    - Verify consistency in: 1/f noise, dark current, persistence
  - Telescope Simulator – Key Parameters to Spectrophotometric Model
    - Wavelength
    - Absolute Flux
    - Spaxel Mapping
  - Cal Unit:
    - Measure Offsets Relative to Telescope simulator

Calibration Sequence – Part 3

- Initial On-Orbit Calibration
  - Detector:
    - Verify consistency in: 1/f noise, dark current, persistence
  - Cal Unit:
    - Measure Offsets Relative to Ground, update solutions
  - Sky Sources
    - White dwarf and solar analog stars for spectro-photometric calibration
    - Wavelengths from compact planetary nebulae
    - Zodiacal Light and Extended Sources to verify flat fields

Calibration Sequence – Part 4

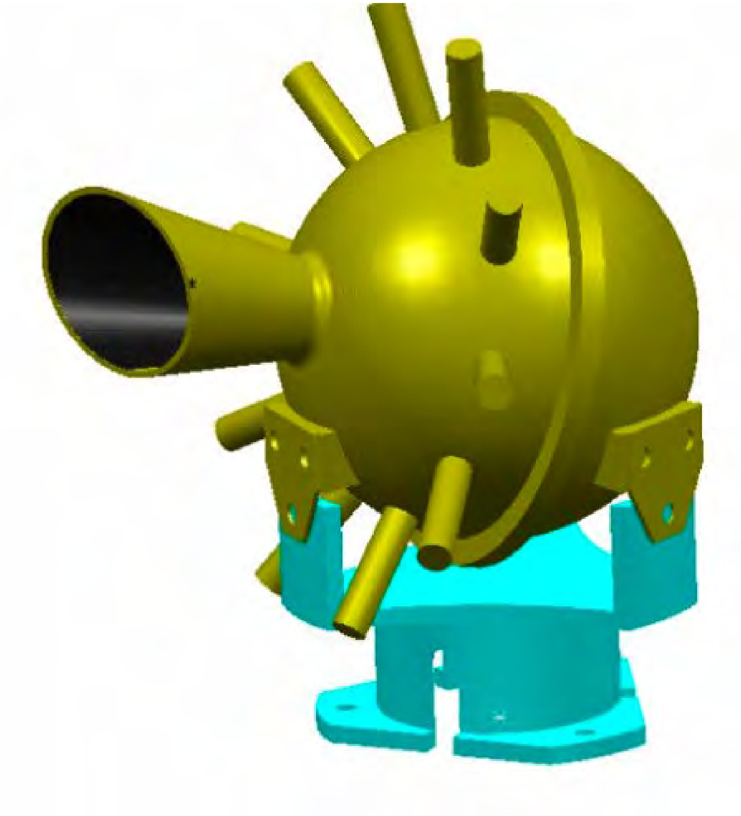
- Calibration Monitoring
  - Detector:
    - Verify consistency in: 1/f noise, dark current, persistence
  - Cal Unit:
    - Measure consistency in wavelength, flux, etc.
  - Sky Sources
    - Monitors changes outside spectrograph (wavefront, throughput, degradation of optics)
  - Time-Dependent Corrections

Ground-Based Calibrations

- See the AI&T Section for the telescope simulator
- Repeat 3x for 3 magnifiers
- Flat fields:
  - LEDs on detector housing
- Radiometric throughput
  - NIST diodes, point sources of varying sizes
- Pinhole selector
  - ”Open” position – throughput, flood illuminated nonlinearity correction
  - “Pinhole” – spaxel coordinates, stray light, baffle performance
- Wavelength solutions
  - Ar Arc lamps, peaks of blended lines will be a challenge
  - Fabry Perot Filter
  - Compare with Internal Calibrator and Offsets

e.g. McPherson wheel for pinhole selection
https://mcphersoninc.com/pdf/648.pdf

On-Sky Calibrator



JWST NIRSpec internal integrating sphere drawing

Following Ideas from JWST NIRSpec
- Integrating Sphere
- Fabry Perot Filters
- Continuum at several bands

Goal: Update ground-based calibration

Options to place integrating sphere in light path
- Mechanism to flip in fold mirror
- >95% throughput silvered mirror
  - Point at a 1” dark patch of a HST/JWST extragalactic deep field

- Additional LEDs behind the MLA + Disperser (TBD)
  - Inside focal plane module to produce diffuse scattered light for detector flat field

Spectro-Photometric Calibration Budget

Component	Allocation	CBE (mmag)	λ Dependent?	Notes
Temporal Stability				
RSR Stability		1*	Yes	Change in relative spectral response or overall transmission between when calibration data was taken and science observations; Telescope and Spectrograph (only spectrograph applies to us)
PSF Stability		1*	Yes	Change is size/shape of PSF; Telescope and Spectrograph (only spectrograph applies to us)
Wavefront stability		<0.3*	Yes	Change in response because of wavefont errors (e.g. micrometeoroid causing a defect)
Flat Stability			No	Change in the flat field response of the detector over time
Pixel Response Stability			No	Change in the per-pixel response/noise of detector over time
Continuum Source Flux Stability			Yes	Change in the absolute flux of continuum source
Line Source Flux Stability			Yes	Change in the absolute flux of line source (SNR effect, probably small, line calibration covered by Spectral Stability)
Correction Errors				
FOV Correction			Yes	FOV of view effects (transmission, AOI color correction)
Flat Correction			Yes	Uncertainity in detector flat field correction
Pixel Correction			No	Uncertainity in detector pixel response correction
RSR Correction			Yes	Uncertaininty in reletive spectral response / transmission correction
Non-Linearity Correction			Yes	Uncertainity in detector linearity (accumulated signal dependant).
Continuum Source Flux Error				Error in flux assumptions from continuum source
Noise Sources				
Persistence			No	Signal from Detector Persistence
Reset anomalies			No	Changes the pedestal level of the ramp
Dark Subtraction			No	Residuals from dark subtraction
IPC		~0	No	Interpixel capacitance (charge sharing)
Brighter Fatter Effect		~0	No	Brighter Fatter effect (flux dependant charge sharing). In principal conserves charge
Reference Pixel Correction			No	Differences between active and reference pixels
MLA Throughput Errors			Weakly	
Data Processing				
Flux Calibrator Uncertainity		10/sqrt(N)*	Weakly	Where N is the number of calibration sources. Includes systematic offsets
Source Extraction Uncertainity			Yes	Data processing uncertainities (flux extraciton, centroiding errors)
Host Galaxy Subtraction Residual			Yes	Residuals from spectral subtraction of the host galaxy
Data Processing Strategy			No	Signal Response uncertainity due to Spectrograph lossy data processing / compression scheme

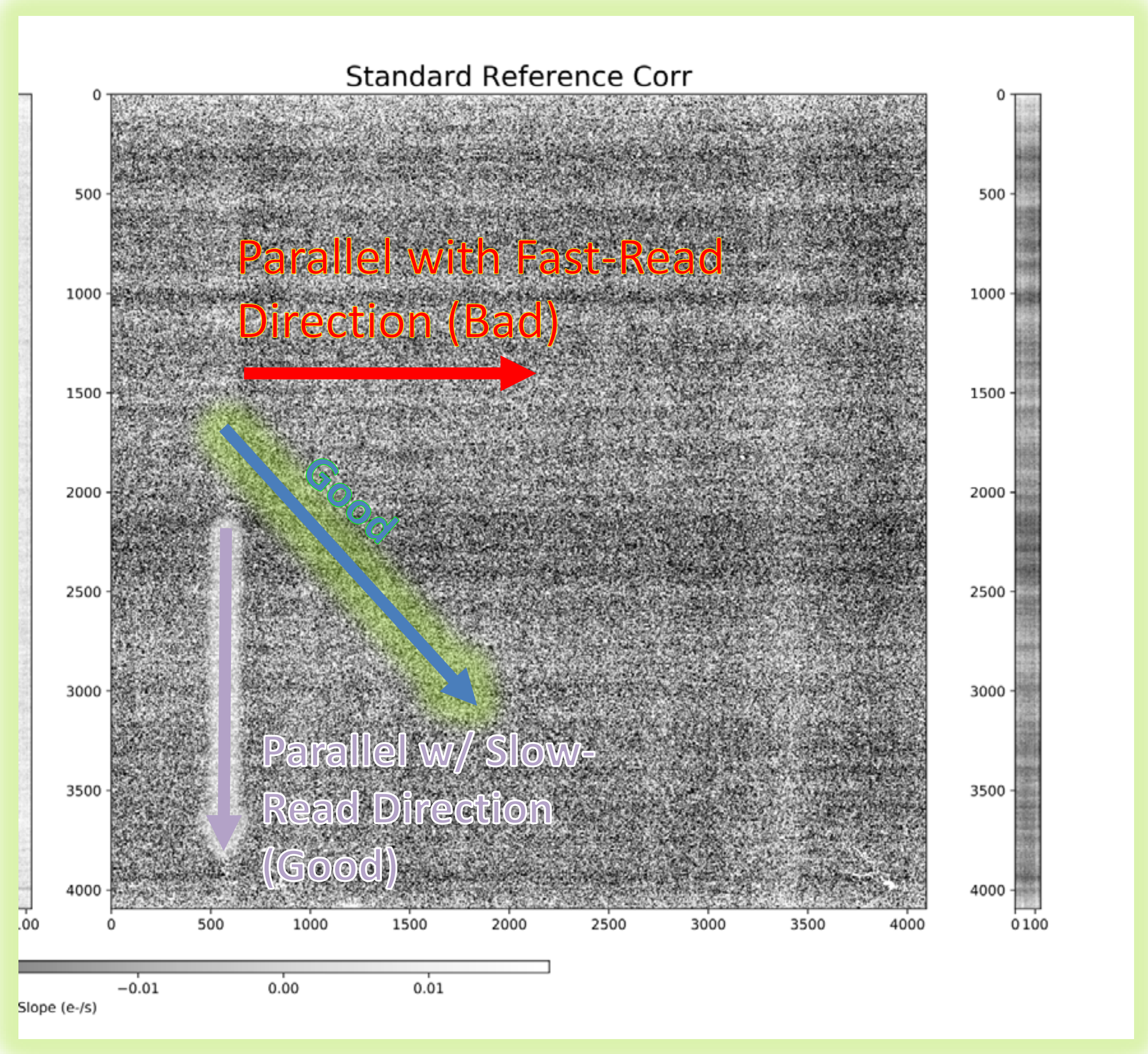
Budget to be further coordinated with Pearl science team

*Estimates from JWST NIRCam photometric monitoring and JWST wavefront stability

1/f Noise and Dispersion Orientation

Lesson from NIRCam grism Time Series:

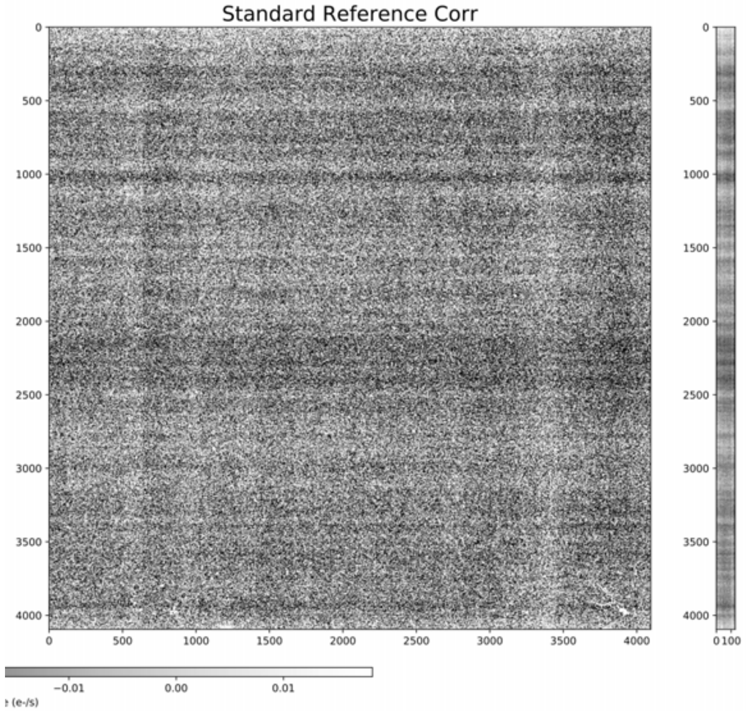
- Don't align with row striping ("spatial" 1/f noise)
- Allow some subtraction on either side of spectra



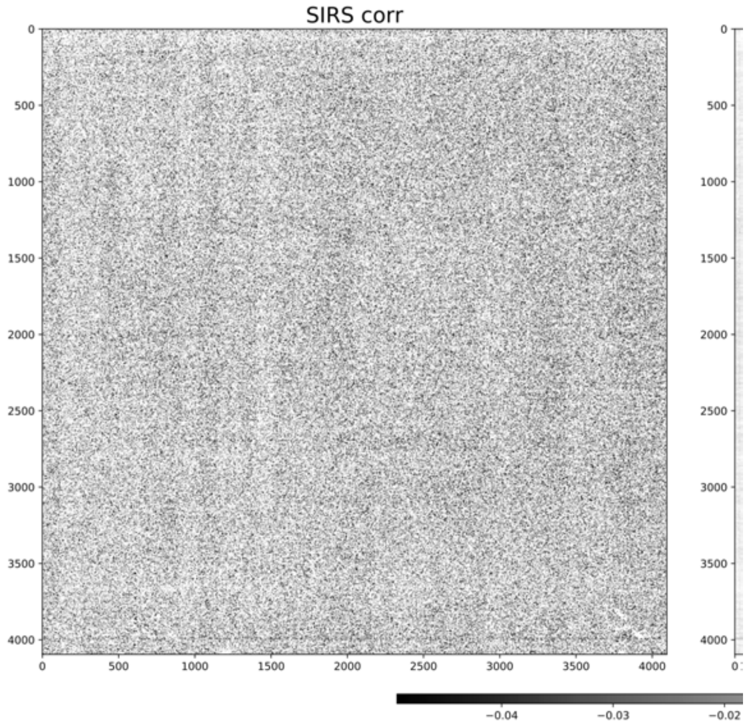
Rauscher et al. 2021 H4RG dark

1/f Noise Mitigation

Standard Reference Pixel Correction



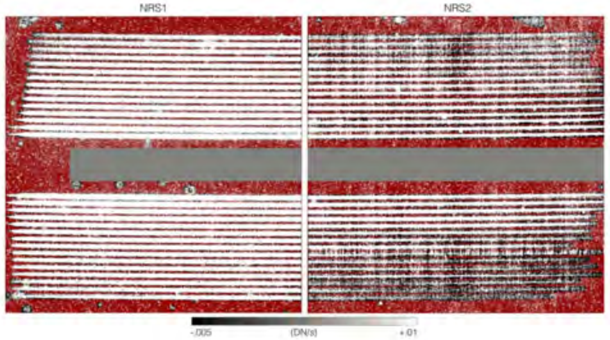
Simple Improved Reference Correction



Use behavior of column reference pixels over time to predict and subtract 1/f fluctuations in active pixel regions. Only works on common-channel noise.

Explore option to more frequently sample reference voltage in clock pattern

Rauscher et al. 2021

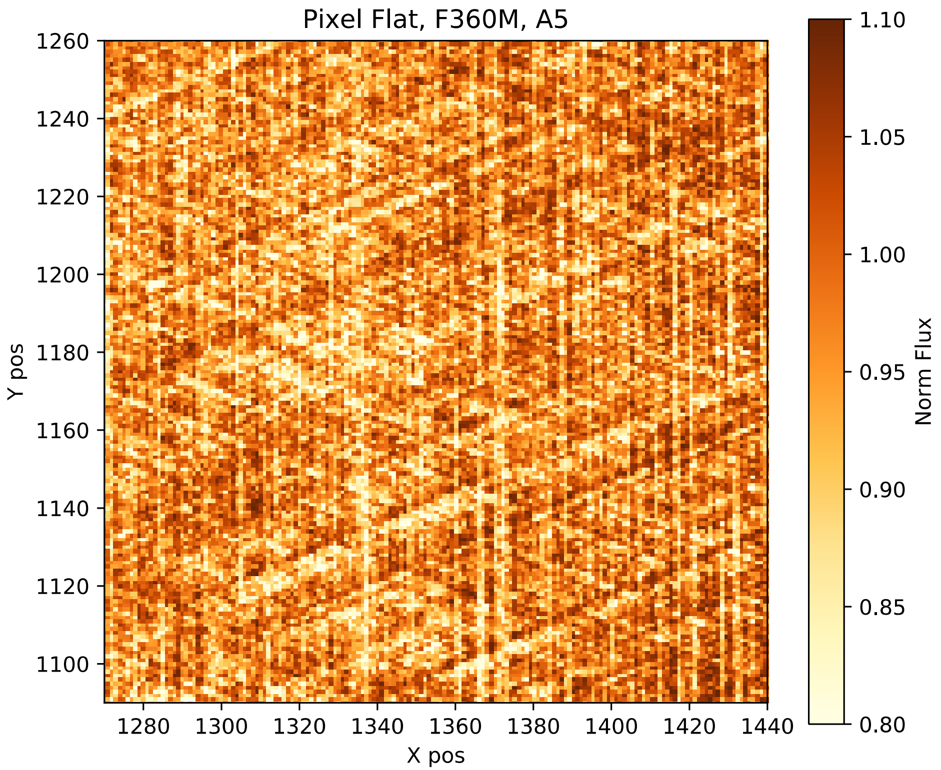


Perform Fourier analysis of background active pixels (ie., between dispersed spectra) to create a noise model and subtract

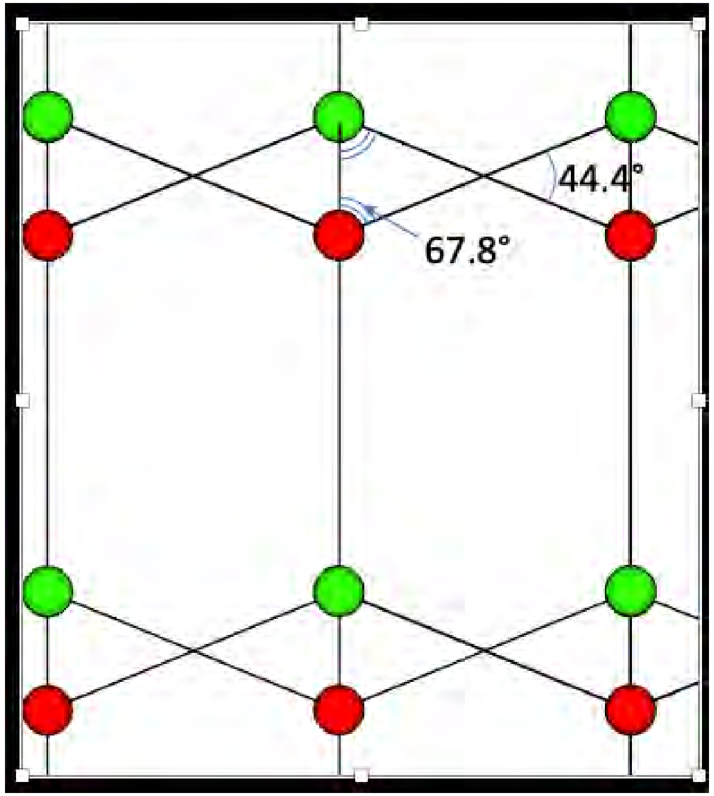
Apply:
- NSClean (Rauscher et al. 2023)
- ROEBA (Schlawin et al. 2023), etc.

Detector Crosshatching

Crystal structure from HgCdTe can appear in flat fields
Wavelength dependent – stronger at shortest wavelengths



Zoom-in on flat field from JWST NIRCam



One projection of zincblende HgCdTe lattice

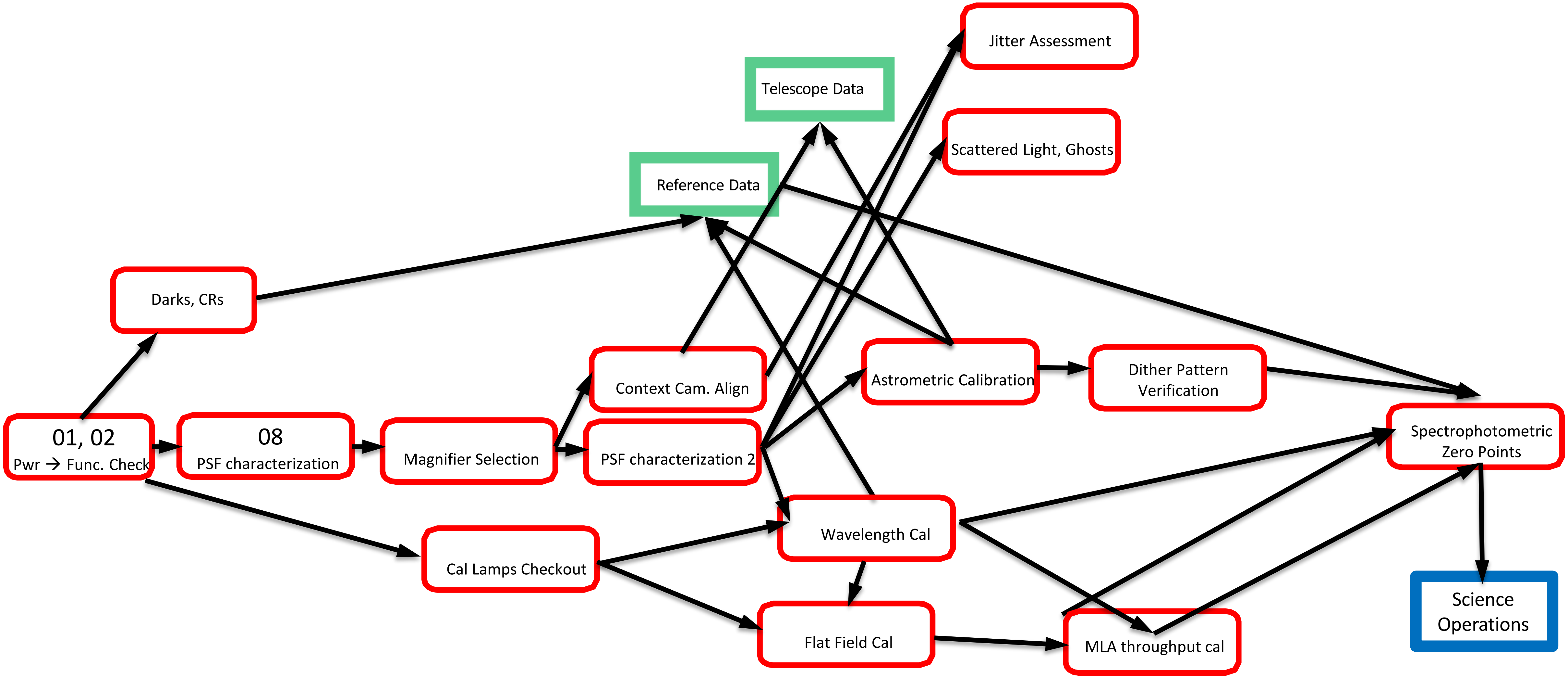
ON ORBIT CHECKOUT

With Inheritance of JWST NIRCam (and NIRSpec)

Draft On-Orbit Commissioning (very preliminary)

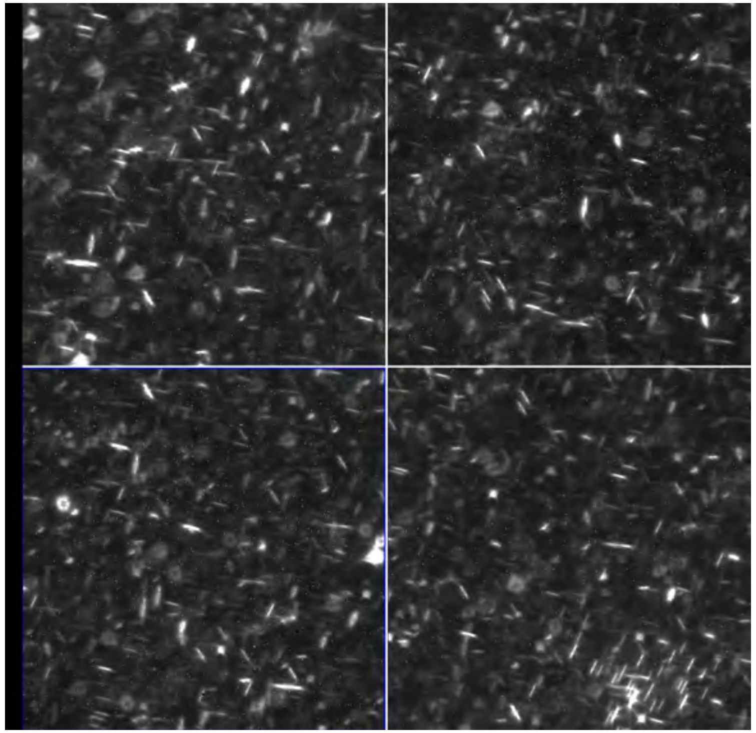
1. Power on and Initialization
2. Functional Checkout
3. FPA heater control
4. Darks - Noise Verification, cosmic ray rate
5. Shutter - opening/closing, timing
6. Pupil alignment?
7. Focus adjustment?
8. PSF and image quality characterization
9. Selection of magnification optic
10. PSF and image quality characterization 2
11. Relative alignment of Context camera and the spectrograph
12. Calibration unit - wheel or mechanism tuning and verification
13. Calibration unit - lamps checkout
14. Wavelength calibration
15. Flat Field Calibration
16. Scattered light, ghosts, glints, etc
17. Spectro-photometric zero points
18. Astrometric calibration
19. Target acquisition and pointing verification
20. Dither pattern verification?
21. MLA - assess throughput and losses
22. Jitter assessment

Draft Overview of On-Orbit Commissioning Activities



Functional Checkout

- Check Temp, Voltage, Current
  - Spacecraft
  - Heaters
  - Mechanisms
- Exercise wheels, shutters, mechanisms (TBD on final design)
- Can start before detectors full cold (TBD K. NIRCam was 130 K for 2.5-µm cut-offs)
- Start w/ Dense field, such as a globular star cluster or planetary nebula (e.g M13, Orion)
  - Check for Vignetting
- Move to a bright target to check pointing and alignment



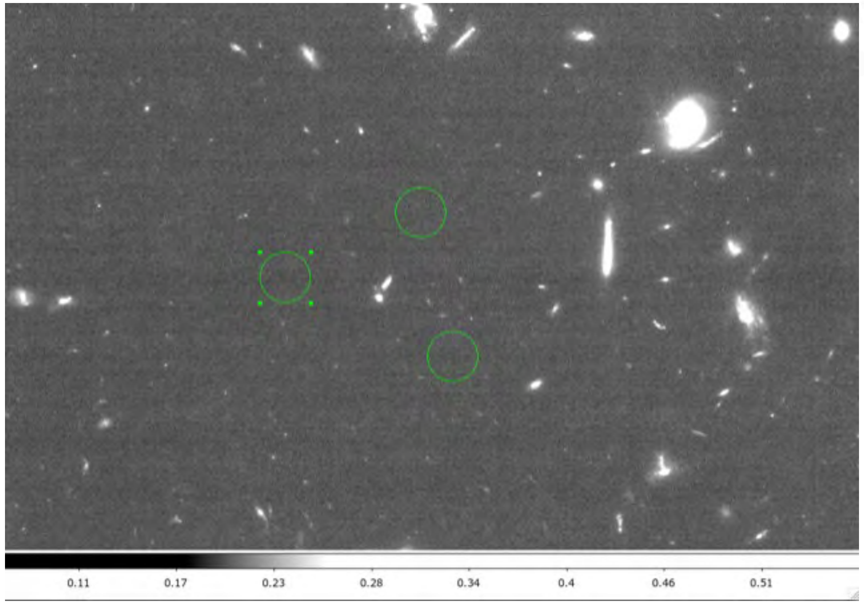
JWST NIRCam First Photons (LMC)

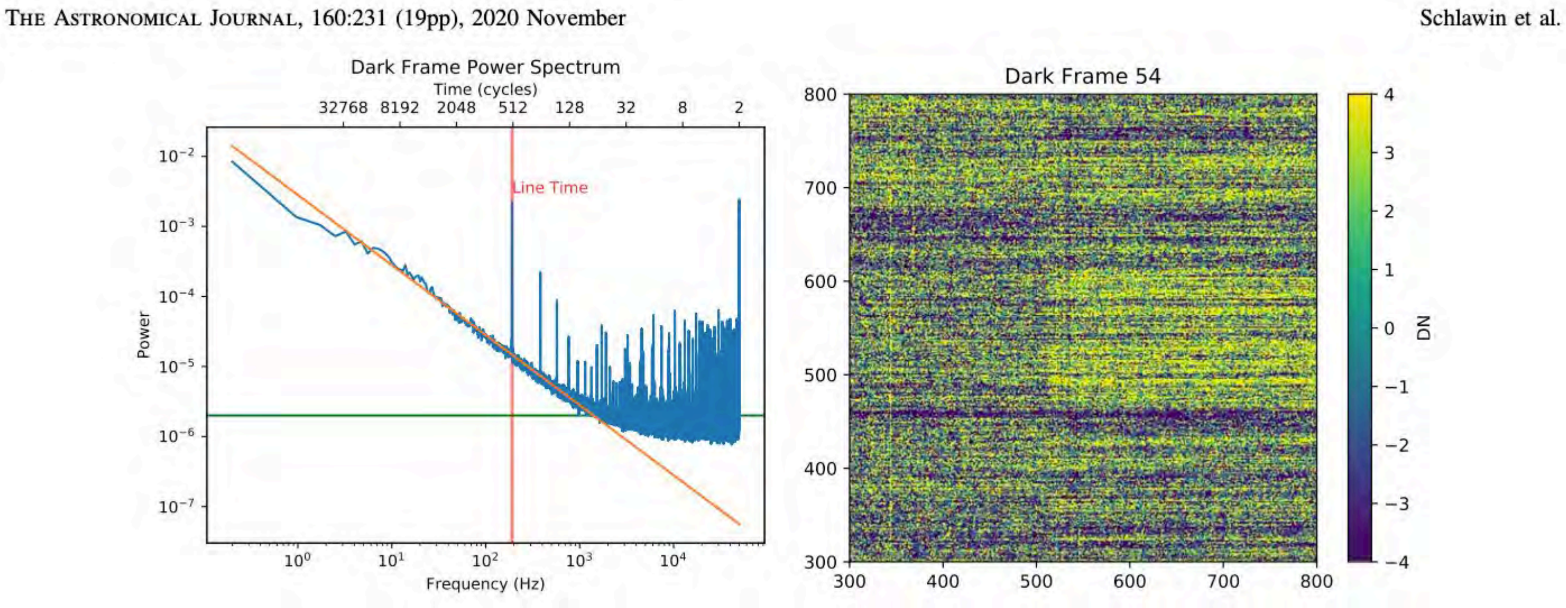
Dark Frames

- read noise, 1/f power spectrum, dark current, cosmic rays

Shutter closed (if available)
Otherwise:

- Use a dark region of a JWST deep field (e.g. regions < 0.07 e-/s or 0.2 MJy/sr)

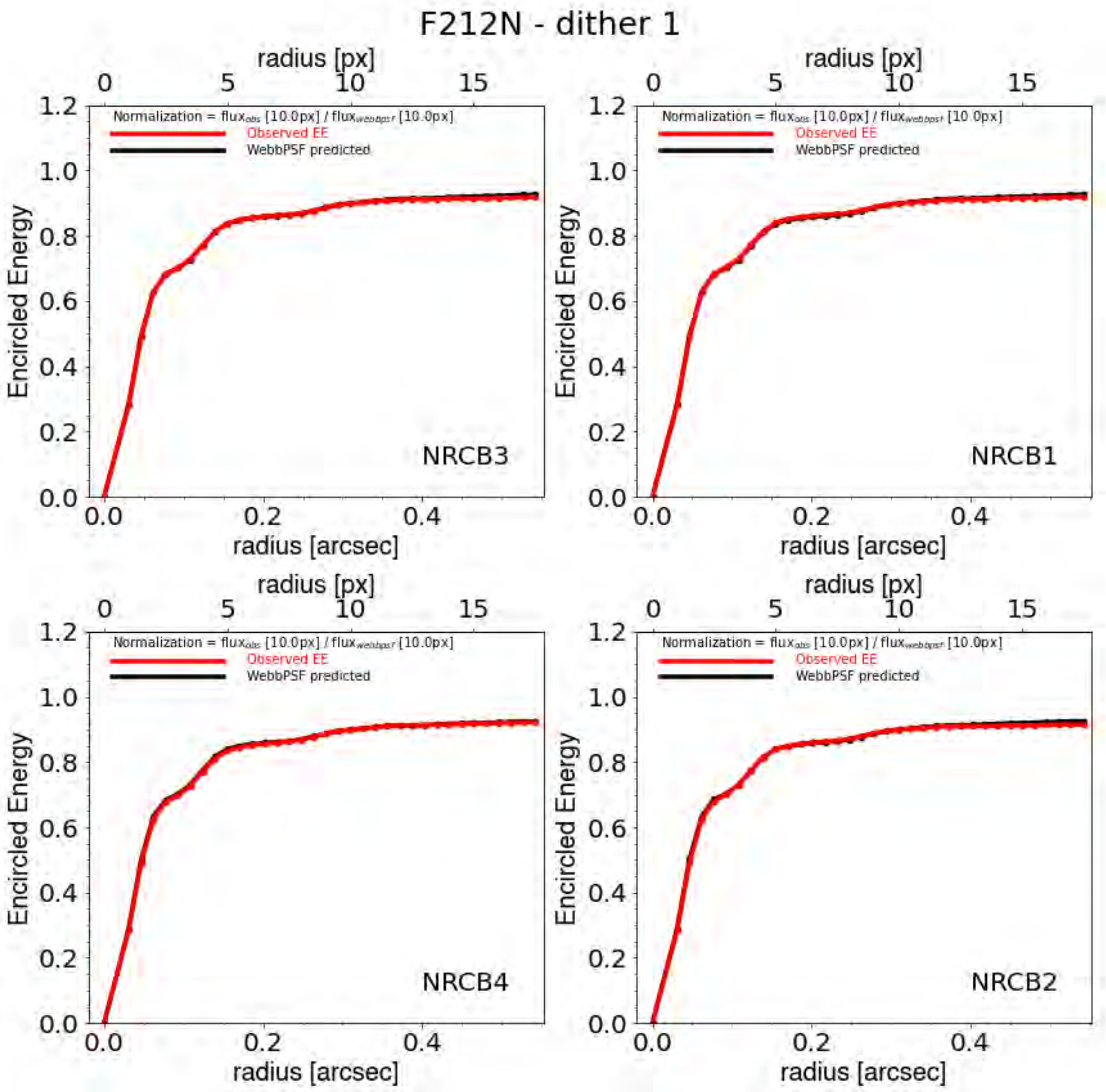




PSF Characterization

Verify enboxed / encircled energy versus radius

No imaging mode, so would require monochromatic wavelength soruces



NIRCam imaging PSF characterization

Magnifier Selection

- Mechanism
  - – Match the FWHM to 2 spaxels
  - – Depends on performance of telescope optics

Scales TBD

0.020”/spaxel

0.030”/spaxel

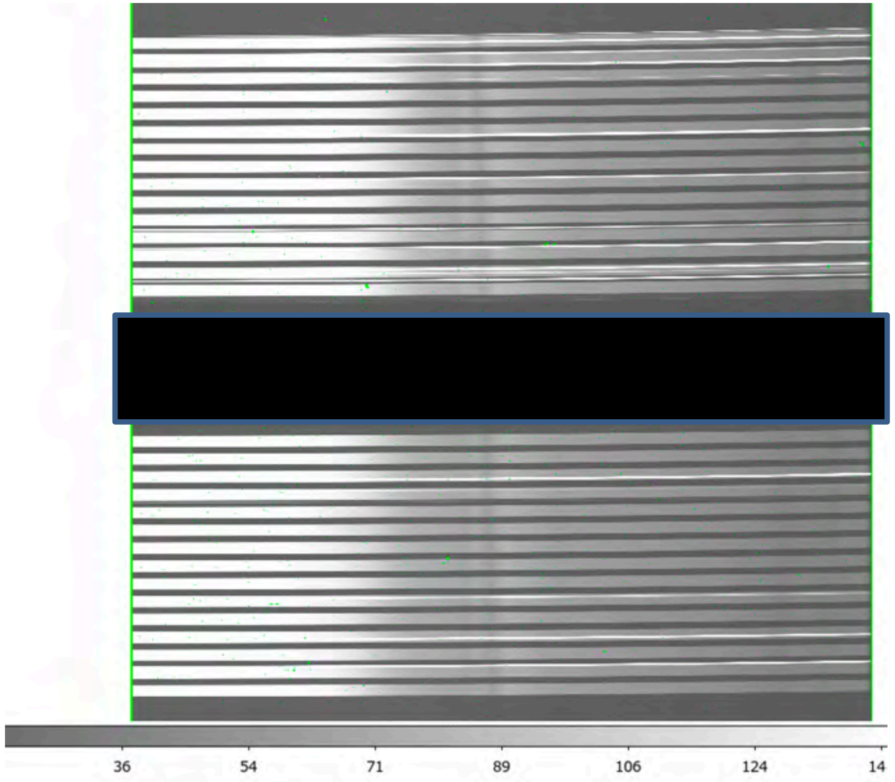
0.050”/spaxel

Diffraction Limit

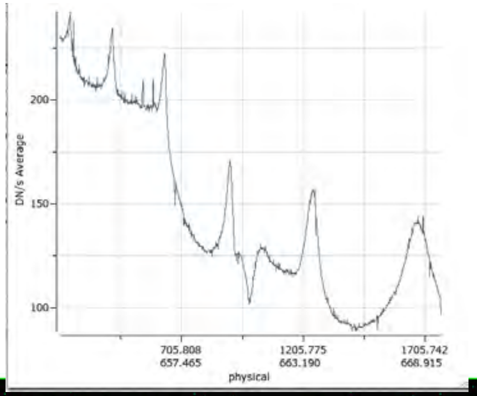
Potential high freq may persist

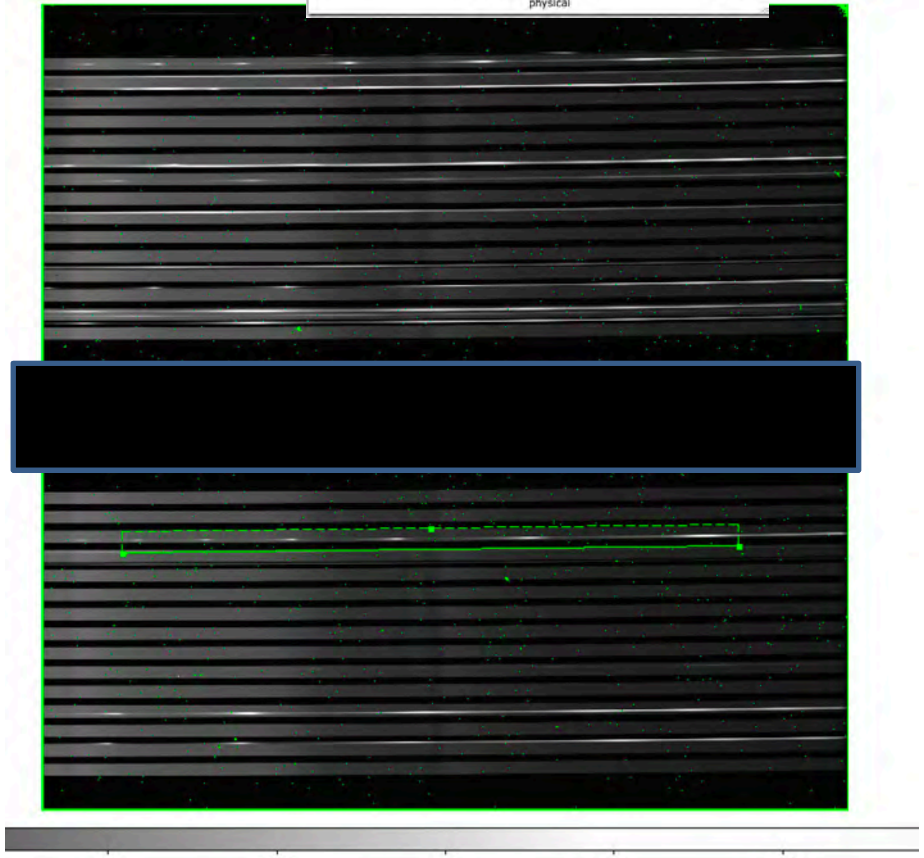
Lamp Checkout

- Voltage and Currents
- Temperature requirements?



JWST NIRSpec Flat lamp 1
Jw0112030001_0210r



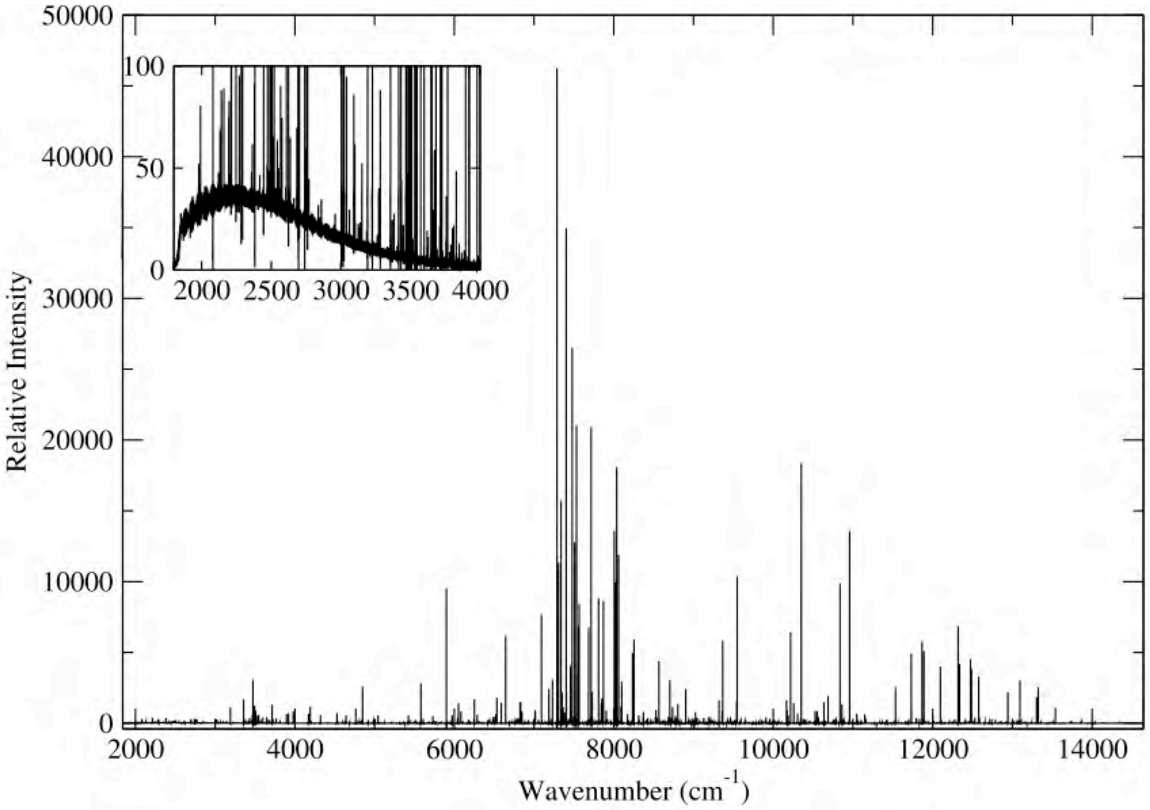


JWST NIRSpec Line lamp 1 (Fabry-Perot)
Jw01132002001_02130

Wavelength Calibration

Update ground-based model with:

Lamp Flats



https://ui.adsabs.harvard.edu/abs/2008ApJS..178..374K/abstract

Compact Planetary Nebulae

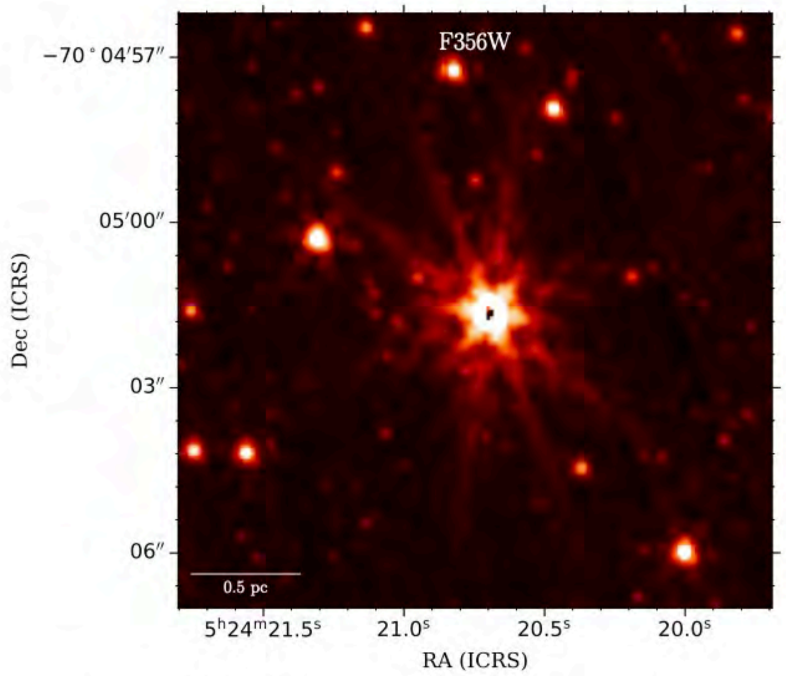
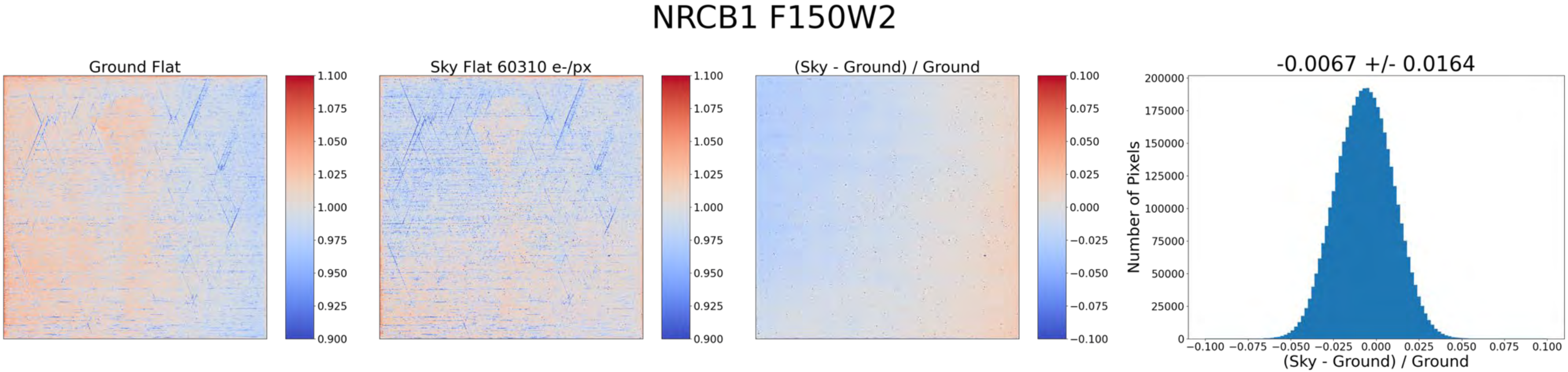


Figure 1. NIRCam F356W image of SMP LMC 058 shown in an Asinh stretch. At this spatial resolution (0.063″) SMP LMC 058 is an unresolved point source.

Flat Fielding

- How flat? Goal: 1 mmag for pixel-to-pixel response
- How stable? < 1 mmag within an exposure, can re-normalize inter-exposure variability

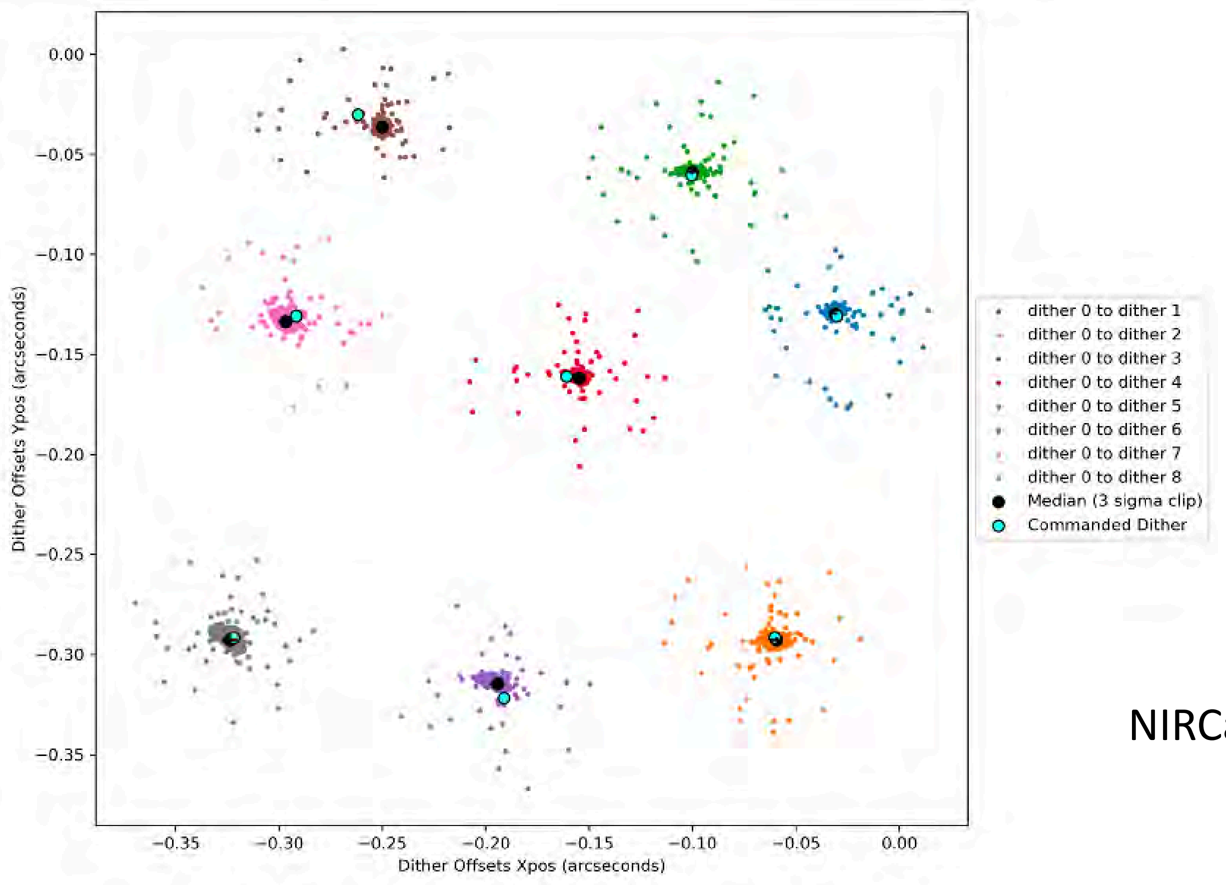


NIRCam flats from Marcia Rieke B. Sunnquist

Dither Pattern Verification

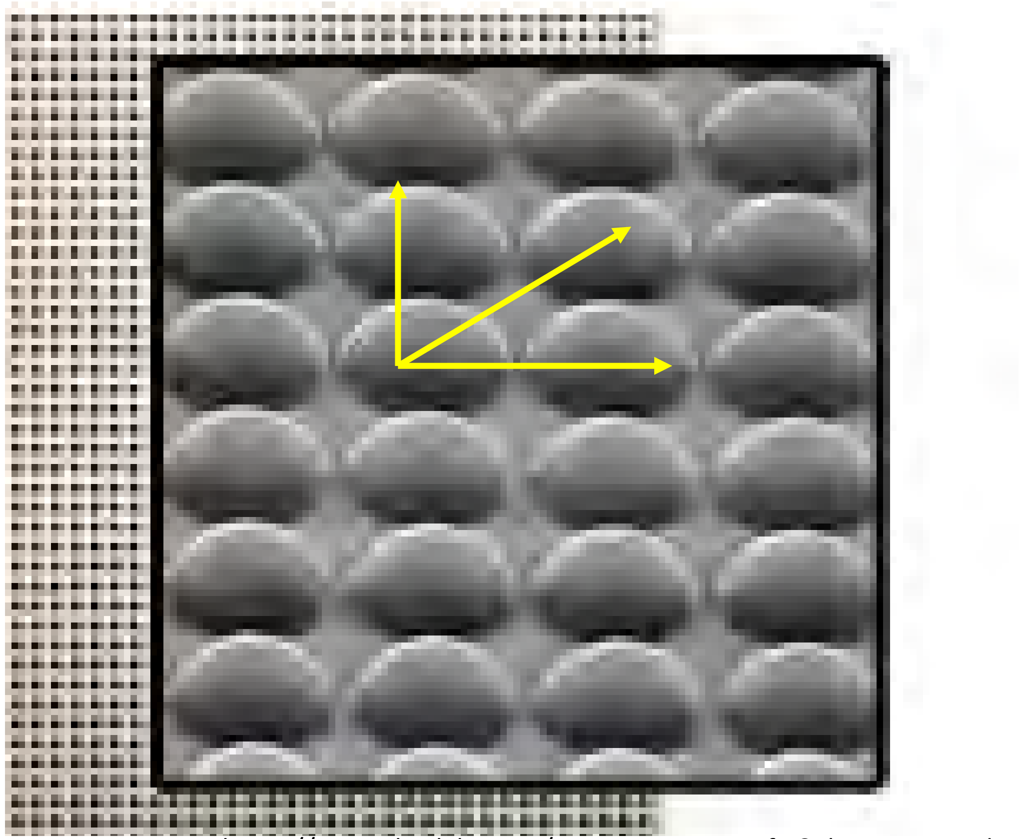
- Sub-spaxel and inter-spaxel

Mod B SW



NIRCam dither pattern verification, K Hainline, M Rieke

- Sub-spaxel scan to characterize loss at the “seams” between MLA elements

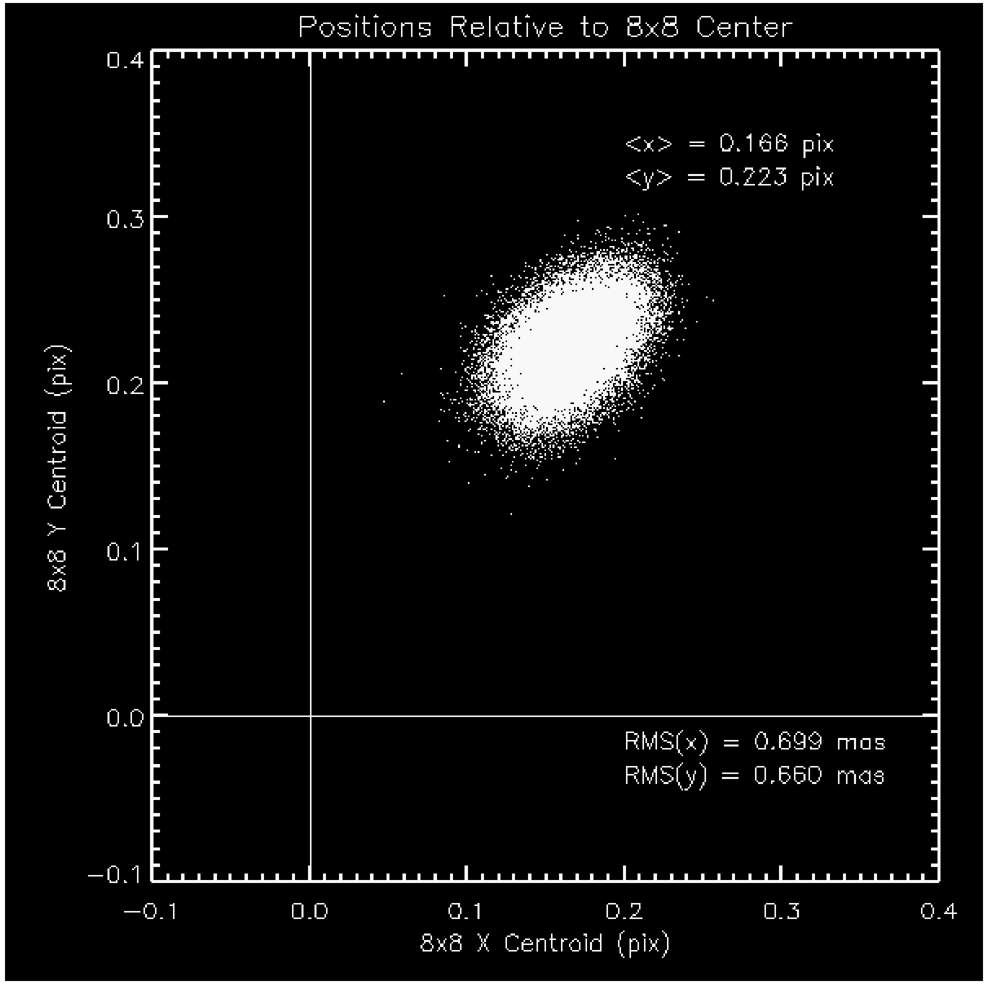


https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=2861

Jitter Assessment

- Compact planetary nebula for spectral + spatial drifts
- Assess Long-Term Drift on ~hr long timescales with full frame
- Fast-timescale jitter better characterized by context camera & probably coronagraph

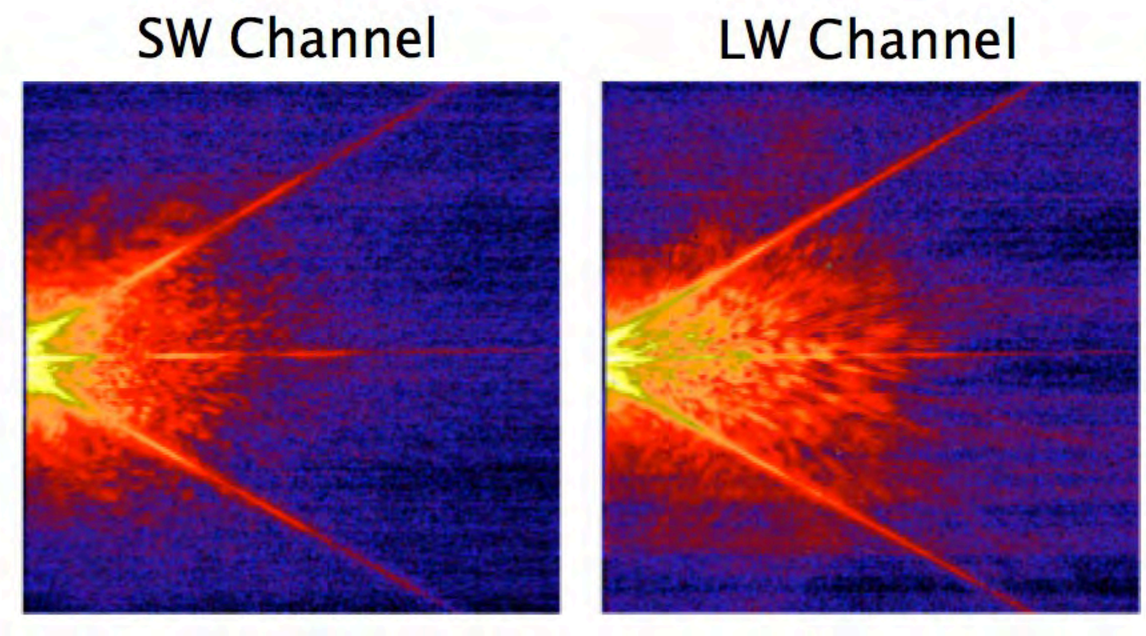
Example JWST NIRCam 8x8 subarray jitter measurements for fast timescale jitter



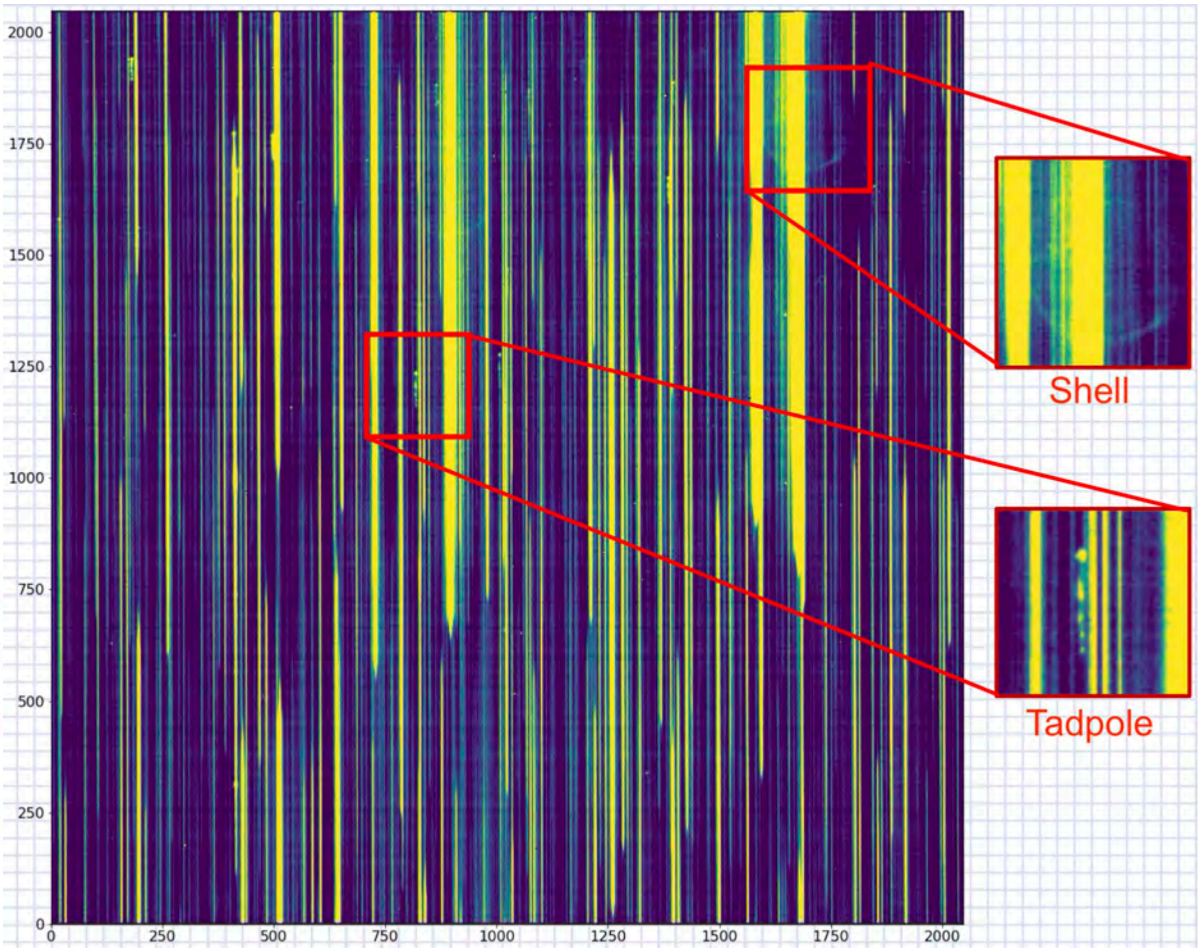
Scattered Light, Ghosts

Select a bright source (e.g. J=3)

- Center of field
- Scan around edges

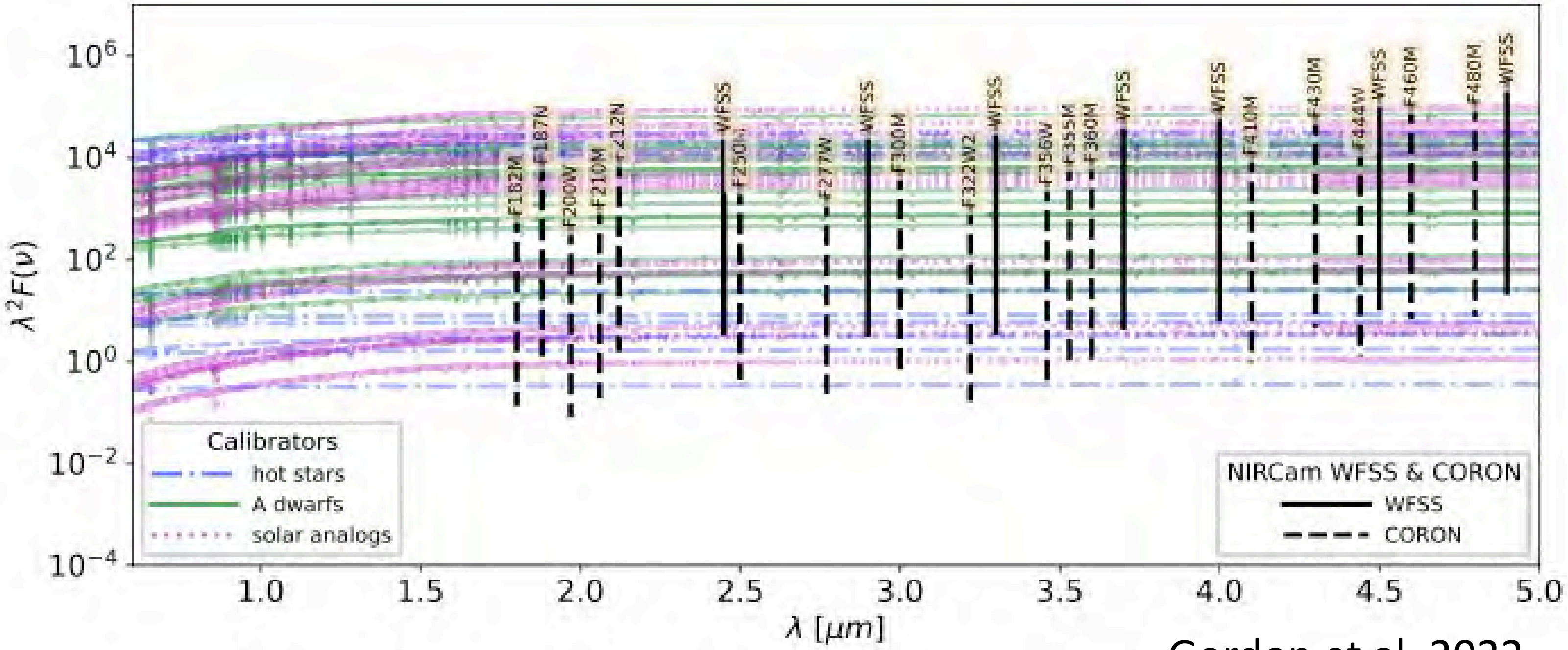


JWST-docs NIRCam "Dragon's Breath"



"Shells" and "tadpoles" on NIRCam grism

- JWST Absolute Flux Working Group Heritage
  - CALSPEC White dwarfs
  - G star solar analogs
  - Over a range of fluxes

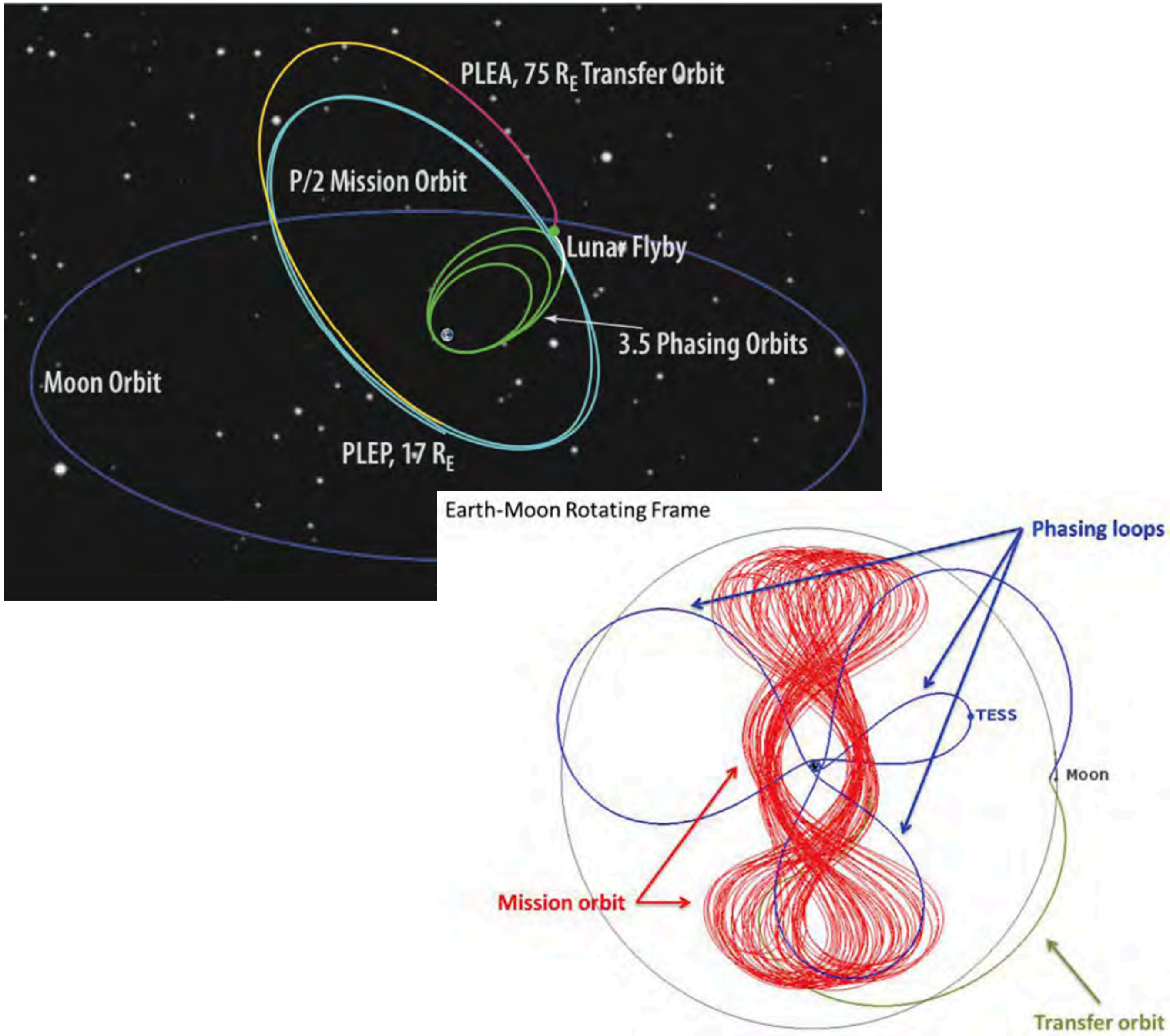


Gordon et al. 2022

11. CONCEPT OF OPERATIONS

Produced by: Ascending Node Technologies LLC for the University of Arizona

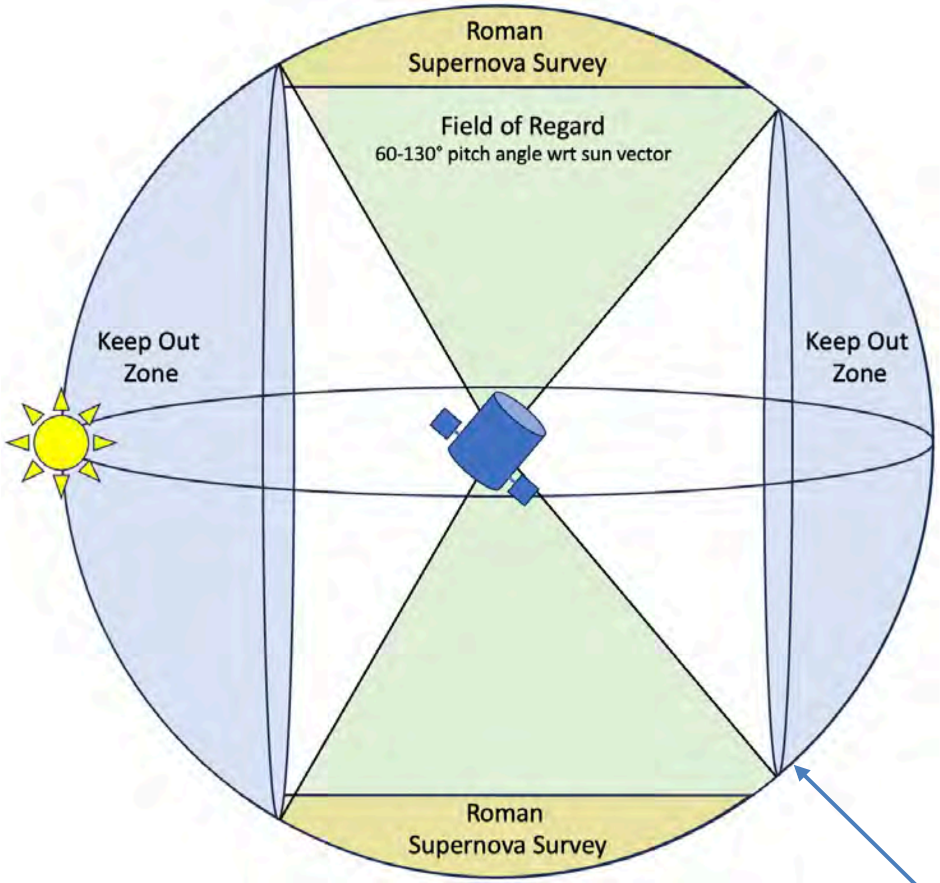
Mission Orbit and Spectrograph ConOps

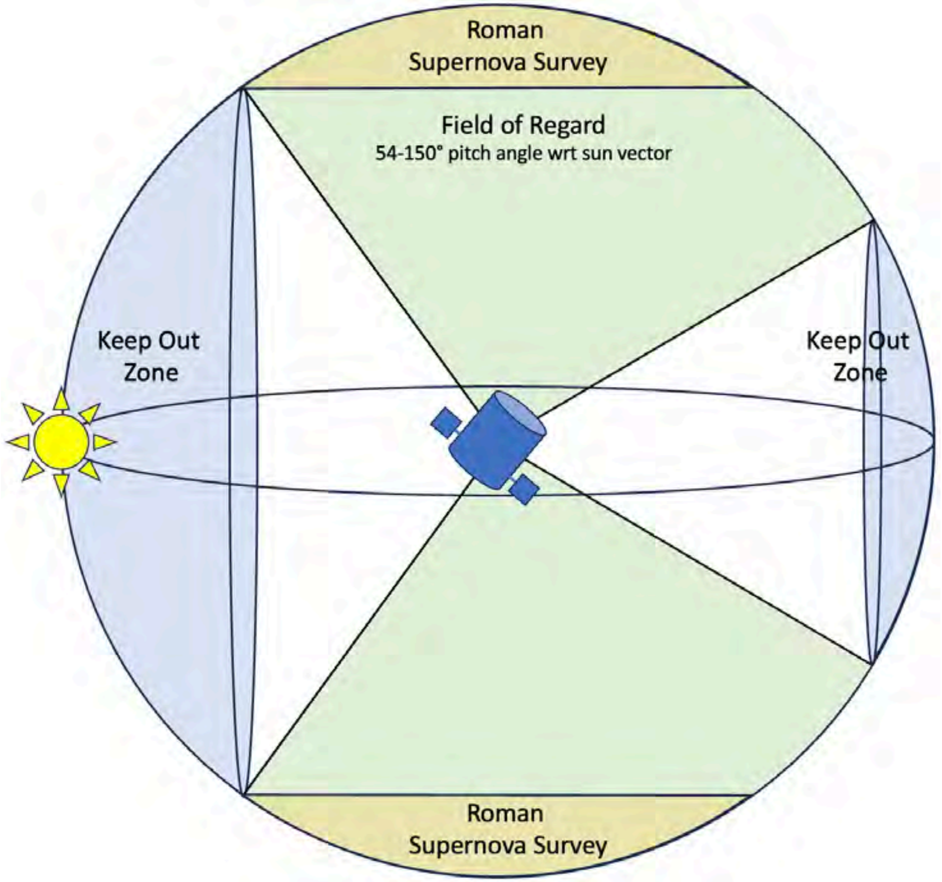


- Pearl orbit
  - High-Earth TESS-like orbit
  - 13.7-day orbital period
  - 2:1 resonance with the Moon
    - Pearl orbits Earth twice for every time the Moon orbits once
  - Enables long observation arcs
  - Low radiation environment

- Mission ConOps
  - Uplink observing sequence (typically every ~5 days, special targets ~1 day)
  - Downlink quicklook data (~every day)
  - Downlink all data 4TB stored in S/C memory during dedicated telecom passes (once / orbit)
  - Mission ConOps levies minimal requirements on Spectrograph

Pearl Field of Regard





Mission L1 Req. OBS-1.2.0 :
Field of regard anti-sunward with pitch angle threshold of 60° to 130° from the Sun vector, and goal of 54° to 150° from the sun vector

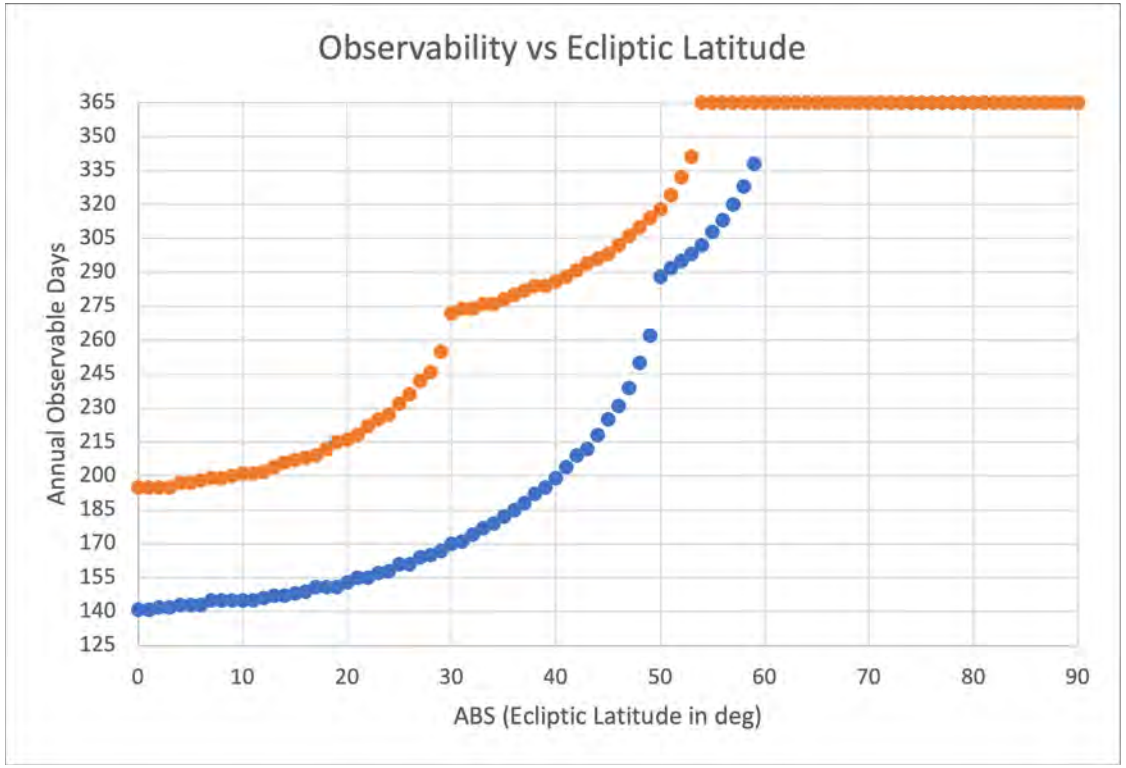
- Entire sky is visible for fraction of the year
- A field of regard of 60° to 130° from the sun vector allows continuous observation of the a region of sky within 30° of each ecliptic pole
- A field of regard of 54° to 150° from the sun vector allows continuous observation of the a region of sky within 36° of each ecliptic pole
    - This region overlaps the Roman High Latitude Time Domain and Wide Survey areas

Pearl Field of Regard
Target Visibility by Ecliptic Latitude

Mission L1 Req. OBS-1.2.0 :
Field of regard anti-sunward with pitch angle threshold of 60° to 130° from the Sun vector, and goal of 54° to 150° from the sun vector

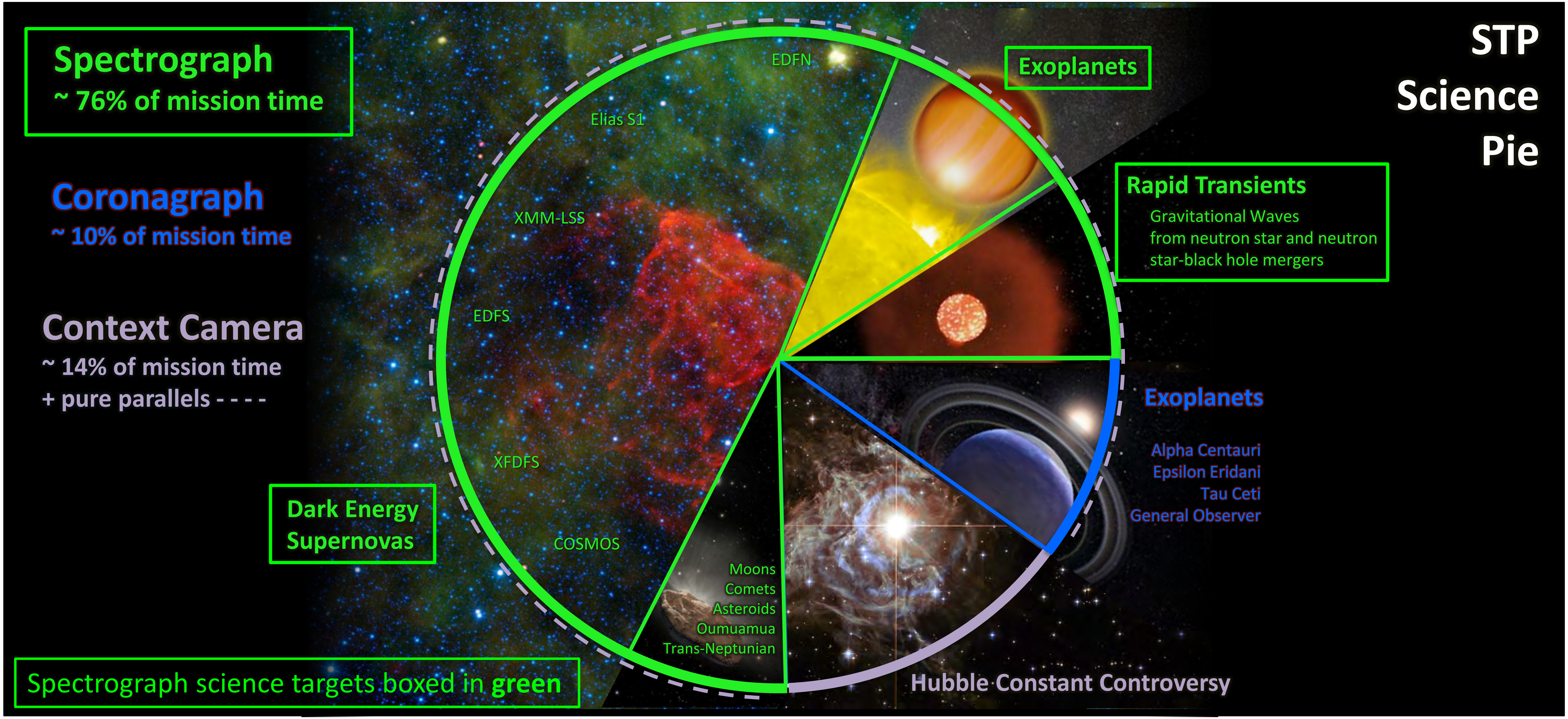
- For a field of regard with pitch angle of 60° to 130° from the Sun vector
  - Ecliptic latitudes > 60° or < -60° can be continuously observed throughout the year
  - Minimum annual visibility of 141 days on ecliptic plane

- For a field of regard with pitch angle of 54° to 150° from the Sun vector
  - Ecliptic latitudes > 54° or < -54° can be continuously observed throughout the year
  - Minimum annual visibility of 195 days on ecliptic plane



Number of annual observable days for
Field of regard of 60° to 130° from the Sun vector in **Blue**
Field of regard of 54° to 150° from the Sun vector in **Orange**

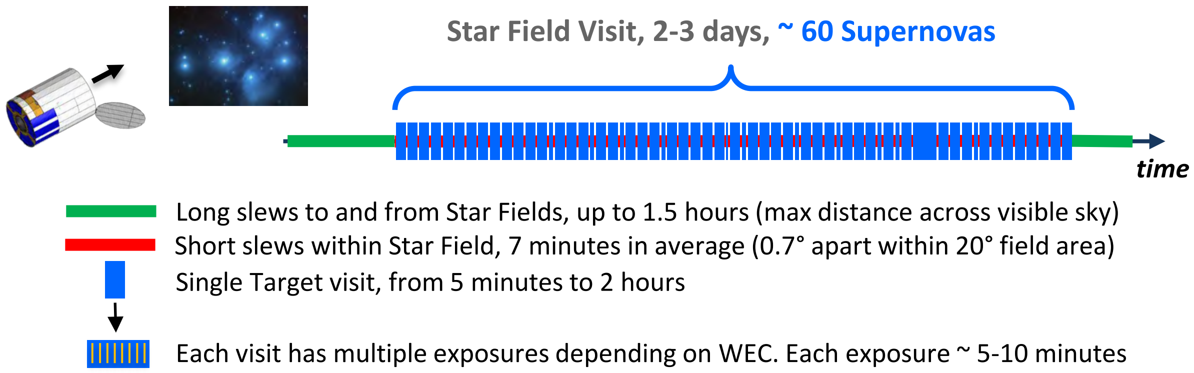
Science Investigation Pie



High Level CONOPs – IFS

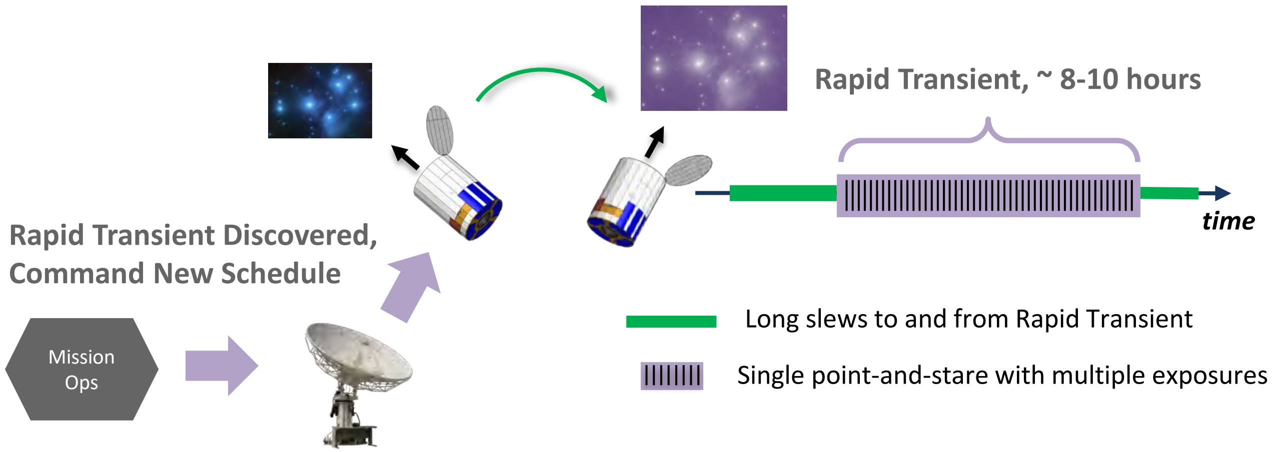
Slow Transients

- Supernova Fields, Exoplanets, Solar System Objects, Public Science Requests
- Observations can be scheduled 1-2 weeks in advance

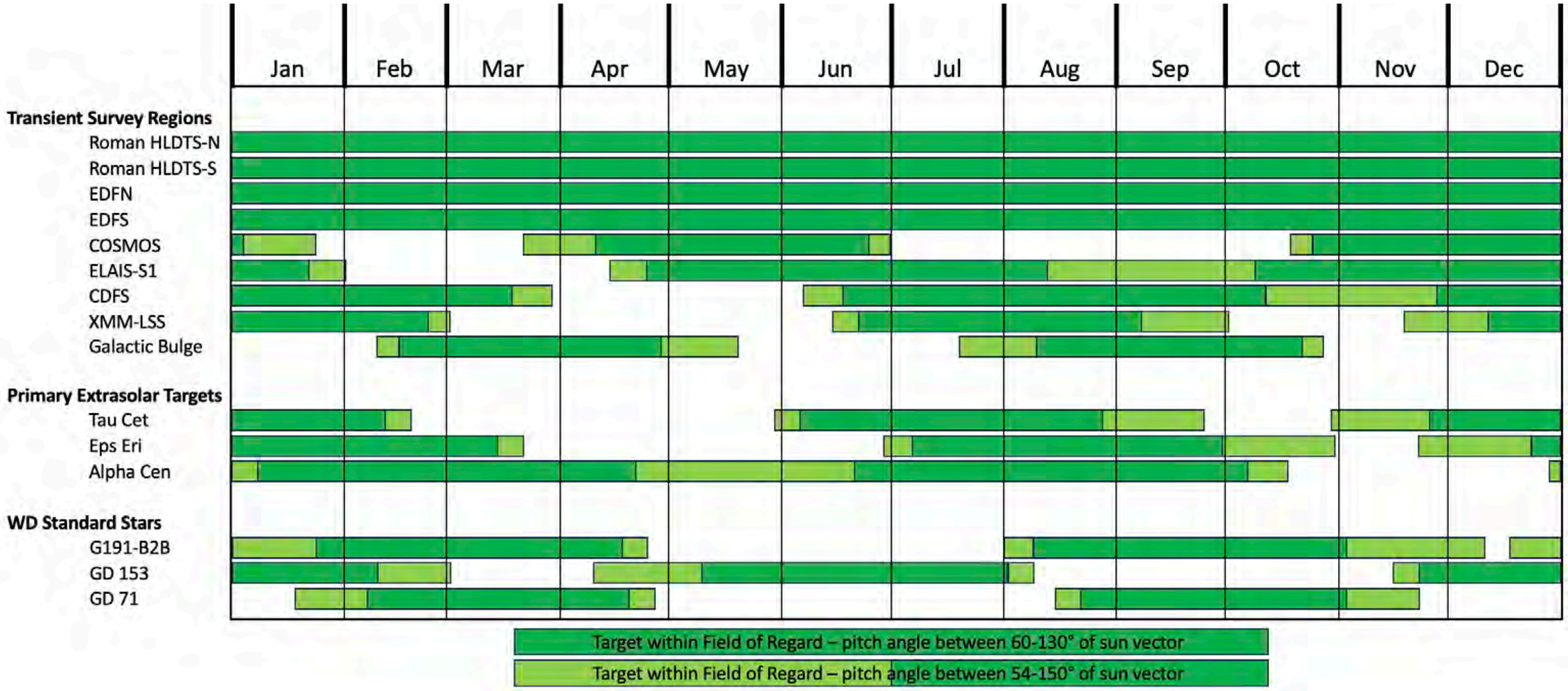


Rapid Transients

- Gravitational waves, neutrino bursts, fast radio bursts, gamma ray bursts
- Once discovered, rapid transient is localized by wide-field-ground base telescopes before STP can be commanded



Pearl Field of Regard
Examples of Target Visibility



- Supernova fields are located throughout the sky. The primary Roman supernova fields are located at high ecliptic latitudes and visible throughout the year
- Standards stars, exoplanets and public request targets are also scattered across the sky

- <u>*There are always science targets available for observation*</u>

12. TEAM ORGANIZATION AND MANAGEMENT APPROACH

Team Organization, Management Approach and Schedule (Outline)

- Team composition
- Management Philosophy
- Evidence of excellence in instrument development
- Development plan
  - schedule targets
  - procurement plans, and long lead plans.
- Schedule

Strengths of Team

1. UA and UCB-SSL have been involved with Pearl from the inception, we know the partners and players.
2. Both have extensive resources as far as experienced people and facilities.
3. We are also plugged into the other instrument and telescope teams. This synergy allows us to:
   – Iterate faster on optical, mechanical, electrical and software interfaces.
   – Use vetted, and tested, electronics and software to reduce our development time.

Program Management Philosophy

Tailor ground-based instrument management style to achieve a low-cost space instrument.

- Small focused teams for Systems, Optomechanical, Electronics, AI&T, and Software.
- Tailor Reviews
  - Minimal formal external reviews (SRR, PDR, CDR, etc.), <u>only those that the customer wants.</u>
  - Use tabletop reviews with SMEs, pushes progress and keeps team headed in the right direction (successful for Pearl Telescope and ESC/WCC).
- Use the synergy with the other Instruments and Telescope Teams to our advantage.
- Communications
  - Due to geographical diversity (only 1 time zone between Tucson and SSL) use Teams & Slack to keep communications timely.
  - Regular f2f meetings for the groups. Plan less frequent f2f for entire team.
- Minimize documentation
  - Only the required procedures and reports to document the work (final optical & mechanical design, thermal analysis, AI&T plan/results, etc.)
- Configuration control only final design documentation/drawings. Changes require cognizant engineer, SE and PM approval.
  - SOEDMS and SharePoint for repositories and document share.
- No Safety & Mission Assurance (SMA) effort will be applied to the effort. The only way to deliver the IFS at the price point.
- Issue tracking with GitLab.

Program Management Schedule & Costing

- Schedule
  - Use MS Project
  - Detail WBS to Level 3 using bottom-up approach with input from discipline leads.
  - Iterate on task duration and resource allocation to ensure delivery early in 2026.
  - Forms baseline schedule for Flight System Phase.
  - Re-assess and update task progress on a weekly basis to catch issues early.
- Costing
  - Study Basis of Estimates
    - Excel spreadsheet containing labor rates and estimated hours.
    - Where practical, get ROMs from vendors on major hardware. Use costs from similar recent projects and/or engineering experience in case we are unable to get firm estimates during the study period.
    - Both institutions have extensive capabilities so we will perform cost trades between the institutions to get best price for engineering/fabrication/AI&T tasks.
  - Monthly Risk Management Assessment to form robust risk register and to inform the Project of cost and schedule liens as well as any opportunities.
  - Track costs monthly based on actuals/projections to minimize chance of overruns.
  - Update ROM costing as firm quotes become available.

Instrument Excellence

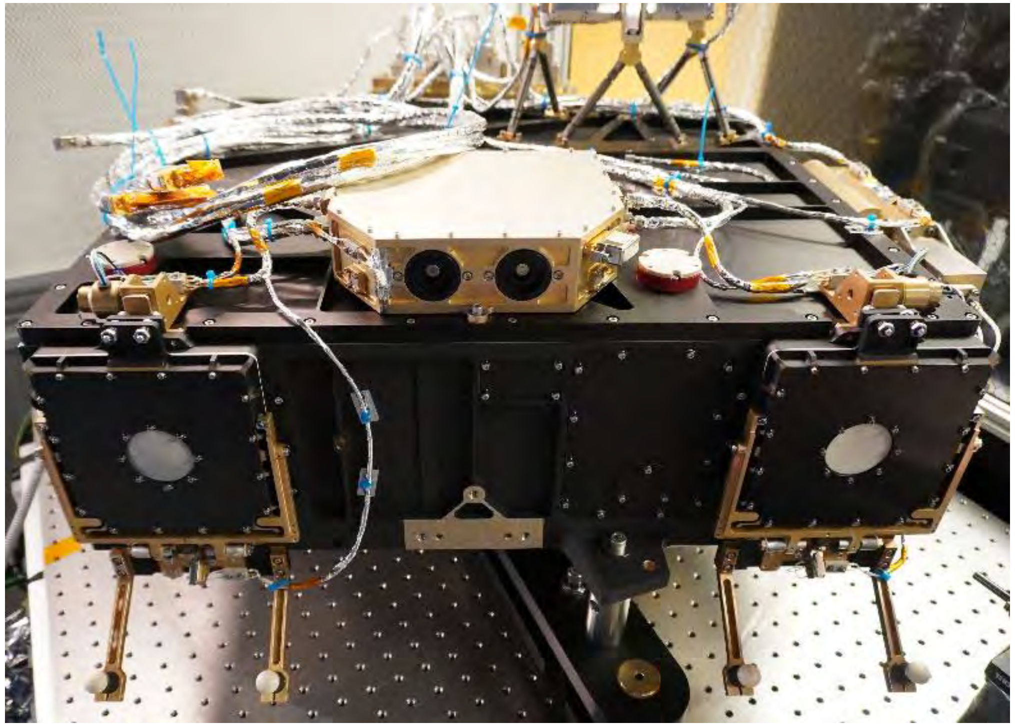
- UCB/SSL
  - UCB-SSL has contributed to more than fifty NASA missions since its inception in 1958.
  - This includes seven PI led explorer class missions: COSI, ICON, THEMIS, RHESSI, FAST, CHIPS, and EUVE.
  - The engineering staff at SSL has extensive experience in developing and delivering spaceflight instruments over a wide range of costs and complexity, from CubeSats to Flagship Missions.

- UA
  - UA led both the James Webb Space Telescope (JWST) Near Infrared Camera (NIRCam) project and the OSIRIS-REx mission.
  - For NIRCam UA was ultimately responsible for providing the flight packaging, testing, and optimizing the camera's Teledyne HAWAII-2RG IR detectors (ten H2RGs for flight) along with their SIDECAR ASIC readout electronics.
  - UA has similarly been testing and characterizing mid-IR H2RG detectors for the NASA NEO Surveyor to launch in 2027.
  - Further relevant to the Pearl IFS instrument, team members previously led the development of the LMIRcam instrument on the Large Binocular Telescope Interferometer, which utilizes a microlens IFU and selection of magnifiers (known as the ALES instrument mode) within an all-reflective optical design to provide R=20-100 spectral resolution over the 3 – 5 microns wavelength range (H2RG detector operated with SIDECAR ASIC and MACIE controller), sitting behind a pair of high-performance adaptative optics systems on twin 8.4-meter mirrors.
  - UA has a long history of supporting space missions including using the Kuiper 61" on Mt. Lemmon to scout moon landing locations for Apollo 11 up to and including, providing key instruments for NASA's flagship missions Hubble, Spitzer, and JWST.

The next slides highlight projects which had direct involvement and engineering leadership provided by members of the Pearl IFS team.

Carruthers Geocorona Observatory

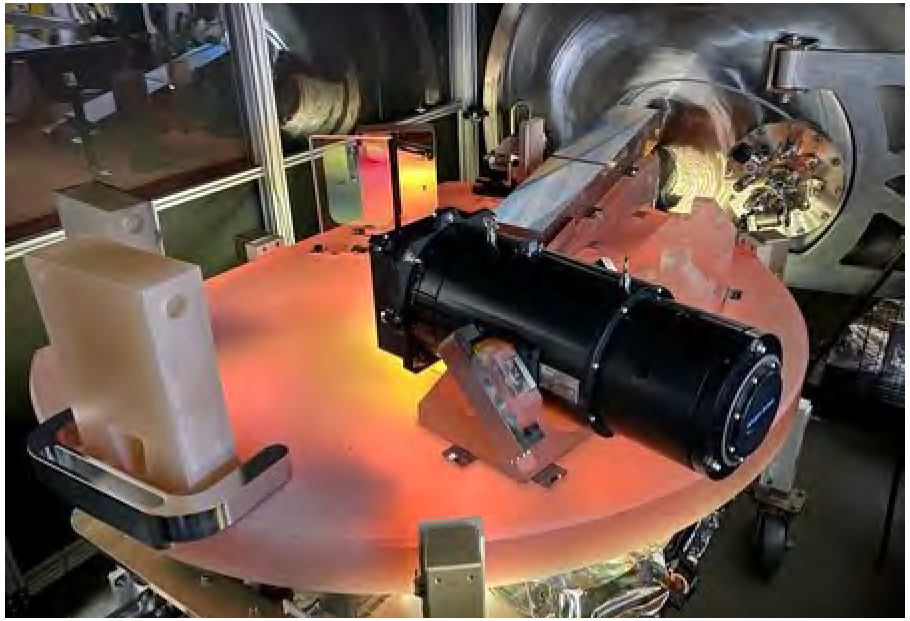
- NASA heliophysics MoO rideshare with IMAP to Earth/Sun L1.
  - Class D, $75M PIMMC.
  - Expected to launch in mid-2025. SIR scheduled for December 2023.
- UCB/SSL provides overall PM, PSE, SMA, Mission Ops and Geocoronal Imager (GCI) payload.
- UCB/SSL contributions for the GCI:
  - Instrument management / systems engineering
  - Optical design and opto-mechanics
  - MCP image intensifiers (x2)
  - Deployable door mechanisms (x2)
  - Payload electronics & FSW – Instrument Control Package (ICP) and stepper motor driver (SMD) electronics
  - Payload AI&T

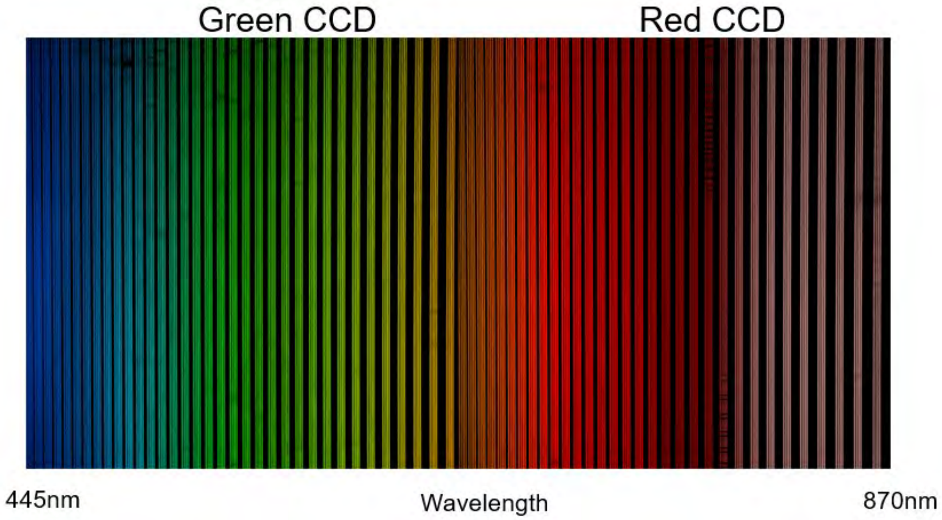


Instrument Excellence - KPF

Keck Planet Finder (KPF)

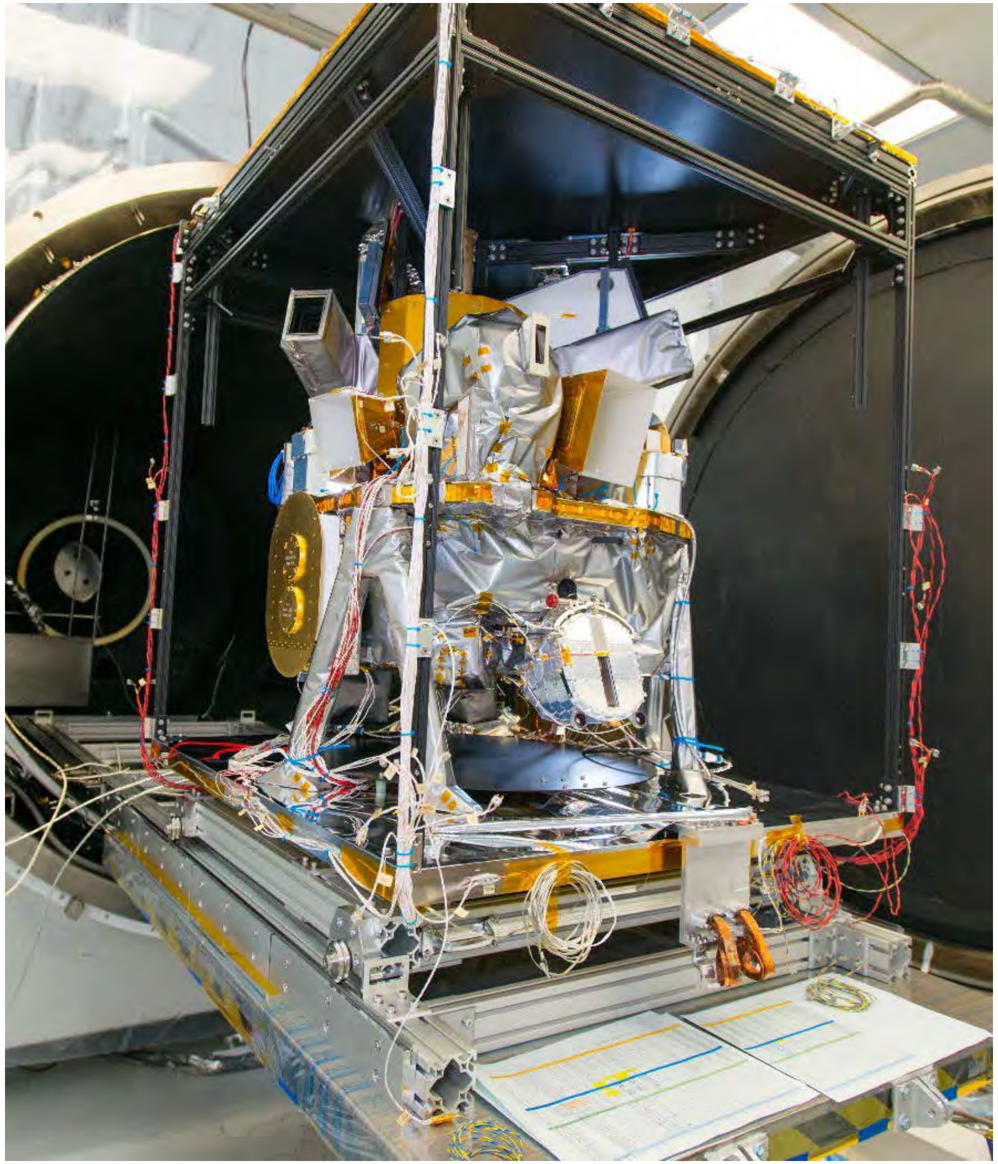
- First of its kind extreme precision radial velocity (ePRV) spectrograph.
  - $22M Keck facility class instrument. Funded ~60% by private foundations, remaining through NSF MSIP.
- Delivered to Keck in August 2022; performing routine science since March 2023.
- UCB/SSL contributions to KPF:
  - Instrument management / systems engineering
  - Spectrograph optical design and opto-mechanics
  - CCD detector cryostats (x2)
  - Optical fiber system
  - Calibration bench that interfaces with lamps, LFC, and Fabry Perot Etalon
  - Instrument AI&T/Calibration at UCB/SSL
  - Assembly and alignment of the IFU
  - Led installation effort at Keck observatory





Ionospheric Connection Explorer (ICON)

– NASA heliophysics explorer class mission.
  - Class C, $175M PIMMC.
  - Launched into low inclination LEO orbit in Oct 2019
– UCB/SSL provided overall Science PI, PM, PSE, SMA, Mission Ops and Payload implementation
– UCB/SSL contributions to the ICON payload:
  - Payload management / systems engineering for six instruments.
  - Far Ultraviolet (FUV) spectrographic imager
  - Extreme Ultraviolet (EUV) spectrograph
  - Payload electronics & FSW – Instrument Control Package (ICP) and stepper motor driver (SMD) electronics
  - Payload thermal design



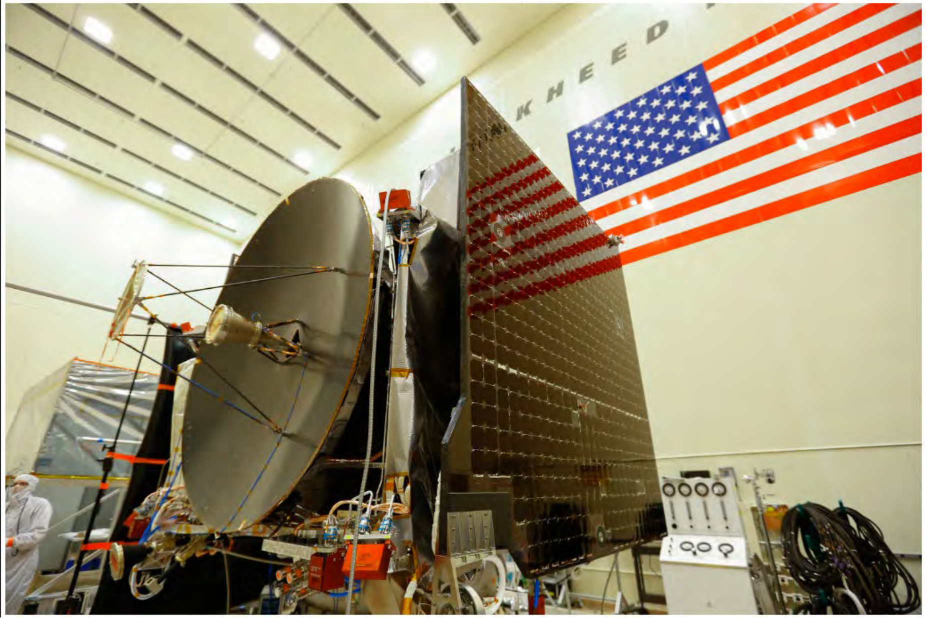
Instrument Excellence – OSIRIS-REx

OSIRIS-REx Asteroid Sample Return Mission

*(**O**rigins, **S**pectral **I**nterpretation, **R**esource **I**dentification, **S**ecurity-**R**egolith **Ex**plorer)*

- $250M+ Mission managed by UA, Ops Planning Lead, Science Team Lead and Data Processing.
  - Launched September 8, 2016
  - Sample return: September 24, 2023
  - *Continuing Mission APEX (OSIRIS-APophis Explorer)*
- Responsible for OCAMS camera suite.
  - Performed design, fabrication, AI&T on OCAMS.
  - Responsible for flight Software.
- Demonstrates capabilities to build a robust system.

Photographer: Robert Markowitz

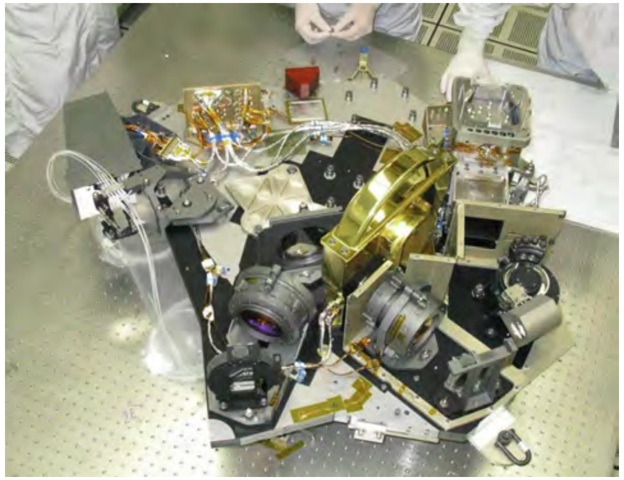


Credit: Lockheed-Martin

Instrument Excellence – NIRCam

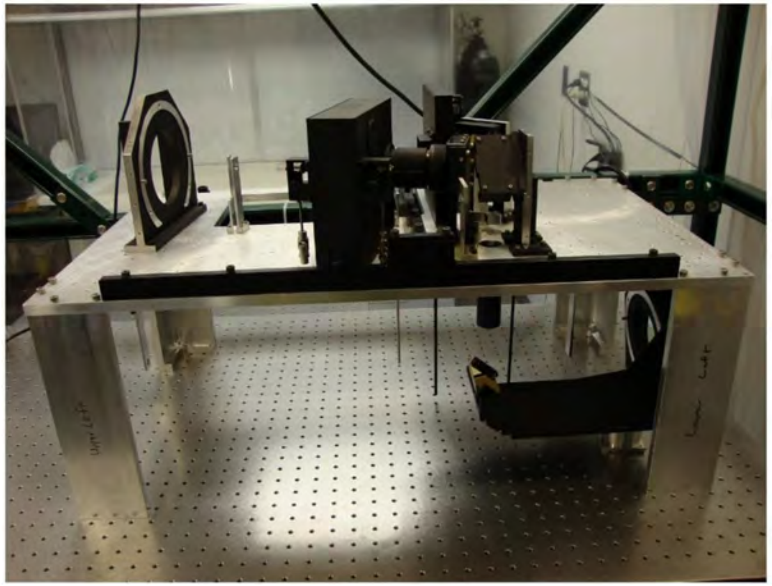
- James Webb Space Telescope (JWST) Near Infrared Camera (NIRCam)
- $500M+ Mission managed by UA
- Launched: December 25, 2021
- UA currently responsible for the on-orbit commissioning.
- For the instrument UA was ultimately responsible for providing the flight packaging, testing, and optimizing the camera's Teledyne HAWAII-2RG IR detectors (ten H2RGs for flight) along with their SIDECAR ASIC readout electronics.

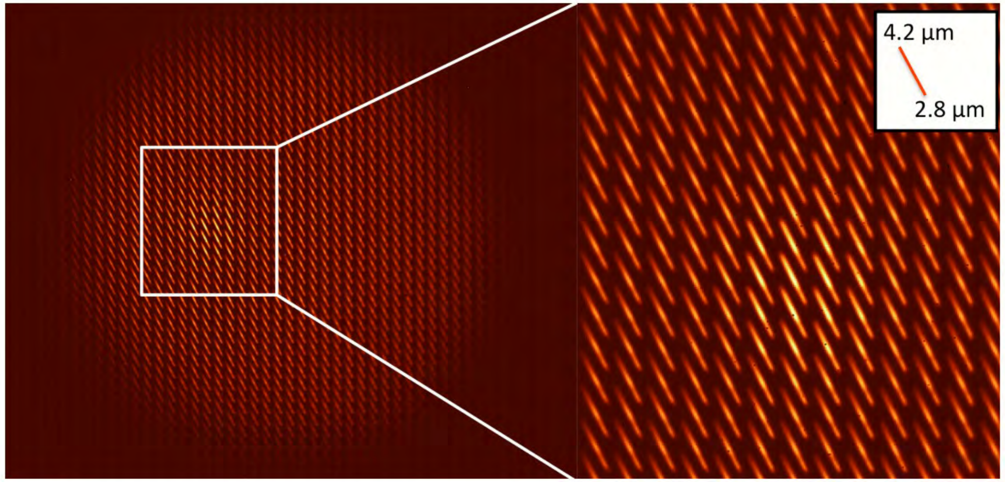
Credits, Image: NASA, ESA, CSA, STScI, Klaus Pontoppidan (STScI)
Image Processing: Alyssa Pagan (STScI)



LMIR CAM

- The L- and M-band Infrared Camera (LMIRcam) for the Large Binocular Telescope (LBT).
- Ground based instrument led by UA and collaborated on with the University of Virginia and the University of Minnesota.
- Funding provided by the NSF.
- First Light June 2015.
- It utilizes a microlens IFU and selection of magnifiers (known as the ALES instrument mode) within an all-reflective optical design to provide R=20-100 spectral resolution over the 3 – 5 microns wavelength range.
- H2RG detector operated with SIDECAR ASIC and MACIE controller, sitting behind a pair of high-performance adaptative optics systems on twin 8.4-meter mirrors.





ALES mode First Light (Skemer et al., June 2015)

Development Plan

- The development plan is to continue with smaller based internal reviews during the Flight Study Phase. We will use table-top reviews with SMEs to inform our design choices.
- Early in the design phase we will start our Long Lead procurements, specifically the development of the MACIE firmware porting to the Zync FPGA.
- After finalizing the reviews, we will start to receive quotes on nominal lead items and move into fabrication.
- The FPM work will proceed in parallel at UA while the other components are built and tested at SSL.
  - FPA work will start with the MACIE boards we have available as we wait for ported firmware.
  - Testing on the engineering FPA will occur as EDU detector arrives. The engineering FPM will be built up and then shipped to SSL once the FDU arrives for form/fit/function.
  - In parallel the flight FPM will be tested and characterized before shipping to SSL for final integration.
- Final integration and testing will then be performed at culminating with final delivery to UA for final integration into the instrument package.
- The team will support the integration and final alignment in the telescope as needed. The post delivery support is beyond the scope of this study.

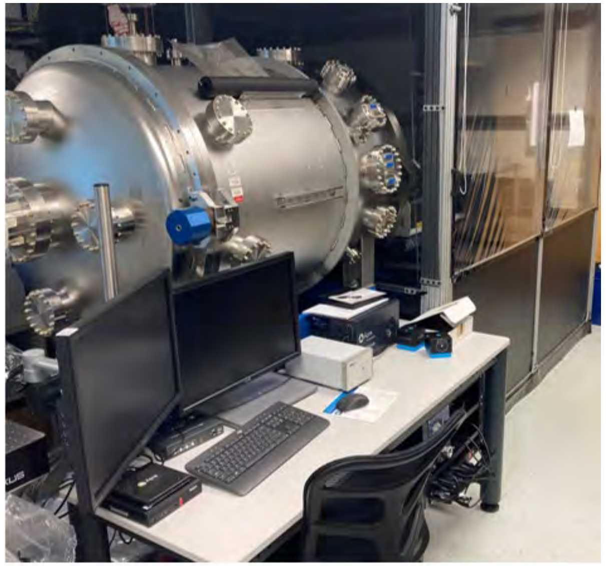
13. FACILITIES AND AI&T

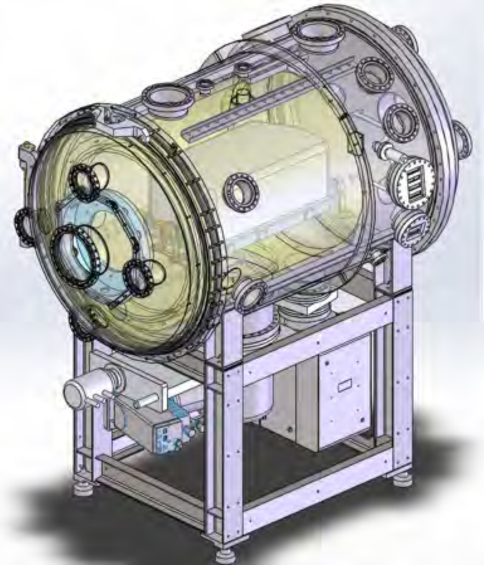
UA Facilities

- Az Detector Lab
  - Equipment, and technical staff for the handling, testing, characterizing, and packaging of detectors.
  - Well-equipped, state-of-the-art detector laboratory established for characterization of the HAWAII-2RG SCA's developed NIRCam.
  - Class 10,000 cleanroom with a Class 100,000 anti-chamber and HEPA filtration system.
- Machine Shop
  - Shop specifically equipped for the fabrication of astronomical instruments, laboratories for assembly and integration.
- Assembly and Testing
  - Steward Lab houses 1m diameter x 2m long thermo-vac chamber for environmental testing
  - Applied Research Building (ARB)
    - Houses a 3m diameter x 6m long TVAC large enough to test the fully integrated Pearl instrument suite if that is required.
    - Houses lab and clean room space with 2500 sq. ft. dedicated to Pearl instruments.

SSL Facilities

- Addition 325 Optics Lab
  - Equipment and technical staff available for assembly, alignment, and vacuum characterization of opto-mechanical systems (115nm – 3 um).
  - Class **<u>100</u>** assembly cleanroom with precision cleaning area, GN2 dry-boxes, NVR monitoring, and high vacuum bakeout chambers.
  - 1m diameter x 1.5m long calibration chamber with TVAC capabilities.
- Technician Resources
  - SSL machine shop is used for fabricating our most difficult flight parts. Machinists are trained to handle and prioritize flight parts that may even need modifications in place during AI&T.
  - Cable & PCB assembly technicians trained and certified to JPL flight standards.
- Additional technical facilities
  - Subassembly vibration testing on SSL shaker table
  - Three flight TVAC chambers that can be used for subassembly up to instrument level testing. Dedicated chamber personnel available to execute tests.
  - Two additional class 10,000 assembly cleanrooms with class 100 flow benches.





Pearl IFS within SNAP focal plane TVAC chamber

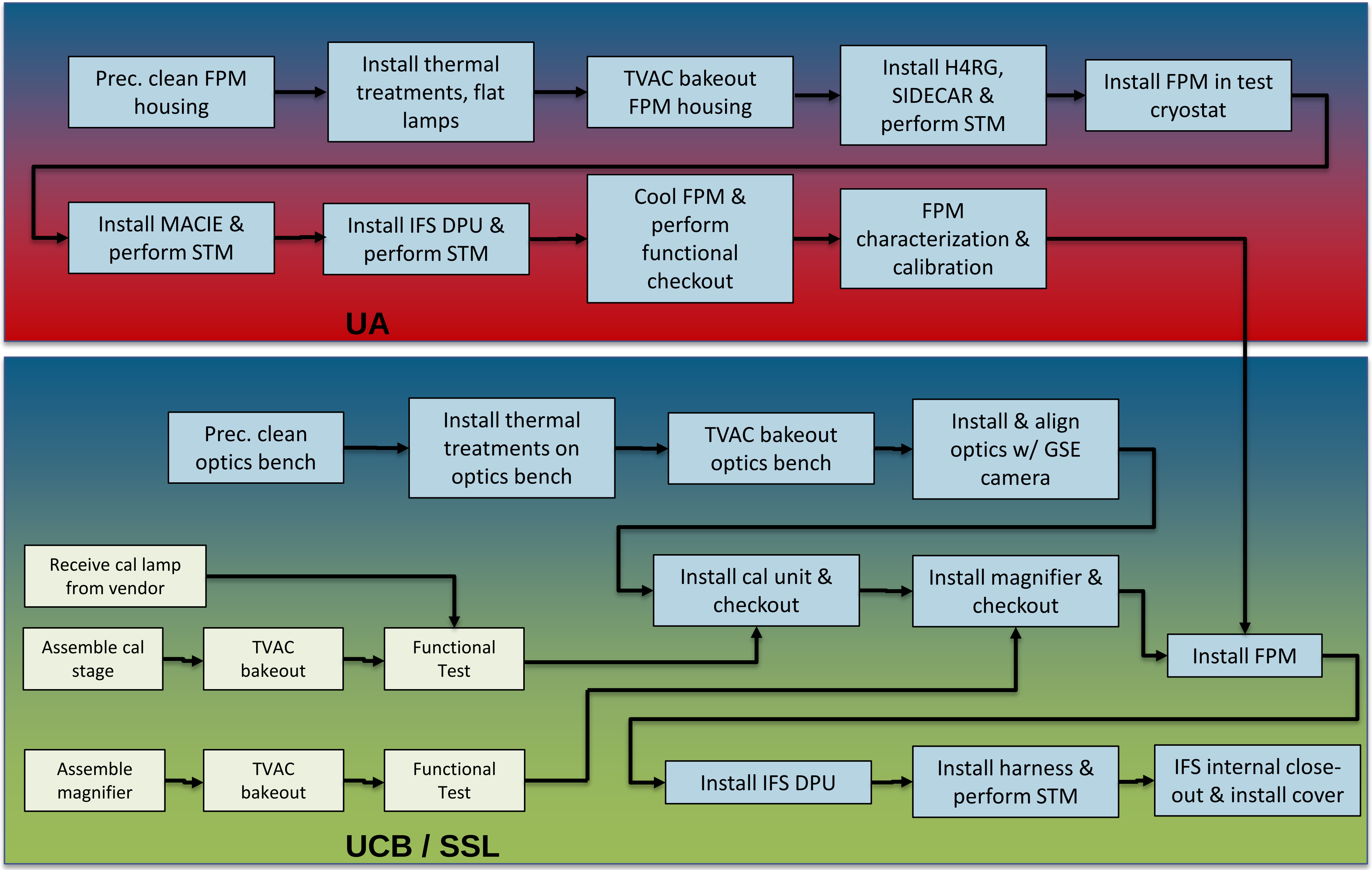
IFS Instrument AI&T Approach

- IFS assembled and aligned at SSL, while FPM work occurs in parallel at UA.
  - Develop an instrument alignment plan that allows for late integration of the FPM. Instrument level env. testing will occur ASAP after FPM delivery to SSL.
- We assume that minimal environmental testing is done at the integrated payload and observatory levels.
  - Observatory: Acoustics (TBD), No TVAC.
  - Possibly P/L level TVAC. Team holding this as an opportunity to de-scope instrument level thermal balance (save on cost & schedule).
- Develop EM/qual units for new designs, qualify to proto-flight levels…. Avoid over-testing of the FM instrument!
  - Assume there is no CLA cycle that provides realistic loads for the instrument. Team plans to be strategic about where PF level dynamics testing occurs.

FM Subassembly Integration and Test

- Optics
  - Interferometric surface figure measurements of optics pre and post mounting.
  - Reference optic to mount with alignment GSE prior to IFS integration (see alignment plan).
- FPM
  - Vacuum Bake-out of the housing, Detector calibration & characterization at UA.
- Mechanisms
  - Integrate, then vacuum bake-out certification.
  - Functional test & characterize performance pre-delivery.
- Structures
  - IFS structures are machined and plated alloys, precision cleaned at SSL.
  - Bench and cover will undergo a vacuum bake-out certification test at SSL post thermal treatment installation (heaters, thermistors, tapes, paints).
- IFS Electronics
  - Vacuum Bake-out, 8 TVAC cycles at vendor/partner. Functional test & characterize performance pre-delivery.
- Harness
  - Vacuum Bake-out

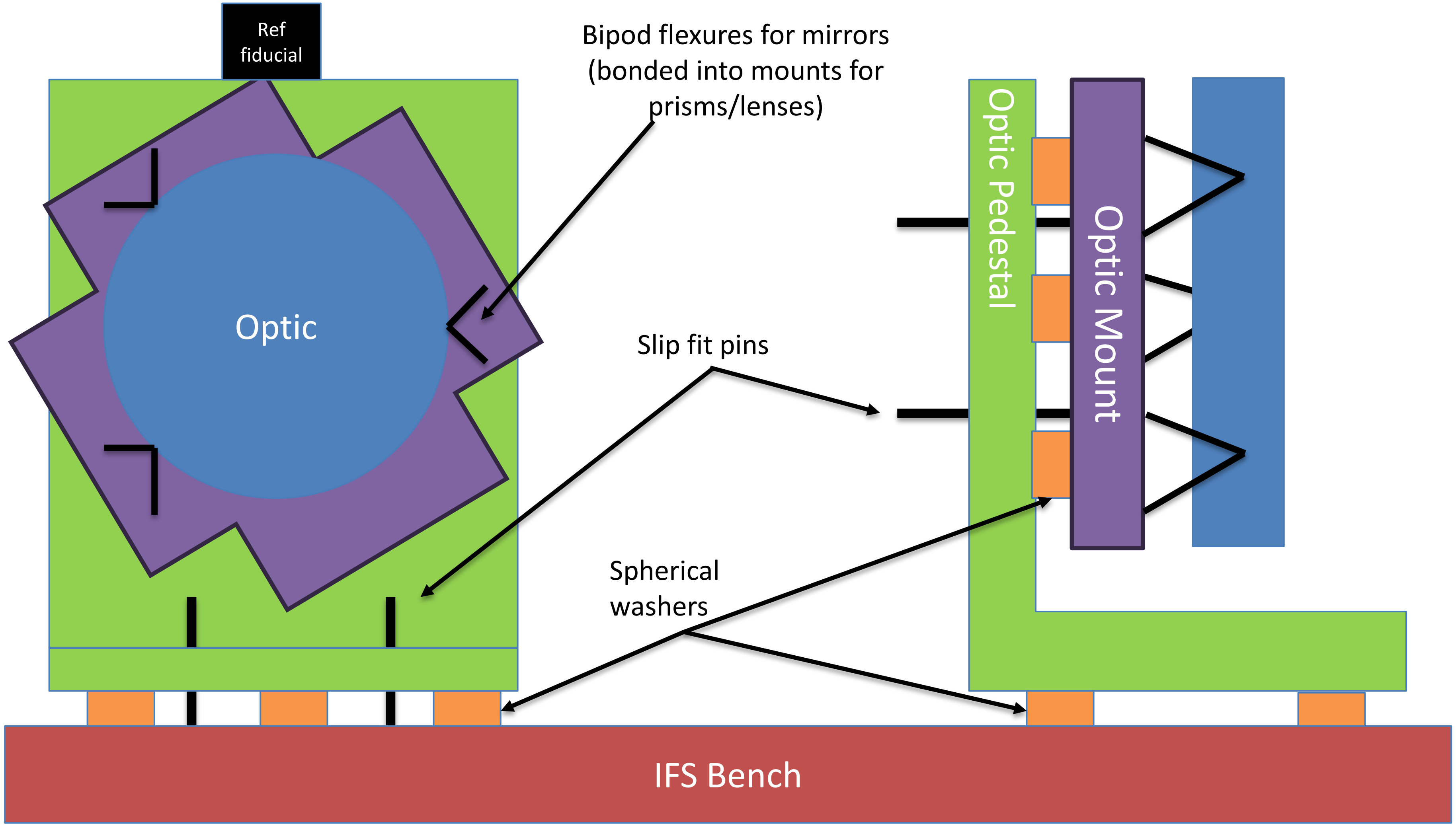
IFS Build Flow



IFS Alignment Plan

- Adopt a "Deterministic" alignment approach that uses mechanical fiducials tied to the individual optic axes:
  - Align optics to their mounts using alignment fiducials (tooling balls, SMRs, alignment cubes, etc.).
  - Integrate optics onto bench, rely on precision metrology (laser tracker) to locate in the nominal position/orientation. Tie all optics to a common coordinate bench coordinate frame (IFS-Frame).
  - Verify spectrograph performance where feasible prior to integration of the H4RG.
- Alignment approach successfully executed for similarly toleranced off-axis systems, both for space and ground-based instruments.
- In vacuum alignment at temperature provides final verification prior to flight closeout of the optics.
  - OGSE simulates Pearl Telescope f/# and PSF provided to the spectrograph (TelSim). TelSim will be fed with various source inputs: Monochromator, broadband continuum, and arc lamps.
  - RT to operational temperature offsets will be compensated using pre-determined shim sets. If image quality is not as expected, we will break vacuum and replace the shim (no active alignment planned in vacuum).

Generic Optic Sub-Assembly



Heritage Flight Mirror Sub-Assembly

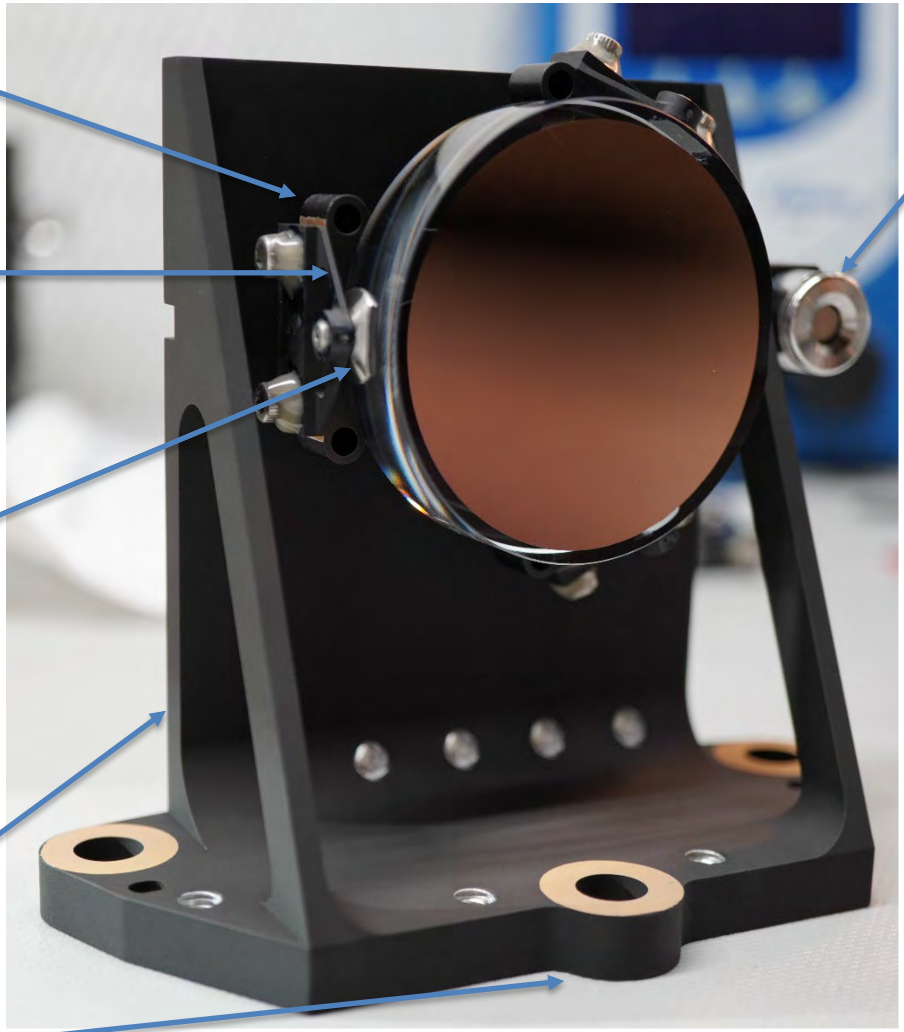
Optic mount

6061-T6
Bipod Flexure

Invar-36
Bond Pad

Optic Pedestal

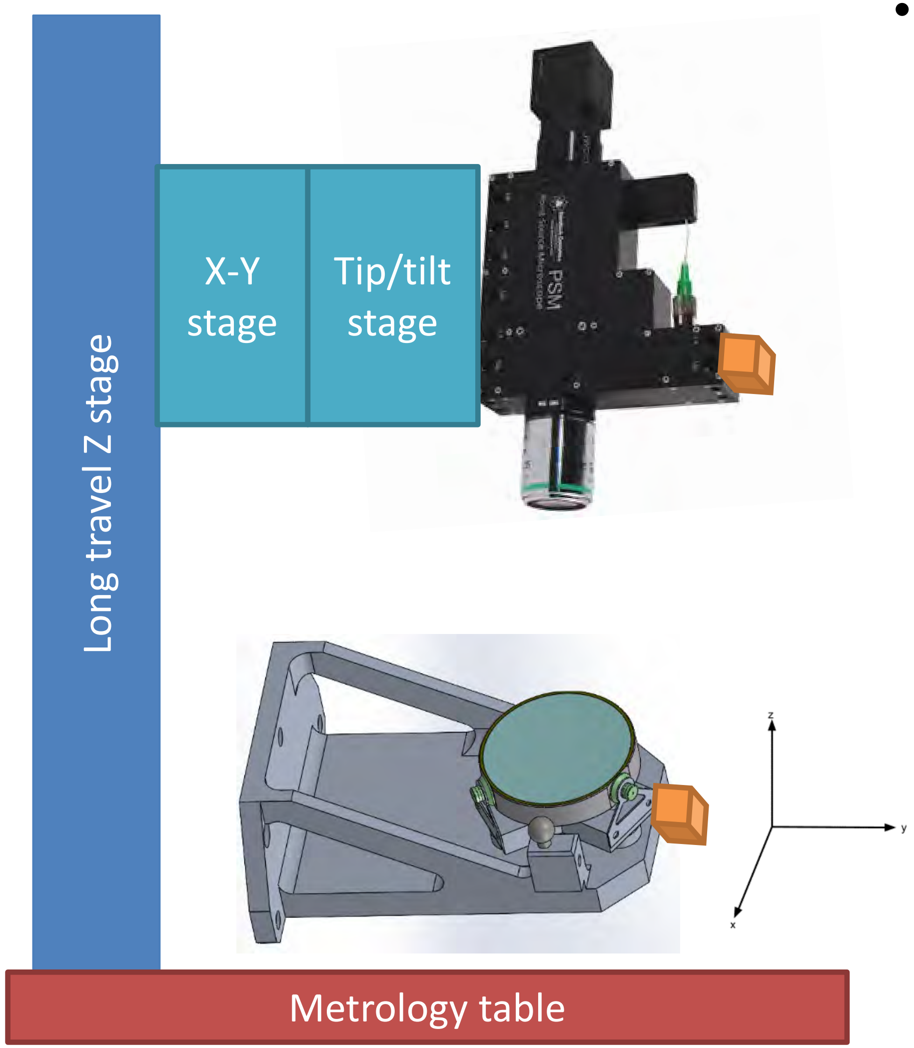
Concave spherical washer feature milled into feet (not shown in this view)



Magnetic nest for SMR/Tooling ball placed parent optic vertex

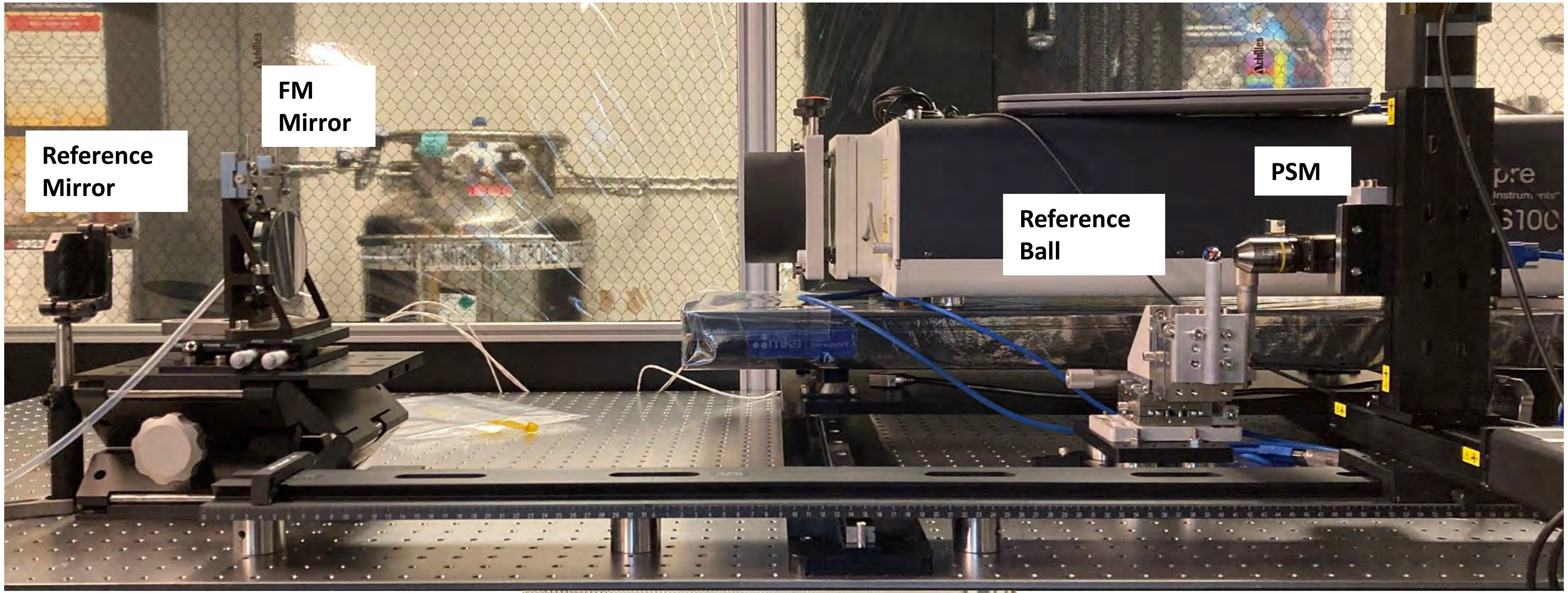
Not applicable here, but an example of a reference fiducial integral with the pedestal. (RBF!)

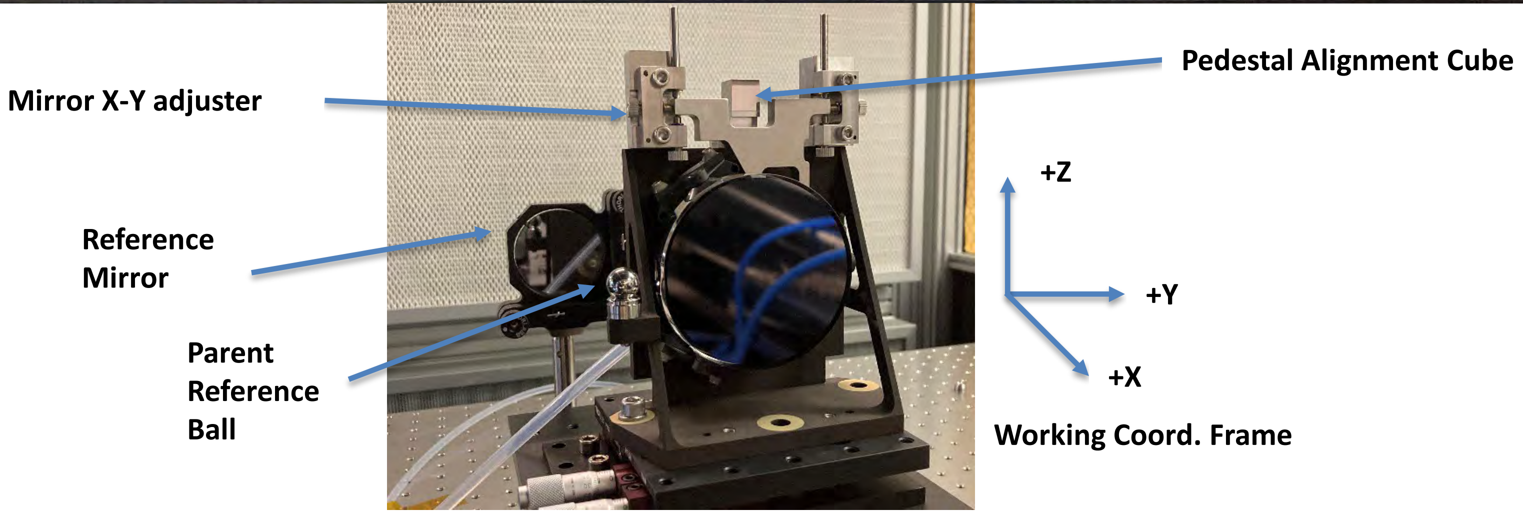
Optic to Mount Alignment (Mirror)



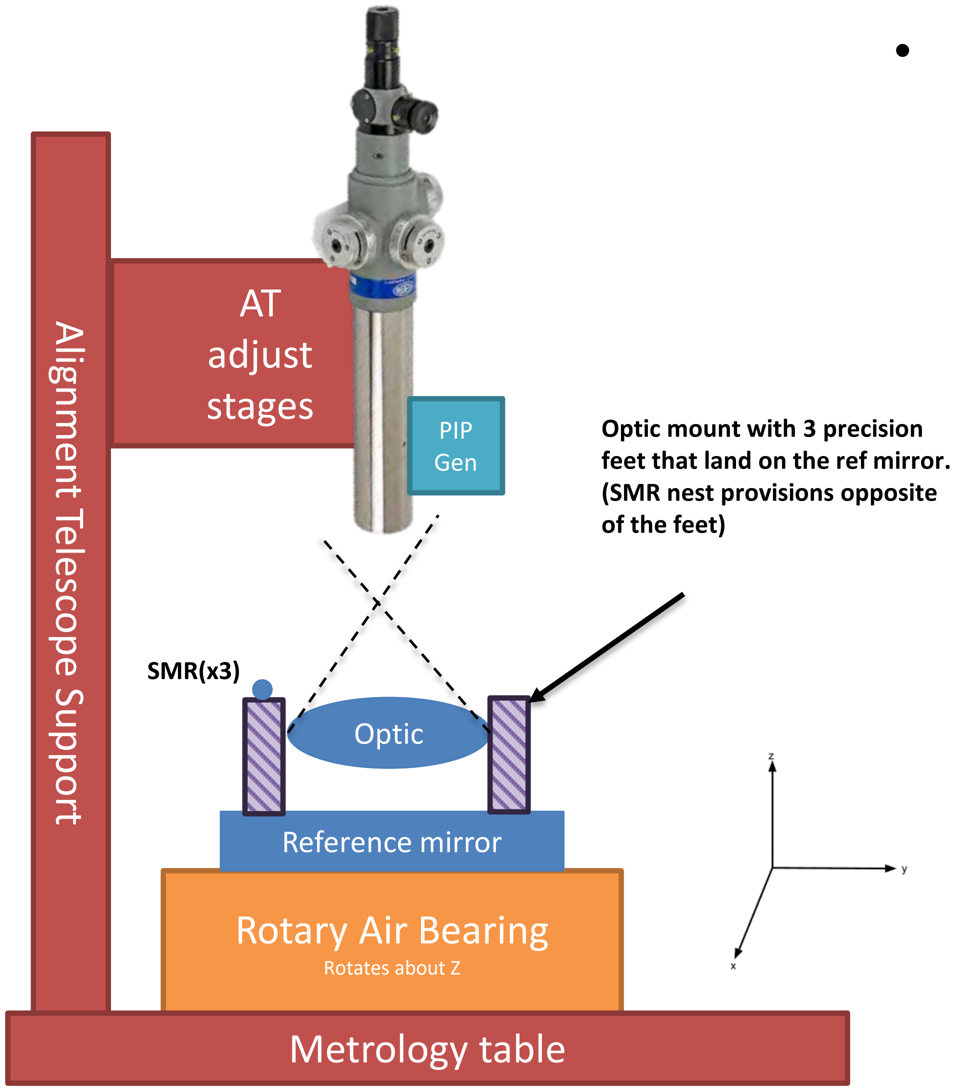
- Mirror Alignment Recipe:
  1. With objective removed, align PSM to XY face of the pedestal reference cube (via tip/tilt stage)
  2. Install objective, translate PSM (Z, then X & Y) until a return is produced by tooling ball.
     - PSM is now aligned to bracket in 5 DoF.
  3. Translate PSM in Z to center of optic (or parent) RoC.
     - Double check PSM X/Y/Z & tip/tilt w tracker
  4. With optic mount attachment fasteners loose, adjust optic in X/Y until a return is produced by the tooling ball.
     - Assume high thread count nudger screws/spring plungers are located radially around the optic.
     - Zemax analysis will inform aberrations (coma, astigmatism, defocus). This will tell us what adjustments need to be made in step 5.
  5. Adjust tip/tilt and/or focus using shims.
     - Iterative process using Zemax as the check. GSE shims used for alignment iterations. Need to develop plan for final shim design (lapping or flight ring shims?)

Example Alignment Setup (Mirror Sub-Assy)

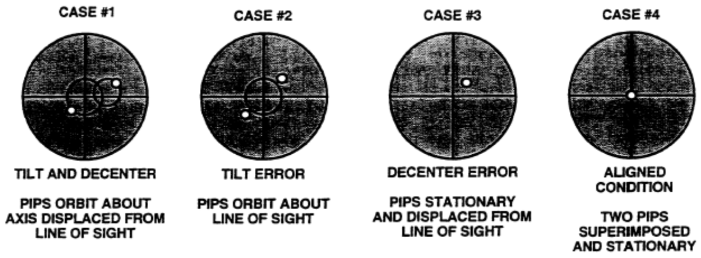




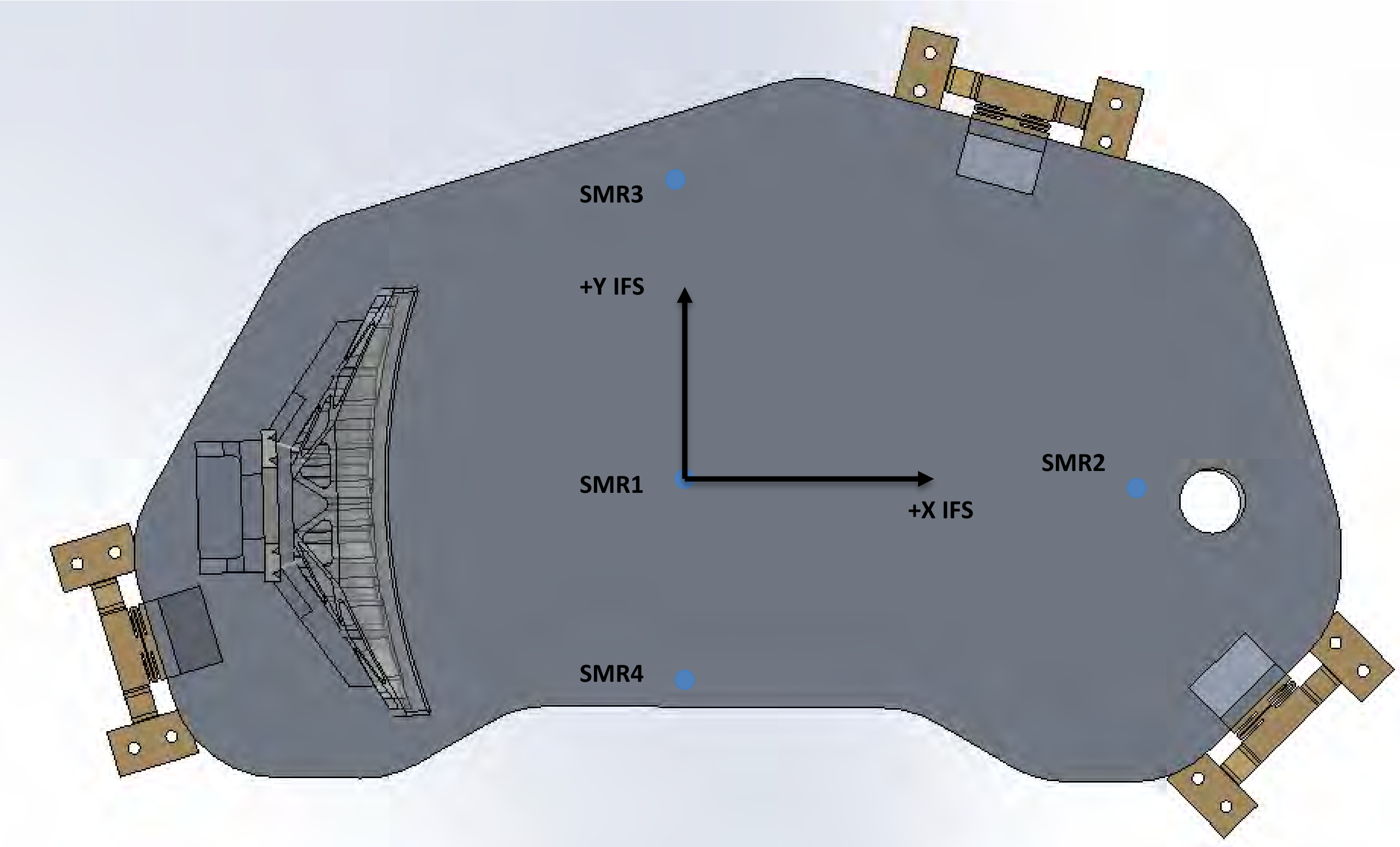
Optic to Mount Alignment (Tx Element)



- Tx Element Alignment Recipe:
  1. Set alignment telescope (AT) focus to ∞. Align reference mirror to AT while rotating the air bearing.
  2. Install FM optic and mount onto reference mirror/air bearing setup
     - Assume high thread count nudger screws/spring plungers are located radially around the optic.
  3. Using the PIP generator, adjust AT focus until first surface return is observed.
     - Note that S2 of the prisms can't (and won't) be easily checked (due to dispersion + beam deviation).
  4. Adjust tip/tilt/decenter using GSE nudgers. Rotate air bearing until minimized PIP deviations are observed.
     - Iterative process using Zemax as the check.
  5. Bond optic to mount. Verify alignment by repeating step 4 during curing.



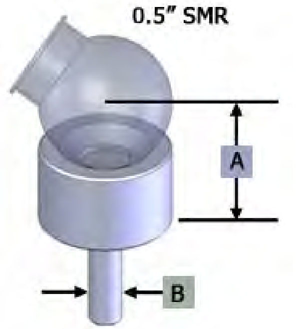
IFS coordinate frame definition



- Origin located at M1-M3 focus
- +X points away from mirror along M1-M3 axis towards SMR2
- +Z defined by bench plane (best fit of 4 SMRs)
- +Y completes RHR definition

SMR nest considerations (for IFS bench)

- Propose using four ½" SMRs with shanked nests – requires reamed holes in the bench.
  - Fourth SMR gives better plane fit, easier to determine outlier measurement (if any).
  - Shank diameter from 0.1" to 0.25" or greater.
  - Ream hole to 0.0005" over → nests repeat quite well.



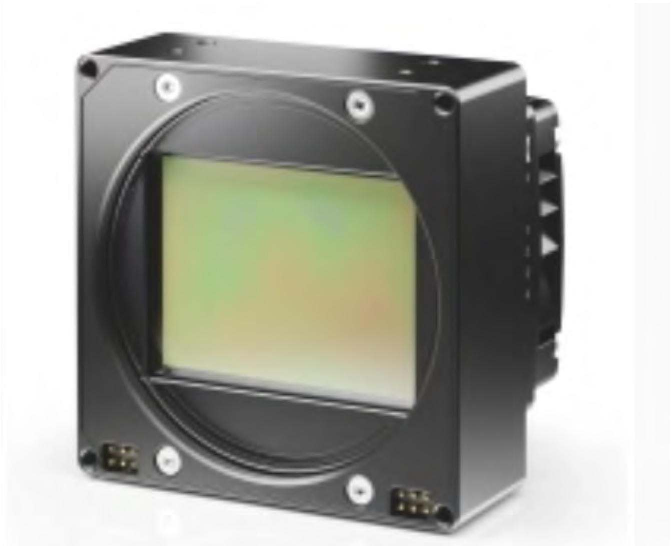
Shank dia.	B
0.100"	.1
1/8"	.125
5/32"	.156
3/16"	.1875
1/4"	.25
9/32"	.2812
5/16"	.3125

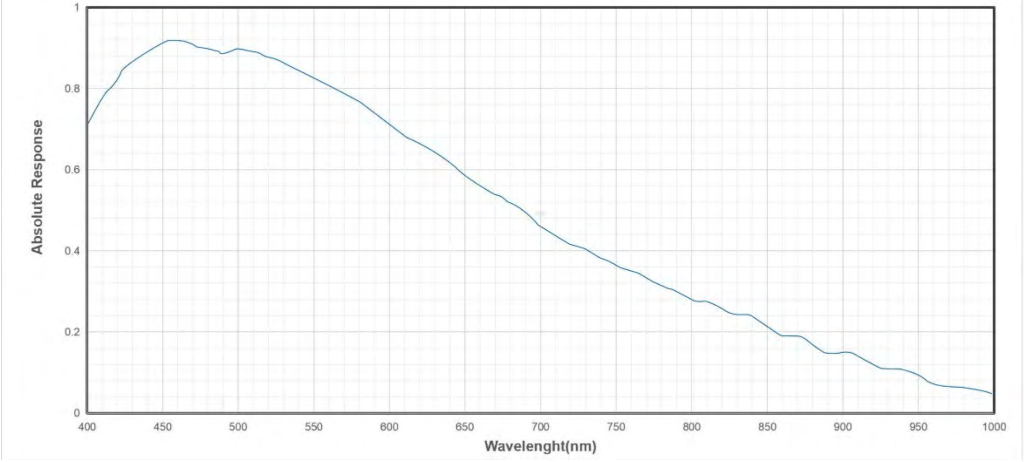
- Alternate method would be to use drift nests – no bench machining required.
  - Kapton tape applied to bench surface, nest filleted with EA9394 to tape surface.
  - Less accurate in terms of absolute placement.
  - Repeatability can be an issue, busy work areas result in bumped (or lost) nests. ☹

Optic Installation / In Air Alignment Steps

1. Establish IFS coordinate frame using SMRs and Laser Tracker (LT)
2. Setup PSM at SMR1 focus; replace SMR with tooling ball and align PSM in X/Y/Z to ball center.
3. Install M1/M3 mirror & locate nominal position with slip fit pins. Remove tooling ball at SMR1 location and verify M1/M3 focus at PSM focus. Adjust as necessary
   – Sets the first optic position co-incident with the coordinate frame.
4. Install M2 & locate with nominal position with slip fit pins. Verify position/orientation in IFS-frame using the LT. Adjust as necessary.
5. *Perform optical check of the Offner relay in double pass*
6. Repeat step 4 for the transmissive elements.
7. Install fold mirror and verify plane position/orientation in the IFS-frame using the LT.
8. Install GSE camera, verify coarse alignment with fibers positioned at the telescope FP.
9. Install magnifier.
   – TBD what/if any metrology is done before this step.
10. Align IFS to Telescope Simulator

GSE camera considerations



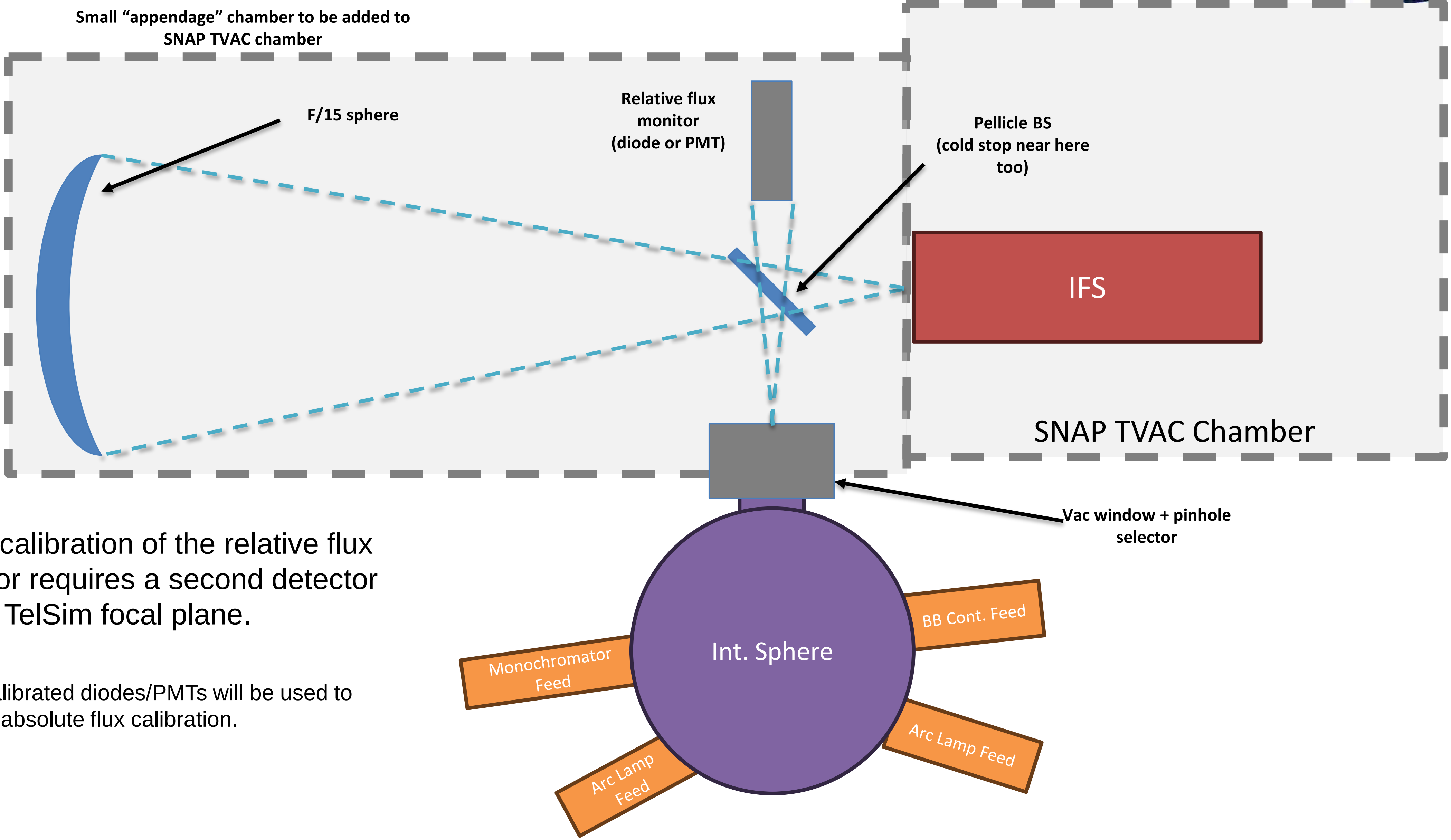


QE is an issue out to 1.7 um. Ok for prelim initial alignment checks before EM H4RG arrives (and easier to use in air in the lab……)

Specifications:

Part Number:	MX1510MR-SY-X4G3
Resolution:	151 MP 14192 x 10640
Frame rates:	6 Fps at 12 bit, 4.6 Fps at 14 bit, 2 Fps at 16 bit
Sensor model:	Sony IMX411 ALR-C
Chroma:	Monochrome B/W
Sensor type:	CMOS BSI - Backside illuminated
Sensor size:	Medium format (Type 4.2)
Sensor active area:	53.36 x 40.01 mm (Diagonal 66.7 mm)
Readout method:	Rolling shutter
Pixel size:	3.76 µm
Digitization:	16, 14, 12, 11 bit
Data interface:	PCI Express Gen3 x4 (PCIe)
Dynamic range:	80 dB
Full Well Capacity:	50 000 e-
On-chip binning:	1x1, 2x2, 3x3
Readout noise typ.:	1 e-
Signal to noise ratio:	46 dB
Gain range:	36 dB
Exposure range:	90µs to 12s
I/O Ports:	2IN/2OUT
Power consumption:	15 Watt
Lens mount:	M72
Weight:	455 grams
Dimensions WxHxD:	80 x 80 x 45 mm
Cooling:	Fan or Water or Heatsink

Telescope Simulator Concept



Initial calibration of the relative flux monitor requires a second detector at the TelSim focal plane.

NIST calibrated diodes/PMTs will be used to provide absolute flux calibration.

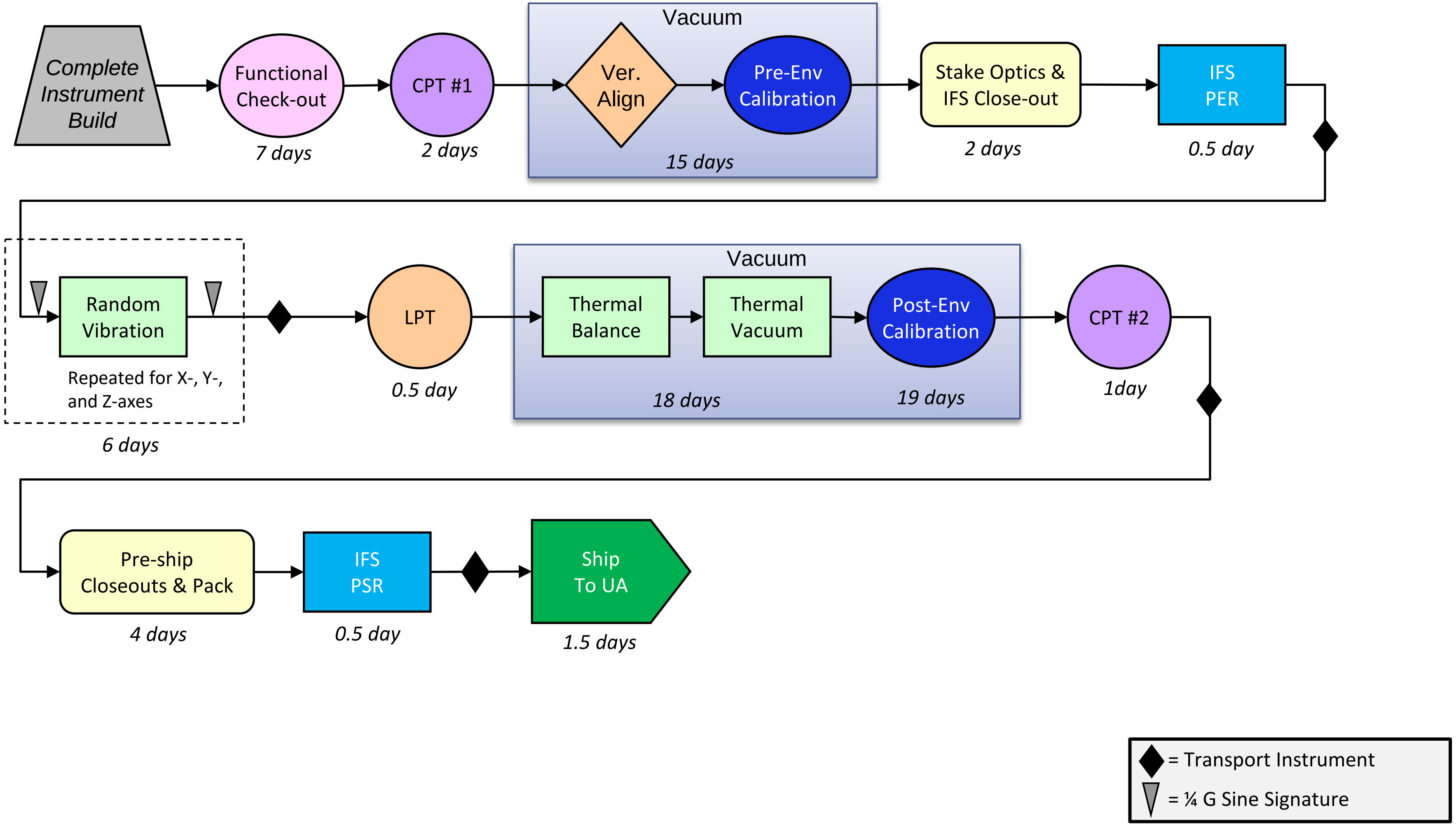
Equipment Needs

- On hand @SSL:
  - Faro Vantage S Laser Tracker
  - Point Source Microscope + Adjustment stages
  - Brunson 2024BL Alignment Telescope & PIP Generator
  - Alignment Goodies: SMRs, metrology stands, athermalized scale bars, etc.
  - Monochromator, fiber feeds, etc.
- To Buy:
  - Rotary Air Bearing
  - Alignment telescope support structure & metrology table
  - TelSim Components: optics, flux monitors, integrating sphere, lamps.
  - Appendage chamber for TelSim
  - GSE camera

Environmental Test Philosophy

- GEVS approach is employed.
- No structural hardware models for the Instrument
  - Qualification models for mechanisms.
  - Qual model optic mount and FPM housing *may* be employed for designs that have little or no spaceflight heritage.
- Random Vibration
  - IFS computer and cal lamp will be tested at the vendor
  - Deferred to Instrument level for all other subsystems
- No shock testing planned for Instrument components.
- Thermal Balance test is performed at the Instrument Level.
- Minimum of 12 TVAC cycles for electrical subassemblies.

IFS Testing Flow

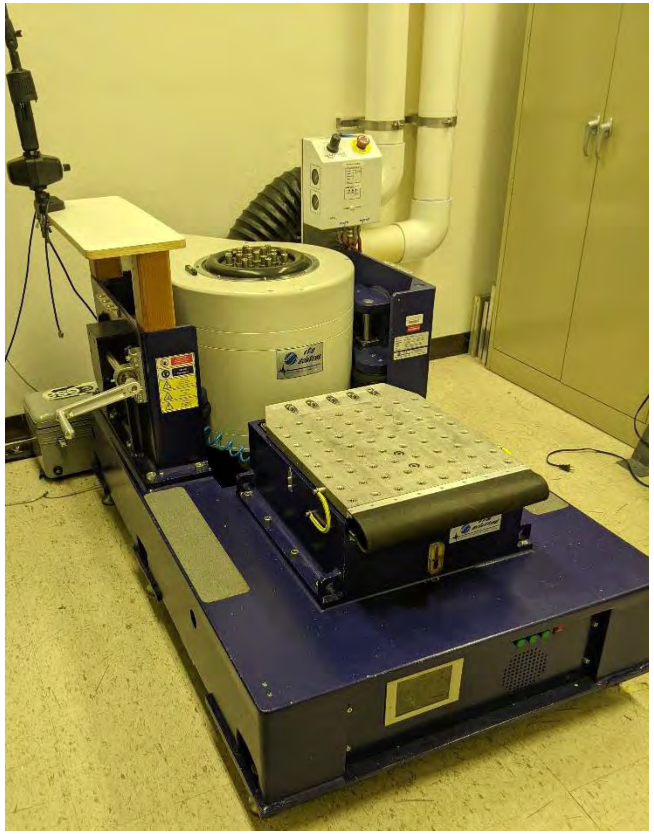


IFS Vibration Testing

- EM/Qual models see GEVS Qual level random vibration.
  - Baseline plan will be to test these subassemblies on the SSL shaker.

- In lieu of a CLA, integrated IFS will see either GEVS minimum workmanship or acceptance (TBD).
  - Open trade for instrument test location; either Quanta Labs or NTS Santa Clarita (SSL has experience with testing at both facilities).

- For all testing, Random vibration will be bookended with sine signatures to assess both mode and amplitude shifts pre-post test.



SSL Shaker Table
MTS L620M shaker 1320lbf
400mm x 400mm

IFS TVAC Test Facility

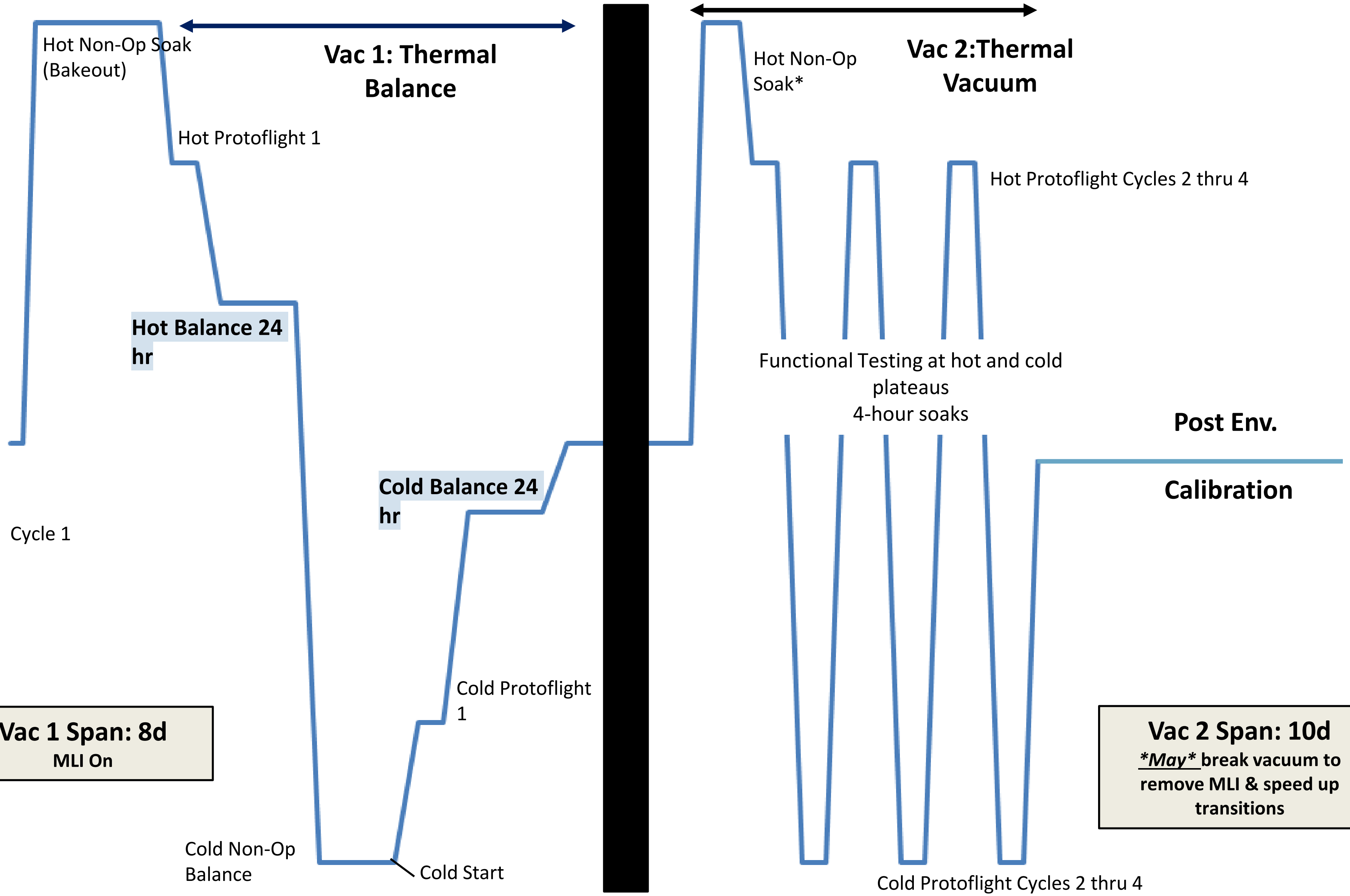
- <u>Baseline plan</u>: SNAP Focal Plane test chamber at SSL for both calibration & TVAC tests

- Chamber upgrades separately funded and expected to complete in Q1-Q2 2024 :
  - Functional checkout of chamber & pumping systems (done)
  - Installation of TQCM & RGA (done)
  - Upgrade LN2 shroud (in process)
  - Install vacuum monochromator & flux monitoring system (in process)

- Additional upgrades required for IFS:
  - Custom instrument baseplate within shroud
  - “Telescope simulator” calibration optics, source & flux monitoring in IR.
  - Additional LN2 cooling circuits (TBD)

SNAP FPM test chamber installed in A325 optics lab at SSL.

IFS TVAC test details



Vac 1 Span: 8d
MLI On

Vac 2 Span: 10d
May **break vacuum to remove MLI & speed up transitions**

IFS Ground Calibration

- Ground calibration will consist of the following tests:
  1. Determine wavelength solution for each spaxel.
  2. Radiometric performance across the instrument bandpass.
  3. Determine initial cross dispersion & line spread functions.
  4. Re-test items 1-3 above with different magnifications & simulated telescope PSF.
  5. Out-of-field stray light / baffle performance.
  6. Detector flat field, linearity, and dark current tests.
- Minimum subset of tests done as part of a pre-environmental calibration baseline.
- Subset of calibration tests will be performed at temperature during TVAC cycles.

AI&T Processes

- Develop fast and lean plan for assembly; follow ground based development approach where critical procedures are developed and reviews for complex operations and tests.
- Not every operation will be tied to paper.
- Shop orders & test plans are approved by PM/SE/Cog-E. Deviations are worked real time with input from PM/SE/I&T lead.
- Conducted tabletop reviews and TRRs for some of the critical operations and environmental tests.

Ship to UA for Payload Integration

- Optics Package Shipping
  - 2 layers ESD material, and 1 layer bagging
  - Purge and Seal
  - Temperature and Humidity Controlled Truck
  - Shock monitor
  - Custom shipping container, shock isolated interface plate
- Electronics Box Shipment
  - 2 layers ESD material, and 1 layer bagging
  - Bagged foam lined container
  - Shock monitor

Launch Site

- Ideally, IFS will be under continuous purge or vacuum. A detail to work with the project
- Bagging and RBF covers will be removed prior to encapsulation
- Inspect Instrument exterior and fairing interior prior to encapsulation

UA & UCB-SSL
PEARL IFS DESIGN STUDY
SLICER IFU STUDY

November 6, 2023

Design Study Table of Contents

1. EXECUTIVE SUMMARY

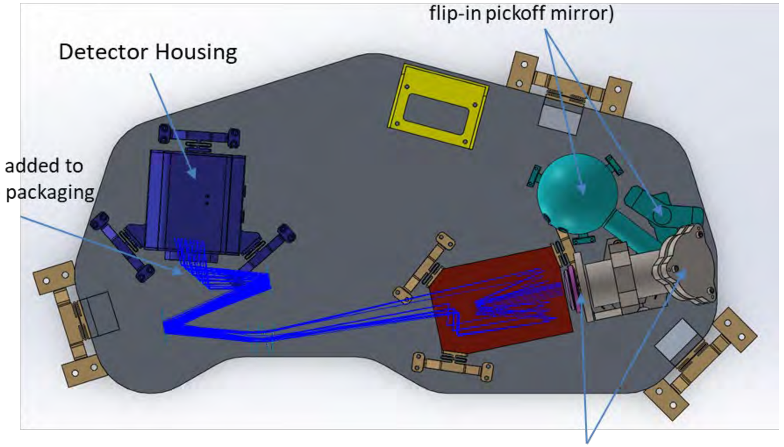
Executive Summary - Overview

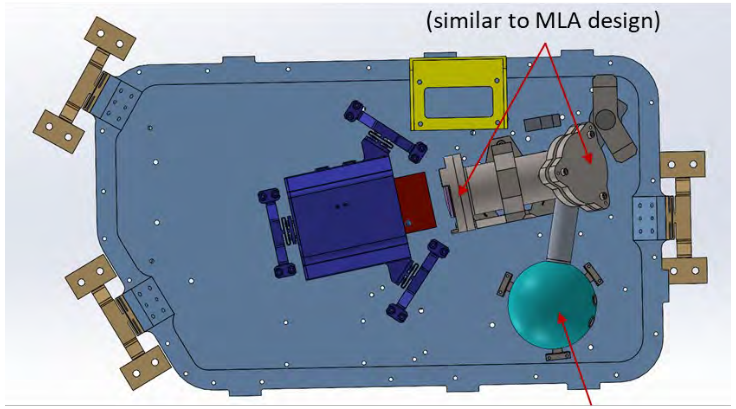
- The purpose of this document is to give the summary on the current state of the Pearl IFS Design Study with the use of a “Image Slicer Integral Field Unit (IFU)” versus the use of an “Microlens Array (MLA) IFU” in the October 23rd study documents.
- Presently we have investigated two separate preliminary slicer concepts from the ORKID-2 GFSC group based on work for WFIRST and one from Hi-Spectral LLC, based on work for DKIST.
  - The ORKID-2 group has designed a conventional spectrograph utilizing a slicer IFU. This work is being performed in collaborative manner that can be used for Pearl's needs as well as ORKID-2’s. This is a continuation of the design work that they originally conceived of for WFIRST.
  - Hi-Spectral has a very compact design that uses an integral grating that eliminates the need for additional optical elements such as a prism and additional reflective surfaces. The design is an outgrowth of an ongoing 7-week feasibility study that was funded by UA.

Optics and Optomechanical Design Summary

- The ORKID-2 design can accommodate 3 magnification scales in the slicer IFU and then uses a set of prisms for the dispersing element and freeform mirrors to feed the detector.
- The Hi-Spectral design is very compact and uses an integral grating for the dispersion element. This leads to the detector being very close to the IFU unit. It may require having the IFU integral with the focal plane module (TBD).
- Both use Canon manufactured slicers.
- Both can package in the volume allowed.
- Design maturation needed to establish CBE against L2 requirements, but we see no obvious showstoppers at this early conceptual stage.

ORKID-2 design.





Hi-Spectral design.

Electrical and Software Design Summary

- Depending on which slicer design is chosen the only electronics and software difference is that the ORKID-2 design may not require a magnifier mechanism. Those scales are achieved in IFU itself.
- Otherwise, the electronics and software is identical to the MLA based IFU spectrograph design.

Key Risks

Risk ID	Risk	Description
Slicer 1	Stray Light Performance	If the edges of the individual slices are not well defined due to uncertainties in the manufacturing process, then the stray light performance may be worse than stray light models of the slicer design will predict.
Slicer 3	Cost Uncertainty	If the cost of the slicer increases beyond initial estimates due to cost growth associated with lack of design maturity or more fabrication runs due to lower-than-expected production yields, then the spectrograph cost margins will be reduced.
Slicer 4	Slicer Alignment	If the optical path of the spectrograph cannot be aligned due to a misalignment in the as-built slicer then a new slicer will need to be procured since the optical components in the slicer cannot be realigned after fabrication / assembly.
Slicer 5	Slicer Performance Uncertainty	If the performance of the slicer is lower than the design value due to unforeseen uncertainties or deficiencies in the design or manufacturing of the slicer then the performance of the spectrograph will be reduced.
Slicer 6	Performance vs Baseline Design	If the performance (IQ, throughput, etc) of the slicer is lower than the baseline MLA design due to the nature of the slicer design (additional surfaces, more uncertainity in slice performance, etc) then the performance of spectrograph will be reduced versus the baseline design.
Slicer 7	Additional Qualification Tests	If additional testing needs to be performed on the slicer design due to the low heritage and possible incompatibilities between the slicer and expected spectrograph environments, then cost and schedule margin will need to be used to perform the tests (and possibly buy additional hardware).

Likelihood					
5		4	3		
4					
3		5, 7	1		
2			6		
1					
	1	2	3	4	5

Consequence

Level	Likelihood	Consequence
1	Remote (<1% chance)	Negligible <1% loss of margin
2	Unlikely (1-10% chance)	Minimal 1-10% loss of margin
3	Possible (11-50% chance)	Moderate 11-50% loss of margin
4	Likely (51-70% chance)	Significant 51-100% loss of margin
5	Highly likely (>70% chance)	Margin Exhausted

Heritage - Summary

- The slicer IFU does have ground and space flight heritage on a number of past missions and future missions.
  - JWST's NIRSpec (built by SSTL) and MIRI (built by Cranfield University) both utilize a slicer based IFU.
  - Solar-C Solar Ultraviolet, Visible and infrared Telescope (SUVIT) may use a Canon slicer for its integral field unit.

JWST MIRI Up to 21 slices (Channel 1)
0.177 to 0.656 arcsec widths

Compliance Matrix - Comparison

ID	Title	Requirement Text	MLA IFU	SLICER IFU (ORKID-2)	Slicer IFU (Hi-Spectral)
IFS 2.1	Spectrograph Spectral Bandpass	Simultaneous spectrophotometric measurement over the entire continuous, well calibrated 0.4-1.7µm wavelength band.	Comply	Comply	Comply
IFS 2.2	Spectrograph Spectral Resolution	Spectral resolution (L /dL) >100 at all wavelengths and spaxels.	Comply (CBE: ~103-280)	Comply (R>100)	Comply (R>100)
IFS 2.3	Spectrograph Spatial Sampling	Accommodating a range of scale such that the spatial resolution samples a telescope PSF ranging from the diffraction limit (DL) to 6 x DL at 1um, e.g. scales ranging from 0.020 to 0.050 arcsec per spaxel. The scale is expected to be selected in-flight and static thereafter.	Comply (CBE, 3 magnifications 0.020, .030, 0.050 arc, nominal)	Comply (3 magnifications 0.02, .04, .08 arcsec as per program agreement).	Comply (3 magnifications 0.020, .030, 0.050 arc, nominal)
IFS 2.4	Spectrograph Spaxel Format	Maximize the number of spaxels, with a minimum of 50 x 50 spaxels (for a MLA type design).	In Assessment (CBE 49x45)	Comply (56x56, 56x56, 28x28)	In assessment (48 x 40 or 80 x 50, depending on design)
IFS 2.5	Spectrograph FOV	IFS shall have a minimum field of view of 1.0 x 1.0 arcsec at the finest sampling scale.	In Assessment (CBE 0.98” x 0.90”)	Comply	In assessment
IFS 2.6	Spectrograph Spaxel Cross-Contamination	Minimize cross contamination between neighboring spaxel’s spectra on the detector to < 2% (TBR), including diffraction.	Expect Compliance	Expect Compliance (slicer design more amenable than MLA)	Expect Compliance (slicer design more amenable than MLA)
IFS 2.7	Spectrograph Nyquist Sampling	Nyquist sampling or better for each spaxel spectral element and cross-dispersion profile at the detector.	Expect Compliance	Expect Compliance	Expect Compliance

- Compliance against each of the key requirements was assessed for the study.
    - Compliance for some requirements still marked as TBD.
    - Slicer and MLA design maturation needed to establish CBE against L2 requirements, but we see no obvious showstoppers at this early conceptual stage.

Compliance Matrix - Comparison

ID	Title	Requirement Text	MLA IFU	SLICER IFU (ORKID-2)	Slicer IFU (Hi-Spectral)
IFS 2.8	Spectrograph Spatial Stability	Predictably maintain spaxel spectral location within 1/10 pixel and spaxel trace width variation to within 3/10 pixel, given example optical and thermal environment perturbations over > 2h duration (and goal 10h).	TBD	TBD	TBD
IFS 2.9	Spectrograph MLA Fill Factor	A fill-factor for IFU focal plane segmentation of > 95% minimum. Goal > 98%.	Comply	n/a	n/a
IFS 2.10	Spectrograph Optical Throughput	Total optical throughput of > 50%, and 80% nominal, maximized for L > 1 um.	Comply (~65% min across bandpass)	Expect Compliance	TBD
IFS 2.11	Spectrograph Thermal Background	Control on thermal background to ensure that on-orbit variations are << detector statistical and systematic errors, e.g. nominally < 0.005 e-/pix/sec; preferably < 0.002 e-/pix/sec.	TBD	TBD	TBD
IFS 2.12	Spectrograph Stray Light	Internally scattered light of <1% of the input signal reaching the detector within its effective spectral response range.	TBD	TBD	TBD, grating orders may be an issue.
IFS 2.13	Spectrograph Calibration	On-orbit capability for measuring spectral calibration (to L/1000), count rate non-linearity (at several wavelengths) and sensor flat fielding.	TBD	TBD	TBD
IFS 2.14	Spectrograph Electronics	Electronic and calibration units are separate and likely distant (~5 m) from the optics bench.	Expect Compliance	Expect Compliance	Expect Compliance

Design option: Image Slicer vs. MLA

Benefits of Slicer:

- Fewer pixels (50%) required + dark area eliminated: allows denser packing on detector
- Data extraction simplified
- Diffraction complications reduced (1-d vs 2-d)
- Denser spectral packing can allow 3 magnifications to fit on 1 detector, needing only single magnifier and eliminating mechanism.
- Gaps between slices are easier to calibrate than gaps between lenslets.
- Monolithic element much more stable than traditional train of optics

Disadvantages of Slicer:

- All-or-nothing: no way to alter what we get
- Single vendor: no competition, hostage to their cost and schedule, creates schedule risk
- Team is still figuring out its performance (specifically stray light and diffraction)
  - R&D means a longer schedule, and thus more schedule margin
- More variation in detector spot sizes over bandpass and scales means more under/oversampling
- more surfaces = lower throughput

Slicer vs. MLA IFU Trade Summary

- The UA/SSL team has determined that the MLA based IFU design is deficient in a few of the key L2 requirements, but there is a clear path to closure during final design study phase of the project prior to fabrication.
- The slicer-based design immediately resolves those deficiencies, in addition to improving cross contamination of neighboring spaxels.
- The slicer-based IFU design provides a more robust scientific solution and has a good probability of meeting the project's goals and requirements.
- Of-course the slicer carries inherent programmatic risks of added cost, schedule, and technical complexity that is explained in this document.

Slicer Baseline and Path Forward

- If the Project decides that a Slicer IFU is preferred over the MLA IFU then we would baseline the ORKID-2 design due to the ORKID-2 design's maturity compared to the Hi-Spectral design.
- That being said, we would recommend bringing on Hi-Spectral to work on the slicer design given their experience in building slicers and their close connection to the slicer manufacturer, Canon.
- Another recommendation is that if a slicer design is chosen that we have a $200K 3-month study to continue to develop the slicer design to reduce schedule risk. This study should start in December 2023.

2. OPTICAL DESIGN

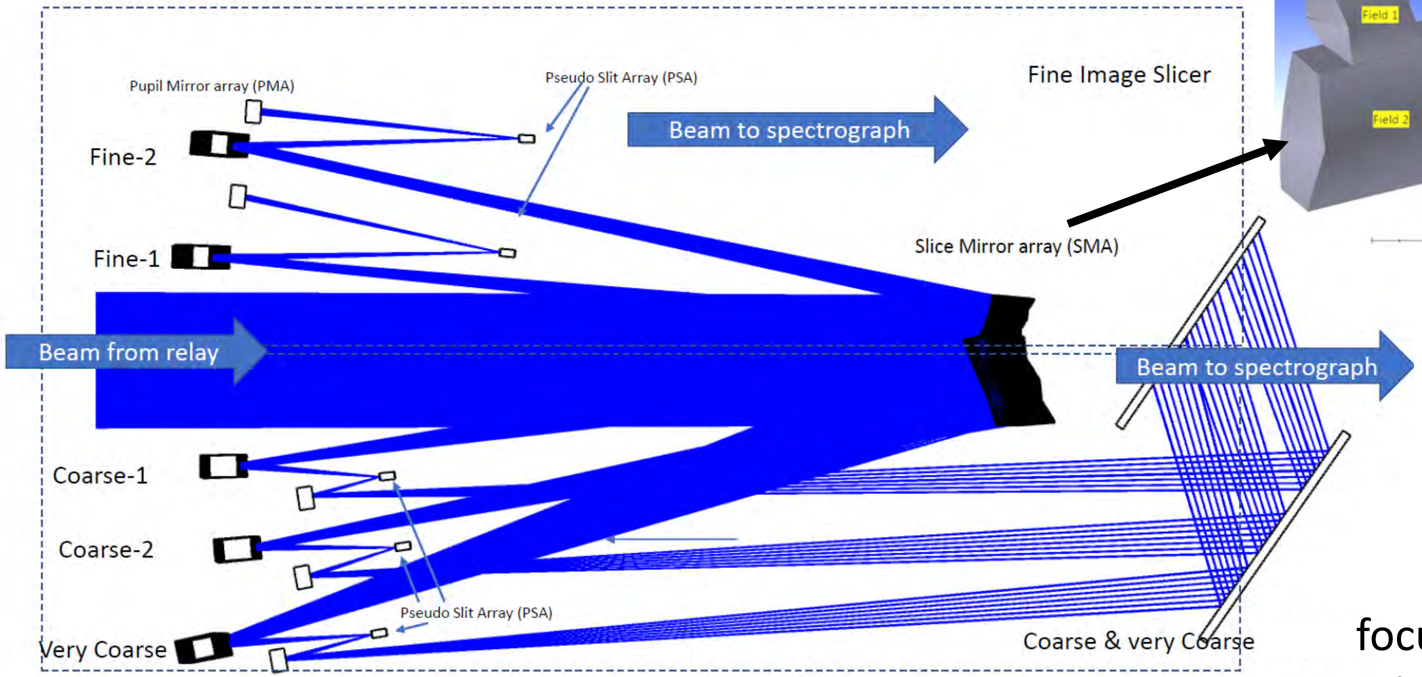
Optical Design Outline

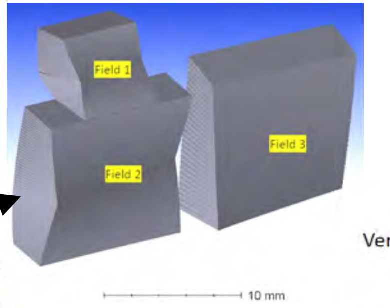
- Status
- Current Design
- Design Performance
- Summary/Future Work

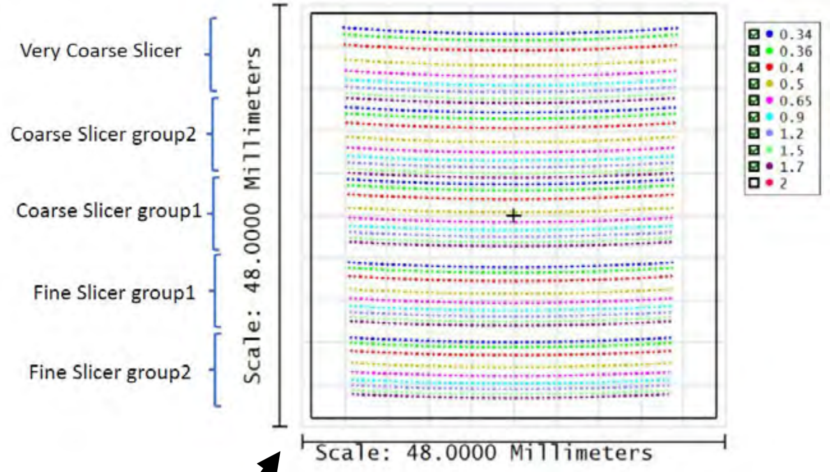
Slicer Design Status

- Canon slicer technology has developed in recent years to become competitive with heritage technology
  - precise cutting of monolith substrate, as opposed to optical contacting of plates
  - feature sizes down to 50nm; dimension accuracy 5nm; surface roughness < 1nm rms, suitable sufficient for optical surfaces in the visible; surface figure 50 nm
  - may be lower cost and faster to deliver than heritage methods
  - was not available during initial Pearl design work, and slicer was deemed too expensive/slow; now being considered as option
- ORKID-2 has developed initial optical design for slicer based on Canon capabilities
  - using heritage knowledge from Roman IFS (and Winlight slicers)
  - design aligned to Pearl requirements
  - motivation is to share resources for synergy between ORKID/Pearl projects; strictly collegial relationship, no contract/funding
  - would produce optical design and analysis, but ordering and additional engineering belongs to UA/SSL
  - ORKID-2 design effort continues with Pearl science team input
- Hi-Spectral under recent contract with UA to develop Canon slicer concept design independently
  - 7-week study to develop preliminary design concept, still in work
  - good relationship with Canon
  - previous optomech slicer design experience
  - design promising in early stages, still coming up to speed on requirements
- ORKID-2 and HiSpectral efforts described separately in next slides

ORKID-2 Design Description





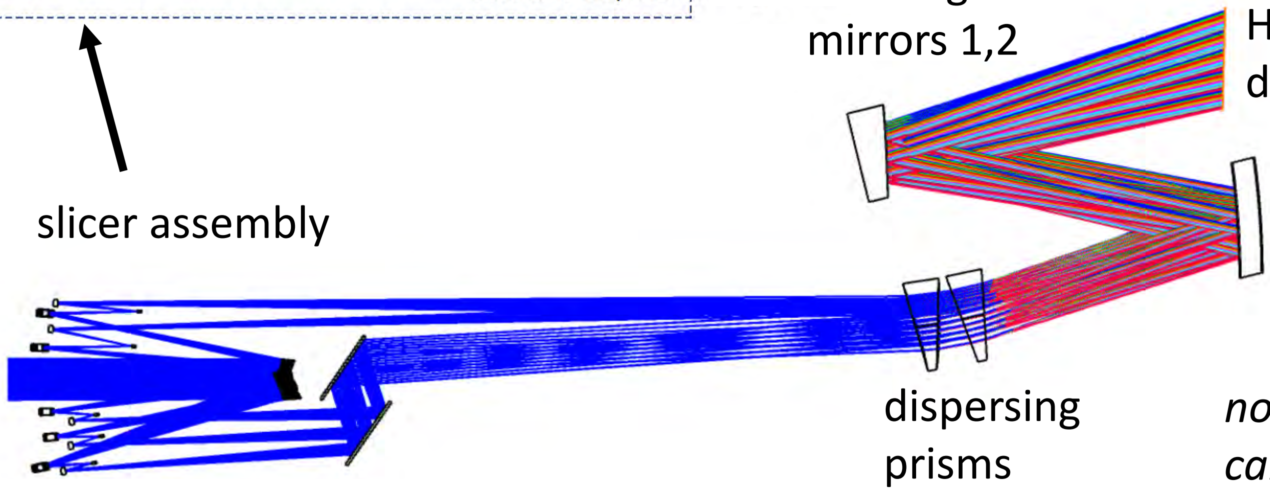


slicer assembly

focusing mirrors 1,2

H4RG detector

from telescope, magnifier



dispersing prisms

not shown: magnifier, calibration path

ORKID-2 Design Description

- Features:
  - achieves 3 magnification scales on single H4RG-10 detector, no swapping mechanism needed
  - 56x56, 56x56, 28x28 spaxels achieved for 20, 40, 80 mas/spaxel scales (fine, coarse, v.coarse)
  - accessible pupils at prisms for defining cold volume (different sized pupils for different magnifications)
  - anamorphism not considered

- Magnifier: relays from telescope image to slicer entrance with telecentric rays (TBD)
  - 10x fixed magnification
  - similar to MLA magnifiers: triplet and field lens
- Slicer assembly: slices and rearranges image, feeds rays to disperser entrance pupil
  - single assembly from Canon
  - slices adjacent FOVs with 3 different magnifications, select FOV by steering target
  - slicer widths 100, 200, 400 um
- Disperser/focuser: disperses and relays slicer output onto H4RG-10 detector, achieves resolution of >100 over bandpass
  - ORKID-2 design for 0.34-2.0um, can be adapted
  - uses 2 freeform-surface mirrors; team considering alternate designs with 3 mirrors or different folding scheme
  - optics oversized to accept larger diffraction f/# (TBR)
- Calibration path: inserts calibration light from devoted flux sources into optical path
  - similar to MLA cal path

ORKID-2 Design Performance

- Geometric spot sizes on detector mostly diffraction-limited
  - 5.7um average and 18.3um max over bandpass, FOV, and 3 sampling scales
- Diffraction contributes to spot size and shape, being studied
- Resolution > 100 across entire bandpass
  - minimum 117 over all FOV and 3 sampling scales
- Throughput: 70% average over bandpass including margin
- Number of spectra on detector >50x50 for 2 scales
- Stray light analysis TBD
  - ghost reflections not expected to be an issue since mostly reflective design

- **Expected to meet all L2 requirements**
  - designed with different range of magnifications than specified in L2 requirements, as directed by Pearl science team

ORKID-2 Design Performance: Spot Sizes

Spot size on detector, at 400, 600nm and compared to diffraction limit

Units are microns rms radius (FWHM ~1.7x larger)

Slicer	Field	wavelength:400nm			wavelength:600nm		
		mm	um	DL (um)	mm	um	DL (um)
FG1	1	0.00775	7.74789	17	7.39E-03	7.38959	27.1
FG1	2	0.00765	7.6476	17	6.59E-03	6.59082	27.1
FG1	3	0.0082	8.20468	17	8.57E-03	8.57235	27.1
FG1	1	0.0075	7.50201	17	5.05E-03	5.04954	27.1
FG1	2	0.00747	7.46733	17	5.03E-03	5.02514	27.1
FG1	3	0.00746	7.46462	17	5.03E-03	5.02971	27.1
FG1	1	0.00901	9.00931	17	7.68E-03	7.68382	27.1
FG1	2	0.00896	8.9567	17	8.10E-03	8.10085	27.1
FG1	3	0.0095	9.497	17	7.83E-03	7.82579	27.1
FG2	1	0.00617	6.16941	17	5.79E-03	5.78899	27.1
FG2	2	0.00706	7.06399	17	6.72E-03	6.71649	27.1
FG2	3	0.00539	5.38974	17	5.01E-03	5.00832	27.1
FG2	1	0.00443	4.42709	17	4.52E-03	4.51699	27.1
FG2	2	0.00439	4.38576	17	4.47E-03	4.46964	27.1
FG2	3	0.00436	4.36085	17	4.45E-03	4.44721	27.1
FG2	1	0.00666	6.66446	17	6.01E-03	6.00884	27.1
FG2	2	0.00578	5.78144	17	5.17E-03	5.16859	27.1
FG2	3	0.00764	7.64255	17	6.99E-03	6.98779	14.2

DL: Diffraction Limit

FG: Fine Slicer Group

CG: Coarse Slicer Group

VCG: Very Coarse Slicer Group

Most of fields have diffraction limit performance, except some edge fields at Coarse and very Coarse .

Slicer	Field	wavelength:400nm			wavelength:600nm		
		mm	um	DL (um)	mm	um	DL (um)
CG1	1	0.01225	12.2509	8.7	1.21E-02	12.0619	14.2
CG1	2	0.00986	9.85509	8.7	9.53E-03	9.53073	14.2
CG1	3	0.01391	13.9082	8.7	1.37E-02	13.725	14.2
CG1	1	0.00574	5.73986	8.7	5.70E-03	5.70203	14.2
CG1	2	0.00573	5.73042	8.7	5.68E-03	5.68347	14.2
CG1	3	0.00567	5.66721	8.7	5.70E-03	5.70051	14.2
CG1	1	0.01106	11.0598	8.7	1.13E-02	11.3039	14.2
CG1	2	0.01313	13.129	8.7	1.34E-02	13.3689	14.2
CG1	3	0.00901	9.01248	8.7	9.14E-03	9.13657	14.2
CG2	1	0.00971	9.71041	8.7	9.54E-03	9.53628	14.2
CG2	2	0.01359	13.5861	8.7	1.32E-02	13.21	14.2
CG2	3	0.0064	6.39855	8.7	6.31E-03	6.30613	14.2
CG2	1	0.00504	5.03562	8.7	5.59E-03	5.59343	14.2
CG2	2	0.00499	4.99038	8.7	5.50E-03	5.50318	14.2
CG2	3	0.00479	4.78672	8.7	5.41E-03	5.40504	14.2
CG2	1	0.01022	10.2211	8.7	9.61E-03	9.60953	14.2
CG2	2	0.00745	7.44943	8.7	6.81E-03	6.81343	14.2
CG2	3	0.01373	13.7251	8.7	1.30E-02	12.9929	14.2
VCG	1	0.00899	8.99307	9.3	8.89E-03	8.888	15.1
VCG	2	0.00564	5.63733	9.3	6.58E-03	6.58026	15.1
VCG	3	0.01825	18.2523	9.3	1.34E-02	13.4008	15.1
VCG	1	0.00695	6.9537	9.3	6.29E-03	6.28595	15.1
VCG	2	0.00797	7.96992	9.3	7.22E-03	7.22099	15.1
VCG	3	0.00608	6.08375	9.3	5.72E-03	5.71854	15.1
VCG	1	0.00797	7.96733	9.3	7.39E-03	7.38521	15.1
VCG	2	0.01194	11.9436	9.3	1.03E-02	10.3243	15.1
VCG	3	0.00517	5.17169	9.3	5.20E-03	5.19906	15.1

Optical design controls aberrations well: geometric spot sizes on detector are mostly below diffraction limit over 3 magnifications, bandpass, and FOV: ***5.7 um average*** *and* ***18.3 um max***

Optical design is being optimized to improve optical performance

ORKID-2 Design Performance: Diffraction

- Diffraction effects are significant and must be considered in the IFS design and performance
- Mirrors at all pupils must be large enough to accept diffracted light from slicer apertures, or else flux is lost
  - diffraction from the slicers causes effective f/# to vary with wavelength
  - significant energy is in diffraction “rings”, and light loss depends on how many rings are captured at pupil locations
- Effect drives the disperser/focuser optics to be larger, which introduces more aberrations – must achieve balance
- Vignetting the diffracted light that overfills the pupil mirrors introduces additional diffraction that widens the spots on the detector
- Issue is being actively studied
- MLA design has the same issue in 2D

ORKID-2 Design Performance: Detector Spot Instability

- Position of the Telescope PSF will vary on the slicer apertures for a given target measurement
- Since the optical design reimages the slicer apertures directly onto the detector (i.e. spatial-spectral degeneracy), then this variation causes spot shape and magnitude changes at the detector
- Spot shape changes cause a centroid error (error in wavelength measurement) and magnitude changes cause a photometry error, and therefore these instabilities degrade spectrophotometric accuracy
- Spots on detector are also affected by disperser/focuser aberrations and diffraction (see previous slide)
- Issue is being actively studied
- MLA design has the same issue in 2D

<u>Losses at pupil mirror:</u>

	wavelength (um)		
Offset	0.4	1	1.7
0	0.7%	3.7%	8.7%
0.5	3.7%	4.2%	8.8%
1	3.0%	6.1%	9.1%
1.5	5.0%	9.2%	9.8%

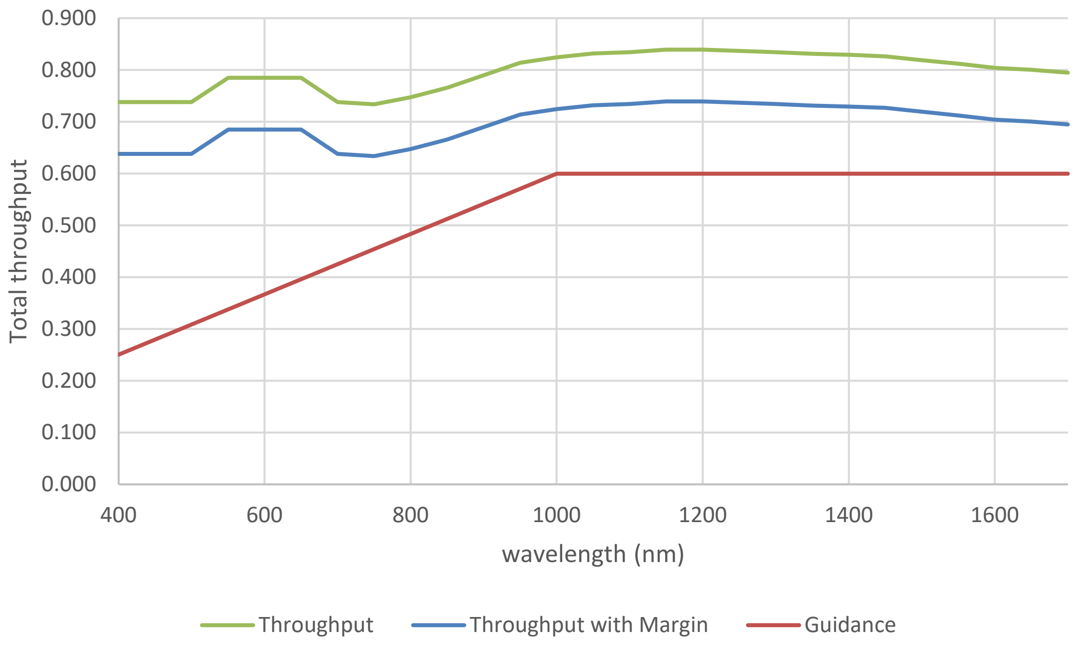
offset is in units of slicer widths

Oct 2023 modeling shows significant loss of flux in the current model from "clipping" from one mirror in assembly
Loss is function of wavelength and PSF position on slicer
Diffraction modeled using POPPY code, Oct 2023
Models case for 20 mas/spaxel where diffraction effects expected to be most significant

ORKID-2 Design Performance: Throughput

- Optical Throughput Budget
  - Multiplies reflectance/transmittance of all surfaces
  - for preliminary estimate, assumes reasonable, well-performing coatings:
    - reflective coatings are protected-Ag coatings from Viavi
    - antireflection coatings 98.5%
  - includes 10% margin
- Estimate meets program L2 requirement (July 2023) and program guideline (August 2023)
  - doesn't include sensor or telescope
  - note guideline based on LAM estimate plus margin; LAM estimate assumed catalog AR coatings and protected-Ag coatings

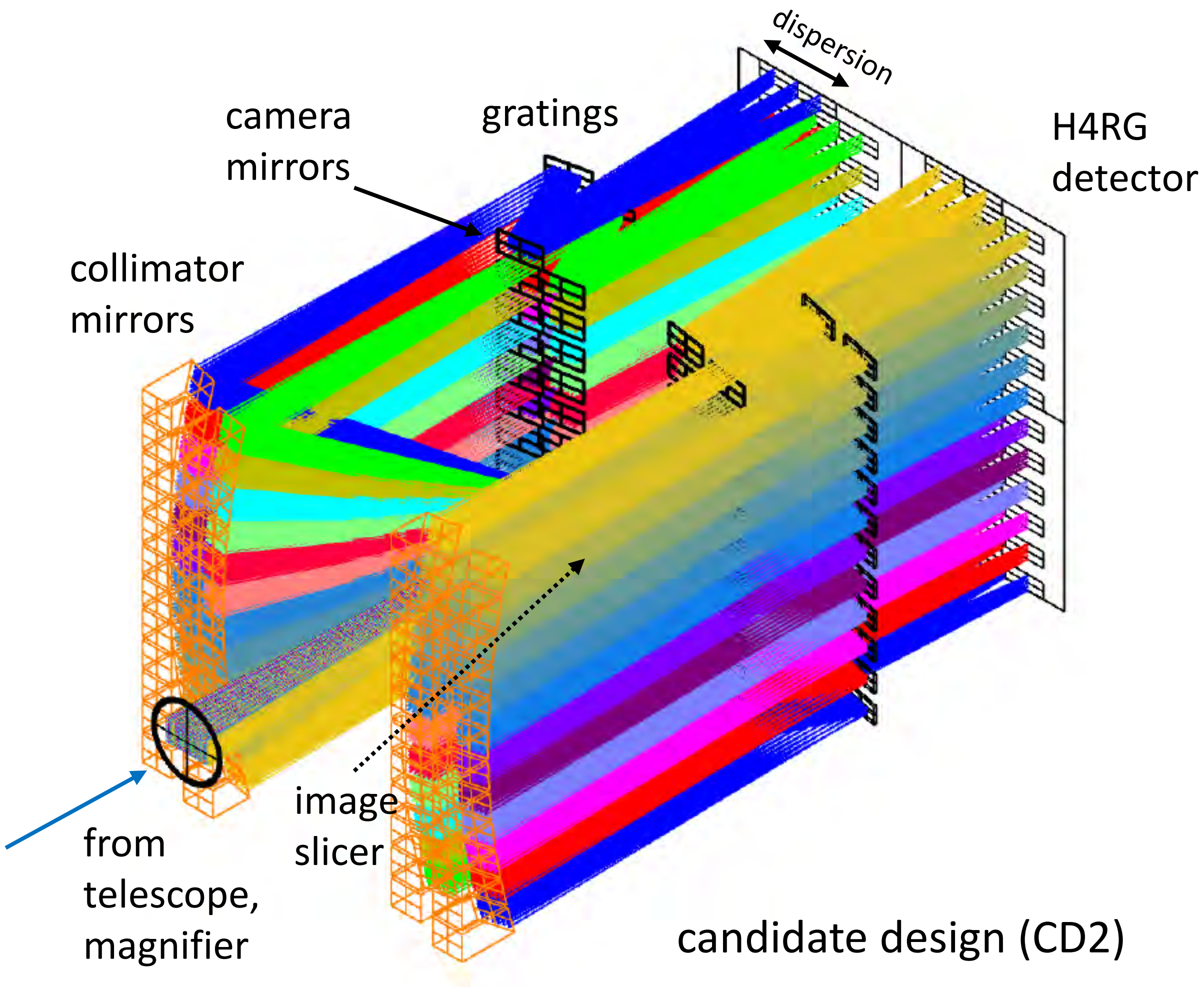
program guideline:



Also L2 requirement: Total optical throughput of > 50%, and 80% nominal, maximized for wavelength > 1 um.

Hi-Spectral Design Description

- Magnifier (TBD):
  - reimage from CCW to Pearl instrument volume
  - 3x magnification
  - magnifier could be integrated into Canon assembly
- Slicer assembly:
  - includes gratings for dispersion
  - currently have 3 candidate designs, varying fabrication difficulty and number of spaxels
  - best option achieves 48x40 spectra without difficulty, second best option achieves 80x50 but checking with Canon about difficulty
  - mirrors sized to account for slit diffraction
  - consists of 4 machined pieces in precision housing
  - current layout has detector immediately past assembly, but needs room for window, mounts, direct detector calibration LEDs, etc
- Calibration path:
  - TBD, folds into magnifier path, similar to ORKID and MLA configuration



candidate design (CD2)

not shown: magnifier, calibration path

Hi-Spectral Design Description

- Features:
  - combines slicer and disperser/focuser into single unit
  - very compact, thermally and mechanically stable
  - can machine precise built-in stops at intermediate images for stray light control
  - mitigates tilted input image
  - Canon typically easily achieves required tolerances
  - only uses ~50% of detector pixels, limited by physical sizes of the mini-spectrographs
  - currently working to 1 magnification scale only
  - currently undersamples telescope/magnifier PSF at input, may not be optimal
  - pupils are within assembly, likely would need cool entire assembly
  - design very preliminary, initial study still in progress

Hi-Spectral Design Performance

- Geometric spot sizes TBD, first-order layouts only
- Diffraction not well addressed at this early stage
  - minimized by undersampling at entrance slit
  - open issue of detector spot instability (spectrophotometric errors from varying position of telescope PSF on slicers)
- Resolution >100 in all candidate designs
  - resolution may be significantly larger depending on candidate, leading to higher detector readout noise and SNR degradation, TBR
- Throughput: TBD, grating performance not known
- Number of spectra on detector may be >50x50, TBD
- Magnification: only 1 scale so far, achieving 3 scales is TBD
- Stray light analysis TBD
  - grating orders may produce stray light
  - scattered light been studied in physical prototype design
  - ghost reflections not an issue since entirely reflective design

- **Too early to assess whether designs meet all requirements**

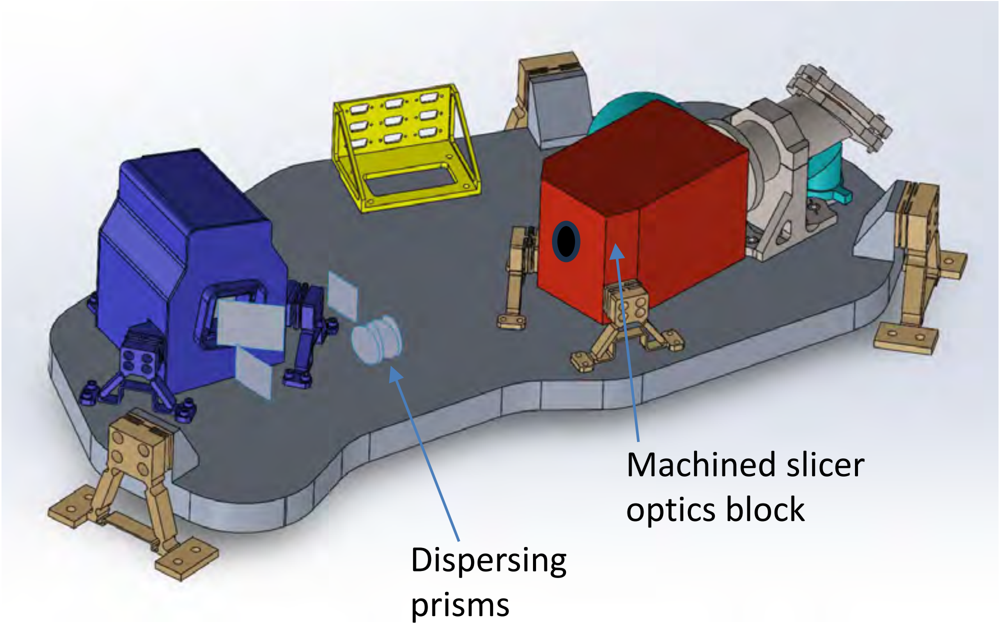
Summary/Future Work

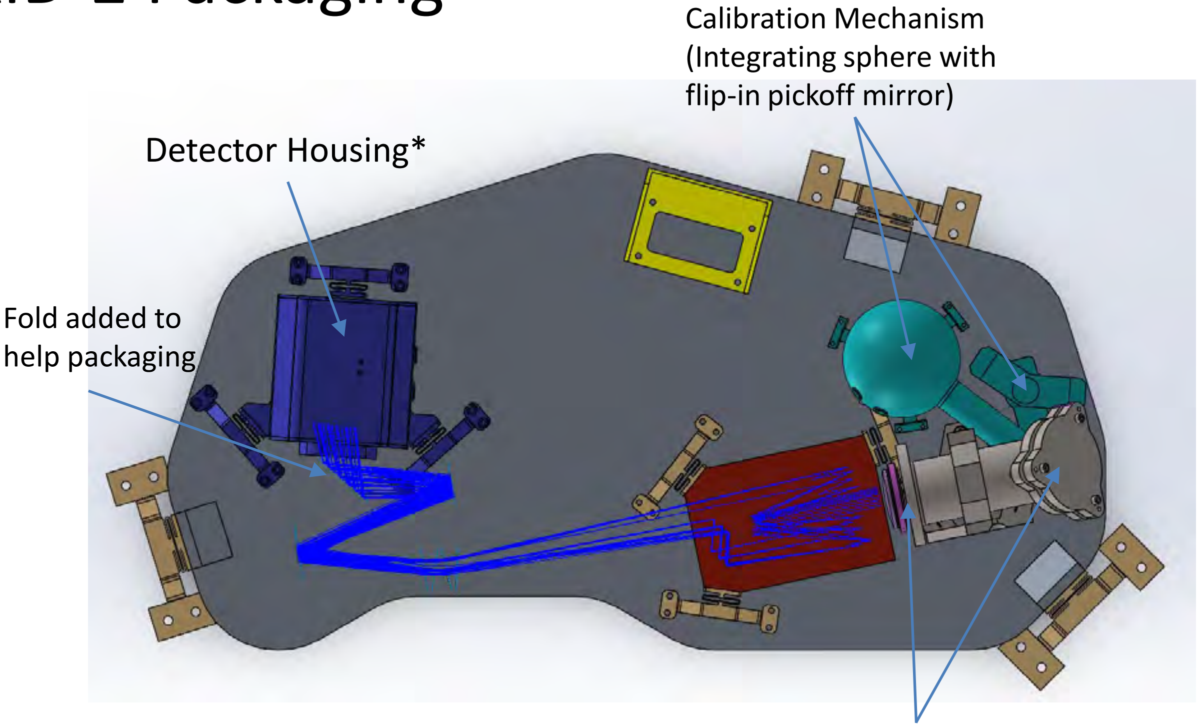
- Conceptual designs still in work
- We believe that there are likely no showstoppers to meeting all requirements, given further development

- Work in next phase:
  - clarify next steps with ORKID-2 and/or Hi-Spectral
  - continue development towards closing all L2 requirements
  - mature diffraction analysis and effects on performance

3. OPTOMECHANICAL LAYOUT

Optomechanical Design
ORKID-2 Packaging



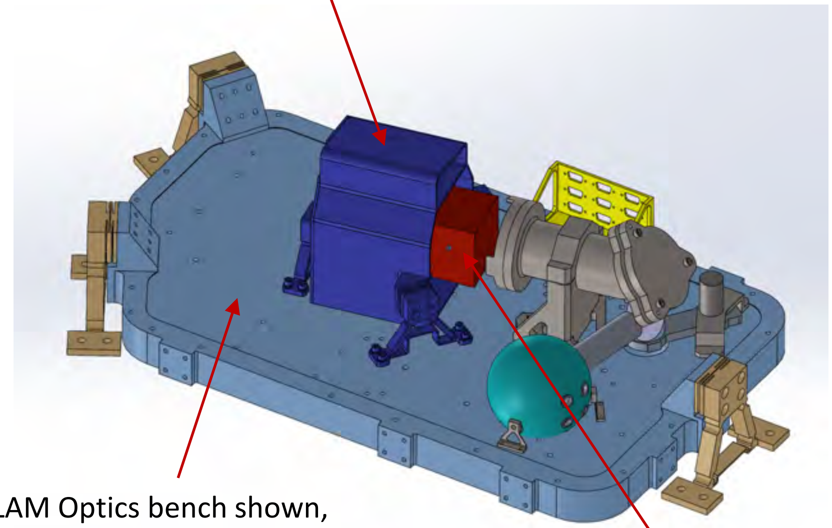


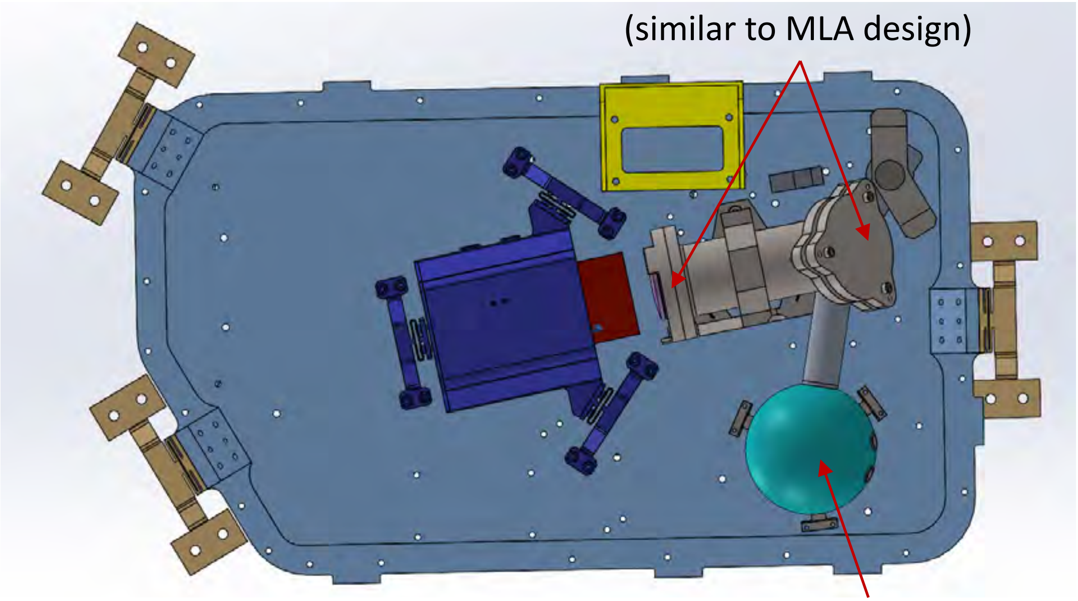
- ORKID-2 packaging volume similar to MLA design (900mm long bench vs. 800 for MLA)
- Optics mounts not yet designed
- Focal plane currently needs to be pushed to front of detector housing, needs to be optimized to make room for detector calibration LEDs and filter inside housing.
    - ORKID-2 optical design is underway; updated focusing mirror layout may allow more working distance to better fit detector housing
- Assume similar location of magnifier, but no need for multiple magnifications so no mechanism
- Calibration lamps, integrating sphere, and pickoff mirror assumed same as MLA

*Note: LAM detector housing design is shown for layout purposes, would be redesigned to accommodate ORKID-2 optical design

Optomechanical Design

Hi Spectral Packaging

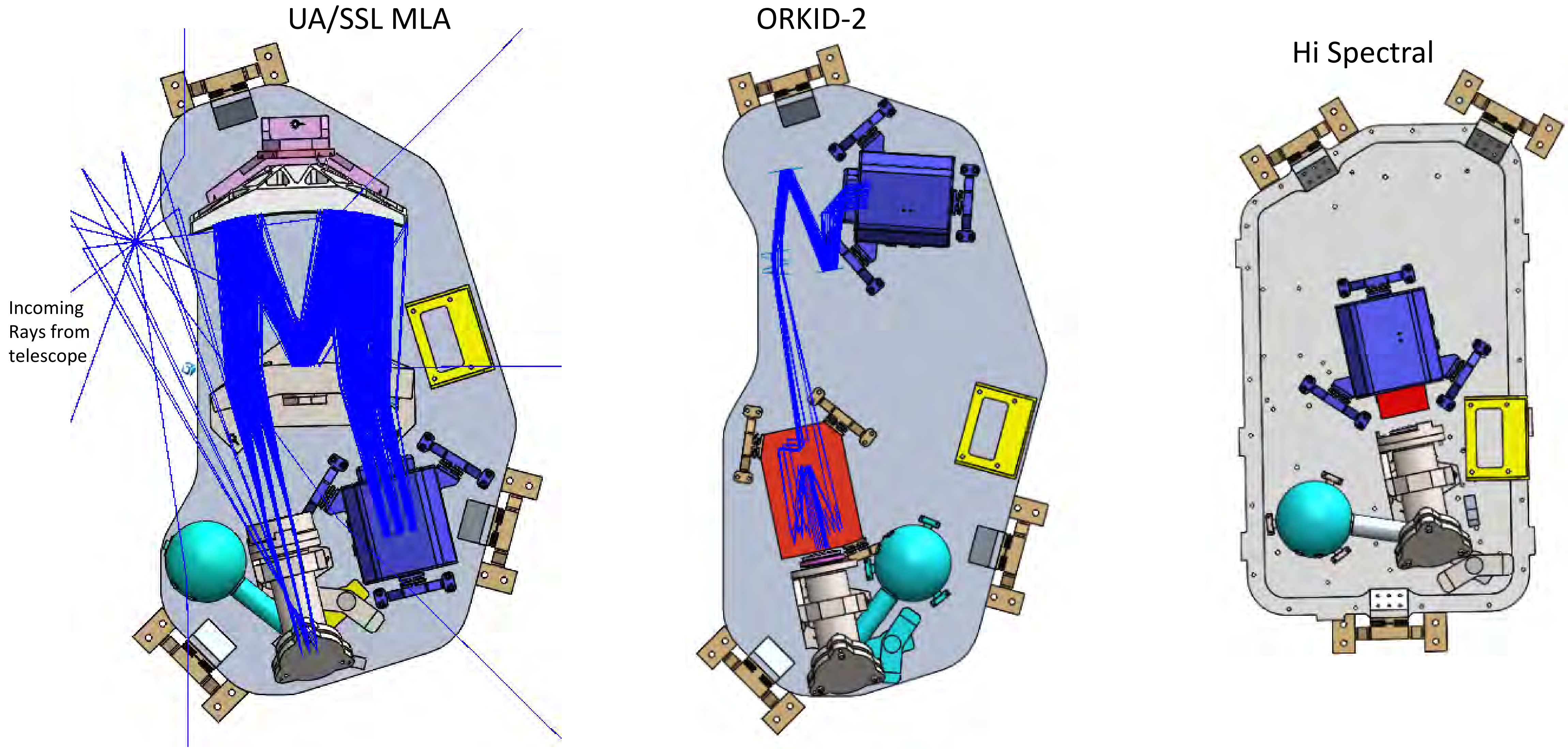




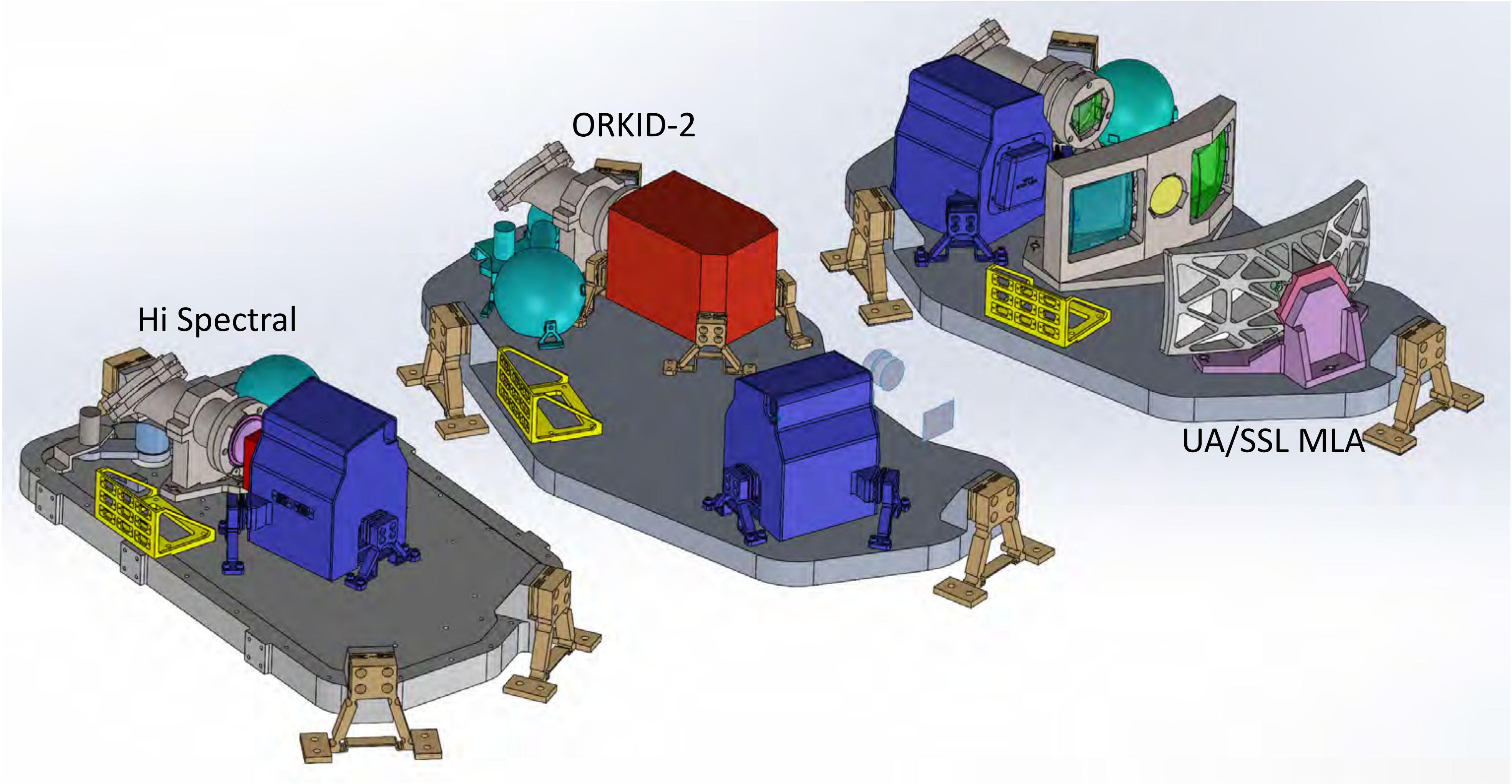
- Hi Spectral design considerably smaller than ORKID-2 and MLA design, due to slicer and dispersion grating integrally machined in 70mm x 70mm x 100mm block (approx.)
- Currently focus is a few mm outside slicer block, so no room for field flatness calibration LEDs. Possibility of increasing gap being investigated.
- Small size of slicer block gives option of mounting directly inside detector housing
- Assume similar location of magnifier mechanism to MLA design
- Calibration lamps, integrating sphere, and pickoff mirror assumed same as MLA, ORKID-2

*Note: LAM detector housing design is shown for layout purposes, would be redesigned to accommodate Hi Spectral optical design

Optomechanical Packaging
Comparison of 3 designs



Optomechanical Packaging
Comparison of 3 designs



4. ELECTRONICS AND SOFTWARE

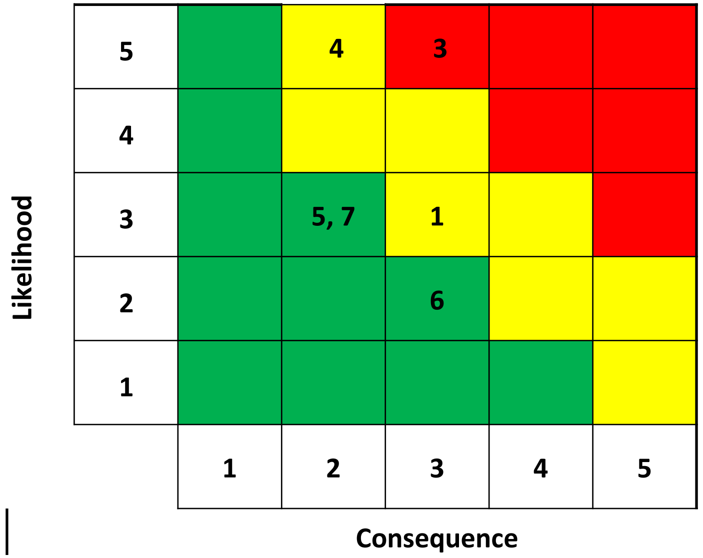
Electronics and Software

- Depending on which slicer design is chosen the only electronics and software difference is that the ORKID-2 design may not need a magnifier mechanism as those magnification scales are achieved in the IFU itself.
- Otherwise, the electronics and software is identical to the MLA based IFU spectrograph design.

5. RISKS

Key Risks

Risk ID	Risk	Description
Slicer 1	Stray Light Performance	If the edges of the individual slices are not well defined due to uncertainties in the manufacturing process, then the stray light performance may be worse than stray light models of the slicer design will predict.
Slicer 3	Cost Uncertainty	If the cost of the slicer increases beyond initial estimates due to cost growth associated with lack of design maturity or more fabrication runs due to lower-than-expected production yields, then the spectrograph cost margins will be reduced.
Slicer 4	Slicer Alignment	If the optical path of the spectrograph cannot be aligned due to a misalignment in the as-built slicer then a new slicer will need to be procured since the optical components in the slicer cannot be realigned after fabrication / assembly.
Slicer 5	Slicer Performance Uncertainty	If the performance of the slicer is lower than the design value due to unforeseen uncertainties or deficiencies in the design or manufacturing of the slicer then the performance of the spectrograph will be reduced.
Slicer 6	Performance vs Baseline Design	If the performance (IQ, throughput, etc) of the slicer is lower than the baseline MLA design due to the nature of the slicer design (additional surfaces, more uncertainity in slice performance, etc) then the performance of spectrograph will be reduced versus the baseline design.
Slicer 7	Additional Qualification Tests	If additional testing needs to be performed on the slicer design due to the low heritage and possible incompatibilities between the slicer and expected spectrograph environments, then cost and schedule margin will need to be used to perform the tests (and possibly buy additional hardware).



Level	Likelihood	Consequence
1	Remote (<1% chance)	Negligible <1% loss of margin
2	Unlikely (1-10% chance)	Minimal 1-10% loss of margin
3	Possible (11-50% chance)	Moderate 11-50% loss of margin
4	Likely (51-70% chance)	Significant 51-100% loss of margin
5	Highly likely (>70% chance)	Margin Exhausted

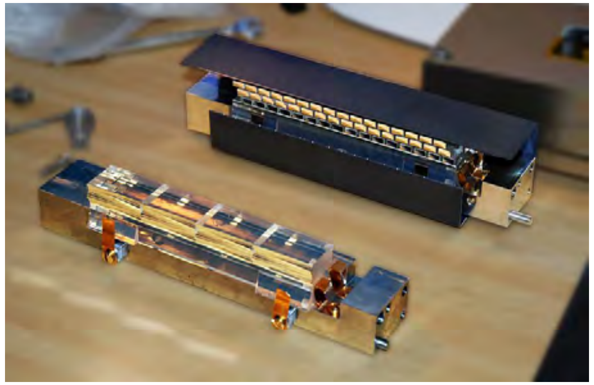
Risk Details

ID	Risk Title	Risk Type	Full Risk Statement	L	C	Mitigations
Slicer 1	Stray Light Performance	Implementation	If the edges of the individual slices are not well defined due to uncertainties, in the manufacturing process, then the stray light performance may be worse than stray light models of the slicer design will predict.	3	3	•Fabrication EM unit to characterize as-built stray light performance vs modeling. •Production of a "qualification design" with multiple characteristic edges to characterize uncertainty in production processes.
Slicer 2	Slicer too Large	Implementation	If the slicer is too large to be accommodated in the current volume of the spectrograph design due to the size of the slicer and its associated optics, then the mass and volume of the spectrograph will increase.	1	2	•Allocation additional volume and mass. •Early implementation of Slicer design in Spectrograph to estimate mass/volume uppers.
Slicer 3	Cost Uncertainity	Implementation	If the cost of the slicer increases beyond initial estimates due to cost growth associated with lack of design maturity or more fabrication runs due to lower-than-expected production yields, then the spectrograph cost margins will be reduced.	3	5	•Allocate additional cost margin to accommodate slicer cost growth.
Slicer 4	Slicer Alignment	Implementation	If the optical path of the spectrograph cannot be aligned due to a misalignment in the as-built slicer then a new slicer will need to be procured since the optical components in the slicer cannot be realigned after fabrication / assembly.	2	5	•Procure flight spare slicer to be swapped into the spectrograph in the event the flight slicer is misaligned.
Slicer 5	Slicer Performance Uncertainity	Implementation	If the performance of the slicer is lower than the design value due to unforeseen uncertainties or deficiencies in the design or manufacturing of the slicer then the performance of the spectrograph will be reduced.	3	2	•Produce and characterize early EM slicer to compare slicer design with as-built performance.
Slicer 6	Performance vs Baseline Design	Implementation	If the performance (IQ, throughput, etc) of the slicer is lower than the baseline MLA design due to the nature of the slicer design (additional surfaces, more uncertainity in slice performance, etc) then the performance of spectrograph will be reduced versus the baseline design.	2	3	•Produce and characterize early EM slicer to compare slicer design with as-built performance.
Slicer 7	Additional Qualification Tests	Implementation	If additional testing needs to be performed on the slicer design due to the low heritage and possible incompatibilities between the slicer and expected spectrograph environments, then cost and schedule margin will need to be used to perform the tests (and possibly buy additional hardware).	3	2	•Identify flight environments early for spectrograph and assess compatibility of slicer and components. •Early identification of qualification (and lifetime) tests and allocation of cost/schedule to procure qualification units and perform qualification testing.
Slicer 8	Single Supplier	Implementation	Canon is the single source supplier for these slicers. If Canon can not deliver then we risk delays and cost overruns, with few/no options for mitigation in the schedule allowed.	2	3	•Produce and characterize early EM slicer to compare slicer design with as-built performance.
Slicer 9	Failure of Slicer in Flight	Mission	If the slicer does not survive duration of mission due to incompatibility of the slicer with flight environments, then the performance of the spectrograph will be degraded, or spectrograph will lose functionality.	1	4	•Identify flight environments early for spectrograph and assess compatibility of slicer and components. •Early identification of qualification (and lifetime) tests and allocation of cost/schedule to procure qualification units and perform qualification testing.

6. HERITAGE

Example Image Slicers on The Ground

Going back to Bowen 1938



https://www.eso.org/public/images/ann1012b/

MUSE
48 dissectors
48 mirrors

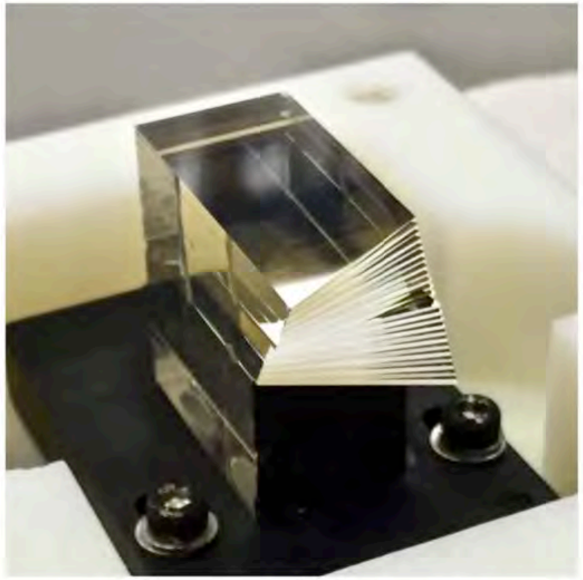


Figure 6. A close-up view of the medium slicer. As shown here, the element is on its side relative to its orientation inside the instrument. This element is made from optically contacted Zerodur. Each of the 24 slitlets is 0.5 mm thick and 14.8 mm tall. The reflective faces are convex with a radius of curvature of 5206 mm. The coating is multilayer enhanced silver.

Keck Cosmic Web Imager
24 slitlets

https://ui.adsabs.harvard.edu/abs/2018ApJ...864...93M/abstract

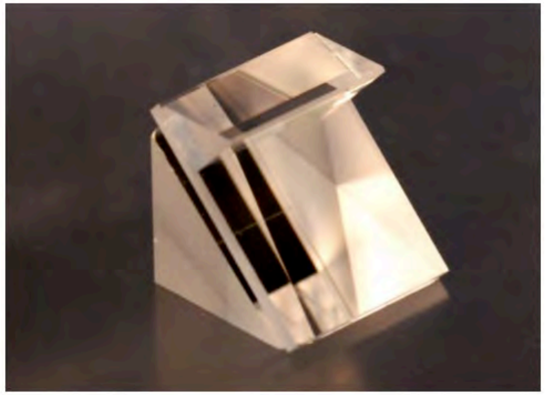
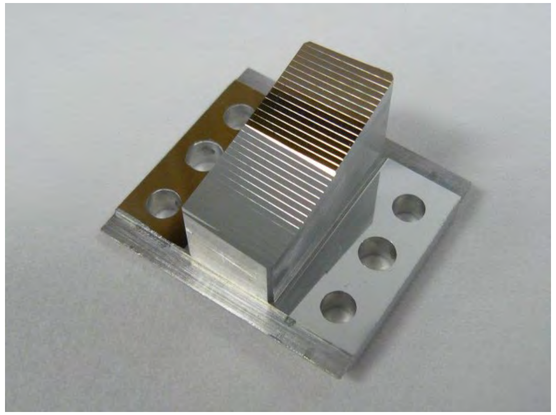


Fig. 2. Photograph of the optical element of the image slicer.

Subaru HDS:
5 slices, 0.3” x 7.8”

https://ui.adsabs.harvard.edu/abs/2012PASJ...64...77T/abstract

Example Image Slicers That Have Flown



https://sci.esa.int/web/jwst/-/nirspec-ifu-image-slicer

JWST NIRSpec 30 slices
0.1 x 3 arcsec each

https://jwst-docs.stsci.edu/jwst-mid-infrared-instrument/miri-instrumentation/miri-spectroscopic-elements

JWST MIRI Up to 21 slices (Channel 1)
0.177 to 0.656 arcsec widths

These survived:

- Acoustic
- Vibe
- Thermal Vac
- Launch

They also look monolithic, like the Canon design (e.g.)

https://www.spiedigitallibrary.org/conference-proceedings-of-spie/9904/1/Development-of-compact-metal-mirror-image-slicer-unit-for-optical/10.1117/12.2231947.full

Slicers that Are Planned for Flight

- Solar-C Solar Ultraviolet, Visible and infrared Telescope (SUVIT) may use a Canon slicer for its integral field unit
- They have performed thermal cycling, humidity, vacuum and radiation tests for their silver coatings for space qualification.

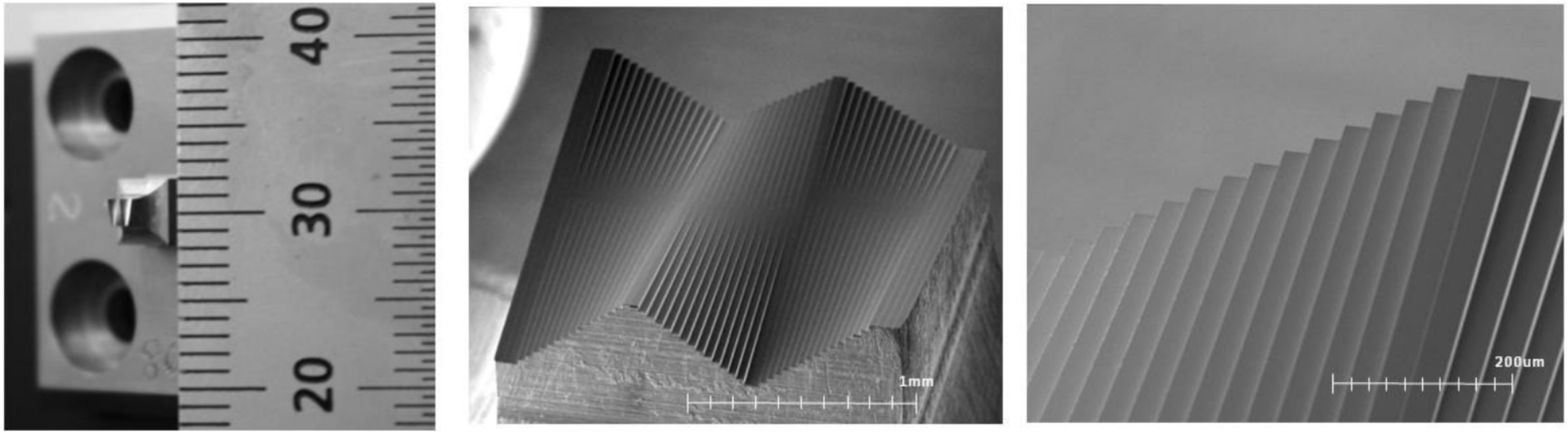


Figure 5. Picture and the scanning electron microscope (SEM) images(X50, X200) of the micro slicer mirrors

https://ui.adsabs.harvard.edu/abs/2014SPIE.9151E..1SS/abstract

(Development of micro image slicer of integral field unit for spaceborne solar spectrograph Y. Suematsu, T. Sukegawa, Y. Okura, T. Nakayasu, Y. Enokida, M. Koyama, K. Saito, S. Ozaki, S. Tsuneta)

Summary of Example Slicers

Name	Status	Type of Observatory	Operating Wavelengths (um)	Number of Slitlets	Manufacturer	Resolution
Cosmic Web Imager	Operating	Ground/Keck	0.35 to 1.05	24	Winlight Optics	1000 to 2000
MUSE	Operating	Ground/VLT	0.47 to 0.93	48 x 24 channels	CRAL	1800 to 3600
SUVIT-IFU	Planned	Space/Solar-C SUVIT	0.4 to 1.1	45	Canon	10^5
NIRSpec IFU	Operating	Space/JWST	0.6 to 5.3	30	SSTL	100-2700
MIRI MRS	Operating	Space/JWST	5 to 27.9	21	Cranfield U/UK ATC	1500-3500
IFC-S	De-scoped	Space/Roman	0.4 to 2.0	20		100

https://www.eso.org/public/images/ann1012b/ (MUSE)
https://jwst-docs.stsci.edu/jwst-mid-infrared-instrument/miri-instrumentation/miri-spectroscopic-elements (JWST MRS)
https://www.electrooptics.com/analysis-opinion/i-made-mirrors-onboard-james-webb-0 (JWST MRS)
https://ui.adsabs.harvard.edu/abs/2017SPIE10590E..1RG/abstract (IFC-S)
https://ntrs.nasa.gov/citations/20190027219 (FC-S)

APPENDIX A. SPECTROGRAPH FLIGHT SOFTWARE