SAGE IV Pathfinder multi-spectral imaging spectrometer telescope paves the way for semi-custom CubeSat imaging missions

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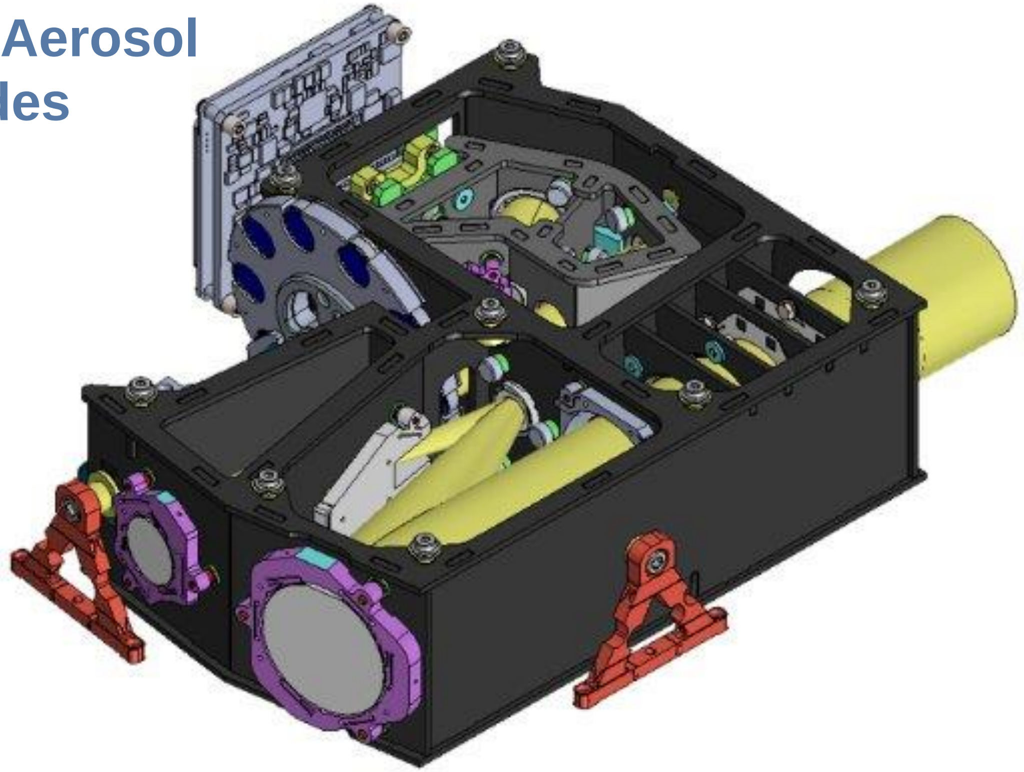
Benefits of the SAGE IV Pathfinder Telescope

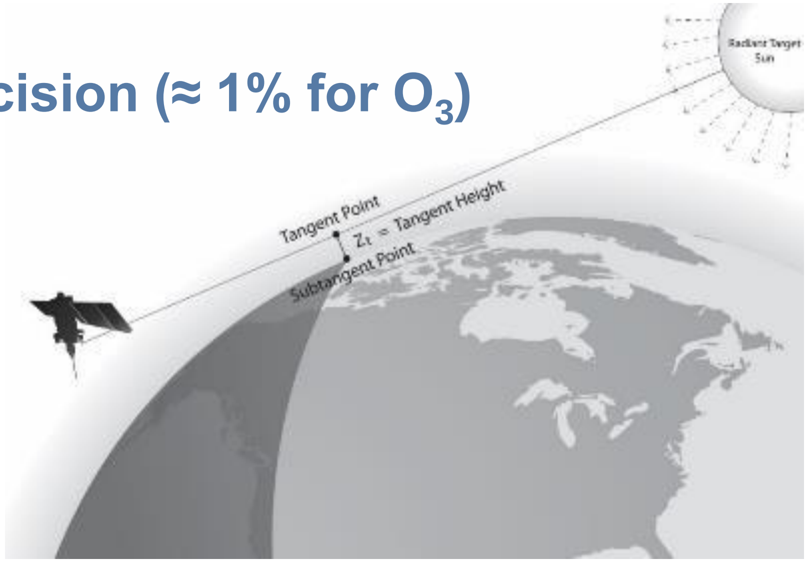
- **SAGE IV Pathfinder looks to usher in the next generation of SAGE instruments**
  - NASA Langley has been executing Stratospheric Aerosol and Gas Experiment missions for over four decades
- **NASA applied a systems-engineering-first approach at the outset of SAGE IV**
  - Paired with Quartus' analysis-heavy design approach, this resulted in the development of a thermally insensitive small format imager
- **We are advocating that this telescope, and other analysis-heavy optical systems, have designs and analytical models that can be heavily leveraged to reduce the cost of future missions**



CAD model of the SAGE IV telescope

The SAGE Series of Instruments

- **SAGE utilizes the method of solar occultation to retrieve vertical profiles of atmospheric species and state**
  - Solar occultation looks at the sun as a source and measures transmission though the atmosphere at specific wavelengths to indicate the presence of particular species
- **Pros of the Occultation Method**
  - Bright Source → Very High Signal-to-Noise → High Precision (≈ 1% for O_3)
  - Excellent vertical resolution in the atmosphere (≈ 1 km)
  - Relative measurements are self-calibrating for every science event
- **Cons of the Occultation Method**
  - Only two measurements per orbit (sunset & sunrise)



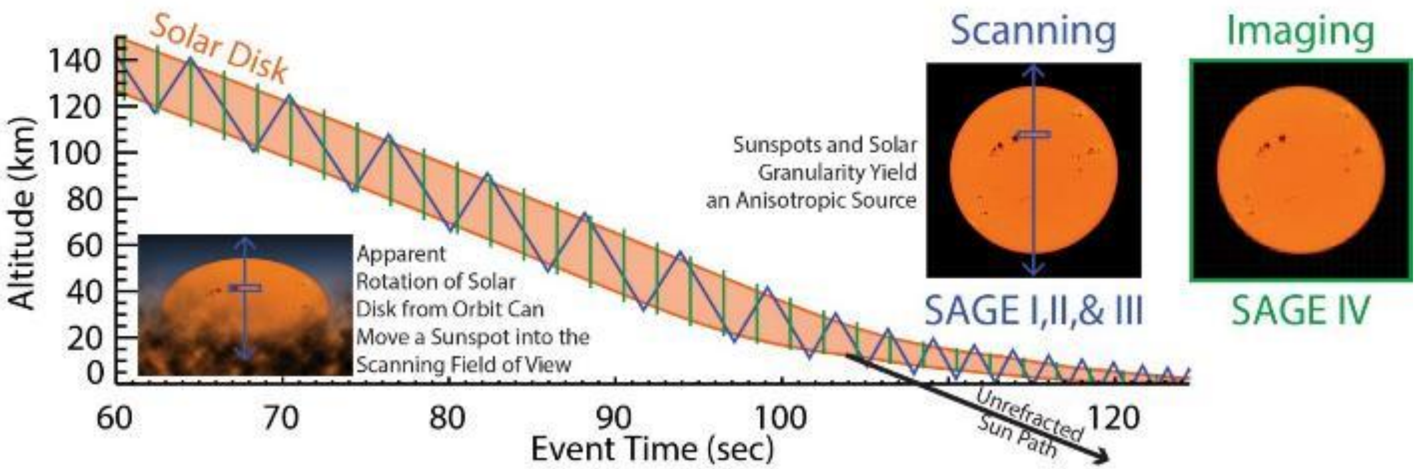
Solar occultation views the sun through the atmosphere

Why are SAGE measurements Important?

- The Clean Air Act mandates that NASA monitor atmospheric ozone
  - In addition, accurate records of stratospheric aerosols are a vital piece of the puzzle regarding climate change
- SAGE has historically been shown to be one of the best measurement systems for precision and accuracy of stratospheric ozone and aerosol retrievals
  - Many instruments use SAGE data as a calibration standard

SAGE III/ISS is currently on orbit collecting data

Scanning (SAGE I/II/III) vs. Solar Imaging (SAGE IV)



SCANNING

- **Pointing knowledge is critical and requires heavy (≈350 kg) and expensive mechanisms.**
  - Assumptions made about instrument mechanical stability during an event
- **External meteorological data are required to compute refraction for tropospheric and lower stratospheric pointing.**
- **Assumed radiometric symmetry of the solar disk**

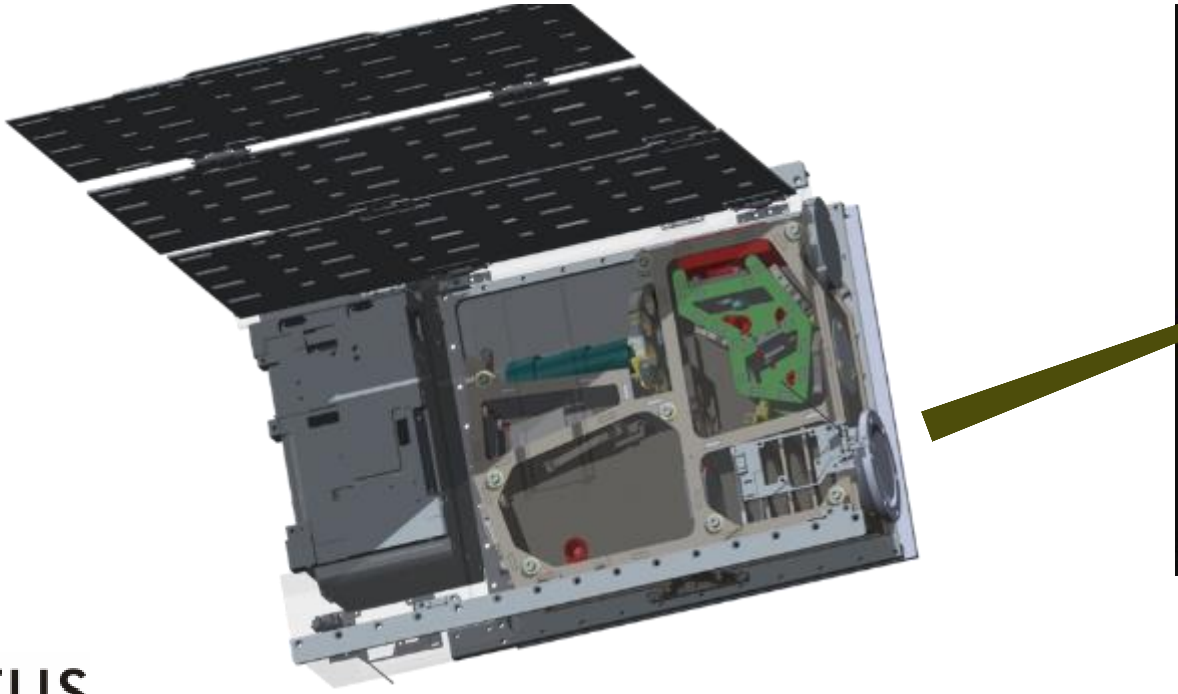
SOLAR IMAGING

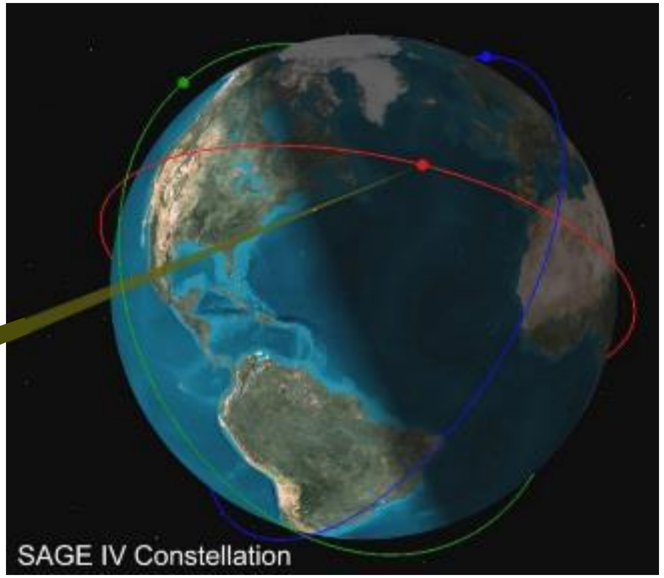
- **Absolute pointing is intrinsic to solar imaging**
  - No assumptions are required for tracking mechanisms
- **Atmospheric refraction information is retrievable**
- **Anisotropy of the solar disk is measured**

SAGE IV Pathfinder Flight Mission Concept

Stray Light Model of SAGE IV

- **Develop a solar occultation imager capable of SAGE-quality ozone and aerosol measurements**
- **The instrument and spacecraft fit inside a 6U CubeSat form factor**
    - **Enables sustainability and a constellation for better coverage**





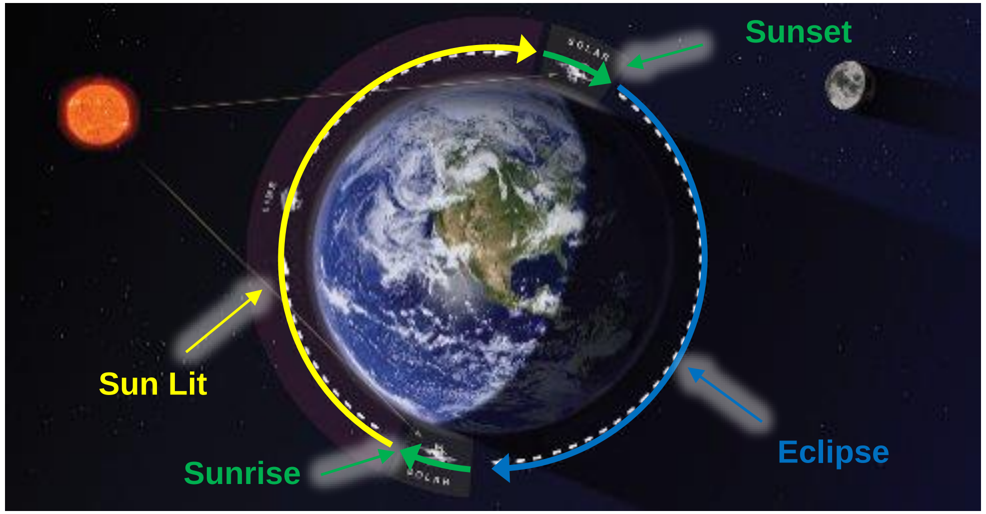
Key Telescope Requirements

SAGE IV Pathfinder draws most requirements from previous SAGE instruments:

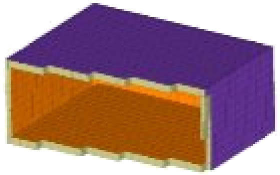
- **FOV: 1 degree (60 arcmin)**
  - Previous instruments scanned 33-40 arcminutes to capture solar disk with margin
  - SAGE IV was extended to 60 arcminutes to allow for spacecraft pointing uncertainty
- **Optical Performance: near-diffraction limited spot size of 90% EE in a 30 μm pixel**
  - Allows for trades between size and performance of future iterations of the design
- **Stray light rejection: < 1.0E-4 PSNIT at 0.5° outside of the FOV**
  - Observations in solar occultation can span 4-5 orders of magnitude
  - As such out-of-field stray light rejection is critical to the science mission
  - Sun is the brightest object, but ocean glint or "lit-up" atmosphere can cause measurement errors
- **For the Science goals to be met all of this must survive launch and over the LEO on-orbit thermal environment**

SAGE IV Telescope Development Trades

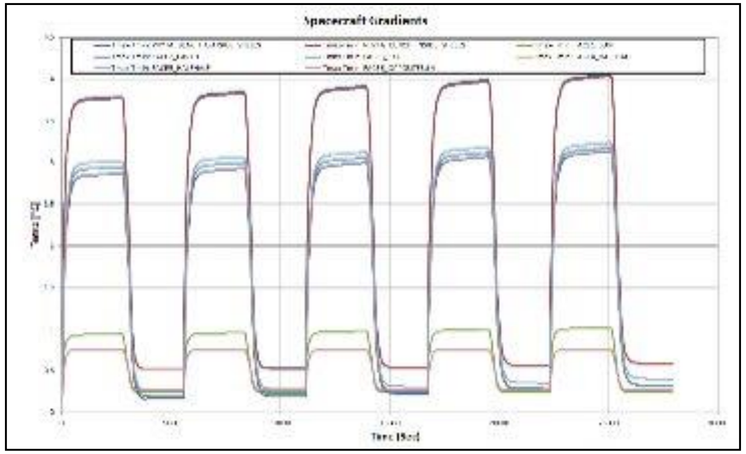
- **The SAGE IV telescope project kicked off with analysis based trade studies to quantitatively explore various designs:**
  - **OPTICS TRADE STUDIES**
    - **Architecture; Sensitivity Study; Fabrication Considerations**
  - **MATERIAL SELECTION**
    - **On orbit thermal analysis was used to predict chassis thermal gradients over a defined "Event"**
    - **Analysis was run with different materials to compare performance with different materials for mirrors, mounts, and bench/metering structure**



Space Craft Thermal Model

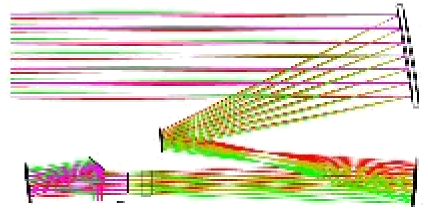


Space Craft Temperatures On Orbit



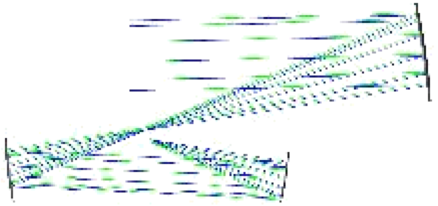
Telescope Optical Architecture Trade Study

- **Several optical architectures compared:**
  - Expected optical performance;
  - Stray light management
  - Complexity (fabrication and alignment → Cost)
  - Availability of collimated space for filters
- **Performance was more of a driver than cost**
  - The result was a more complex, high performing system



Bai Design
- Same telescope front end
- Only one mirror to image, reducing expected image quality

Expected Op. Perf.	2
Collimated Space	3
Stray Light Features	2
Complexity	2

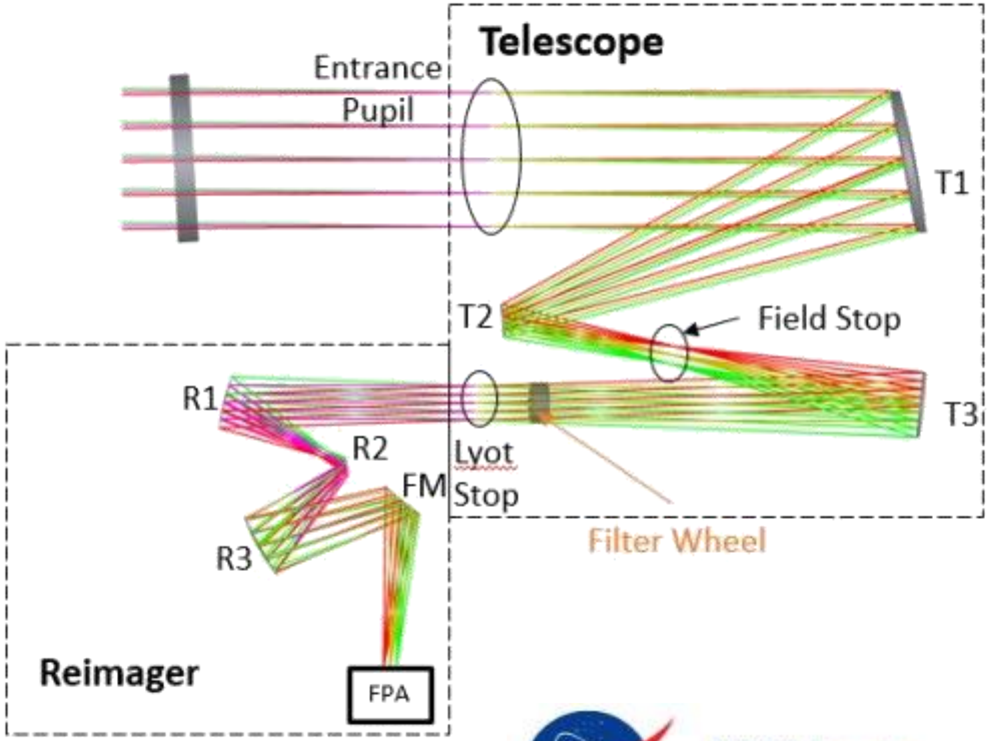


Off-Axis, Eccentric Paul-Gregorian
- Much simpler System
- Only 1 intermediate focus
- Entrance pupil is system stop
- NOTE: Requires fold mirrors

Expected Op. Perf.	2
Collimated Space	3
Stray Light Features	2
Complexity	3

Final Architecture
- 2 intermediate focus
- Entrance pupil & system stop
- Collimated Space for filters
- Requires fold mirror
- Split design allows decoupling of subsystems

Expected Op. Perf.	3
Collimated Space	3
Stray Light Features	3
Complexity	1

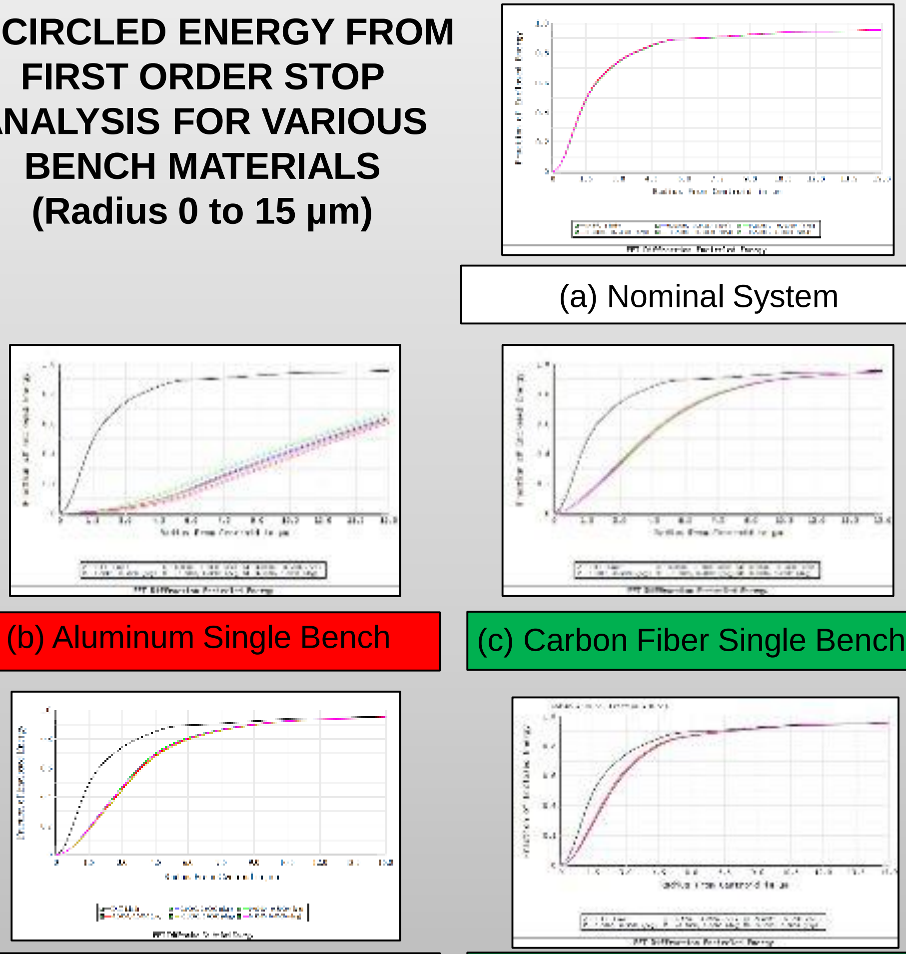


Metering Material and Architecture Trade

- **Used common metrics to explore materials:**
  - **Thermal Stability:** [k/CTE]
    - Large is better: lower gradients & thermoelastic effect
  - **Thermal Distortion:** (Transient): [CTE*ρ*C_p / k]
    - Lower is better at handling temporal variances
  - **Specific Stiffness:** (strength to weight ratios) [E / ρ]

- **Two material paradigms were explored with 1st Order Stop analysis:**
  - **High conductivity:** (minimize thermal gradients)
    - Aluminum Bench / SiC Mirrors
    - SiC Bench / SiC Mirrors
  - **Low CTE:** (more thermally insensitive)
    - Carbon Fiber Bench / Zerodur Mirrors
  - **C.F./Zerodur & all SiC design both could work**
    - *C.F. Bench & Zerodur Mirrors deemed lower risk with evolving thermal boundary conditions*

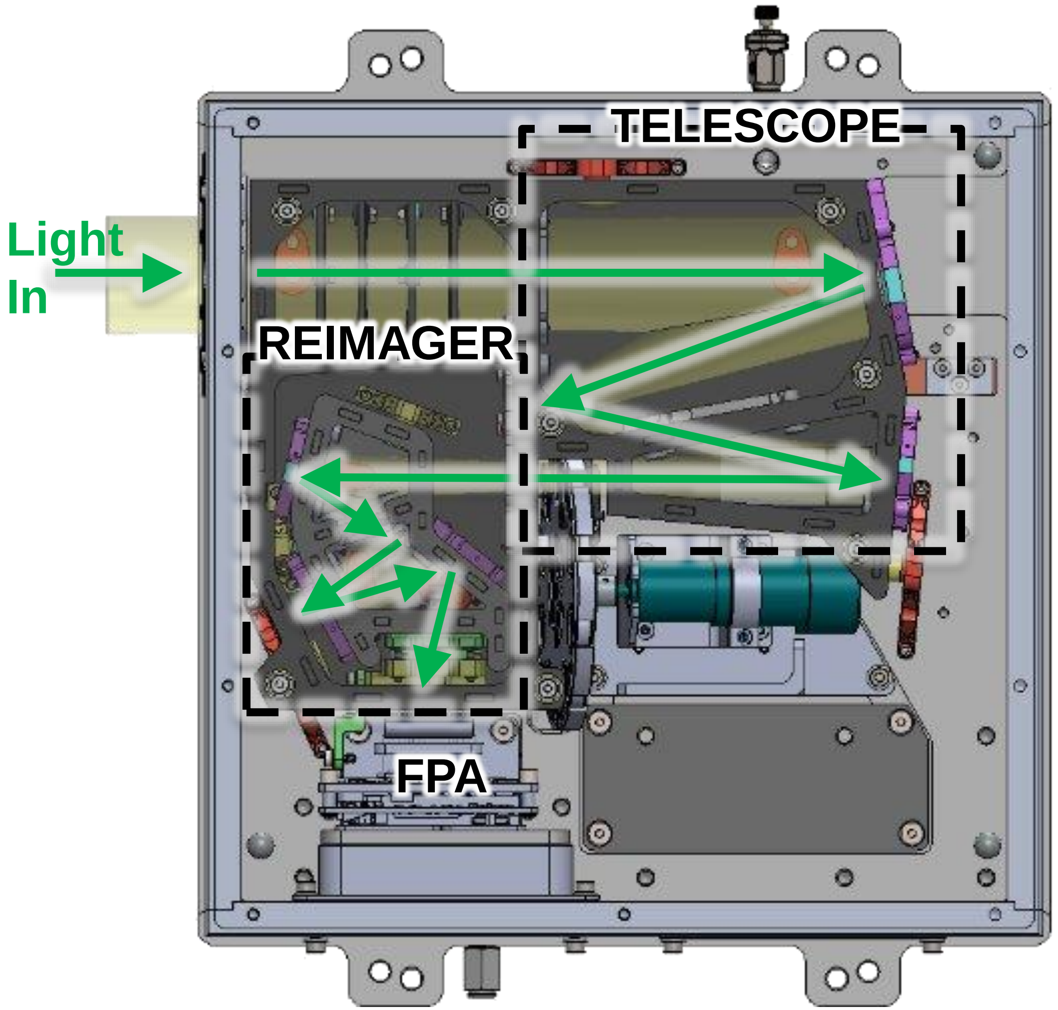
ENCIRCLED ENERGY FROM FIRST ORDER STOP ANALYSIS FOR VARIOUS BENCH MATERIALS (Radius 0 to 15 μm)



(a) Nominal System
(b) Aluminum Single Bench
(c) Carbon Fiber Single Bench
(d) Silicon Carbide Single Bench
(e) Carbon Fiber Dual Bench

A Paradigm Shift in Science Instrument Development

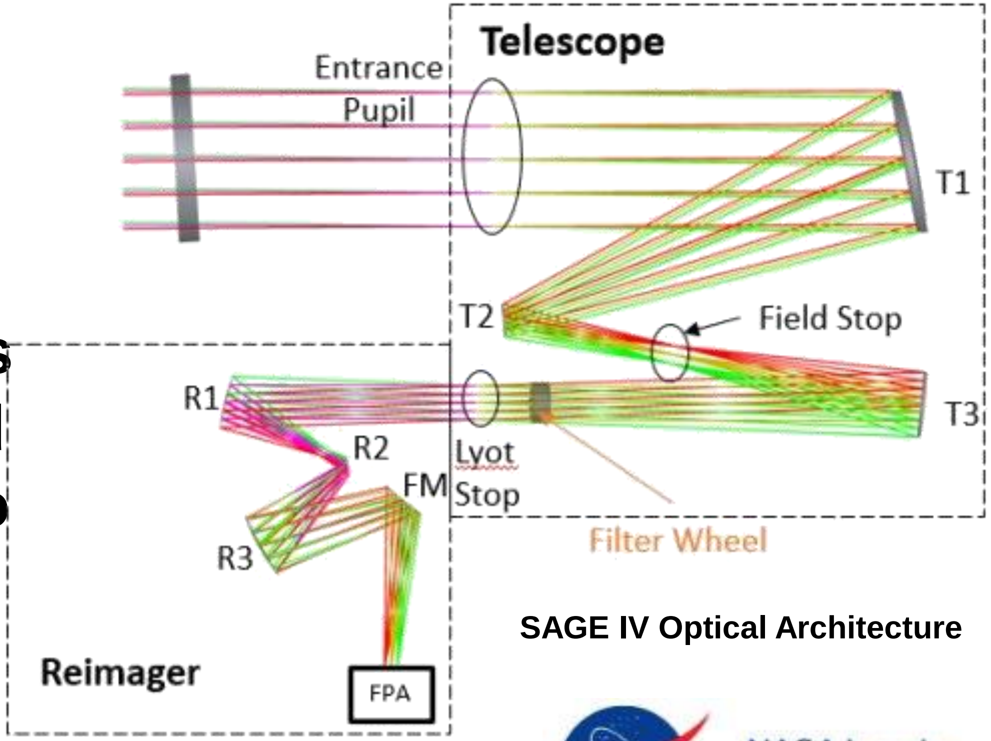
- **The resultant SAGE IV Pathfinder telescope, while designed for a particular mission, has many key features that new missions could leverage**
  - **We propose low TRL missions explore existing instruments, like SAGE IV Pathfinder, to determine how an mission might leverage existing hardware and analytical tools that are available**
- **If the science community begins to embrace this paradigm shift it will lower the barrier of entry to high performing space science missions**



Reusable Optical Analysis Tools

- **Development of the optical system required many analytical tools to be developed or refined for this unique telescope, including:**
  - Performance merit functions
  - Operational wavefront error budgets
  - Stray light models
  - Fabrication tolerance budgets
  - Optic metrology techniques
- **The implementation of these analytical tools is costly, if these tools are validated beyond this particular use case, they can be used to accelerate and reduce the cost of future missions**

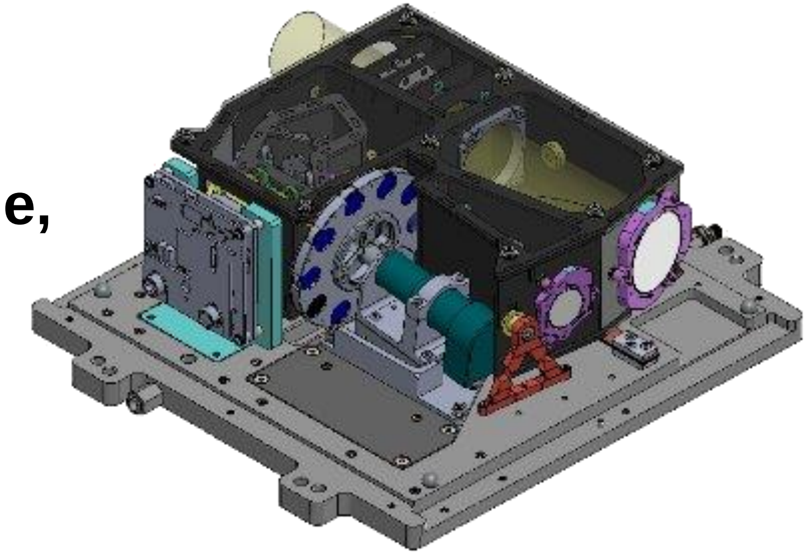
Stray Light Model of SAGE IV



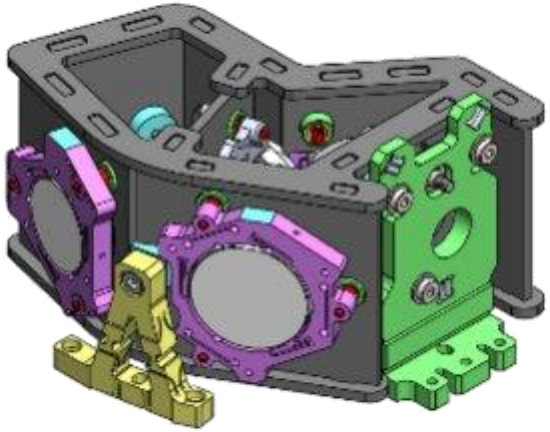
SAGE IV Optical Architecture

Optical Variants for Future Reduced Cost Missions

- **Key optical items that could be altered on a future mission to save development costs typically associated with a new system include, but are not limited to:**
  - Change front and/or back-end modules
  - Aperture
  - Field of view
  - Filters to observe at different wavelengths
  - Detectors (pixel density, materials, etc…)
  - Reduction of complexity
    - i.e. reduce complex stray light suppression, use the back end as a proven 4° FOV TMA, etc..
  - Leverage mechanical components and analyses for alternate optical components
    - i.e. include refractive elements, gratings, etc..



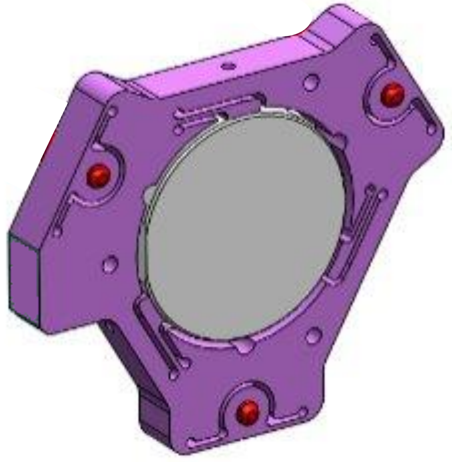
SAGE IV Telescope on Surrogate Chassis



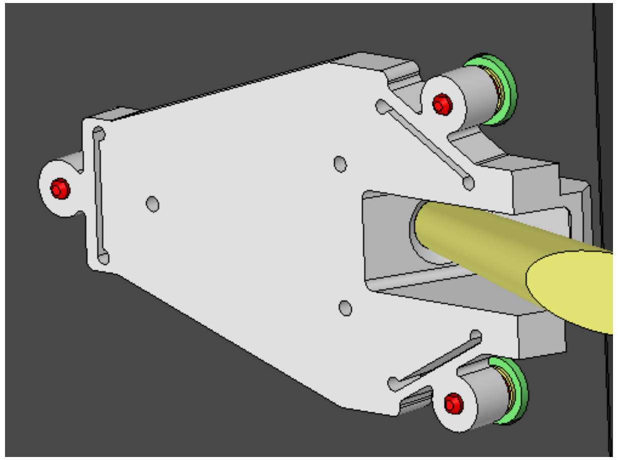
Backend Reimager Module

Exploitable SAGE IV Opto-mechanical Development

- **As with the optical design, significant development was done of mechanical components and system level design and analysis tools**
  - **Analysis of components and system level STOP models can be used to verify expected performance of new systems using established parameters**
- **The following component level designs can be leveraged with relative ease for new layouts and component sizes**
  - **Mirror mounts and optical stops**
  - **Metering structure design methodology and inserts**
  - **Mounting features and components**



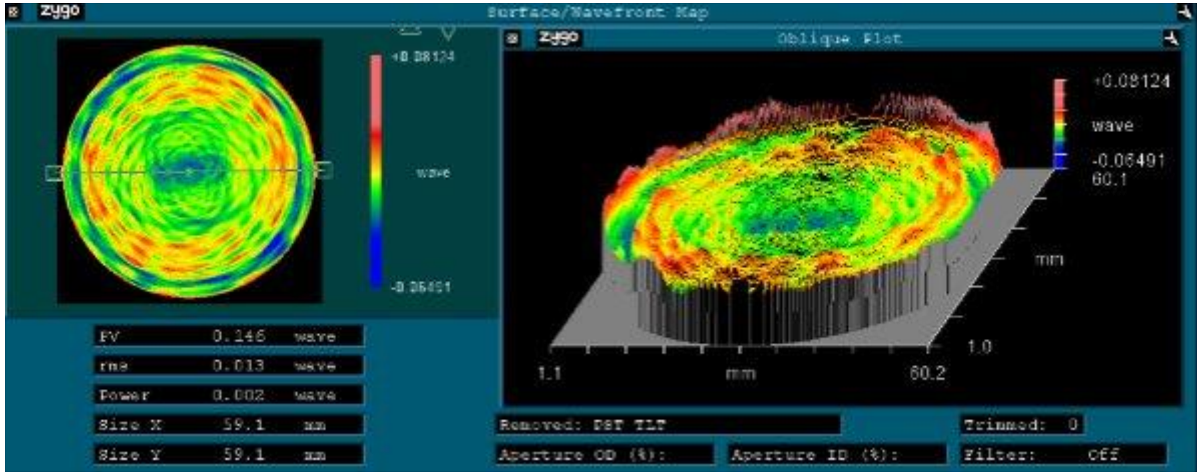
Example of a Mirror Mount Design



Example of an Optical Stop

Developed Assembly and Fabrication Techniques

- **Fabrication, metrology, and alignment tools and techniques are critical for a successful optical system, and generally take time/money to mature**
  - While these optics are modeled as off-axis aspheric surfaces, the optics were fabricated and measured in a manner similar to freeforms, requiring significant process validation
  - Using these established processes will save significant efforts and costs by gaining some amount of economy of scale not often available on one-off space systems
- **In addition, as more missions utilize the same components, fabricated parts could be procured in larger quantities**
  - Previous spares could be repurposed for new missions, further reducing costs

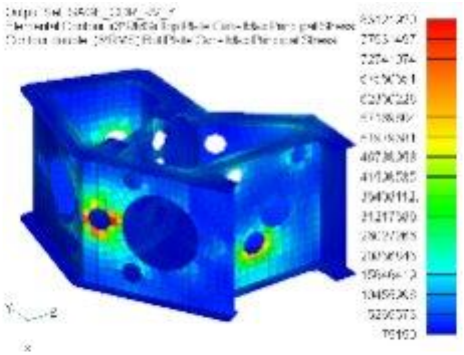


Optical Surface measurements

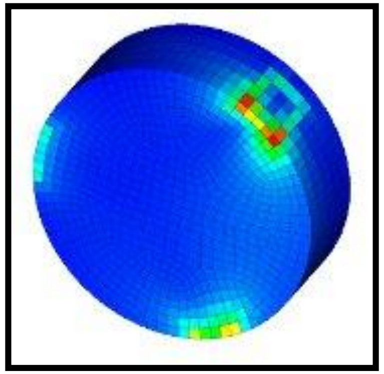
Leveraging Analytical Tools Predicated on Validation

- **Leveraging existing system designs and analysis tools to reduce the cost of future missions is predicated on the ability to believe the analysis performed**
  - Random Vibration Structural Analysis
  - STOP Analysis
  - Stray light analysis
- **Analysis predicts all of the performance requirements after launch and while exposed to on-orbit operational environments**

Examples of Random Vibration Structural Analysis Results



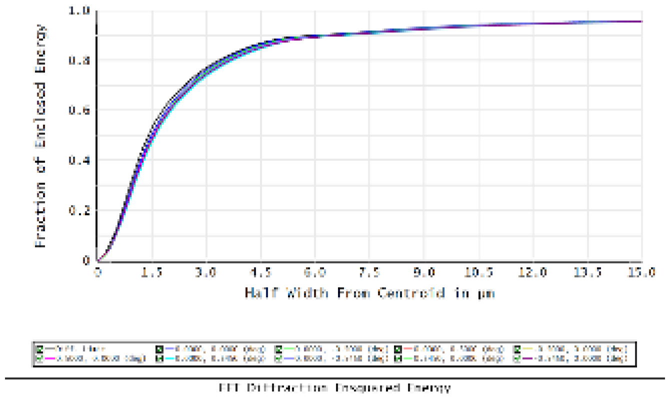
Y Direction
3σ Max Principal stress = 83.12 Mpa
Allowable = 305.9 Mpa
MS = +0.42



Y Direction
3σ Max Principal stress = 4.93 Mpa
Microyield = 6.9 Mpa (1 ksi)
Microyield MS = +0.40

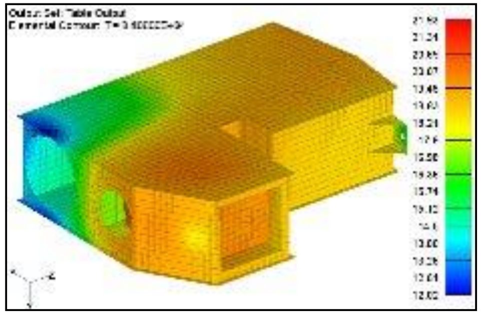
SAGE IV Pathfinder STOP Analysis Models

- **Structure Thermal and Optical Performance (STOP) analysis shows that the selection of thermally agnostic materials with low CTE should indeed maintain performance as required during an event**
  - **If effort were expended to validate these models beyond the single use case of SAGE IV, these models would be more usable for future missions**

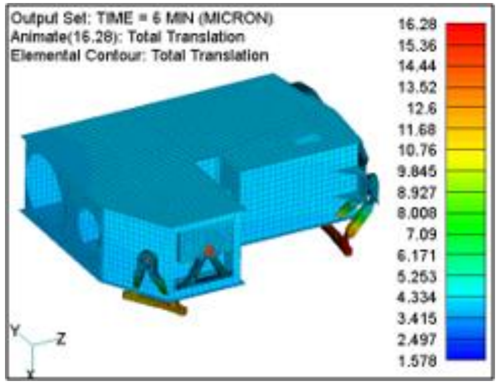


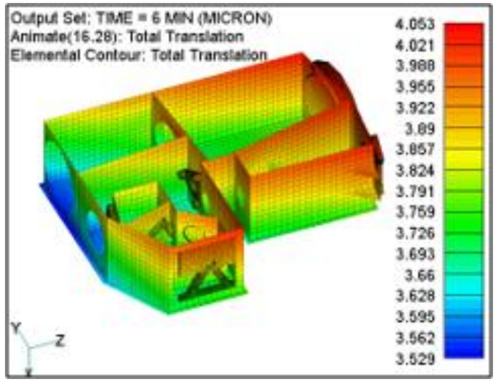
Expected Performance at
t = 0 minutes (before sunrise)

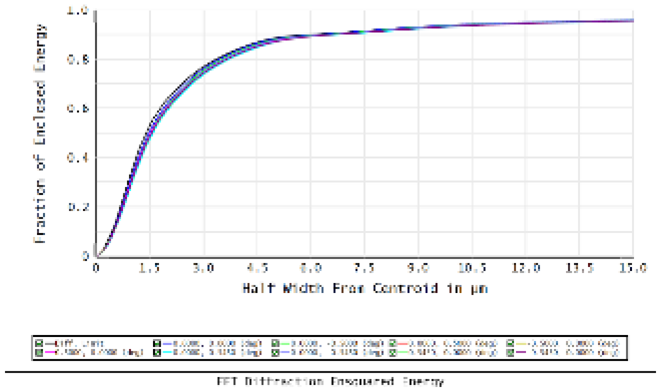
Temperatures (°C)



Displacements (micron)



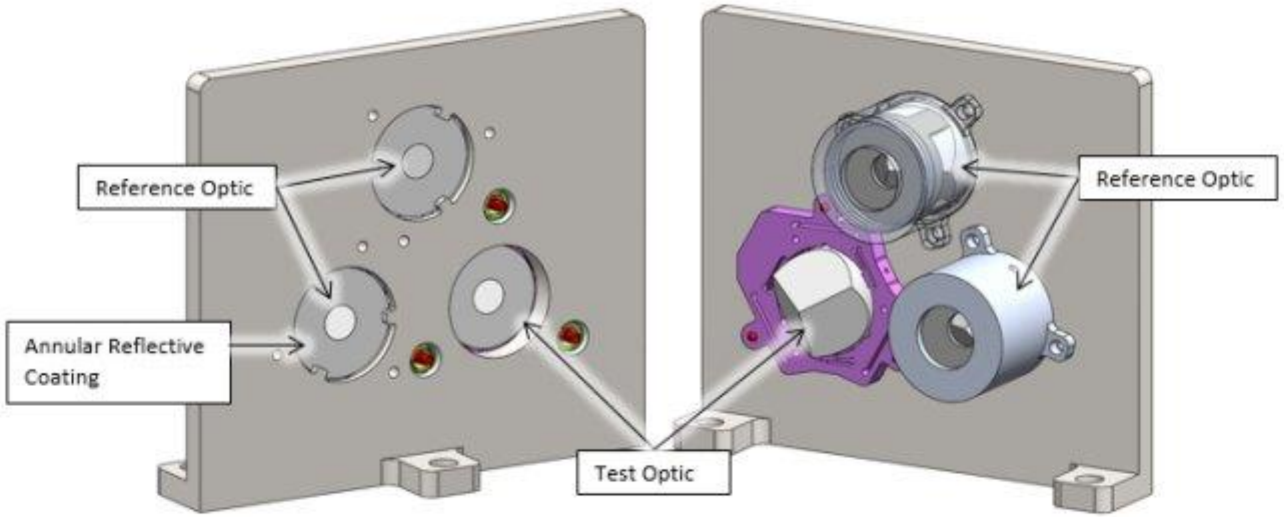




Expected Performance at
t = 6 minutes (after sunrise)

STOP Analysis Validation for Broad Usage

- **Quartus plans to do testing focused on validating the STOP analysis and components to a level beyond what is needed for the SAGE IV mission**
  - **This validation will allow the same models to be used for any future missions that look to leverage the SAGE IV-like component designs and analysis tools for new applications, greatly reducing the cost and schedule of future missions**

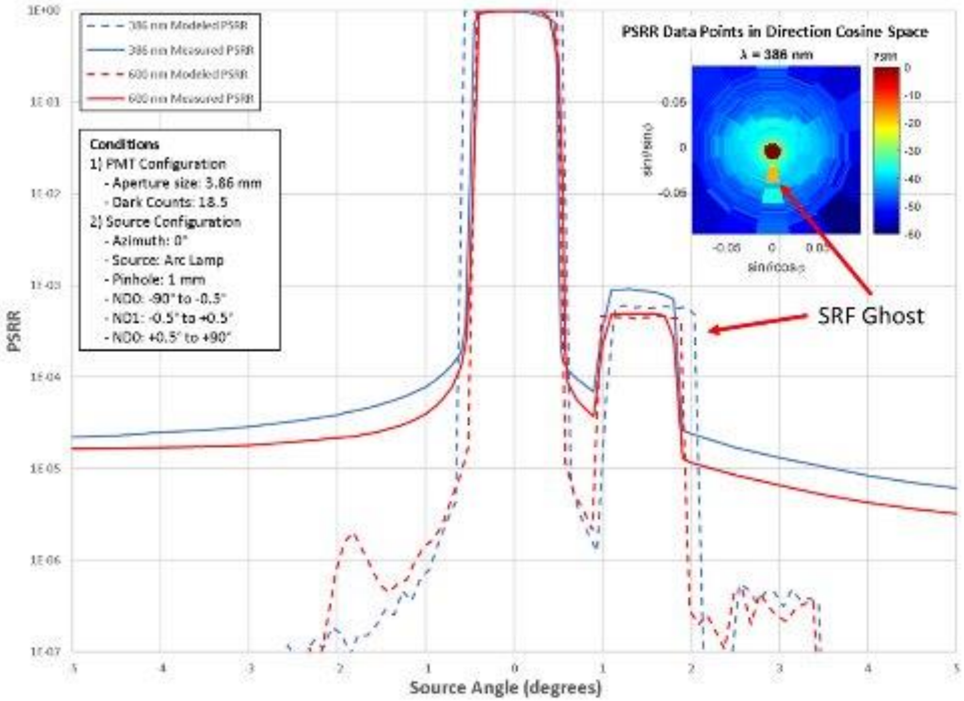


Conceptual test setup for component level testing

Stray Light Model Validated

- One of the critical aspects of this telescope design is the stray light rejection to ensure only photons from the pixel field of view (IFOV) land on each pixel
- Stray light analysis performed, showed only a single anticipated artifact:
  - An expected 1st order ghost reflection from the solar filter wedge, which will be managed in CONOPS
- Testing at Space Dynamics Lab (SDL) verified the analysis trends and approach
  - Demonstrated the system exceeds the performance requirement goal [< 1E-4 at 0.5º outside the FOV]
- This model and its conservative parameters can be leveraged on new missions to reduce risk from stray light

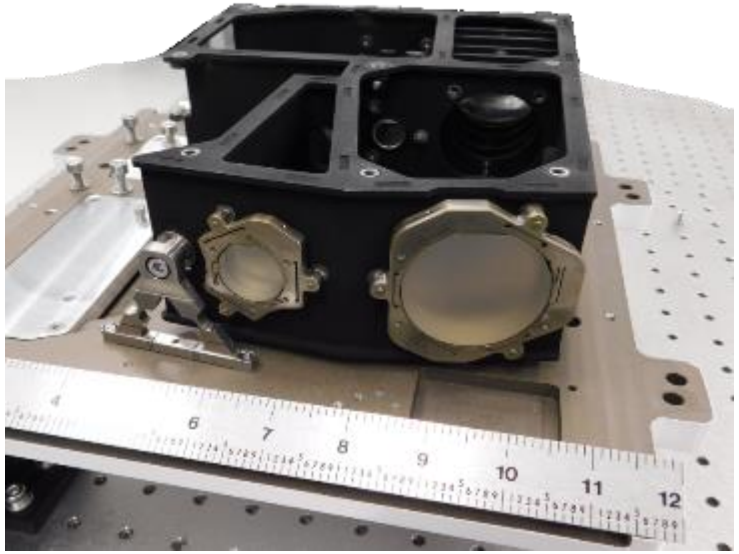
Stray Light Model of SAGE IV



Modeled and Measured PSNIT of 386/600 nm

Doing More Science for Less

- **The 2017 Committee on the Decadal Survey for Earth Science and Applications from Space called out a need to reduce mission costs for space based Earth observations**
  - To meet the increasing demand for space borne science missions, it is imperative that mission costs be brought down without prohibitively increasing risk
  - While the need for larger science missions will remain robust, significant gains can be made on reducing the cost of smaller missions
- **It is neither unusual nor novel for industries to leverage existing designs**
  - At the close of a project, it is uncommon to find that the developed tools can be as easily repurposed to future projects as we found on SAGE IV Pathfinder
- **We encourage the science community to explore what can be developed leveraging this and other existing instrument designs**
  - This paradigm shift can allow for the world's limited science resources to be stretched further



SAGE IV Pathfinder telescope hardware

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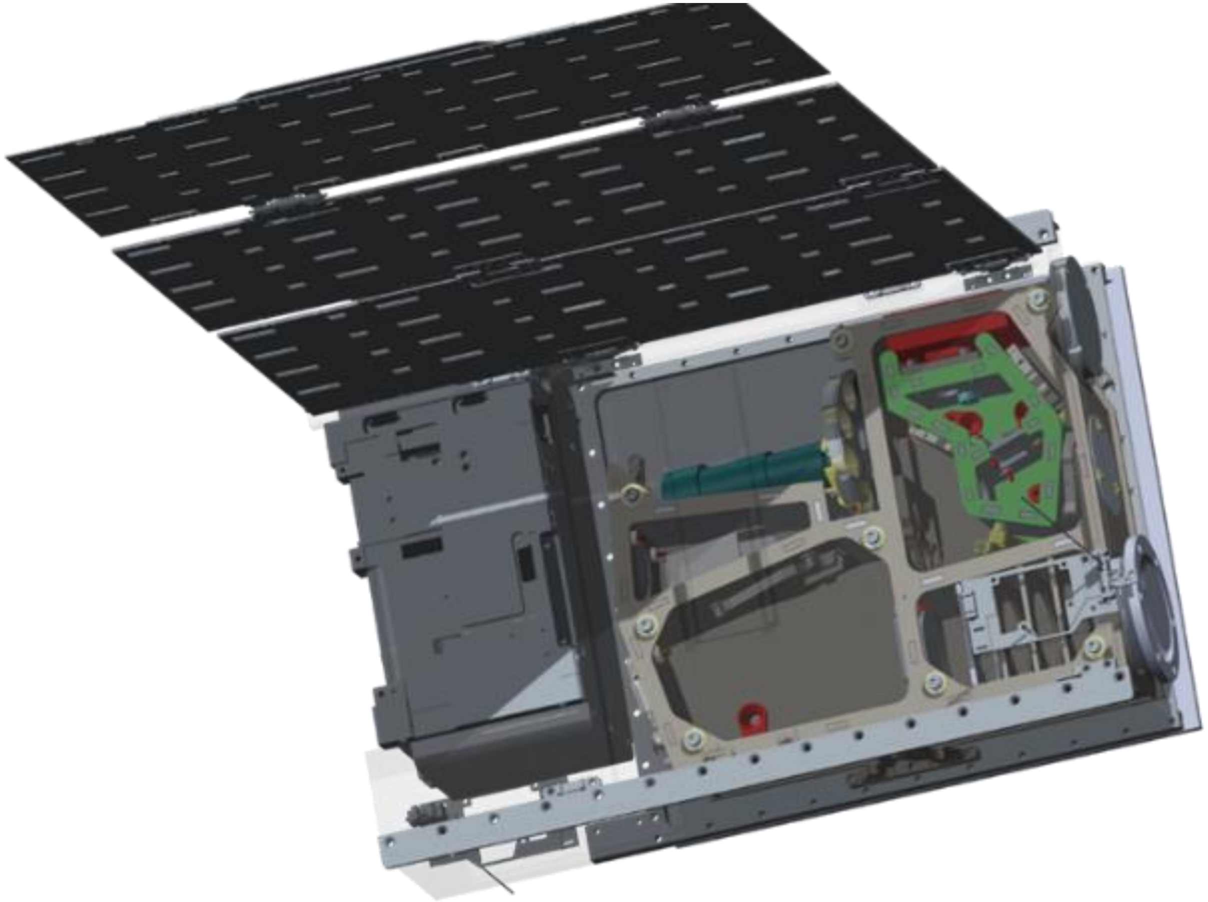
  - Special thanks to the SAGE IV Pathfinder co-principal investigators:
    - Rob Damadeo
    - Charles Hill



See a SAGE IV Pathfinder model

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