SAGE IV Pathfinder
Earth Science Technology Forum

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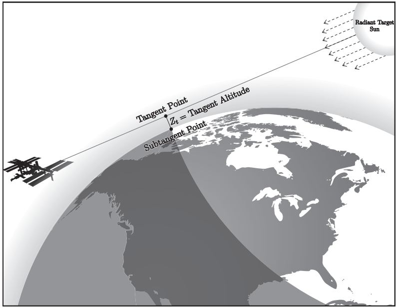
Why are these measurements important?

ESTO
Earth Science Technology Office

- NASA's science priorities primarily follow the Decadal Survey.
- The Clean Air Act mandates that NASA monitor atmospheric ozone, which is also identified in the DS Explorer program.
- Accurate records of stratospheric aerosols are a vital piece of the puzzle regarding climate change and are now a Designated Observable under the 2017 Decadal Survey.
- Current spaceborne observations of ozone and aerosol involve one of several methods.
  - limb sounders (e.g. MLS)
  - backscatter (e.g. SBUV)
  - occultation (e.g. SAGE)
- SAGE has historically been shown to be one of the best measurement systems for precision and accuracy of stratospheric ozone and aerosol retrievals.

The SAGE Series of Instruments



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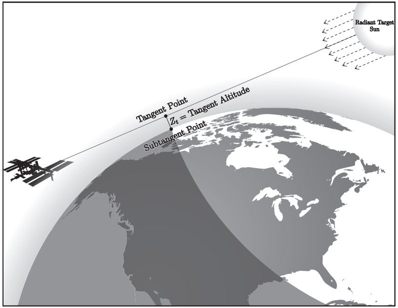

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- Pros of the Occultation Method
  - Bright source $\rightarrow$ Very high Signal-to-Noise $\rightarrow$ High precision ($\approx$ 1% for O_3)
  - Excellent vertical resolution in the atmosphere ($\approx$ 1 km)
  - Relative measurements are self-calibrating for every science event

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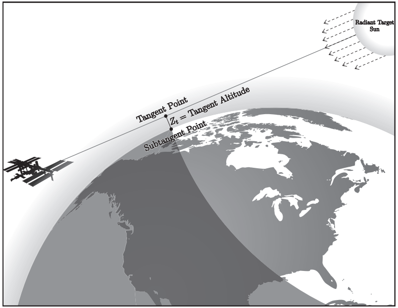

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- Cons of the Occultation Method
  - Only two measurements per orbit

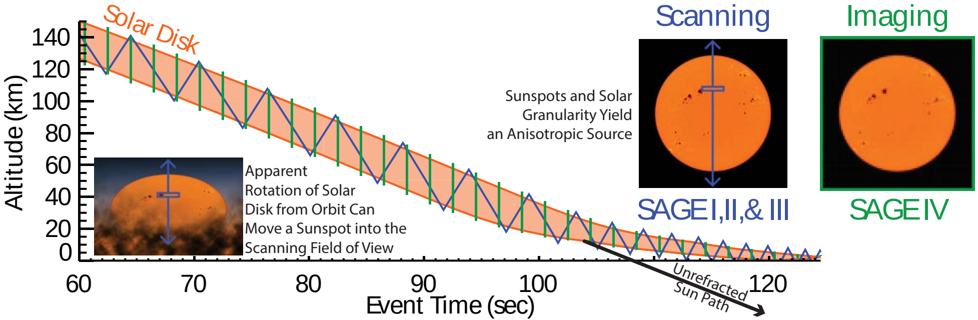
Why Not Just Build A Mini SAGE III?

Four decades of expertise in solar occultation at NASA Langley give us insight into areas that can be improved.

Limitations of SAGE I/II/III's scanning technique

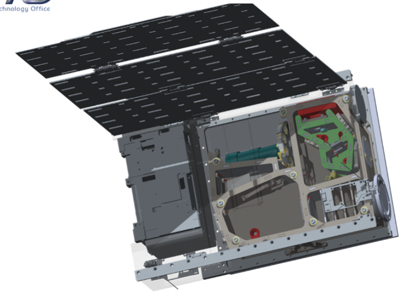
- Pointing knowledge is critical and requires heavy ($\approx$ 350 kg) and expensive mechanisms, or for a CubeSat extremely accurate and reliable ADCS.
- Assumptions made about instrument mechanical stability during an event
  - Linearity of scan mirror motion (CubeSat: pointing knowledge vs. accuracy)
  - Azimuthal tracking expects a uniform image (problem down low . . . clouds complicate this)
  - Nonorthogonal transient behaviors (e.g., mirror reflectivity, thermal behavior)
- External meteorological data are required to compute refraction for tropospheric and lower stratospheric pointing
- Assumed radiometric symmetry of solar disk (creates a noise floor for scanning small FOVs)

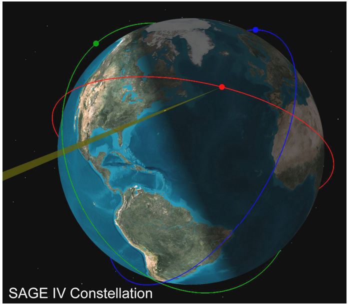
What Are The Benefits of Solar Imaging?



- 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.

Flight Mission Concept





- Solar occultation imager capable of SAGE-quality ozone and aerosol measurements
- Instrument and spacecraft fit inside a 6U form factor
  (not our primary motivation, but great benefits!)
- Enables sustainability and a constellation for better coverage
- Future: IR extensibility for better H_2O, gain CH_4 and CO_2
- Future: Possible limb scattering instrument

IIP Goals and Objectives

- Develop a laboratory SAGE IV prototype enabling a follow-on transition to a low-risk flight mission
  - Demonstrate the radiometric performance of the system through laboratory and Sunlook testing
  - Utilize commercially available parts with a clear path to flight
- Three Year Plan:
  - PY1: Develop requirements, process major procurements, build and test telescope
  - PY2: Assemble Filter Wheel, finalize firmware and software, test subsystems, receive detector, integrate
  - PY3: Test fully integrated system in laboratory environment and Sunlook, use lessons learned to perform mission studies
- SAGE IV relevance to 2017 Decadal Survey Report
  - Aerosols and ozone are designated as observing system priorities.
  - SAGE IV meets definition of newly-recommended Venture-continuity missions by "bringing forward innovative approaches to sustain measurements at lower costs."

Internal Team

Name	Org	Role
Rob Damadeo	E303	Co-Principal Investigator
Charles Hill	E303	Co-Principal Investigator
Mike Obland	E304	Project Manager
Luke Murchison	D206	Systems Engineer
Tom Johnson	D207	Avionics and Integration Lead
Stanley Ikpe	D203	Electronics Lead/Detectors
Abou Traore	D211	Optical Eng. Support
Ed Nemie	D202	Mechanical Lead
Mark Banchy	D207	Software Developer
Drew Sellers	D207	Software Developer
Tak Ng	D203	Firmware Developer
Rich Wright	D203	Firmware Developer
Anish Parikh	E3	Scheduler

Name	Org	Role
Meredith Hartzheim	D211	Opto/Elec. Tech
Tory Scola	D206	Thermal Analyst
Bob Wagner	D206	Structural Analyst
Jennifer Esparza	B103	Contract Specialist
Marie Avery	B602C	Program Analyst

Involved Organizations

- Quartus Engineering — SSAI Subcontractor
  - Design and critical stray light analysis of telescope
  - STOP analyses and tolerancing
  - Fabrication of telescope and surrogate chassis
- Teledyne Imaging Sensors — Partner Organization
  - Fabrication of the detector and its electronics
- Blue Canyon Technologies — Partner Organization
  - Informs boundary conditions and design constraints
  - Provides interface between instrument and spacecraft
- NASA Langley Research Center — Funded by ESTO
  - Fabrication/Integration of Filter Wheel Assembly and TEC
  - Embedded control systems (Firmware and Software)
  - Avionics and support systems
  - Overall management of work

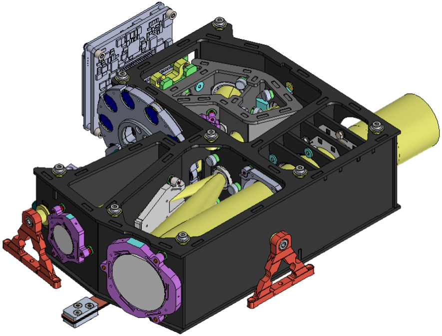
Detector

- Detector Specifications
  - SiPIN Diode Array
  - Large potential wells for high SNR
  - Low pixel cross talk and no Charge Transfer Inefficiency
  - Individually registered pixels
  - Read noise and dark current are well within acceptable levels at room temperature
- Advanced acquisition of Detector Demo Kit
  - Shorter lead time procurement that allows early hardware in the loop testing with the instrument control electronics and associated firmware/software
  - Delivered on schedule and completed acceptance testing
- Delivery expected in 10 months. Currently using a surrogate detector.
- Available detector variants allow for relatively easy transition to the infrared.

Telescope: Mechanical Design – Opto-Mechanics

- Components affecting optical performance use materials with matched CTE to bench/optics

- Optical Components (INVAR 36)
  - "CTE Matched" to Zerodur
  - 7× Mirror Mounts
  - 3× Knife Edge Stops (Entrance Pupil, Field Stop, and Lyot Stop)
- Inserts (INVAR 36)
  - "CTE Matched" to metering structure
  - Reworkable liquid pinning components

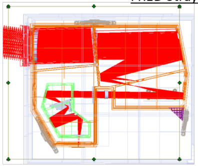


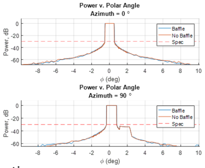
- System is insensitive to bulk motion of benches
  - Mounting Flexures (TITANIUM)
    - 3× Primary and 2 Reimager Bipods
    - FPA Blade Flexures
  - *Not all components listed here*

Telescope: Stray Light Analysis and Testing

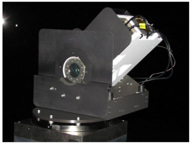
- One of the critical aspects of this telescope design is the stray light mitigation to ensure only photons from the pixel field of view (IFOV) land on each pixel.
  - Stray light analyses showed a high performing system with a single anticipated artifact: a 1*st* order ghost reflection from the external solar filter wedge.
  - The ghost is easily mitigated in CONOPS to eliminate impacts to science.
- Testing at Space Dynamics Lab (SDL) verified the analysis trends.
  - The demonstrated system exceeded the performance requirement goal ($< 1 \times 10^{-4}$ at 1° outside the FOV).

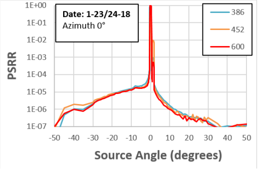
FRED Stray light analysis





SDL Stray light Testing



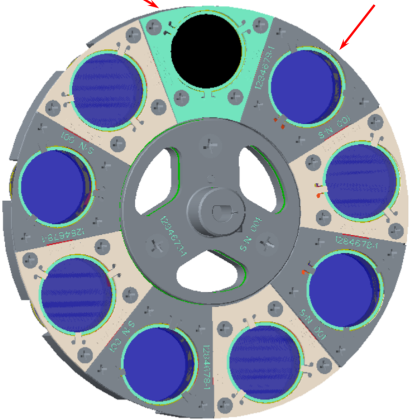


SDL commented that it was "the best instrument they have tested."

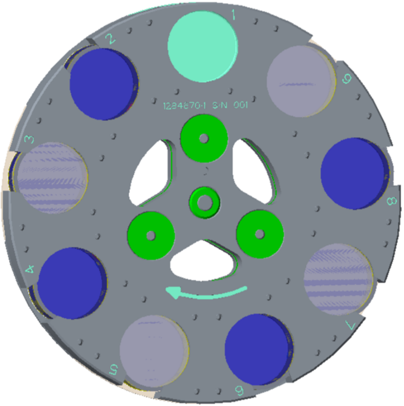
Filter Wheel Design

1x Light block

8x Interference filters



Front side view



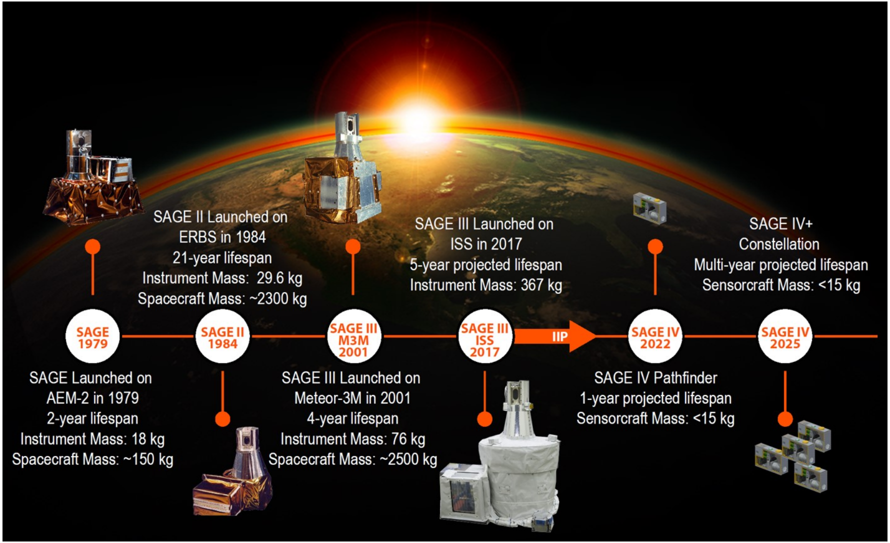
Rear side view

Filter Wheel Optics: Bandpass Filters

- Ohara SK 1300 (Synthetic Fused Silica)
- Out of band blockage: OD >2 from 200–1150nm
- Procured and received from Alluxa

Channel	Center Wavelength	FWHM	Transmission	Species
1	$386.0 \pm 3.0nm$	$15.0 \pm 3.0nm$	$> 70\%$	Aerosol
2	$448.0 \pm 0.50nm$	$2.0 \pm 0.5nm$	$> 80\%$	NO_2
3	$452.0 \pm 0.5nm$	$2.0 \pm 0.5nm$	$> 80\%$	NO_2
4	$525.0 \pm 3.0nm$	$15.0 \pm 2.5nm$	$> 90\%$	Aerosol
5	$600.0 \pm 2.0nm$	$15.0 \pm 3.0nm$	$> 80\%$	O_3
6	$1020.0 \pm 3.0nm$	$15.0 \pm 3.0nm$	$> 80\%$	Aerosol

A Pathfinder for SAGE Miniaturization

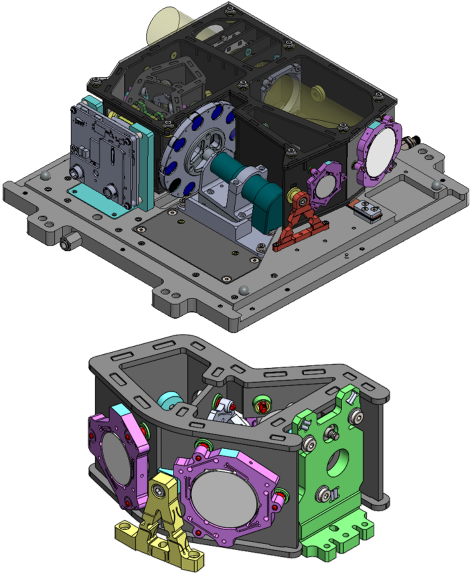


Backup

Target Measurement Performance Parameters

Parameter	SAGE IV
Measurement Vertical Resolution	< 1.0 km
Stratospheric Ozone Precision	$< 1.0\%$
Stratospheric Aerosol Precision	$< 1.0\%$
Stratospheric H_2O	$< 5.0\%$
Stratospheric NO_2	$< 5.0\%$
Exoatmospheric Measurement Precision	$< 0.05\%$
Encircled Energy	90% at 30 μm (0.5 arcmin)
Sampling Frequency	0.5 Hz

SAGE IV Pathfinder Telescope



Avionics: Design Overview

- Design Concept
  - Path to Flight
  - Utilize COTS development boards/Firmware Intellectual Property (IP) as much as possible
    - Microsemi SmartFusion2 Dual Axis Motor Controller Starter Kit (DVP-102-000417-001): Includes Motor Control FPGA IP for filter wheel stepper motor control
    - Microsemi SmartFusion2 Advanced Development Kit (M2S150-ADV-DEV-KIT): Includes FPGA IP for many digital interfaces (SPI, UART, etc.)
    - Xilinx ZC702 Evaluation Board for the ZYNQ-7000: Utilizes the Sundance DSP FMC-CL Cameralink module with FPGA IP
- Modular design provides flexibility for IIP subsystems
- Stepper Motor Selection
- Resolver versus Encoder Trade Study

Software Summary

- Approaching Build 1 release
  - Motor Control Firmware Interface Utilizing an off-the-shelf software/firmware component for motor control providing significant time savings
  - Operator Support Software (OSS) Large amount of re-use from previous projects providing significant time savings
  - Camera Control Board (CCB) - Utilizing an off-the-shelf software/firmware component for the Camera Link interface
- Near-Term Testing
  - Transfer raw images over Ethernet to the OSS to save in a file. Verify the images transfer and match without errors
  - Integrated motor controller test Ground System + Motor Controller Software + Motor Controller Firmware