Sizing the Sun: Theodolite Investigations of Ground-Based SAGE III/ISS Solar Collimators

Cassidy Klahn

NASA Langley Research Center
Guardians of Honor

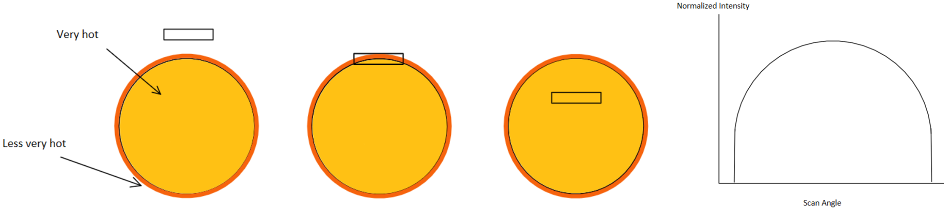
8/14/25

Goal For SAGE III: Accurate Limb Pointing

- In the inversion algorithm, the size of the Sun is a hardcoded value and it is used alongside ISS and solar ephemeris to calculate SAGE III position and pointing assuming we can properly locate the Sun edges during a scan
- We need to know where the SAGE LOS is pointing to create the I/I_o calibration curve for in-atmosphere measurements
- It is also needed to assign the correct tangent altitudes to measurements
- The system bicells are able to (azimuthally) track the vertical centroid of the Sun to within an arcminute, so an accurate and precise determination of the solar edges at scan top and scan bottom is needed for accurate limb pointing and solar placement

How Do We Determine the Edges with Data?

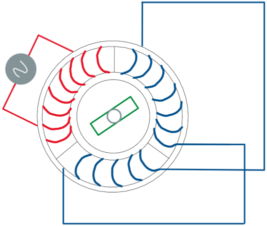
- Scanning the Sun generates a limb darkening curve at the edges because of the solar atmosphere
- The SAGE III algorithm has always placed the edges of the photosphere during a scan at the limb darkening curve inflection points, where the second derivative is equal to zero



Visualization of a solar scan and limb darkening curve

Comparing Solar Size With the Instrument: Scanning the Sun

- SAGE III's scan head consists of a rotating scan mirror, as well as a rectangular science slit
- This system scans the field of view vertically over the Sun
- The RVDT (Rotary Variable Differential Transformer) is used to measure the angular displacement of the scan mirror, which can later be used to measure an angular solar diameter

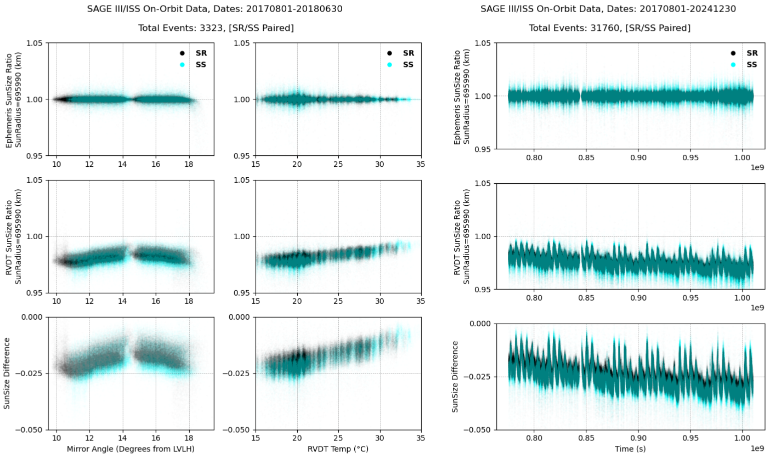


RVDT diagram

What is the Problem?

- There is a discrepancy in absolute pointing knowledge between on-orbit occultation observations using known orbital geometry/ephemeris at solar edges and expected scan mirror motions using pre-launch calibrations.
- That is, the calibrated RVDT angular positions of the detected edges yield a different apparent solar diameter (up to 3%, which is about 1 arcmin) than what is expected by algorithmic calculations based on solar position, ISS position, and the known solar radius.
- This implies that either the RVDT-measured angular position of the scan mirror is not accurate or that the method of detecting the solar edge is not accurate to better than 0.5 arcminutes

What is the Problem?



Ephemeris and RVDT comparison

Possible Problems with the RVDT

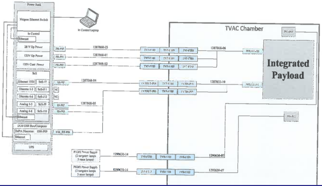
- Temperature dependence (expected)
- Scan mirror flexure pivots relaxing their rigidity over time through repeated use on orbit, resulting in a smaller measured solar diameter than what would be expected from ground calibrations
- Slight nonlinearity between RVDT voltage and scan mirror angle that was observed and characterized on the ground and mildly affects the stability of the scan mirror rate. (This is caused by torsion strain in the scan mirror axle by torquing against the flexure pivots.)
- Possible RVDT vacuum susceptibility (unlikely)

Possible Problems with Solar Edge Characterization

- Stray light in the telescope (aperture diffraction, secondary mirror and spider)
- The science slit is relatively small and adds to the aperture diffraction of the telescope
- The optical train post-science-slit imaging heavily involves diffraction effects through other optical elements (e.g., diffraction grating) that complicate determination of throughput diffraction beyond the simple sinc function applied to the slit alone
- This can invalidate the simplifying assumptions used to derive the inflection point method for solar edge detection
- Generally for a discrete data set, there can be a range of measured values where the second derivative is calculated by interpolation to be equal to zero, generating inherent uncertainty in inflection method

Finding the Truth: Testing SAGE III and the RVDT

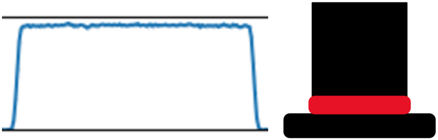
- Pointing Image Generators (PIGs) and Collimated Source Benches (CSBs) are SAGE III ground support equipment that create collimated solar and lunar images for ground testing of the flight instrument
- Most ground testing was performed with CSBs
- During the Thermal Vacuum (TVAC) Test of SAGE III, two PIGs were used in the vacuum chamber for operational testing; PIG #2 was used in the simulated WAKE direction and PIG #3 (currently lost) in the simulated RAM direction for sunset and sunrise geometries respectively
- Because we still have access to (most of) these collimators, my internship has involved accurately measuring the generated solar image sizes using calibrated theodolites and comparing these measurements to RVDT angular measurements and edge detection algorithm methods



TVAC testing layout

Investigating TVAC Data

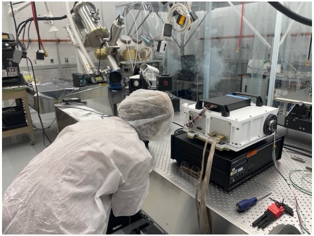
- Thermal Vacuum Testing is pre-flight ground testing performed in a space-like environment (large vacuum chamber that can be heated with quartz heaters or cooled via shroud quenching with liquid nitrogen to simulate orbit cycles)
- Data archived from this test can help us rule out vacuum susceptibilities in the instrument RVDT and analyze edge detection accuracy
- PIGs and CSBs don't generate typical limb darkening curves like the Sun when we scan them (no solar atmosphere); they resemble top hats
- We can still apply the standard edge detection method to see how we would register the size of the image compared to the theodolite-measured angular sizes

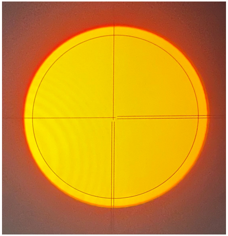


Scan of a PIG vs. a top hat shape

Theodolite Measurements

	Vertical Diam (degrees)	Horizontal Diam (degrees)
CSB 1	0.526278 ± 0.000508	0.530194 ± 0.000481
CSB 2	0.509861 ± 0.000678	0.581056 ± 0.000632
PIG 2	0.533819 ± 0.000504	0.531236 ± 0.000365

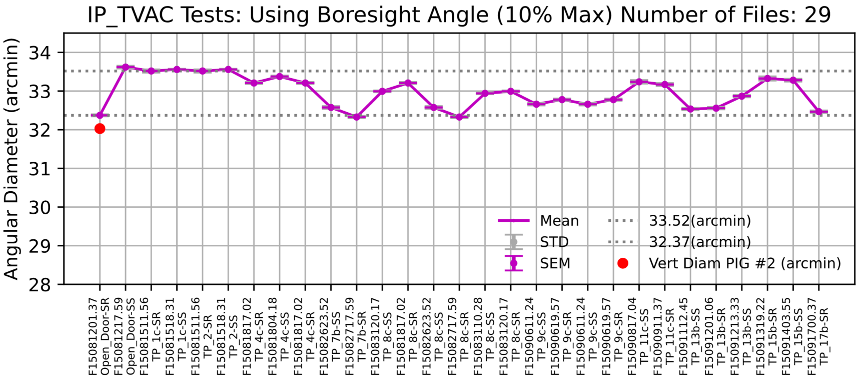




Theodolite measurements of PIG#2 collimated image in clean room

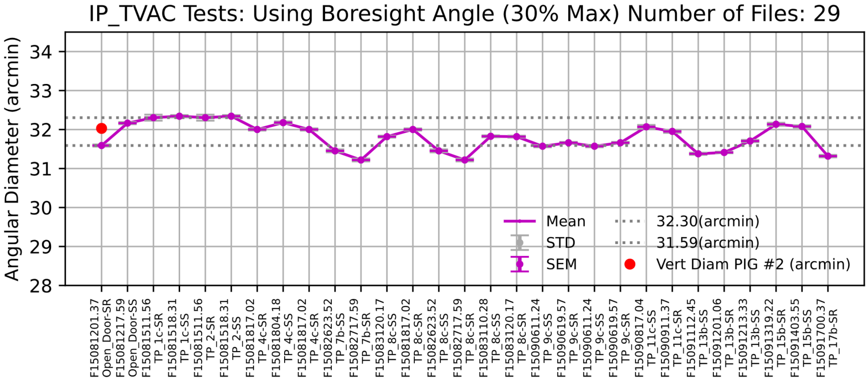
Edges at 10 Percent of the Max

- Characterize solar edges based on percentage of the maximum and compare results to theodolite measurements



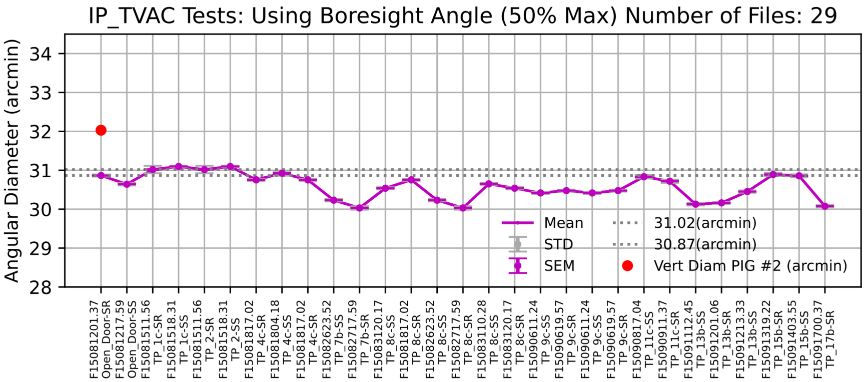
Mean elevation angle difference for F-Files with edges characterized at 10 percent of the maximum

Edges at 30 Percent of the Max



Mean elevation angle difference for F-Files with edges characterized at 30 percent of the maximum

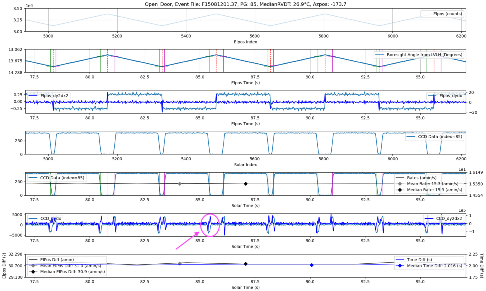
Edges at 50 Percent of the Max



Mean elevation angle difference for F-Files with edges characterized at 50 percent of the maximum

Compare to Inflection Points

- F-Files are generated during testing for each event and include multiple scans, we can use the current edge characterization method to find inflection points on each scan
- Using the inflection method, the edges tend to be located at points on the order of 50 percent of the maximum CCD count value
- The measured angular diameter values tend to be closer to 30 percent of the maximum
- These findings are consistent with a measured angular diameter larger than produced with the edge detection algorithm, which indicates a need to question the currently used edge characterization methods



Plots for single F-File showing inflection shape