SOFIA

Stratospheric Observatory for Infrared Astronomy

An Overview of the SOFIA Observatory Performance: Current Status and Future Improvements and Capabilities

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OUTLINE

- Objectives
- Challenges in Airborne Astronomy
- In-flight assessment of Observatory performance
  - Pointing accuracy, stability and drift
  - Tracking
  - Image Quality – Size and shape
  - TA Focus
- Future improvements and observatory upgrades
- Summary

Objectives

SOFIA has reached Full Operation Capabilities (FOC).
This presentation is to provide a selected overview of the current Observatory performance.

We focus on certain areas such as image stabilization, pointing, and tracking which pose specific challenges to the Observatory.

Improvements plan to reduce the image size and close the gap with the FOC+4 requirements are presented.

SOFIA Overview

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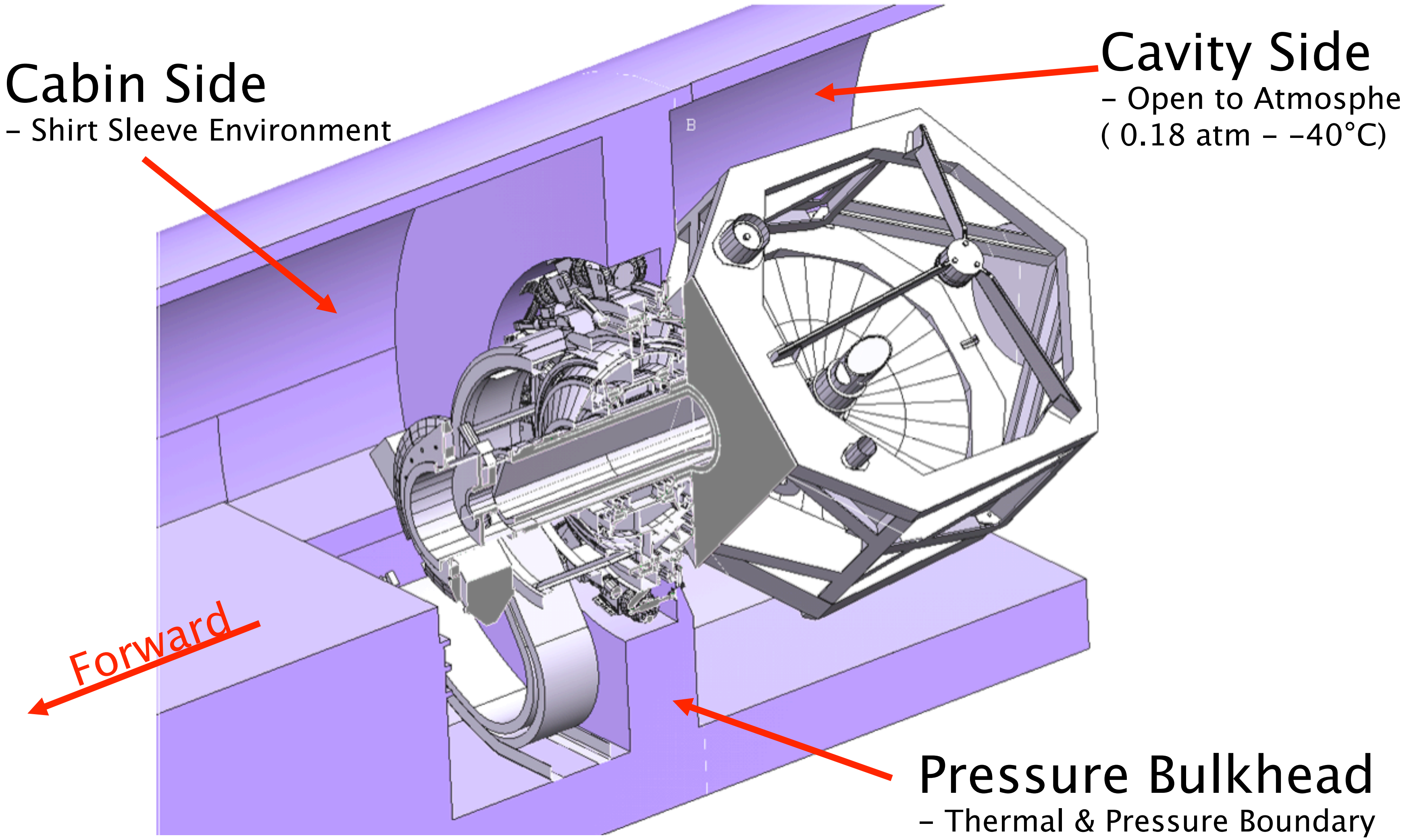
- 2.5-m telescope in a modified Boeing 747SP aircraft
  - Imaging and spectroscopy from 0.3 µm to 1.6 mm
- Operational Altitude
  - 39,000 to 45,000 feet (12 to 14 km)
  - Above > 99.8% of obscuring water vapor
- Joint Program between the US (80%) and Germany (20%)
  - First Light images were obtained on May 26, 2010
  - Science Ops at NASA-Ames; Flight Ops at Armstrong FRC (Palmdale- Site 9)
  - Deployments to the Southern Hemisphere and elsewhere



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SOFIA Overview

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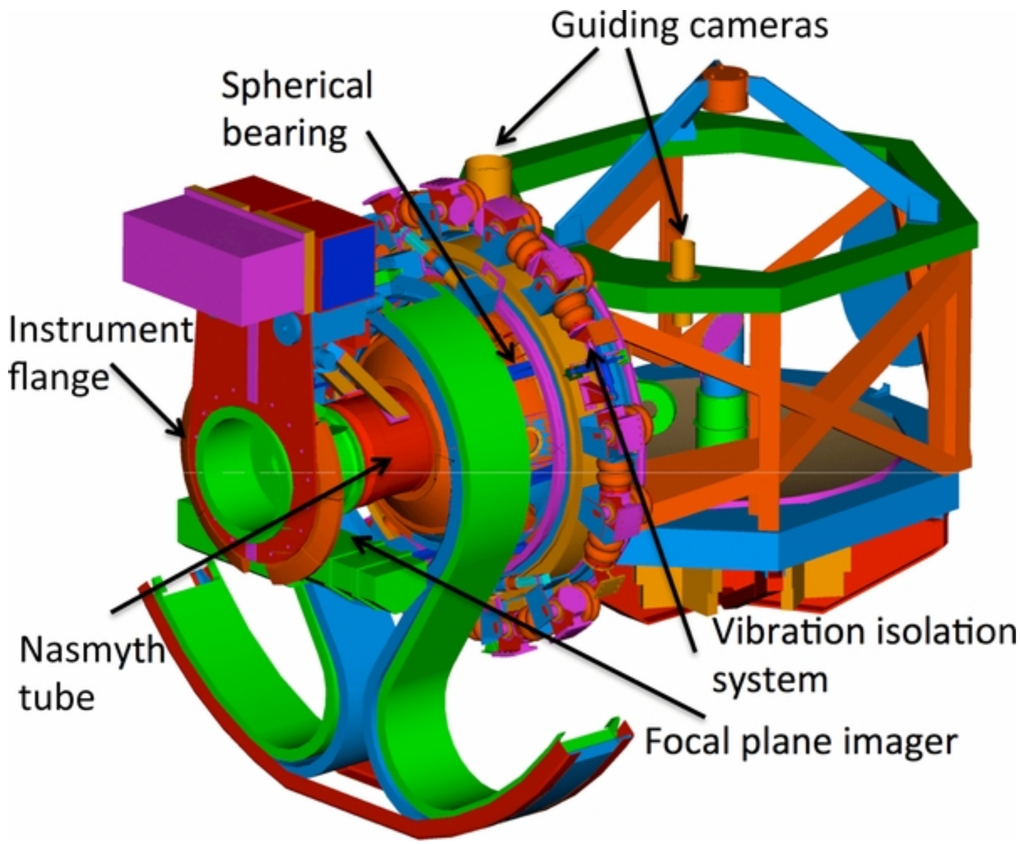

Telescope Assembly (TA):

- Dumbbell design with a central support
- Low-friction hydrostatic oil spherical bearing
- Controlled C.G. via balancing plates
- Structural assembly designed to reduce aerodynamic and aero-acoustic loads
- TA structure is supported on the aircraft bulkhead with a vibration isolation system, which is the only physical connection of the telescope to the aircraft

SOFIA's Challenges

Environment

- Significant Pointing challenges are due to aircraft motion and open door cavity

Large range in operating wavelength

- Optical to FIR (300 um)
- SIs operating at short wavelengths (1-40 microns) demand more stringent requirements compared to far-IR instruments.

Large Science Instrument (SI) suite

- Large variety of observing techniques
- Specific observing modes per each SI

SOFIA's Challenges

Many other challenging aspects of the SOFIA mission are not covered here.

- Mission Operations
- Observatory operations planning
- Observing cycle planning and scheduling
- Aircraft Operations and maintenance
- Flight Planning

Mission Communications & Control System (MCCS)

The MCCS is a system of systems responsible for diverse functions on SOFIA including power control, network functionality, flight management, archival services, video distribution, water vapor monitoring, **supervisory control to the TA**

A primary responsibility of the MCCS is to assist the telescope in pointing

Converts sky reference frame into native telescope inertial reference frame coordinates.

This coordinate conversion allows that the desired target is centered on an investigator-chosen pixel in the focal plane defined to be the science instrument boresight.

Stages of Pointing Stability

1. Platform - Aircraft
   - 747-SP angular stability is nominally 500-1000 arc-sec
   - Aircraft imparts translational vibration into Telescope
   - “Dome” is Open Port Cavity with Mach 0.84 wind outside and a large airflow circulation flow inside
   - Telescope looks through shear layer over cavity opening

2. Rotation Isolation System (RIS)
   - Passive isolation from aircraft rotation
   - Spherical hydrostatic bearing (minimal friction)
   - Requires a controlled C.G.

Stage 2: Resultant Stability is about 50-100 arcsec

Stages of Pointing Stability

3. "Rigid Body" closed loop controller

- Gyros as primary sensors
- Spherical torque motors as actuators
- Focal plane imager to correct gyro drift

Stage 3: Resultant Stability is about 2-6 arcsec

4. Flexible Body Compensation (FBC)

- Requires sensors to determine state (uses accelerometers)
- Modeling is used to predict resultant image motion from quasi static and dumbbell mode structural bending
- Both fine drive torque motors and secondary mirror chopper mechanism are used to steer image back to desired location
- "Open Loop" Control System

Stage 4: Resultant Stability is about 1 – 1.5 arcsec

- Observatory performance
    - Static pointing
        - Absolute pointing
        - Tracking schemes
        - LOS rewinds
        - Matched chop-nod
        - Drift
    - Dynamic pointing
        - Pointing Stability
        - Image size
        - Jitter

Emphasis on MCCS and TA (MCCS, telescope, transforms, etc.)

SOFIA Science Instruments

Instrument Name	Acronym	Home Institution	Country	Type of Instrument
Echelon-cross-Echelle Spectrograph	EXES	UC Davis	U.S.	Echelon Spectrometer
Faint Object InfraRed CAmera for the SOFIA Telescope	FORCAST	Cornell	U.S.	Mid-IR Camera and Grism Spectrometer
Field-Imaging Far-Infrared Line Spectrometer	FIFI-LS	MPE, Garching	Germany	Imaging Grating Spectrometer
First-Light Infrared Test Experiment Camera	FLITECAM	UCLA	U.S.	Near-IR Camera and Grism Spectrometer
German Receiver for Astronomy at Terahertz Frequencies	GREAT	MPIfR, KOSMA, DLR-WS	Germany	Heterodyne Spectrometer
High Speed Imaging Photometer for Occultations	HIPO	Lowell Observatory	U.S.	Optical High-speed Imager
High-resolution Airborne Wideband Camera	HAWC	University of Chicago	U.S.	Far-IR Bolometer Camera
High-resolution Airborne Wideband Camera Polarization	HAWC+	Jet Propulsion Lab (JPL)	U.S.	Far-IR Polarimeter

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DLR

SI Observing Modes

- FORCAST provides imaging and grism spectroscopy beyond 28 μm
- GREAT was recently upgraded to incorporate two arrays of seven pixels each (beyond the initial single pixel detectors) of high-resolution spectroscopy
- FLITECAM can be partnered with the high-speed, multi-channel optical instrument, HIPO, to observe transitory phenomena from a mobile platform with both imaging and spectroscopic observations
- EXES offers a combination of high spectral resolving power (R=100,000) and mid-infrared wavelengths that are unavailable from any ground- or space-based observing platform, existing or planned
- FIFI-LS offers access to spectroscopic observations at a wavelength that has not been achieved before (42-210 μm)
- HAWC+ is the only instrument capable of taking polarization data in the far-IR

SOFIA Observational Maneuvers

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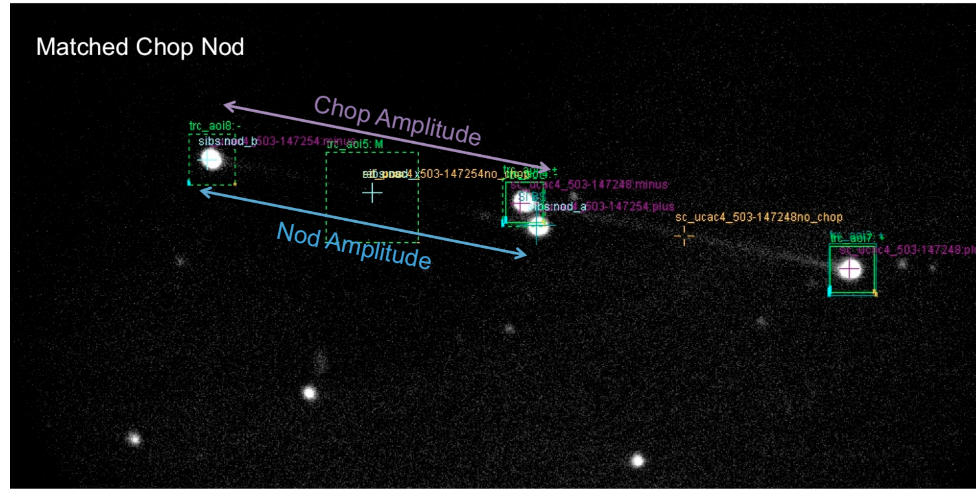
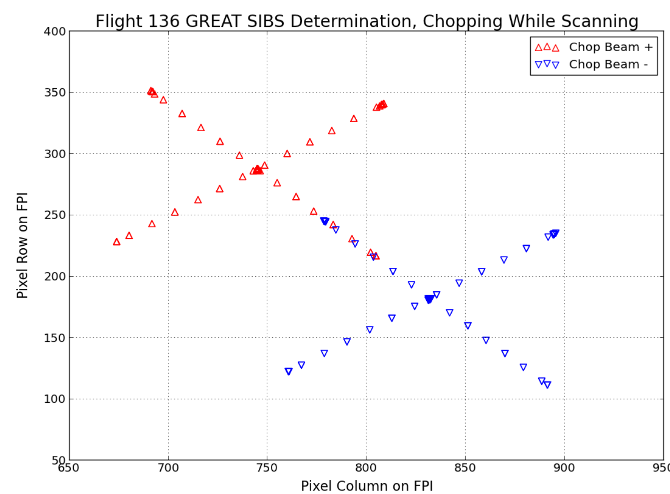
- Telescope Assembly (TA) provides array of maneuvers for imaging and spectroscopy that can be combined to suit the needs of the observation:
  - Chop
  - Nod
  - Scan
  - Dither



Matched two-point chop and two-beam nod



Scanning while chopping

Testing of Errors in Standard Maneuvers

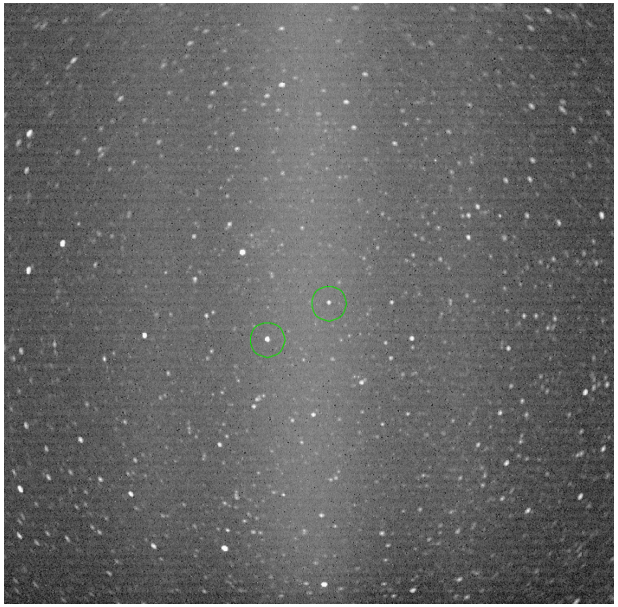
- Nod, chop, tweak, and dither maneuvers performed in various coordinate reference frames across several SOFIA flights

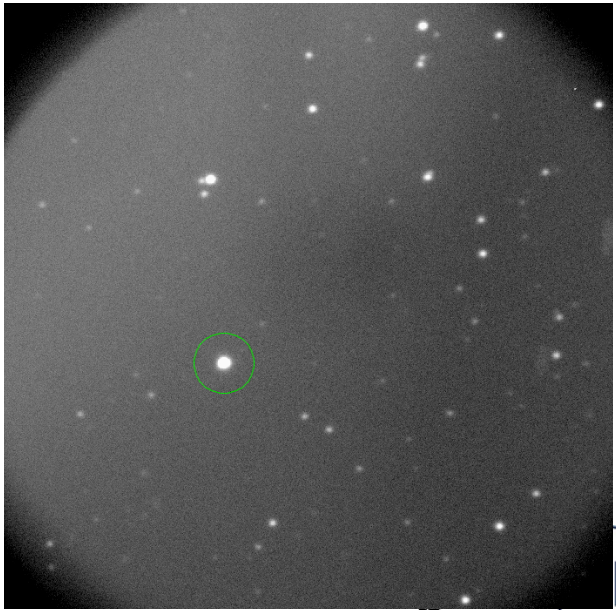
	Flight	Nod	Chop	Tweak	Dither
Average Amplitude Error (")	127	0.16	0.56	0.09	0.14
	177	0.06	1.97	0.25	0.01
	179	0.04	0.99	0.17	0.01
	183	0.03	0.07	0.14	0.08
Average Angle Error (°)	127	0.04	3.86	0.06	0.25
	177	0.56	0.23	0.32	0.64
	179	0.31	0.65	0.23	0.58
	183	0.12	0.33	0.48	0.38

Summary of all test results for flights 127, 177, 179, and 183

Pointing Procedure

- Initial pointing error using avionics data only: ~600 arcsec
- Use WFI to pick two known stars and do a "coord.correct" to update system pointing information. After this step pointing error is ~30"
- In the FPI, identify another star to update the system and fine-tune pointing. After this step, pointing error is the final value of < 0.5"





Main Tracking Modes

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- **On-Axis Tracking**: Use a bright, centroidable object for tracking that is also on the boresight. Most accurate
- **Off-Axis Tracking**: Use an object that is offset from the boresight. Used when the infrared target is not visible at visual wavelengths. Small decrease in performance
- **Fine-Field Imager Tracking**: Use an object on the FFI for tracking while keeping an object at the boresight in the FPI. Used when no trackable objects are available in the FPI. Degraded performance
- **Non-Sidereal Tracking**: Tracking involving a moving object. See next slide.

Non-Sidereal Tracking Options

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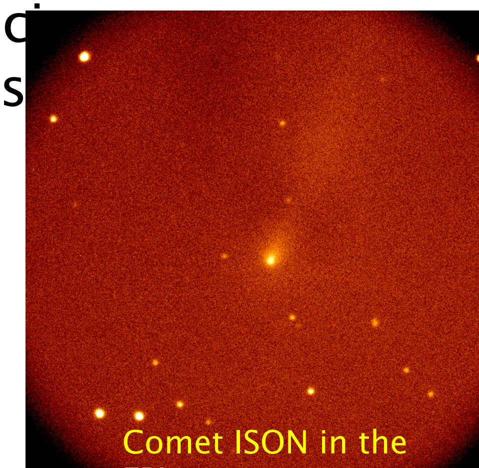
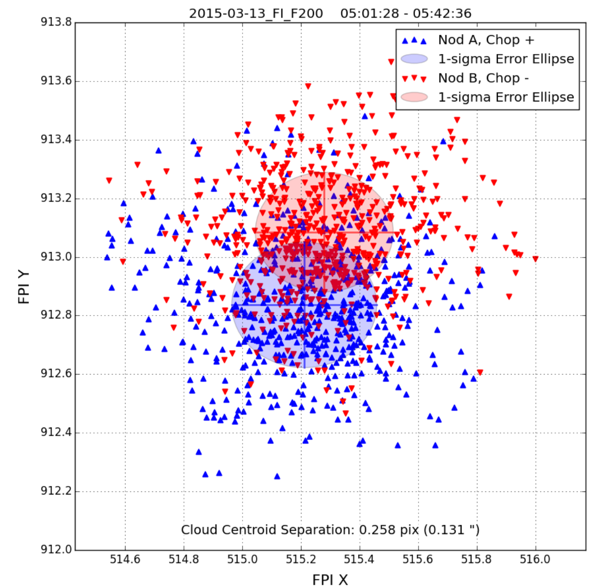
- **Direct Tracking:** Track directly on the non-sidereal source on the boresight, using an ephemeris to update position information. Used for most observations and the most accurate.
- **Offset Sidereal Tracking**: Track on a sidereal source keeping the non-sidereal object on the boresight. Used when object is too faint or too extended for centroids. Accuracy is degraded.
- **Offset Non-Sidereal Tracking**: Track on a non-sidereal source keeping a different non-sidereal (or sidereal) source on the boresight (e.g. track on a planet while observing an asteroid). Has never been needed for any sc observations, but the capability exists. Leas g mode!
- **Examples from past observations**: Main-belt asteroid calibrators for FORCAST, comet ISON, Jupiter, Ganymede, and an artificial geosynchronous satellite for engineering tests



Comet ISON in the FPI

Data Collected to Monitor Performance

- FPI Centroid data from housekeeping
  - Pointing Stability measurements
  - Pointing drift in the FPI
  - Matched Chop–Nod Performance
  - Chopper stability
- FPI Images
  - Pointing Accuracy from astrometry
  - FPI image quality trending
- FORCAST and FLITECAM Calibration Images

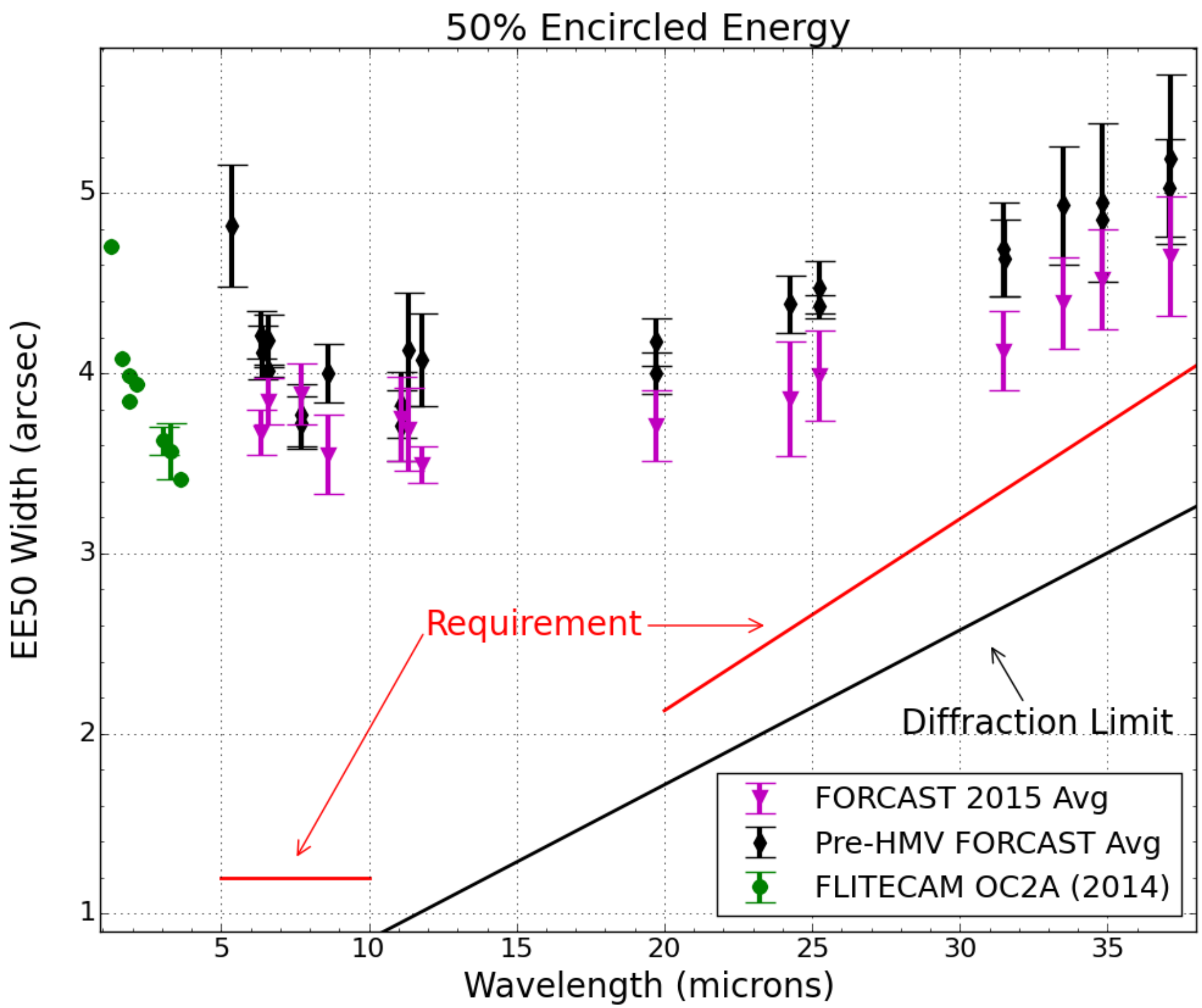


Matched Chop–Nod Centroid Cloud plot

Routine Performance Data Analysis Work

- Convert FPI images to FITS format and run astrometry tool on the first ~30 seconds of each observing leg to determine pointing accuracy from the boresight
- For appropriate matched chop-nod observations, run script to evaluate performance
- Calculate pointing stability and FPI drift for appropriate observations
- When processed calibrator data is available for FORCAST and FLITECAM, calculate image size and ellipticity from images
- Calculate FPI image size and ellipticity for ~200 random points during the flight while tracking
- Upload all performance data to the engineering mySQL database

Image Size



- Image size improved after HMV
- Cause of improvement are related to FBC PSU fix
- FORCAST reports seeing airy rings at longest wavelengths in 2015

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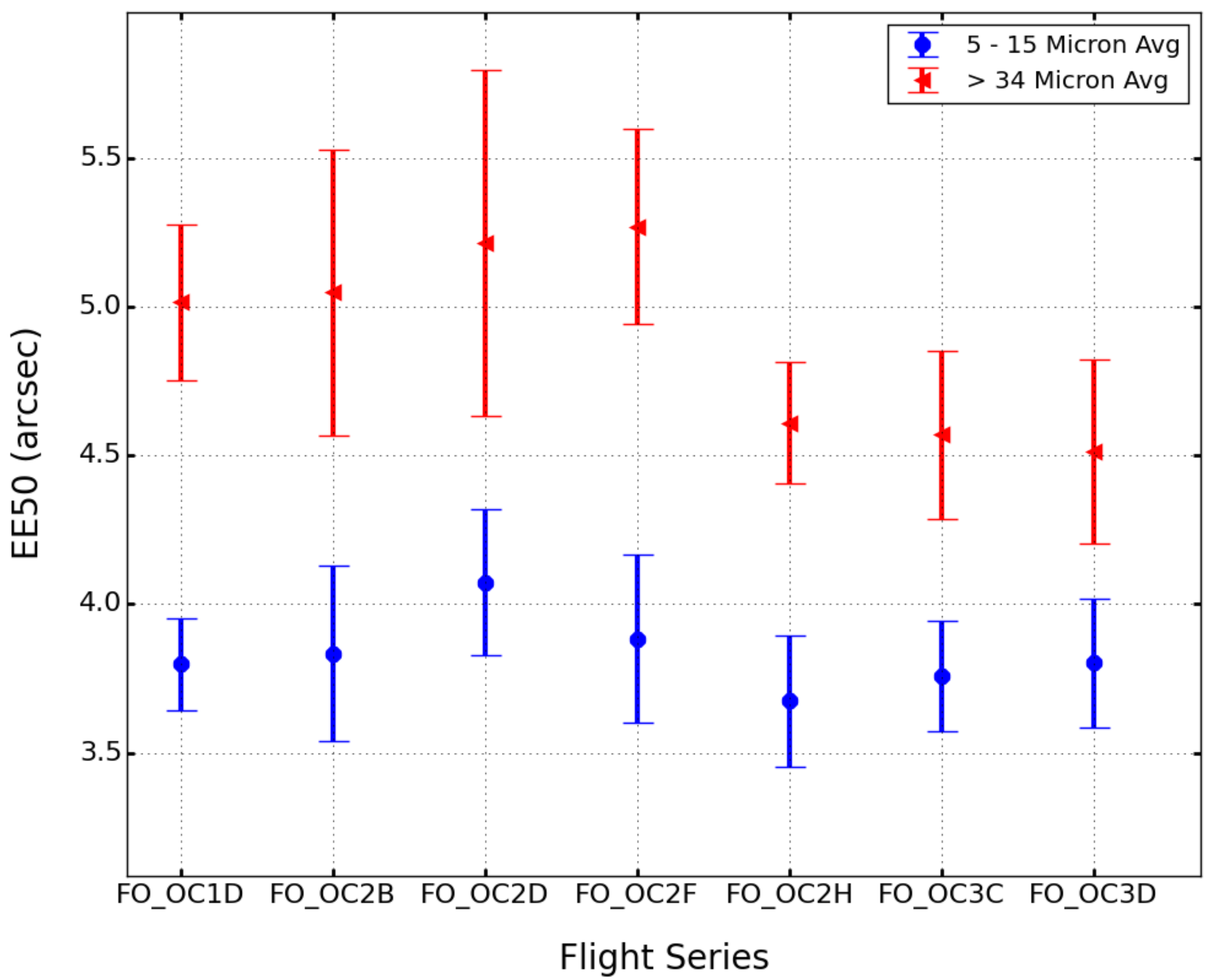
FORCAST Image Size vs. Flight Series



- Clear improvement in image size at longer wavelengths after HMV
- Improvement less clear at 5–15 microns

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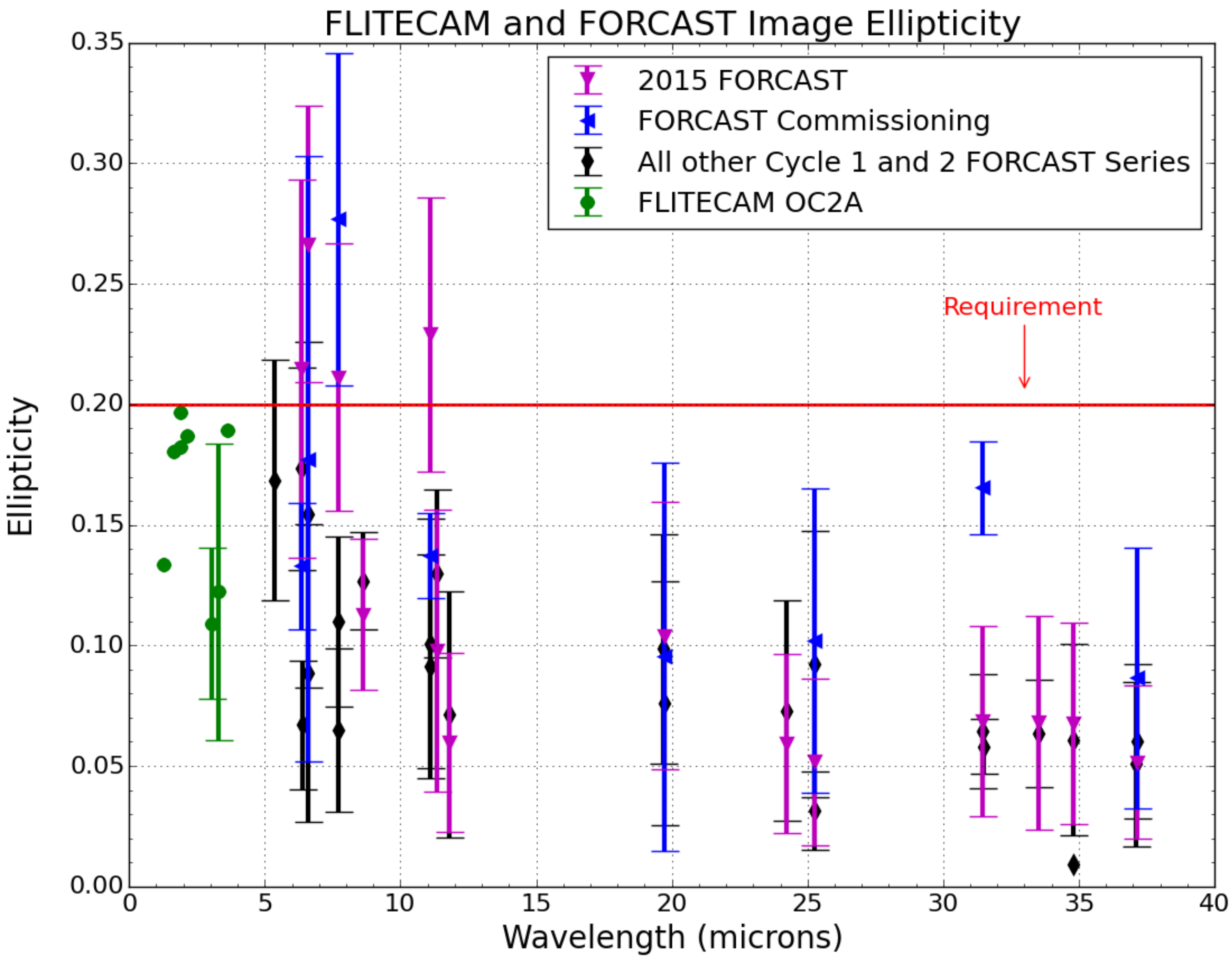
Image Ellipticity



- Ellipticity requirement met as an average of all wavelenghths
- Ellipticity worst at short FORCAST wavelengths

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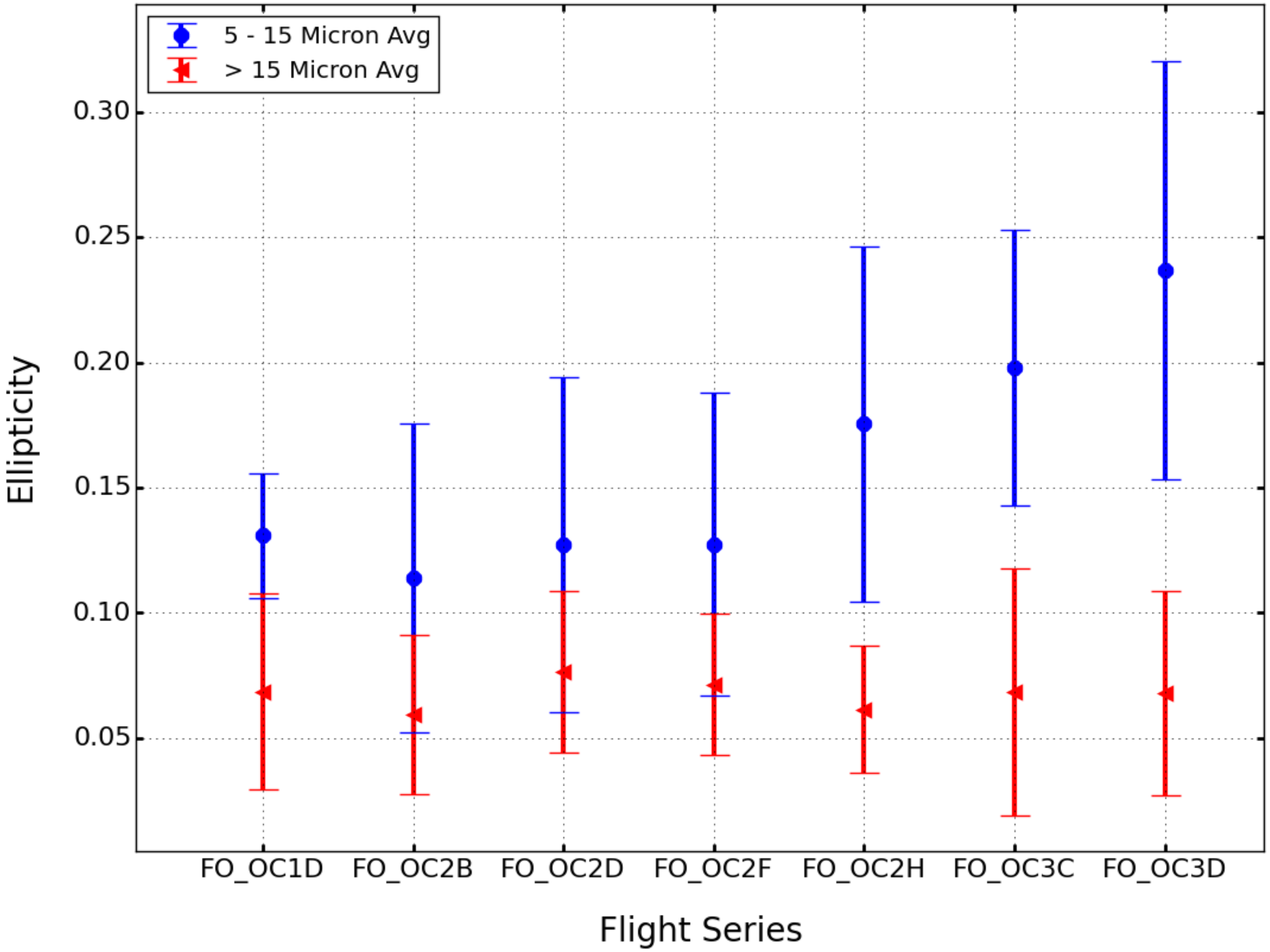
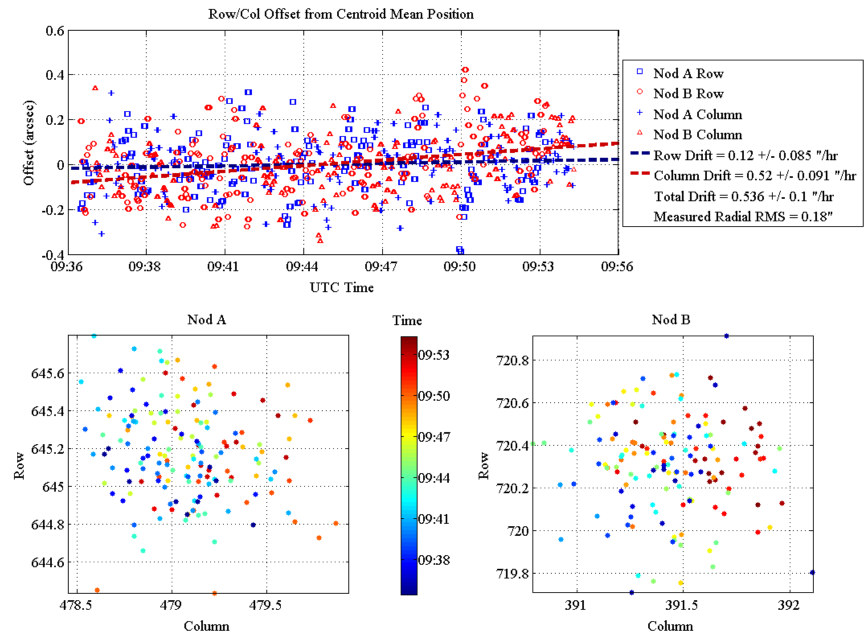
Image Ellipticity Trends



- At > 15 microns, FORCAST image ellipticity has been stable over time
- Between 5 and 15 microns, the FORCAST image ellipticity has been trending upwards
- The cause for this increase is undetermined, but could be due to image processing issues with asteroids

Pointing Drift

- As measured in the FPI, the pointing drift is extremely low for both sidereal and non-sidereal targets
- Evidence from 5 flights using HIPO, FLITECAM, and FORCAST shows that there is differential pointing between the FPI and Science Instrument
- The drift measured at the SI has been measured as high as 1 ”/hr, which is outside of the requirement



Moderate drift of ~0.5 “/hr detected during an observation on FORCAST flight 169

Pointing Stability

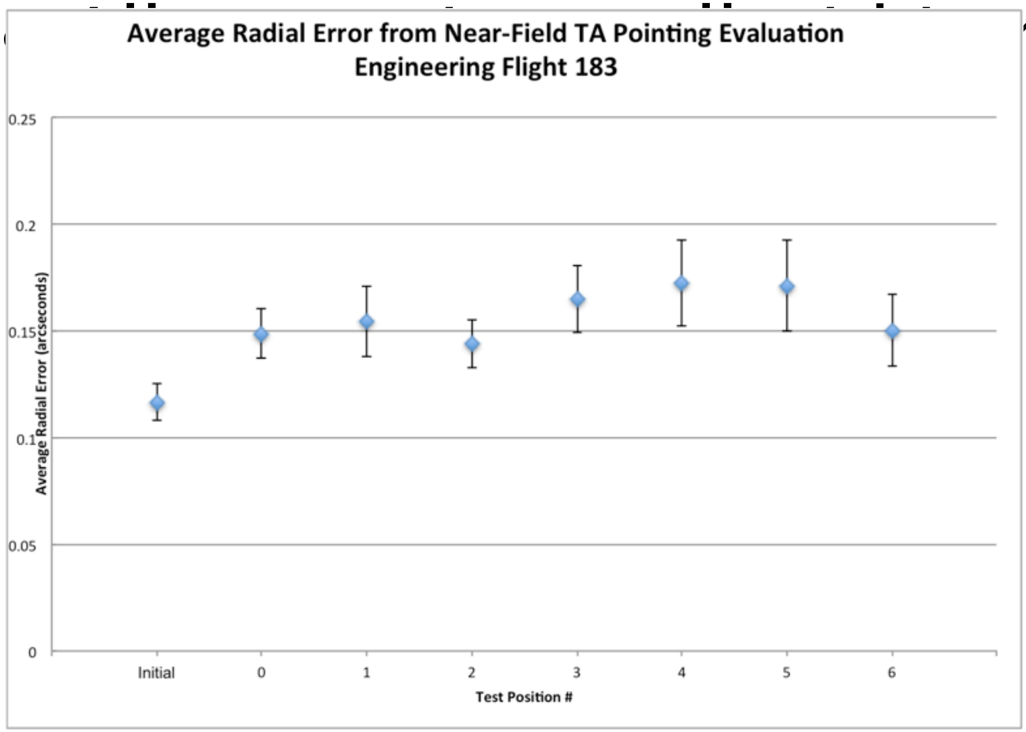
- The pointing stability is measured to be 0.19 arcsec RMS from 106 measurements in Cycle 2 and 3
- Very good stability is achieved, even for the large offset tracking cases

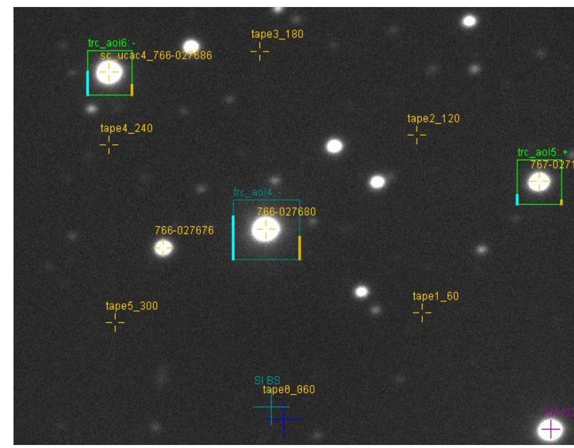
Pointing Accuracy

- Initial pointing accuracy is measured by astrometry for observations with 3 or more stars visible in the FPI
- The pointing accuracy is typically less than 0.25”when the object is bright enough to calculate a centroid in the FPI
- When the object is not visible in the FPI, the median pointing accuracy is 0.41 arcsec

Near-Field Pointing Accuracy Test Results

- Test evaluated pointing accuracy for moves within ~100” of coordinate-corrected position
- … required 0.3”

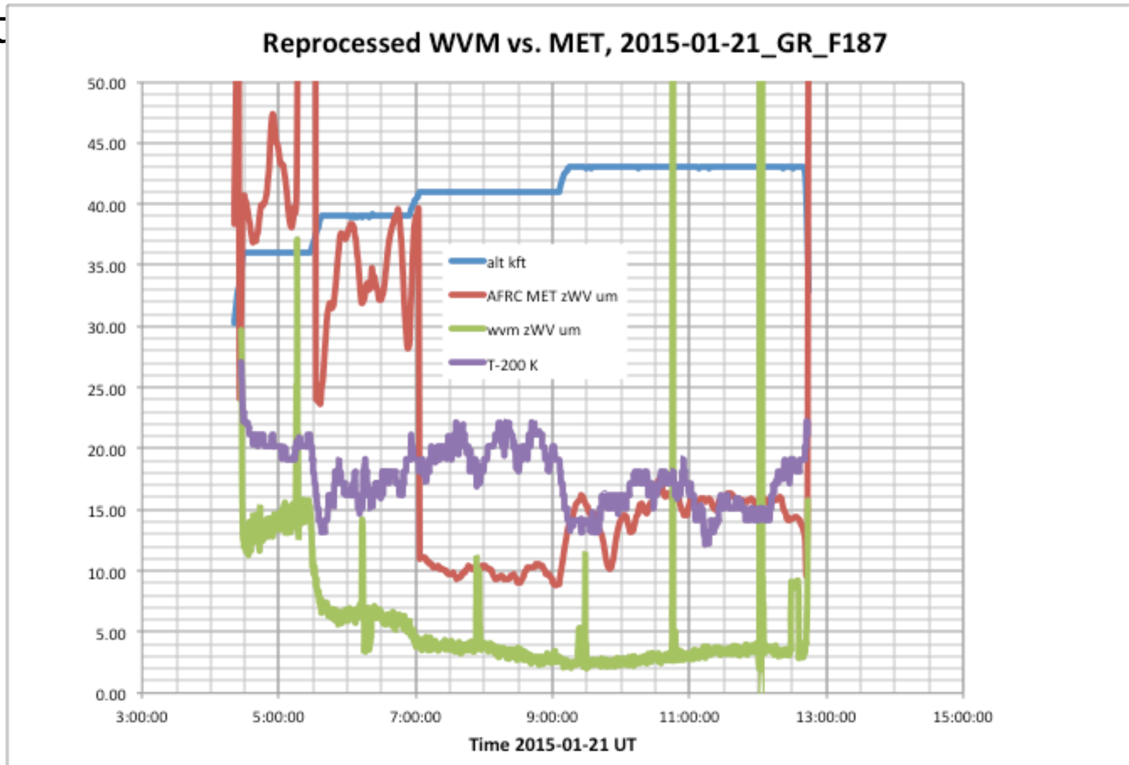




Test setup

Water Vapor Monitor Status

- WVM operational, but currently does not provide real-time zenith water vapor data in flight
- Post-flight processing can produce meaningful data, but fine-tuning of the algorithm is still in progress
- Goal is to have the WVM provide meaningful (but not perfect) real-time data by the end of October, 2015, with further improvements thereaft



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Current Mid- and Long-term improvement plans for:

- Observatory efficiency
- Observatory performance
    - Static pointing
    - Dynamic pointing

Observatory Efficiency

We are in the process of creating efficiency metrics and monitor them on a regular basis.

Some inefficiencies are from Human interfaces and lack of automation

- Field acquisition
- Set up time
- Operators workarounds
- Etc..

Additional inefficiency is driven by **not optimized Observatory Systems**:

- Excessive overhead on typical telescope maneuvering
  - Telescope nods, scans, dithers
  - Tracking loops
  - Chopper performances

Observatory Performance

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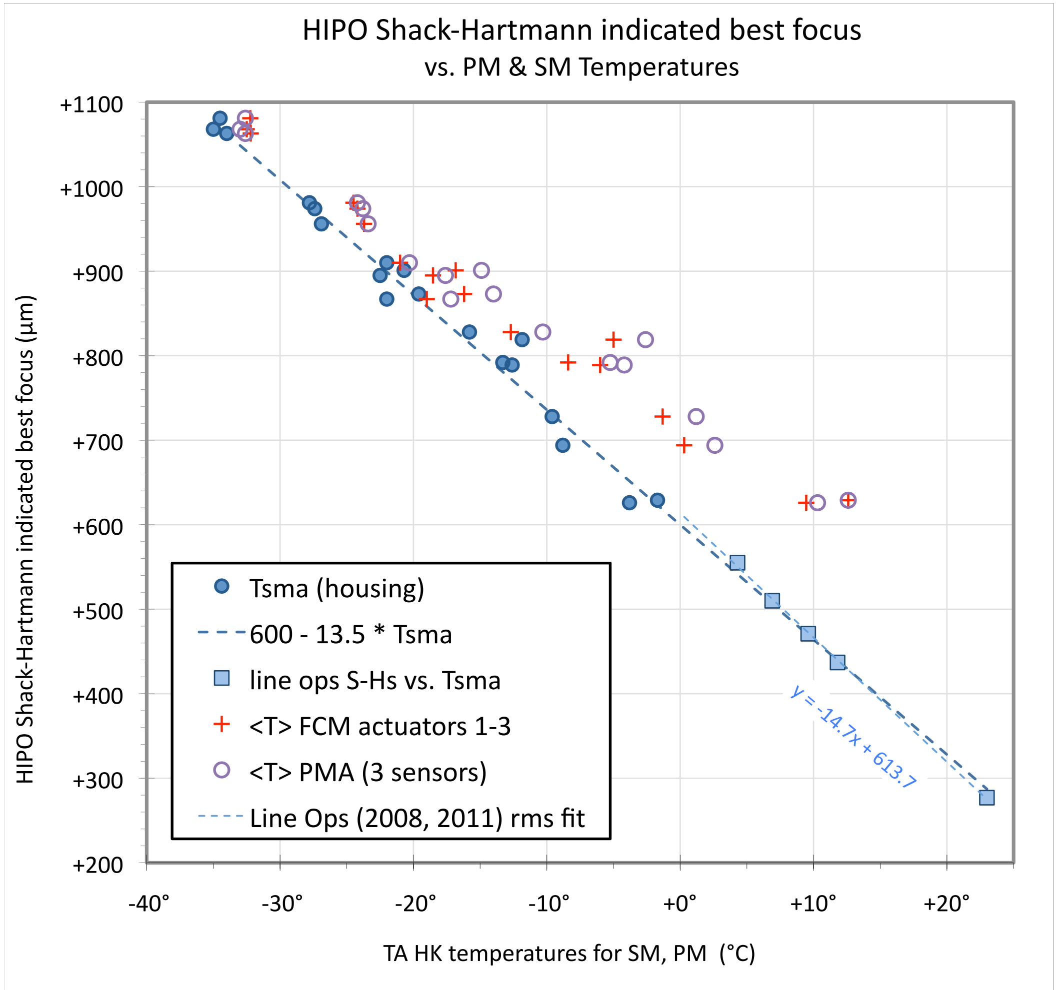
Static Pointing

- Tremendous improvements made the past year
- We strongly benefited from the newFPI and new tracking schemes
- We are still evaluating the consistency of pointing performance on a larger set of configurations:
  - Observing modes
  - Observatory conditions: Aircraft altitude, elevation angles, magnitude and offset of tracking star, etc..
- Tracking capabilities depend on having a set of “tracking algorithms” suitable for a variety of tracking targets.
- Need to build up statistics to evaluate how reliable and repeatable our results are.

TA Main Focus



It is imperative that we stay in focus at all times.
We cannot afford any significant contribution to image size due to defocus.

We use a semi-automatic focus control:

- Allow the MCCS to change FCM t in the background as the measured relevant cavity temperature changes
- Need to implement an FPI autofocus capability that evaluates a visible source in FPI images

Dynamic Pointing (Image quality, Jitter)

- There are gaps between our current performance and requirements in image quality.
- Reduction of the image size has an impact on the sensitivity for <u>all</u> the science instruments operating up to 40um:
- Image size reduction will allow to take advantage of the potential SOFIA high angular resolution

- Image jitter and distortion is being reduced through application of active damping of the structure/optical elements and through disturbance reduction.
- Overall performance shows, as expected, the jitter lessening at higher altitude, lower disturbance level flight.
- Jitter is seen to be lessened at high and low end TA elevation relative to mid-elevation.

Image Improvement Plan – Dynamics Reduction
– Near to Mid-Term Timeframe –

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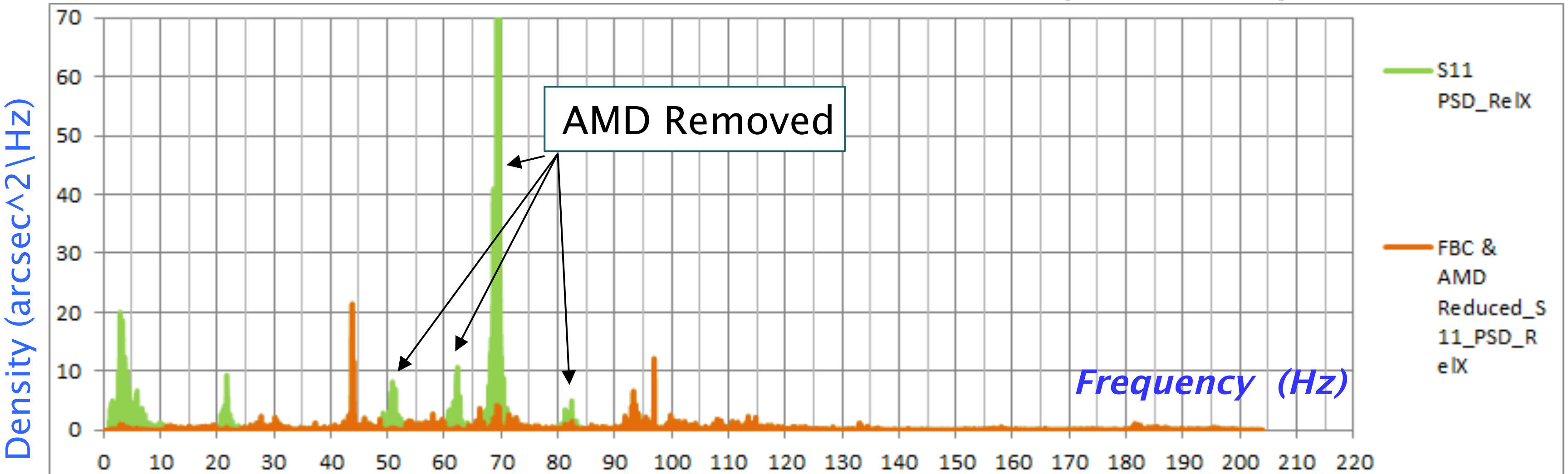
Image Motion Control Improvements	*Status*
• 1) FBC Improvement via noise removal in motion sensing within TCM feed-forward control	• In Work: by DSI
• 2) FBC Improvement via potential in improved TCM control architecture and/or logic	• In Work: by DSI
	• In Work & Flight Proven: Software completion
• 3) AMD System implementation for PM mode damping	• Under Program consideration
• 4) Add more sensors •Pressure Feed Forward Sensors •Improved PM rotation sensing (of lower frequency, 1-10 Hz, residual rotational motion) via a 2nd Gyro (2-axis) mounted on the Shearbox	• Partly In Work/ Partly Pending Consensus and Funding: prototype SMAF hardware of flight quality developed (see next page)
• 5) Higher frequency image steering (10 – 100+ Hz e.g. with SM Active Flexure System) utilizing control input from accelerometers, Shearbox 2nd Gyro measurements, and/or FPI+ image motion	

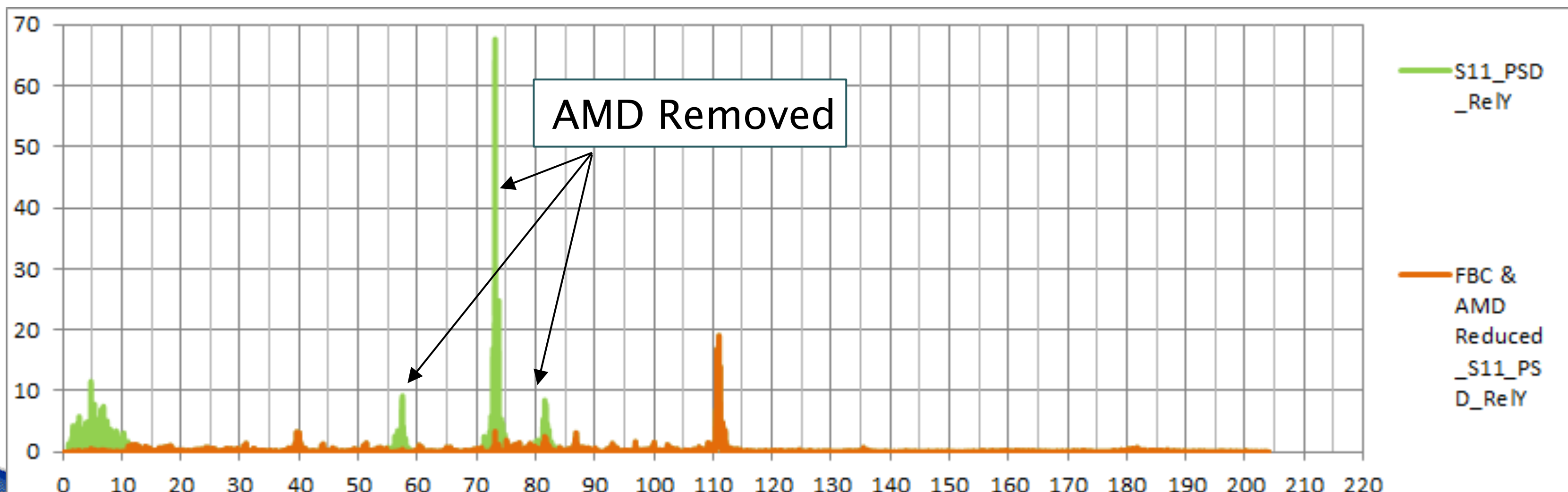
NASA DSI DLR USRA

Assumed Jitter Content Removal Thru AMDs in Combination w/ FBC Improvements

X-Elevation Jitter Content, Baseline from Aug 2013 Flight w/ DYN FBC



Elevation Jitter Content, Baseline from Aug 2013 Flight w/ DYN FBC



Frequency (Hz)

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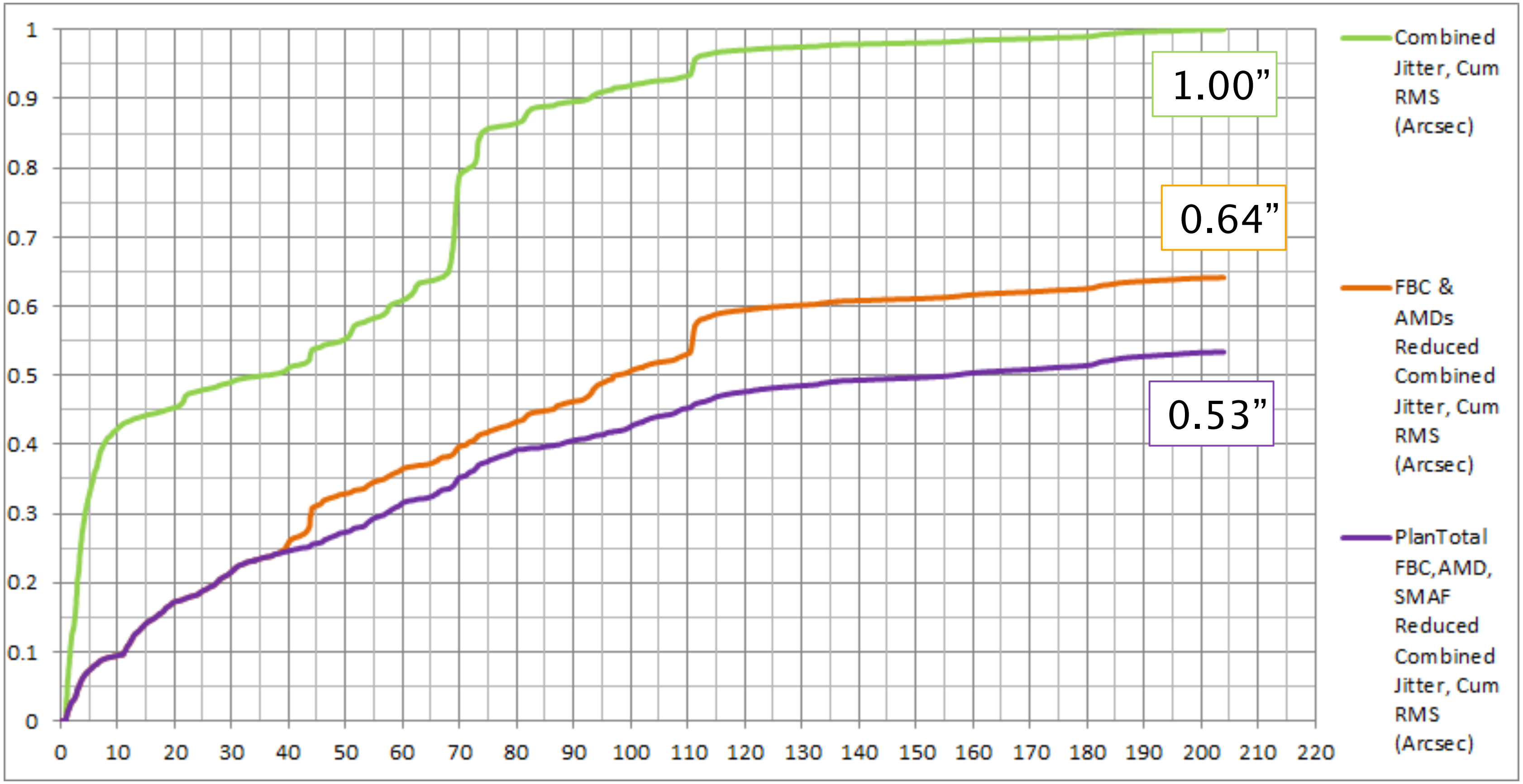
Reduction in Cumulative Jitter Thru AMDs in Addition to FBC Improvements

AMDs with FBC Improvement (Orange – Middle Curve)
Relative to Baseline from Aug 2013 Flight w/ DYN FBC (Green – Top), &
Total Improvement within Plan (Purple – Bottom Curve)



Frequency (Hz)

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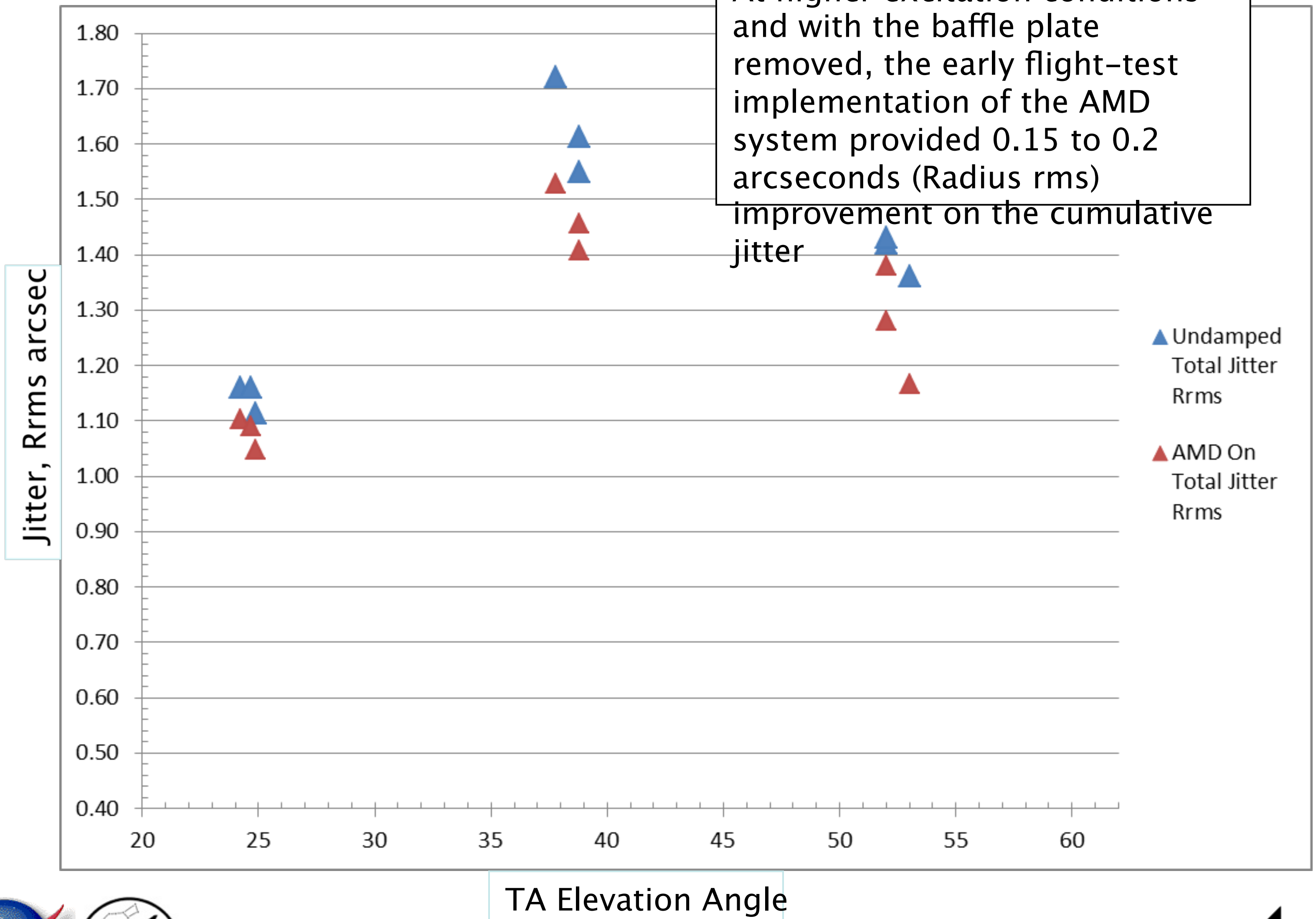
Jitter vs. TA Elevation, Flight Data at 38k-39k ft Altitude

No-Baffle Plate, SFDC Data of Dec. 2011 (SCAI 9 Flight)



At higher excitation conditions and with the baffle plate removed, the early flight-test implementation of the AMD system provided 0.15 to 0.2 arcseconds (Radius rms) improvement on the cumulative jitter

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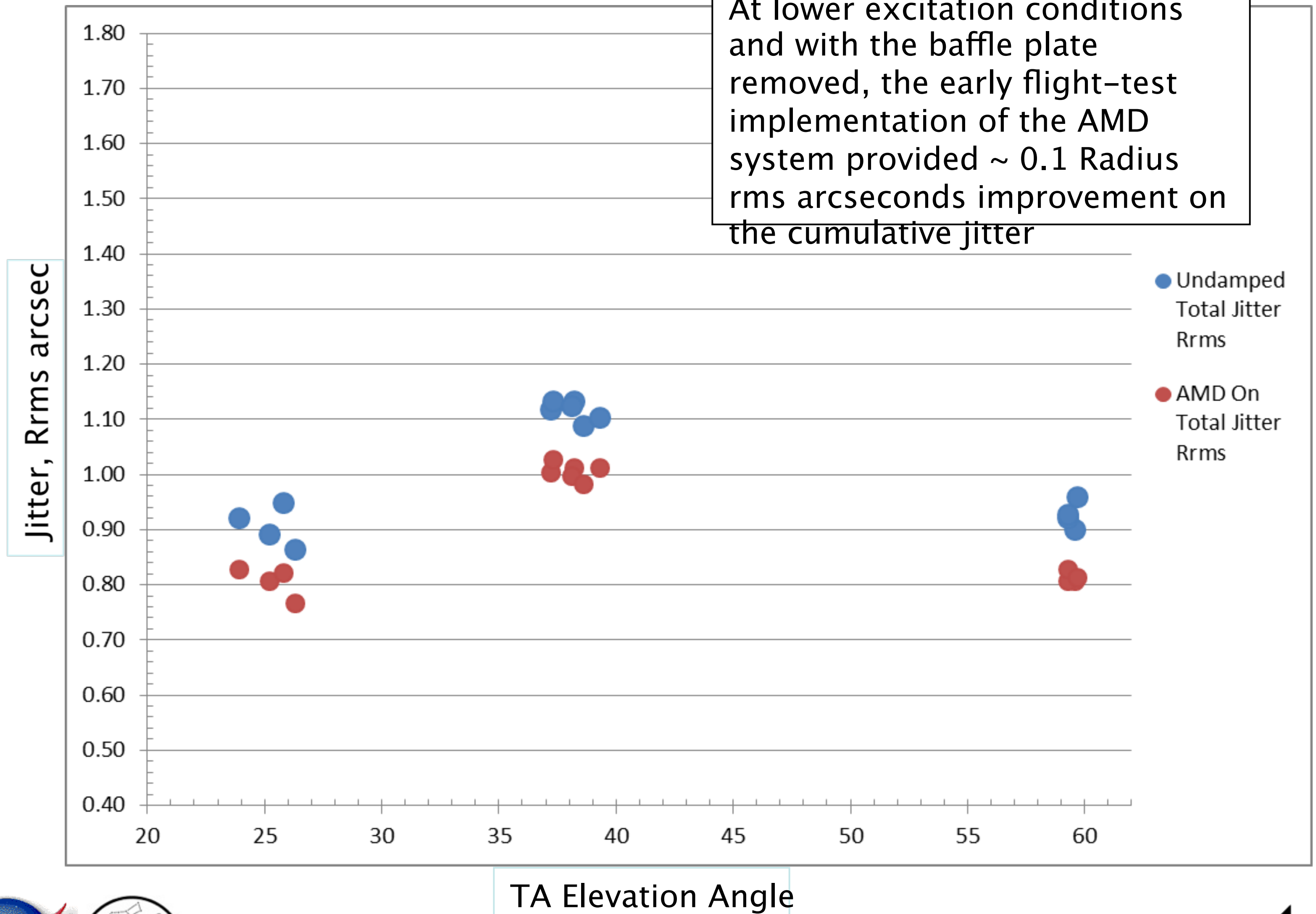
Jitter vs. TA Elevation, Flight Data at 44k-45k ft Altitude

No-Baffle Plate, SFDC Data of Dec. 2011 (SCAI 9 Flight)



At lower excitation conditions and with the baffle plate removed, the early flight-test implementation of the AMD system provided ~ 0.1 Radius rms arcseconds improvement on the cumulative jitter

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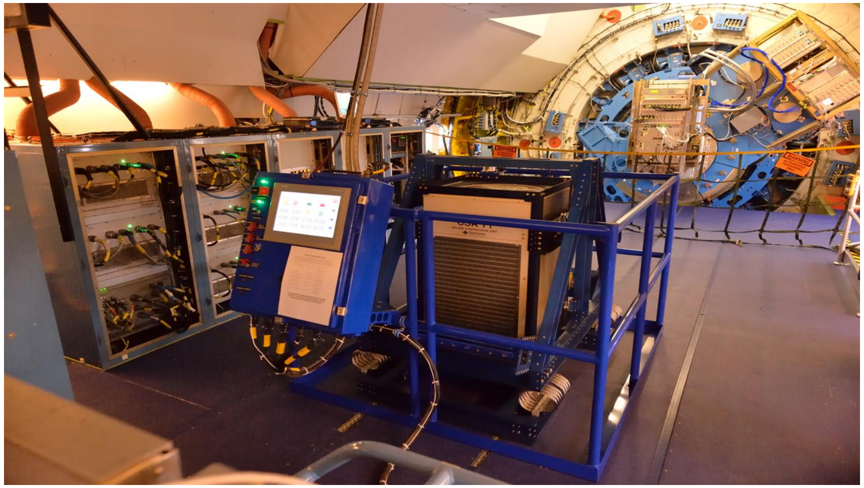
SOFIA is a Platform for New Technology: upGREAT

The upGREAT channels are the second generation receivers for the GREAT project.

Channel	Frequencies (THz)	Lines of interest
upGREAT Low Frequency Array (LFA)	1.9– 2.5 (14 pixels)	OH lines, [CII], CO series, [OI]
upGREAT High Frequency Array (HFA)	4.7 (7 pixels)	[OI]

Medium sized arrays using closed-cycle coolers.
The upGREAT LFA has been commissioned in 2015, The HFA channel ready in 2016



Maps ***more than an order of magnitude faster*** than the previous instrument