

Image Quality Status

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Outline

- Summary of components for image size
- Units used to measure image size
- Details of units (equations)
- Values from past knowledge and TACFL flights
- Comparison to FORCAST Images
- Comparison to Requirements
- Possible up grades and other issues

Summary of components for Image Size

- Image motion:
 - » Telescope disturbance ($f > 0.5\text{Hz}$)
 - » Telescope tracking ($f < 0.5\text{Hz}$...ie times longer than 2sec)
 - » Chopper jitter
 - » Chopper overshoot
- Optics:
 - » Mirror surfaces
 - » Alignment
 - » Focus
 - » Chopper Coma
- Science:
 - » Diffraction
 - » Shear layer
 - » Instrument



Units used to measure image size

- We will always be talking about the image size in the focal plane of the telescope.
- There are a number of ways that are used to describe the image size.
- When talking about telescope motion, we usually use the rms motion in the focal plane. This motion is a function of frequency, but astronomers are usually most interested in the integrated motion at all frequencies. RMS (i.e. R_{rms})
- When specifying optical design one usually uses 80% enclosed energy at a given wavelength usually optical. Theta (80%)
- When talking about data in the science instrument we usually refer to the full width at half maximum. FWHM (i.e. X_{FWHM})

Details of each unit: RMS image motion

- Root Mean Square (RMS) image motion is measured in arcsec in the focal plane.
- For SOFIA it is usually measured in the Elevation Direction (y) and the Cross Elevation Direction (x)
- It is measured as the value $y_{rms} = 1/((n-1)^{1/2}) \times (\sum_{1}^n (y(n) - \bar{y})^2)^{1/2}$
- Because x and y are independent, the RMS (total) is:
 $R_{rms} = (y_{rms}^2 + x_{rms}^2)^{1/2}$ or $R_{rms} = ((R_1^2 + R_2^2 + \dots + R_n^2)^{1/2}) / (n-1)^{1/2}$
- The RMS image motion is a function of frequency so is usually integrated to get the total motion.
- Image motion can include both jitter and tracking.

Details of Each Unit: Theta (80%)

- The Theta (80%) is what is used on SOFIA to measure the quality of the optics. It is the enclosed energy specified at about 0.55 microns.
- It includes all of the optical components of all mirrors out side of the instrument. It also includes the misalignment of the optics, focus and the effects of the chopper coma.
- When the pointing error is random (Gaussian) then the Theta (80%) $\approx 2.54 R_{\text{rms}}$ (See Erickson and Dunham 2000 SPIE 4014)

Details of Each Unit: FWHM

- The FWHM is what the astronomer easily measures in his instrument.
- It includes all effects on the image discussed previously plus diffraction, image blur due to shear layer motion ('seeing') and any instrument distortion.
- When astronomers measure FWHM with their instrument, they include all effects discussed above.
- Astronomers usually will measure the distribution of the energy as a function of radius from the center of the image and determine the FWHM of the best fit Gaussian distribution.
- Astronomers also measure FWHM in x and y and the value in radius is about the average of the x and y value.

Details of Each Unit: 50% Enclosed Energy (Theta 50%)

- Theta (50%) is also used by astronomers.
- It is usually very close to the FWHM, so for our purposes we will assume they are the same.
- Various components of FWHM, Theta (80%) and Theta (50%) are added together as a root sum square when they are independent.

Summary of Units and equations

- $\text{FWHM} = 1.8 R_{\text{rms}}$
- $\text{Theta } 80\% = 2.54 R_{\text{rms}}$
- $\text{Theta } 80\% = 1.5 \text{ FWHM}$
- $\text{Theta } 50\% \sim \text{FWHM}$

Note: These are approximate and valid for Gaussian type distributions.

Values of Image Size from previous knowledge and TACFL

- When it says small error, we mean under 0.3 arcsec (Theta(80%))
- **Green**=good, **Red**=bad, **Blue**=unknown

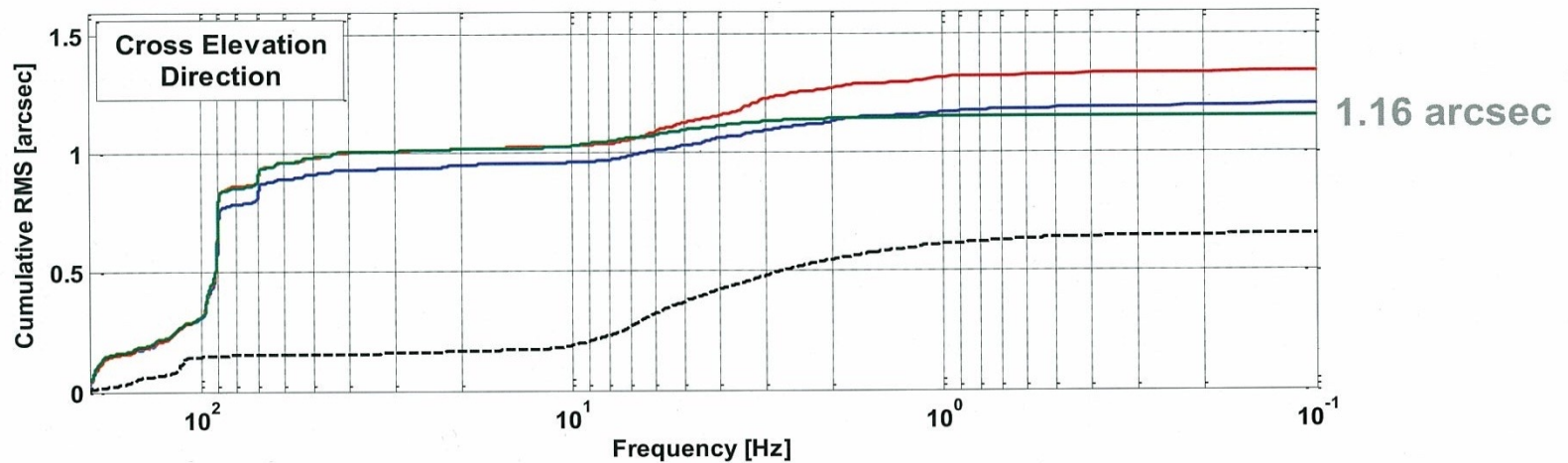
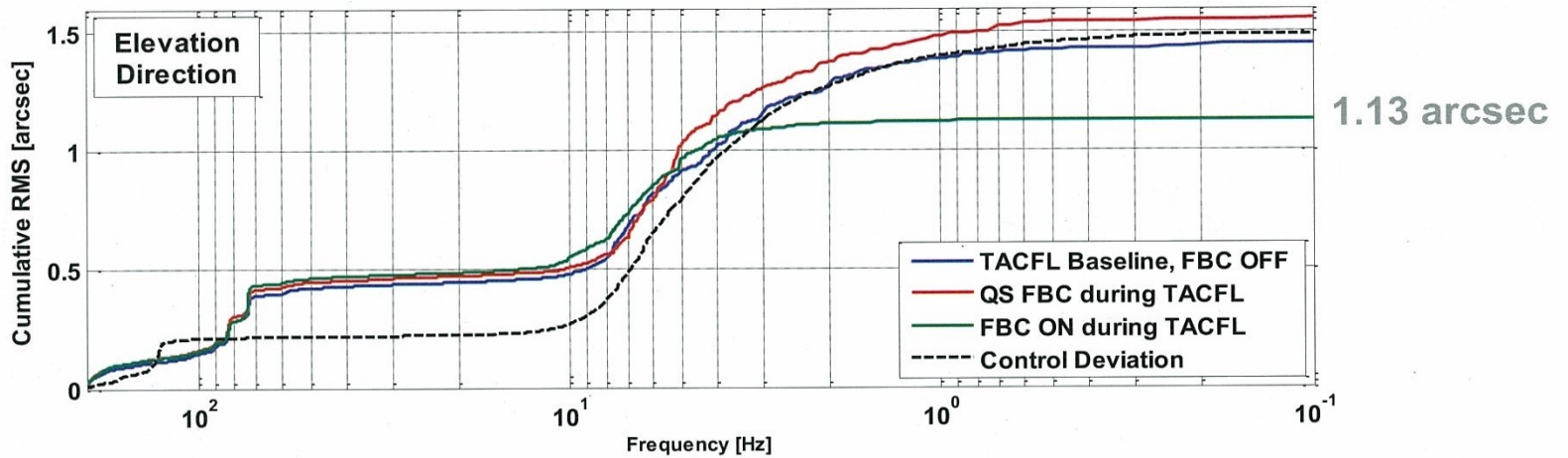
Image Motion (rms)

- Telescope tracking:
 - » With Gyro's only about 0.2 arcsec/second
 - » With FFI Guide cameras .5? arcsec rms
 - » With FPI camera .2? arcsec rms
- Chopper Jitter and overshoot
 - 250 Hz motion (now is $< \sim .2$ arcsec rms)
 - Overshoot (depends on amplitude)
- Telescope disturbances: 1.6 arcsec rms (Theta(80%)
 ~ 4.2 arcsec) dynamic FBC on.
 - » Vibrations from the plane
 - » Wind forces on the telescope structure



400 Hz Sampling - FBC Performance

FBC Performance - Reverse Cumulative RMS



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Optics: Theta (80%)

- Primary Mirror Surface: 0.4 arcsec
- Secondary Mirror Surface (SiC): ~0.4? arcsec
“ ” (Al): ~7.0 arcsec
- Tertiary. Mirror Surface: 0.4?
- Alignment: small (but could be large if misaligned)
- Focus: <0.5 arcsec
- Chopper Coma: 8 arcsec at 4 arcmin chop
([2 arcsec/ arcmin]x Chopper Throw)

Image Size at Instrument

- Diffraction FWHM \sim (wavelength (microns)/10):
Diffraction is limited by primary mirror size.
- Shear Layer: **unknown**: (models and KAO show effect small at wavelengths beyond 10 microns and greatest in Visible (0.5 microns \sim 3 arcsec FWHM). Will be measured by Ted Dunham with telescope V&V next yr.
- Instrument: FORCAST 0.75 arcsec pixels, There is some distortion in the optics at 10 microns and below (DeBuizer private communication)
- Instrument: GREAT one beam which is about 15 arcsec FWHM at 150 microns.

Table Summary of Image Size in Arcsec as of Sept 2010

| Components of Image Quality | RMS Motion | Theta 80% | FWHM |
|--------------------------------------|------------|------------|------------|
| gyros | | | |
| FFI | .5? | 1.3? | .87? |
| FPI | .2? | .5? | .3? |
| Chopper Jitter | <.2 | <.5 | <.3 |
| Overshot | | | |
| Telescope Disturbances | 1.6 | 4.2 | 2.8 |
| Primary Mirror Surface | | 0.4 | 0.27 |
| Secondary Mirror Surface (SiC) | | 0.4 | 0.27 |
| Secondary Mirror Surface (Al) | | ~7 | 4.7 |
| Tertiary Mirror Surface | | 0.4 | 0.27 |
| Alignment | | <.3 | <.2 |
| Focus | | <.5 | <.3 |
| Total (FPI and SiC secondary) | | 4.3 | 2.9 |

Comparison to FORCAST Image Size from TACFL flight

- Jim DeBuizer has reduced the FORCAST Jupiter/Ganymede images at 24.2 and 37.1 when the focus was good. At the the time the dynamic FBC was on and working.
- At 24.2 microns 8 images of 1.2 second integration give an average FWHM of 3.47 arcsec. Removing the size of Ganymede and the diffraction give a FWHM of 2.8 arcsec.
- At 37.1 microns the same value is FWHM of 2.5 arcsec.
- These numbers are smaller but similar to the FWHM 2.9 arcsec with the root mean square sum shown in the previous table. This indicates we have identified major component of the image quality as jitter.
- Terry Herter measured that the 5 micron image from the telescope tests was FWHM of about 4 arcsec. This was due to FBC off, focus or seeing.

Comparison to Requirements

SOFIA Level 1 Requirements

| Requirement | Status |
|--|--------|
| • Effective aperture dia.: 2.5 m | OK |
| • Elevation range: 20 - 60 deg. | OK |
| • Wavelength range: 0.3 - 1600 microns | OK |
| • Image size (visible): D(80%) = 5.3 arcsec: first science flight (including telescope jitter but not shear layer seeing) | OK |
| D(80%) = 1.6 arcsec: first science flight plus 3 years* | OK |
| • Operations capability: 6 hours at/above 41 kft | OK |
| • Operations capability: Access to SIs | OK |
| • Operations capability: 40 PI/GI teams/year | OK |
| • Operations: 960 hours / year starting year 4 | OK |

* Implementation of (pointing) upgrades will be subject to a cost/benefit analysis once SOFIA is flying and telescope performance is characterized in the flight environment.

The image size at First Light

- The image quality requirement for first light was Theta (80%) of 5.3 arcsec at 0.55 microns without shear layer seeing.
- From both the 5 micron image motion with dynamic FBC on and FORCAST images of Ganymede at 24 and 37 microns we get Theta (80%) of about 4 arcsec.
- We met the image size specification for first light!!
- The largest component is image jitter.

The image size at First Light plus 3 years

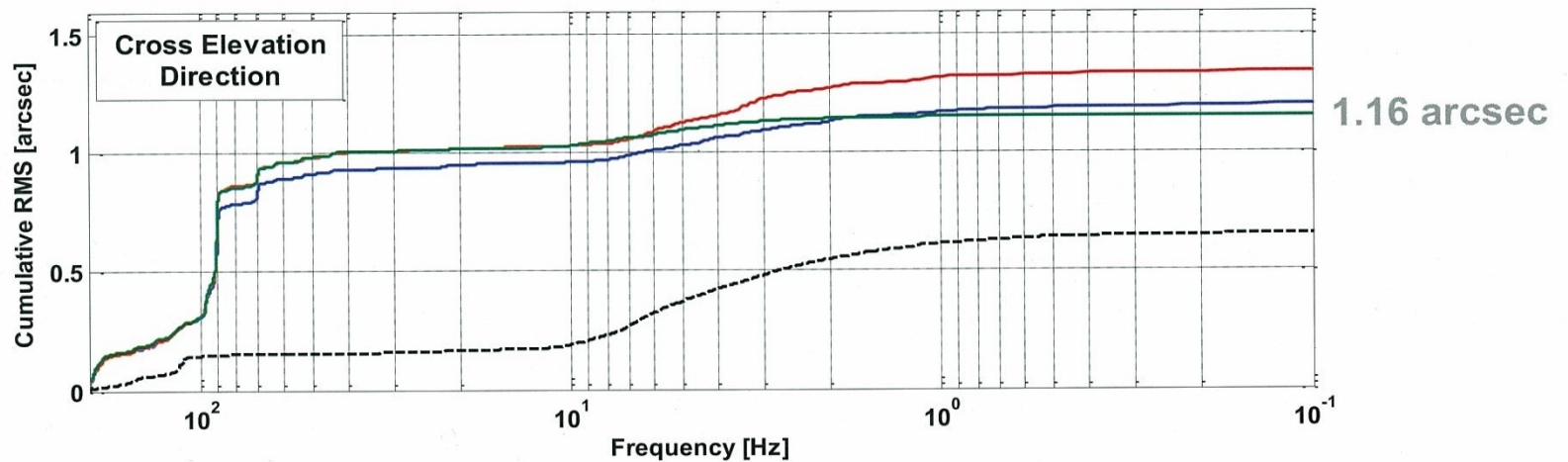
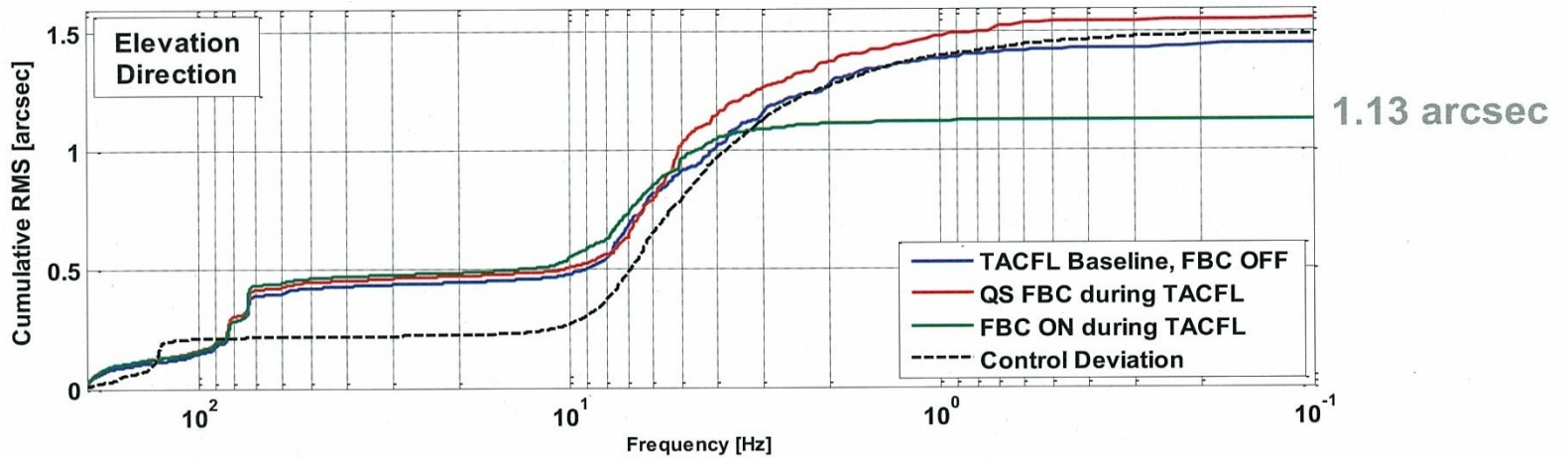
- The image quality at first light plus 3 years was to be Theta (80%) of 1.6 arcsec at 0.55 microns without shear layer seeing.
- The original optical quality with shear layer seeing and jitter removed was 1.5 arcsec.
- We seem to have met this requirement on basic optical quality with out jitter.
- If the jitter can be reduced to 0.5 arcsec rms, then the specification of 1.6 arcsec can be met for overall image quality.
- Becklin's statement: Going below 0.5 arcsec rms jitter should not be attempted until science justification.

Ways to Fix the Image Size



400 Hz Sampling - FBC Performance

FBC Performance - Reverse Cumulative RMS



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Image Motion: Ways to fix

- Telescope disturbance:
 - » The dynamic FBC uses the chopper. There is a time lag of **22.5** ms, that we can fix to make it closer to **10** ms (see Figure).
 - » Fix 90 Hz chopper spider motion by using mass dampers.



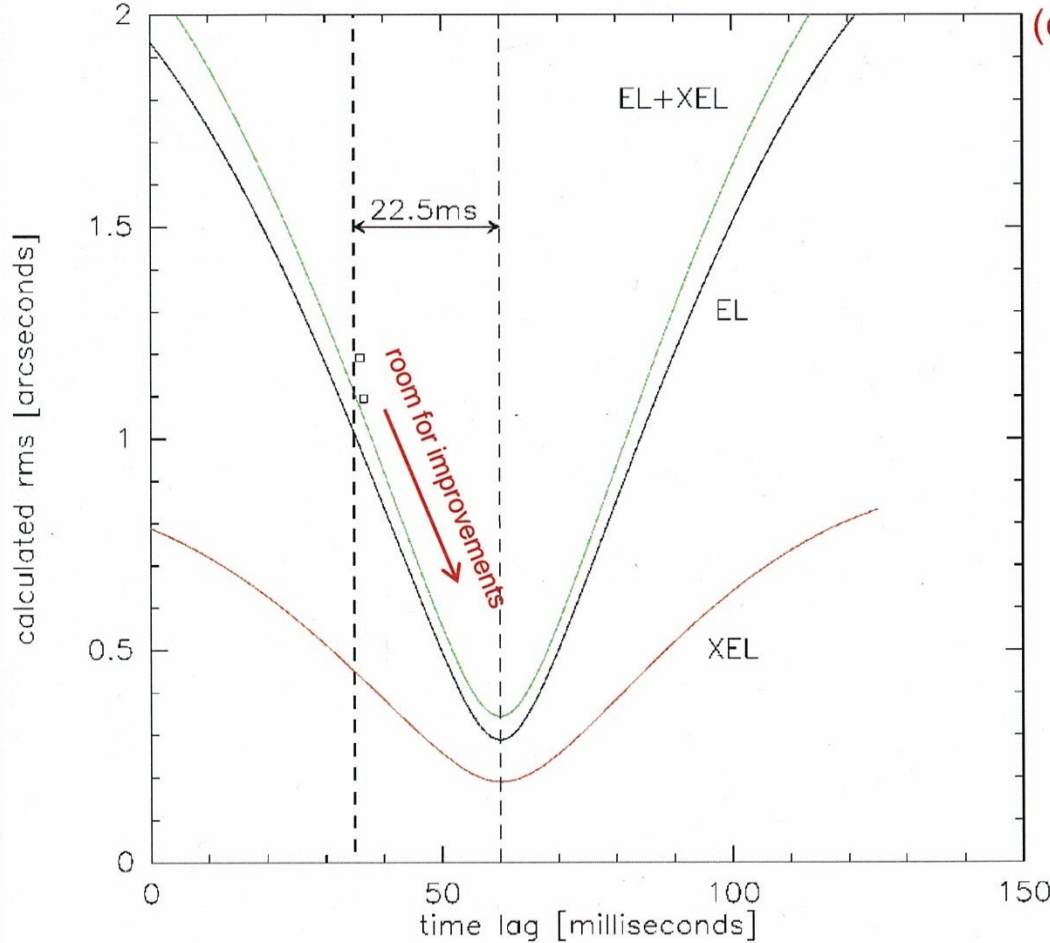
Control Deviation Feed Forward ON (optimal)



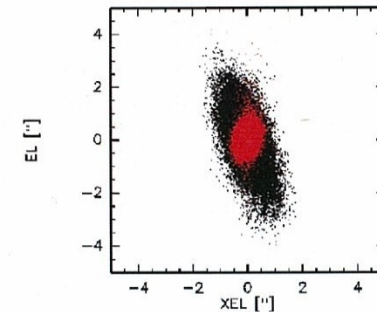
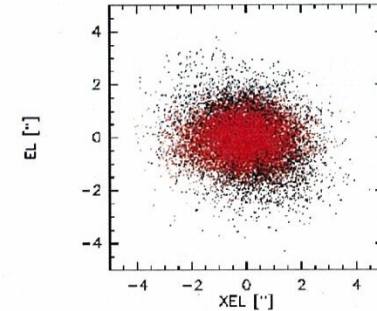
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theoretical FORCAST pointing jitter with active SMA feed forward varied over different phase delays



FORCAST jitter
(control deviation removed by FF)



Gyro Control Deviation jitter
(control deviation removed by Feed Forward)

Other Pointing improvements

- For FFI and WFI need to correct for thermal drift between primary telescope and guiders. (Gravity flexure between primary telescope and guiders are presently part of static FBC.)
- Gyro drift needs to be minimize and calibrated, especially for daytime use. Presently appears to have magnetic pick up.

Other Fixes

- We're stuck with the Chopper Coma but we can at least keep an eye on it to make sure that it does not effect the science.
- Either re-mill the A1 secondary mirror or repair it using an ion beam. If we have to use the A1 mirror, it will be the largest contributor to the amount of image size error.

CONGRATULATIONS to the TA crew
and the entire SOFIA team for meeting
the Early Science Pointing Spec at the
TACFL!!!

