Reducing SOFIA's image jitter: an ongoing challenge

Friederike Graf

DSI Upgrades & Controls

DSI Development Ames
1) 5 - 10 $\mu$m: 50% encircled energy $\leq 1.8$ arcsec at an observing altitude of at least 41,000 feet under light turbulence (or better) flight conditions.

2) 25 $\mu$m: diffraction limited imaging, where diffraction-limited is defined by satisfying a Strehl ratio of at least 80%.

→ EXES, FORCAST (FLIPO and FPI+) would benefit from smaller image size.

→ EXES and HIRMES could save integration time (EXES up to a factor of 4 and HIRMES 10-20%) if image size is decreased.
Goal Image Size only possible if:

Image Jitter \( \leq 0.4 \text{ arcsec rms at focal plane} \)

How can we achieve that?
Telescope Assembly (TA)

- Science Instrument Flange
- Focal Plane Imager
- Nasmyth Tube
- Primary Mirror
- Suspension Assembly
- Secondary Mirror
- Tertiary Mirror

Cabin: T ~ +20°C

Cavity: T ~ -40°C
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Sensors & Actuators

Focal Plane Imager

Accelerometers

Fiber Optic Gyros

Fine Drive (FD) & Coarse Drive (CD)

~3-6 Hz

Secondary Mirror up to 50 Hz
SOFIA's Control System

- Gyros
- Fine Drive
- TA Plant

Control Deviation

Attitude Command

Cascaded control of LOS, XEL, EL

TA Control
SOFIA's Control System

Cascaded control of LOS, XEL, EL

Cumulative RMS

~ 1.9 arcsec

baseline measurement

Control Deviation

Attitude Command

Gyros

TA Plant

Fine Drive

TA Control

[Hz]
Why FBC?

→ Flexible body deformation occurs, especially Nasmyth tube bending, due to inertial forces (gravity, turbulence etc.)

FBC: Flexible Body Compensation

by U. Lampater
FBC: FEM & Ray Tracing

FBC Matrix:

Acceleration $\Phi_{EL}$

$\Phi_{XEL}$

Image Motion Estimation

1g load-case

Focal Plane

Mirror M1

Mirror M2

Mirror M3

$\alpha_{3F}$

$\alpha_{2}$

$\alpha_{12}$
The FBC System

Flexible Body Compensation

Image Motion Estimation

Accelero-meters

Feed Forward

SMM

Secondary Mirror Mechanism

Control Deviation

Attitude Command

Gyros

TA Plant

Fine Drive

TA Control

FBC System
The FBC System

→ FBC is key element for potential improvements

Flexible Body Compensation

FBC off

FBC on

~ 50 %

TA Control

TA Plant

Fine Drive

Gyros

Attitude Command

Control Deviation

The FBC System

Flexible Body Compensation

FBC off

FBC on

~ 50 %
Jitter Improvement Strategies

1) Sensor noise reduction

2) Optimization of image motion estimation

3) 30% reduction of the internal delay in the control loop \(\rightarrow\) improves disturbance rejection

4) Adapted SMM feed-forward

Flexible Body Compensation

Image Motion Estimation

Accelero-meters

Feed Forward

SMM

Gyros

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Fine Drive

Secondary Mirror Mechanism

Attitude Command

TA Control

TA Control

Sensor noise reduction

Optimization of image motion estimation

30% reduction of the internal delay in the control loop \(\rightarrow\) improves disturbance rejection

Adapted SMM feed-forward
Motivation for 4) adapt SMM FF

→ 22 Hz mode intensified by FBC

→ reproducible in simulation
Simulation Results in XEL

Baseline data from flight 271:

Baseline data from flight 331:

→ 11-13% Improvement in XEL
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XEL
Jitter
flight results

→ 20-50 Hz performance improved:
→ 9-13% improvement
Overall Improvement

Improvement ~ 25-30%
• Reactivation of optical path sensors and flight data acquisition (started in Nov 2017)

• Use optical path sensors for higher flexible mode estimation

• Improve Fine Drive disturbance rejection

• Implement fancy compensation ring in TCM

• Reactivate Active Mass Dampers

• (Image Motion Compensation)

• (Active Flexures)
Why more sensors?

Not enough sensor data → We need accelerometers along optical path!
Optical Path Sensors (OPS)

Image Motion Estimation

Accelometers
Optical Path Sensors

Feed Forward
SMM

Control Deviation

Gyros
TA Plant
Fine Drive

Attitude Command

Flexible Body Compensation
Secondary Mirror Mechanism

TA Control
One set of old (~2011) sensor data available for first analysis and simulation:

→ New data will be collected early 2018 for further analysis

→ Relevant, well-known frequencies are represented

→ In order to actually remove these modes we need a higher TCM bandwidth
1. OPS and new FBC increase knowledge about image motion
**Idea:**
Improve FD disturbance rejection in rigid-body range and reduce impact of flexible modes on FD feedback

**Expectations:**
- FD bandwidth can be increased
- FD is able to better compensate below 10 Hz
- Stress on SMM can be reduced (focus on flexible mode compensation)
1. OPS and new FBC increase knowledge about image motion

2. FD Observer increases FD bandwidth → better VIS mode suppression
Improved TCM

- New compensation ring concentrates mass at the suspension points and is made of stiffer materials (Tungsten / AlSiC)
- The new ring takes strain energy out of the unwanted resonance modes (300Hz and 425Hz)

- Closed-Loop bandwidth is improved by 80% providing a faster chop transition (10ms -> 7ms*) and a faster steering capability for flexible body compensation and disturbance rejection
- Prototype is manufactured and tested, flight unit is expected to be available Summer 2018

*for small chop throws, large chop throws are limited by the amplifier
1. OPS and new FBC increase knowledge about image motion
2. FD Observer increases FD bandwidth → better VIS mode suppression
3. New TCM damps 300 Hz mode → bandwidth ~80-90 Hz
Active Mass Dampers

- Six actively controlled reaction masses (reaction force 10lbf) for vibration damping
- Mounted on Whiffle Tree support structure of Primary Mirror
- Test flights during SCAI in December 2011 with limited power show significant improvement on image jitter and size.
  - System was optimized to target Primary Mirror rocking modes at 70 Hz and bending at 173 Hz
  - Adressing bending could improve on higher order optical aberrations (Astigmatism)

Mode Shape of 173 Hz
Mode as calculated by FEM Analysis (unscaled!)

12/11/2017 Friederike Graf
1. OPS and new FBC increase knowledge about image motion (~2019-2020)

2. FD Observer increases FD bandwidth → better VIS mode suppression (~2018)

3. New TCM damps 300 Hz mode → bandwidth ~80-90 Hz (~2018)

4. AMDs take out PM modes (~2018)

+ defocus decrease leads to…
• EXES could save integration time of factor 2-4
• EXES can get close to their originally planned resolution of ~ \( R = 100,000 \)
• HIRMES starts at 25 microns and saves 10-20% of integration time
• …
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...

Thank you!
Questions?