SOFIA Calibration

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Outline

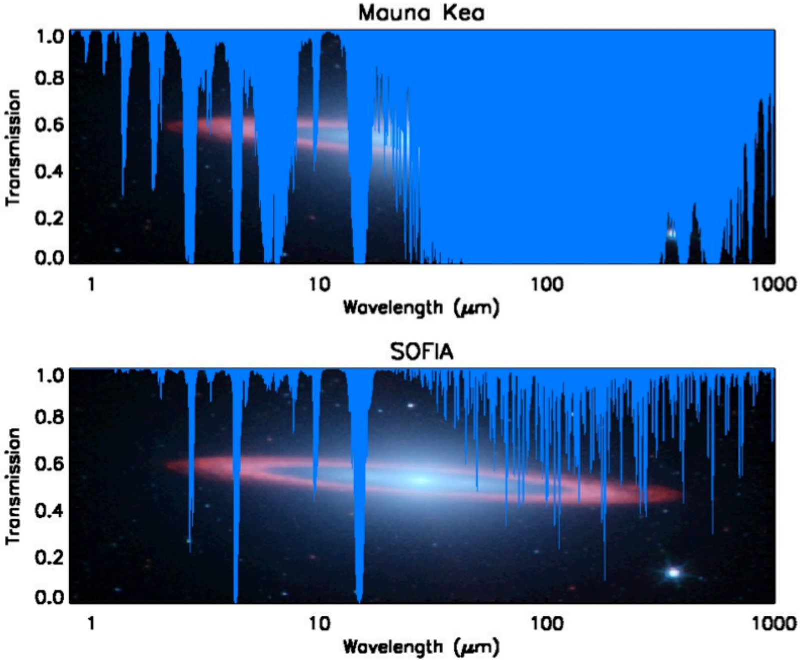
- ***Short overview of SOFIA***
- ***Results and calibration strategy from Early Science (2011)***
  - ***Two instruments: FORCAST & GREAT***
  - ***6 Short Science flights***
  - ***10 Basic Science community flights with FORCAST***
  - ***7 Basic Science community flights with GREAT***
- ***Cycle 1 and beyond***
- ***Conclusions***

SOFIA Overview

- *2.5-m telescope in a modified Boeing 747SP aircraft*
  - *Imaging and spectroscopy from 0.3 μm to 1.6 mm, especially the obscured IR (30-300 μm)*
- *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*
  - *Short and Basic Science in 2011: 17 flights for the community with FORCAST and GREAT; 35 science flights in total*
  - *20 year design lifetime – can respond to changing technology*
  - *Science Ops at NASA-Ames; Flight Ops at Dryden FRC (Palmdale- Site 9)*
  - *Deployments to the Southern Hemisphere and elsewhere*
  - *Goal is >120 8-10 hour flights per year*

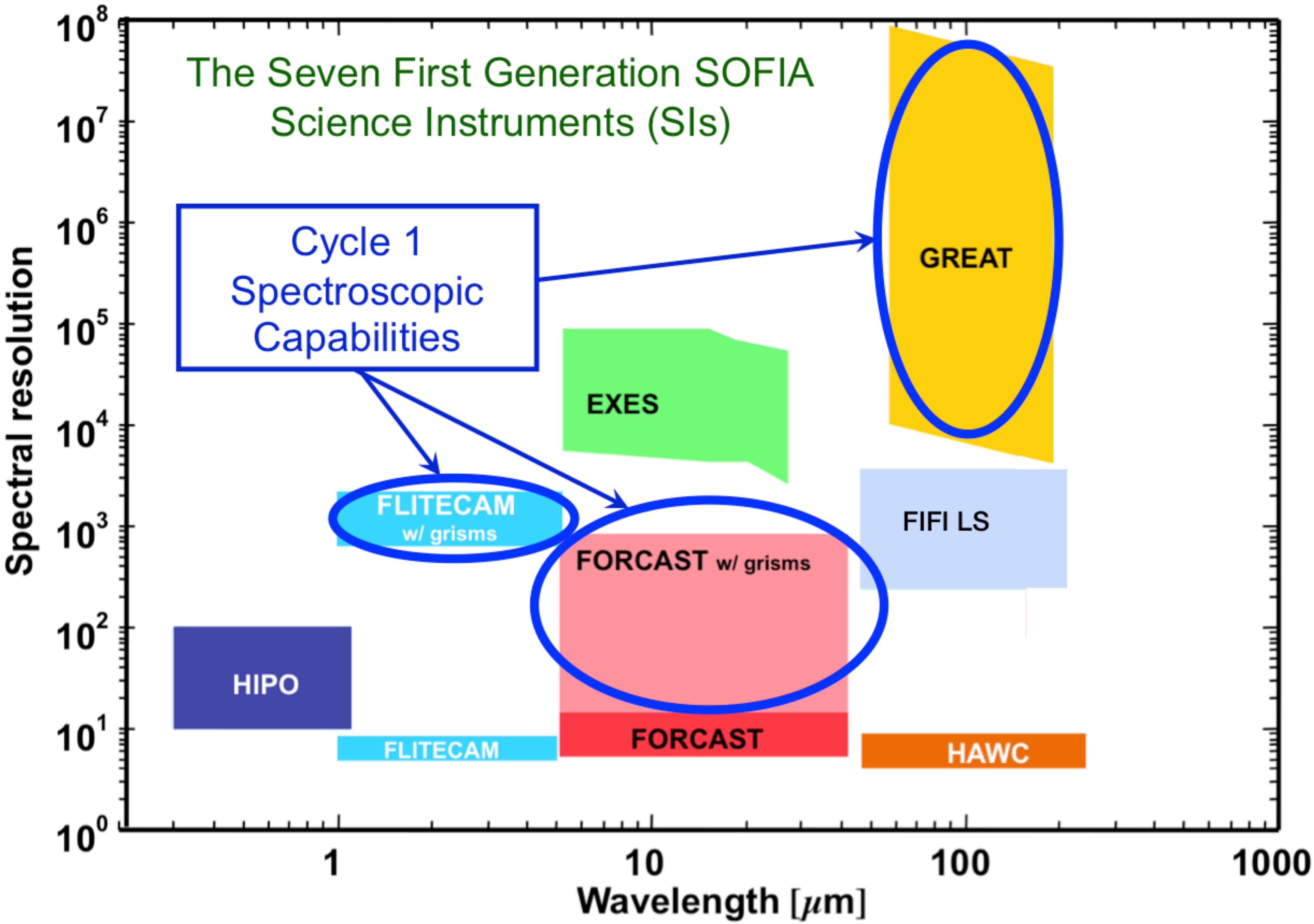
The SOFIA Observing Environment

- ***Above 99.8% of the water vapor***
- ***Transmission at 14 km >80% from 1 to 800 µm***
- ***Emphasis is on the obscured IR regions from 30 to 300 µm***




SOFIA Test flight on July 13, 2010
SOFIA
STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY
NASA
DLR
N747NA

SOFIA First Generation Instruments



Calibration Results from Short and Basic Science (2011)

- Two instruments: FORCAST & GREAT
- 35 science flights
  - 6 short science (3/3)
  - 10 FORCAST flights for the community
  - 7 GREAT Flights
  - Rest engineering and guaranteed time
- Resulted in two special SOFIA issues:
  - FORCAST ApJ Letters (8 papers, but only short science)
  - GREAT A&A (22 papers, of which 4 technical papers)

Faint Object infraRed CAmera for the Sofia Telescope: FORCAST

5 to 40 μm Facility Camera

- **Detector:** **Si:As & Si:Sb BIB Arrays, 256 × 256 pixels**
- **Plate Scale:** **0.77”/pixel ⇔ 3.4’ × 3.2’ FOV**
- **Spatial Resolution:** **λ(μm)/10 arcseconds for λ > 15 μm**
- **Simultaneous Imaging in two bands:**
  - **Short: Continuum 18.7, 21.0, 24.4 μm**
  - **Sensitivity: 12-20 mJy 5σ 1 hour**
  - **PAH (5.5, 6.2, 6.7, 7.7, 8.6, 11.2 μm), Line 18.7 μm [SIII]**
  - **Long: Continuum 32.0, 33.2, 34.8, 37.6 μm,**
  - **Sensitivity: 30-40 mJy 5σ 1 hour**
  - **Line 33.5 μm [SIII], 34.6 μm [SiII]**

Herter et al. 2013, PASP (in press) -calibration

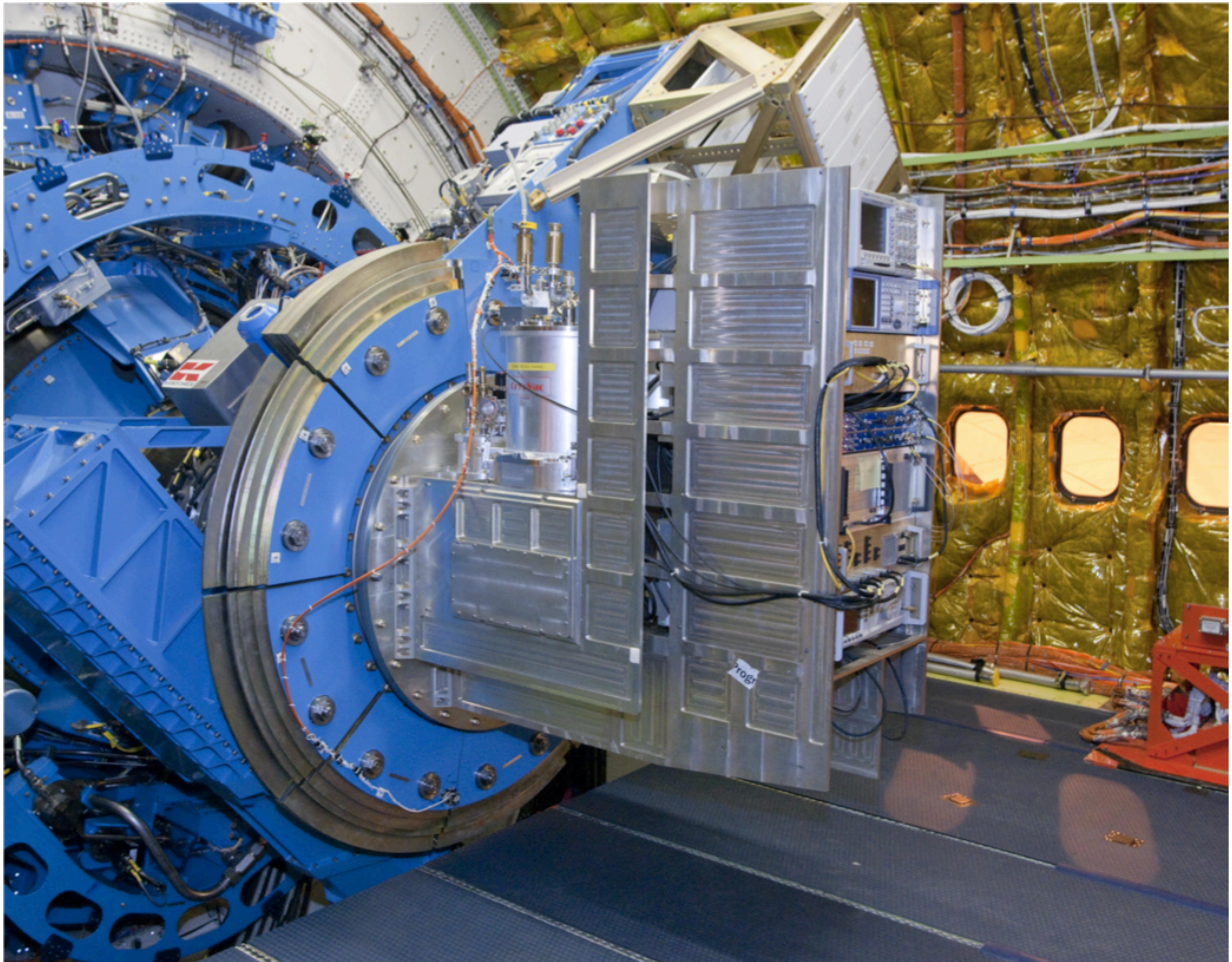
FORCAST

GREAT: Heterodyne Spectrometer

German REceiver for Astronomy at Terahertz frequencies

- ***PI: R. Güsten, Max-Planck Institut, Bonn (guesten@mpifr-bonn.mpg.de)***
- ***Detector: dual channel hot-electron bolometer (HEB): Low: 1.252 – 1.352; 1.417 - 1.520 THz (240 - 200 µm) & 1.815 - 1.91 THz (165 - 155 µm) Mid: 2.507 – 2.514; 2.67 – 2.68 THz (120 - 110 µm)***
- ***L-channel fill in most of the Herschel HIFI gap between band 5 & 6***
- ***Backends: AOS & XFTTs (2.5GHz BW, 44 kHz res (64k channels)) R= 10^6 -> 10^8***
- ***Science: Spectroscopy of CII (158 µm), HD (112 µm), and many other molecules***
- ***Targets: Galactic and extragalactic ISM, circumstellar shells***
- ***Single-sideband (SSB) noise temperature: T_{SYS} ~ 2500 K at 158 µm***
- ***High frequency 4.7 THz channel targeting [O I] 63 µm expected in 2014***
- ***Also small 7 beam L2 array (up-GREAT)***

GREAT on the SOFIA Telescope



Early Science Calibration Plan

- For Basic Science we had the following strategy:
- For FORCAST:
  - Observe at least 3 calibrators in each flight, over the duration of the flight
    - One calibrator must be from the list of primary standards
    - Same calibrator can be observed more than once
    - If a secondary calibrator is used it must be observed against a primary at the same altitude
    - Asteroids considered secondary and must be paired with a primary stellar standard
- For GREAT:
  - Observe a planet at the start a flight series (Mars, Jupiter or Saturn)
  - If no planet is observed during a flight, observe a bright line-source (NGC7027 or NGC7023) to monitor calibration accuracy (one channel tuned to CII)

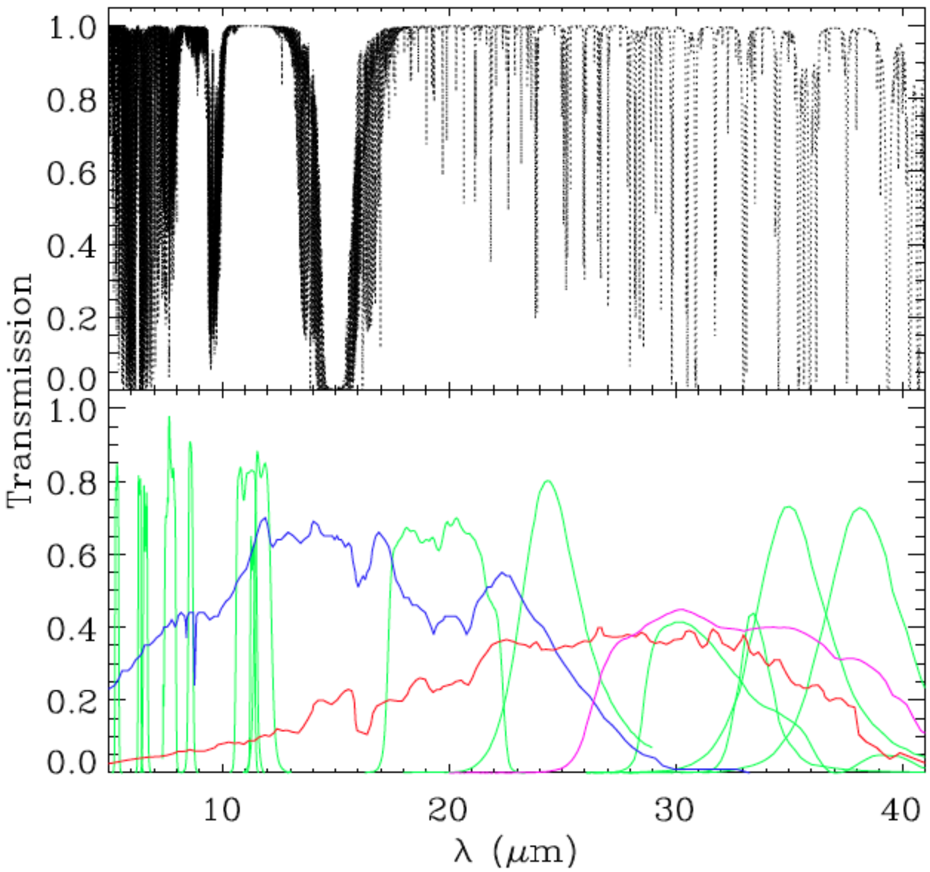
Calibration standards

- In early science we almost completely relied on modeling work done and being validated by Herschel, but we also did some modeling based on M. Cohen and Kurucz models
  - Stellar models (the "Leeuwen group", L. Decin)
  - Models of planets and planetary moons (R. Moreno)
    - We used ESA2
  - Asteroids, ThermoPhysical models with shape information (Th. Müller - Garching) – only two
  - No secondary calibrators

FORCAST Calibration: Stellar Calibrators

- Bright, well studied stars, with well determined physical properties (Size, Teff, Surface gravity, metallicity, brightness etc.)
- The primary calibrators for FORCAST Basic science have all been modeled for Herschel by the Leeuwen group (L. Decin) using state of the art atmospheric models (MARCS,TURBOSPECTRUM) and validated by Herschel.
- We have used these models to predict what flux densities FORCAST sees in each filter (including instrument throughput, filter characteristics and atmospheric transmission)

FORCAST Throughput



Atmospheric transmission at 41,000 ft (7.1 μm PWV). Filter throughput (green), SWC QE (blue), LWC QE (red), Dichroic transmission (magenta)

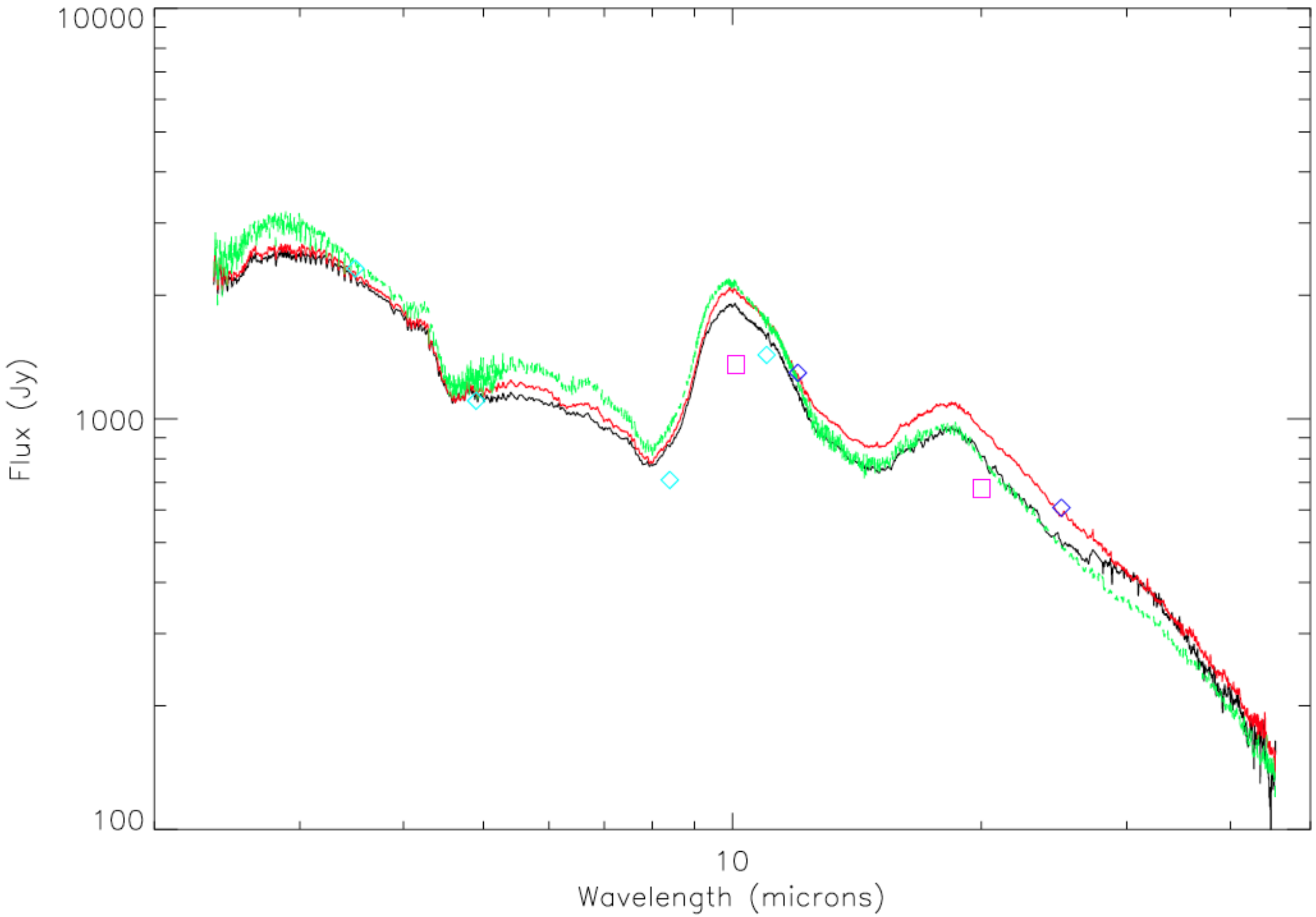
Stellar calibrators

Star	Spectral type	Flux (37μm) [Jy]	Number of time observed	Rms
Sirius (α CMa)	A1V	10.8	7	0.054
α Boo	K2 IIIp	63.1	126	0.069
α Cet	M2 III	19.7	11	0.049
β And	M0 III	22.6	28	0.088
β Peg	M2.5 III	34.4	69	0.055
γ Dra	K5 III	13.3	65	0.064
β UMi **	K4 III	13.2	3	0.068
μ Cep*	M2e Ia	280	125	0.113

* Variable !

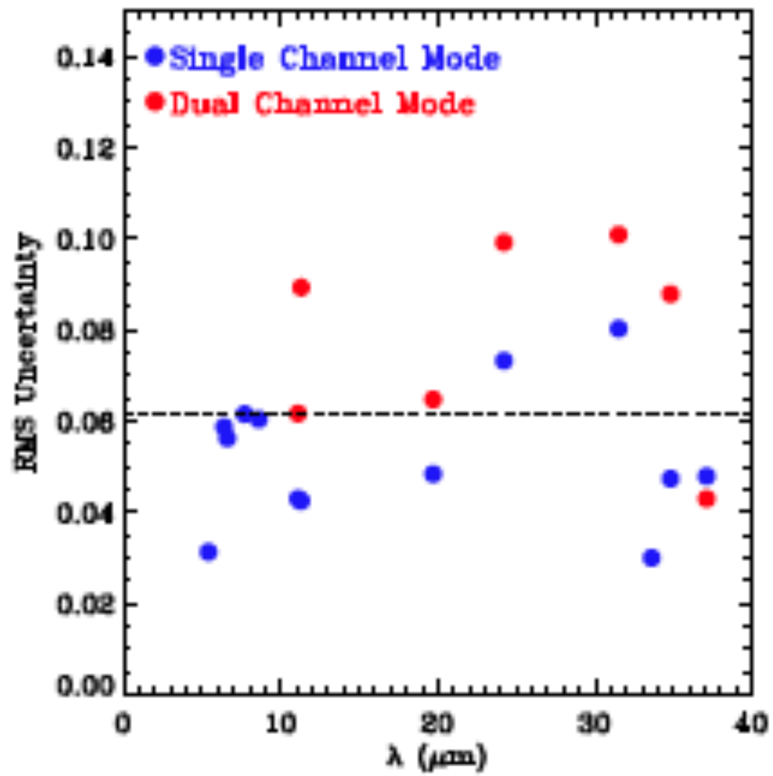
** Scaled by 1.18

μ Cep



ISO spectra (3 epochs) overlaid with IRAS (blue diamonds) and ground based photometry:Tokunaga – purple squares, Gillett – pale blue diamonds

FORCAST Calibration (RMS uncertainty)



Standard deviation of normalized calibration response relative to mean calibration response (per flight). Blue (single channel -no dichroic), red (dual channel). LWC filters have blue leak in single channel mode (corrected).

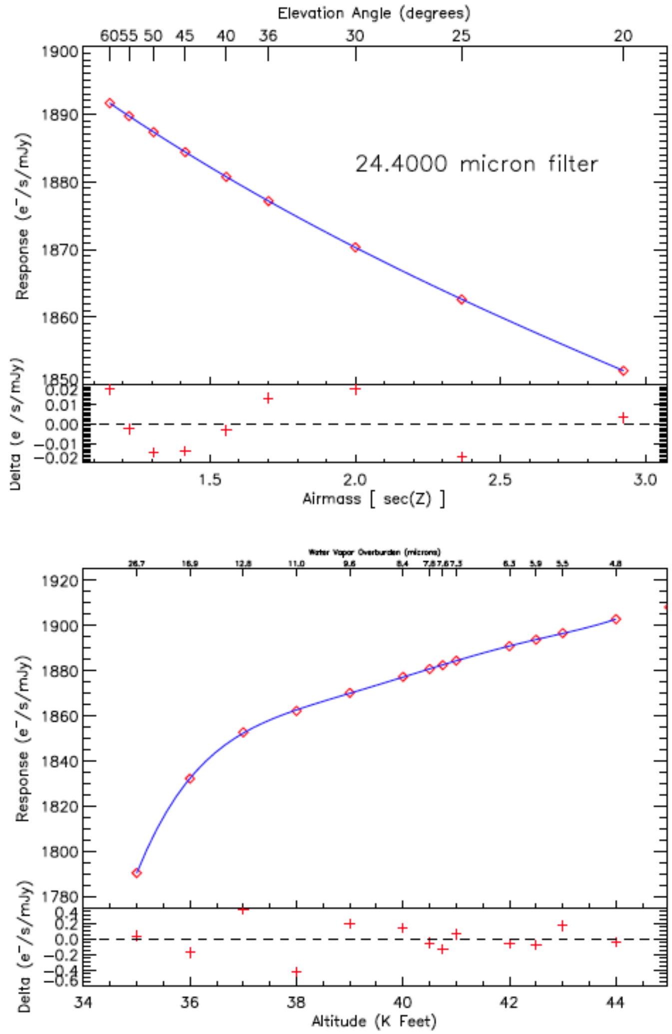
Asteroids

- Only Pallas & Europa used for FORCAST in Basic Science
  - Model predictions for exact date and time provided by T. Müller, MPE, using his thermophysical model
  - Some discrepancies compared to stellar standards and large errors for Europa (rms= 0.113) but only three observations.
  - Large uncertainties at the shortest wavelengths

Special challenges for SOFIA

- *Constraints flight planning (more calibrators, especially red, would help)*
- *We still have an atmosphere, which adds to the background and attenuates the signal*
  - *We open at 37,000ft, start science observing at 39,000 ft, then 41,000 ft , and stay the last three hours at 43,000 ft (or 45,000 ft for less time).*
  - *Even at the same altitude the atmosphere can (will) change, BECAUSE WE ARE FLYING!*
  - *We therefore have to rely on atmospheric models, to correct for elevation and change in altitude*

FORCAST

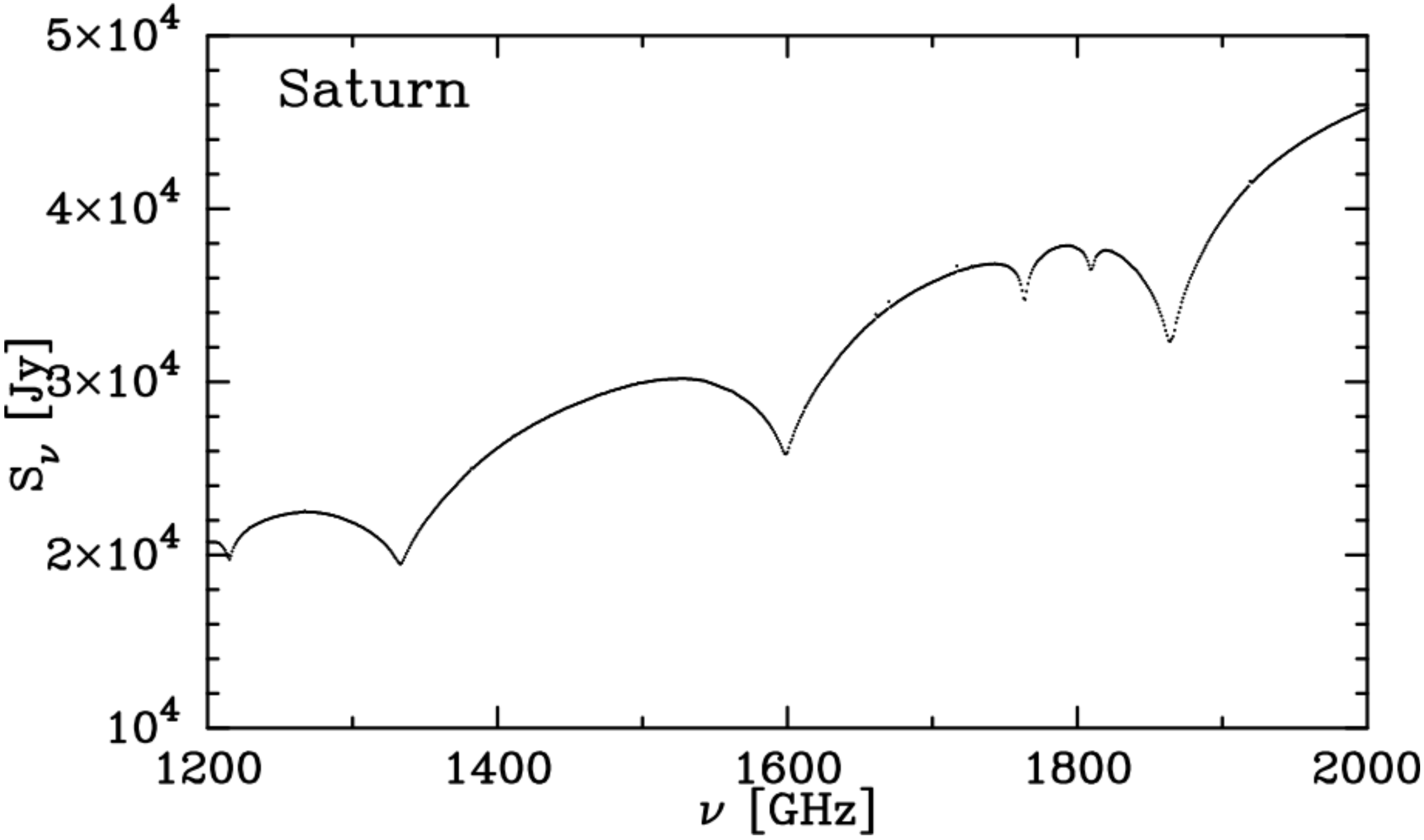


Response vs. airmass and altitude for the 24.2 μm filter derived from the atmospheric model, ATRAN. FORCAST calibration uses a standard atmosphere at 41,000 for a telescope elevation of 45 degree.

GREAT Calibration

- Two independent models for Mars (in good agreement with each other). The GREAT team used:
  - http://www.lesia.obspm.fr/perso/emmanuel-lellouch/mars/
- GREAT also used the ESA2 models for Jupiter and Saturn, which are available as FITS (and ascii) files.
  - The next slide shows Saturn in the GREAT low frequency band
  - Spectrally clean continuum bands (also in terms of atmospheric transmission:
    - L1A_cont 1264.0 LSB
    - L1B_cont 1474.0 LSB
    - L2_cont 1900.8 USB

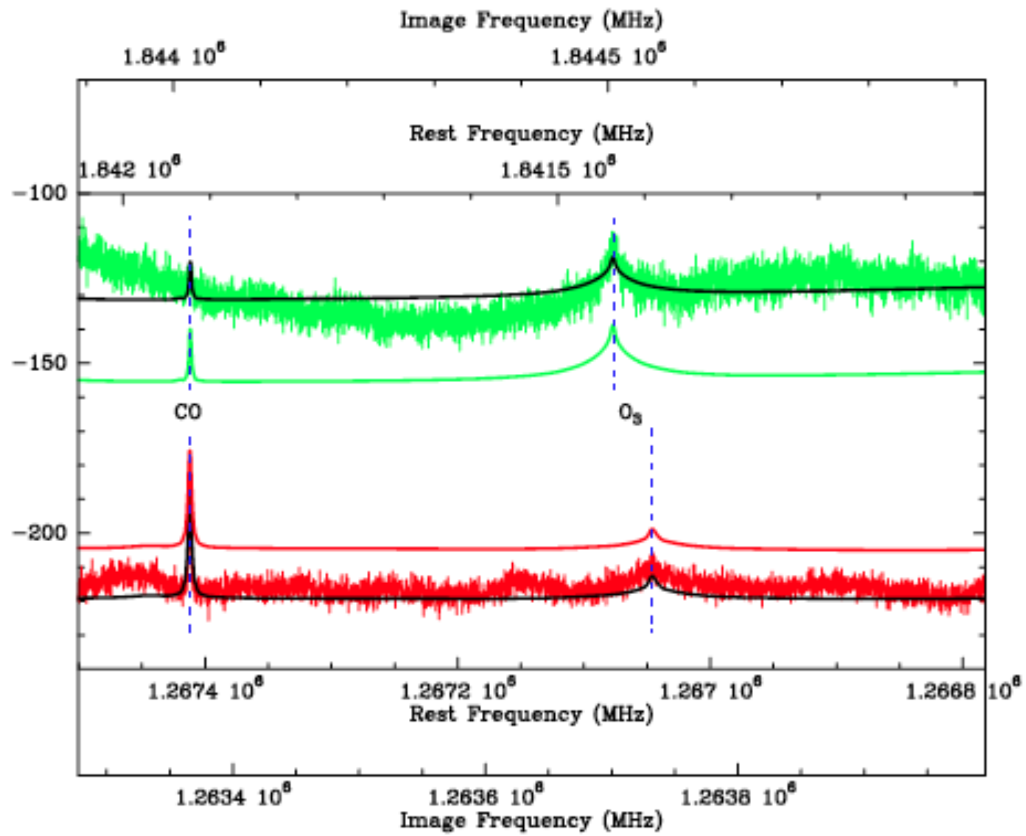
ESA2 model for Saturn in the GREAT low frequency bands



GREAT calibration – atmospheric transmission

- A heterodyne instrument like GREAT essentially measures the atmospheric transmission as part of its hot/cold/sky calibration. Because GREAT is a dual channel instrument, one should be able to fit for a common *pwv* content applicable for both bands. However, as shown in Guan et al. (2012), none of the commonly available atmospheric models do a good job
- The atmospheric transmission is often dominated by the *pwv*, but is in addition substantially affected by the 'dry' atmosphere.
- Guan et al. investigated three models:
  - ATRAN (Lord 1992), ignores collision induced absorption (CIA) of N_2 and O_2, which is the largest contributor to the dry opacity (quasi-continuum opacity)
  - MOLIERE (Urban et al. 2004), CIA contribution factor of two higher than in AM
  - AM (Paine 2011) – adopted by GREAT

GREAT Sky Calibration (Mixers L1 & L2)



Simultaneous $T_{sky} - T_{hot}$ spectra for L1 (red) and L2 (green) showing to ozone lines. The solid black lines are independent fits, while the red andc green lines are the results of a common fit with a single *pwv*, showing that a consistent *pwv* cannot be derived from a common fit

Plans for Cycle 1

- 3 instruments
  - GREAT, improved mixers for L1 & L2, M-channel also offered for OH (2.514 THz) – no change in strategy (Herschel models for planets, still need southern line standard for deployment
  - FORCAST, imaging and grism spectroscopy – Herschel stellar standards for both imaging and spectroscopy, could use well-calibrated asteroids
  - FLITECAM, imaging and grism spectroscopy – Calibrated supertemplate stars from M. Cohen

Cycle 2 and Beyond

- Cycle 2 will offer FIFI-LS and EXES
  - FIFI-LS will use Herschel stellar standards, also need for accurate asteroid models and planetary moons as well as Uranus & Neptune
- Cycle 3: HAWC+ (FIR camera + polarimeter)
  - Herschel stellar standards, asteroids, planetary moons, Uranus & Neptune
  - Secondary standards (from Herschel archive)

Conclusions

- Lessons learned from Early science
  - 20% of science time used for calibration
  - Lack of good standards places severe constraints on flight plans
  - Clear need for reliable asteroid models
  - 20% absolute accuracy; can probably reach 10% after proper instrument commissioning