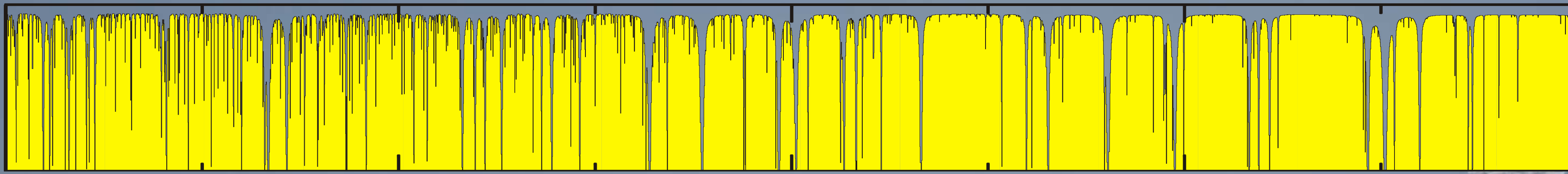

ATM 1-5 THz, 14 km altitude

**German Receiver for Astronomy at THz Frequencies**

# GREAT


## Modular dual-channel heterodyne receiver for high-resolution spectroscopy with SOFIA

# GREAT - the Consortium

MPIfR
KOSMA
MPS
DLR-Pf


*GREAT, L#1 & L#2 channels*

## PI-Instrument funded and developed by

- MPI Radioastronomie (2.7 THz channel)
  - R. Güsten (PI)
  - S. Heyminck (system engineer)
  - B. Klein (FFT spectrometer)
  - I. Camara, T. Klein (2.7 THz LO)
- Univ. zu Köln, KOSMA (1.4/1.9THz channels)
  - J. Stutzki (Co-PI)
  - U. Graf (1.4 &1.9THz LO, Optics)
  - K. Jacobs (HEB mixers up to 2.7 THz)
  - R. Schieder (array-AOS)
- DLR Planetenforschung (4.7 THz channel)
  - H-W. Hübers (Co-PI: 4.7 THz HEB, IF, cal unit)
- MPI Sonnensystemforschung
  - P. Hartogh et al. (CO-PI: CTS)

# Configuration - overview

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| Channel | | Frequencies [THz] | Lines of interest |
|---|---|---|---|
| low-frequency | L1 a,b | 1.25 – 1.52 | [NII], CO series, OD, HCN, $H_2D^+$ |
| low-frequency | L2 a,b | 1.81 – 1.91 | $NH_3$, OH, CO(16-15), [CII] |
| mid-frequency | M a,b | 2.5, 2.7 | OH($^2\Pi_{3/2}$), HD |
| high-frequency | H | 4.7 | [OI] |

- two out of the 4 cryostats can be operated simultaneously
  - all channel combinations are possible
    - the actual flight configuration is science driven (within operational limitations)
- channel availability
  - all of low-frequency channels operational (baseline for Basic Science)
    - have been flown routinely since April
  - mid frequency channels (under development)
    - engineering flight with 2.5 THz LO successful in November, part of US CfP
  - high-frequency channel (commissioning foreseen Q2 2013)

# GREAT installed aboard SOFIA

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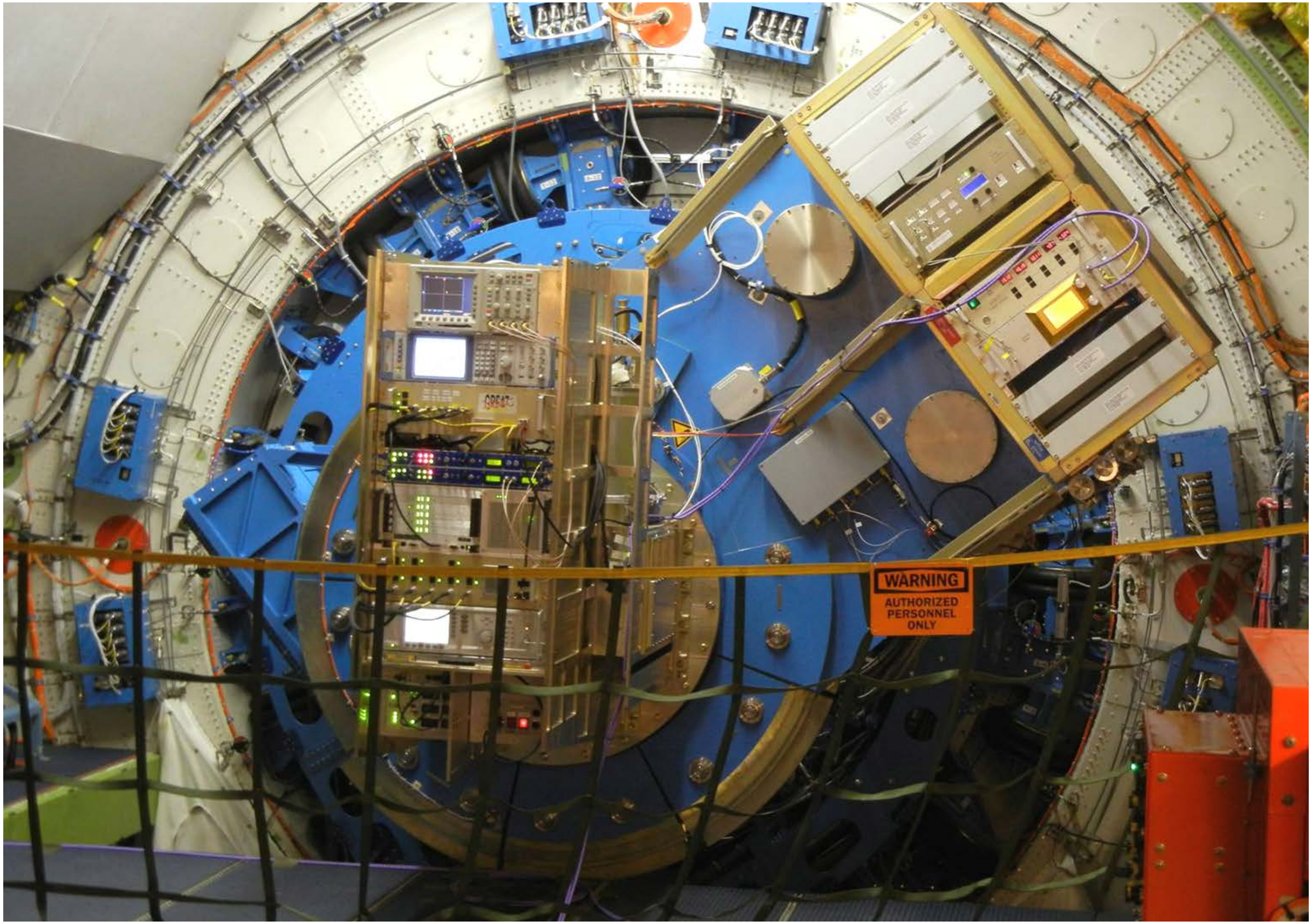

# system performance: L#1 a,b

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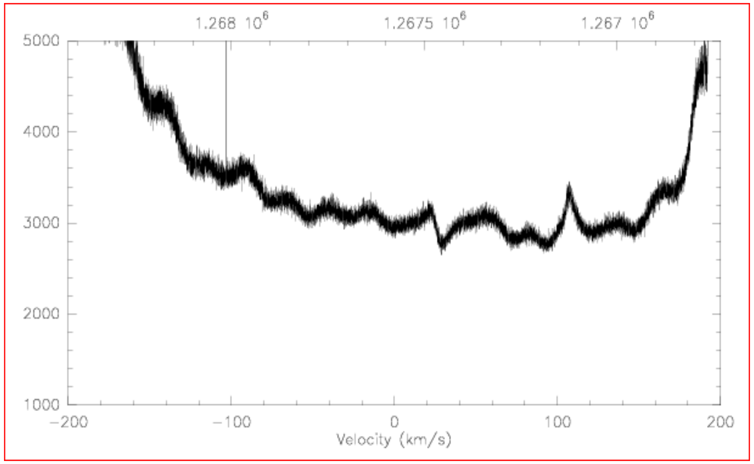
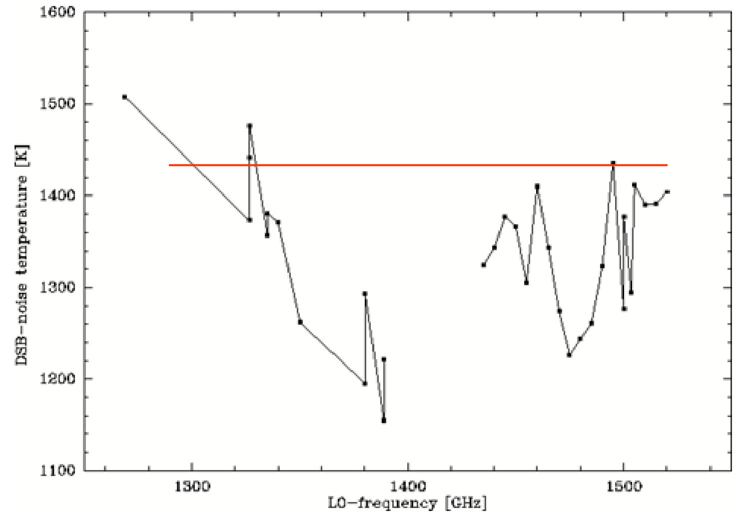
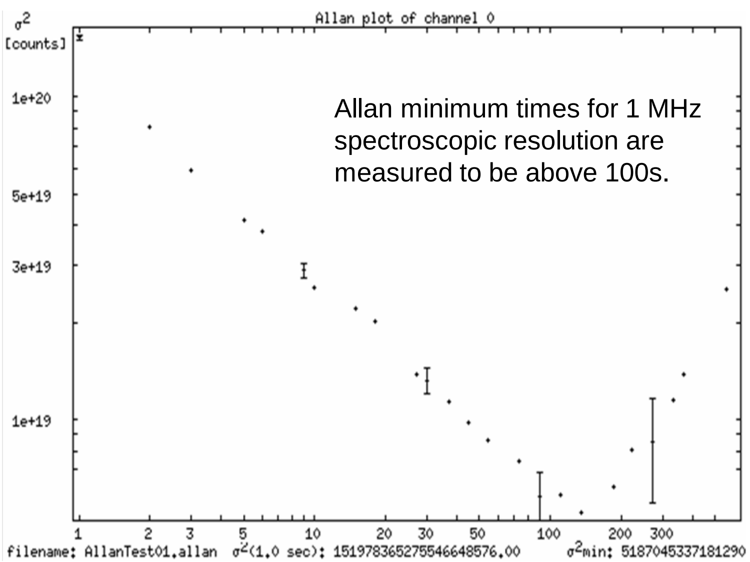



SSB receiver noise performance measured @ 1267GHz




Above: DSB receiver temperature of the L1a,b bands

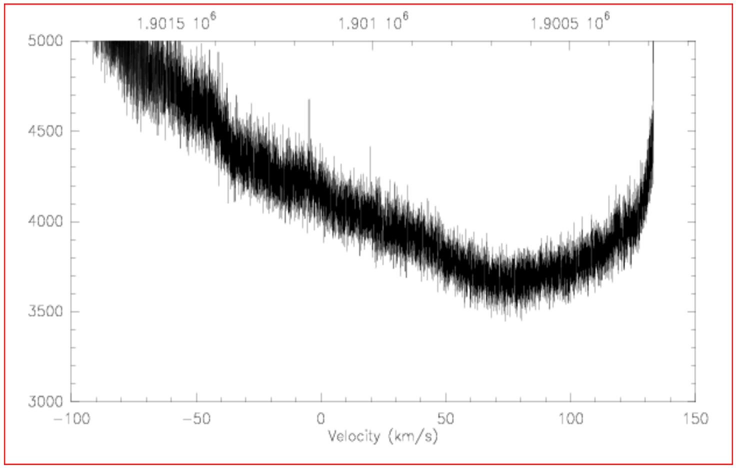



Allan minimum times for 1 MHz spectroscopic resolution are measured to be above 100s.

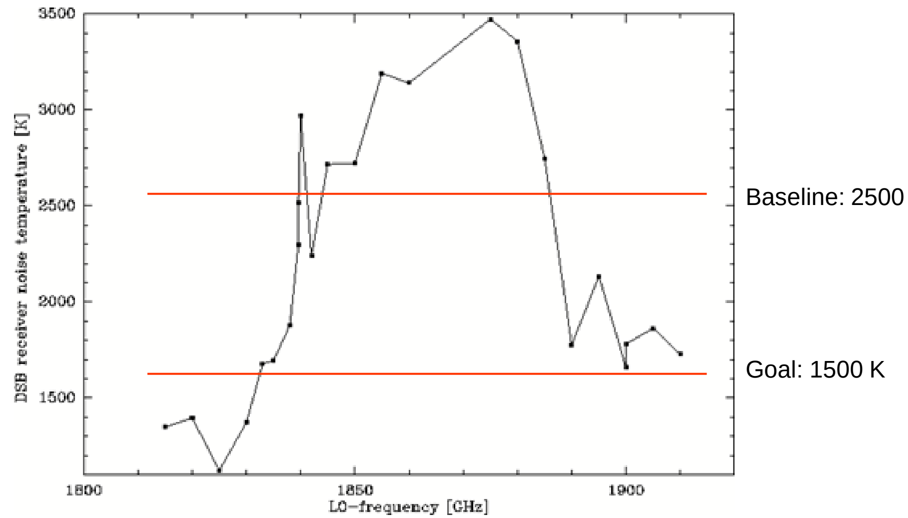
| Parameter | baseline | goal | achieved |
|---|---|---|---|
| RF tuning [GHz] | 1252-1392, 1417-1520 | | |
| Rx noise (DSB) [K] | 2000 | 1400 | 1200 -1400 |
| IF bandwidth [GHz] | 0.6 | 4 | 1.2+ |
| stability, spectr. [s] | >10 | >100 | 100+ |

Note: trade-off IF bandwidth vs. stability (as with HIFI)

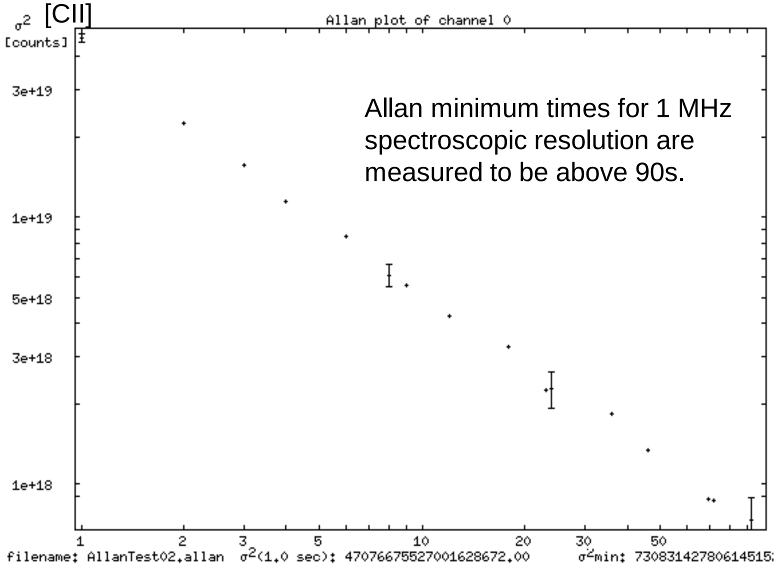
# system performance: L#2a




Above: SSB receiver noise performance measured @ 1.9 THz [CII]




Above: DSB receiver temperatures across the L #2 band




Allan minimum times for 1 MHz spectroscopic resolution are measured to be above 90s.

| Parameter | baseline | goal | achieved |
|---|---|---|---|
| RF tuning [GHz] | 1815 -1910 | | |
| Rx noise (DSB) [K] | 2500 | 1500 | 1300 -1800 |
| IF bandwidth [GHz] | 0.6 | 4 | 1.2+ |
| stability, spectr. [s] | >10 | >100 | 100+ |

# GREAT offers a suite of back-ends, operated in parallel

| Back-ends | Width [GHz] | Resolution[(#)] [MHz] | Provided by |
|---|---|---|---|
| AOS: acousto-optical spectrometer array | 4 x 1.00 | 1.6 | KOSMA |
| AFFTS: Fast Fourier Transform spectrometer | 2 x 1.50 | 0.212 | MPIfR |
| XFFTS: upgraded in 08/11 | 2 x 2.50 | 0.088 | MPIfR |

Note: [(#)] spectral resolution is measured as equivalent noise bandwidth, the 3 dB bandwidth is generally smaller.

# GREAT operation

## GREAT operates

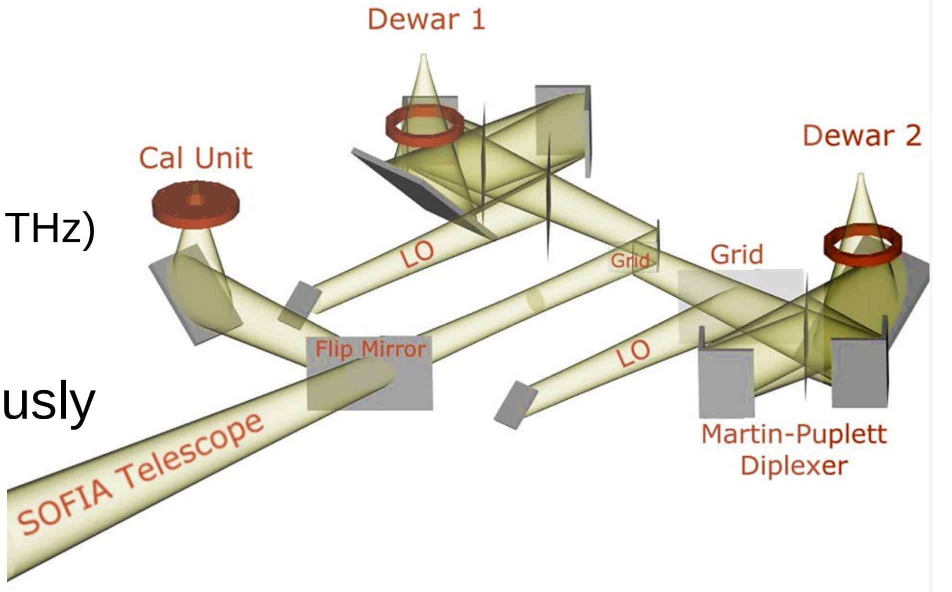
- with diffraction limited optics

  HP beam widths: 22″ (1.4) and 12″ (2.5 THz)

  ↳ pointing and boresight: < 2-3″

- co-aligned channels, simultaneously

  ↳ co-alignment between channels: <3″




Warning: for configurations involving the H-channel, requirements will be tighter by ×2

## The modular design allows changing

- between in-band frequencies within minutes, in flight
- configurations (channels) between flights

# GREAT Observing Modes

- classical observing mode: telescope position switching
  - general guideline for FIR total power observations: maintain sky background
- preferred for compact objects: chopping with secondary
  - dual beam switching with 1-2 Hz, throw up to several arcmins
- advised for extended structures: „on-the-fly“ scanning
  - due to excellent Allan Variance stability times of overall system

GREAT observations can be executed as

- single pointed
- raster map
- on-the-fly

# observing prep & data pipeline

- GREAT is available to SOFIA communities in **collaboration**
- GREAT as PI instrument operates in **service mode** only
  - handling of the observations is by the GREAT team
  - preparation of OT observations by SMO (supported by GREAT)
- observations are executed in the environment of „KOSMA control“ via **observing scripts**
  - preparation of set-up is supported by USRA/DSI
- GREAT delivers calibrated data in standard **CLASS** format and raw data in modified **FITS** format

# GREAT detects first photons

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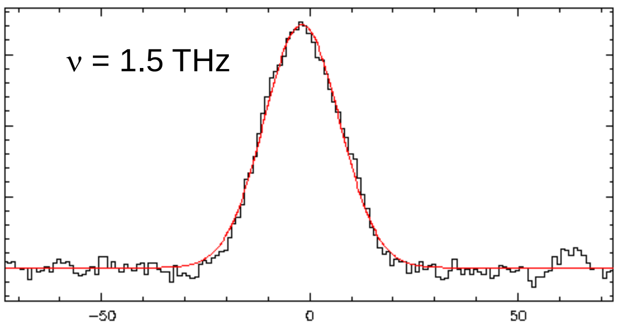
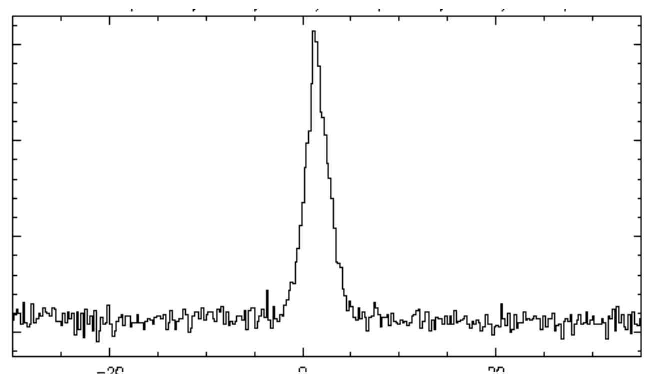
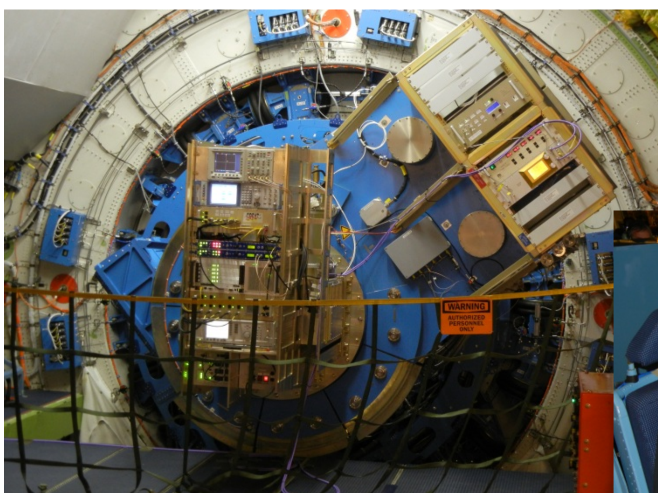
On 1st April 2011, GREAT successfully concluded its commissioning flight

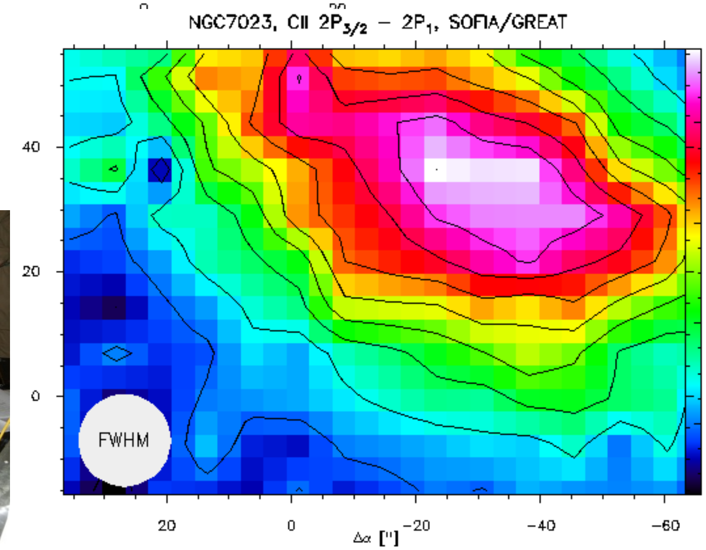
Total power scan across Saturn




[CII] 1.9 THz towards NGC 7023







# Early Science Projects

- Short & Basic Science projects covered a wide range of astrophysical topics, with good response to G+US CfP
  - 26 science projects (G+US) have been observed
  - all data have been pre-released to PIs (except one)
  - final release of data within days (20% calibration accuracy)
- overall BS2 was amazingly successful
- but every flight had new challenges, new surprises
- overall „science“ efficiency was low (room for ⇧ ×2)

we concluded a typical observatory commissioning (in this sense: reality matched expectations), but now for „cycle 1“ the shortcomings are to be addressed /solved

# Basic Science Publication Plan

- publication in A&A special volume accepted by Editors
  - latest deadline for submission: Jan 31 2012
  - latest deadline for acceptance, to be included: March 31, 2012

- total number of GREAT projects executed: 25+1
- commitment from PIs to join special volume: 19+2
- „technical“ papers on GREAT 4

# GREAT Early Science Projects

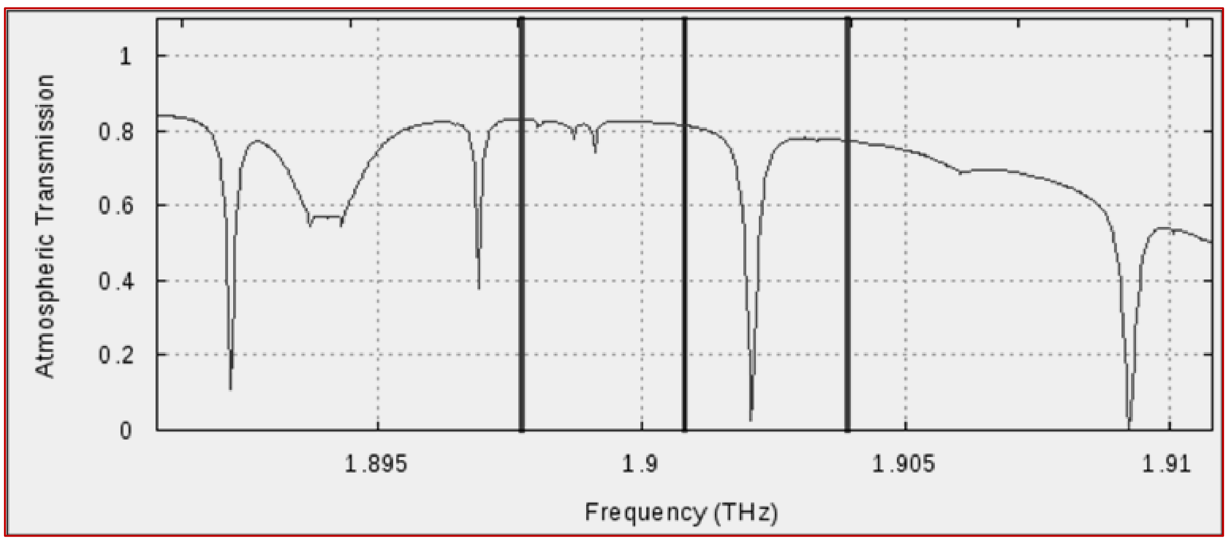
MPIfR
KOSMA
MPS
DLR-Pf

| Project ID | PI name | working title | flight ID | | data processing pipeline | | | | publication status | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | SS2 | BS2 | pre-release | final release | data analysis | contact* | draft | submitted |
| | | | | | | | | | | |
| 1 | R. Simon | S106 – case study of the PDR | 02 | 05 | x | | | -- | x.x | xx.xx. |
| 2 | J.Perez-Beaupuits | The ionized and hot gas in M17SW | 01 | 05 | x | | | HW | | |
| 3 | G. Sandell | [CII] and CO observations of BD+40 4124 | 01 | | x | | | HW | | |
| 4 | F. Wyrowski | High-J CO outflows | 03 | | x | | | HW | | |
| 5 | B. Parise | Search for $H_2D^+$ | 02 | 02/10/11 | x | | | HW | | |
| 6 | A.Gomez | High-J CO outflows in Cep-E/A | | 02/03 | x | | | MR | | |
| 7 | A. Gusdorf | OH excitation observations in Cep A | | 03/11 | x | | | MR | | |
| 8 | B. Parise | OD detections | D2 | 02/03/05/10 | x | | | HW | | |
| 9 | J. Eislöffel | L1157 (L1448), check CII (07) | | 02/10/11 | 12.08. | | | HW | | |
| 10 | F. Wyrowski | $NH_3$ absorption towards hot cores | | 04 | x | | | HW | | |
| 11 | K. Menten | OH excitation studies (ex Cep A) | OCF4/03 | 01/06/07 | x | | | MR | | |
| 12 | H. Wiesemeyer | $^{18}OH$ 2.5 THz absorption studies | A2 | 06 | x | | | -- | | |
| 13 | D. Neufeld | Discovery of interstellar mercapto radicals (SH) with SOFIA/GREAT | | 10/11 | x | | | HW | | |
| 14 | M. Requena | CO excitation in the CND | 02/03 | 03/11 | x | | | -- | | |
| 15 | M. Röllig | CII in IC342 – data under review | (01)/D1 | | 16.11. | | | MR | | |
| 16 | Y. Okada | [CII]158um emission in IC1396A | | 05/07 | x | | | -- | | |
| 17 | M. Kaufman | $H_2O$ masers (non detections) | | 01 | 12.08. | | | HW | | |
| 18 | Di Li | Resolving the PDR Transition Zone with CII and CI (rho Oph) | | 03/04 | 12.08. | | | MR | | |
| 19 | R. Sahai | [CII] 158µm line in the PN NGC6720 | | 01/03/10 | 12.08. | | | HW | | |
| 20 | E. Chapillon | MWC480 – upper limit only | | 10 | 16.11. | | | MR | | |
| 21 | Stutzki/Graf | Orion-B – PDR structure | A2 | | x | | | -- | | |
| 22 | S. Leurini | IRAS05358 – too short observations | A2 | B | x | | | | | |
| 23 | Ricken/Ossenkopf | The structure of hot gas in Cep B | 02 | 04 | x | | | -- | | |
| 24 | A. Gusdorf | CO excitation W28F/SNR shock | D2 | | x | | | MR | | |
| 25 | N. Schneider | Pillars – CII /CO studies | A3 | | 16.11. | | | MR | | |
| | | | | | | | | | | |
| T 1 | Heyminck/Graf | GREAT – instrument paper | | | | | | | | |
| T 2 | B. Klein | Broadband FFT spectrometers for GREAT | | | | | | | | |
| T 3 | Guan/Stutzki | Stratospheric Atmospheric Calibration | | | | | | | | |
| T 4 | Jacobs/Pütz | THz HEB waveguide mixers for GREAT | | | | | | | | |

Decision pending (data under review) for projects: 5, 15

# Instrument calibration - I

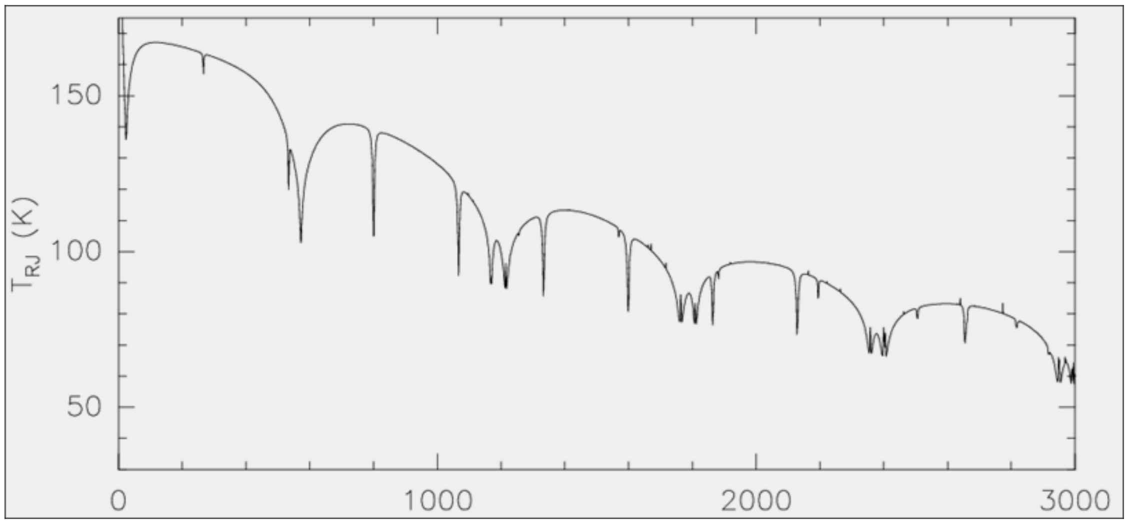
- the calibration of GREAT spectra involves several steps
  - the temperature scale is defined against internal calibration loads, providing ambient & cold (LN) references
  - the atmospheric absorption is then fit – frequency dependent – with appropriate models of the high atmosphere (challenging)




Atmospheric transmission at 41 kft flight altitude and excellent 10 µm PVW at the [CII] frequency
[see the GREAT time estimator on the DSI web pages]

# Instrument calibration - II

- finally, the coupling of the GREAT beam to the astronomical object is determined by observations of suitable planets (Mars & Jupiter)




RJ temperatures of Jupiter at FIR wavelengths [Model by (ESA2) Rafael Moreno)]

the so determined GREAT beam coupling efficiency 0.57 (±10%) compares very well with calculated figures for the SOFIA optics

# Experience from ES Operation

- flights have been challenging (beyond all expectations) but also rewarding: when shipping GREAT last year, nobody had foreseen 19 flights and loads of excellent science data.
- this was made possible by an outstanding team effort by all involved (from ground crew to TO/MD to flight deck, and above), showing impressive flexibility when needed.

  [fair to also mention here my dedicated team that got carried away by its success..]
- observatory performance: improving (ok for shared risk), but not adequate for routine observation phase.
  - in-flight operation must become more reliable (main failures: MCCS/translator, on board infrastructure, and occasionally telescope/wobbler)
  - pointing (tracking) accuracy must be improved to better than 1-2 arcsec

    this will limit/define our science with (M)/H -channels
  - observations must be made more efficient (depending on the observing modes, the net time for GREAT science can be increased by factor 2)
  - staffing: in critical areas, ramp-up asap (understaffing was schedule driving).

# GREAT upgrades

- as a PI instrument GREAT will be upgraded continuously with new technologies as they become available
- while maintaining baseline performances as committed in our MOU, for/during cicle1 we prepare to integrate/commission
  - improved HEB mixers (gain in particular for the M-channel)
  - a lower noise solid-state local oscillator (LO) for L2,
  - a re-designed solid-state LO for the M-bands with better lifetimes
  - a novel broad-band photonics LO (L1, L2), prototype for upGREAT
  - re-modeled optics (for easier, more precise adjustment to boresight)
  - re-commission M1 channel (part of CfP)
  - engineering of the M2 channel (optimized for HD)
  - and ultimately the H-channel (Q2/2013)