German Receiver for Astronomy at THz Frequencies

ATM 1-5 THz, 14 km altitude

Last news from SOFIA and the GREAT instrument

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Bonn, Germany
Outline

- SOFIA observatory status / introduction
- GREAT instrument overview
- upGREAT instrument
- Cycle I and II science overview
- Call for proposals Cycle III
- Cross-calibration prospects SOFIA/Herschel
SOFIA Overview

- 2.5-m telescope in a modified Boeing 747SP aircraft
  - Imaging and spectroscopy capable from 0.3 \( \mu \text{m} \) to 1.6 mm
  - Emphasizes the obscured IR (30-300 \( \mu \text{m} \))

- Operational Altitude
  - 39,000 to 45,000 feet (12 to 14 km)
  - Above > 99.8\% of obscuring water vapor, PWV ~ 1-20 \( \mu \text{m} \)

- Joint Program between the US (80\%) and Germany (20\%)
  - First Light images were obtained on May 26, 2010
  - 20 year design lifetime – can respond to changing technology
  - Science Ops at NASA-Ames; Flight Ops at Armstrong FRC (Palmdale- Site 9)
  - Deployments to the Southern Hemisphere and elsewhere
  - Goal is >120 x 10 hours flights per year
SOFIA status

- SOFIA just transitioned from development to operations Phase on May 29th 2014. Milestone in the project and 6 science instruments are now available for Cycle III (EXES, FIFI-LS, FLITECAM, FORCAST, GREAT, HIPO).

- Successful commissioning of the last two instruments FIFI-LS (based on PACS/Herschel) and EXES (Echelon-cross-Echelle Spectrograph) in early 2014.
SOFIA status

- US White House initial budget proposal in March 2014 for FY 2015 envisioned shelving SOFIA in 2015 (*drastic cut in funding: only 12M*$.)

- A revised budget is proposed, after passing Congress and Senate and propose to allocate ~ 70-87 M$, enough to normally operate SOFIA in 2015.

- New bill still to be approved by the full Senate. Final vote before October 1<sup>st</sup> 2014

- SOFIA airplane just arrived in Germany for heavy maintenance by Lufthansa (~8MEuros cost) - 3.5 month period

- Very good chances that SOFIA continues at least for 2 years

- Then, formal review committee will judge on science output
The SOFIA Observatory
Telescope and Optical Layout

- Pressure Bulkhead
- Spherical Hydraulic Bearing
- Nasmyth Tube
- Secondary Mirror
- IR Tertiary Dichroic
- Visible Tertiary Mirror
- Primary Mirror
- IR Tertiary Mirror
- Focal Plane Imager
- Science Instrument
SOFIA instruments

First Generation SOFIA Science Instruments (SIs)

Cycle 1 Spectroscopic Capabilities

Commissioned in February-April 2014
GREAT - the Consortium

Principle Investigator instrument - funded, developed & operated by

- MPI Radioastronomie
  - R. Güsten (PI)
  - S. Heyminck (system engineer, PA/QA)
  - B. Klein (FFT spectrometer)
  - C. Risacher (upGREAT)

- Universität zu Köln, KOSMA
  - J. Stutzki (Co-P: software)
  - U. Graf (system engineer)
  - K. Jacobs (HEB mixers up to 4.7 THz)

- DLR Planetenforschung
  - H-W. Hübers (Co-PI: 4.7 THz HEB & QCL)

- MPI Sonnensystemforschung
  - P. Hartogh et al. (CO-PI: CTS)
GREAT - System Overview

<table>
<thead>
<tr>
<th>Channel</th>
<th>Frequencies (THz)</th>
<th>Lines of Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>low-frequency L1 a,b</td>
<td>1.25-1.50 (single pixel)</td>
<td>[NII], CO series, OD, HCN, H₂D⁺</td>
</tr>
<tr>
<td>low-frequency L1 a,b</td>
<td>1.81-1.91 (single pixel)</td>
<td>NH₃, OH, CO(16-15), [CII]</td>
</tr>
<tr>
<td>mid-frequency M a,b</td>
<td>2.5 – 2.7 (single pixel)</td>
<td>OH(²τ₁₃/2), HD</td>
</tr>
<tr>
<td>high-frequency H</td>
<td>4.7 (single pixel)</td>
<td>[OI]</td>
</tr>
<tr>
<td>upGREAT Low Frequency Array (LFA)</td>
<td>1.9 – 2.5 (14 pixels)</td>
<td>OH lines, [CII], CO series, [OI]</td>
</tr>
<tr>
<td>upGREAT High Frequency Array (HFA)</td>
<td>4.7 (7 pixels)</td>
<td>[OI]</td>
</tr>
</tbody>
</table>

- GREAT is a highly modular heterodyne spectrometer \( R \sim 10^8 \)
- operating in science-defined frequency bands \( 1.25 < \nu < 4.7 \) THz
- 2 out of currently 4+1 cryostats can be operated simultaneously

channel availability (as of May 2014)

- 2 low-frequency channels are operational since Early Science (2011)
- 2 mid frequency channels:
  - \( M_a \) operational; \( M_b \) on hold for mixer upgrade, waiting for commissioning slot
- high-frequency channel (commissioned in 05/14)
System description
GREAT optics

- pre-adjusted to the nominal optical axis
- diffraction-limited
  - HP beam-width: 22" (1.4 THz) and 16" (1.9 THz)

- two optics-plates
- LO-injection
- Calibration unit
- Beam-measurement setup
KOSMA waveguide mixer

- top (left to right)
  - optical image of the 1.9 THz HEB inside the waveguide
  - SEM micrograph of a 2.5THz NbTiN HEB on SiN substrate with beam-leads

- right:
  - mixer block with horn antenna and IF-connector
The performance of the Cycle-1 GREAT has improved significantly.
Comparison GREAT channels Trec

GREAT Trec for all channels

- L1 receiver at 1336 GHz
- L2 receiver at 1902 GHz
- HFA receiver at 4745 GHz
- Ma receiver at 2512 GHz
- Mb receiver at 2676 GHz
GREAT Spectrometers

GREAT operates a wide suite of back-end spectrometers, integrating new technologies as available:

- until now the usable IF bandwidth was defined by the HEB roll-off
- with new NbN HEB devices this will change
- for upGREAT, a ~4 GHz IF bands/pixel have to be processed

<table>
<thead>
<tr>
<th>back-end spectrometer</th>
<th>Bandwidth [GHz]</th>
<th>Resolution [MHz]</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOS: acousto-optical array</td>
<td>4 x 1.0</td>
<td>1.6</td>
<td>de-commissioned</td>
</tr>
<tr>
<td>CHIRP Transform spectrometer</td>
<td></td>
<td></td>
<td>de-commissioned</td>
</tr>
<tr>
<td>AFFTS: Fast Fourier Transform</td>
<td>2 x 1.5</td>
<td>0.212</td>
<td>operational</td>
</tr>
<tr>
<td>XFFTS: Fast Fourier Transform</td>
<td>2 x 2.5</td>
<td>0.088/0.044</td>
<td>operational</td>
</tr>
<tr>
<td>4G-FFTS</td>
<td>2 x 4.0</td>
<td>0.035</td>
<td>in development</td>
</tr>
</tbody>
</table>

Note: (#) spectral resolution is measured as equivalent noise bandwidth, the 3 dB bandwidth is generally smaller.
Newest addition: 4.7 THz H-channel

Our latest addition, the high-frequency channel successfully commissioned with truly outstanding performance:

- observations of [OI] at 4.74 THz (mostly galactic, due to ATM)
- based on new technologies: the NbN HEBs will be pumped by a novel QCL local oscillator (DLR-Pf)
- We had a choice of 2 mixers with comparable noise figure $T_{\text{rx}} \sim 1400$ K
  - an open-structure HEB [DLR-Pf, Hübers]
  - a waveguide HEB [KOSMA, Jacobs]
- 3 flights commissioning in May 2014 – very successful
extension of GREAT into heterodyne arrays for SOFIA
upGREAT development

extension of GREAT into 2 hexagonal arrays, operating in parallel

- 2x 7 low-frequency pixels (LFA)
- 1x 7 high-frequency pixels (HFA),
- or (m)any combination with GREAT’s single pixel detectors
GREAT receivers

upGREAT receivers
upGREAT general layout

Sky signal from telescope

Local Oscillator LFA

Optics LFA

Common Optics

Optics HFA

Local Oscillator HFA

14 times

HEB mixer Bias -T
LNA 1 C11F4
Cryostat - 4K
upGREAT cryostat LFA

14 times

IF processor
XFFTS
IF processor
XFFTS

7 times

HEB mixer Bias -T
LNA 1 C11F4
Cryostat - 4K
upGREAT cryostat HFA

7 times

IF processor
XFFTS
IF processor
XFFTS
## upGREAT Instrument Characteristics

<table>
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<tr>
<th></th>
<th>Low Frequency Array (LFA)</th>
<th>High Frequency Array (HFA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RF Bandwidth</strong></td>
<td>1.9-2.5 THz (goal)</td>
<td>~4.745 THz</td>
</tr>
<tr>
<td><strong>IF Bandwidth</strong></td>
<td>0.2-4 GHz</td>
<td>0.2-4 GHz</td>
</tr>
<tr>
<td><strong>HEB technology</strong></td>
<td>Waveguide-based HEB NbN on Si membrane</td>
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</tr>
<tr>
<td><strong>LO technology</strong></td>
<td>Cooled photonic mixers (goal) / solid-state chains (backup)</td>
<td>Quantum cascade lasers (QCL)</td>
</tr>
<tr>
<td><strong>LO coupling</strong></td>
<td>Beamsplitter (goal) or Diplexer (backup)</td>
<td>Beamsplitter</td>
</tr>
<tr>
<td><strong>Array layout</strong></td>
<td>2x7 pixels for orthogonal polarizations in hexagonal configuration with central pixel</td>
<td>1x7 pixels in hexagonal configuration with a central pixel</td>
</tr>
<tr>
<td><strong>Expected $T_{REC}$</strong></td>
<td>~600-1200K DSB 0-4GHz IF</td>
<td>~800-1600K DSB 0-4GHz IF</td>
</tr>
<tr>
<td><strong>Backends</strong></td>
<td>0-4 GHz (goal) with 128k channels</td>
<td>0-4 GHz (goal) with 128k channels</td>
</tr>
</tbody>
</table>
upGREAT LFA Cryostat
Pulse tube closed-cycle cooler

Main characteristics of the PT coolers

Coolers are model PTD-406C from transMIT (Giessen, Germany)

2nd stage cooling power of 0.88W@4.2K with a ~7 kW compressor or 0.6W@4.2K with a ~4 kW compressor

Custom modified to include small Helium Pots to stabilize the lowest temperature.

Vibration are minimized by separating the rotary valve fro the cold head by a 70cm Helium line.

Tilting with ±45º will be possible with low impact on cooling power (10%)
HEB development for upGREAT

- Hot Electron Bolometer (HEB) new development at KOSMA of NbN HEB on Si
- Devices for 1.9-2.5 THz and 4.7 THz – waveguide based
- Improved IF bandwidth compared to the GREAT mixers (0.5-4GHz compared to 0.5-2.5 GHz)

- Fabrication of first LFA and HFA devices finalized.
- HFA mixers tests in December 2013
- LFA mixers to be tested and integrated Q1-Q2 2014.
GREAT Flight Records

- GREAT performed 15+2 flights during SOFIA‘s Early Science
  - observed a total of 26 science projects (G+US)
  - final release of data completed in Nov 2011
  - 22 papers published in A&A Special (Vol.542)

- during Cycle 1 GREAT concluded
  - 15.2 successful flights so far, incl.
  - 9 flights during New Zealand deployment.
  - 3 in Jan 14 closed Cycle 1
  - 6 Flights in May 2014 started Cycle II

- For Cycle1, more than 2 dozen projects will have received quality-validated data.
- We aim at „pooled“ publication in October 2014
Search for light hydrides has been very successful: SH, OD, p-H$_2$D$^+$. 

Detection of OD ground-state (1.39 THz) during Basic Science (Parise et al. A&A 542 L5). p-H$_2$D$^+$ ground-state during Cycle 1 (New Zealand - Schlecker et al. in prep.). SH $\Lambda$-doublet detected in BS, follow-up during Cycle 1 on half dozen targets (Neufeld et al.).
Probing infall with ammonia absorption against dust continuum

- during ES 3 massive clumps with red-shifted absorption detected
- half dozen additional targets observed during cycle 1 follow-up

G34.26+0.15 VLA X band
Probing clean MHD shocks

Gusdorf et al.: SN driven MHD shocks W28F (A&A 542), IC443 ongoing in Cycle 1
- CO and rot H$_2$ complementary data base
- GREAT: subthermally excited high-J CO
- model: only stationary C-type shock fit
physics: [10$^4$ cm$^{-3}$, 45-100 µG, 25 km/s]

CO profiles towards southern tip of shock (blue circle)

Color image: CO(6-5)
Probing clean MHD Shocks - II

CO excitation study towards 3 IC443 cores – archetypal SN driven MHD shock
Milky Way’s most active stellar nursery

Güsten & Zinnecker: NGC3603 – a most prominent southern PDR / mini star-burst

One of many PDR studies performed with GREAT

Good system stability allows on-the-fly mapping of structures extending over several arcmins
A unique opportunity: Magellanic Clouds

GREAT performed 5 science projects towards the Large & Small Magellanic Clouds

30 Doradus

30 Doradus in the LMC
- most productive star formation site in Local Group; R136 cluster contains most massive stars known
- Science goal: study ISM physics / star formation process in extreme environment of low metallicity gas exposed to high UV field

Color composite near-infrared image (Ks filter) towards the central part of 30 Dor, extracted from ESO’s VISTA Magellanic Cloud survey. Superimposed in red is the velocity-integrated emission of ionized carbon [CII], observed with GREAT.

Data provided by Requena-Torres et al.
High resolution [OI] observations

Very first high-resolution observations at 4.7 THz [OI] since the Kuiper Observatory (very few observations were achieved then, Tsys was ~100 000K now ~5000 K, therefore a factor ~20 improvement)
NGC 7027 [OI] maps

SOFIA/GREAT

HST/NICMOS2
Cycle 3 call for proposals

- Proposal for US and international partners for up to 450 hours of science observing using SOFIA
- The deadline for submitting proposals is July 18, 2014
- Proposal selections will be announced in October 2014
- Cycle 3 observing period from March 1, 2015 to January 31, 2016
- Two phases - Phase I preparation and submission of a scientific context, a scientific justification, a feasibility analysis and a high-level description of the proposed targets and observations.
- Proposers who are awarded time will be required to submit detailed observation specifications during Phase II.
Cycle 3 call for proposals

- German time is only accessible through a PI based in a German institute. About 1/5th of the time available there

- Proposal oversubscription rate was of ~3 for Cycle 2.

- Note that there are reserved set of targets and frequencies for some instruments (Reserved Observations Catalog ROC)

More info on:

http://www.sofia.usra.edu/Science/proposals/cycle3/SOFIA_Cycle3_CfP.pdf
Cross-calibration prospects Herschel/SOFIA

HIFI/GREAT cross calibration with the 1.25-1.9 THz frequency range overlap

- Continuum fluxes are compared for a selection of hot cores

- Line fluxes comparison for sources like NGC 7027, NGC 6302
Cross-calibration HIFI/GREAT on hot cores

List of sources studied so far:
G10.47, W31, G10.62, G31.41, G34.3, W49N, W51
Cross-calibration HIFI/GREAT on hot cores
CII maps of NGC7027

Cross-calibration NGC7027 HIFI/GREAT
Cross-calibration NGC7027 HIFI/GREAT

NGC 7027

Tb (K km/s)

LO (GHz)

CO HIFI  ——
CO GREAT ———
CII HIFI  ———
CII GREAT ———
Cross-calibration NGC6302 HIFI/GREAT

CII GREAT with modified coordinates
Cross-calibration NGC6302 HIFI/GREAT

![Graph showing cross-calibration of NGC6302 HIFI and GREAT observations. The graph compares the temperature brightness (Tb) and the ratio GREAT/HIFI observations across different SKY frequencies (GHz).]
PACS/GREAT cross calibration with the [OI] transition at 63um (4.7 THz):
Selection of sources observed in Cycle II with GREAT

GREAT observations can be degraded to PACS frequency resolution for comparisons.

NGC7027
SGRB2M
NGC7023
S140-IRS1
DR21C
G34P26
W49N
Impressions from NZ deployment