The upGREAT heterodyne array receivers for the SOFIA telescope

Christophe Risacher on behalf of the GREAT consortium

1 Max Planck Institut für Radioastronomie, Bonn, Germany
2 KOSMA, Cologne, Germany
3 German Aerospace Center (DLR), Berlin, Germany
2.5-m telescope in a modified Boeing 747SP aircraft
- Imaging and spectroscopy capable from 0.3 µm to 1.6 mm
- Emphasizes 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, PWV ~ 1-20 µm

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 8-10 hour flights per year
SOFIA instruments

First Generation SOFIA Science Instruments (SIs)

Cycle 1 Spectroscopic Capabilities

Wavelength [μm]

Spectral resolution

GREAT

EXES

FIFI LS

FORCAST w/ grisms

FLITECAM w/ grisms

HIPO

FLITECAM

FORCAST

HAWC
High resolution spectrometers

- Having resolution $> 10^6$ allows studying in great detail the gas excitation and kinematics
  - Example of spectrum:
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>
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<tr>
<th>Channel</th>
<th>Frequencies (THz)</th>
<th>Lines of Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>low-frequency L1</td>
<td>1.25-1.50 (single pixel)</td>
<td>[NII], CO series, OD, HCN, H$_2$D$^+$</td>
</tr>
<tr>
<td>low-frequency L2</td>
<td>1.81-1.91 (single pixel)</td>
<td>NH$_3$, 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($^2\Pi_{3/2}$), 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>
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</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 Jan 2016)
  - 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 (since 05/14) (4.7 THz for [OI])
  - upGREAT – LFA 14 pixels at 1.9 THz since May/December 2015
- operating up to two independent receiver channels simultaneously
- fully automated tuning procedure (LO, Mixer-BIAS, Diplexer optimization)

**channel independent components**

- main structure: optics-compartments, LO-compartments, electronics rack
- cryostats: liquid Helium/Nitrogen cooled wet dewar
- calibration unit: liquid Nitrogen cooled cold-load, ambient temp. hot load
- IF-system: Input: 0.2 - 3GHz
  Outputs: 4 x 1.55 – 2.65 GHz (AOS);
  2 x 0 - 2.5 GHz (FFTS)
- Spectrometer: FFTS, XFFTS
- control-electronics: optics control, mixer-BIAS, power-supply

**channel specific components**

- optics: LO-coupling, matching mixer beam to the telescope focal plane
- LO-system: VDI solid state chains for all channels in operation so far
- mixer device: HEBs so far for all GREAT channels
Structure 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
GREAT sensitivities: L& M-bands

More powerful solid-state local oscillators (Virginia Diodes Inc.) allowed substituting Martin-Puplett diplexers with coupling grids in channels L1 & L2, thereby providing access to the most sensitive IF frequencies of the HEB.
The performance of the Cycle-1 GREAT has improved significantly.
Newest addition: 4.7 THz H-channel

Our single pixel receiver latest addition, the high-frequency channel is operational since 2014.

- observations of [OI] at 4.74 THz (mostly galactic, due to ATM)
- based on new technologies: the NbN HEBs is pumped by a novel QCL local oscillator (DLR-Pf)
- We had a choice of 2 mixers
  - an open-structure HEB [DLR-Pf, Hübbers]
  - a waveguide HEB [KOSMA, Jacobs]
- the integrated system complies with specs
  - optics, stability, tuneability – all fine
- commissioned in May 2014 and regular use since then.
- Because of atmospheric losses, it greatly helps to observe from NZ (~10-20x better time efficiency).
upGREAT

extension of GREAT into heterodyne arrays for SOFIA
GREAT receivers
Liquid Helium based cryostats

upGREAT receivers
Closed-cycle cooler (Pulse Tube)
# upGREAT Instrument Characteristics

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<th>Low Frequency Array (LFA)</th>
<th>High Frequency Array (HFA)</th>
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<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>
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</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 (baseline)</td>
<td>Quantum cascade lasers (QCL)</td>
</tr>
<tr>
<td><strong>LO coupling</strong></td>
<td>Beamsplitter</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\text{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 with 16k channels</td>
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</table>
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
upGREAT general layout
Pulse tube closed-cycle cooler

Main characteristics of the PT coolers

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

2\textsuperscript{nd} stage cooling power of 0.88W@4.2K with a \sim 7 kW compressor or 0.6W@4.2K with a \sim 4 kW compressor

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

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

Tilting with $\pm 45^\circ$ will be possible with low impact on cooling power (10%)
Comparison single pixel vs array receivers

GREAT L2 receiver 1.9THz
single pixel

upGREAT LFA receiver 1.9-2.5THz
14 pixels
upGREAT LFA Cryostat
Cold optics polar H

Pulse tube cold end, mechanically decoupled from the 2\textsuperscript{nd} stage

Cold optics polar V

Copper tube thermal link

Focal plane subarrays

2\textsuperscript{nd} stage at 3K

1\textsuperscript{st} stage at 40K

IF outputs
upGREAT LFA Focal plane components

IF outputs
SiGe cryogenic LNAs 0-6 GHz
HEB NbN mixers
HEB mixers development

- Hot Electron Bolometer (HEB) 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 (0.2-3.5GHz compared to 0.2-2.5 GHz)

- Waveguide technology was selected for flight models production.
- Fabrication of LFA and HFA devices finalized.
- LFA mixers well characterized
- HFA mixers (4.7 THz) to be characterized after LFA commissioning – the 1\textsuperscript{st} prototypes (H-channel) shows Trec (DSB) \sim 800K min
For the upGREAT LFA, two development are done in parallel:

- Photonic local oscillator – for 1.9-2.5 THz
  - Current devices reach few µW of output power –
  - new designs tests ongoing – goal is >4 µW for the LFA

- 2 Solid state LOs from VDI, for the lower band at 1.9 THz (CII line)
  - 20-30 µW available and close to 40-50 µW when cooling the last triplers
Solid state Local Oscillators

- Last triplers cooled to ~90K and connected via a 1” Stainless steel waveguide with about 1.7dB losses.
- NRAO (Tony Kerr group) provided additional copper plating to decrease its losses.
- Overall output power is about 40-50 µW
V-polar optics

Rotatable beam splitter
wire grids

H-polar optics

Polarization separation and RF/LO coupling

Coupling Optics plate

LFA cryostat cold optics

To SOFIA Telescope

Phase grating

LO optics
Test setup in Bonn with mockup of the GREAT SI structure
The whole instrument structure is tilted to simulate the SOFIA telescope elevation changes ($\pm 20$ degrees changes)

Important to test optical alignment impact, and cryostat temperature variations

No change is seen in the HEB physical temperatures ($<1$ mK) and negligible alignment impact.
Electronics modules
(Bias, IF processor, backends)

New bias electronics for detectors and low noise amplifiers

New generation IF modules – covers 0-6 GHz

New generation spectrometers
IF Processors – FFTS4G spectrometers

- The spectrometer technology developed at MPIfR now **achieves 0-4 GHz instantaneous bandwidth** with up to 64K channels (16K used for the commissioning)

- The IF processor is capable to handle 21 channels with an IF from 0-6 GHz. To accommodate the 0-4 GHz FFTS spectrometers, 4 GHz low pass filters are included to limit the IF input range to 0-4 GHz
Uncorrected Noise temperature for the 7 pixel in the H-Polarization at ~1.9THz show 600-1400K between 0-4 GHz

LO coupling is ~15%

with beam splitter optics

A phase grating is used for the LO beam to separate the beams into 7 equal beams

*(designed and built by Urs Graf)*
Uncorrected Noise temperature for the 7 pixel in the V-Polarization at ~1.9THz show 1200-300K between 0-4 GHz

Signal transmission is only of 50% with beam splitter optics (due to lack of LO power and higher Ic HEB devices)
Uncorrected Noise temperature for the 7 pixel in the V-Polarization at ~1.9THz show 1200-300K between 0-4 GHz

Signal transmission is only of 50% with beam splitter optics (due to lack of LO power and higher Ic HEB devices)
Trec comparing LFA and single pixel L2 receivers

- channel 7H
- channel 8H
- channel 9H
- channel 10H
- channel 11H
- channel 12H
- channel 13H
- L2 single pixel
Cryocooler Infrastructure aboard SOFIA
Cryocooler Infrastructure aboard SOFIA
GREAT/upGREAT Instrument in May 2015
Beam characterization

- Optical beam verification confirms that the beam waists and positions are as designed (13dB edge Taper chosen)

- Beams for the 14 pixels are Gaussian, measurement down to 30dB level, confirming that the smooth walled spline horns built by RPG are performing as expected
Beam characterization in Laboratory
Pointing verification on sky

- Pixels positions derived from laboratory measurement were accurate within 0.4 "
Main observing mode - OTF
First commissioning results

The two polarizations observing in May 2015 W3OH region – not simultaneous though
First commissioning results

upGREAT commissioning

S106 observations

The distribution of the velocity-integrated [CII] emission resembles that of the Spitzer 8 μm continuum, but selected velocity intervals reveal a clumpy bulk emission (Simon et al., in prep).
First commissioning results

IC 1396 E

GREAT (1 pixel)
2 flight legs, total 1.5 hours

upGREAT (7 pixel)
1 flight leg, total 1 hour

Courtesy of Yoko Okada
First commissioning results

upGREAT science demonstration
PI: Erick Young

Horsehead observations

4 hours of observations, flawless observing, several OTF submaps stitched together, repeating rotating the K-mirror at several positions.

The overall map rms is extremely homogenous
Summary (1/2)

- 1\textsuperscript{st} successful demonstration of a 14 multi-pixel heterodyne array at 1.9 THz
- Flightworthy hardware (cryostat, closed cycle cooling system, electronics) fully built and tested
- Instrument tested and ready for installation aboard SOFIA, installation ongoing and 4 commissioning flights in May 2015.
- Performance is state of the art, typically 600-1200K (uncorrected Trec) at 1.9 THz for an IF bandwidth of 0-4 GHz.
All the components used are designed for 1.9-2.5 THz (HEB mixers, optical components, RF window, etc.)

Once the MPIfR photonic LO oscillators development confirms sufficient power at 1.9-2.5 THz – the full RF bandwidth will be usable.

The 7 pixel 4.7 THz HFA array will be commissioned in November 2016 – it will use identical cryostat and similar optics concept.