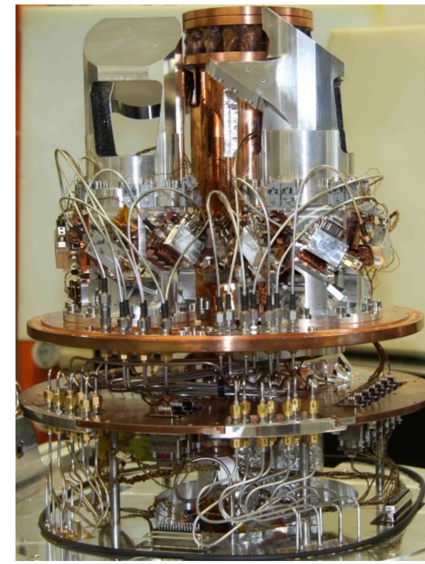
The upGREAT heterodyne array receivers for the SOFIA telescope



Christophe Risacher on behalf of the GREAT consortium

[1] Max Planck Institut für Radioastronomie, Bonn, Germany

[2] KOSMA, Cologne, Germany

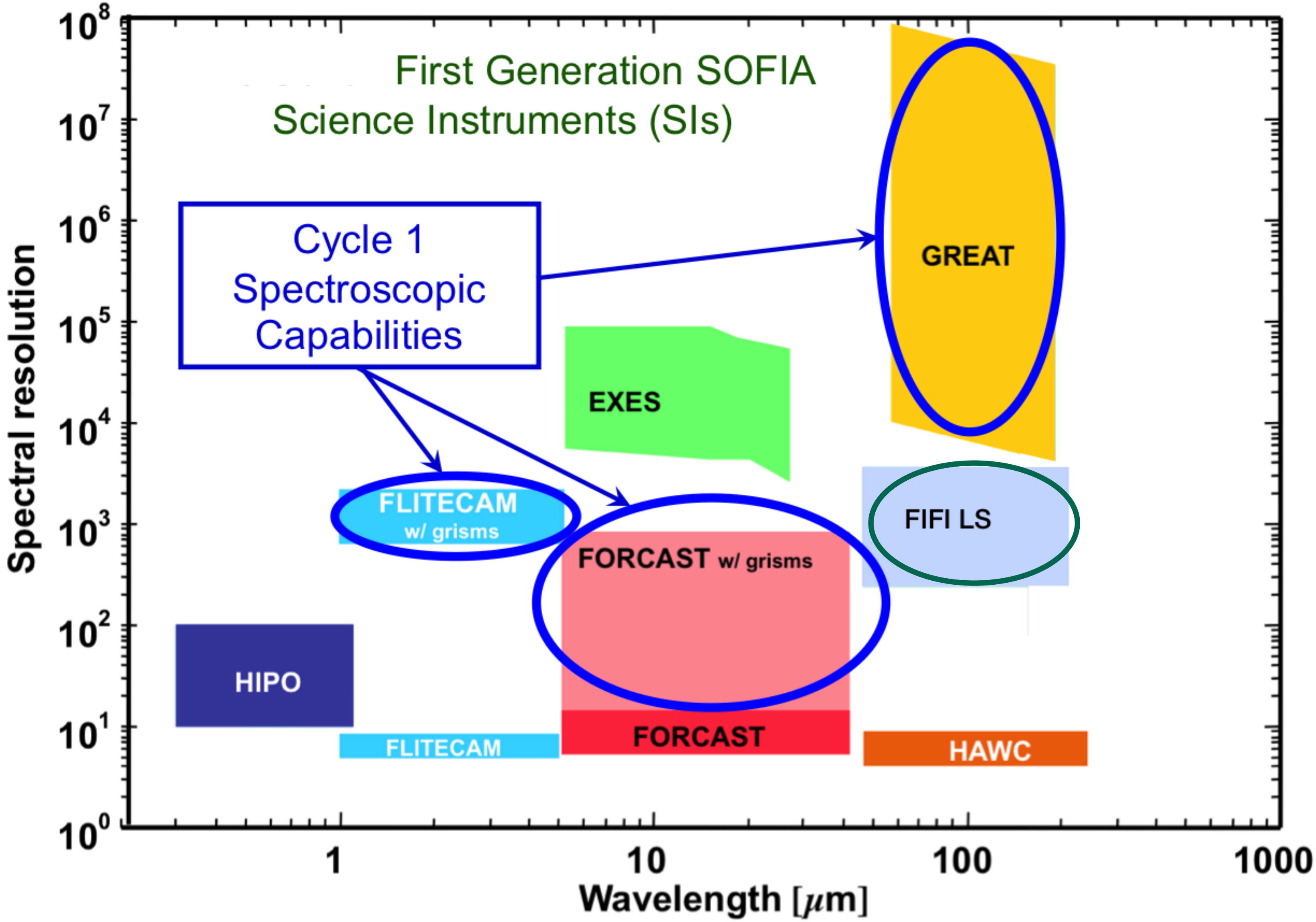
[3] German Aerospace Center (DLR), Berlin, Germany

SOFIA Overview

- 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

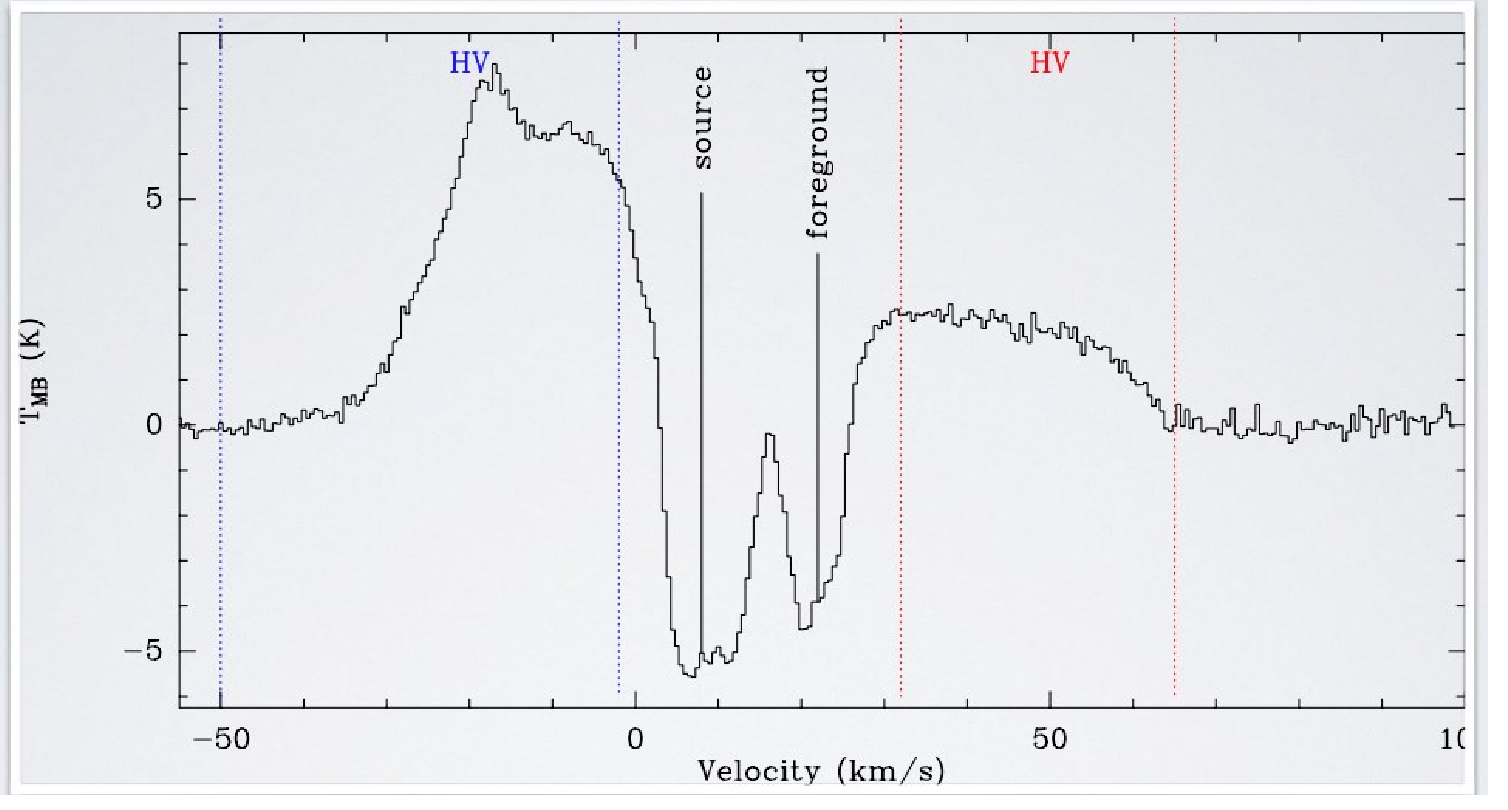
SOFIA instruments

MPIfR
KOSMA
MPS
DLR-Pf



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)

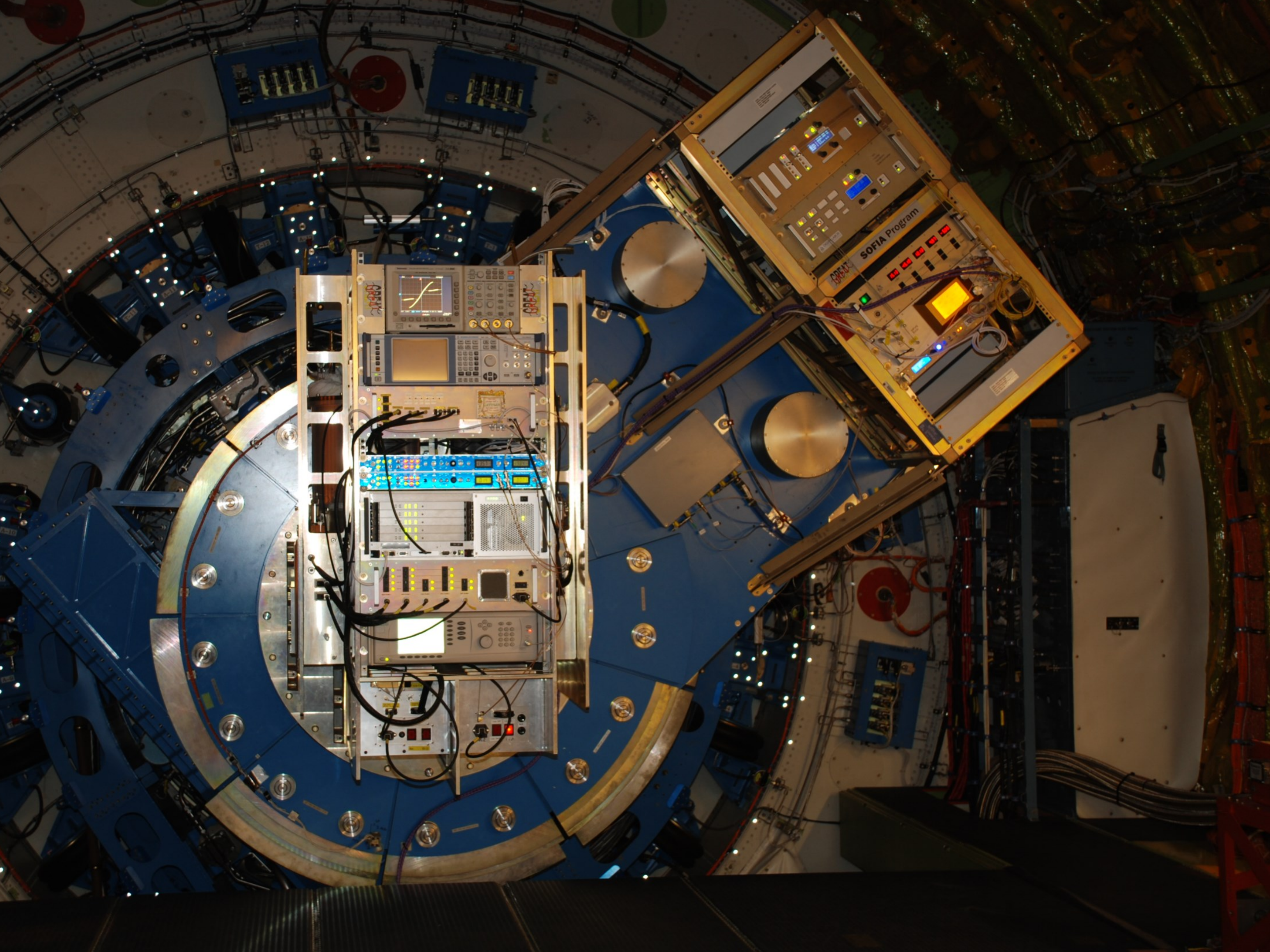
GREAT

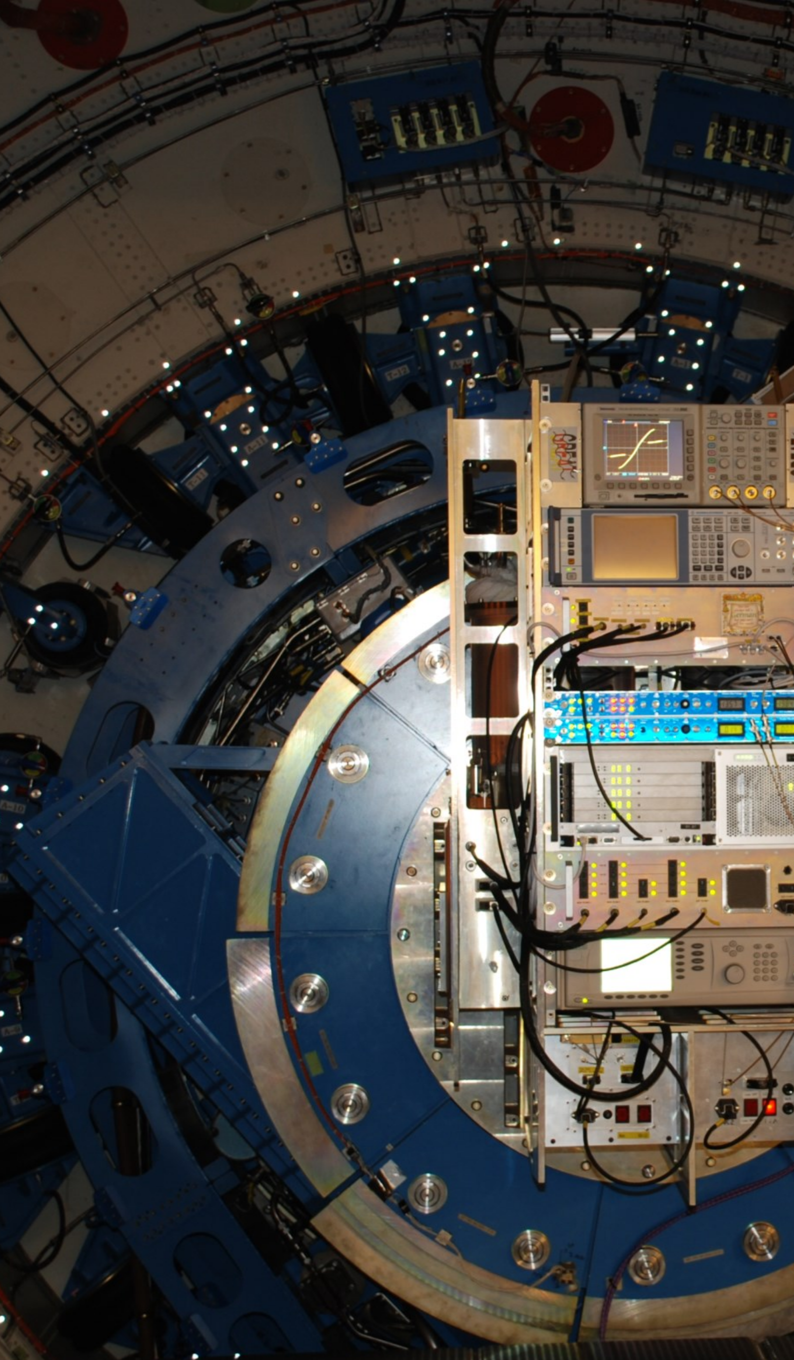
GREAT - System Overview

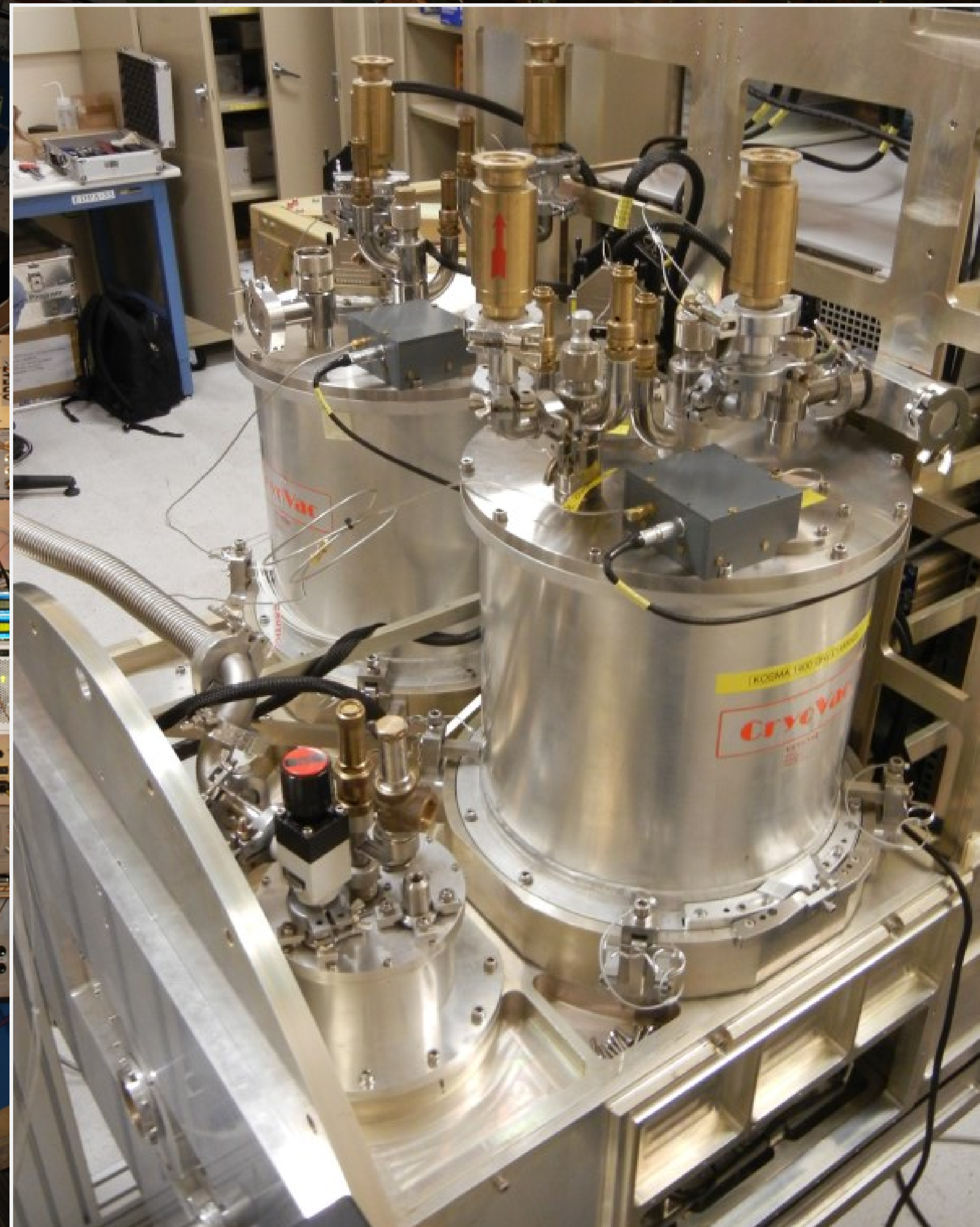
MPIfR
KOSMA
MPS
DLR-Pf

Channel	Frequencies (THz)	Lines of Interest
low-frequency L1	1.25-1.50 (single pixel	[NII], CO series, OD,HCN,H_2D^+
low-frequency L2	1.81-1.91 (single pixel)	NH_3,OH,CO(16-15),[CII]
mid-frequency M a,b	2.5 – 2.7 (single pixel)	OH($^2\pi_{3/2}$),HD
high-frequency H	4.7 (single pixel)	[OI]
upGREAT Low Frequency Array (LFA)	1.9 – 2.5 (14 pixels)	OH lines, [CII],CO series, [OI]
upGREAT High Frequency Array (HFA)	4.7 (7 pixels)	[OI]

- GREAT is a highly modular heterodyne spectrometer ($\Re \sim 10^8$)
- operating in science-defined frequency bands 1.25 < ν < 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**


SOFIA Program




CryoVac

System description Liquid Helium systems

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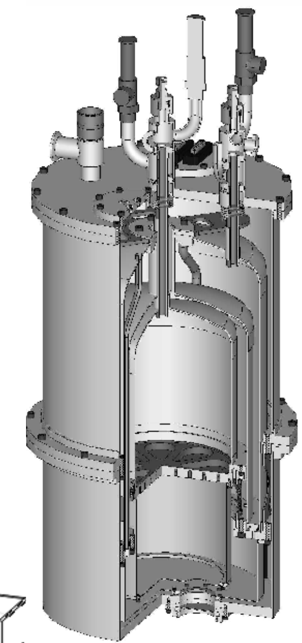
- operating up to two independent receiver channels simultaneously
- fully automated tuning procedure (LO, Mixer-BIAS, Diplexer optimization)

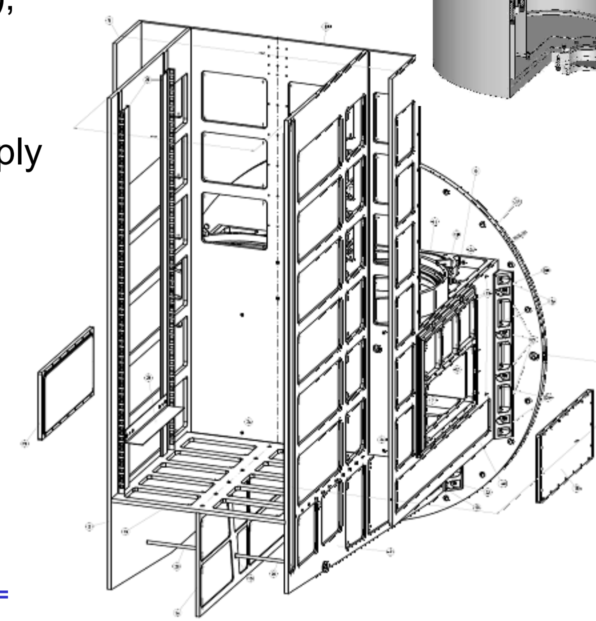


channel independent components

- 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

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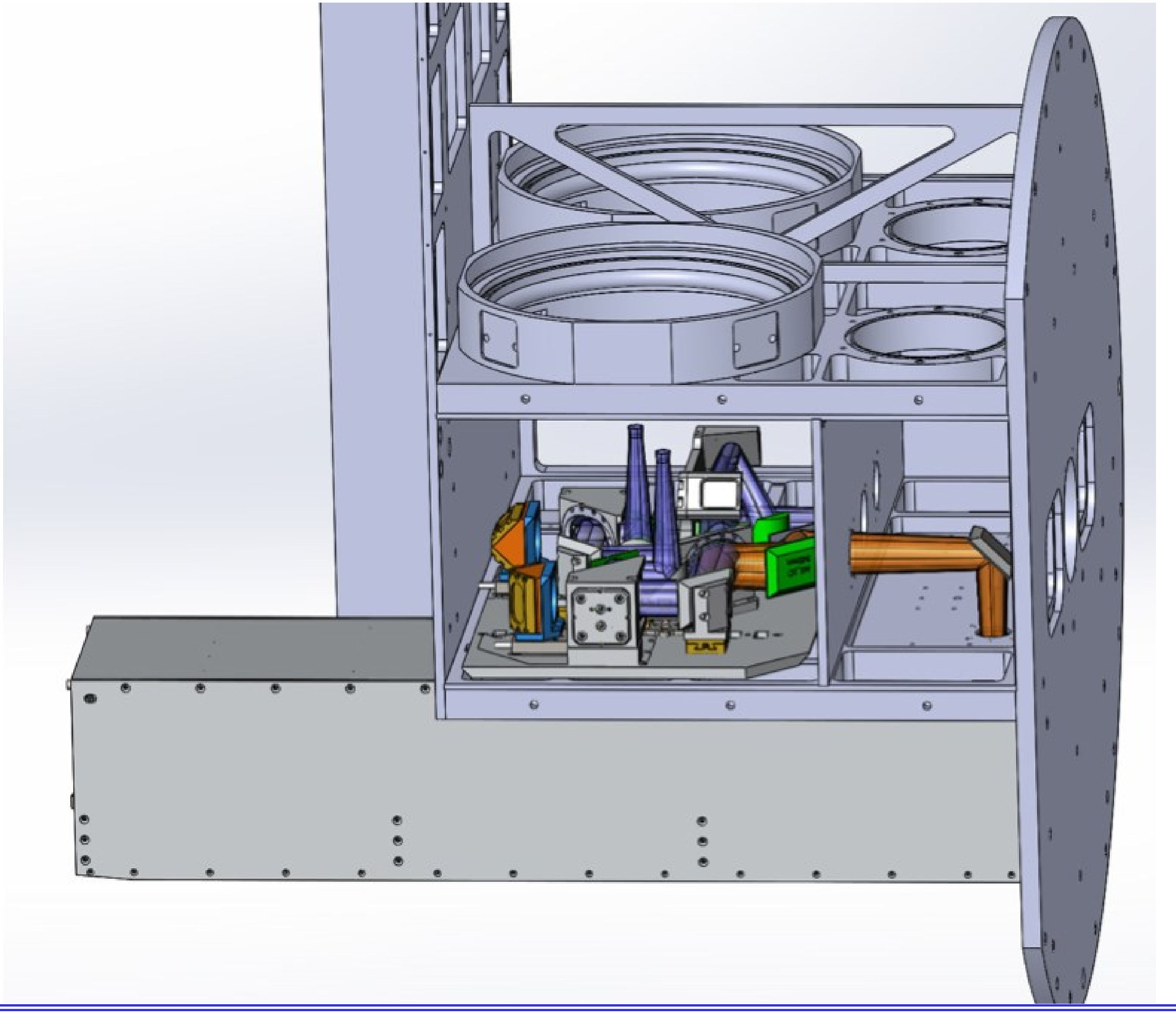
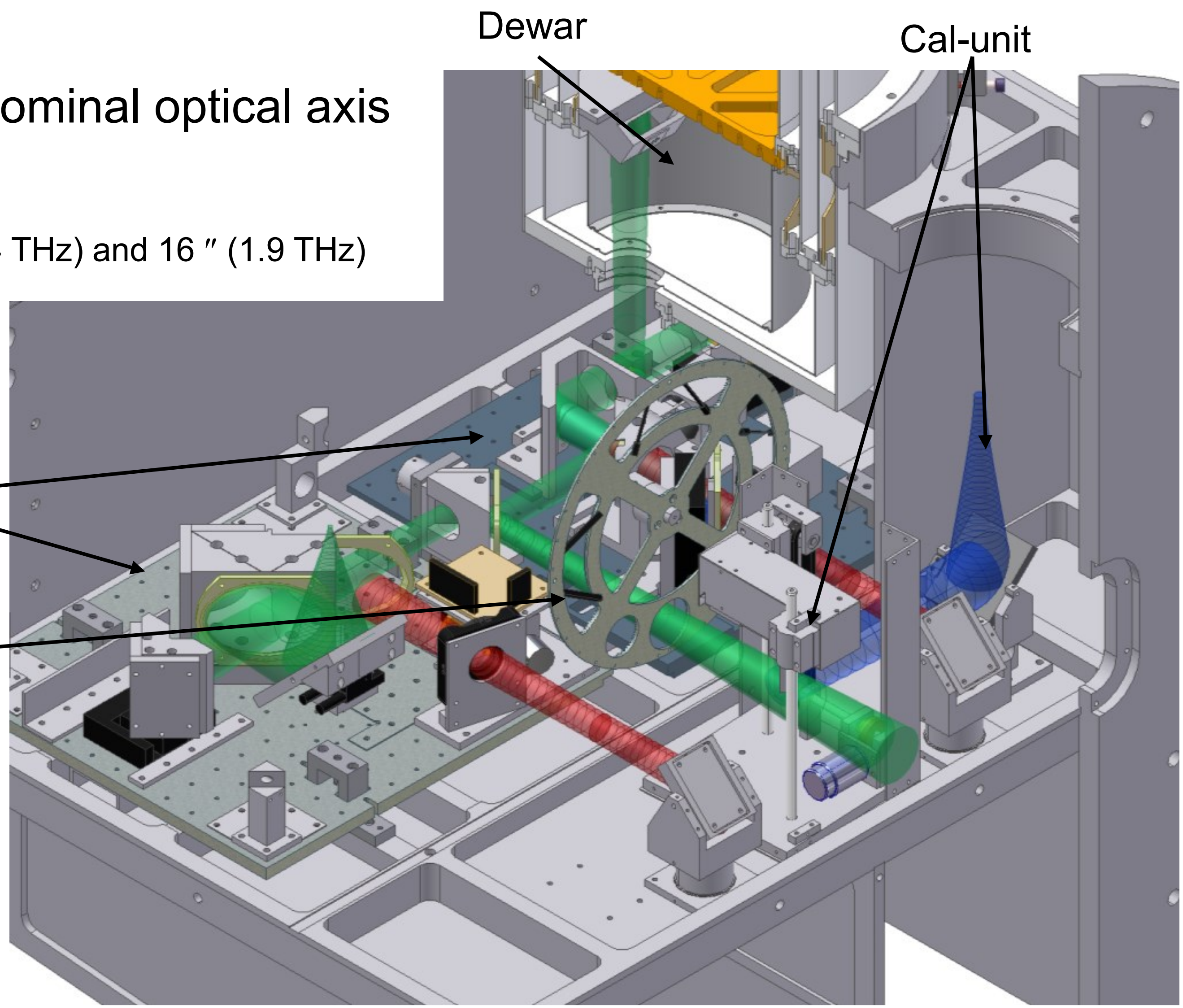
MPS
DLR-Pf



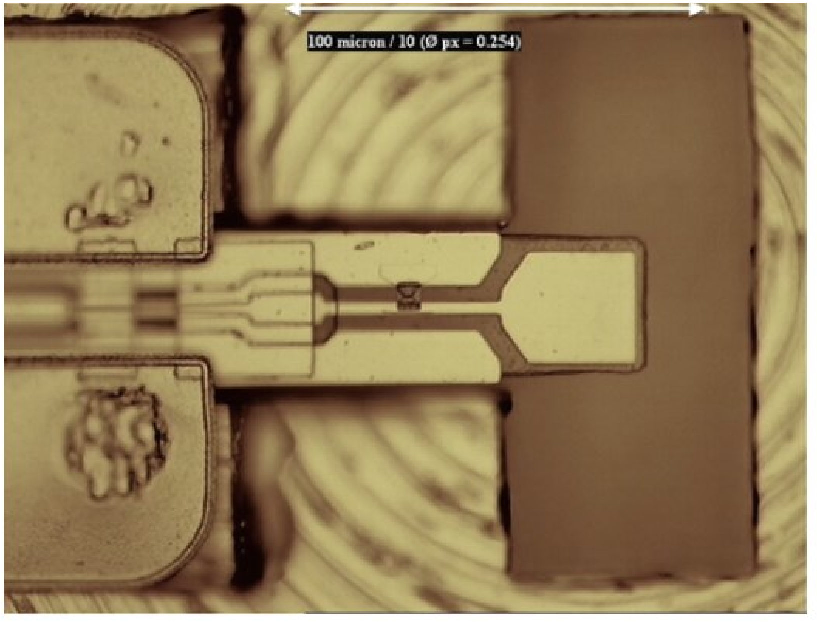
GREAT optics

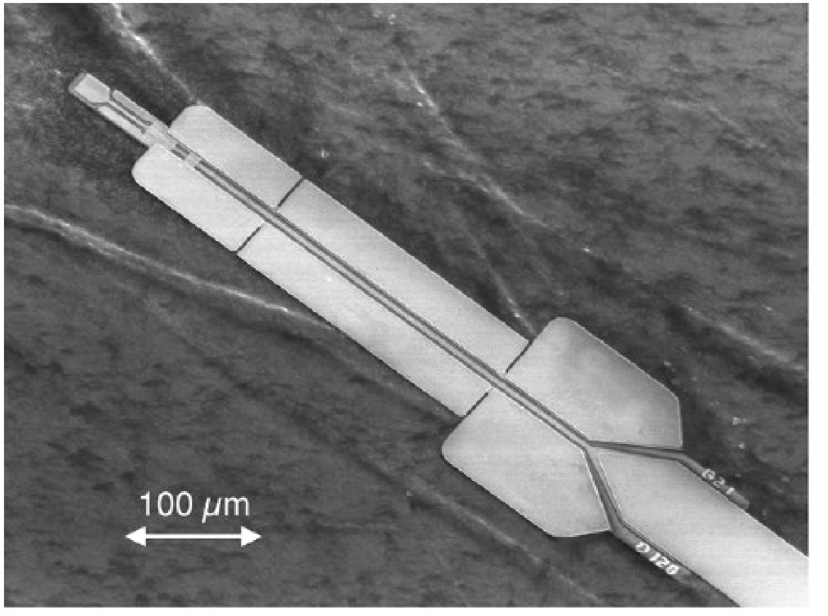
- pre-adjusted to the nominal optical axis
- diffraction-limited
  - HP beam-width: 22″ (1.4 THz) and 16 ″ (1.9 THz)

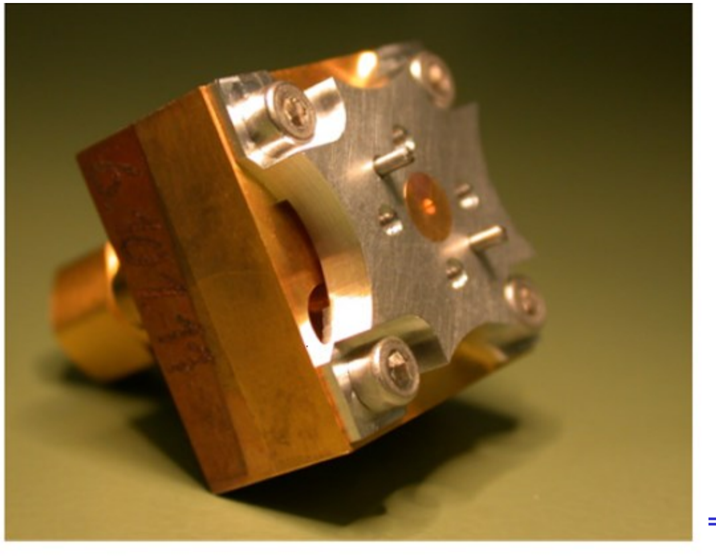
✓two optics-plates
✓LO-injection
✓Calibration unit
✓Beam-measurement setup



KOSMA waveguide mixer







- top (left to right)
  - optical image of the 1.9 THz HEB inside the wave-guide
  - 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

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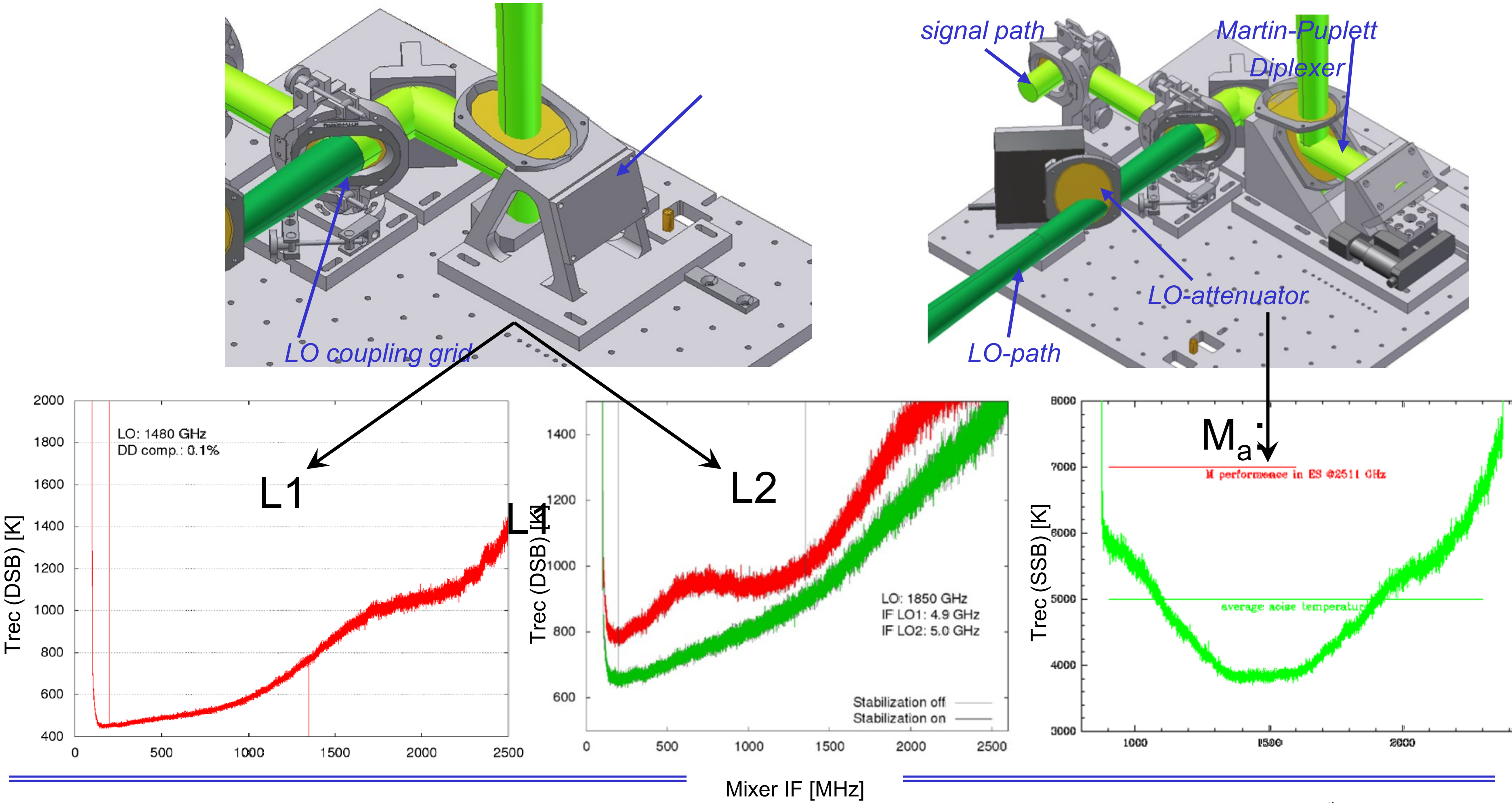
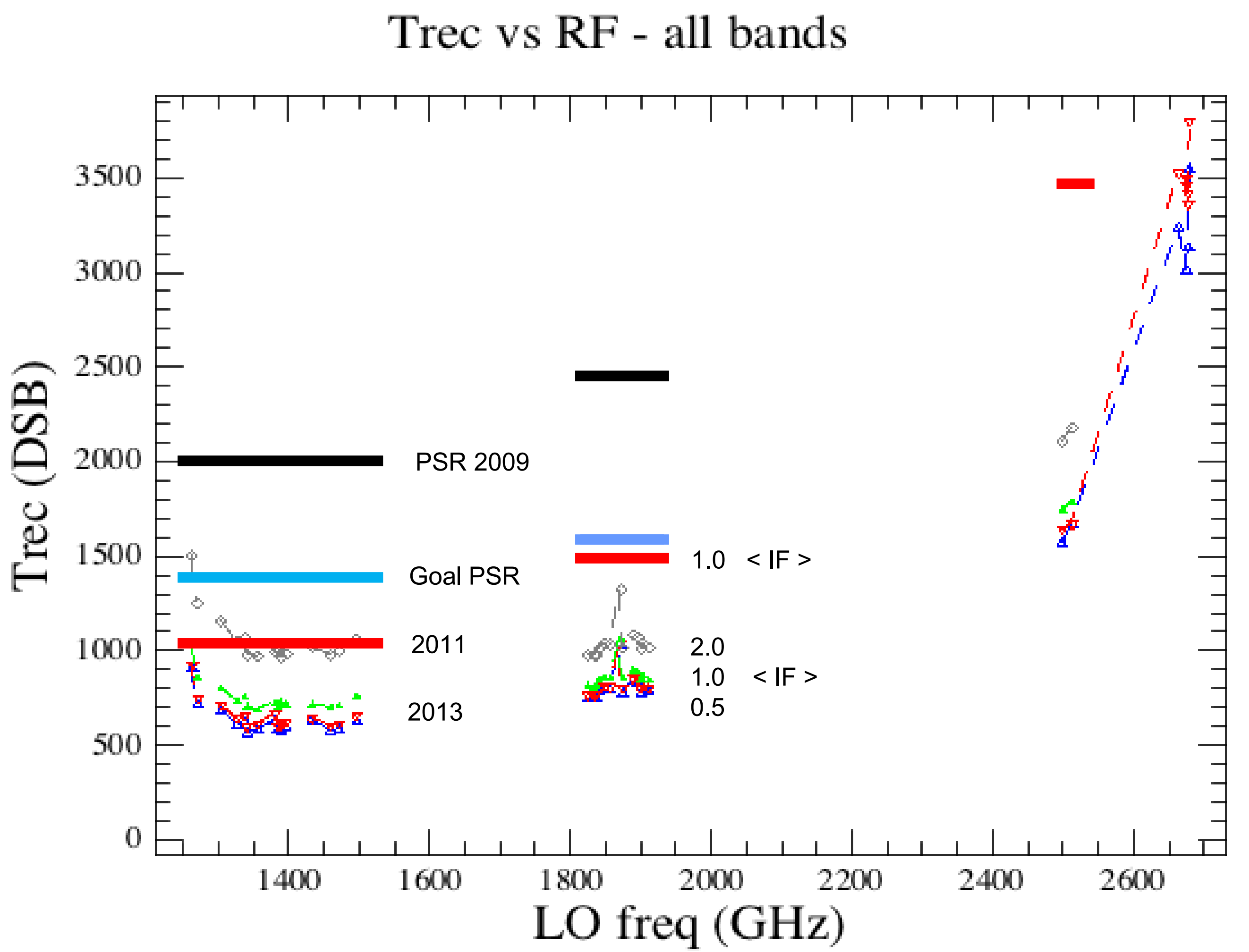
More powerful solid-state local oscillators (Virginia Diodes Inc.) allowed substituting Martin-Puplett diplexers with coupling grids in channels L1 & L2, thereby providing access to the most sensitive IF frequencies of the HEB.



Receiver noise temperatures

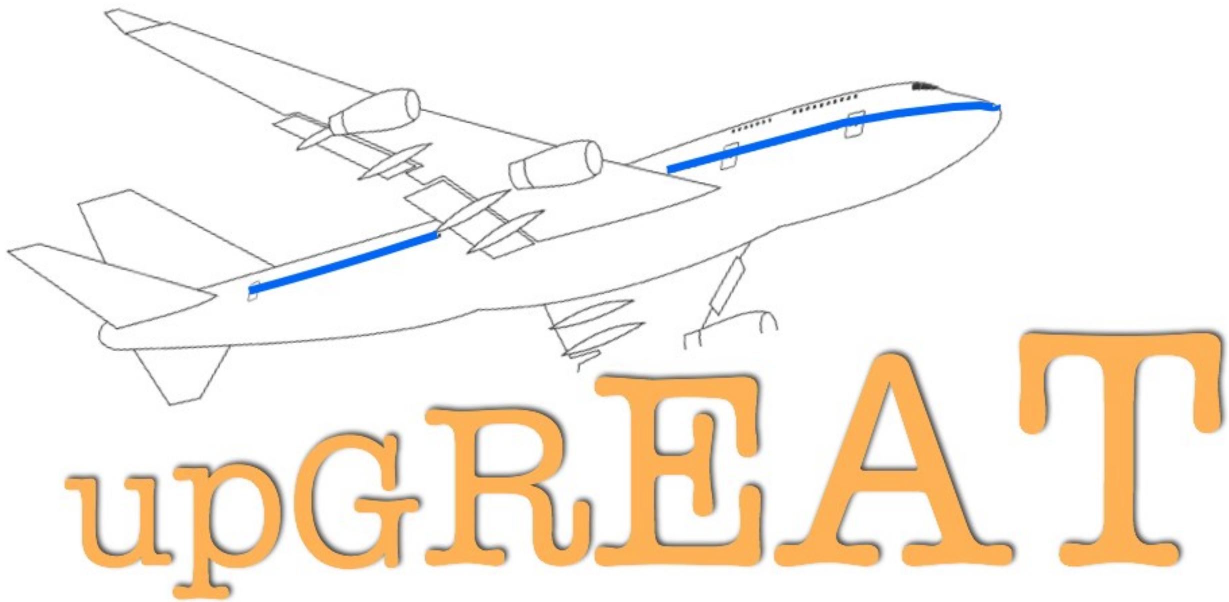
The performance of the Cycle-1 GREAT has improved significantly



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, Hübers]
  - **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).



extension of GREAT into heterodyne arrays for SOFIA

GREAT receivers

Liquid Helium based cryostats

upGREAT receivers

Closed-cycle cooler (Pulse Tube)

upGREAT Instrument Characteristics

	Low Frequency Array (LFA)	High Frequency Array (HFA)
RF Bandwidth	1.9-2.5 THz (goal)	~4.745 THz
IF Bandwidth	0.2-4 GHz	0.2-4 GHz
HEB technology	Waveguide-based HEB NbN on Si membrane	Waveguide-based HEB NbN on Si membrane
LO technology	Cooled photonic mixers (goal) / solid-state chains (baseline)	Quantum cascade lasers (QCL)
LO coupling	Beamsplitter	Beamsplitter
Array layout	2x7 pixels for orthogonal polarizations in hexagonal configuration with central pixel	1x7 pixels in hexagonal configuration with a central pixel
Expected T_{REC}	~600-1200K DSB 0-4GHz IF	~800-1600K DSB 0-4GHz IF
Backends	0-4 GHz with 16k channels	0-4 GHz with 16k channels

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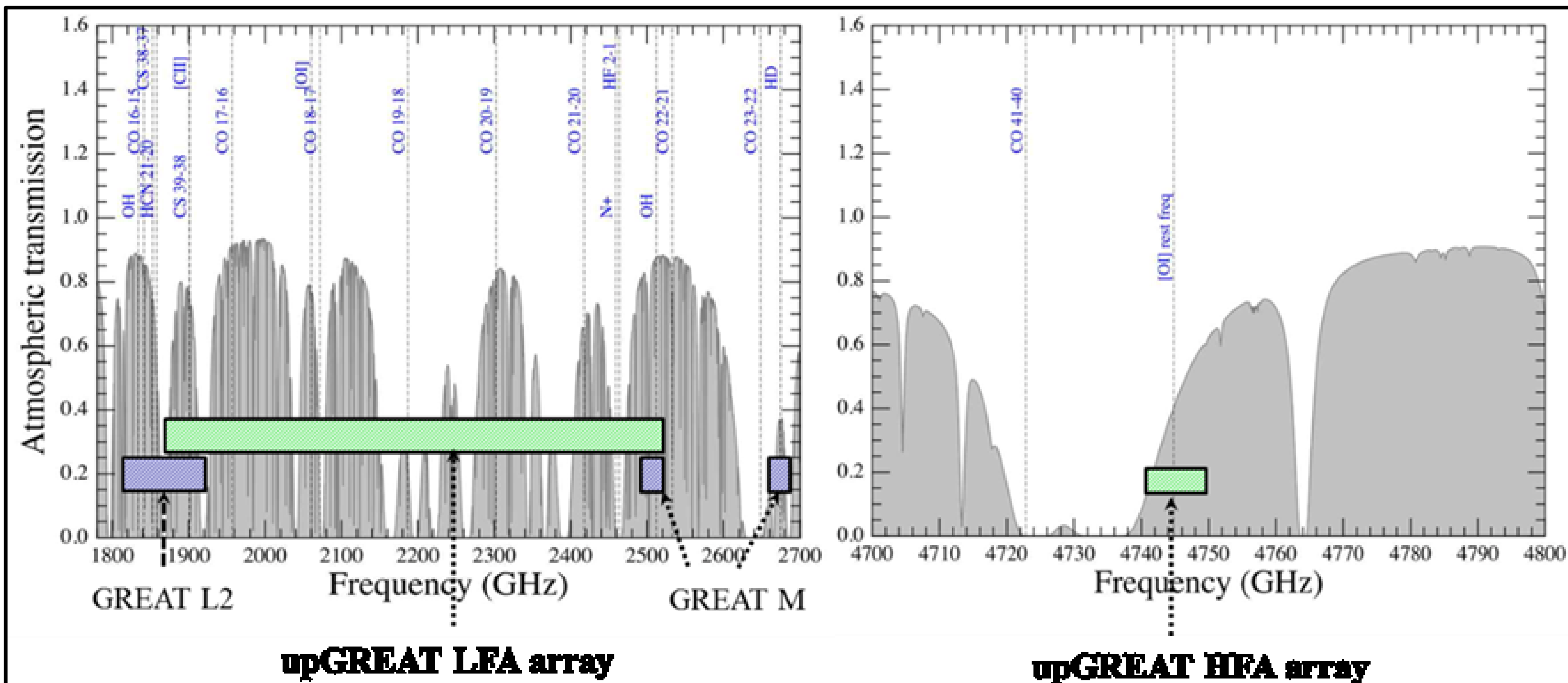
DLR-Pf

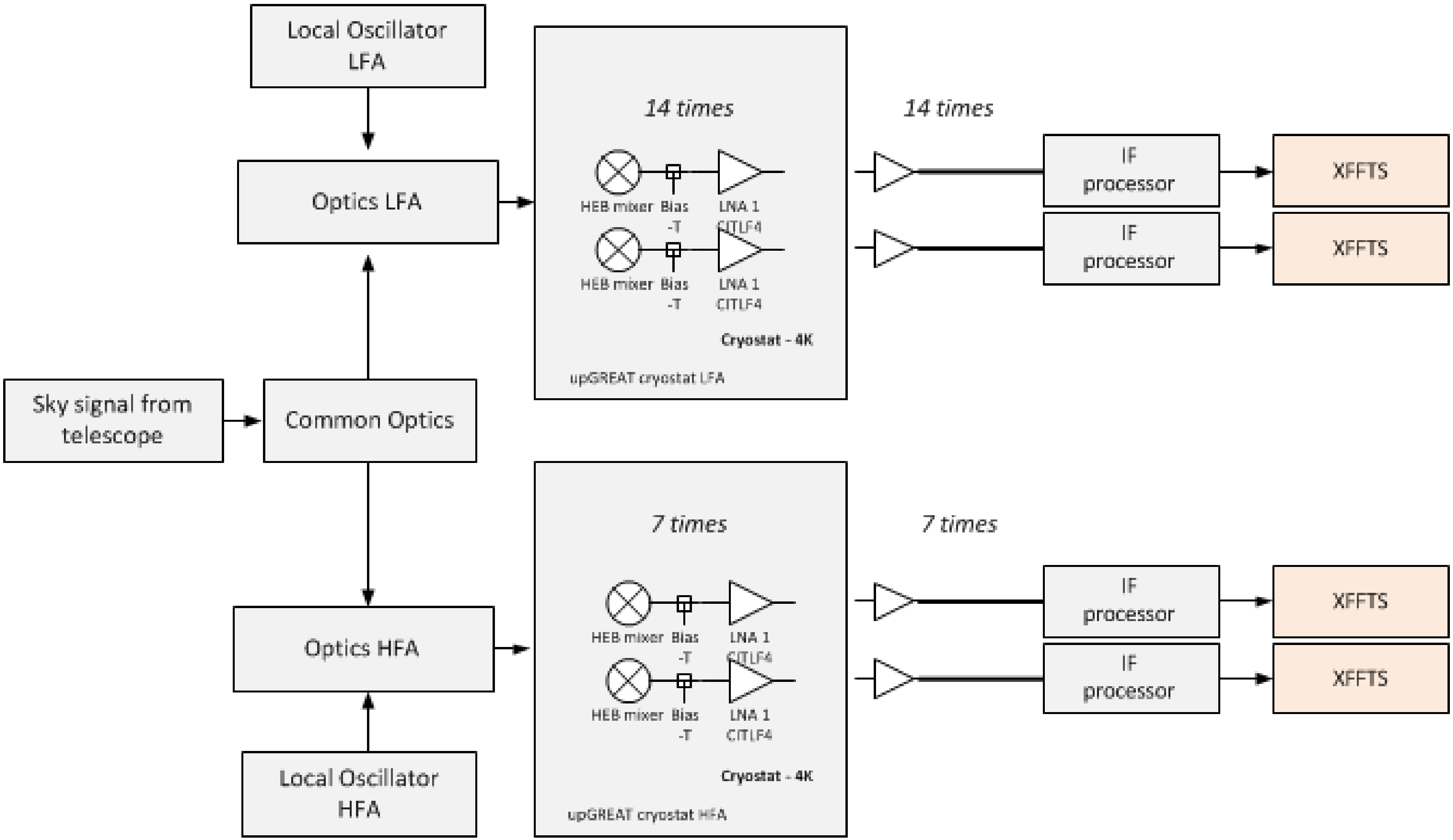
upGREAT development

extension of GREAT into 2 hexagonal arrays, operating in parallel

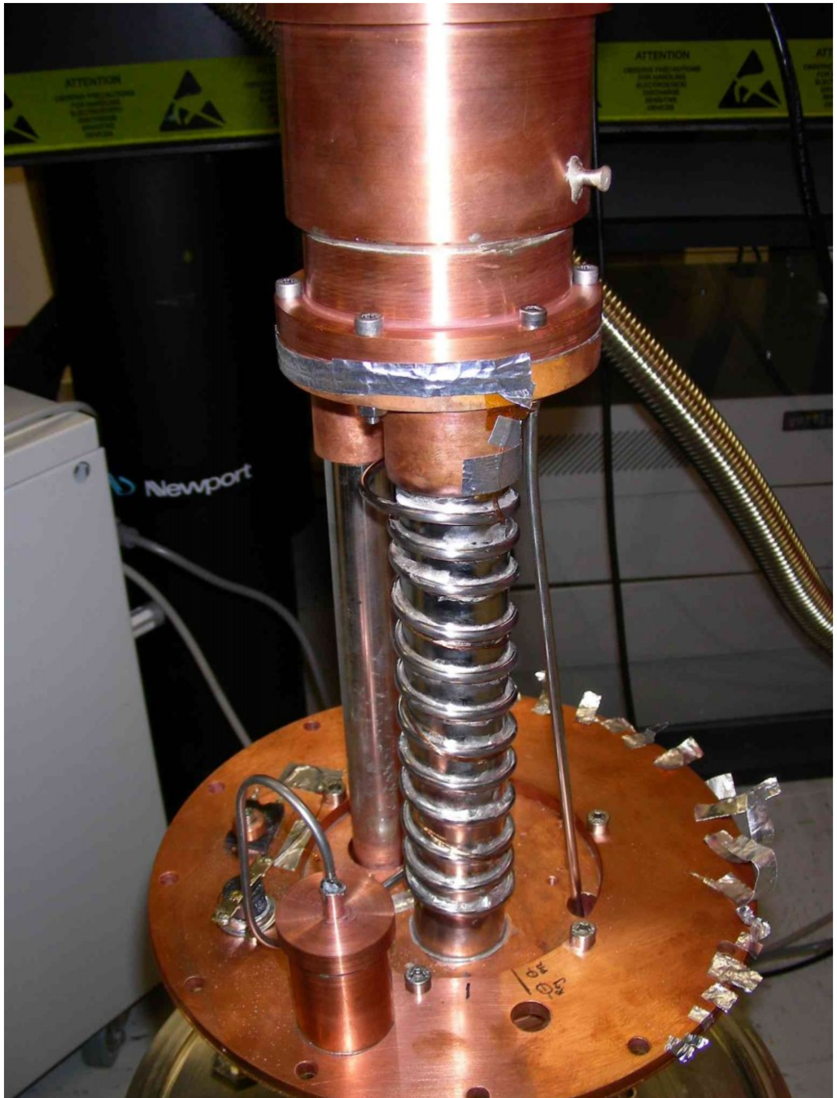
- 2x 7 low-frequency pixels (LFA)
- 1x 7 high-frequency pixels (HFA),
- or (m)any combination with GREAT's single pixel detectors



upGREAT general layout

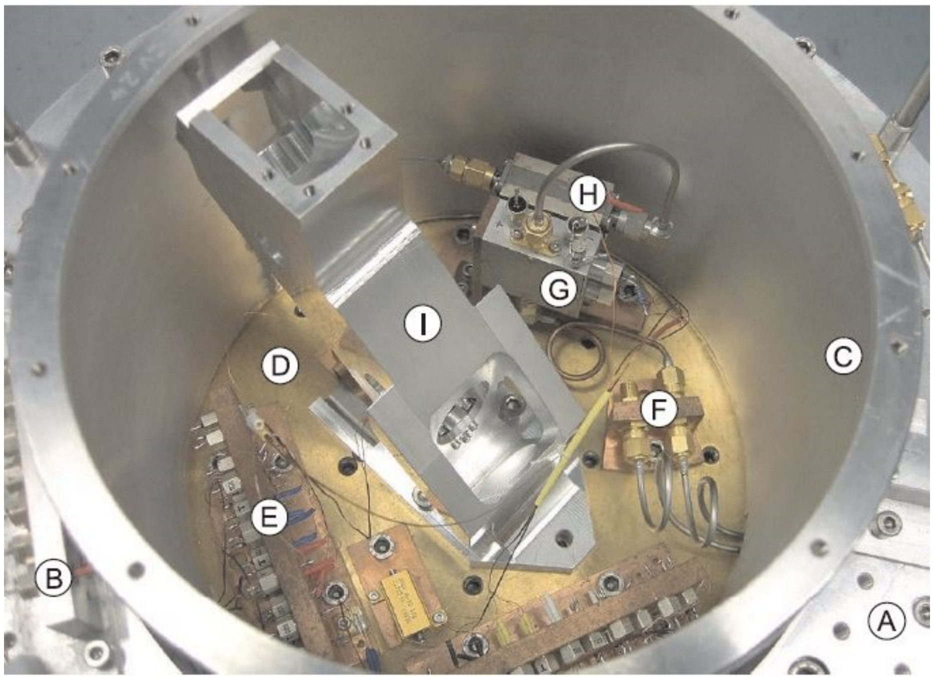


Pulse tube closed-cycle cooler



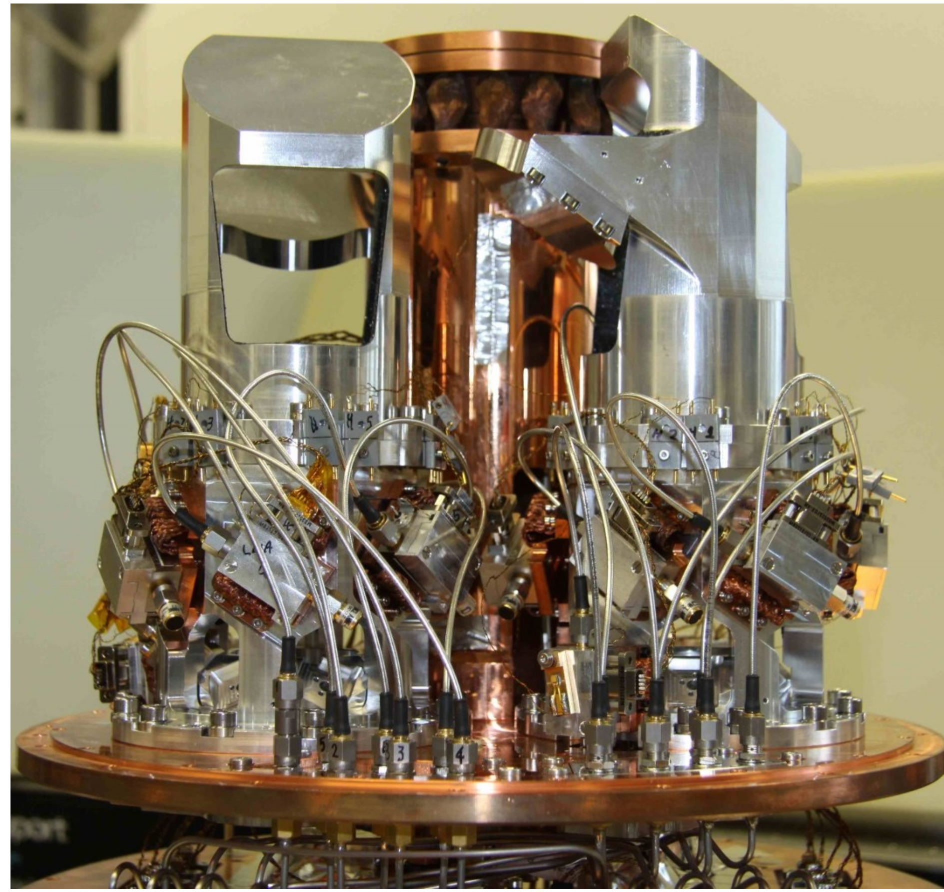
Main characteristics of the PT coolers
Coolers are model PTD-406C from transMIT (Giessen, Germany)
2nd stage cooling power of 0.88W@4.2K with a ~7 kW compressor or 0.6W@4.2K with a ~4 kW compressor
Custom modified to include small Helium Pots to stabilize the lowest temperature.
Vibration are minimized by separating the rotary valve fro the cold head by a 70cm Helium line.
Tilting with ±45° will be possible with low impact on cooling power (10%)

Comparison single pixel vs array receivers



GREAT L2 receiver 1.9THz

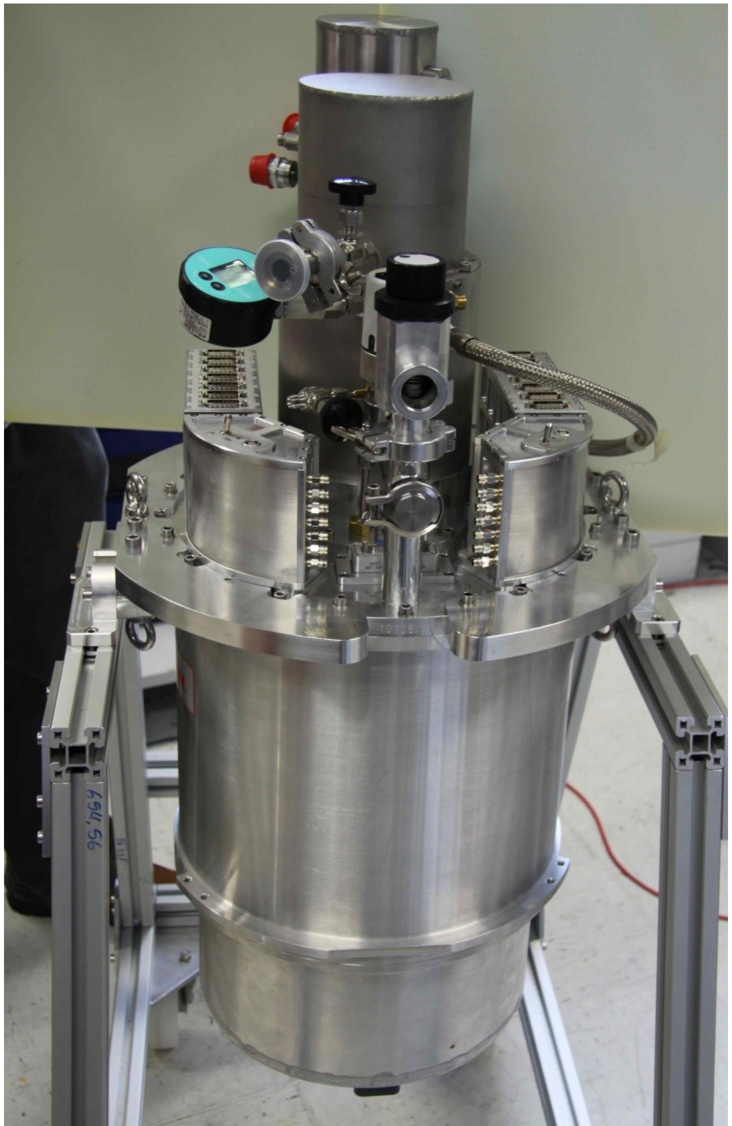
single pixel

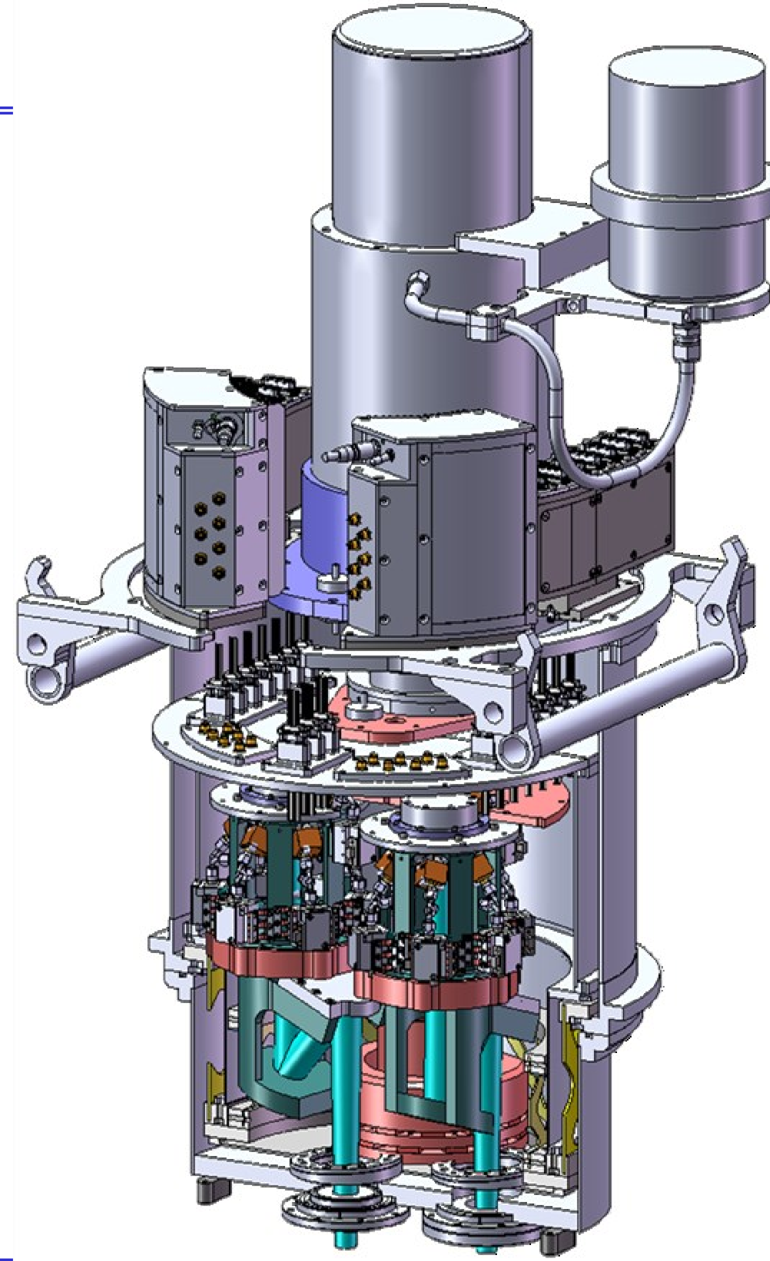


upGREAT LFA receiver 1.9-2.5THz

14 pixels

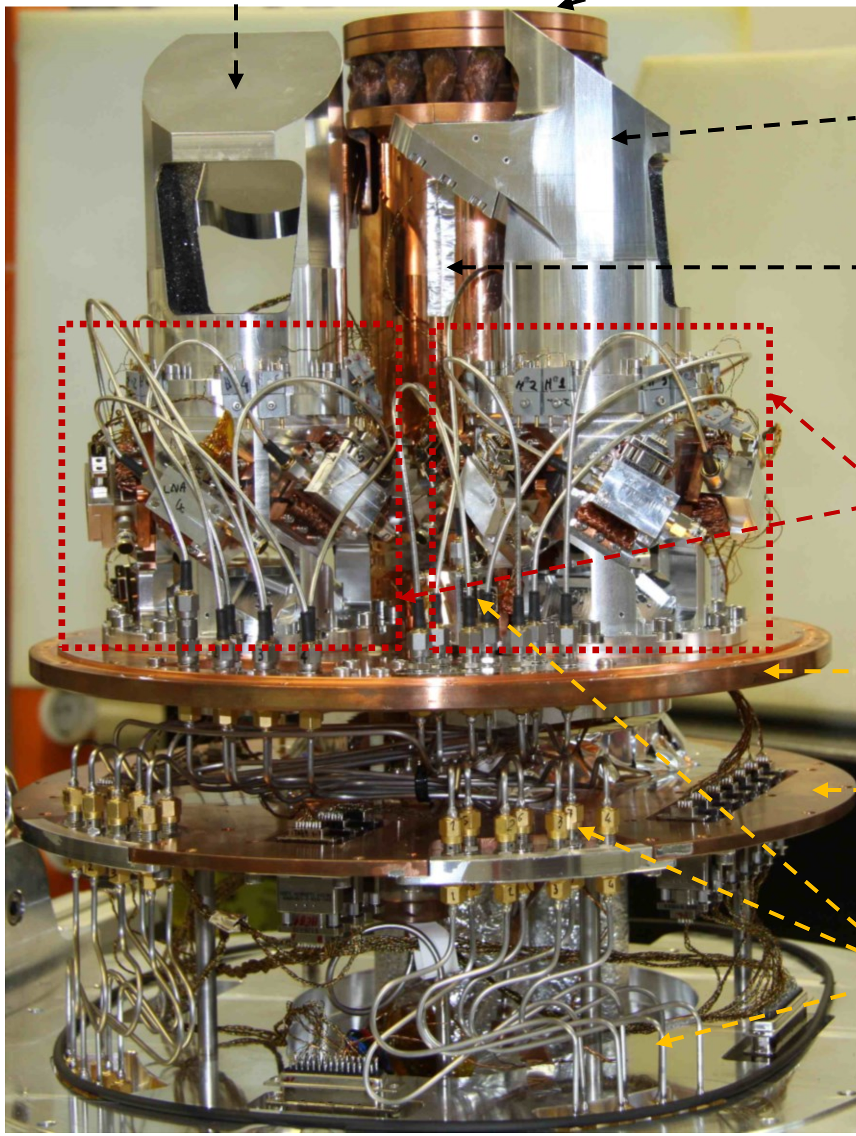
upGREAT LFA Cryostat





Cold optics polar H

Pulse tube cold end, mechanically decoupled from the 2nd stage



Cold optics polar V

Copper tube thermal link

Focal plane subarrays

2nd stage at 3K

1st stage at 40K

IF outputs

upGREAT LFA Focal plane components

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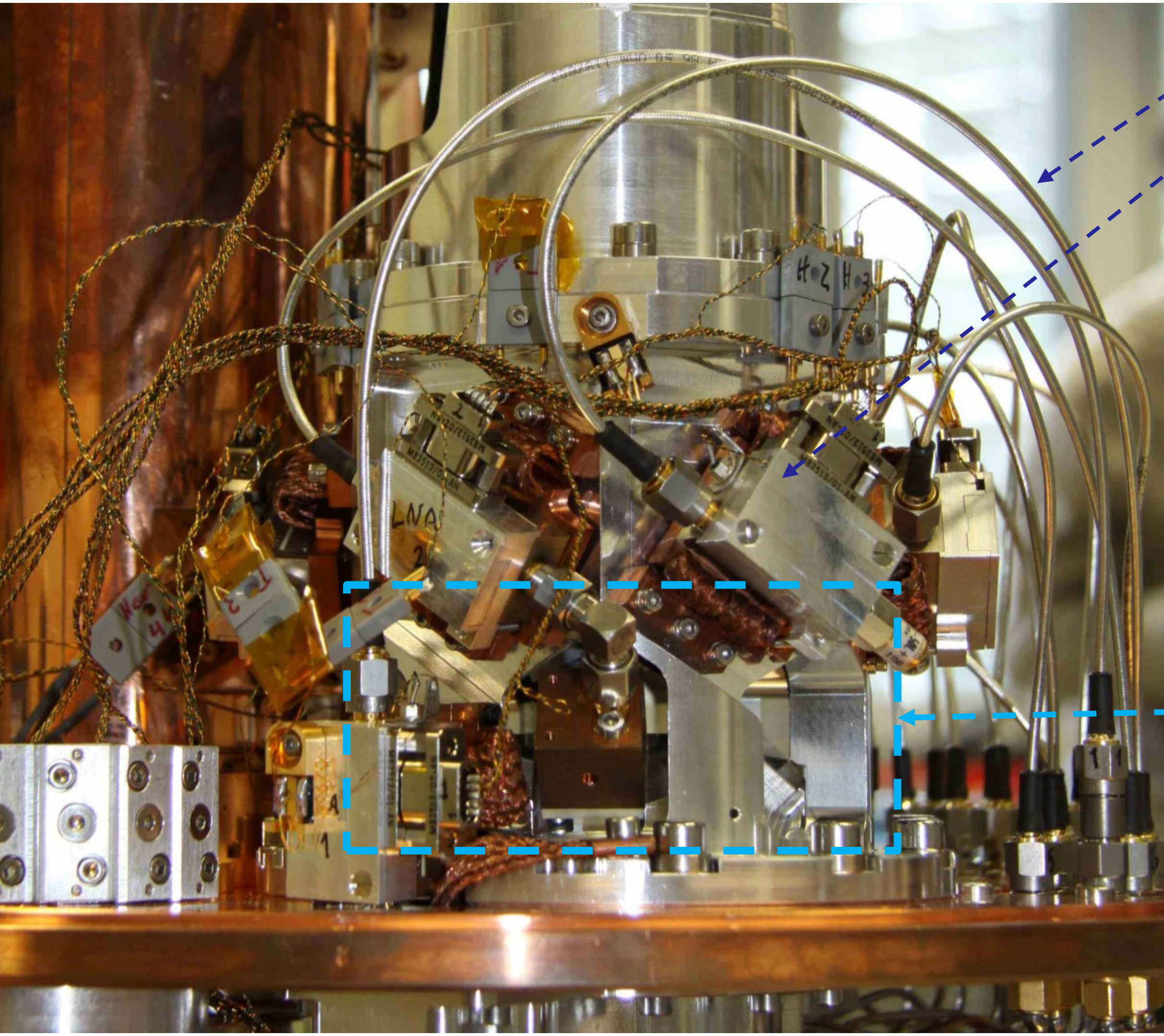
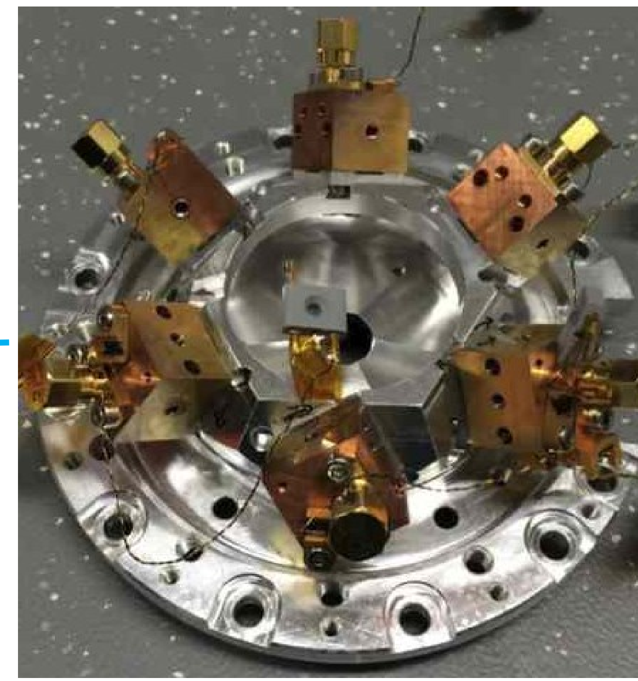


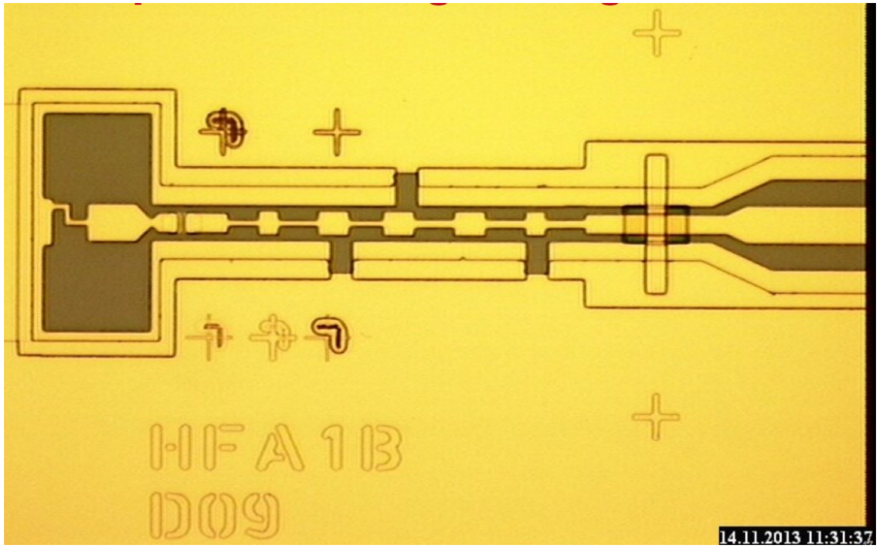
IF outputs

SiGe cryogenic LNAs 0-6 GHz

HEB NbN mixers



HEB mixers development

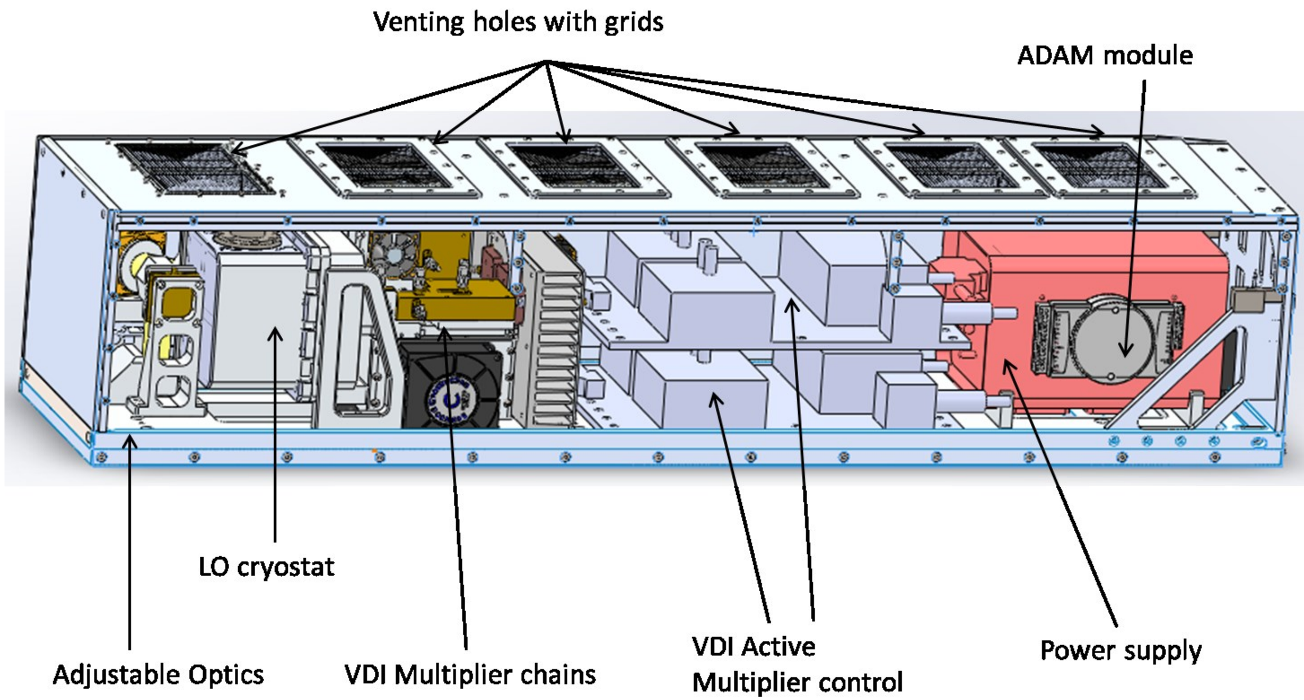


- Hot Electron Bolometer (HEB) development at KOSMA of NbN HEB on Si
- Devices for 1.9-2.5 THz and 4.7 THz – **waveguide based**
- Improved IF bandwidth compared to the GREAT mixers (0.2-3.5GHz compared to 0.2-2.5 GHz)

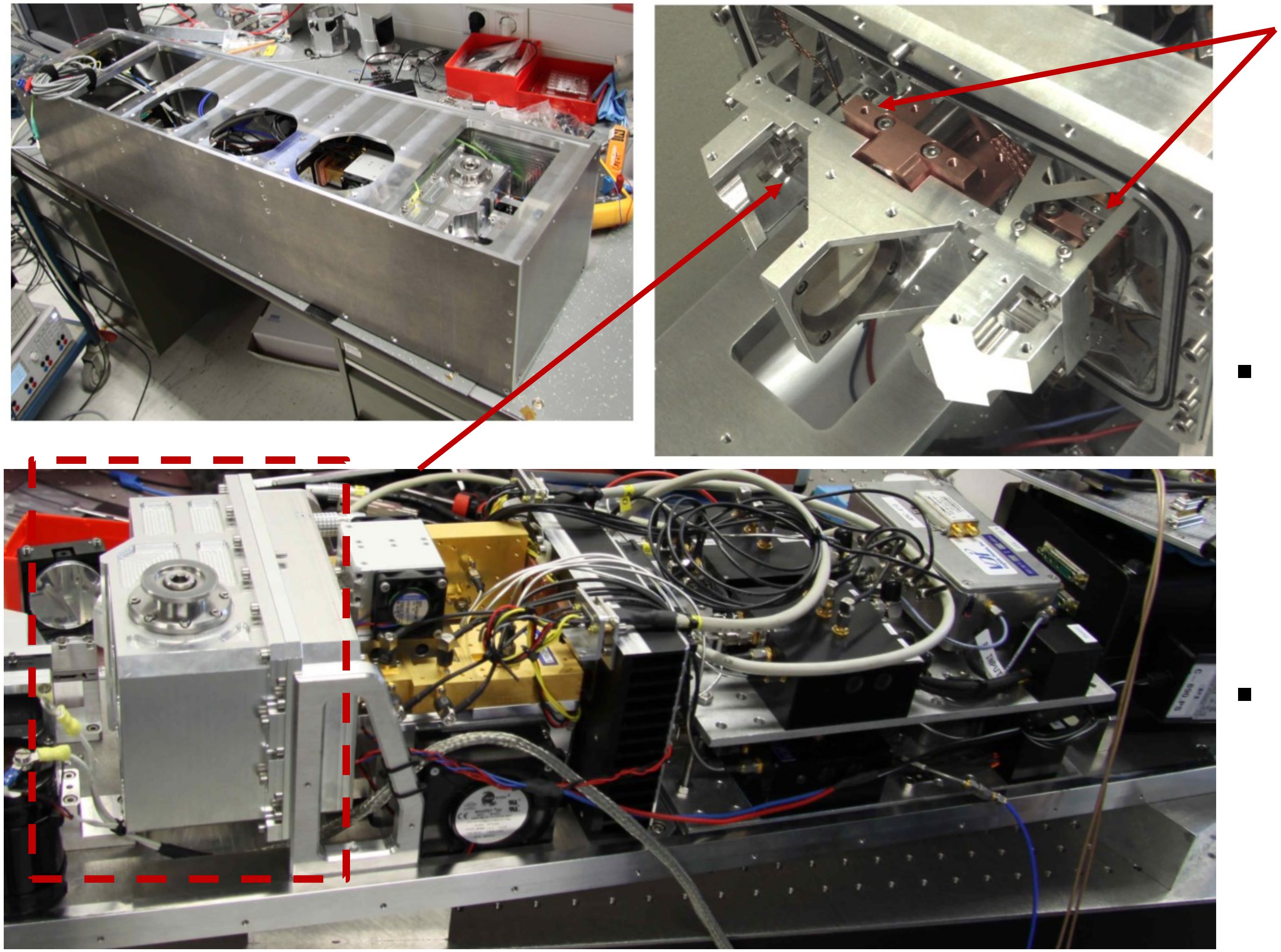
- Waveguide technology was selected for flight models production.
- Fabrication of LFA and HFA devices finalized.
- LFA mixers well characterized
- HFA mixers (4.7 THz) to be characterized after LFA commissioning – the 1st prototypes (H-channel) shows Trec (DSB) ~ 800K min

LFA Local Oscillator

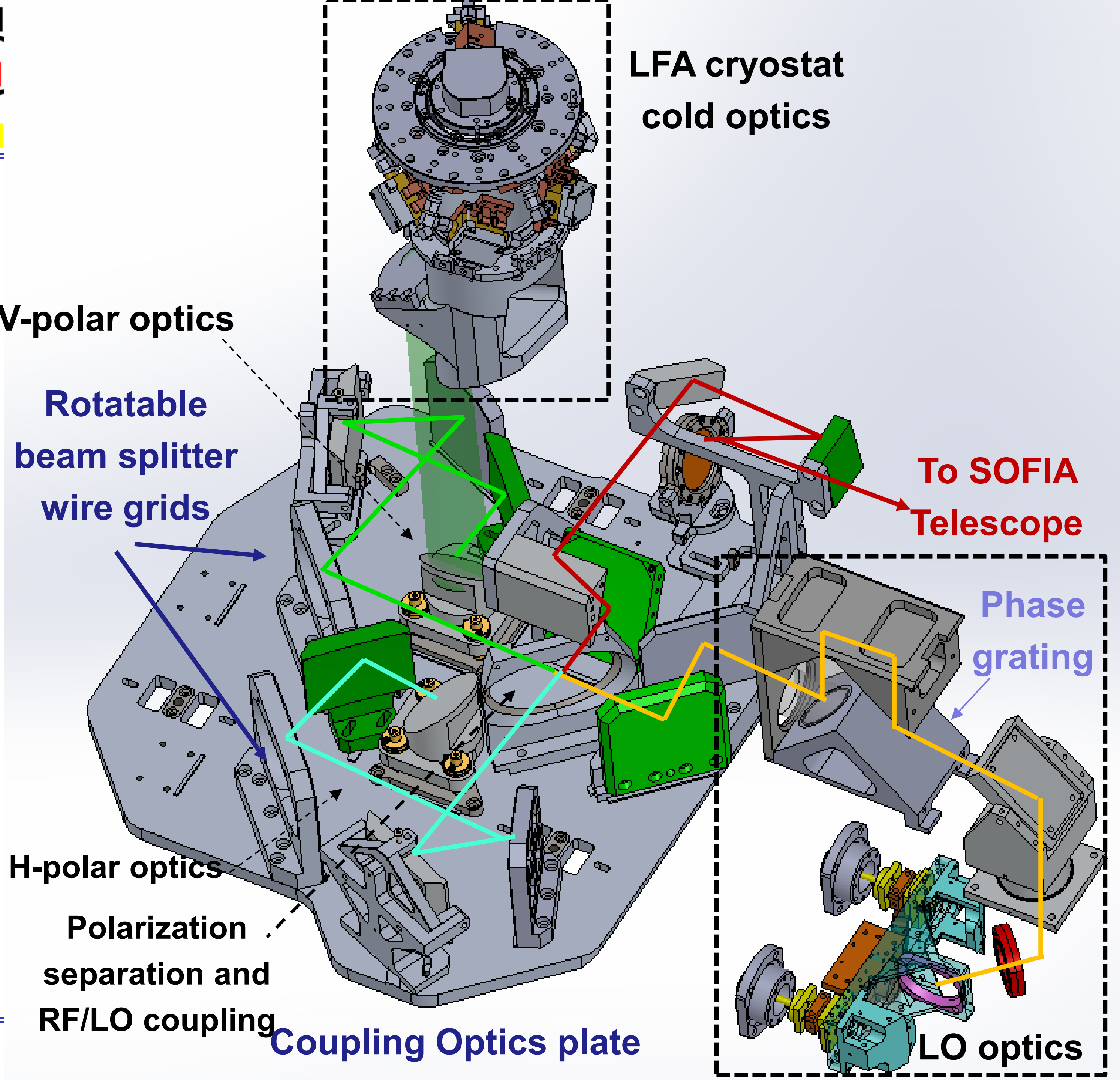
- For the upGREAT LFA, two development are done in parallel:
  - Photonic local oscillator – for 1.9-2.5 THz
    - Current devices reach few µW of output power –
    - new designs tests ongoing – goal is >4 µW for the LFA
  - 2 Solid state LOs from VDI, for the lower band at 1.9 THz (CII line)
    - 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


LFA cryostat
cold optics
V-polar optics
Rotatable
beam splitter
wire grids
To SOFIA
Telescope
Phase
grating
H-polar optics
Polarization
separation and
RF/LO coupling
Coupling Optics plate
LO optics

Test setup in Bonn with mockup of the GREAT SI structure

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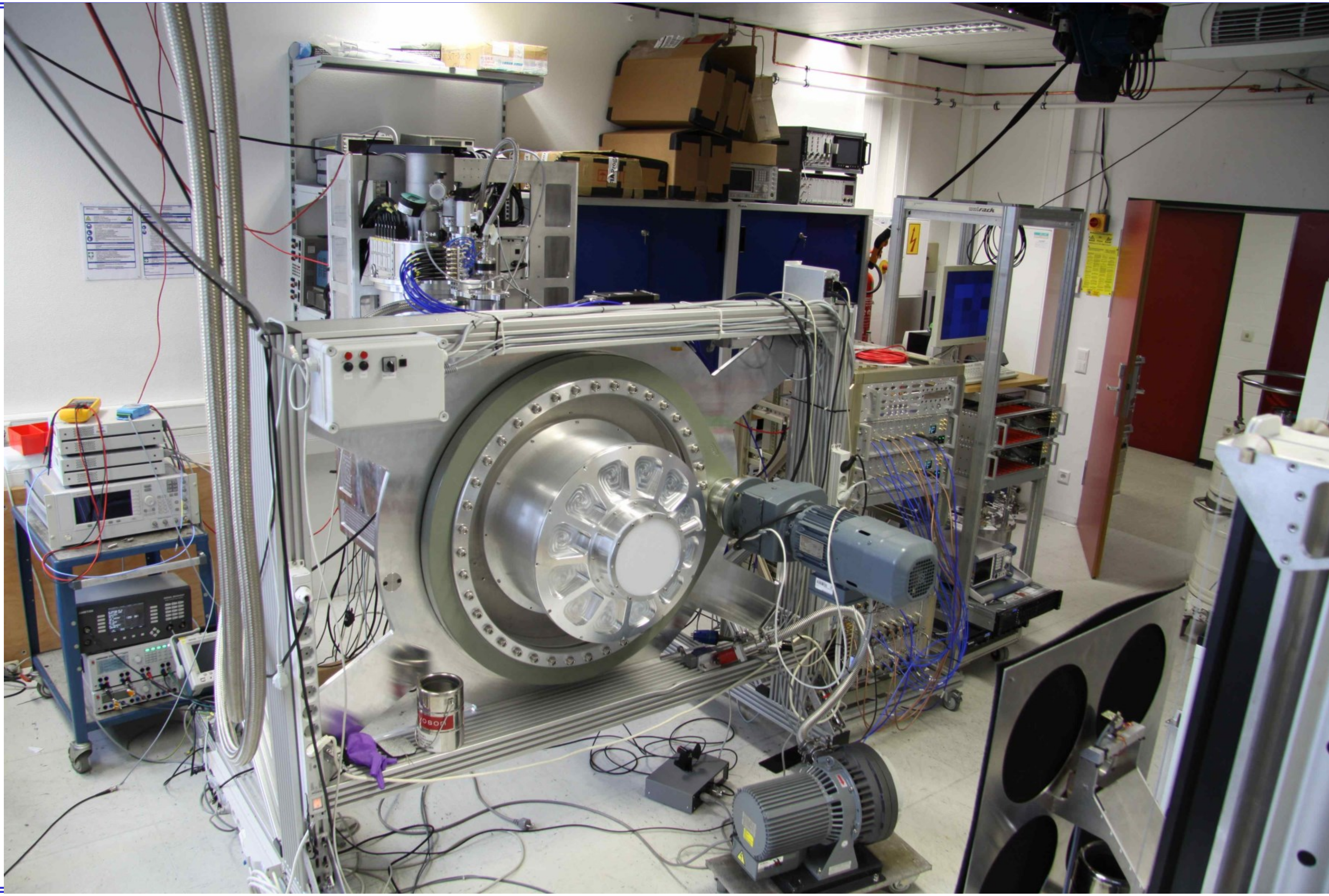
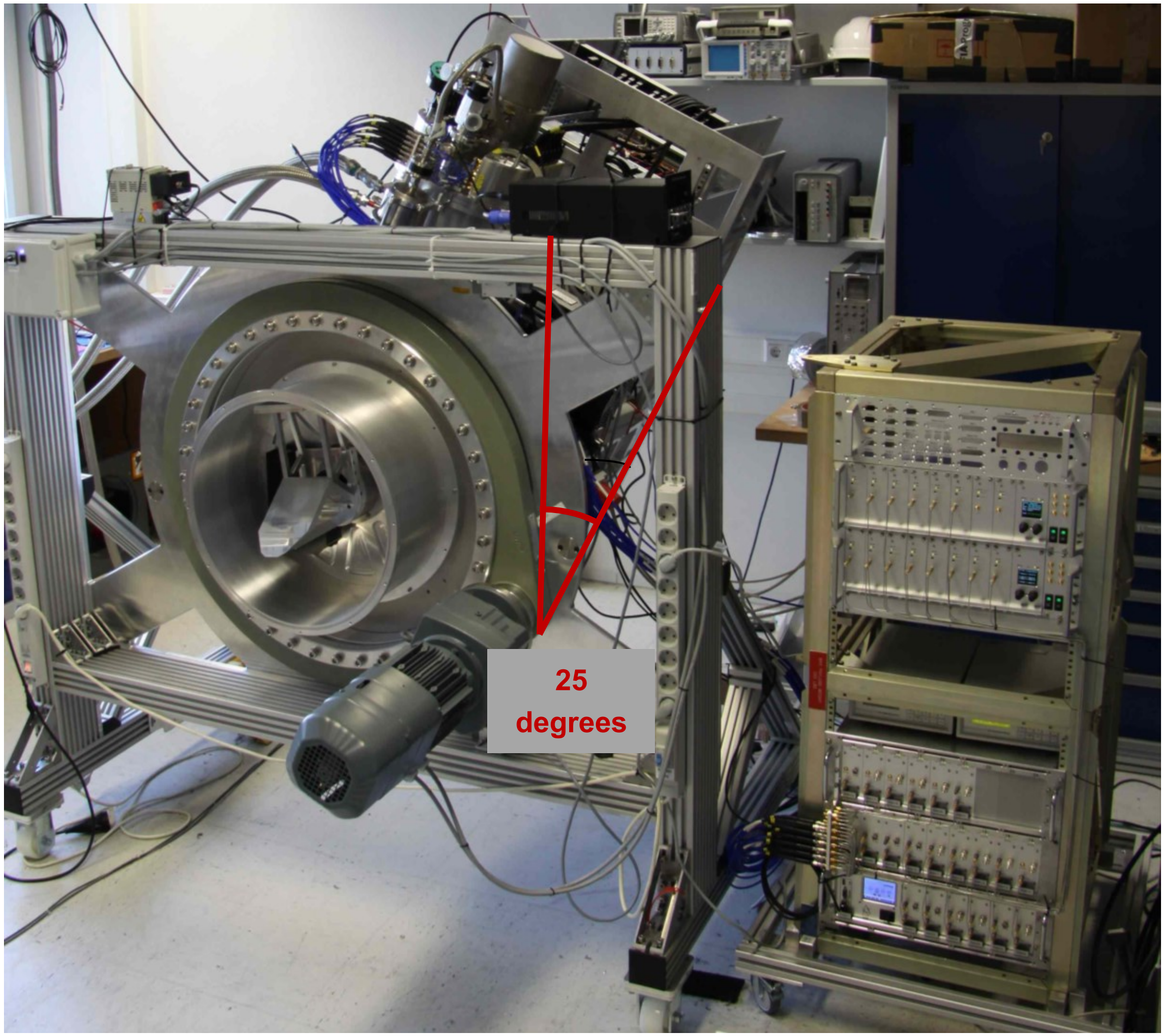


Telescope movement simulator



The whole instrument structure is tilted to simulate the SOFIA telescope elevation changes (±20 degrees changes)

Important to test optical alignment impact, and cryostat temperature variations

No change is seen in the HEB physical temperatures (<1mK) and negligible alignment impact.

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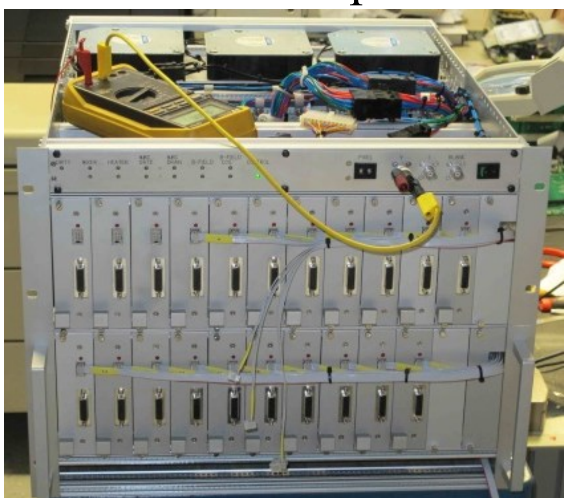
Electronics modules
(Bias, IF processor, backends)

New bias electronics for detectors and low noise amplifiers



New generation IF modules – covers 0-6 GHz

New generation spectrometers

IF Processors – FFTS4G spectrometers

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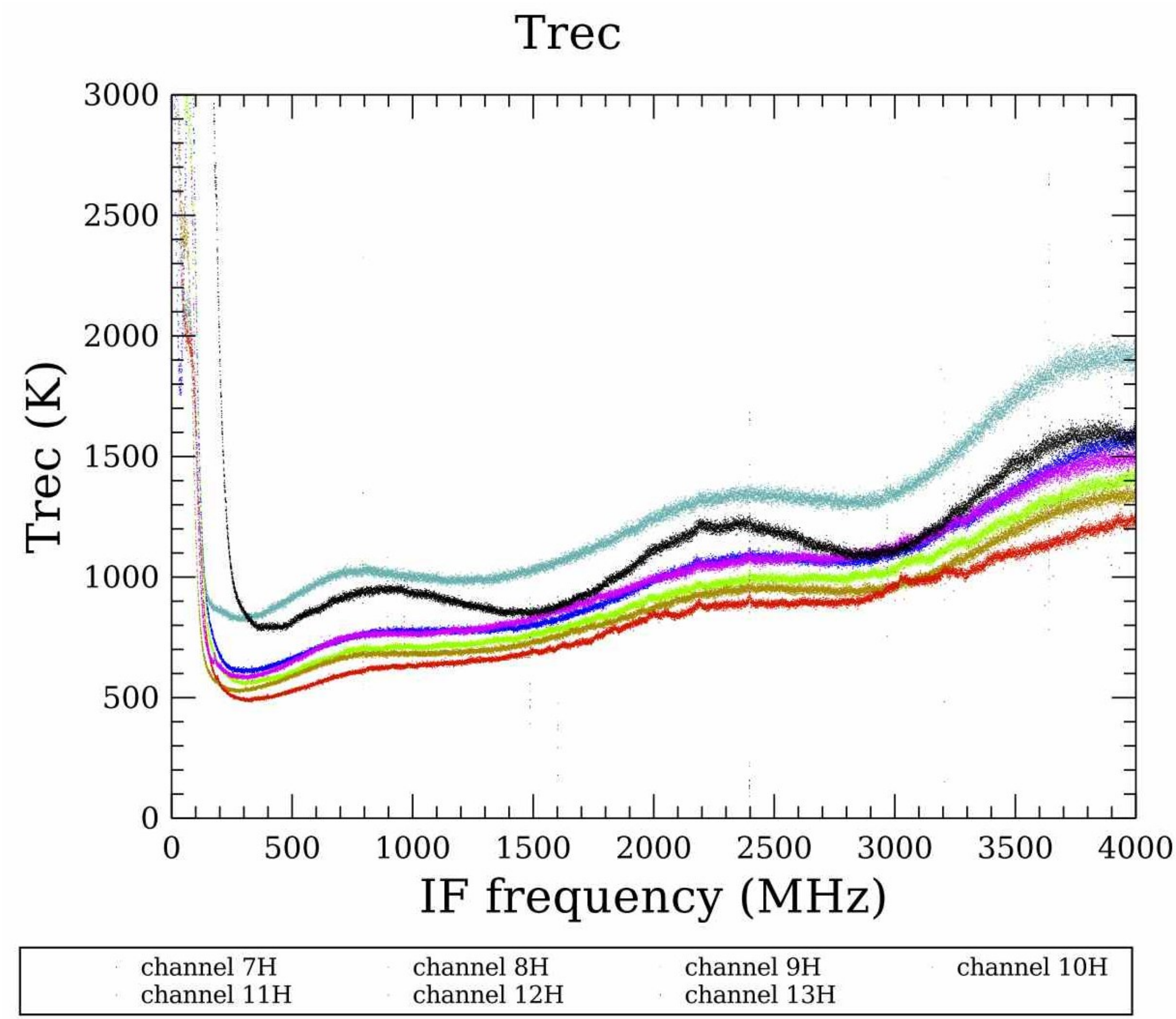
KOSMA
MPS
DLR-Pf

- 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

upGREAT LFA Trec Characterization

H-polarization – 7 pixels



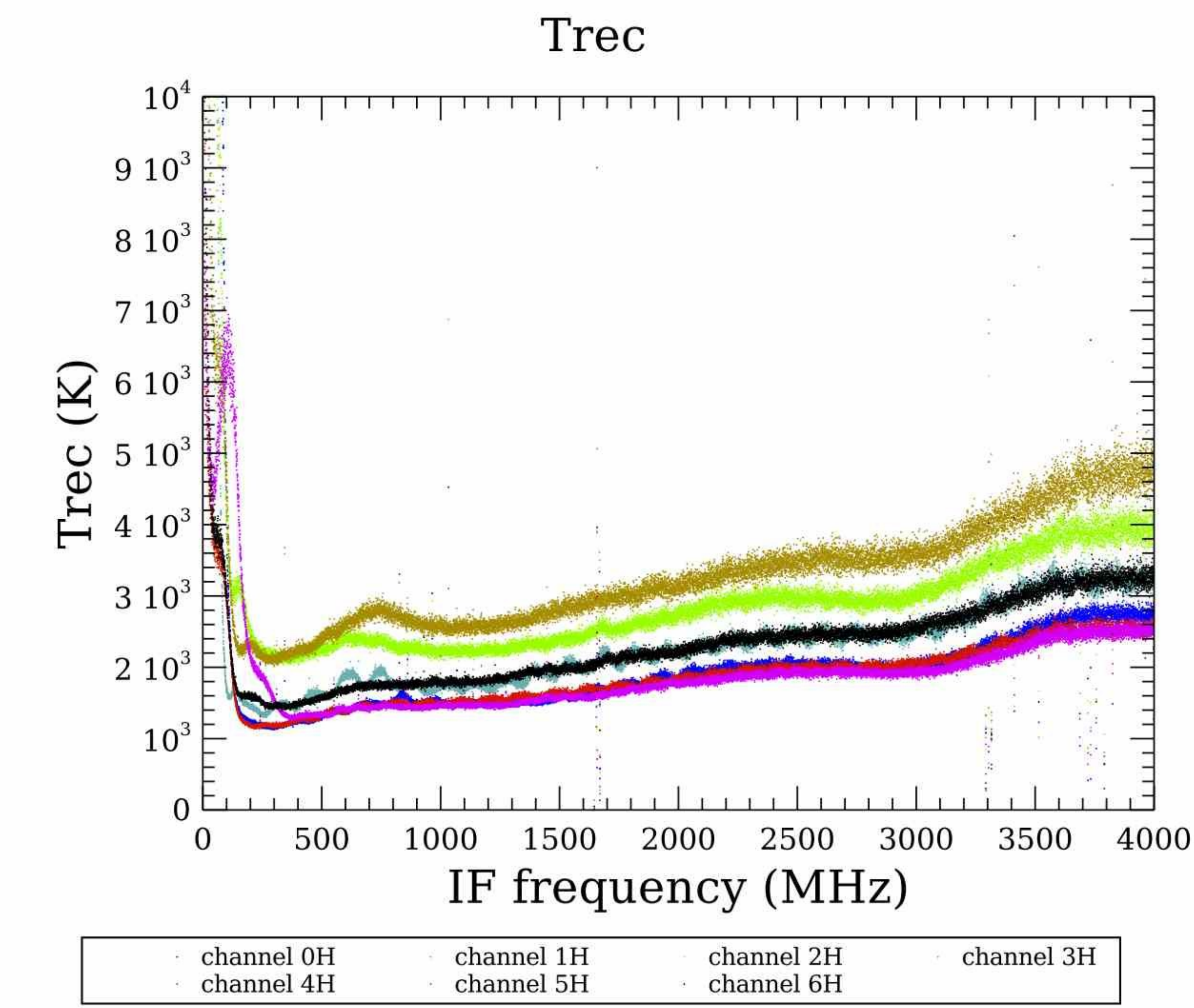
Uncorrected Noise temperature for the 7 pixel in the H-Polarization at ~1.9THz show 600-1400K between 0-4 GHz

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)*

upGREAT LFA Trec Characterization

V-polarization – 7 pixels in May 2015



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)

upGREAT LFA Trec Characterization

V-polarization – 7 pixels in December 2015

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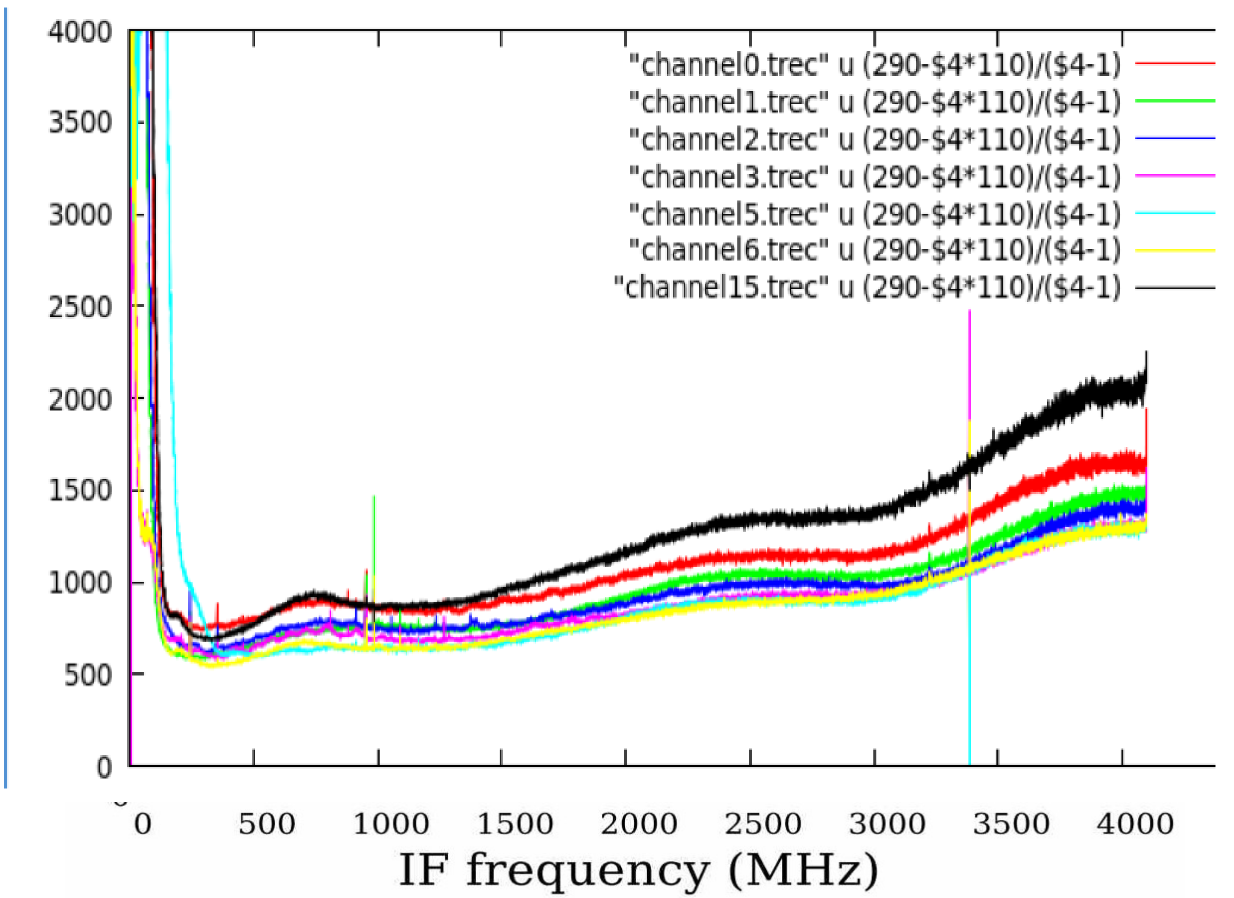
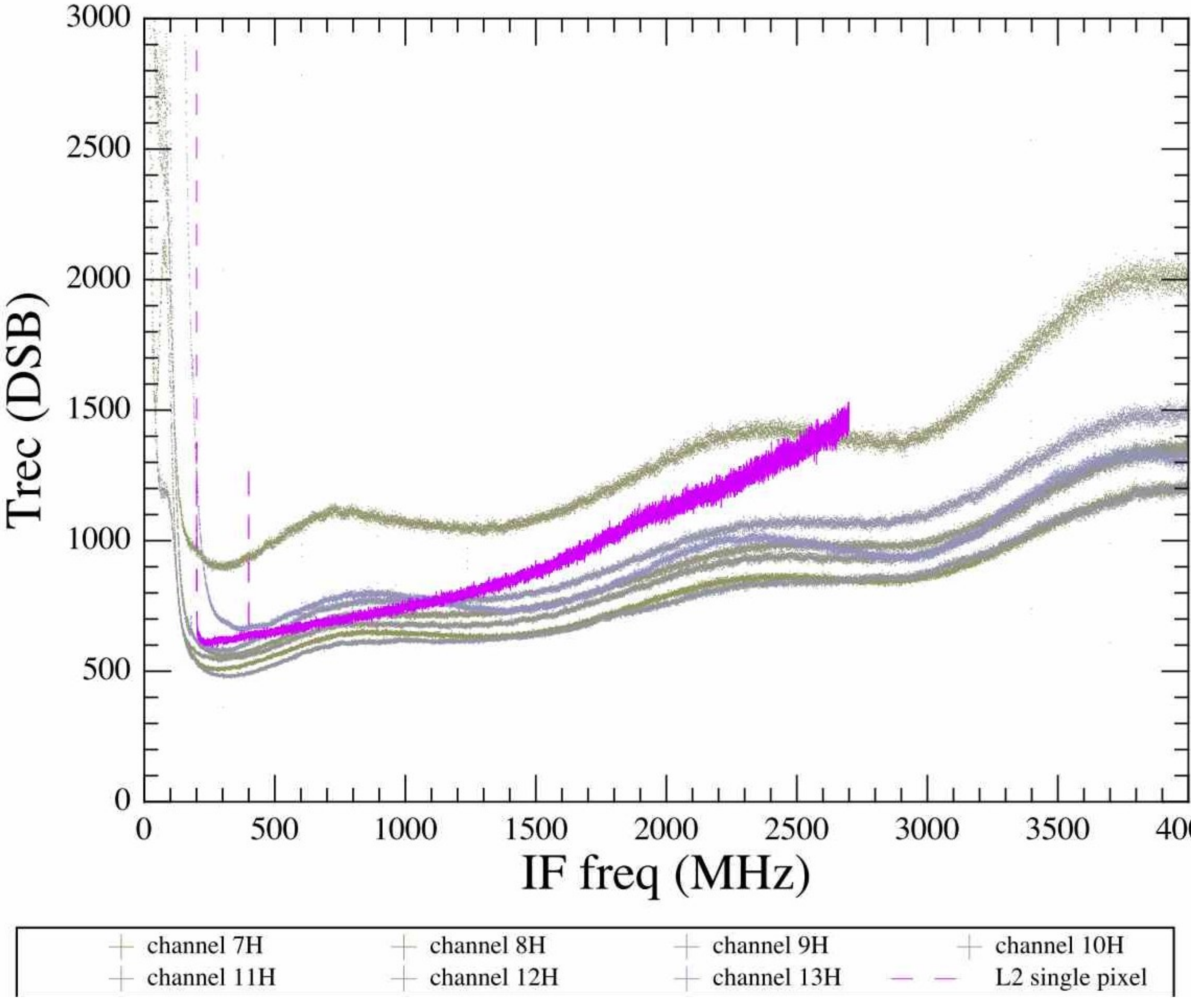


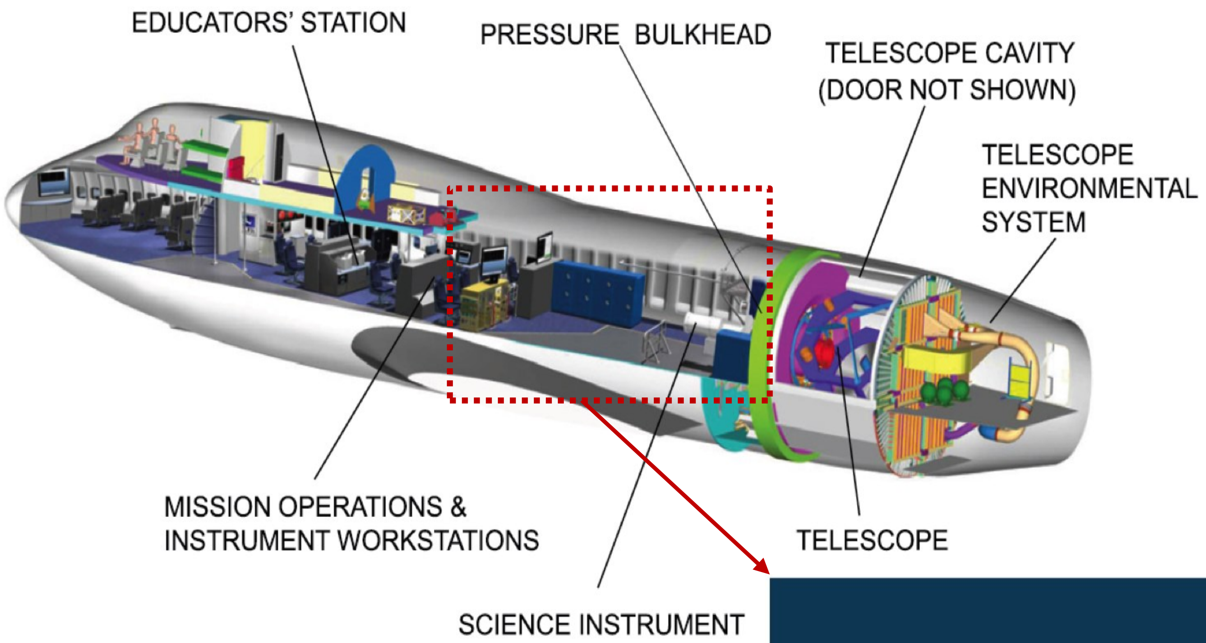
Uncorrected Noise temperature for the 7 pixel in the V-Polarization at ~1.9THz show 1200-300K between 0-4 GHz

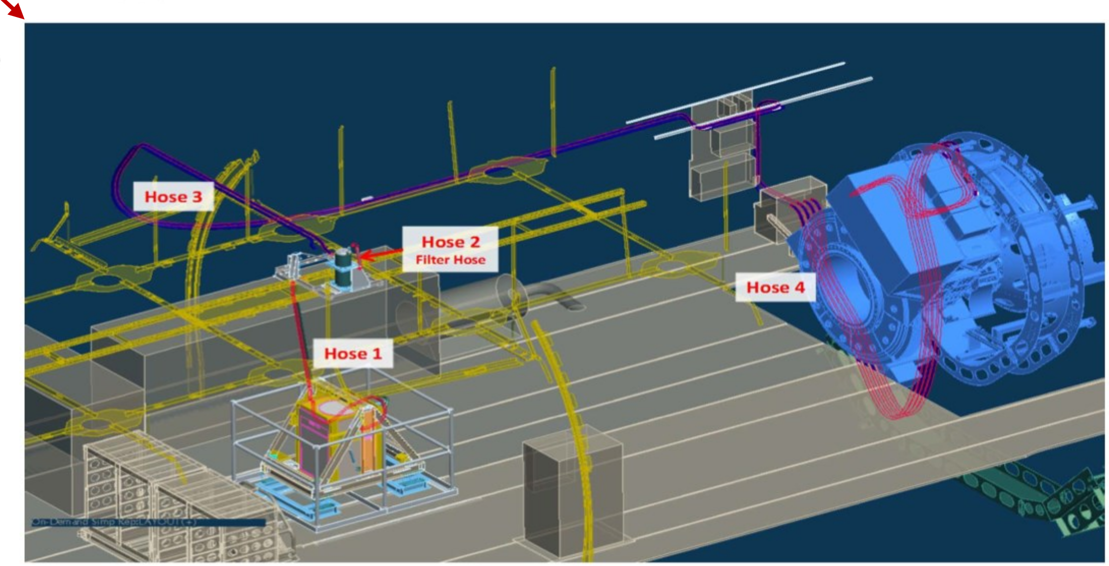
Signal transmission is only of 50% with beam splitter optics (due to lack of LO power and higher Ic HEB devices)

Trec comparing LFA and single pixel L2 receivers

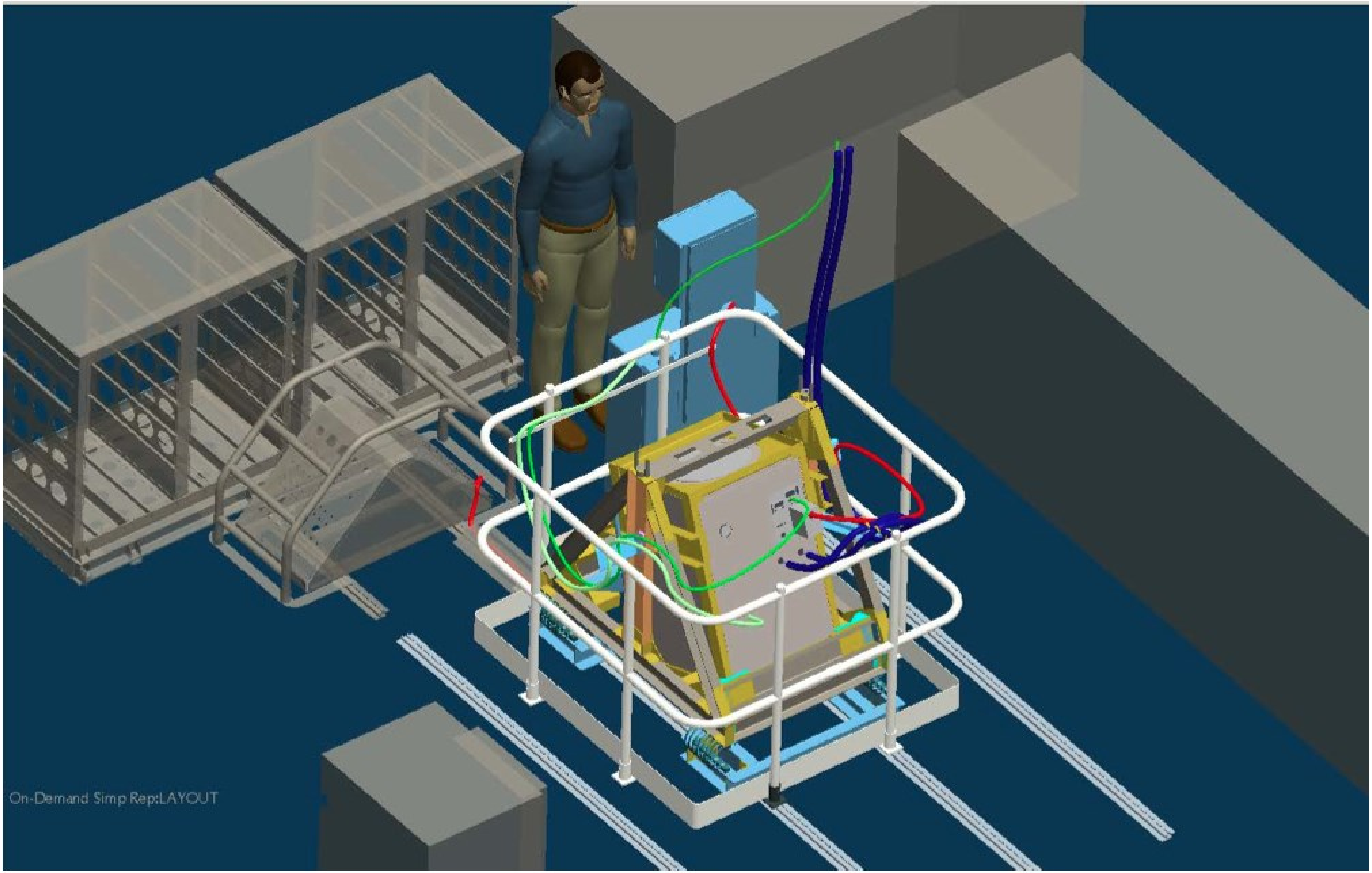


Cryocooler Infrastructure aboard SOFIA





Cryocooler Infrastructure aboard SOFIA



GREAT/upGREAT Instrument in May 2015

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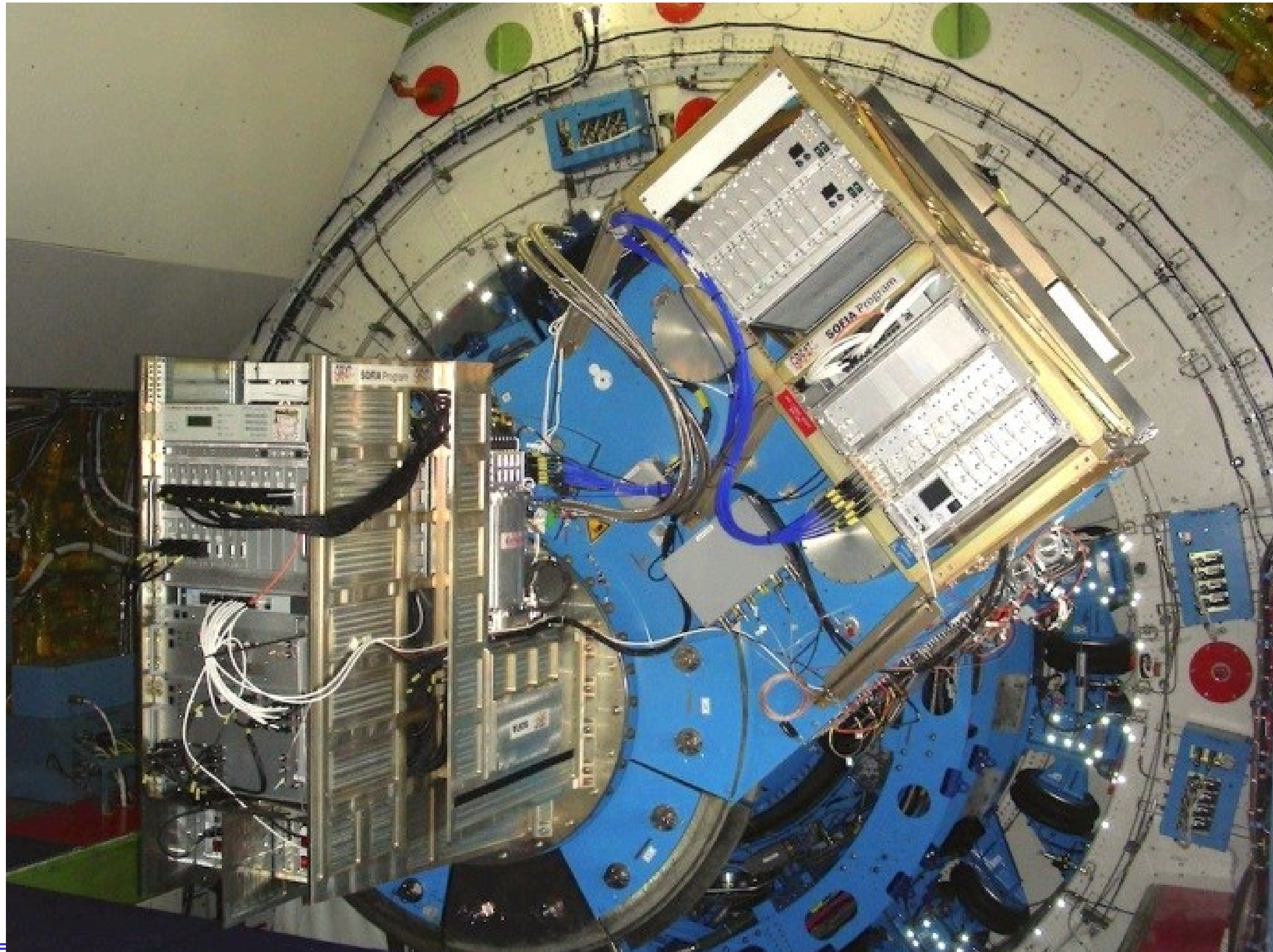

GREAT/upGREAT Instrument in May 2015

MPIfR
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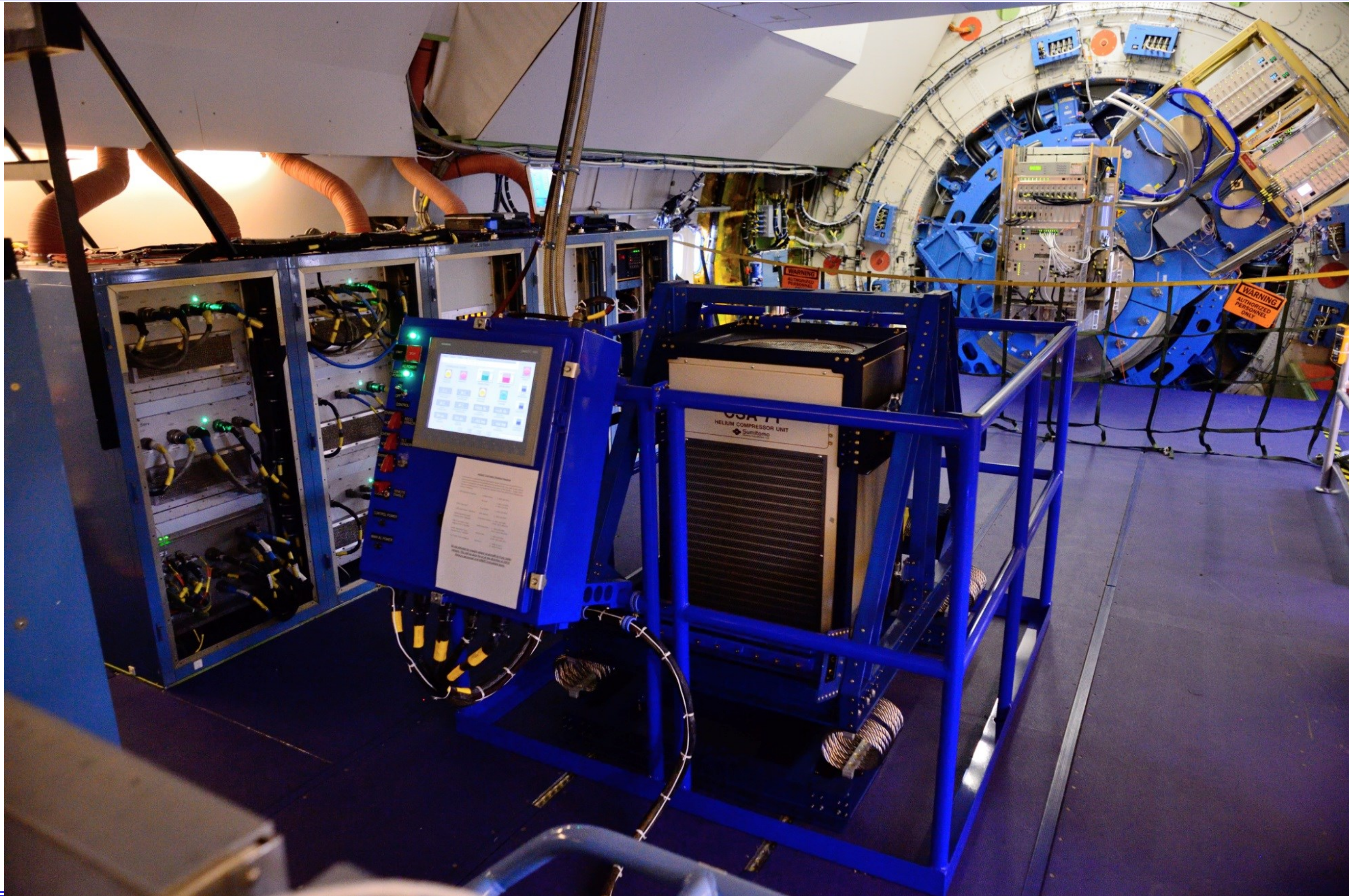
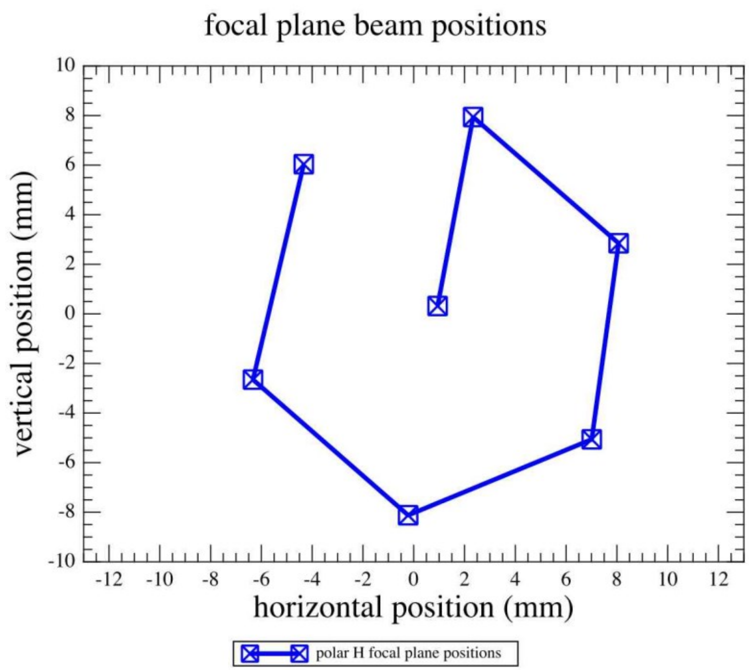
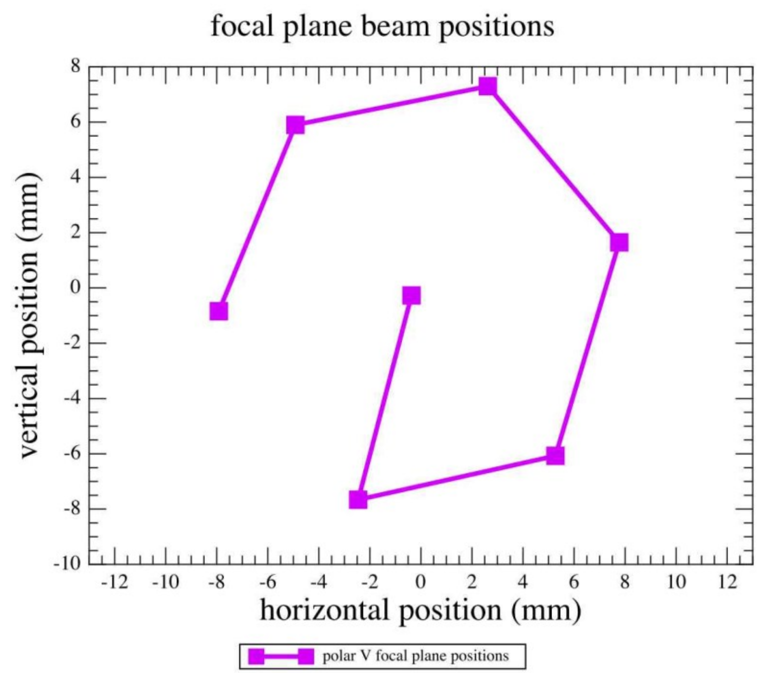


Beam characterization

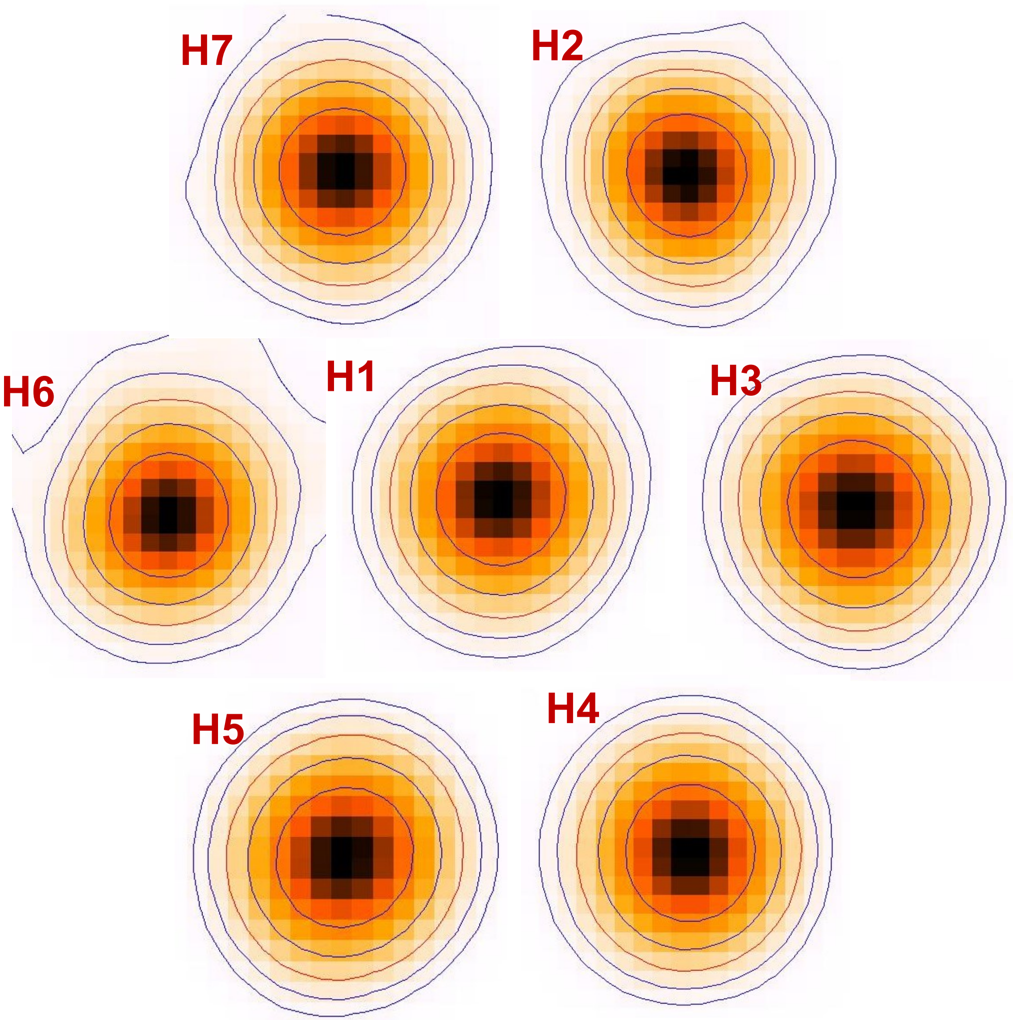
- Optical beam verification confirms that the beam waists and positions are as designed (13dB edge Taper chosen)

- 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

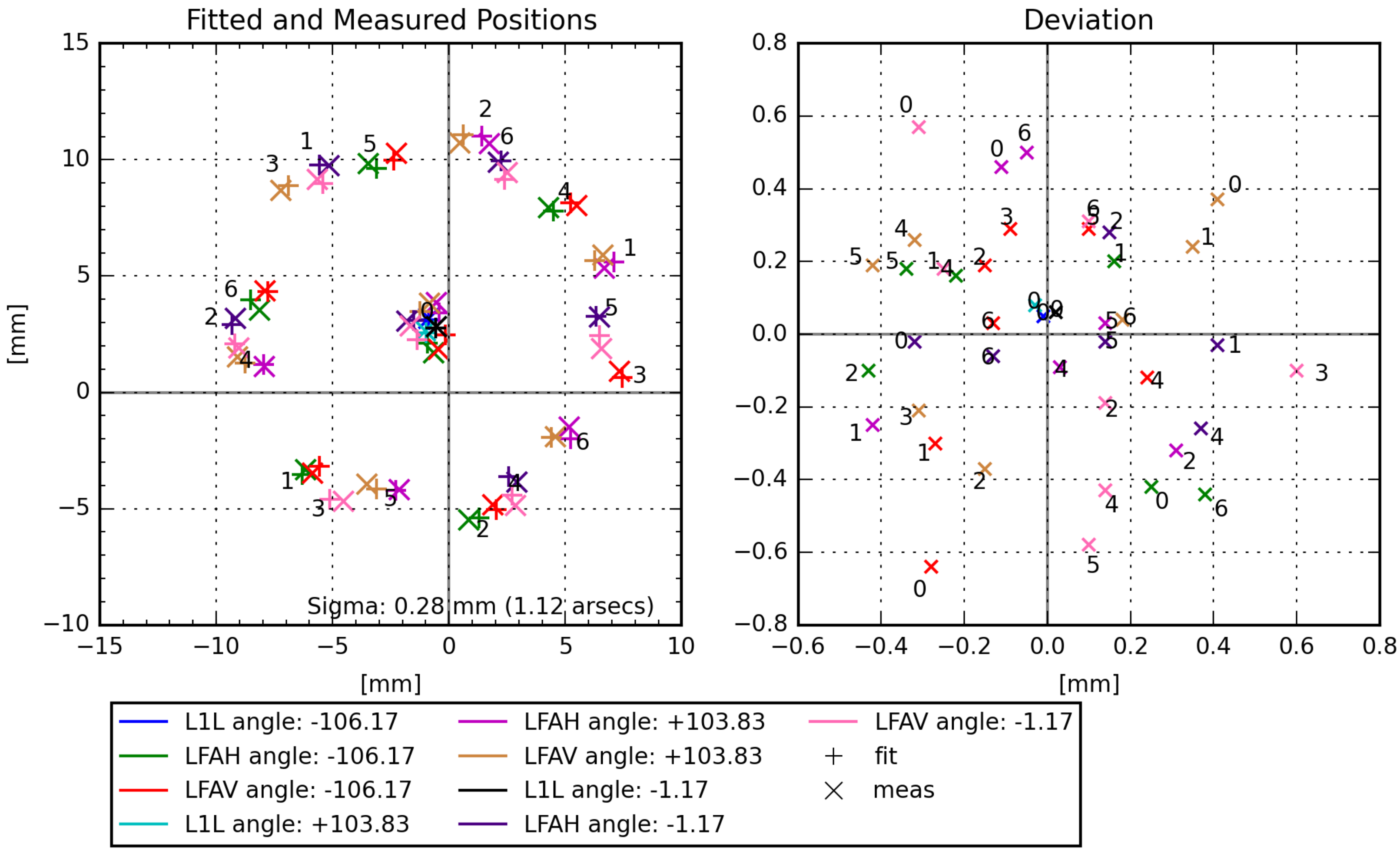




Beam characterization in Laboratory

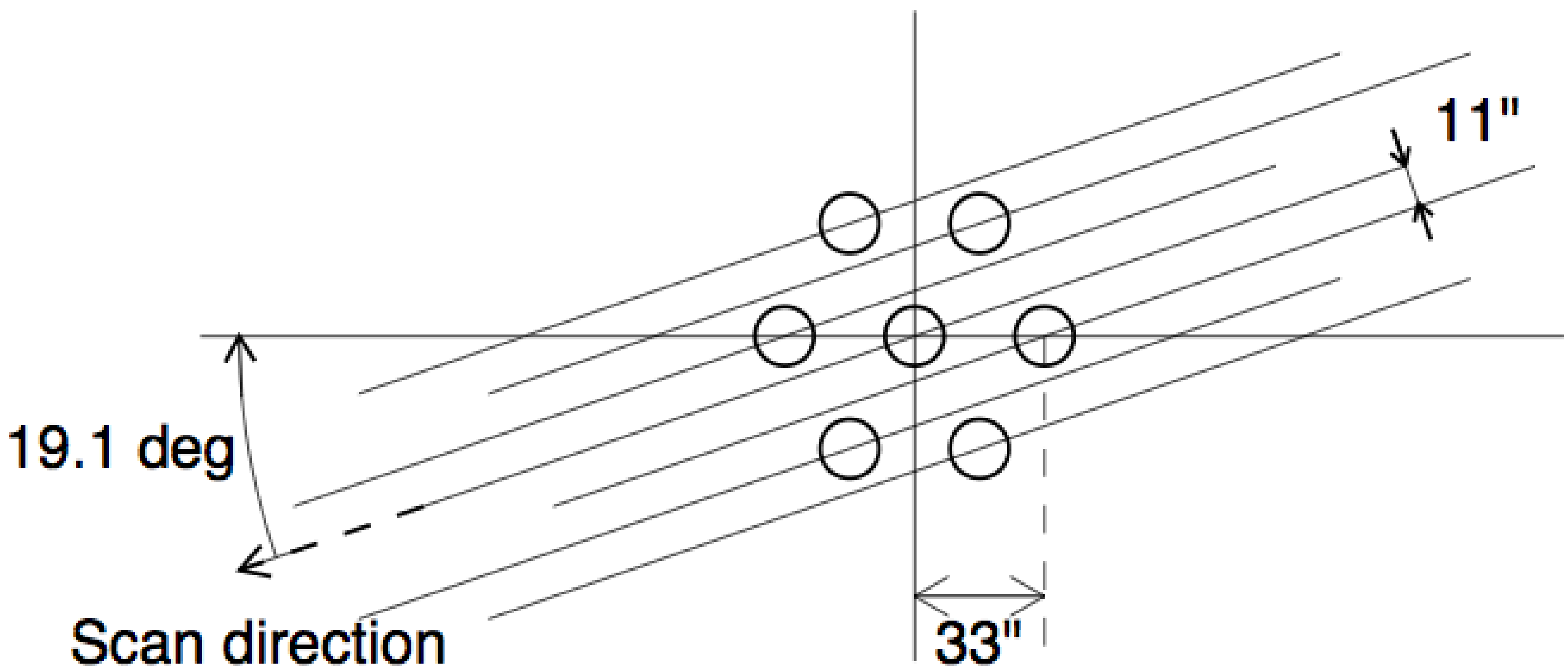


Pointing verification on sky



- **Pixels positions derived from laboratory measurement were accurate within 0.4 “**

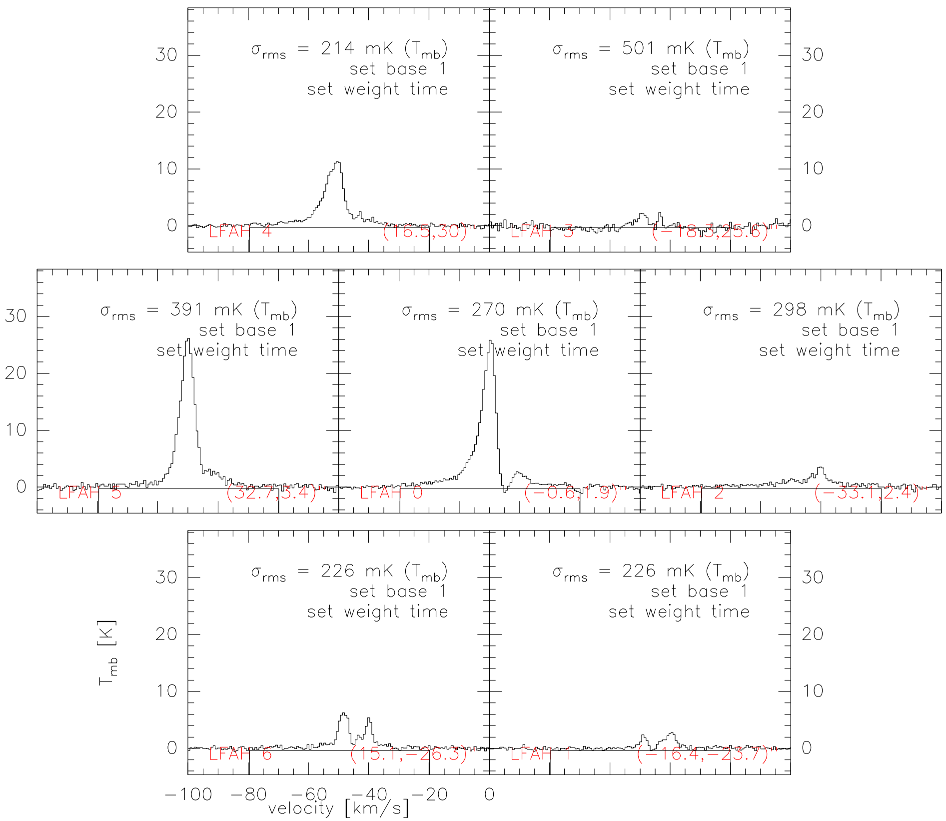
Main observing mode - OTF

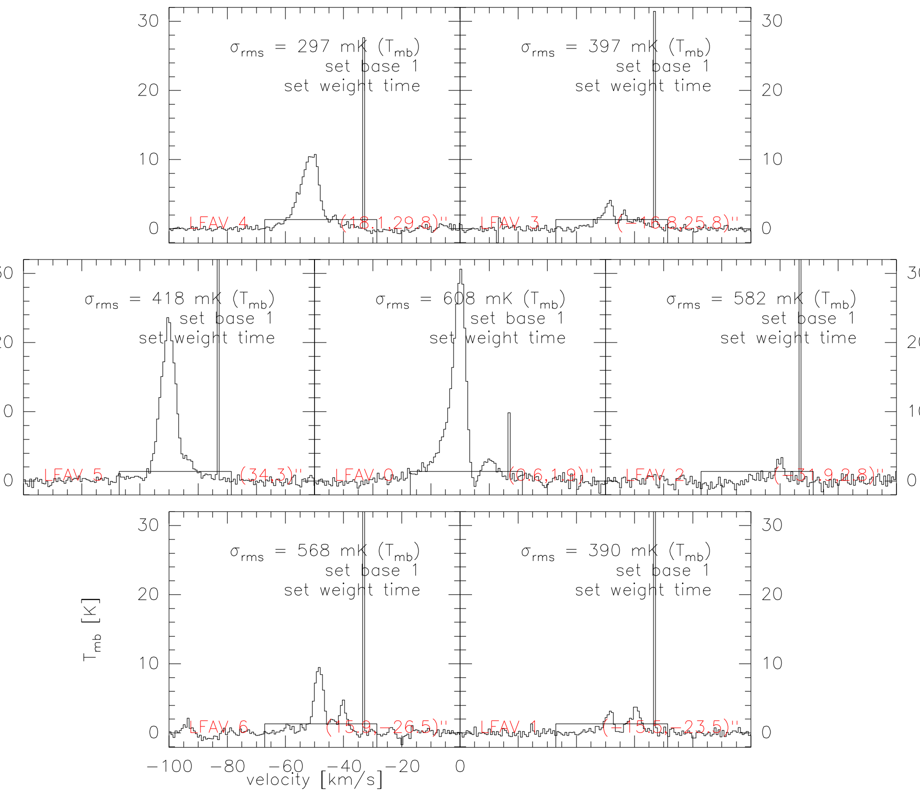


First commissioning results

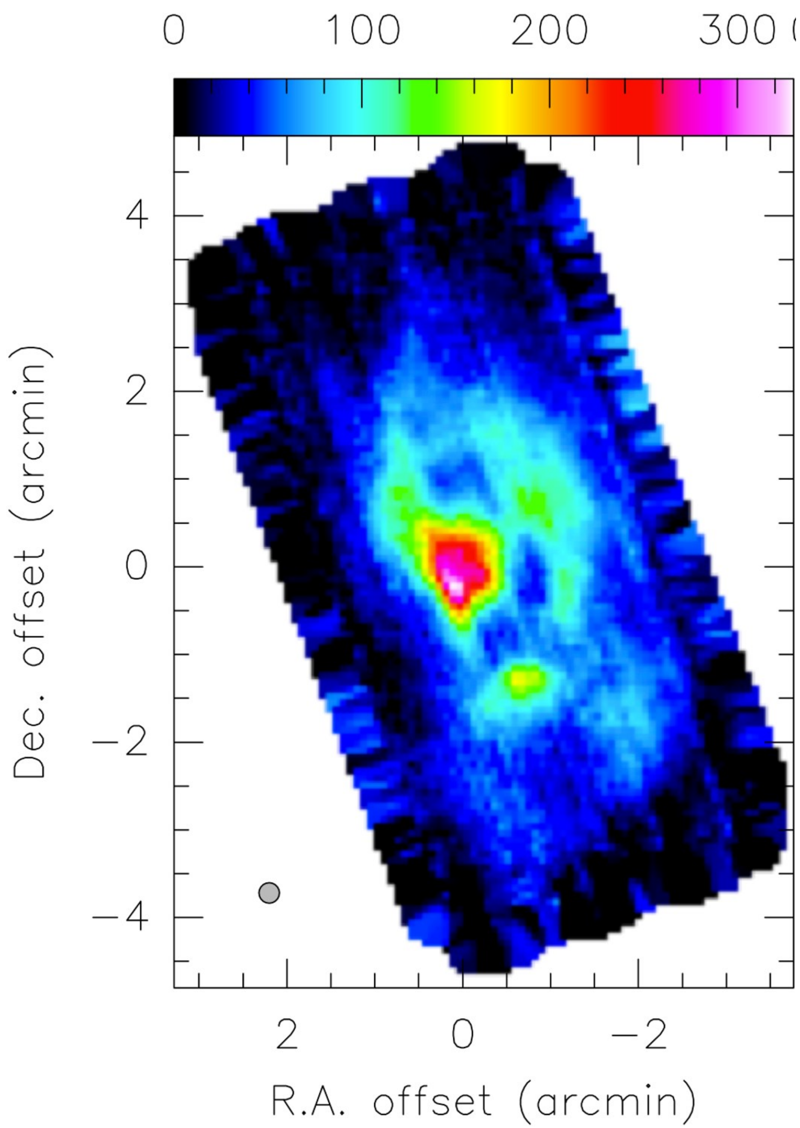
MPIfR
KOSMA
MPS
DLR-Pf

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).

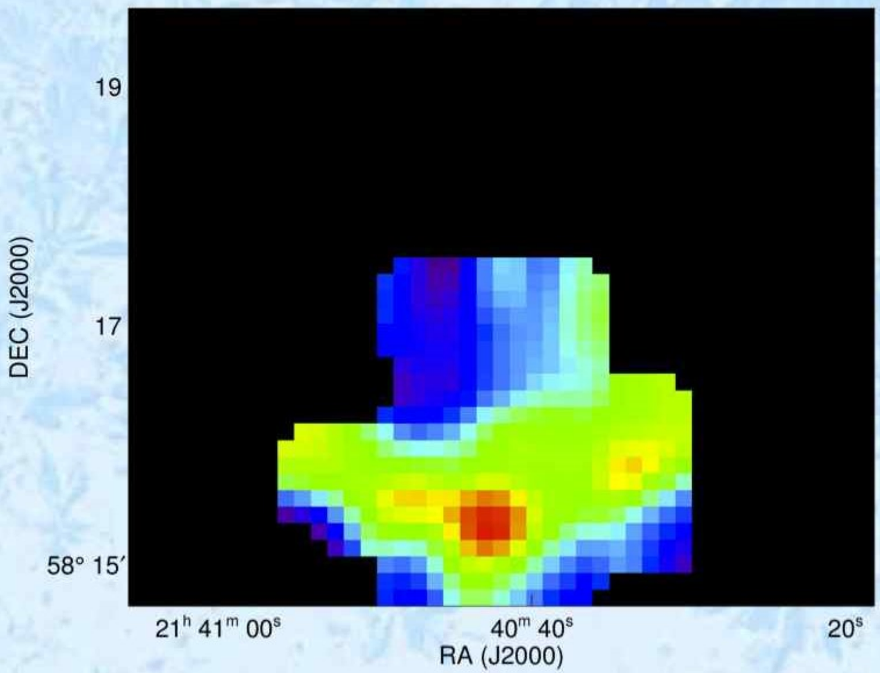
First commissioning results

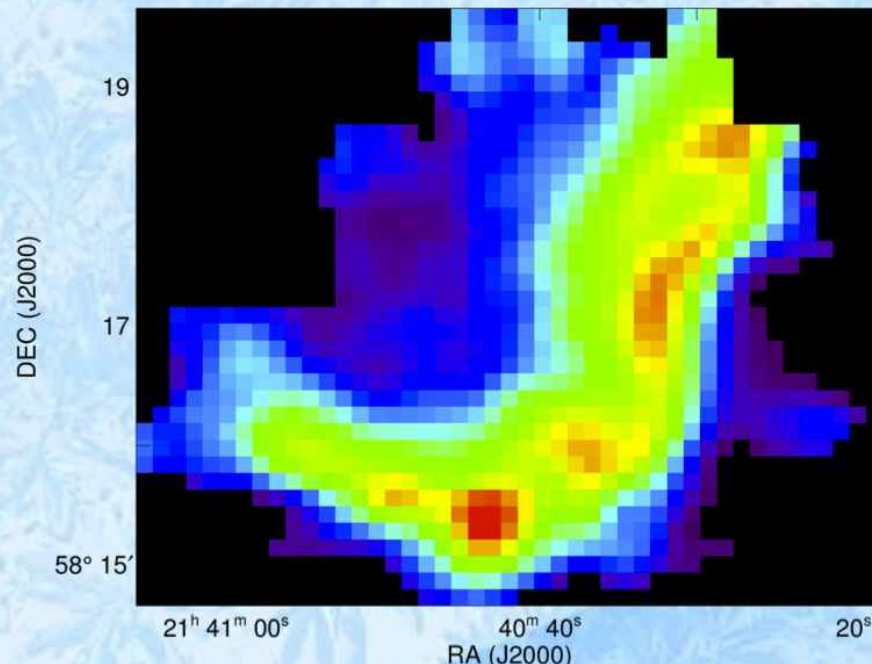
MPIfR
KOSMA
MPS
DLR-Pf

IC 1396 E

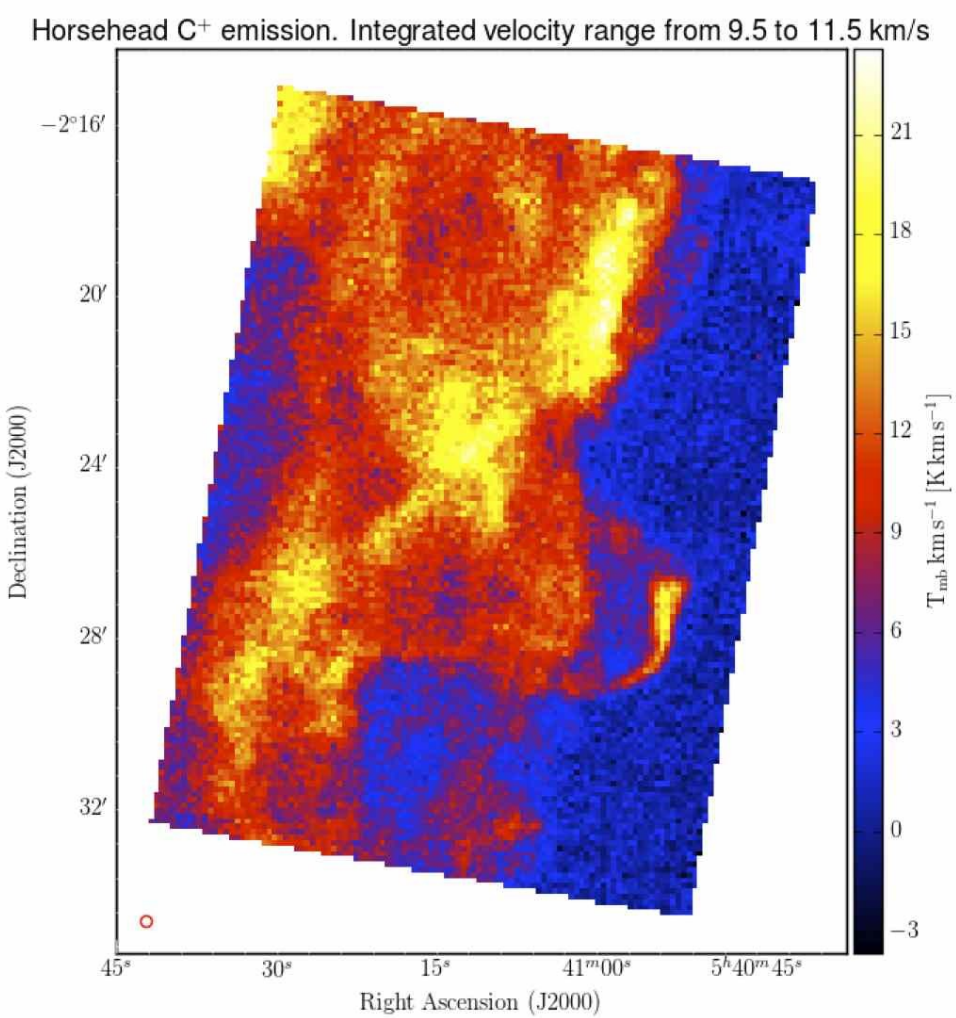
Courtesy of Yoko Okada

GREAT (1 pixel)	upGREAT (7 pixel)
2 flight legs, total 1.5 hours	1 flight leg, total 1 hour





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)

- 1st 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.

Summary (2/2)

- 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.