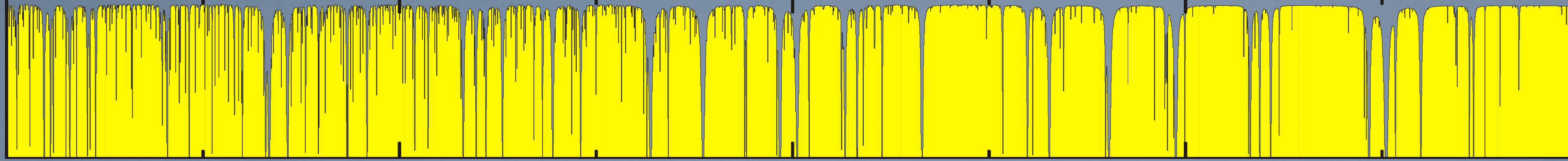
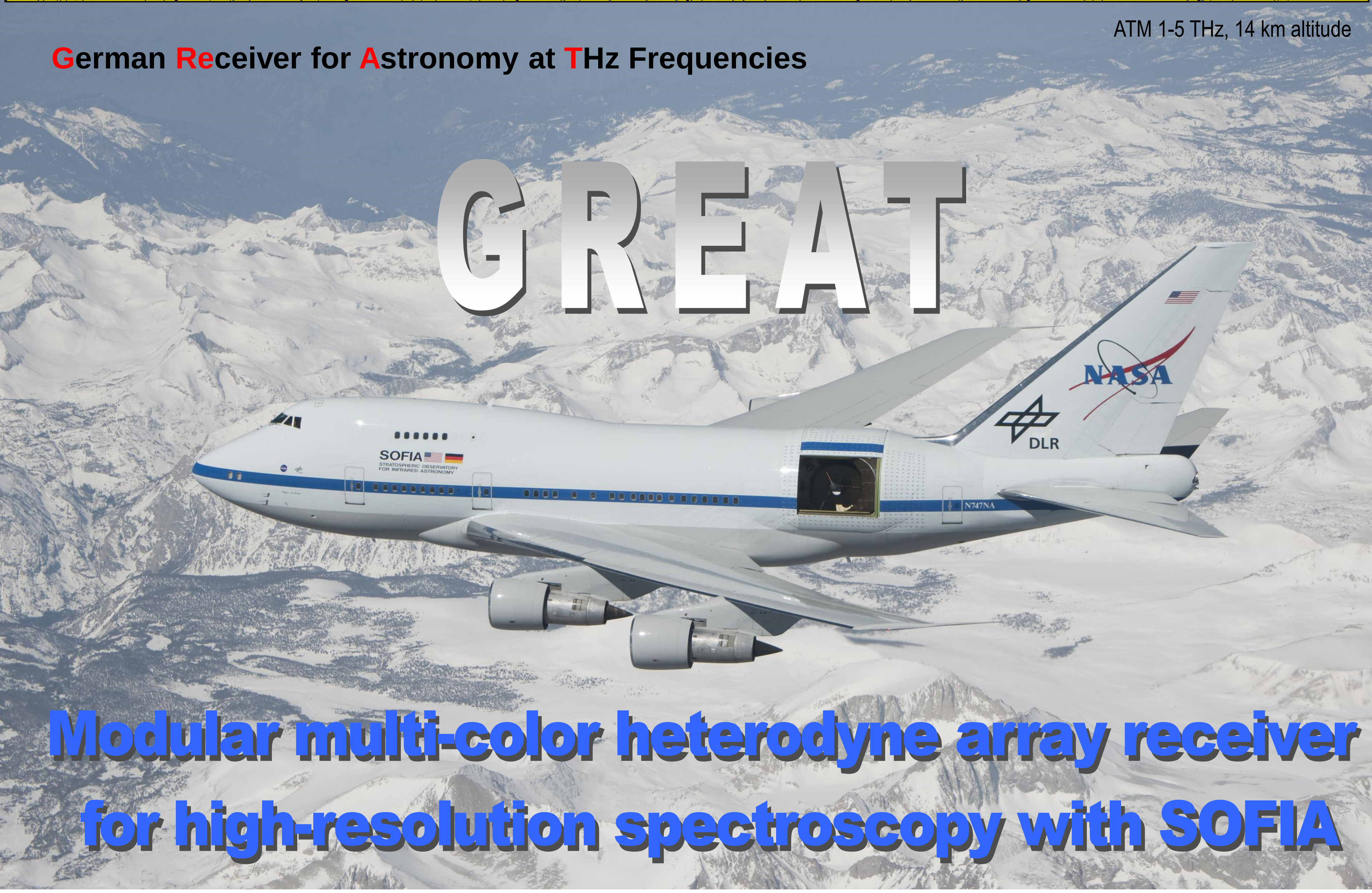


ATM 1-5 THz, 14 km altitude

German Receiver for Astronomy at THz Frequencies

GREAT



Modular multi-color heterodyne array receiver for high-resolution spectroscopy with SOFIA

The GREAT Success Story

GREAT was a convincing success, both scientifically and in its technological and operational achievements

- GREAT - in its various incarnations - participated
  - in 235 successful SOFIA flights, worth ~1800 hours of science time
  - during all observing cycles, starting with Early Science in 2011
  - on all deployments (7x CHC, 2x CGN, 1x PPT)

- GREAT serviced >250 science projects, incl. 5 legacy programs

- GREAT data led so far to >140 refereed publications (04/2024), incl.
  - 5+1 contributions to Nature & Science
  - 13 publications on technology

    [⇒ "best 2018 paper" award by IEEE for Risacher et al. presenting upGREAT]

Lessons learned – overview

What made GREAT special, and what can be learned from it ?

- The **Consortium** unites German expertise in the field of heterodyne spectroscopy
  - consorts with long-term experience in building state-of-the-art submm instruments and operating (at) remote telescope facilities (KOSMA, Nanten2, SMT, APEX)
  - direct and timely involvement in the built of Herschel/HIFI spectrometer
  - consorts deeply involved in relevant THz basic research
- Programmatic: GREAT operated as Principal Investigator-class instrument
- Ansatz to utilize advances of THz technologies: organize build & operation in such a way that technological innovations could be implemented timely:
  ⇨ leading to a modular design approach

GREAT - the Consortium

MPIfR
KOSMA
MPS
DLR-Pf

Consortium established in 1998, in response to DLR call for instrument proposals.

Over the years the project has attracted many exceptionally talented engineers and scientists (>50), whose countless contributions have made the project a success

- MPI für Radioastronomie
  - R. Güsten (PI until 2018)
  - S. Heyminck (early system engineer, PA/QA)
  - B. Klein (FFT spectrometer) (Co-PI)
  - C. Risacher (upGREAT project manager)
  - C. Duran (4GREAT project manager)
- Universität zu Köln, KOSMA
  - J. Stutzki (Co-PI, PI after 2018)
  - U. Graf (system engineer)
  - K. Jacobs (HEB mixers)
- DLR Optische Sensorsysteme
  - H-W. Hübers (Co-PI)
  - H. Richter† (QCL)
- MPI Sonnensystemforschung
  - P. Hartogh (Co-PI)

GREAT Programmatic I

Key to success: different to other contributions to the SOFIA instrument suite GREAT operated as a (German) PI instrument, whose development and operation was predominantly self-financed by the members of the GREAT consortium. Total investments by consorts exceed 25-30 M€.

- Per agreements with DLR these investments were partially compensated by guaranteed (G) observing time (1/4 - 1/3 of German 20% time share)
- In return for offering GREAT to the US Guest Observer community GREAT was awarded guaranteed US time (1 for 6 service flights, per MoU with the SMO Director)

Note: “stimulating” science return for the acquisition of funding due to the fact that a considerable proportion had to be applied for in 4-year cycles (DFG peer reviewed, based on science and proposed technological innovations). In this sense, GREAT was doomed to succeed!

GREAT Programmatic II

Under this umbrella, the GREAT PI signed responsible for

1. specification and design of the instrument per science interests of the consortium: reporting to DLR only, while complying with NASA defined safety requirements

   ⇒ this allowed quick, (sometimes) “unconventional” responses to new technological opportunities (science-supported, of course) or specific operational requirements

2. mission & quality assurance, instrument related §
3. operation of the instrument (via obs. scripts) in service mode only
4. calibration and release of validated data by GREAT experts

   ⇒ thereby providing the optimal data quality to our communities

----

Note: we acknowledge the excellent support from the DLR project office (Himmes, Lilienthal), without which this “independent” mode of operation could not have been implemented

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In simple(r) words:

Our Ansatz was to limit the NASA PA/QA process to the necessary and outside of the instrument internals, both for hardware and software

safety: yes, SOFIA compliant

performance: under the sole responsibility of the GREAT PI

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Modular Instrument Design

Its modular design has been key to the success of GREAT

- allowing to implement technological innovations as quickly as possible (during the last 2 decades THz-technology has been rapidly advancing), while
- at the same time keeping the effort required for the necessary (delta) airworthiness certification manageable.

With the PI being responsible for mission assurance of this instrument,

- its modularity was a prerequisite for the continuous improvement of GREAT (often, between flight series), and
- hot swap repairs of fragile hardware (if necessary, between flights)

GREAT instrument software

GREAT operated under *kosma_control*

dedicated software developed by GREAT to support GREAT* in all its incarnations and observing modes in the specific SOFIA environment

- modular design reflecting the hardware architecture with simple interfaces between modules§, but with only a
- single clean interface to MCCS/TA (*kosma_translator***)
- hardware compliant simulators§ for each module proved to be essential for the efficient commission and operation of GREAT
  - full debugging of software prior to hardware use on board
  - rapid and precise identification/resolution of in-flight problems

ownership of software development, with clean interface to MCCS only, was critically important for the successful operation of GREAT as PI instrument

* Adapted software packaged was also used by FIFI-LS

** We acknowledge outstanding support by Sean Colgan and Bill Wohler in the translator development!

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<u>Modules of the simulator</u>

- Front-end
- Back-end
- Local oscillator
- Calibration
- Telescope interface
- Atmosphere
- „artificial“ Source
- Ephemeris

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GREAT instrument software

Features of the GREAT simulator

- debugging of observing modes and scripts (linked to SOFIA TA-simulator)
  - on-the-fly implementation early on
  - large area mapping with tiling
- thorough analysis and improvement of timing sequences and dead-times
- debugging of beam-rotator-telescope interface (common with FIFI-LS)
- pre-flight debugging of array-pointing procedure and analysis
- test and verification of atmospheric calibration

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GREAT Configurations Overview

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- First-light in L1&L2 configuration on April 01, 2011
- As highly modular heterodyne spectrometer ($\Re \sim 10^8$) GREAT operated in science-defined frequency bands $0.49 < \nu < 4.7$ THz
- in 2017 operation was streamlined to two configurations only:

LFA & HFA and **4G & HFA**

	Channel		Frequencies [THz]	Lines of interest	T_{rx}[K] / BW_{3dB} [GHz]
2011	low-frequency	L1	1.26 – 1.52	[NII], CO series, OD, H_2D^+	600 / 2.5
	low-frequency	L2	1.82 – 1.91	NH_3, OH, CO(16-15), [CII]	700 / 2.5
2012	mid-frequency	Ma	2.49 – 2.56	$^{(18)}OH(^2\Pi_{3/2})$,	1500 / 2.0
2014	high-frequency	H	4.74	[OI]	900 / 2.5
2015	upGREAT	LFA	2x7 [1.8– 2.1]	NH_3, OH, CO series, [CII], [OI]	750 / 3.3
2016	upGREAT	HFA	7x [4.74]	[OI]	900 / 3.3
2017	4GREAT	4G-1	0.49 - 0.63	[CI], CH, NH_3, $H_2{}^{18}O$, CO	150 / 4.0
		4G-2	0.89 – 1.10	CO, CH^+, OH^+, NH	300 / 4.0
		4G-3	1.25 – 1.52	[NII], CO series, OD, SH, H_2D^+	600 / 3.3
		4G-4	2.49 – 2.60	$^{(18)}OH(^2\Pi_{3/2})$	1500 / 2.0

Continuous System Upgrades

The modular design allowed for short technological turn-arounds, keeping GREAT at performance/scientific forefronts.

On component level, since commissioning in 2011 we had

- upgraded all our HEB mixers, resulting in much improved noise temperatures and wider IF bandwidth (HEB roll-off)§
- improved all local oscillator sources (and related, the common optics): more output power, wider tuning range, more reliable operation.
- replaced all back-ends with monolithic (digital FFT) spectrometers
- added new science opportunities by opening more sky frequencies (a.o. HeH^+, OI145µm, hydrides/ground-state transitions: NH_3, $H_2{}^{18}O$, HDO)
- enhanced mapping efficiency by introducing multi-pixel arrays of upGREAT
- simultaneous observation at up to 5 frequencies (4GREAT with HFA)

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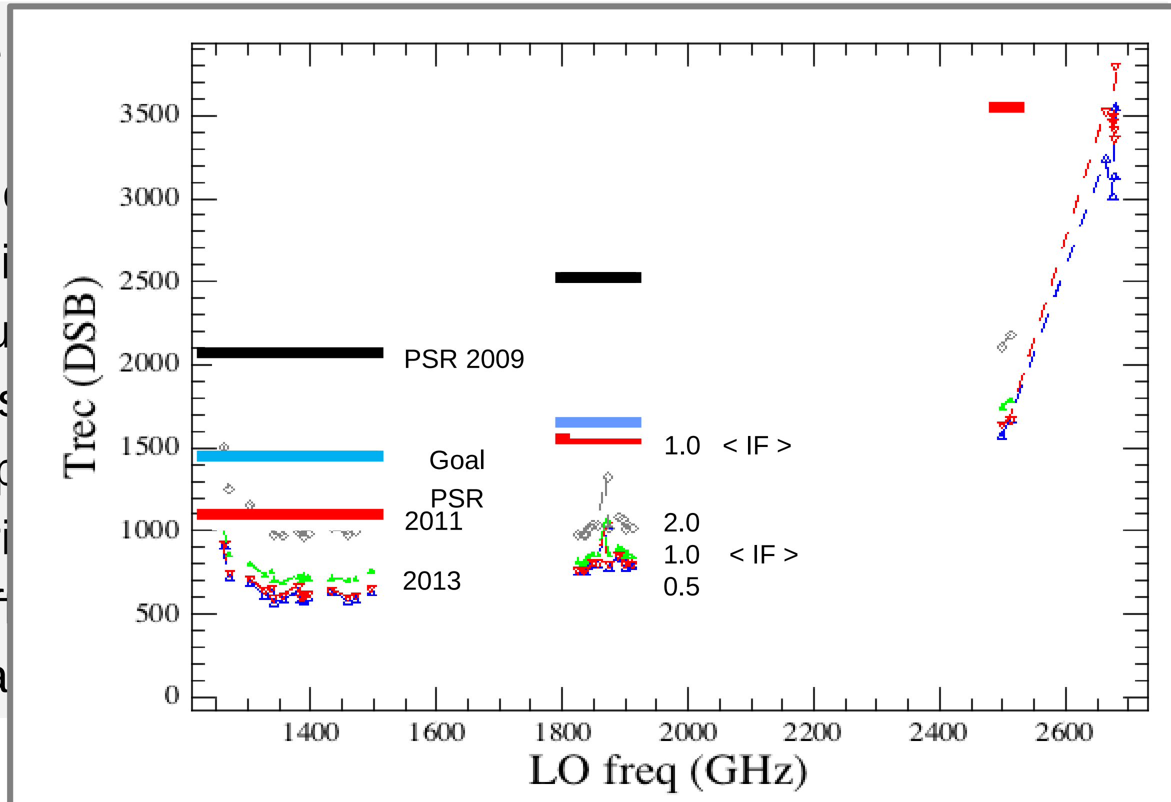

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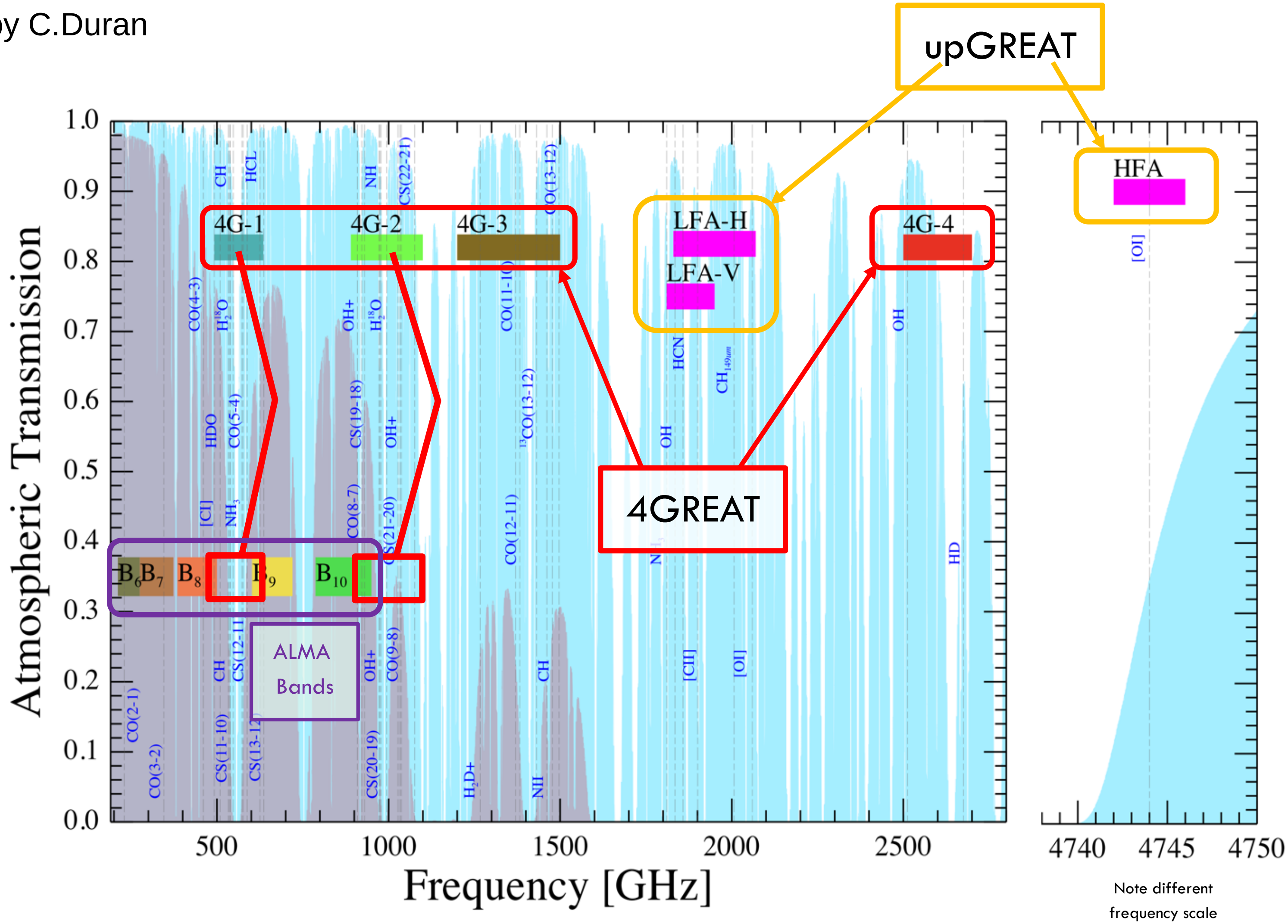
GREAT „final" configuration

MPIfR
KOSMA
MPS
DLR-Pf

Compiled by C.Duran



Atmospheric transmission for SOFIA (43.000 ft, 10 um) and ALMA (5000 m, 200 um).

GREAT – Mission Assurance

MPIfR
KOSMA
MPS
DLR-Pf

GREAT operated cutting edge technologies, which offered novel science opportunities at the risk of instrument failures and potential loss of science.

- novel operation requirements (like the first airborne operation of a closed-cycle compressor)
- fatique of sensitive components due to numerous cryo cycles (mixers, HEMTs)
- limited lifetime of high-frequency solid-state local oscillators (unique pieces of hardware)

Risk mitigation as **PI-class instrument**:

- Operation in service mode only (by experts, with verified observing scripts)
- new critical instrument developments were made available to the communities only after successful (delta)commissioning, otherwise operated „shared risk“
- modular design allowed for flexible response if needed, swap against spare components
  - ressource-limited, for all critical components spares were help in reserve
  - critical spares were also carried on deployments (which safed a few NZ flights)
  - response time was short because developers were also supporting the science flights [GREAT goal was to cover all critical instrument elements by qualified personnel in-flight].
- calibration and data validation was performed by the GREAT consortium

With these measures in place the operation of GREAT was highly reliable (success rate >95%)! Needless to remind that such high-risk operation is possible on manned platforms only

GREAT – Missed Opportunities

The surprising termination of SOFIA not only ended the operation of GREAT as presented here - it also rendered obsolete extensions that had already been initiated.

- the possibility of adding - with time - more sky frequency bands to the (4)GREAT has been a design driver to its modularity. There are several science-driven opportunities that will now be lost:
  - Search for HD (2.67 THz) has always been sensitivity-limited (paucity of LO power). After years of iterative developments with Virginia Diodes, during our last mission, in 07/22, we finally detected HD in Jupiter‘s atmosphere (Wiesemeyer et al. submitted)
  - A very promising (QCL-LO & HEB mixer) development to support velocity-resolved spectroscopy of the 10.7 THz ground-state transition of molecular hydrogen (H_2) is now going nowhere…
- the most obvious, cost-effective extension of upGREAT/HFA would have been to add the second polarization, thereby enhancing the mapping speed by factor of 2.
  - The instrument design did allow for this extension to then 14 pixels, much of the (cryo) harness was prepared. The extension was suspended in view of the dubious intentions of the agencies

GREAT – Final Assessment

For the GREAT consorts developing and operation of GREAT on SOFIA has been a fantastic journey – that will not be repeated.

Set-up as PI instrument we see as causal for the success of the mission

- Consorts had full control on design and build of the instrument, defined by the science interests of the consortium (within boundaries given by agencies, e.g. airworthiness)
- Operation in service mode only, and responsibility for calibration and validation of science data ensured highest data quality with timely release
- Flexibility for system modifications and upgrades as technology allowed
- Compensation by guaranteed observing time as invaluable benefit§

(but) at the price of

- high and unsecured investments w/ science return at discretion of agency

Set-up allowed GREAT a considerable degree of independence in the operation of the instrument, ultimately to the scientific benefit of all

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GT made possible experiments that otherwise (in "facility mode“) would have been difficult (likely impossible) to carry out:
The detection of HeH^+ (NGC7027) and HD (Jupiter) are just two examples of dedicated experiments that only the PI team could perform successfully

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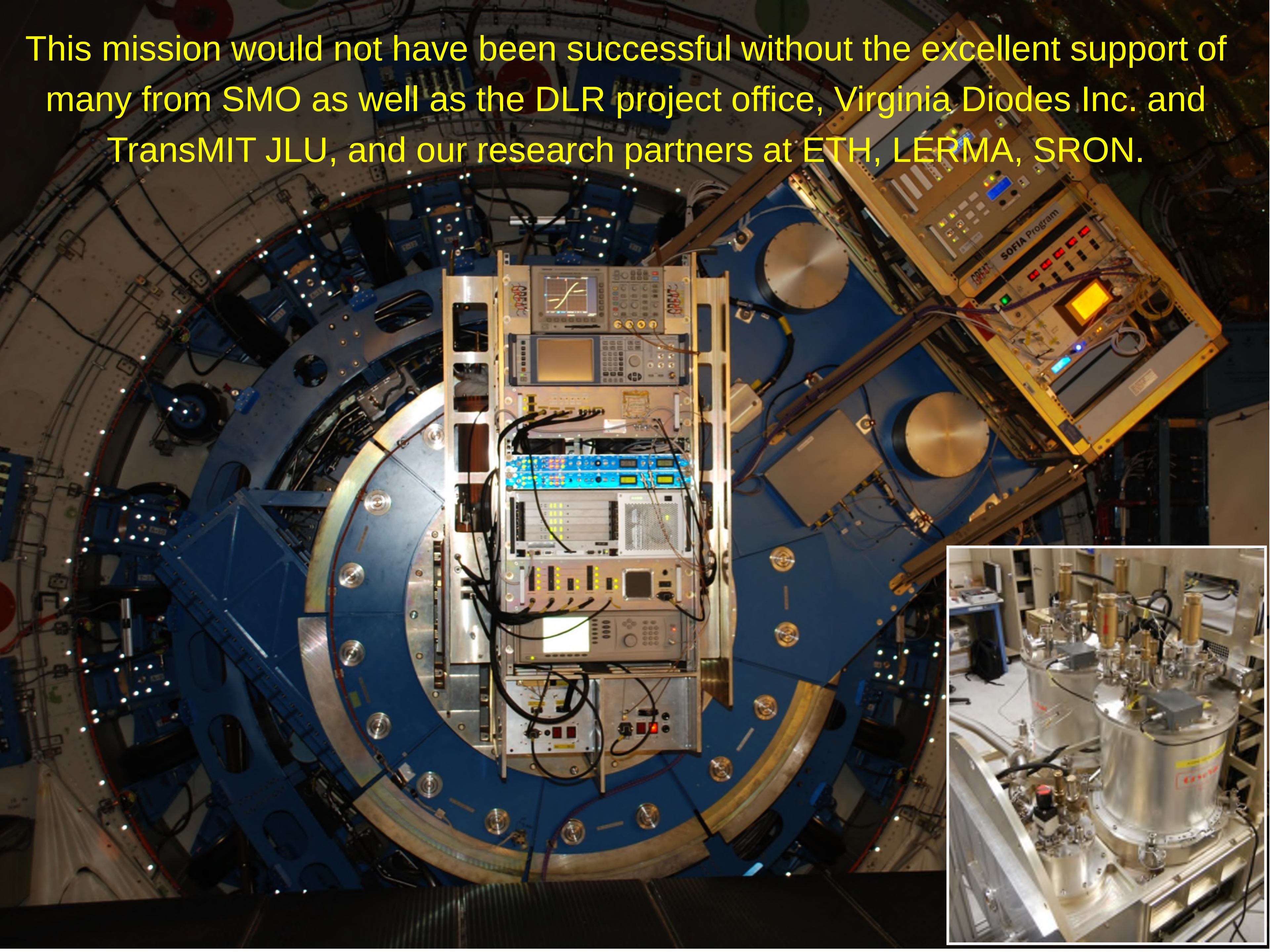
This mission would not have been successful without the excellent support of many from SMO as well as the DLR project office, Virginia Diodes Inc. and TransMIT JLU, and our research partners at ETH, LERMA, SRON.