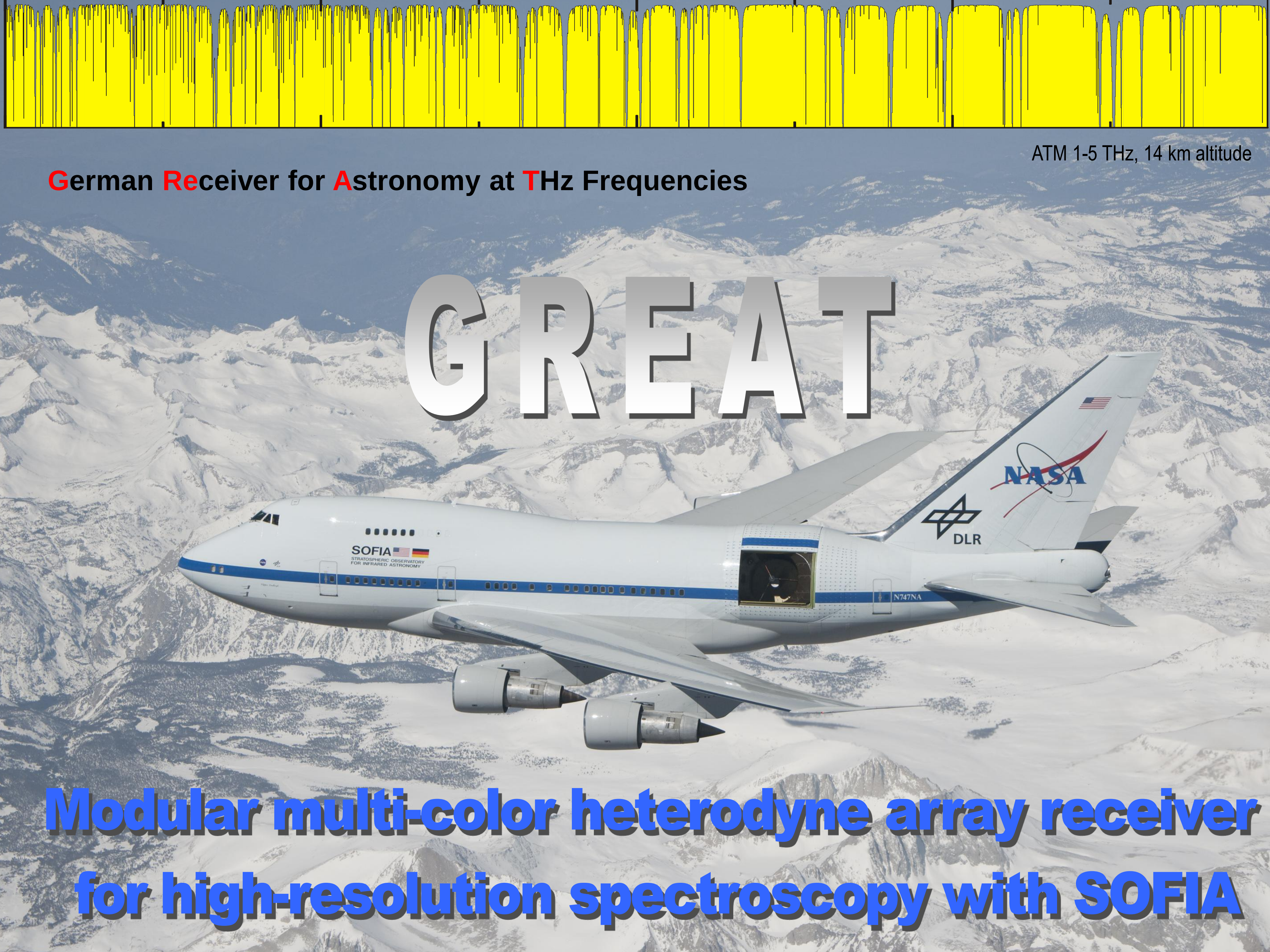
ATM 1-5 THz, 14 km altitude
German Receiver for Astronomy at THz Frequencies
GREAT
NASA
DLR
SOFIA
STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY
N747NA
Modular multi-color heterodyne array receiver
for high-resolution spectroscopy with SOFIA

Introduction: the SOFIA mission

- Herschel & SOFIA mark a *gold-rush* decade for FIR astronomy
- While the operation of Herschel was fuel-limited to 3 yrs, NASA/DLR had committed to a 20 yrs operational lifetime for SOFIA
- Due to serious delays SOFIA took-off only after launch of Herschel
  - First-light science flight 2010
  - full flight capability (100 flights/yr) only in 2014
- In a much disputed & controversial process the agencies decided to retire operation in 09/2022 (after ≈ 800 science flights).

What made SOFIA/GREAT special ?

- At flight altitude access to FIR largely above the influence of Earth's atmosphere (in particular, for high-resolution spectroscopy)
  - except for transitions near telluric lines (ozone, water): $H_2{}^{16}O$, HD, (OI 63)
- “Mercy of the late take-off”: GREAT could
  - build on the technologies & experience developed for Herschel, and
  - take advantage of the rapid progress in THz technologies during the last 2 decades
- Direct access to platform and modular design enabled continuous improvements of the instruments in line with technological progress
  - For >10 yrs GREAT operated close to technological frontiers
- The Consortium operated GREAT as Principal Investigator Instrument

  thus being largely independent of SOFIA/NASA programmatic constraints

Unlike space platforms, consider GREAT an airborne physics **experiment**

GREAT Programmatics

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 GREAT consortium.

- these investments were compensated by guaranteed observing time

Under this umbrella, the GREAT PI/consortium signed responsible for

1. specification, design and built of the instrument: reporting to DLR only, while complying with NASA defined safety requirements[$]
   ⇒ this allowed quick, (sometimes) "unconventional" responses to new technological opportunities or specific operational risks
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

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[$] NASA/DLR signed responsible for the airworthiness certification of the instrument

GREAT - the Consortium

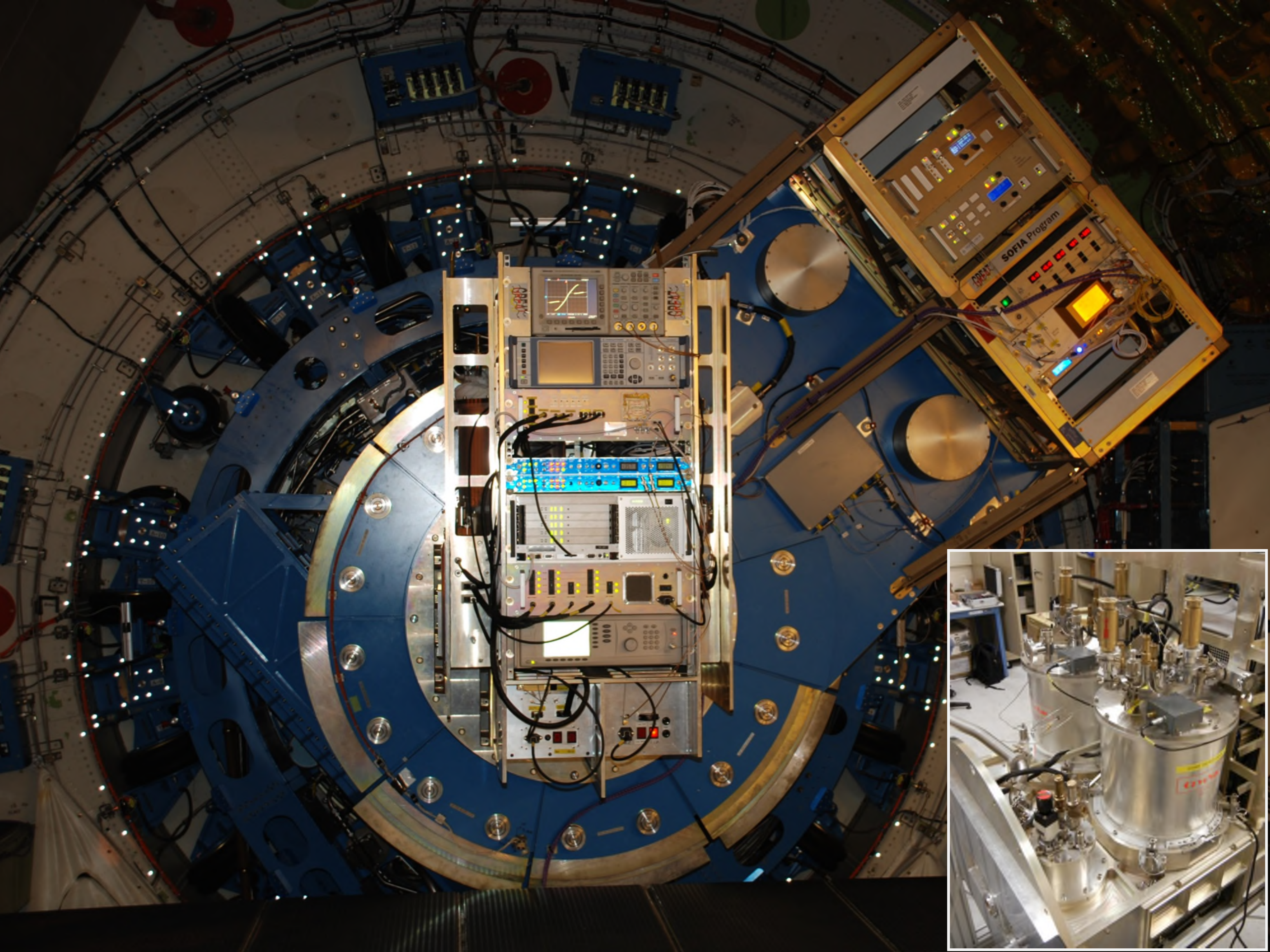
Consortium established in 1998, in response to DLR's call for instrument proposals.

Over the years the project has attracted many exceptionally talented engineers and scientists, whose 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, N.Honigh (HEB mixers)
- DLR Optische Sensorsysteme
  - H-W. Hübers (Co-PI)
  - H. Richter† (QCL)
- MPI Sonnensystemforschung
  - P. Hartogh (Co-PI)

GREAT was quite a 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
  - all deployments (7x CHC, 2x CGN, 1x PPT)
- GREAT serviced >250 science projects, incl. 5 legacy programs
- GREAT data led so far to ~160 refereed publications (03/2025), incl.
  - 5+1 contributions to Nature & Science


SOFIA Program

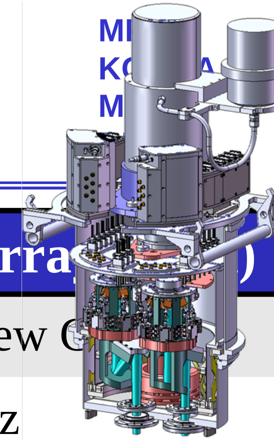
GREAT Configuration Overview

- **game changer (2017+)**: cryogenic onboard infrastructure
  - 2 *Cryomech* compressors (NASA/DLR), permanently installed, ruggedized
- allowed parallel “closed-cycle” operation of
  - 2 pulse-tube coolers (*TransMIT*) / cryostats (*Cryovac)*
- decommissiong of LHe/LN–cooled single-pixel cryostats
- 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

upGREAT – GREAT multiplexed



	Low Frequency Array (LFA)	High Frequency Arra)
RF Bandwidth	1.8-2.1 THz	4.745 THz ± a few G
IF Bandwidth	0.2-4 GHz	0.2-4 GHz
HEB technology	waveguide-based HEB NbN on Si membrane	
LO technology	solid-state chains	quantum cascade lasers
LO coupling	beamsplitter	
Array layout	1+1 x 7 pixels (H/V polarizations) hexagonal configuration pixels co-aligned	1x 7 pixels in H pol only hexagonal configuration
T_{REC} (DSB)	~600-1500K 0-4 GHz IF	~800-1800K 0-4 GHz IF
Backends	0-4 GHz with up to 64k channels	

- Sky signal from telescope split by dichroic (ν_c ≈3.6 GHz) to LFA/HFA ports
- Central pixels of sub-arrays co-aligned and to optical axis/tracker: 1(-2) arcsec
- K-mirror (and long AV) allowed efficient large-scale mapping algorithms (de-rotation on sky)

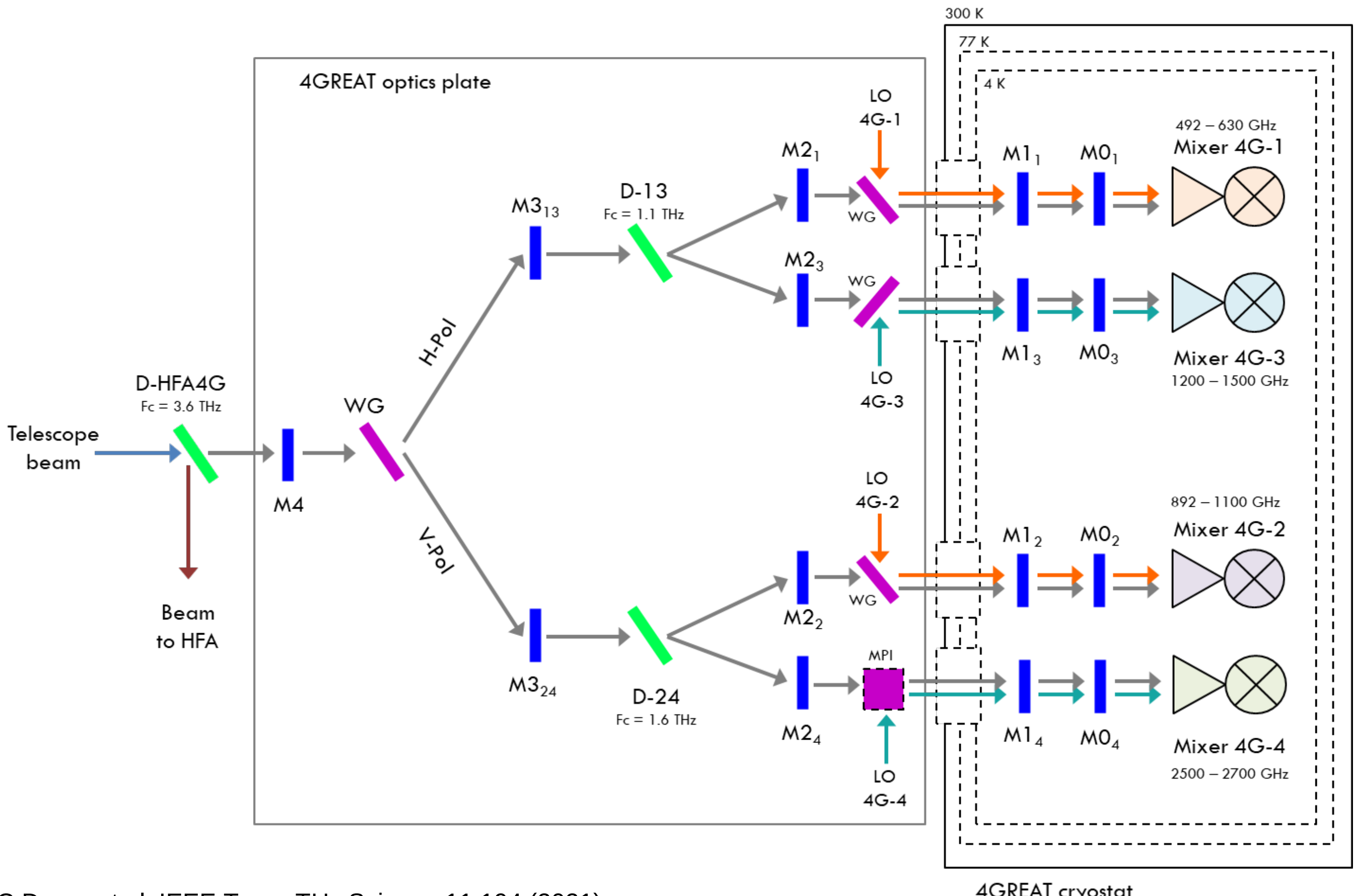
C.Risacher et al. IEEE Trans. THz Science 6,199 (2016)

Four-Color Receiver 4GREAT

MPIfR
KOSMA
MPS
DLR-Pf

After NASA terminated the development of CASIMIR: frequency-multiplexed GREAT addition

- simultaneous observations at 4+1 frequencies, all pixels co-aligned on sky
- operating HEB (0-4) and SIS (4-8 GHz; HIFI FM spare) mixers



HIFI-1 FM spare (LERMA)

HEB (KOSMA)

HIFI-3 FM spare (SRON)

HEB (KOSMA)

C.Duran et al. IEEE Trans.THz Science 11,194 (2021)

Notes on critical GREAT sub-systems: HEB & SIS mixers

MPIfR
KOSMA
MPS
DLR-Pf

- KOSMA NbN HEB for ≥1.8 THz (waveguide /tapered horn)
  - performance excellent (trade-off: noise vs. LO requirement):

    T_{Rec}: 600-800 K DSB (@ 0.5 GHz IF, measured at aperture to telescope tube)

    IF „bandwidth": 3.6 GHz (3dB roll-off)

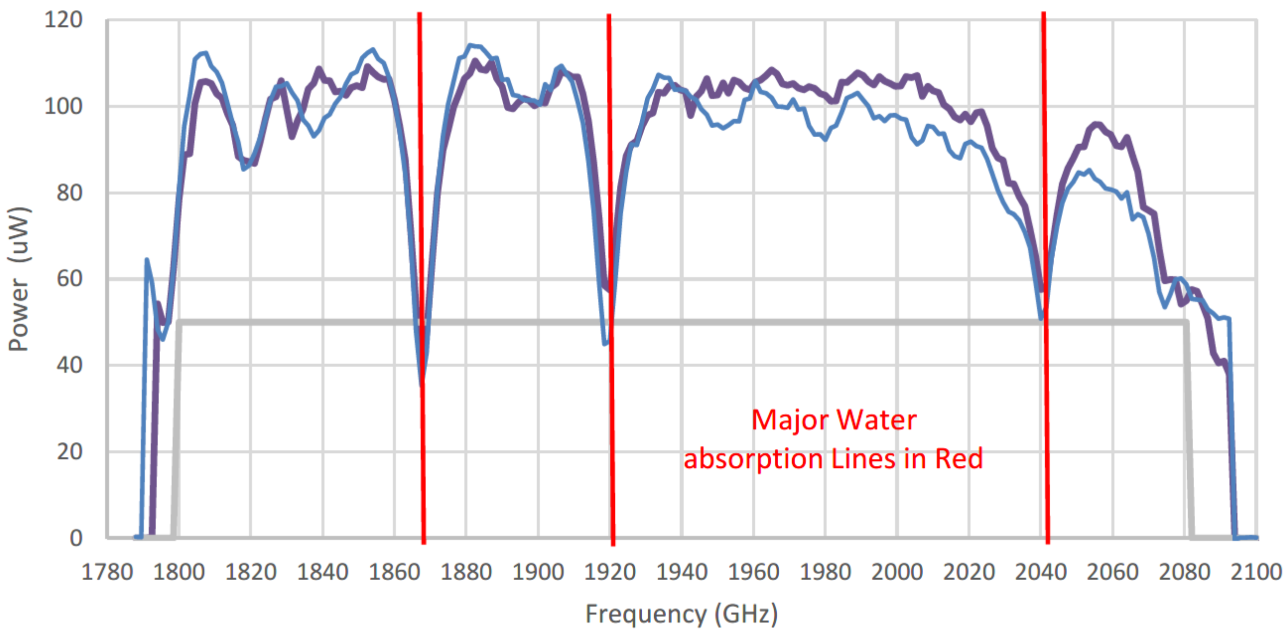
    Allan times (complete system): >100 sec ⇒ long OTF/square deg mapping
  - robust design (only 1x unit replaced, despite numerous cryo-cylces & mechanical stress) #cycles x #mixers: >10.000
  - NbN technology (HIFI, not our devices) space qualified for Herschel
- KOSMA NbTiN HEB for 4GREAT band 3 (1.24-1.53 THz)

  T_{Rec}: 750 K DSB, but roll-off at 2.6 GHz
- SIS (HIFI spares/QM from Lerma, SRON):
  - no new development, performance as demonstrated in HIFI
  - no issues during operation of 4GREAT

Critical GREAT sub-systems: Local Oscillators I

MPIfR
KOSMA
MPS
DLR-Pf

- solid-state cascading multipliers (frequencies up to 2.7 THz)
  - series of development contracts with VDI (MPIfR, NASA 2021+)
  - amazing improvements during last 2 decades (bandwidth, power)
  - 2022: 80-100 µW with 13% RF tuning bandwidth !



The „last“ and best GREAT LO from VdI (2022, NASA) was never flown.
RF bandwidth was defined by NH_3(3-2) and OI 145µm

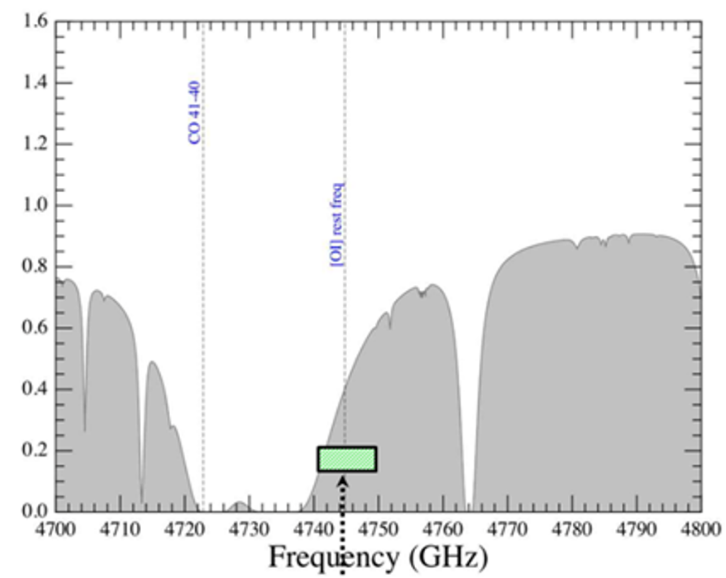
Critical GREAT sub-systems: Local Oscillators II

MPIfR
KOSMA
MPS
DLR-Pf

Quantum-cascade lasers for the HFA (4.745 THz)

- two sucessful, parallel developments (both units flew with GREAT)
  - (DLR Optical Sensor Systems, KOSMA with ETH)
- operation temperature 40-70 K provided by Stirling cooler (Ricor, CryoTel GT)
- RF frequency tunability [GHz]: -1.5 to +6.5 (B), -2.5 to +2.9 (K) @ OI63 µm
- QCL „free running“ (temperature & current stabilized):
  - jitter < 1 MHz, drift: 1 (to a few) MHz
  - GREAT: „astronomical locking“ to telluric OI
  - mitigation: phase-locking on reference signal
- LO output: a few mW !!

- operation very reliable, no loss of hardware
- no space heritage



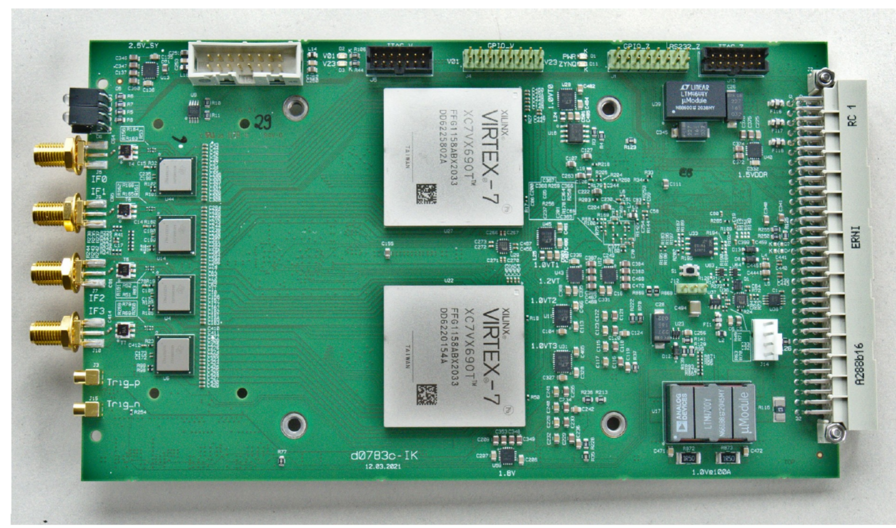
Critical GREAT sub-systems: digital back-ends

GREAT used wideband IF processors and back-ends

- 21 FFT spectrometers with 4 GHz of instantaneous bandwidth
- providing 32k (64k opt.) channels per 4 GHz (ENBW 142 kHz)
  - adequate for 0.1 km/s spectral resolution at 4GREAT lower band edge
- very reliable operation, zero loss of hardware during mission
- no (known) space heritage, power budget might be concern (?)

Bernd's latest board (post-SOFIA)

- bandwidth: 4 x 4.0 GHz
- IF input: 0-4 and 4-8 GHz, selectable
- ENBW: 142 (71 optional) kHz,
- clean spectral response
- power consumption: 90 W



Thijs: Lessons learned ?

For future space (het) mission: what can be learned from SOFIA/GREAT ?
I'm afraid, not so much…

\+ proof of technologies (building on & extending Herschel heritage)

But otherwise, design drivers for airborne SOFIA were rather different

- GREAT operated as PI-class instrument – unthinkable for space mission
- access to the instrument suggested a modular design, which then enabled rapid implementation of the latest technologies
  - fair to state: SOFIA's 2nd generation instruments were the most successful in suite
- design envelopes (power, mass, volume) were rather comfortable…
- agencies responsible for safety, but mission assurance ensured by consortium

Quite obviously,

Our approach on GREAT as airborne physics experiment is not transferable

Missed Opportunities

- Large(r)-scale mapping become possible with the upGREAT arrays (>10x HIFI).
  - actually performed coverage in various legacy programs: several deg^2
  - but mapping a significant fraction of the galactic [CII] emission was in reach

  dedicating one SOFIA flight year to upGREAT [CII] mapping, would have allowed to observe ca. 30 deg^2 with unprecedented sensitivity (Nyquist sampling the 14.1“ beam): with ~1 K T_{mb} rms (at 1 km/s spectral resolution).

    - clearly a missed opportunity (at a fraction of the cost of a space mission)

- Another lost opportunity was our futile attempt on velocity-resolved HD (2.67 THz)

  The experiment was sensitivity-limited (HEB underpumped due to paucity of LO power).

  When, after years of iterative developments with Virginia Diodes, a suitable LO source became available in 07/22 (⇒ HD detection in Jupiter‘s atmosphere; Wiesemeyer poster)

    - the irrational termination of the project made follow-up impossible


All 235 SOFIA/GREAT flights © DSI
Thank you for your interest
in SOFIA/GREAT
2000 km
1000 mi