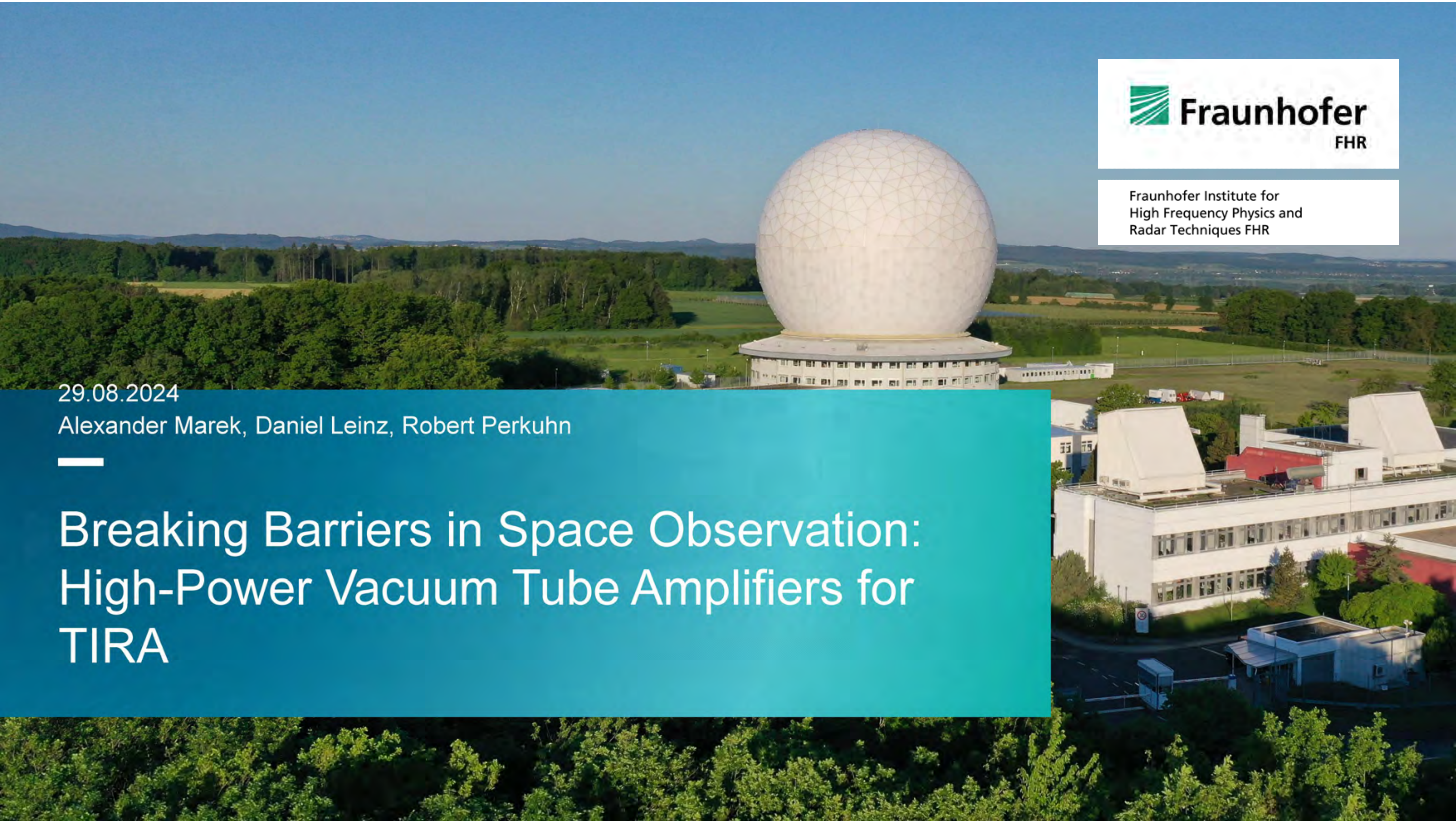

29.08.2024

Alexander Marek, Daniel Leinz, Robert Perkuhn

Breaking Barriers in Space Observation: High-Power Vacuum Tube Amplifiers for TIRA

Fraunhofer FHR

Fraunhofer Institute for
High Frequency Physics and
Radar Techniques FHR

Fraunhofer FHR at a Glance

Tailored solutions for radar systems and electromagnetic sensors – since 1957

- System designs and demonstrators for new radar applications
- Signal processing and imaging methods
- Technology consulting
- Capabilities for measurement, HPC, etc.
- Staff: 386 (2022)

Locations

- Main location: Wachtberg
- Other locations, Networking with Universities

Tracking and Imaging Radar (TIRA)
Overview

- Parabolic antenna
  - Diameter / Weight: 34 m / 240 t
  - System covered by 47.5 m radome
  - Pointing accuracy: 5 cm at a distance of 1000 m
  - Rotational speed: 24° / s (360° in 15 s)
- L-Band Tracking Radar
  - Frequency: 1.33 GHz
  - Detection sensitivity: 2 cm in 1,000 km
- Ku-Band Imaging Radar
  - Frequency: 16.7 GHz
  - Image resolution: < 20 cm

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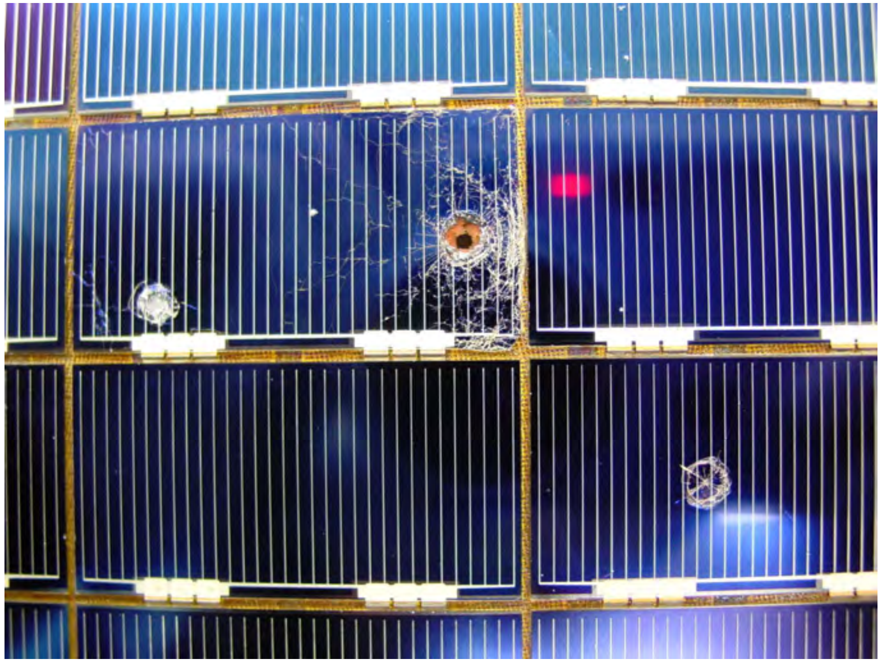
Why do we need Space Observation Radars like TIRA
Space Debris

“Ever since the start of the space age there has been more space debris in orbit than operational satellites”
(First sentence in the ESA’S ANNUAL SPACE ENVIRONMENT REPORT 2024)



Impact holes in the solar panel of the HUBBLE telescope ©ESA

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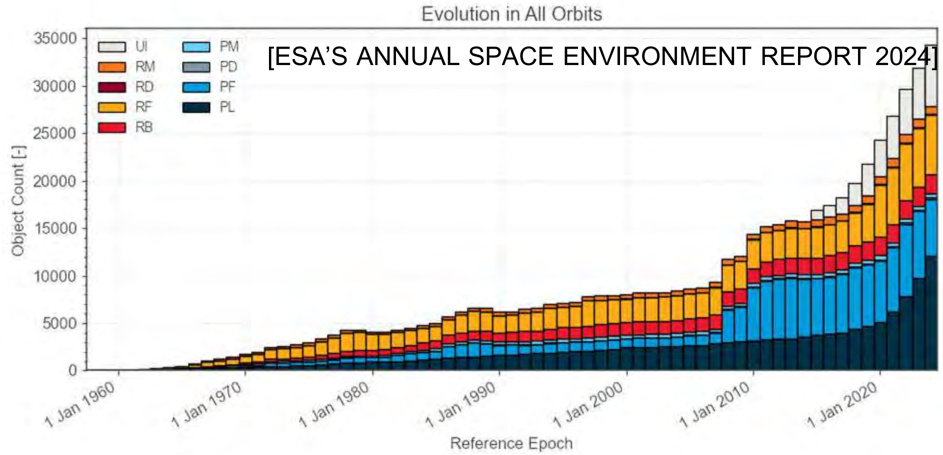
Space Debris

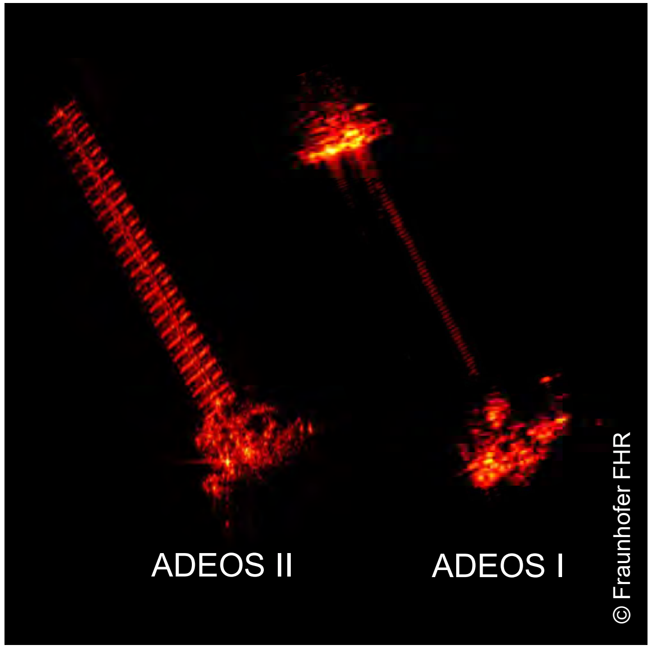
- ~ 75% of the catalogued objects are in the LEO region (altitude 200 – 2.000 km)
- ~ 9% of the catalogued objects are in the GEO region (altitude 36.000 km)
- 700.000 non-trackable objects > 1 cm
  Detectable only with powerful sensors, e.g. TIRA

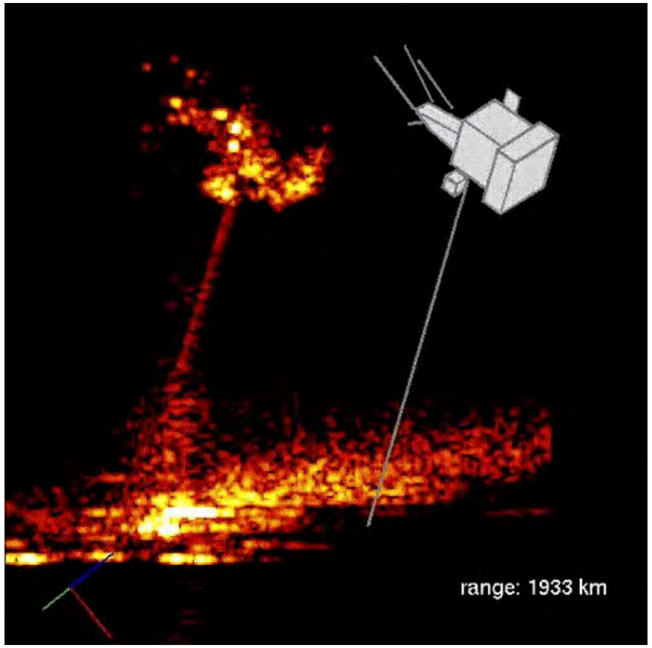
TIRA & space debris

- Searching and tracking of space objects (orbit determination)
- Characterization
- Validation of space-debris models
- Tracking re-entering (risk) objects
- Supporting de-orbiting operations
- Radar measurements of meteoroid streams



Tracking and Imaging Radar (TIRA)
Damage analysis: ADEOS I + ADEOS II



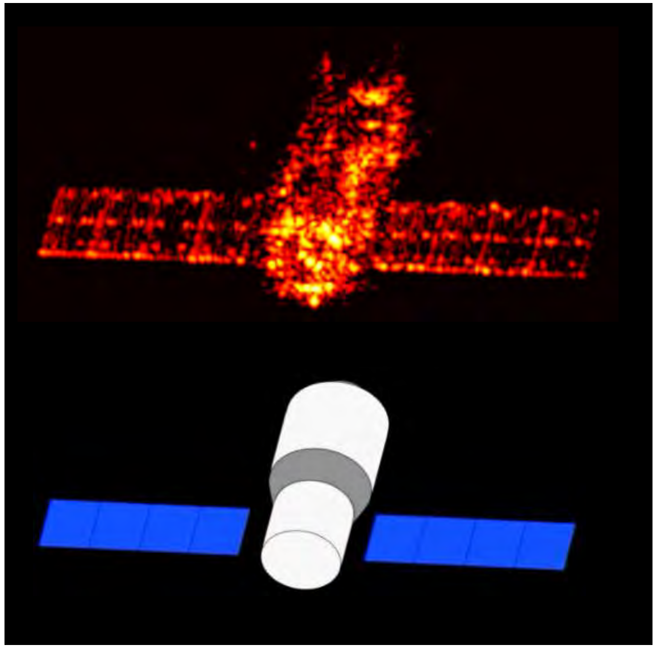


- Damage analysis:
  The solar panel of ADEOS I is torn down. (1997)

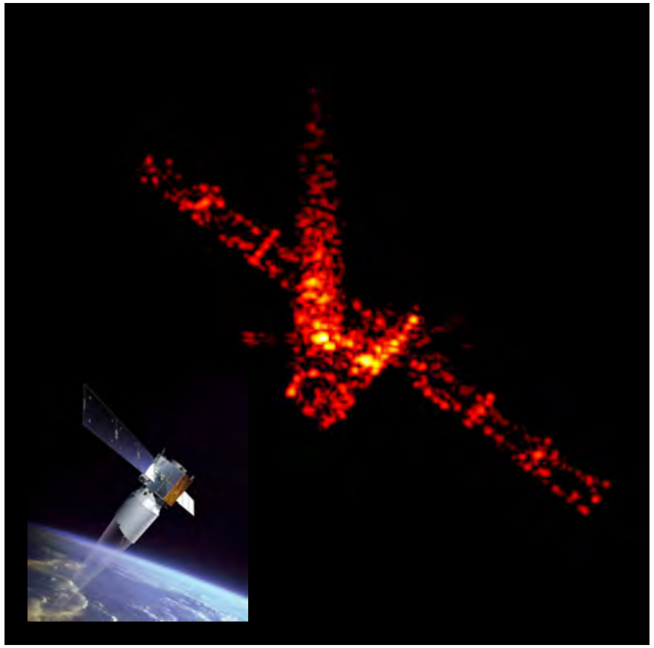
Tracking and Imaging Radar (TIRA)

Examples of ISAR images

- Space debris attitude analysis (in-orbit tumbling analysis): ENVISAT went out of control (2012) and started tumbling



- Atmospheric re-entry analysis: Predictions of time and location of the re-entry of the Chinese space station Tiangong-1 (2018)



- Re-entry support of ESA satellite Aeolos (2023): The vertical reflections in the center are not real, but originate from multiple reflections in a telescope chamber.

L-Band Tracking Radar
Overview

Radar characteristics

- Frequency: 1.33 GHz
- Power: up to 1.5 MW
- Antenna gain: 50 dB
- Beam width 0.49° (8.6 km at R = 1000 km)

Tracking

- 4-horn monopulse system for tracking
- Single-pulse sensitivity 2 cm at range R = 1000 km

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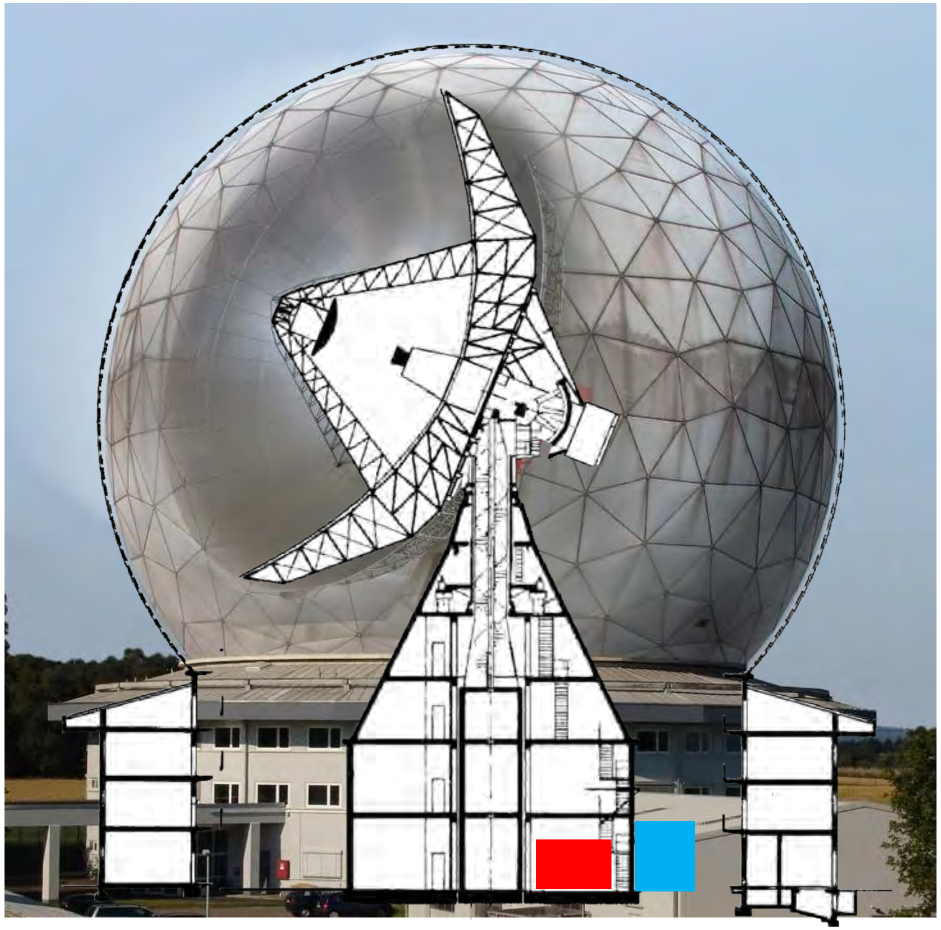
L-Band Tracking Radar
Power Amplifier & Modulator

5-cavity klystron from Thales

- RF pulse output power: ≤ 2 MW
- Gain: 42.4 dB
- Efficiency: 39 %
- Beam Voltage: ≤ 96 kV
- Beam Current: ≤ 58 A
- Weight: 240 kg

Modulator from Research Instruments

- Modulator type: Hard-tube, capacitor-/transformer-coupled
- Switching device: 4x IGCT in series
- HV power supply: 300 kW, DC
- Capacitor bank: 6400 µF



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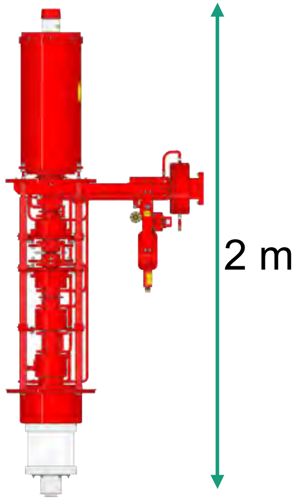

Ku-Band Imaging Radar
Overview

Radar characteristics
- Frequency: 16.7 GHz
- Power: up to 10 kW
- Antenna gain: 73 dB
- Beam width 0.031° (540 m at R = 1000 km)

Imaging
- Coherent, wide-band, LFM-chirp pulse radar
- ISAR
- Image resolution: < 20 cm
- Guided by the tracking radar

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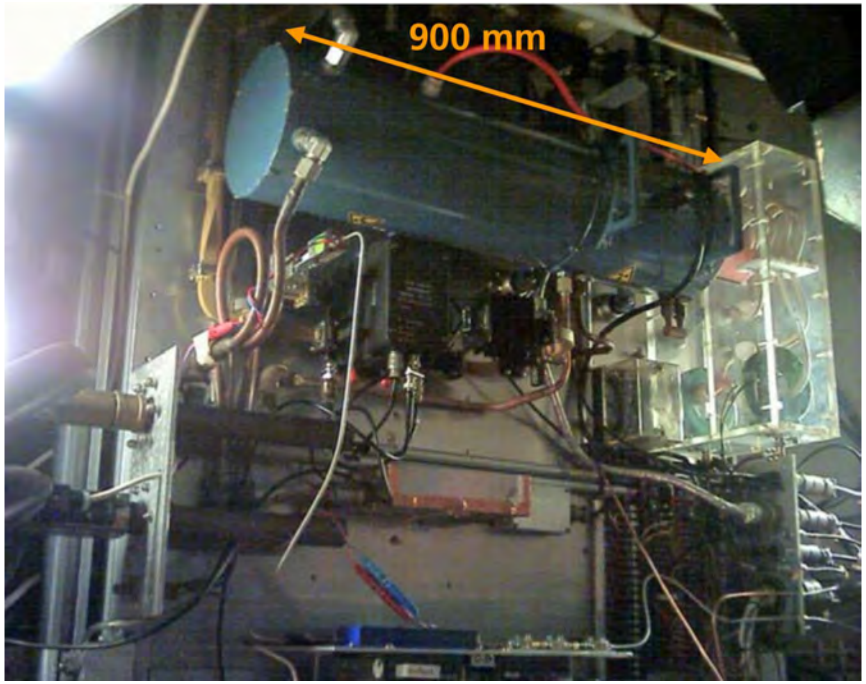
Ku-Band Imaging Radar
Power Amplifiers & Modulator

Traveling Wave Tube (TWT) from Hughes Electronics
- RF pulse output power: ≤ 10 kW
- Gain: 33 dB
- Beam Voltage: ≤ 30 kV
- Beam Current: ≤ 3.5 A
- Weight: 30 kg

Modulator
- Modulator type: Hard-tube, Floating-deck
- Integrated into the antenna pedestal



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Ka-Band Upgrade
Overview

Klemens Letsch at the
3rd ITG International Vacuum Electronics Workshop 2012:
"*Also for the Ku-band transmitter a mid-term upgrade may be necessary resp. a new imaging radar with a higher transmit frequency (e.g. Ka-band) utilizing a larger bandwidth*"

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Radar characteristics

- Frequency: 35 GHz
- Antenna gain: 80 dB
- Beam width 0.016° (280 m at R = 1000 km)

Imaging & Tracking

- Multi-mode tracking
- Full polarimetric

Replacing the Ku-band system

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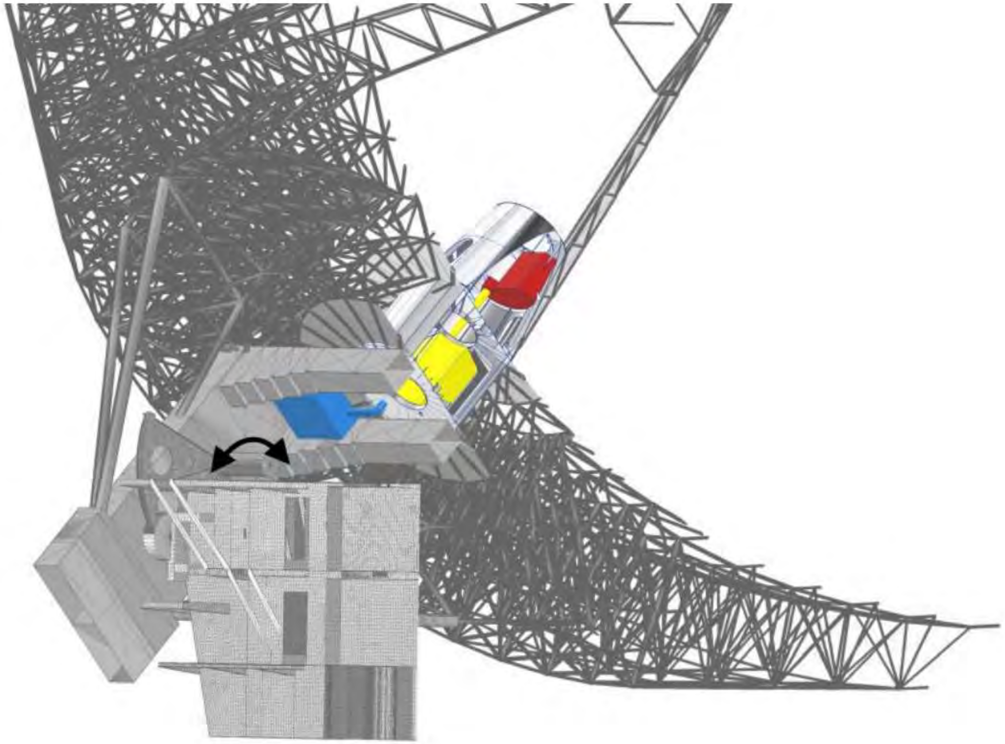
Ka-Band Imaging Radar
Power Amplifiers & Modulator

Traveling Wave Tube (TWT) from CPI

- Best commercial available broadband high-power amplifier
- 2 amplifiers → power combining
- Weight: Heavy magnets (300 kg)

Modulator from AMPEGON

- Integrated into the antenna and pedestal
- Optimized for low weight
- Supports position change during the movement of the antenna



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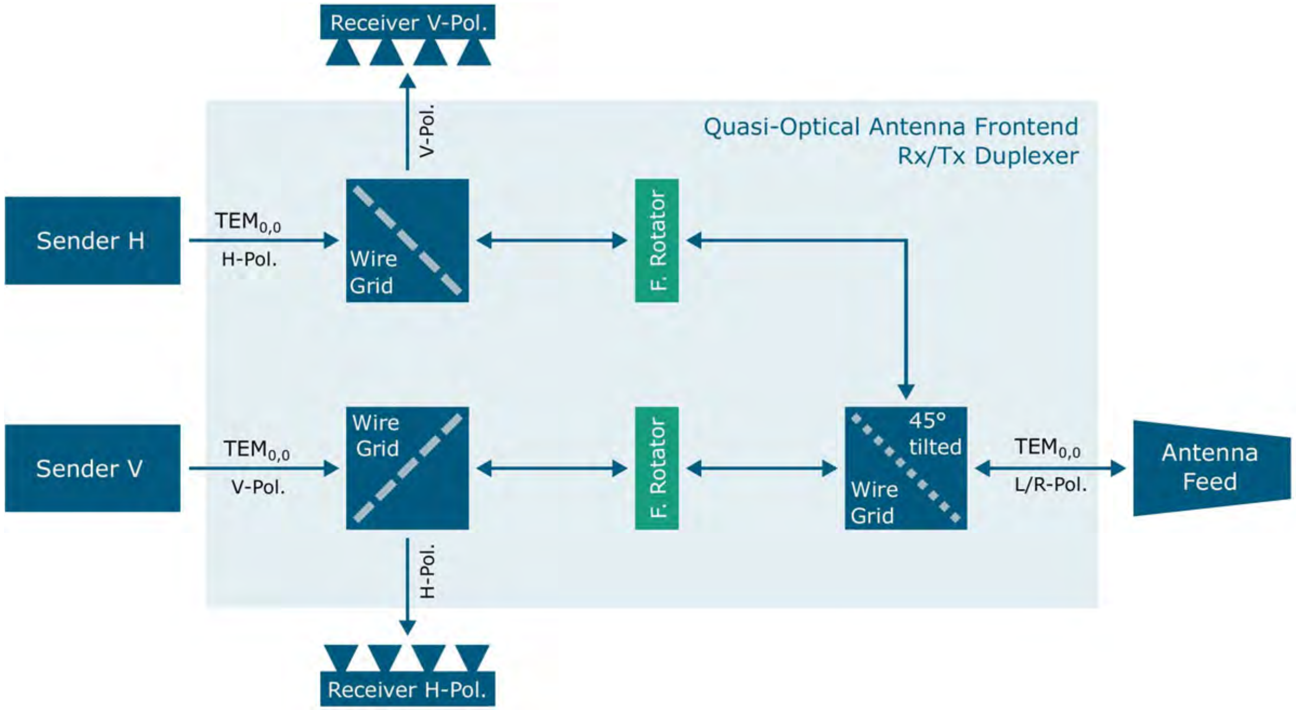
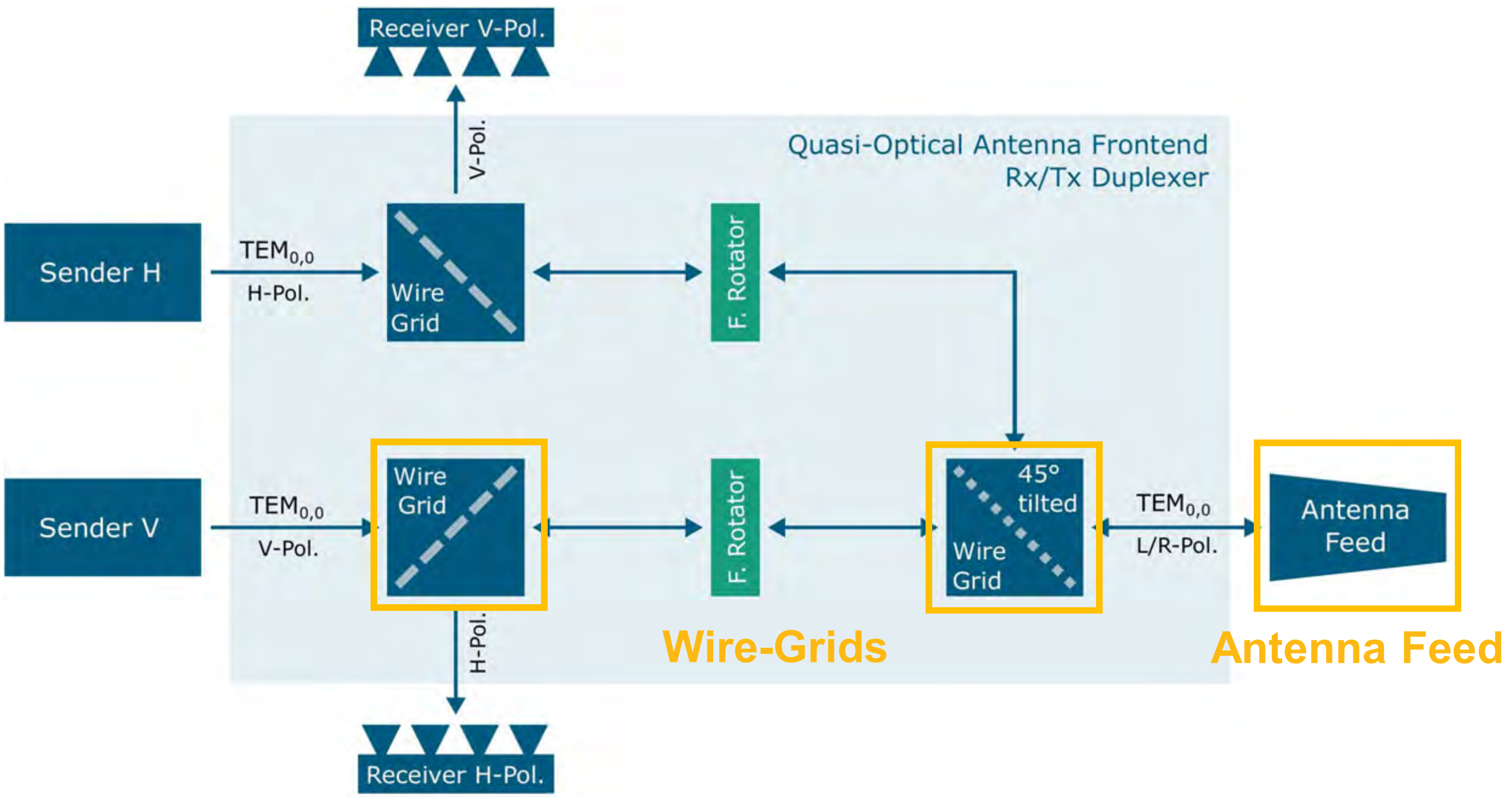
Quasi-Optical Antenna Frontend
Overview

- Transmits the RF power from the amplifiers to the antenna
- Implements a duplexer that separates the high-power Tx signal from the low-power Rx signal
- Q.O. transmission
  - Minimal losses
  - Highest power capabilities
  - Broad bandwidth
  - High isolation between the Tx and Rx channels
- Supports propagation of higher-order TEM modes (multimode tracking)
- Freely selectable Tx polarization



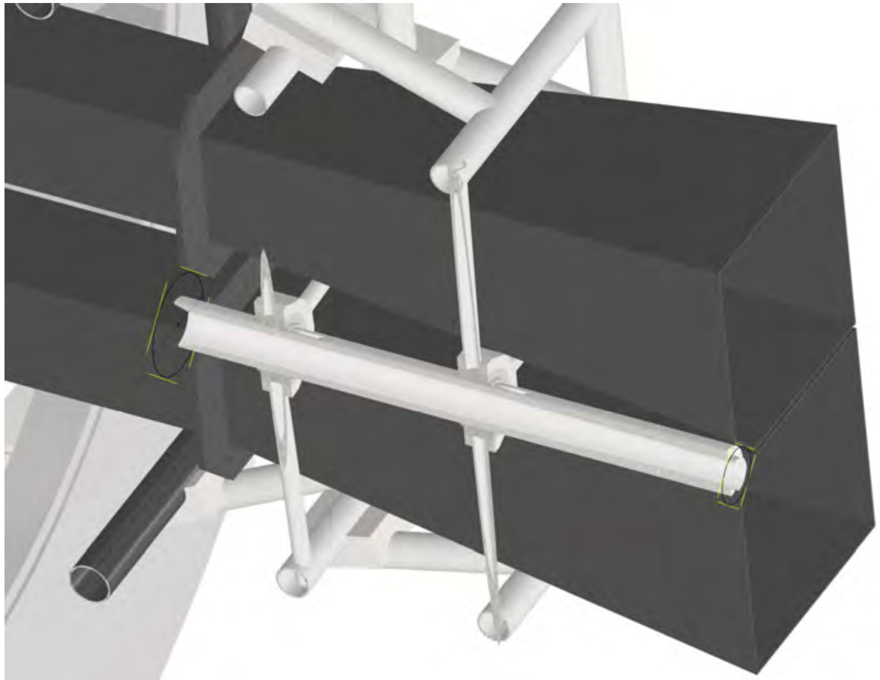
Quasi-Optical Antenna Frontend



Antenna Feed
Oversized Corrugated Circular Waveguide

- Installation of the Ka-band antenna feed between the L-band monopulse horns
  → limited space

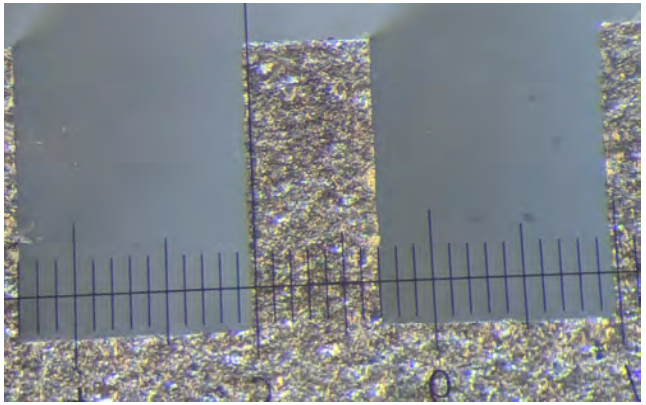
- Overmoded corrugated waveguide as antenna feed
  - Low attenuation
  - High power capability
  - Broad bandwidth
  - Support of higher order modes (multimode tracking)
  - Efficient coupling to the antenna (72% antenna efficiency)

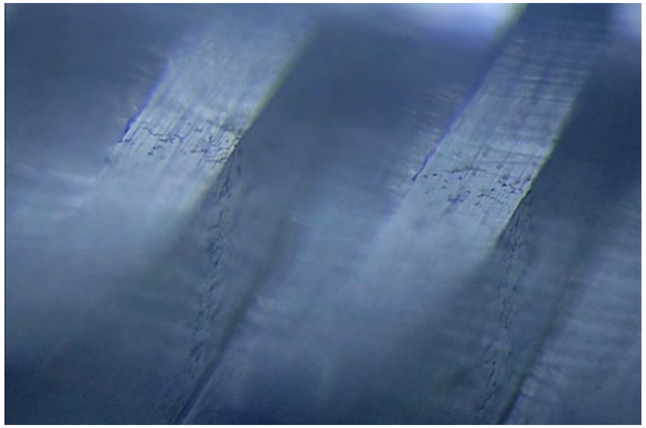


Antenna Feed
Manufacturing

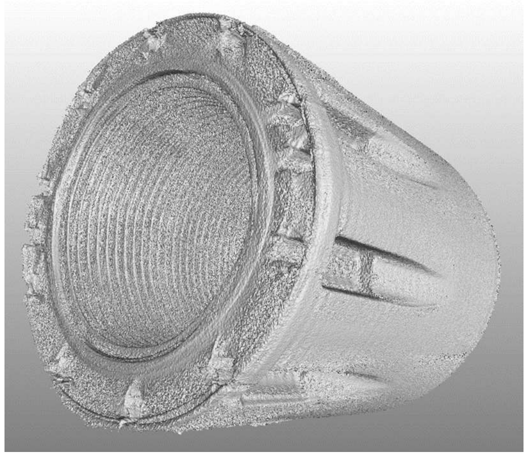
- Production in the FHR workshop
- Direct CNC milling of the corrugated waveguide
- Milling inner radius on the lathe
- Milling corrugations on the CNC
- Max waveguide length of 25 cm
  → Antenna feed consists of 3 sections

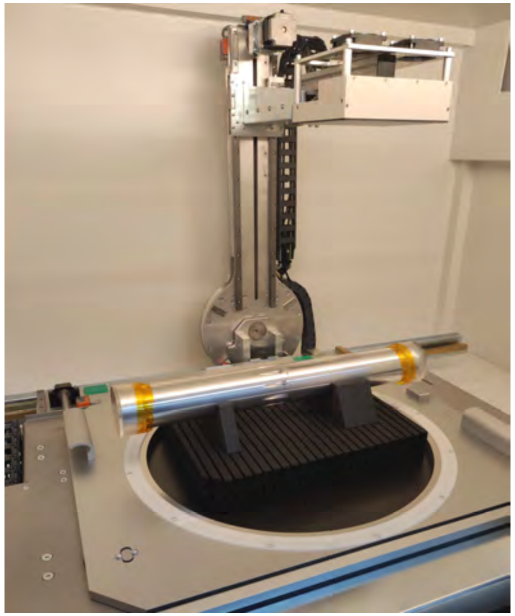
Antenna Feed
Mechanical Measurements

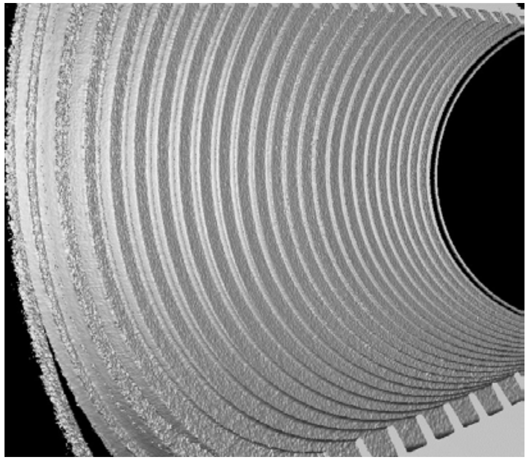


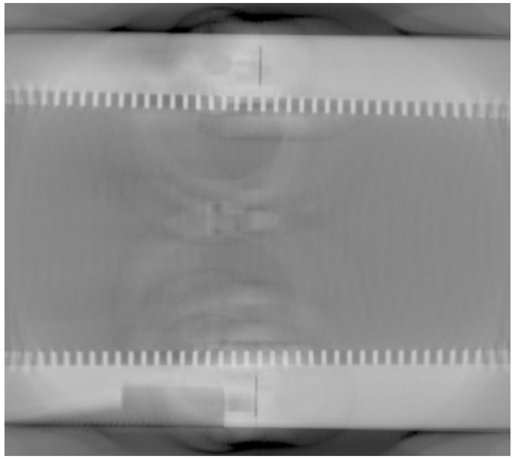


CT measurements









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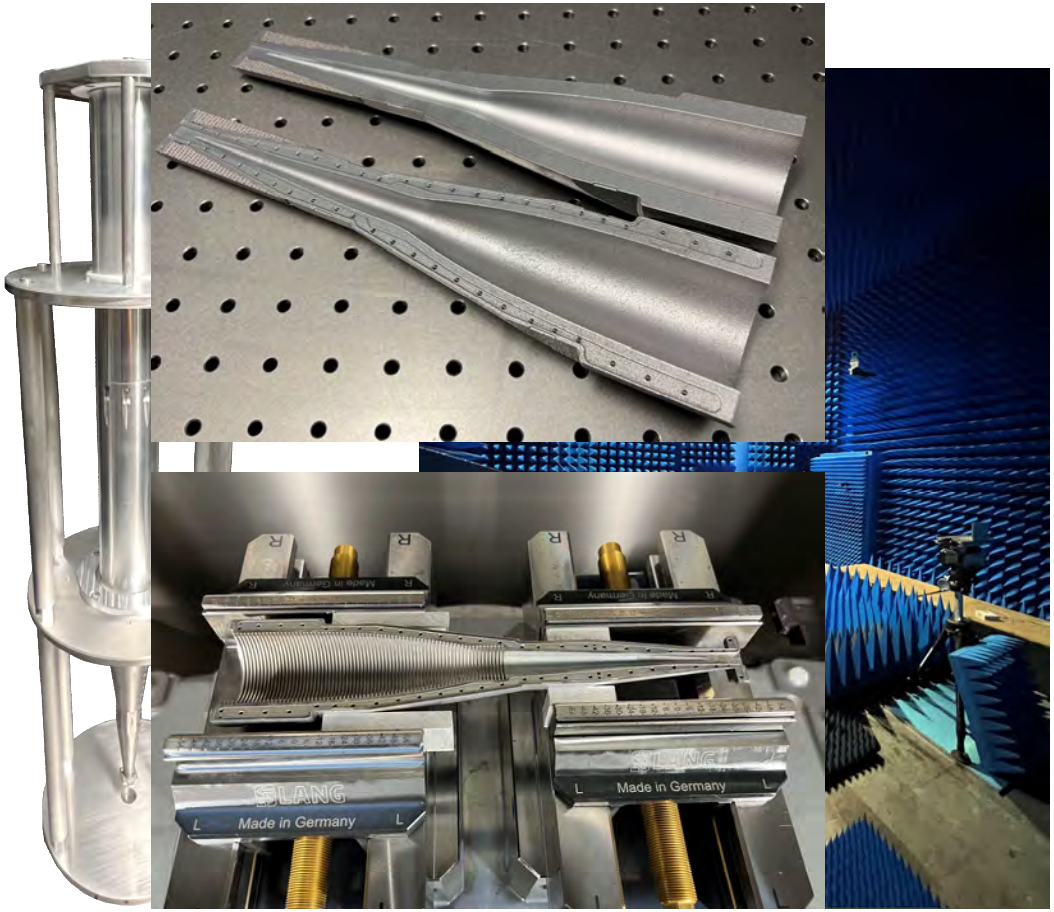
Antenna Feed
RF Measurements

- Measurement of the far-field pattern in one of the FHR antenna measurement chambers
- Reconstruction of the HE/EH mode content at the antenna feed aperture

- Input: $TE_{1,1}$-$HE_{1,1}$ mode converter
- Innovative hybrid manufacturing method
  - 3D printing in metal
  - Finishing work on the CNC milling machine



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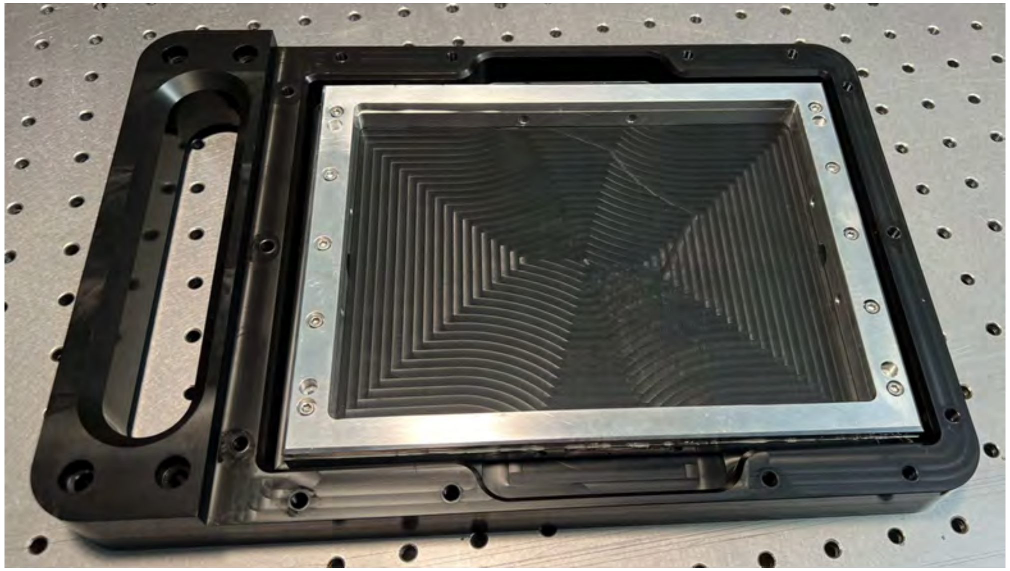
Wire-Grids

- Wires
  - Material: tungston
  - Diameter: 50 µm
- Periodicity: 400 µm

→ Fill factor: 0.125
→ Reflection path: $|T|^2 = -24.2\ \mathrm{dB}$
→ Transmission path: $|R|^2 = -48.4\ \mathrm{dB}$

- Manufactured at the FHR workshop



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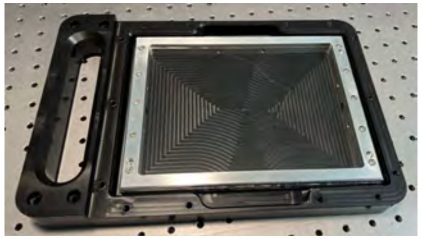

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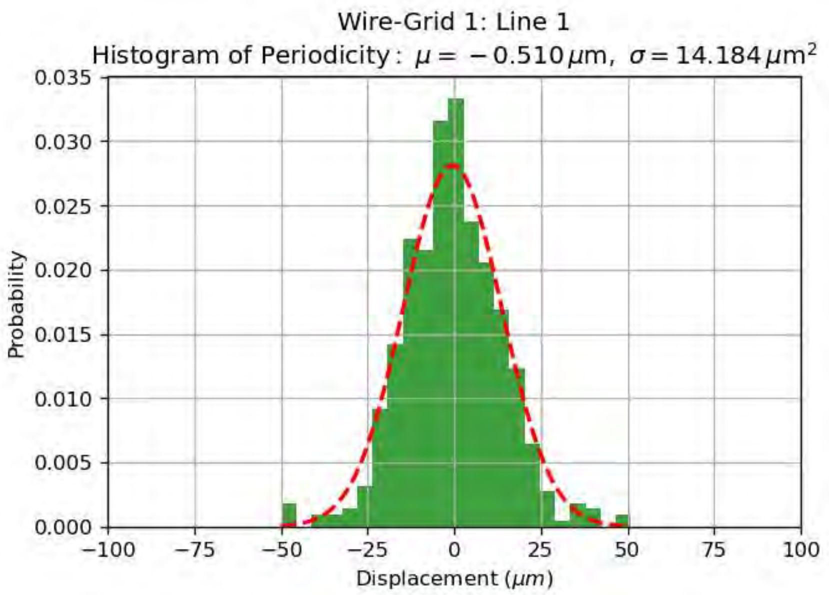

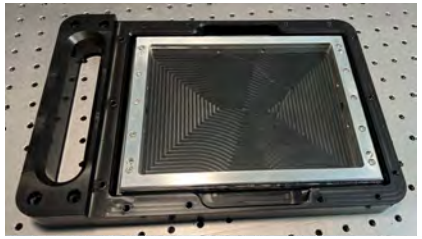

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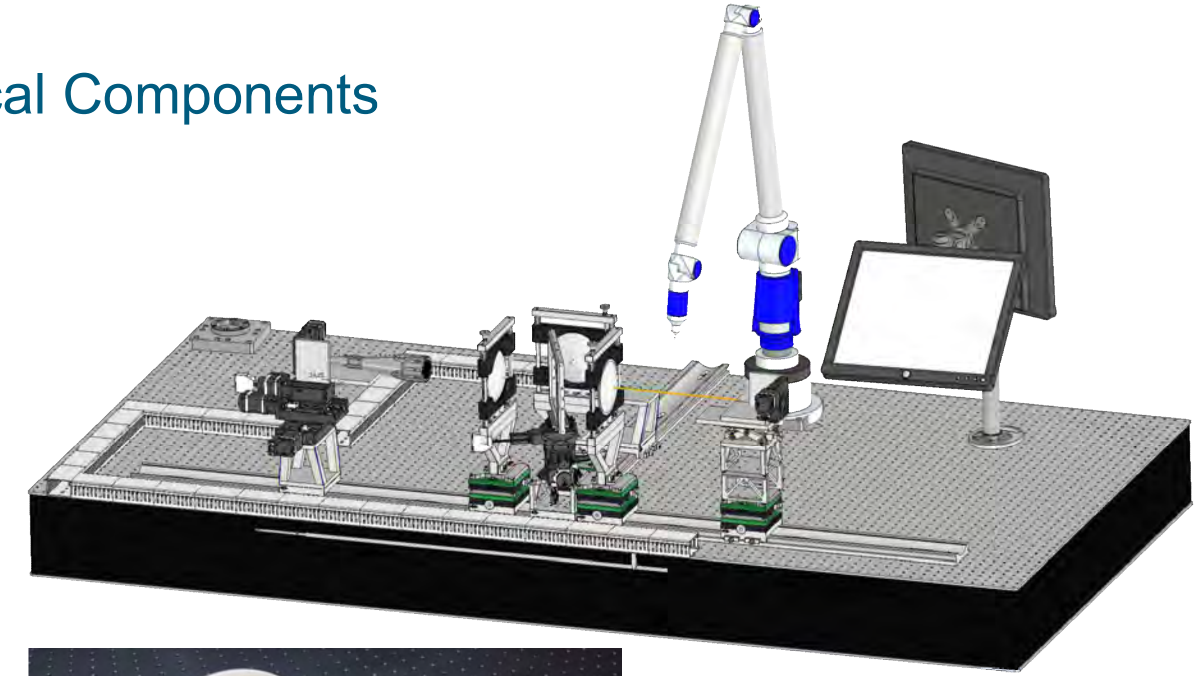
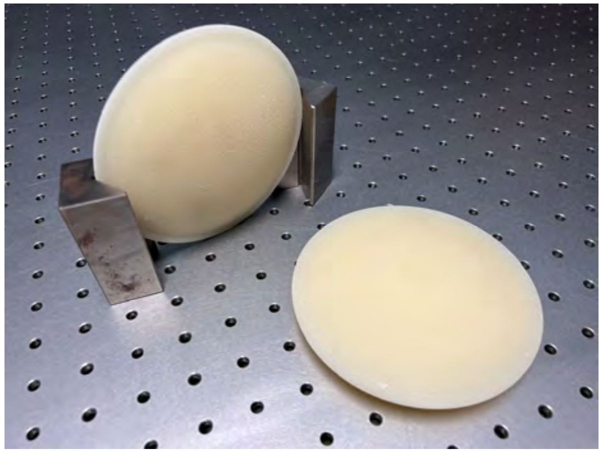
RF Measurements of Quasi-Optical Components

- Optical table for measurements of quasi-optical components
- Quality check
  - Individual low-power measurements of every component
  - Low-power measurements of the complete q.o. antenna frontend

- Example: Wire-Grid measurements
  - Lens system for reflection and transmission measurements
  - Lenses manufactured in Polypropylen by 3D printing





Conclusion & Outlook

- Vacuum tube amplifiers are the back-bone of ground based space-observation radars
- With the Ka-band upgrade, TIRA will remain one of the world's most capable space observation systems
  - Frequency upgrade: High spatial resolution
  - Polarimetry upgrade: Structural and material analyses
- Future upgrades, e.g to higher transmit power, are under discussion

  → TIRA will keep up with the rapid development in space

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Thank you for your attention!
Questions?