Small Waves Big Impact: Sensing Millimetre/Submillimetre Waves from Space

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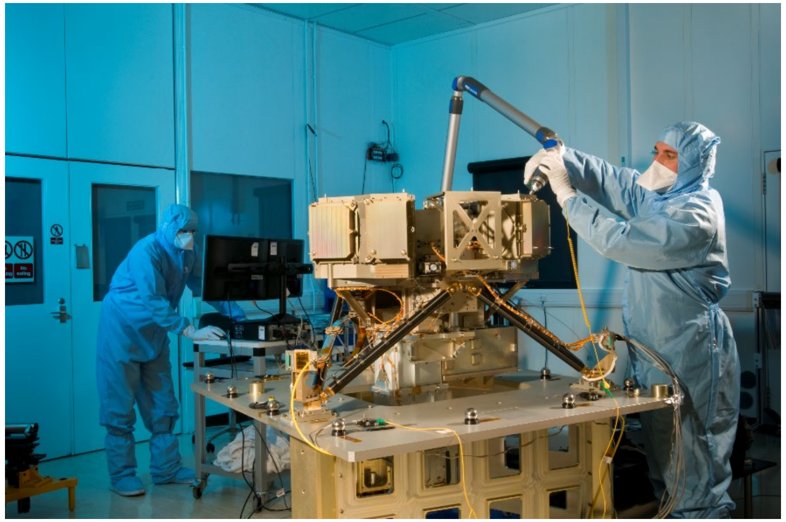
Millimetre Wave Technology & Chilbolton Observatory Group, RAL Space



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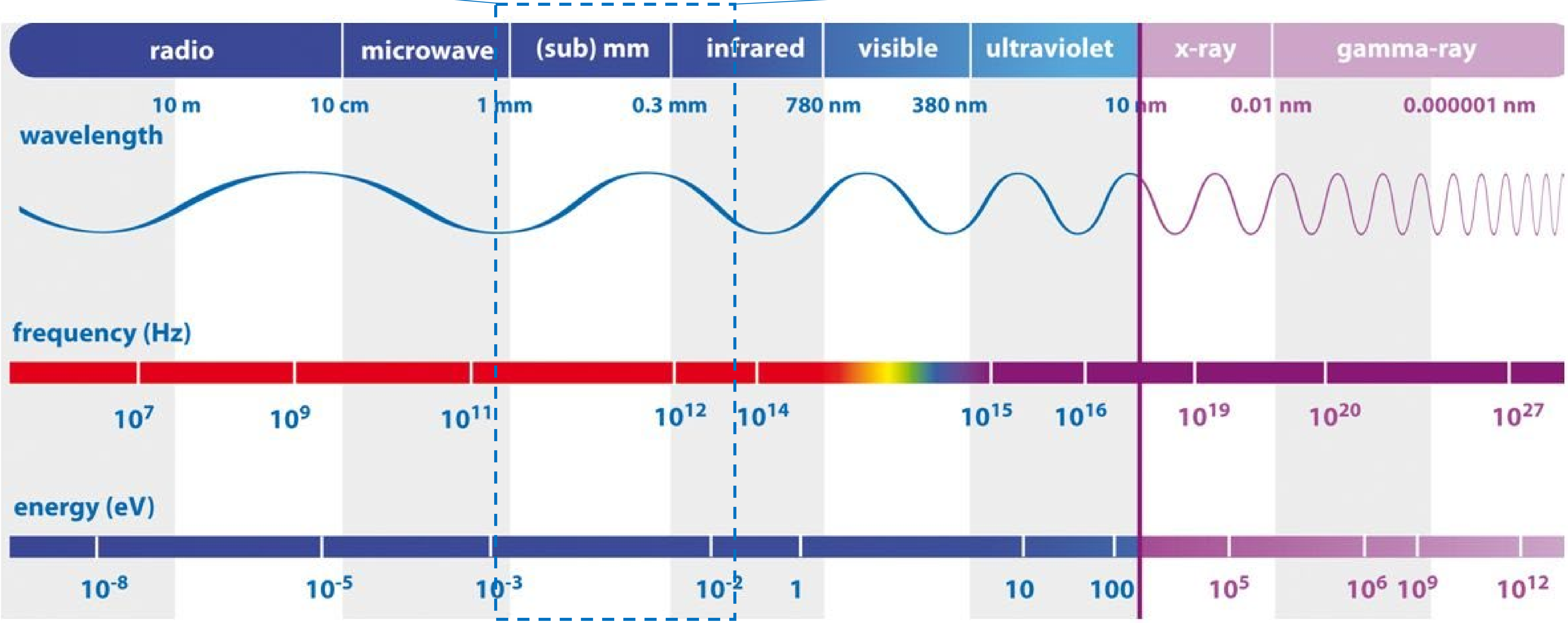
Millimetre/Submillimetre Spectral Range

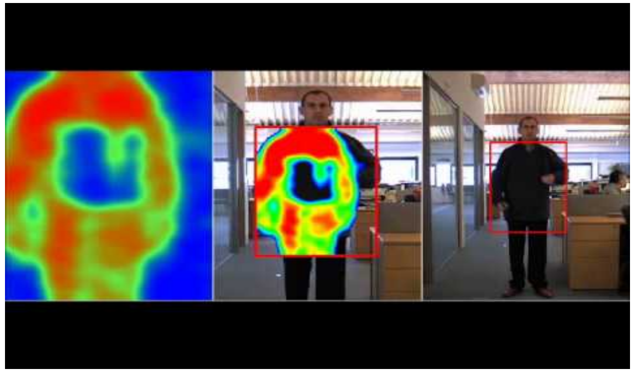
1 THz = 10^{12}Hz = 1,000GHz - ITU defined range 0.03THz to 3THz – Millimetre/Submillimetre-wave region.



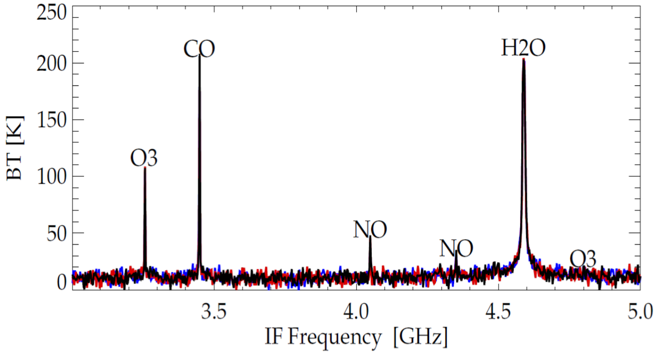
Small Waves…..THz photon energy is small (~meV) but lots of impact.

Millimetre/Submillimetre (THz)-Unique Attributes

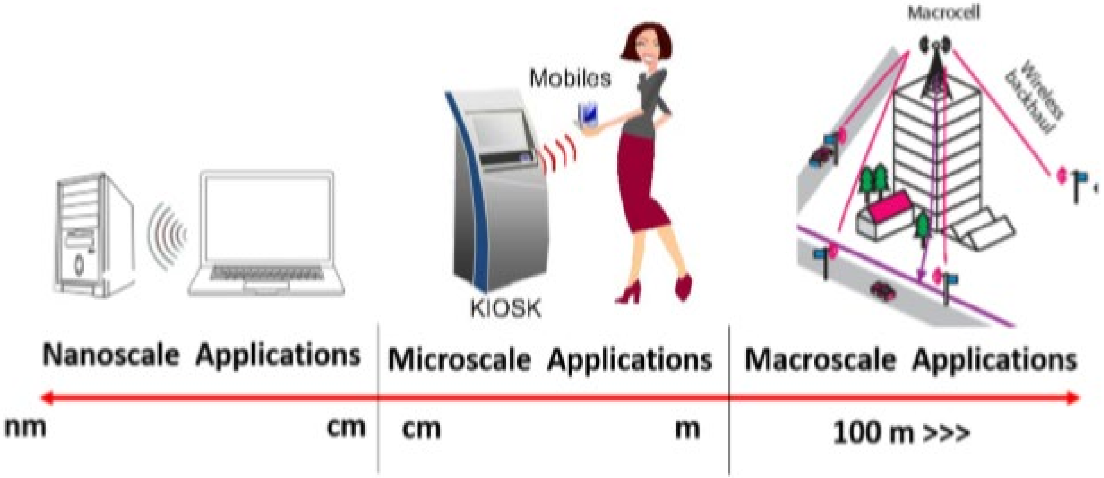
- Low energy implies non ionising and considered safe for human exposure when compared with X-rays.
- Able to penetrate clothing and various dielectric materials that are opaque in visible and infrared.
- Target spatial imaging is possible as is,
- Spectral chemical analysis of molecular species, e.g. H_2O, NOx, CO, O_3, O_2, etc.
- Increasing potential for ultra-high data rate communication.
- Substantial science impact (next slide).



Passive Terahertz Screening



Spectral Simulation @1.14 THz



THz Communication-Different range applications

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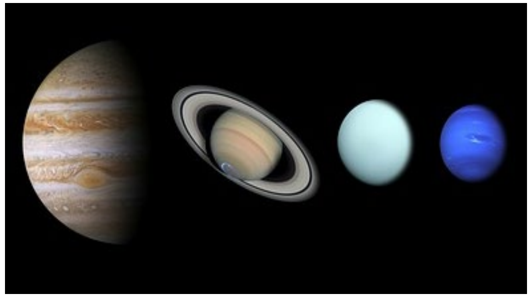
THz Science Applications

- **Astronomy:**
  - Study the cold interstellar medium and cosmic background.
  - Understand stellar and galactic formation, and evolution of the universe.

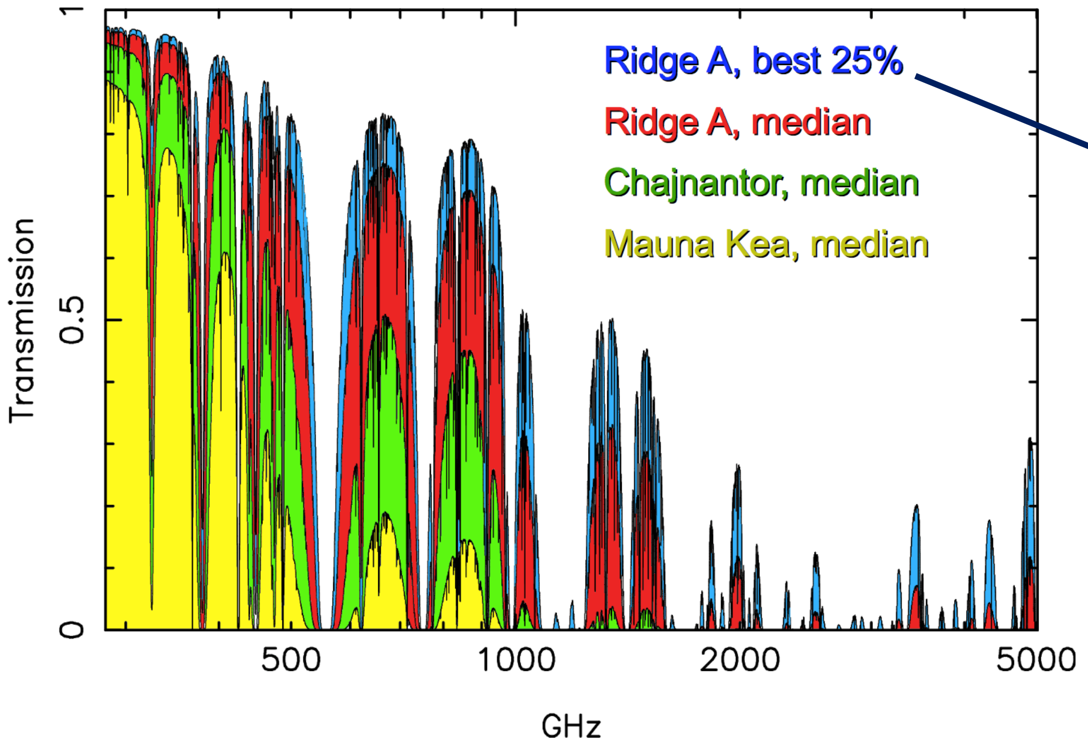
- **Solar System:**
  - Study planetary atmospheres (gas giants) and comets.
  - Provides information relating formation of the solar system.
  - In situ/close encounters best resolution, no THz landers yet.



- **Earth Observation (EO):**
  - Study Earth's upper and lower atmosphere for,
  - Weather forecasting and climate change.

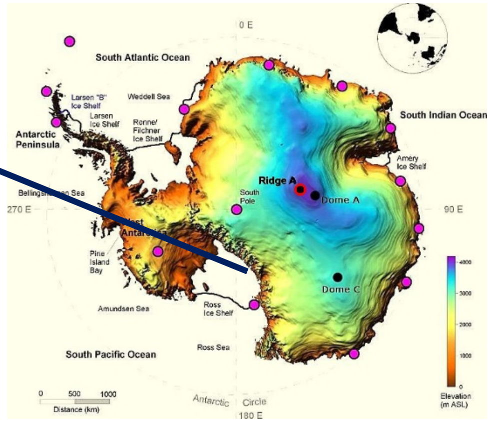
Astronomy Observations

- Possible to construct large-scale ground based THz observatories, but…
- Atmospheric transmission is limited by Earth's atmosphere, even at excellent sites.

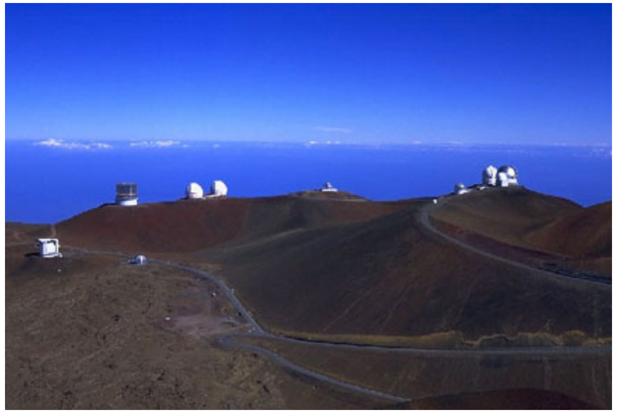


THz Atmospheric Transmission – Credit Stewart Observatory, Arizona

Antarctic Region
Credit Stewart Observatory, Arizona



Mauna Kea, Hawaii
Photo Credit Richard Wainscoat



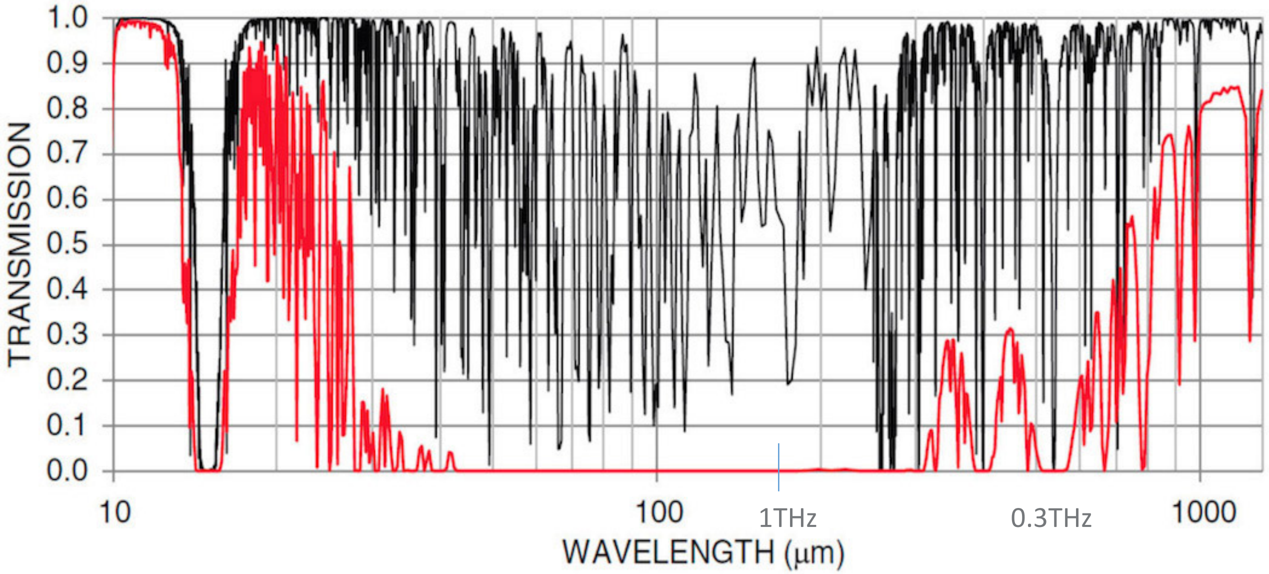

The Atacama Large Millimetre/submillimetre Array (ALMA) Chajnator Atacama – Credit ESO

Higher Altitude is Good

RAL Space

- Airborne observatories improve transmission.

SOFIA Airborne Observatory



Black Line atmospheric transmission from SOFIA. Red is a good ground site.

- Conditions are still not perfect and flights are expensive.
- For astronomy, no atmospheric attenuation = perfect seeing conditions. So…

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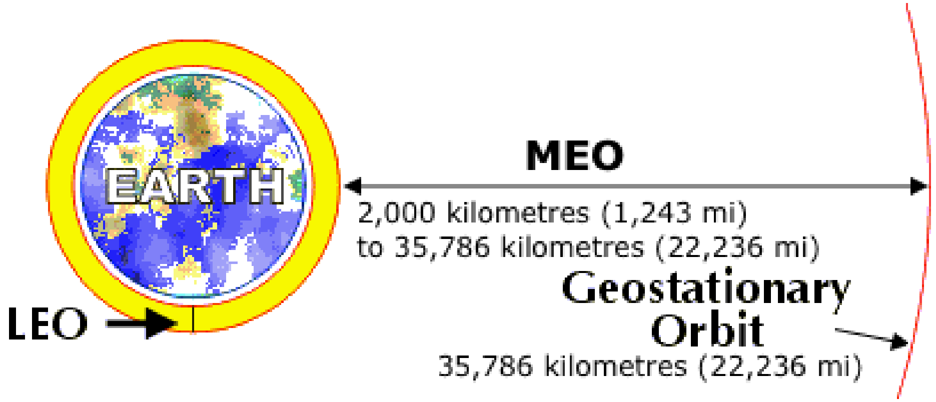
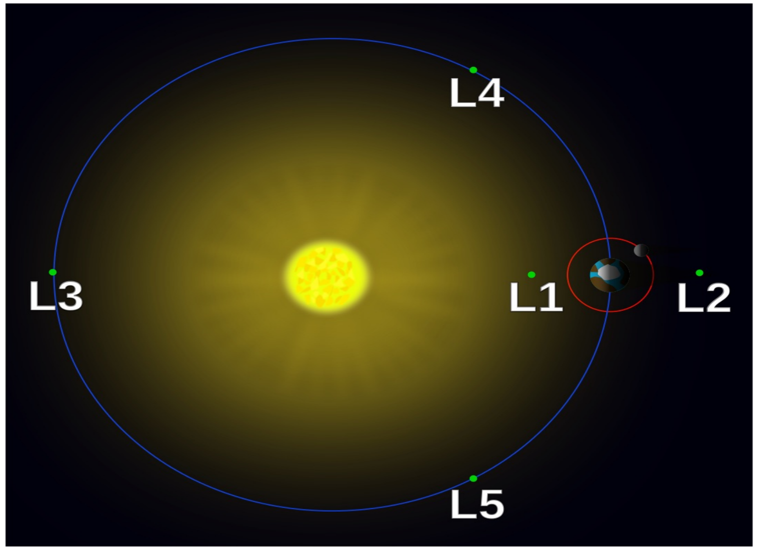
Space is Best

RAL Space

- Low Earth orbit (LEO) - 160km to 2,000 km
- Medium Earth orbit (MEO) – 2,000 km to <35,768 km
- Geostationary Earth orbit (GEO) – 35,768 km
- Lagrangian Points – stable orbits.
- Beyond - solar and planetary exploration.



Int. Space Station in LEO

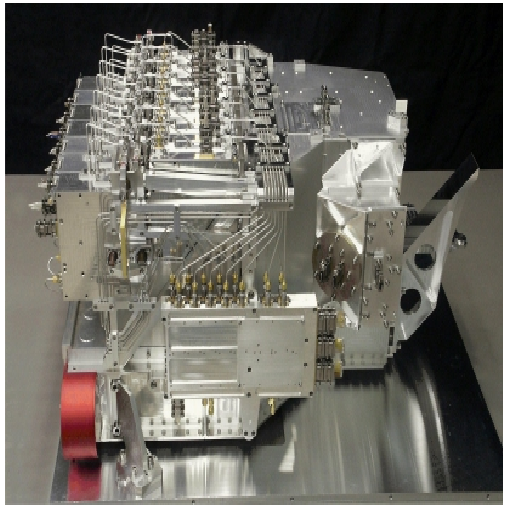


Lagrangian Points

THz Astronomy Mission Example - Herschel HIFI

RAL Space

- **H**eterodyne **I**nstrument for the **F**ar **I**nfrared (HIFI).
- Objective:
    - *Study evolution of galaxies, star and planet formation.*
- Payload Located in the focal plane of the 3.5 metre diametre telescope.
- Seven superconducting heterodyne receiver channels – 0.5 to 1.9THz
- Spectral res. ~0.1 to 1MHz.
- Lifetime: Achieved 3 years at L2 location.
- Used liquid helium coolant.

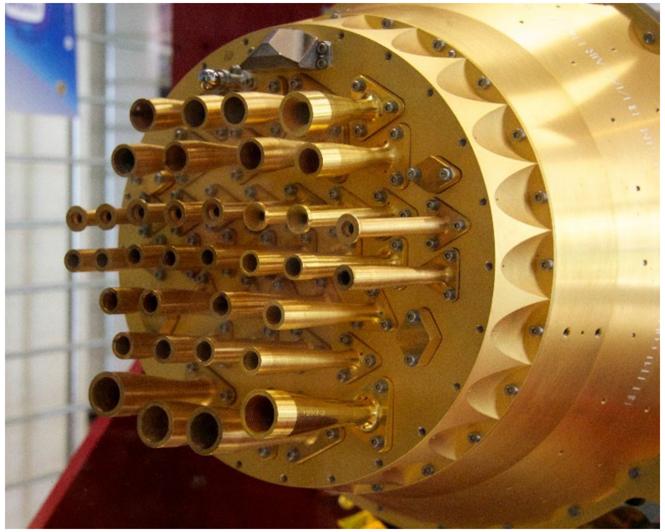


The HIFI instrument payload - ESA

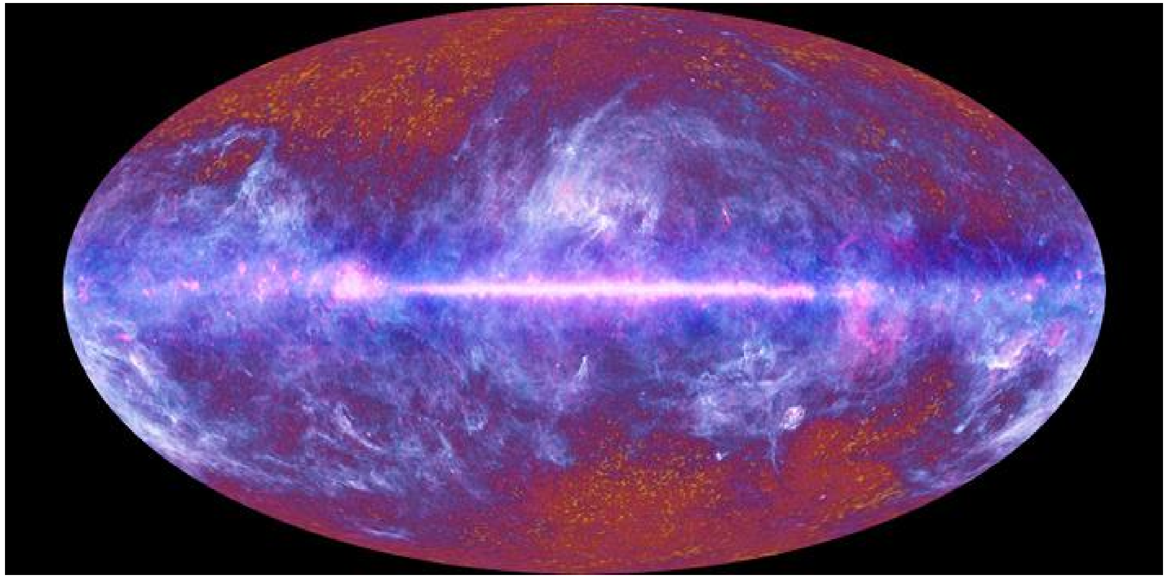
The Herschel Observatory - ESA

THz Astronomy Mission Example - Planck

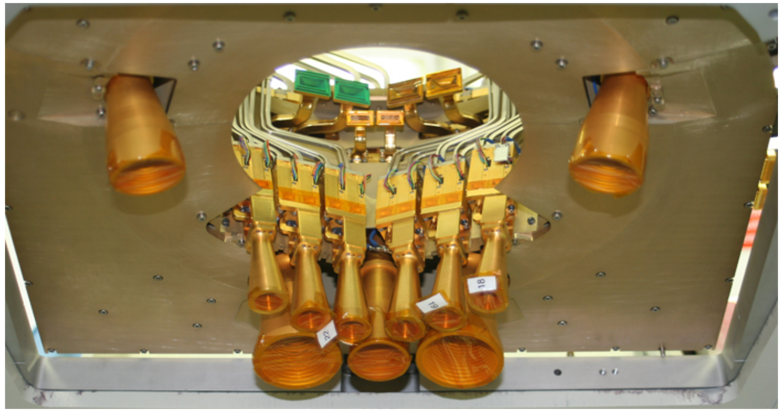
- Planck CMB observatory
- THz imaging camera and low-res. spectrometer
- 1.5m antenna primary with offset secondary.
- Low frequency instrument (LFI) 30GHz to 75GHz cooled to ~20k.
- High frequency instrument (HFI) 0.1THz to 0.9THz cooled to 0.1K.



Planck HFI Unit -ESA



Whole sky image from the Planck Observatory - ESA



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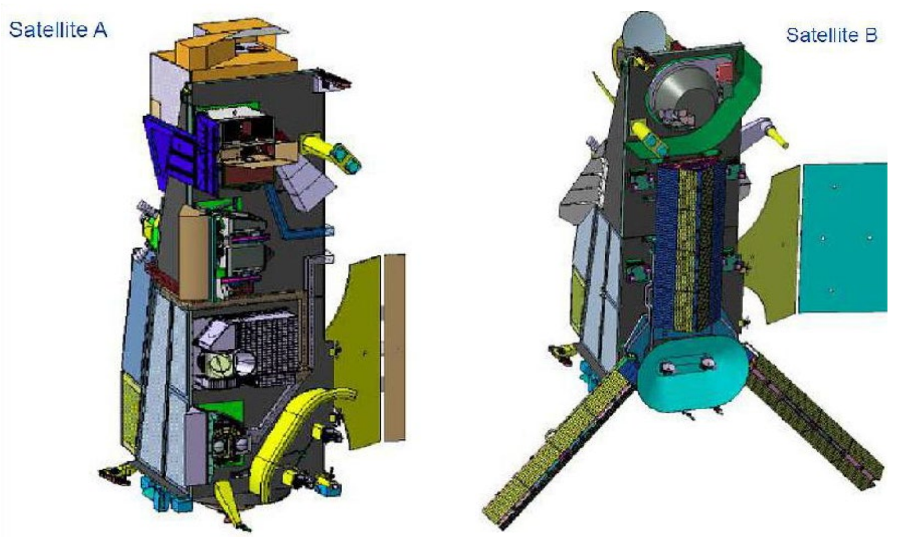
THz Earth Observation form Space

RAL Space

- Can view atmospheric species that are not visible from the ground.
- Can see through aerosols that obscure the visible and infra-red.
- Allows study and monitoring of climate.
- Also supports weather forecasting.
- Polar orbit provides full global coverage.

EO Mission Example- MetOp SG

- Second generation of polar orbiting satellites in low Earth orbit.
- Provides temperature, humidity, wind speed, trace gases, land and ocean images
- Supplies continuity of weather monitoring and observation to beyond 2040.
- Multiple payload on satellites – A and B (3 pairs).
- Microwave sounder (MWS), Microwave imager (MWI) and ice cloud image (ICI) using THz technology to ~600GHz.
- First launch ~2022 with subsequent ~ 7 year paired launch interval.
- Total system lifespan >20 years.



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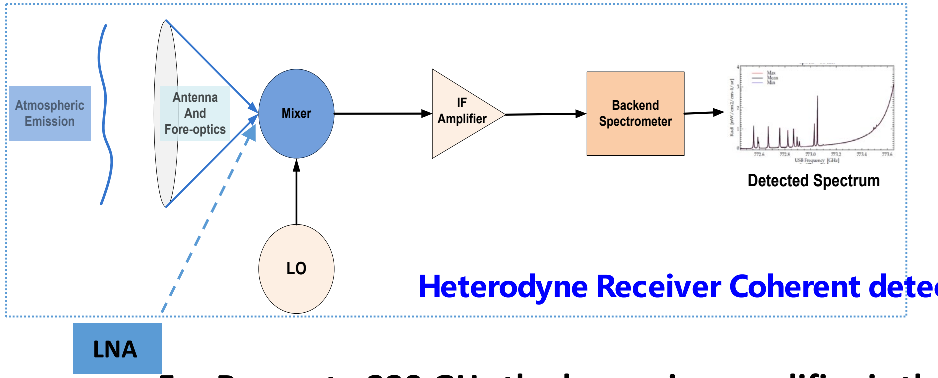
MetOp SG Receiver Technology

- Receiver payloads for MWS, MWI and ICI above 100GHz use heterodyne systems.



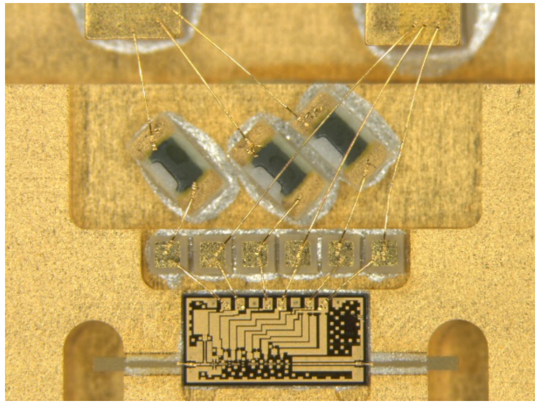
Heterodyne Receiver Coherent detection

For Rxs up to 229 GHz the low noise amplifier is the first element in the Receiver.

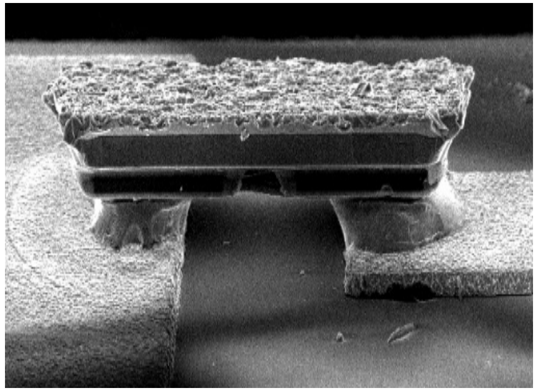
MetOp-SG – Satellite deployment for 20+ years

- Technology mix of semiconductor amplifier, mixer and local oscillators.

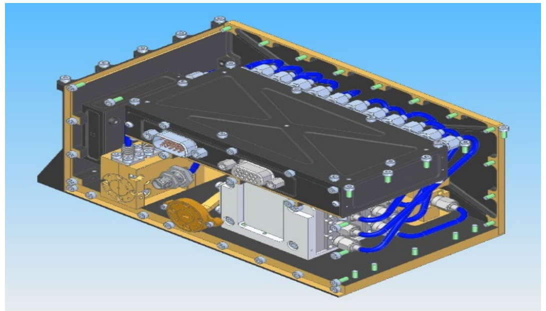
RAL 183GHz Mixer and Diode (inset image)



183GHz Low Noise Amplifier Front-End



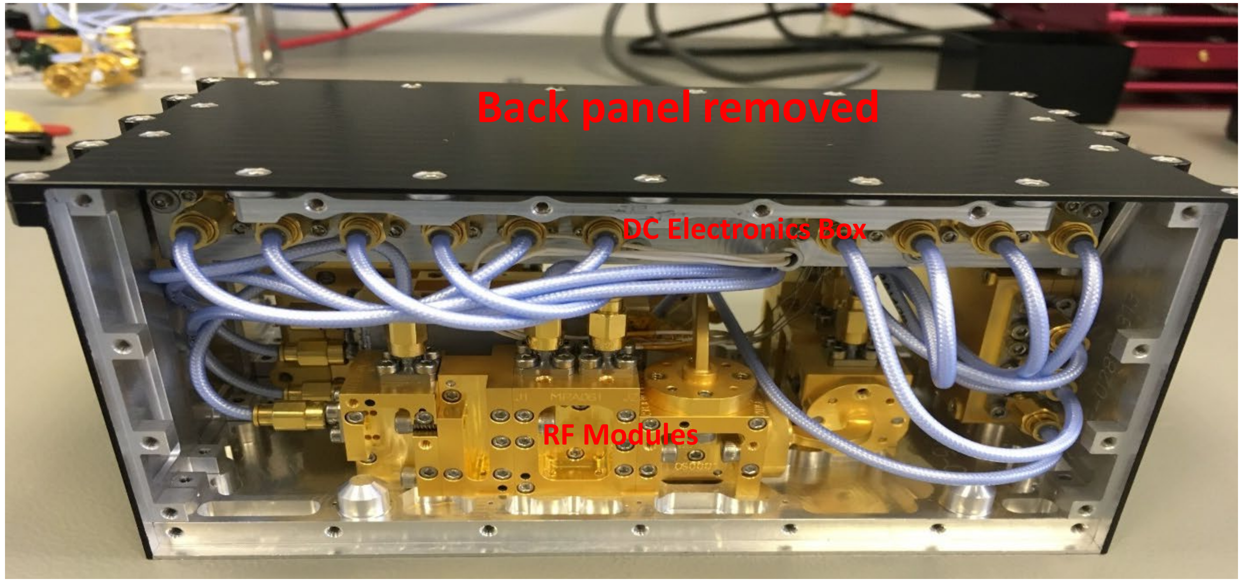
Space qualified RAL flip chip diode for MetOp-SG

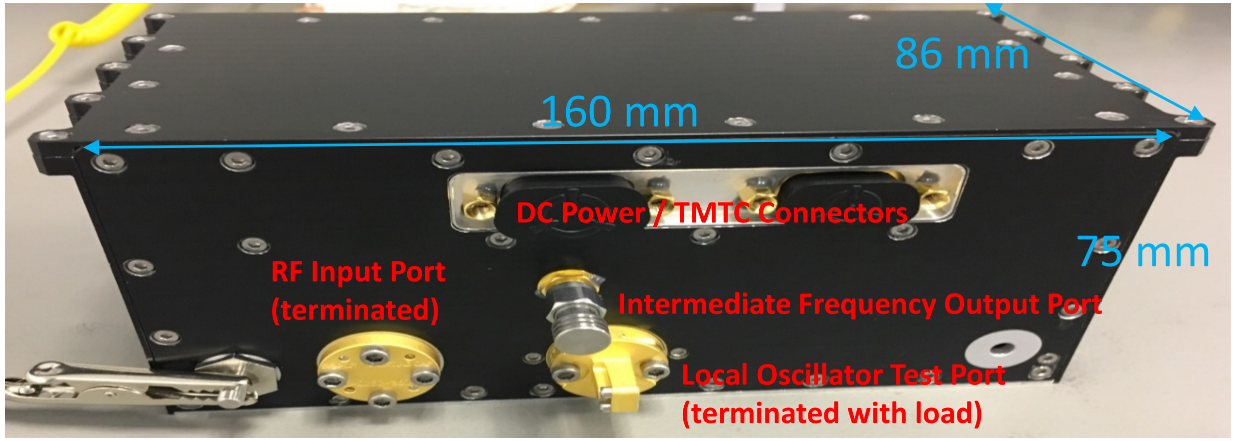


MetOp-SG integrated receiver module concept

MetOp SG Receiver Technology

MWS Front End Receiver
229 GHz Engineering Qualification Model (EQM)





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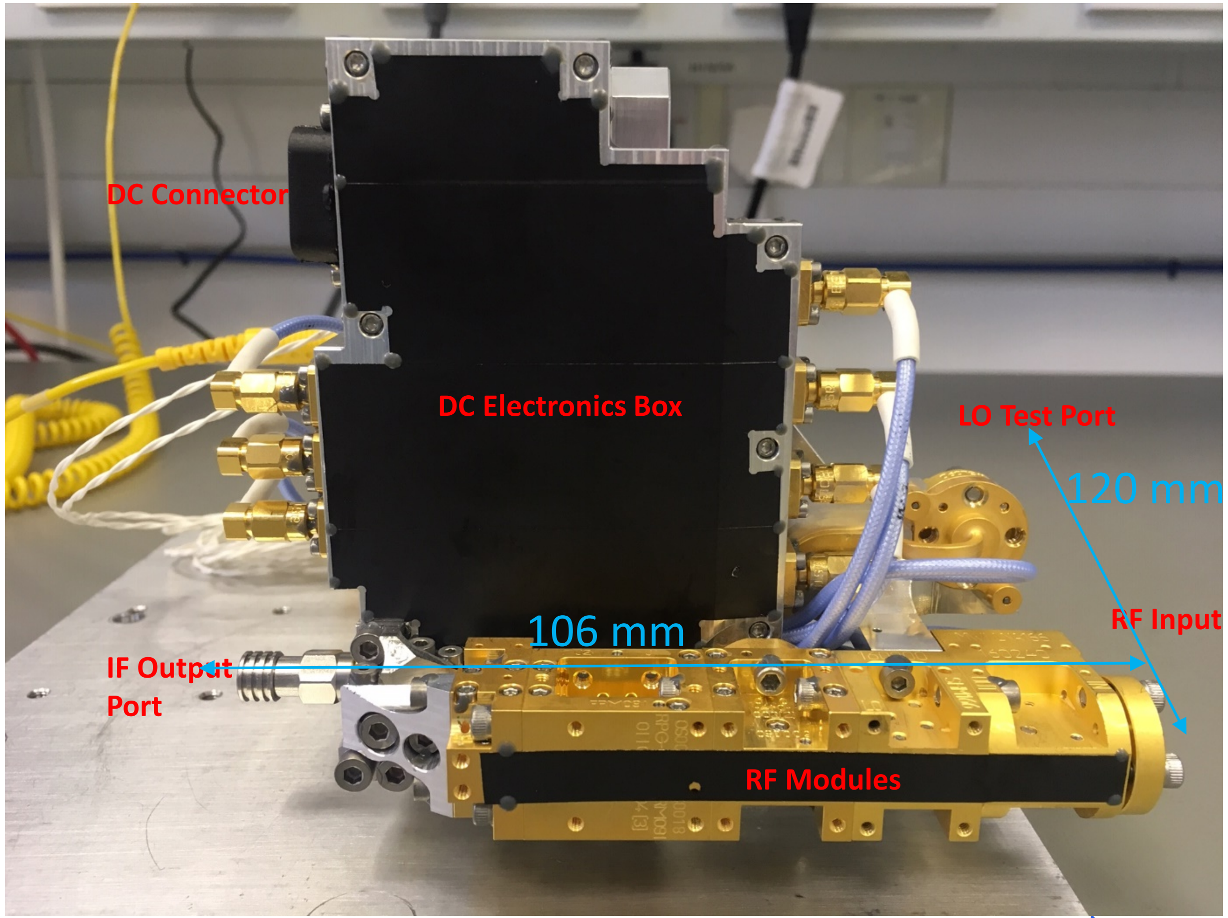
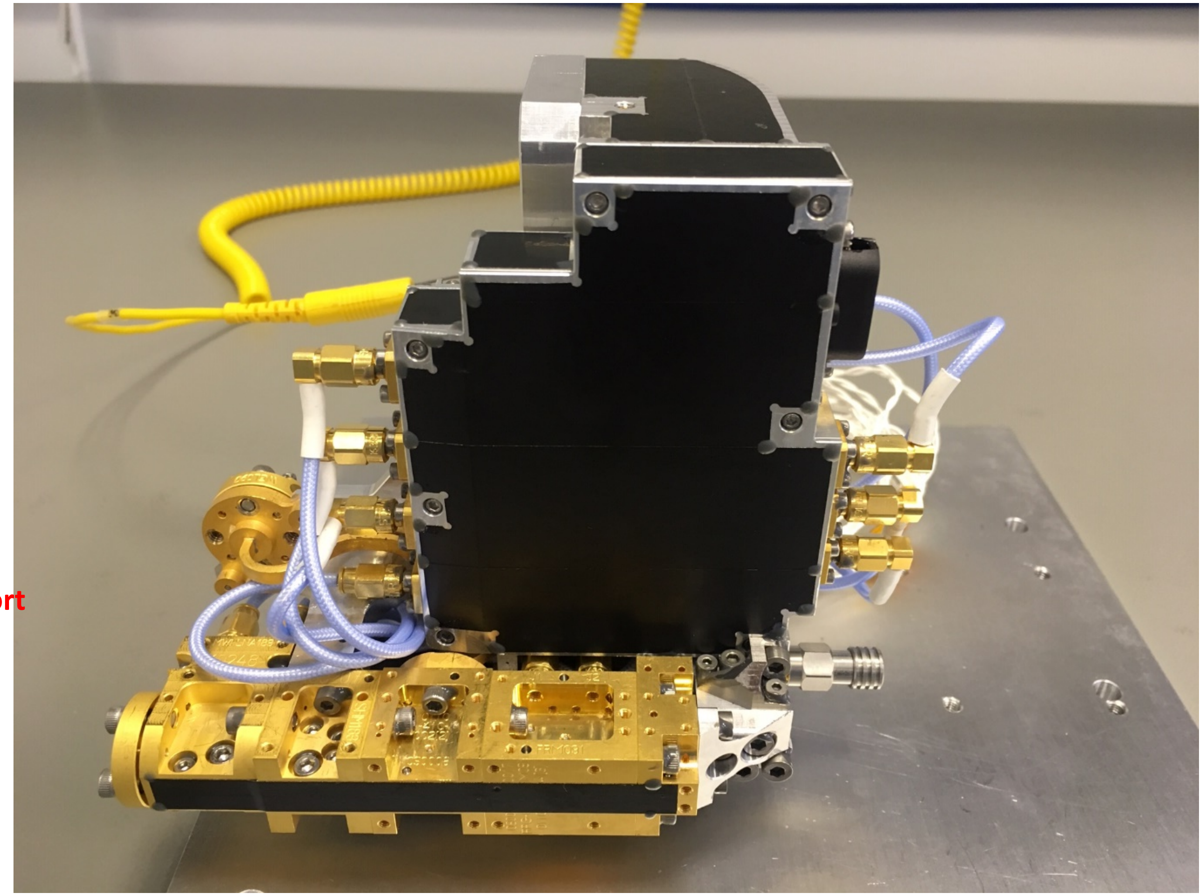
MetOp SG Receiver Technology

MWI Front End Receivers

MWI FERX166 EQM

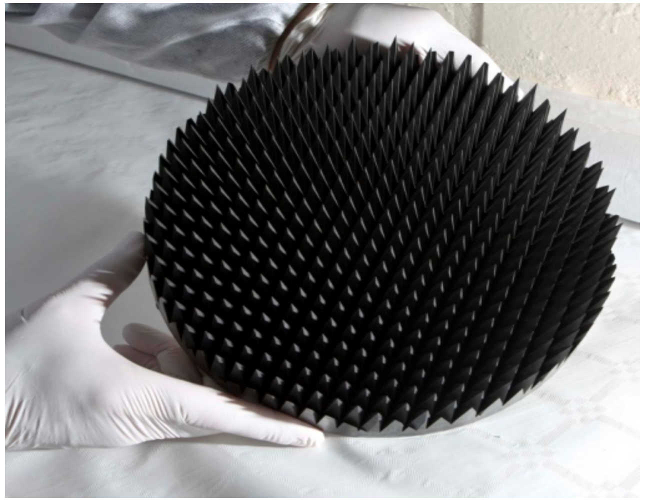


MWI FERX183 EQM

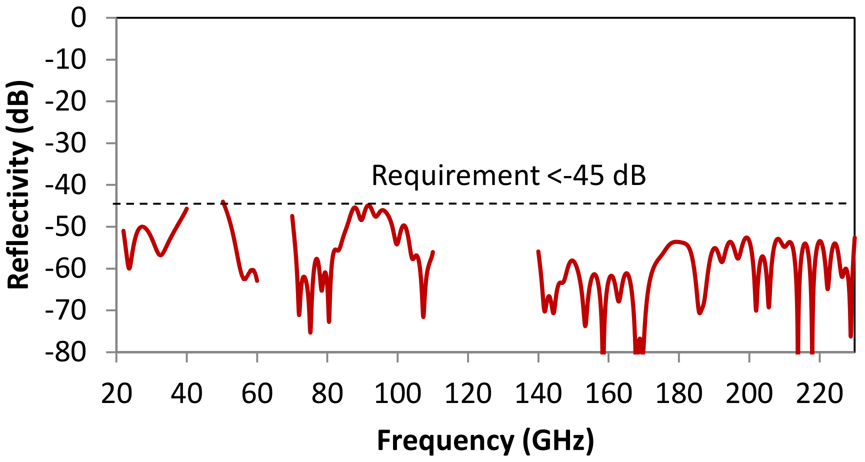


MetOp SG MWS On-ground Calibration

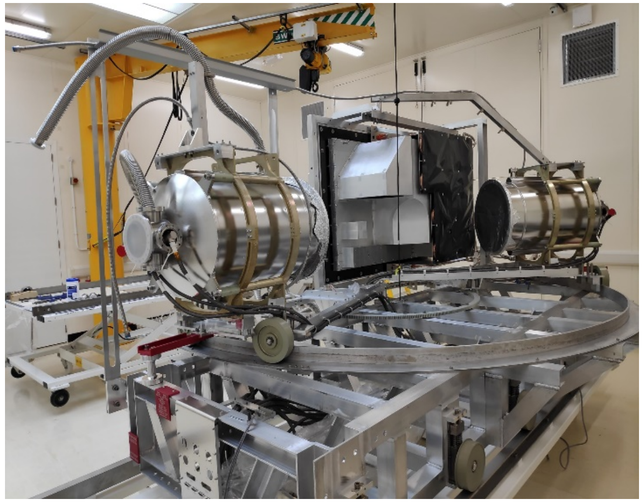
- MWS is a cross track scanning passive radiometer, operating from 23 to 229 GHz.
- Accurate calibration of MWS is essential to reduce the returned temperature uncertainty to ± 0.1 K.
- Pre-launch instrument level calibration required under thermal vacuum conditions.
- The calibration system contains a "cold" black body target, operating at close to 80 K, which replaces the view of cold space and a "Earth" target, which is variable in temperature from 80 to 315K.
- Target absorption better then 99.9999%



Example Calibration Load



Calibration Load measured Reflectivity on a prototype target



MWS instrument On-ground calibration rig

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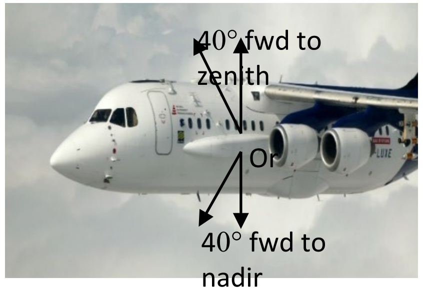
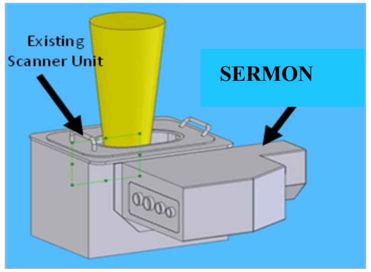
Next Generation MetOp – TG

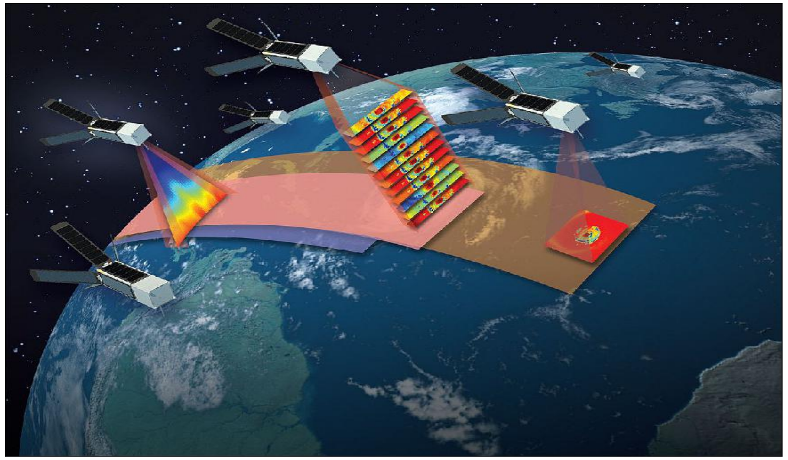
Spectroscopic-system for EnviRonmental MONitoring (SERMON)

- SERMON is a HYper-Spectral Microwave Sounder (HYMS) demonstrator instrument.
- An emerging remote sensing technique that provides improved atmospheric retrievals through detailed spectral profiling.
- Proof of concept will remote sense two well known molecular species O_2 and H_2O (~60 GHz and 183 GHz) with fine (~3MHz) spectral resolution.
- Future application to CubeSat/Small sat configuration.

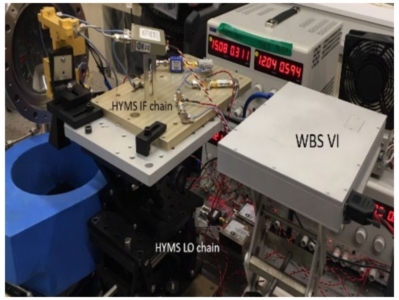


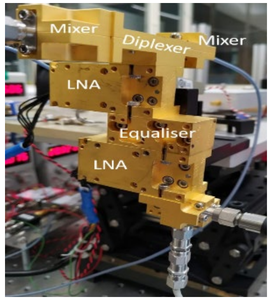


Facility for Airborne Atmospheric Measurements (FAAM) BAE-146 and UK Met Office's DEIMOS instrument.

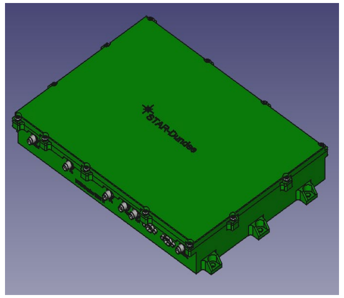


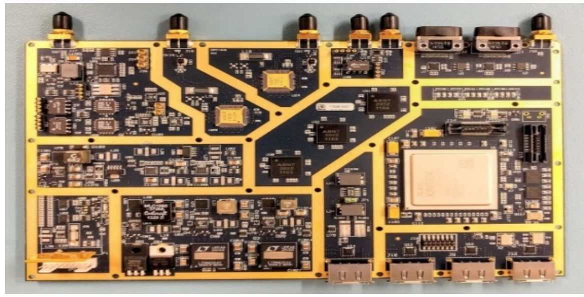
A constellation of identical 3U CubeSats provide sounding . The CubeSat at the left has a temperature profile of a simulated Tropical Cyclone from a Numerical Weather Prediction model. (image credit: MIT/LL, NASA)





60 GHz Radiometer, Tsys ~170 K
Sideband Rejection >40 dB





Ultra-Wideband High-Resolution Spectrometer (STAR Dundee),
8 GHz Instantaneous BW and 1 MHz spectral resolution

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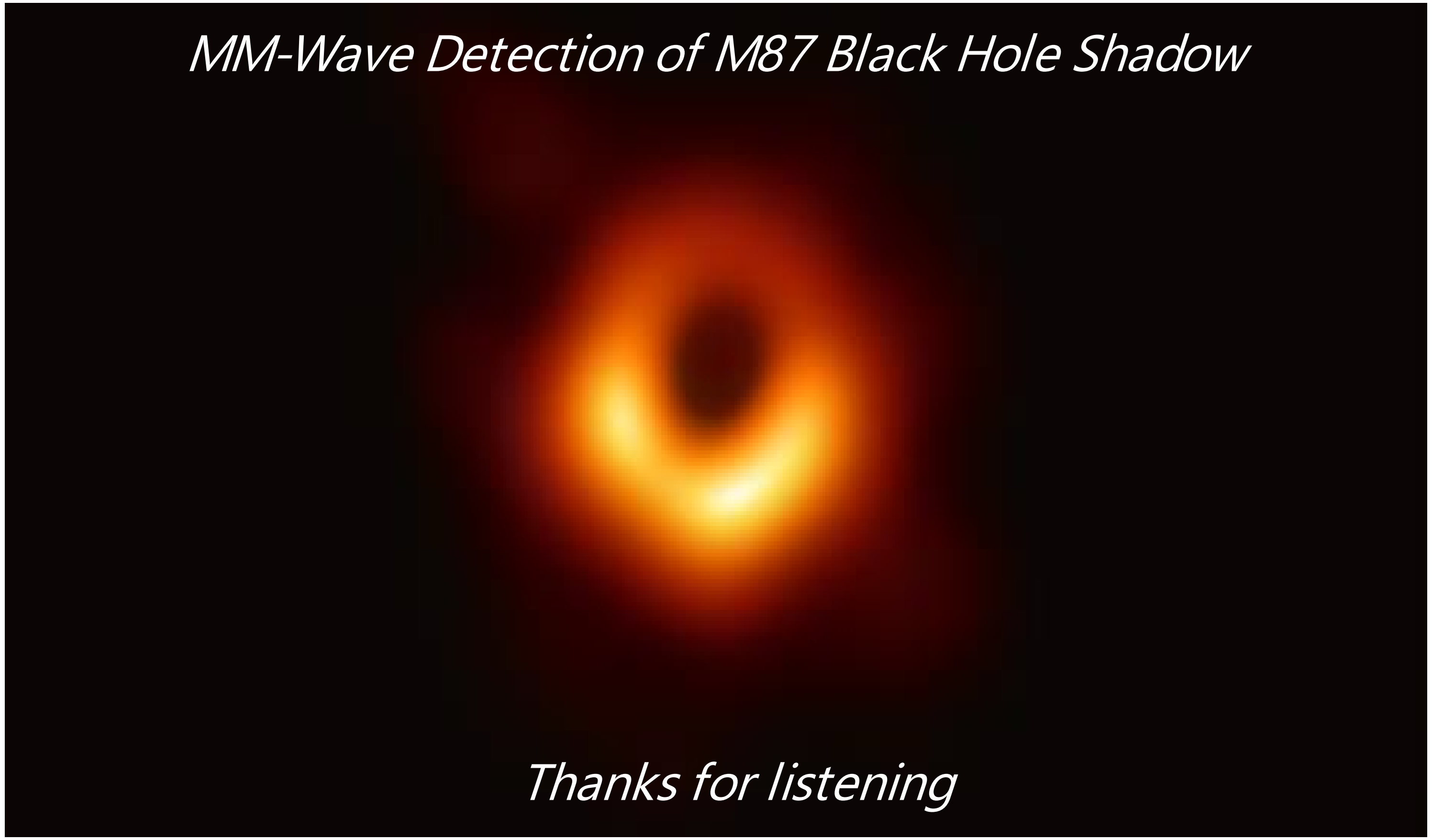
CONCLUSIONS

- The THz Spectral region is region important for science- Earth Observation and astronomy.
  - Provides key astrophysical information relating to stellar and galactic evolution.
  - Is an important remote sounding probe of Earth's atmosphere.
- THz observation from space will increase with MetOP-SG and small generations in constellation forms.
- Many wider operational benefit– weather prediction, security, transportation, process control, gas sensing, telecommunications… . .
- Wave energies might be small, but what they impact is high!

Small Wave Big Impact – First Black Hole Image



Event Horizon Telescope (EHT)