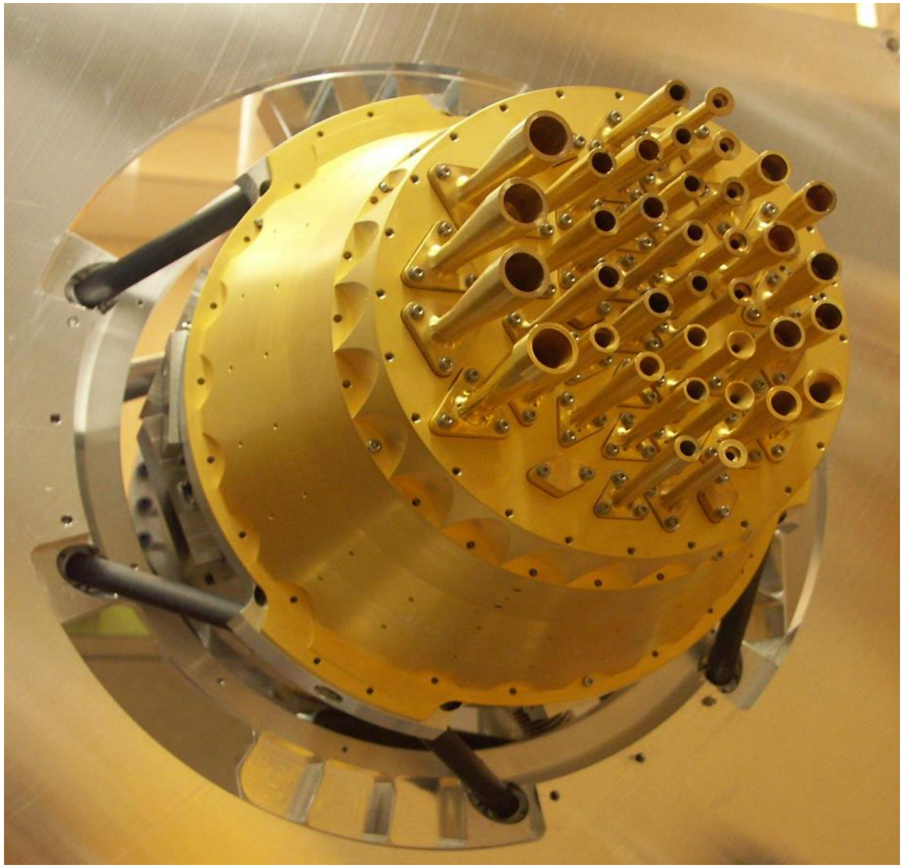
Quasi-Optics

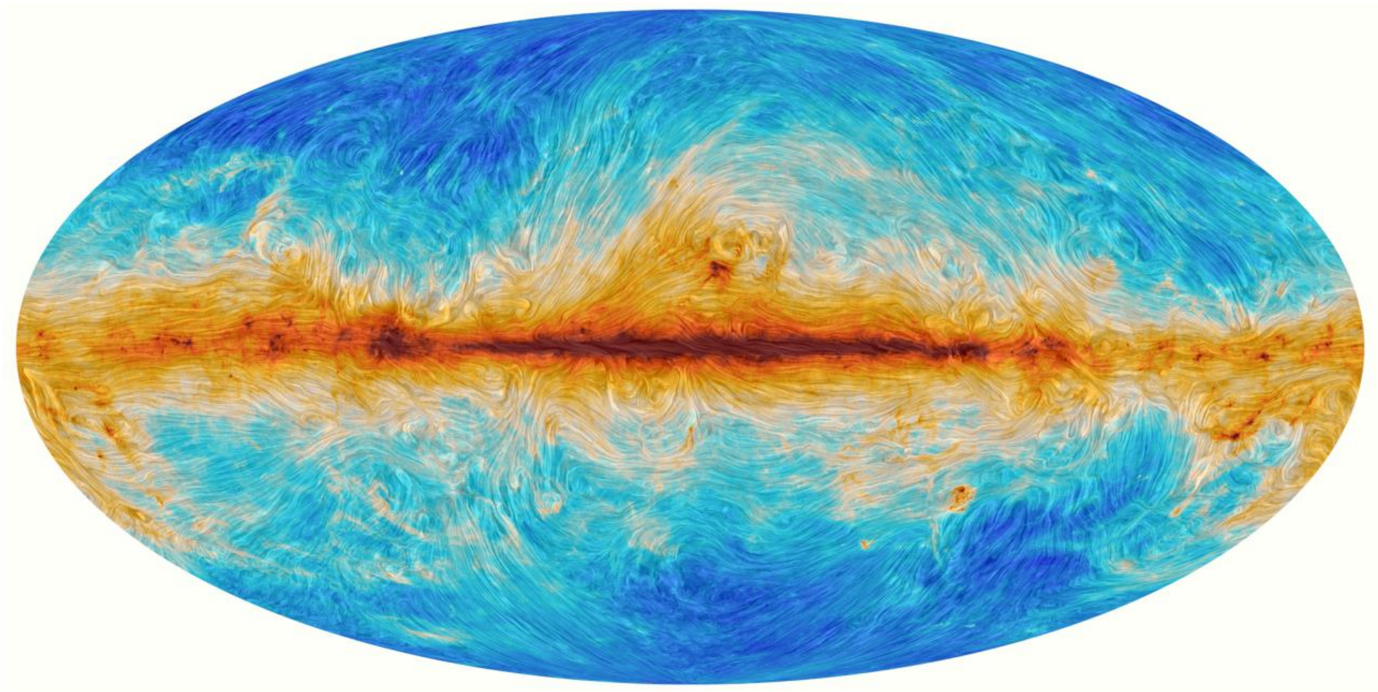


The design and use of THz quasi-optical systems

Or “there and back again”
(The Hobbit, 1937…J. R. R. Tolkien)

Richard Wylde FREng

Quasi-Optical Measurement Systems



:
ESA's Planck

CMB Missions

ta Released 2015

Magnetic field lines traced by dust emission at 353 GHz

Quasi-Optical Measurement Systems

This talk is about the Physics and Engineering of getting information-containing signals to and from EPR samples buried deep in higher field (>3 Tesla) high homogeneous magnets

But… because there is unity in science …I am going to take examples of the techniques from a range of other areas of instrumentation.

For the very highest performance measurement systems operating above about 100 GHz, we have long advocated quasi-optical approaches, which give very low loss, wide bandwidth and polarization agility not available with other circuit structures.

This talk will give some technical background to QO systems and give examples of their use in important measurement campaigns.

Examples will come from

Quasi-Optical Measurements

- Atmospheric remote sensing: JAXA's JEM/SMILES 640GHz BrO Probing SIS-based Radiometer JAXA's Cloud sensing pulsed Radar along with the current MetOP-SG & TROPICs programmes
- Diagnostics in Plasma Fusion research for energy production,
- Free Electron Laser Injection Locking
- ALMA telescope project for Astronomy
- Planck Cosmic Microwave Background anisotropy measurements
- ….and HFESR bridges

What is Quasi-Optics?

This is not a highly technical talk.

I am not aiming to convey the nitty-gritty details of how to design Gaussian-beam transport systems.

Rather the ideas behind the hardware and the calculations need to design EPR Bridges

What is Quasi-Optics?

The free space propagation of EM beams whose size is only a few wavelengths across and where the diffractive spreading of the beam must be controlled.

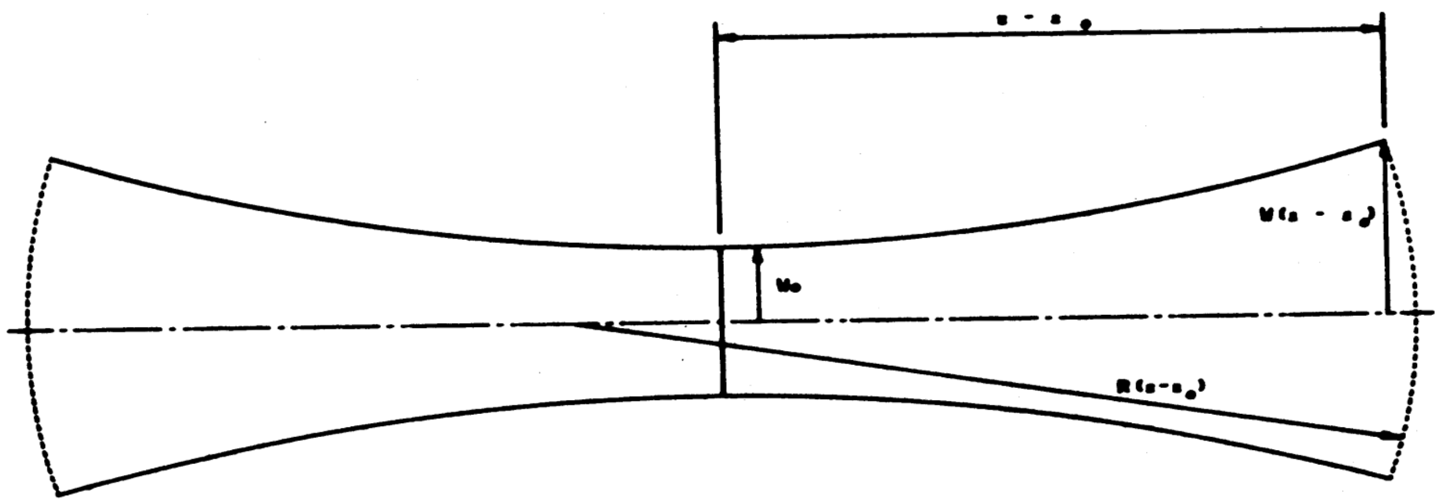
Physical rather than geometrical optics must be used.

Gaussian beam-mode theory

Gaussian beam-mode theory, outlined first in the context of resonant laser cavities by Kogelnik and Li [1966], is the appropriate analytical tool

Gaussian beam-mode theory

Simple beam showing beamwaist



Gaussian beam-mode theory

The fundamental Gaussian Beam-Mode is characterised by just two parameters:

W(z) - radius at 1/e amplitude
R(z) - phase front curvature

which - along with frequency and polarization uniquely define the beam

Gaussian beam-mode theory

Knowing W and R at one point allows you to calculate the parameters anywhere else in a well-defined circuit

$$W^2 = W_0^2\,[1 + \hat{z}^2]$$

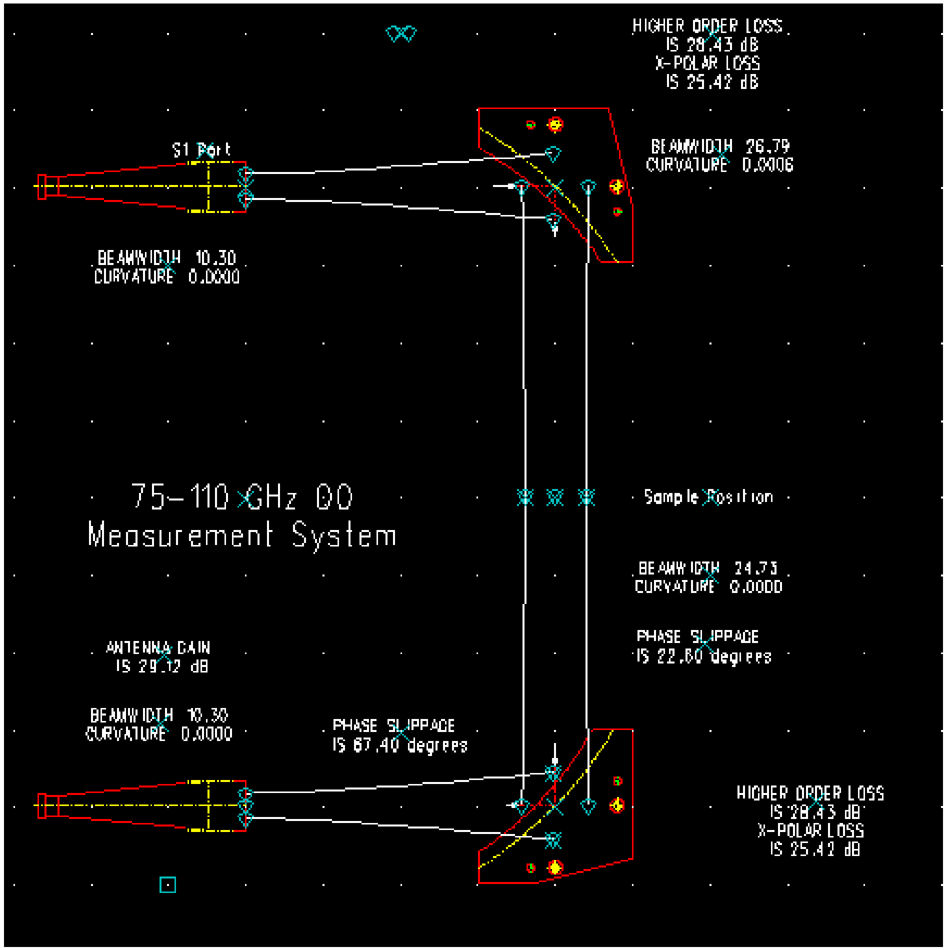
$$R = (z - z_o)\,[1 - (1/\hat{z}^2)]$$

$$\text{And a Phase} = (2p+1)\,\text{ArcTan}(\hat{z})$$

where $\hat{z}$ is the reduced (dimensionless) distance to the beamwaist W_o given by

$$\hat{z} = \lambda\,(z - z_o) / \pi\,W_0^2$$

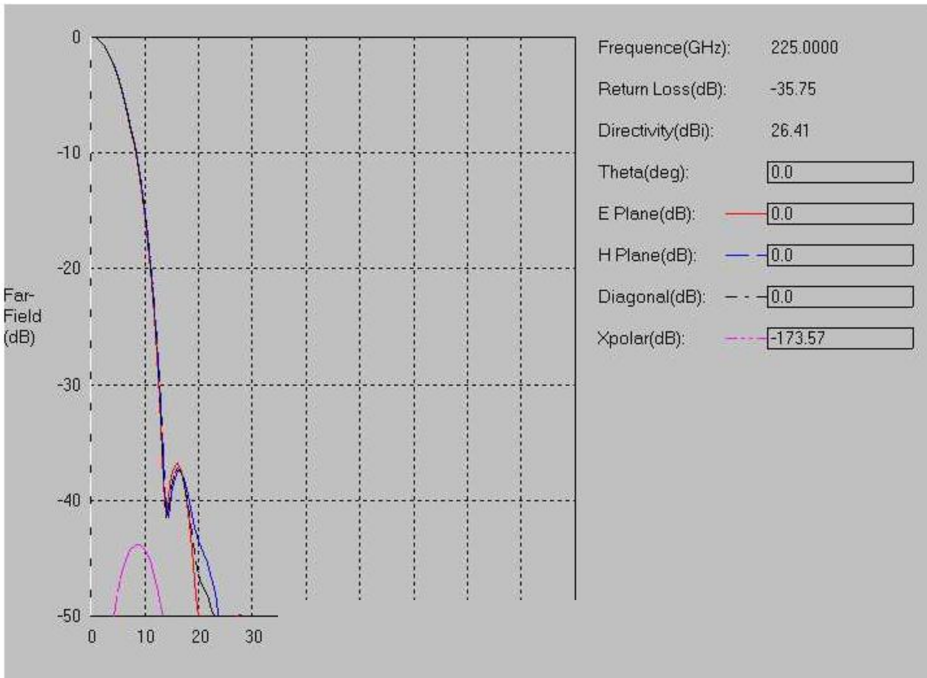
Gaussian beam-mode theory



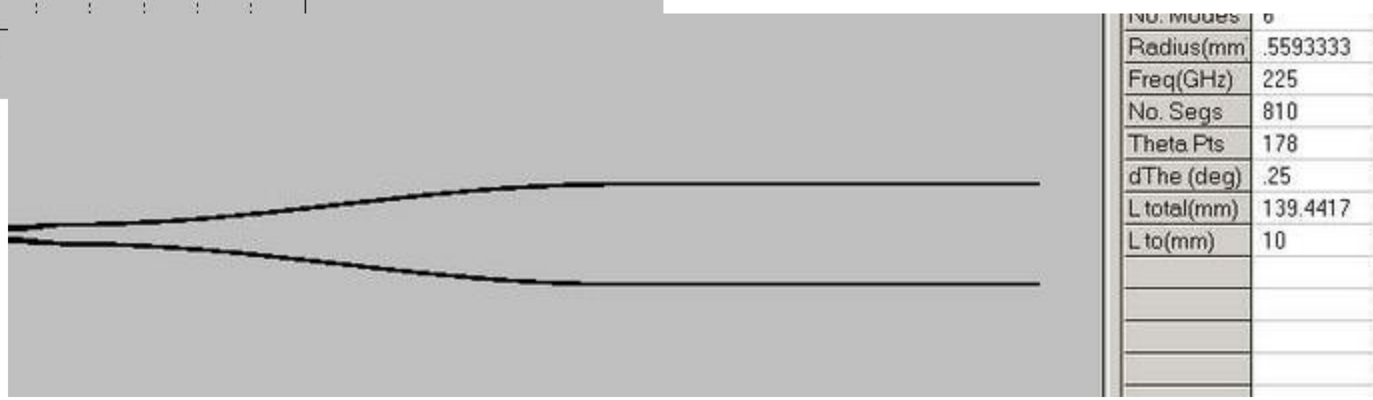
Two mirror system, with mirrors set at sums of focal length.

Waist position is independent of frequency

Beam waist divergence also independent of frequency



Ultra-Gaussian Horns allow the simple Gaussian Beam mode approach to be used to design low loss QO systems

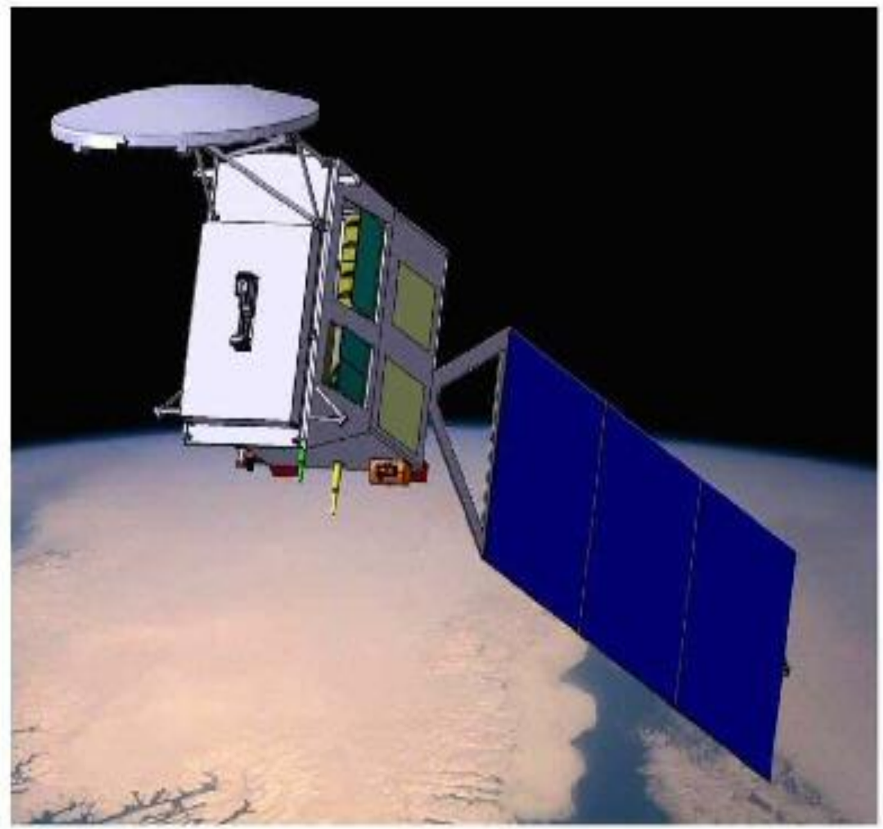


There are QO analogues of all microwave components:

- Waveguide - Free space and mirrors
- Adjustable phase delays – moving mirrors
- Couplers - Polarizing wire grids; Mylar films
- Terminations - Radar Absorbing Material (RAM)
- Attenuators - Sheet absorbers; rotating polarizing wire grids
- Isolators and circulators - Ferrite Faraday rotators and grids
- Filters - Martin-Puplett Interferometers/Drill plate filters/Capacitative and Inductive mesh filters

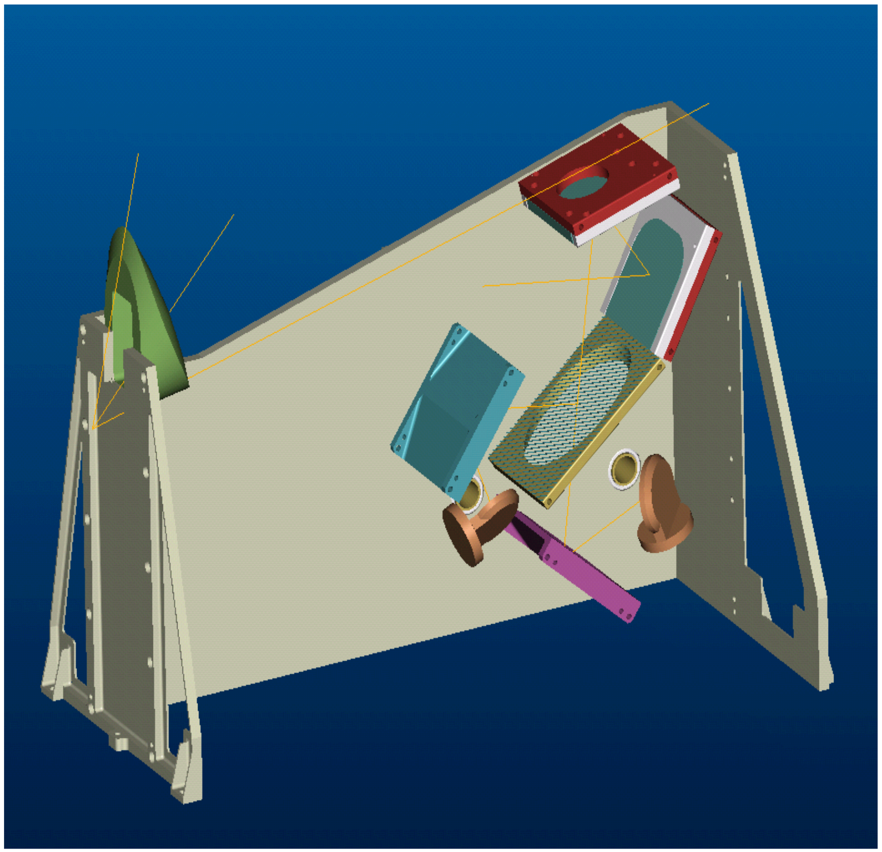
Remote Sensing: An alternative approach to Isolation and Multiplexing

Multiplexing and Isolation can also be provided without gyrotropic materials, if you are prepared to use Circular polarization -a reflected CP wave is (curiously) polarized in the same sense at the outgoing beam, and can therefore be distinguished by an interferometer acting as a Circular polarizer



This is the approach we are taking for the 94.05 GHz Cloud Pulse radar for the ESA/JAXA EarthCARE mission to measure cloud cover from space

Cloud Pulse Radar – Quasi-Optical Feed



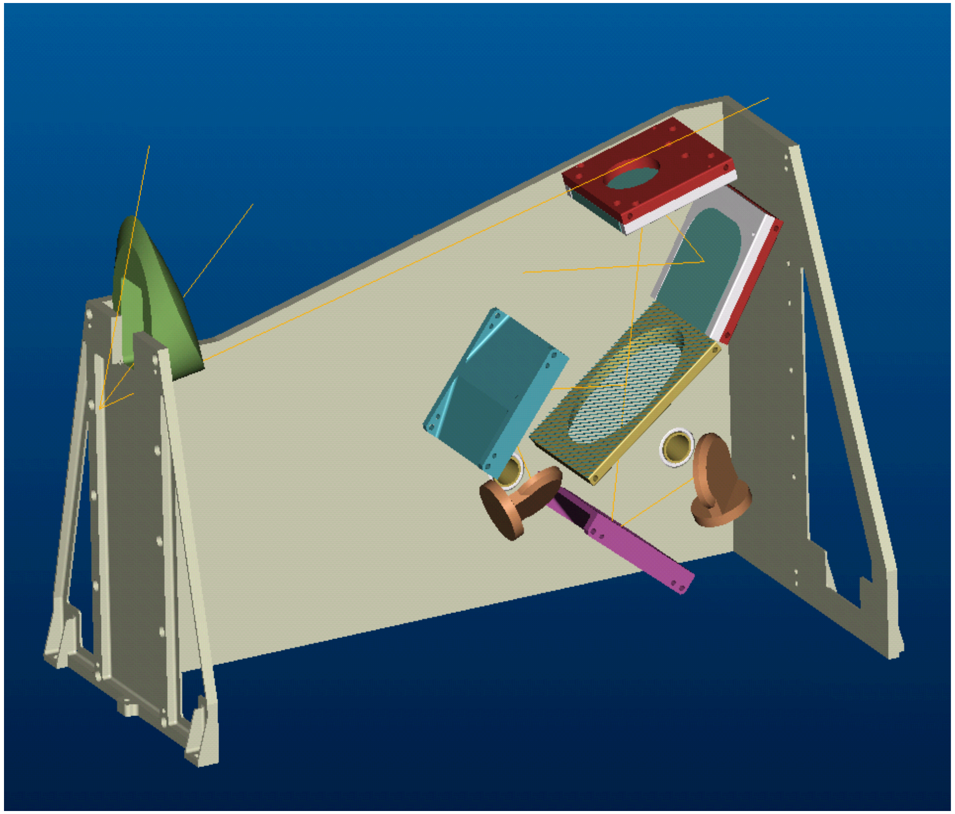
For the CRP, The feed subsystem is required to take high power signals from a waveguide based EIK source and feed the antenna subreflector. Returning signals, reflected from clouds, are to be passed from the antenna subreflector to a LNA receiver.

94 GHz Multiplexer performance goals

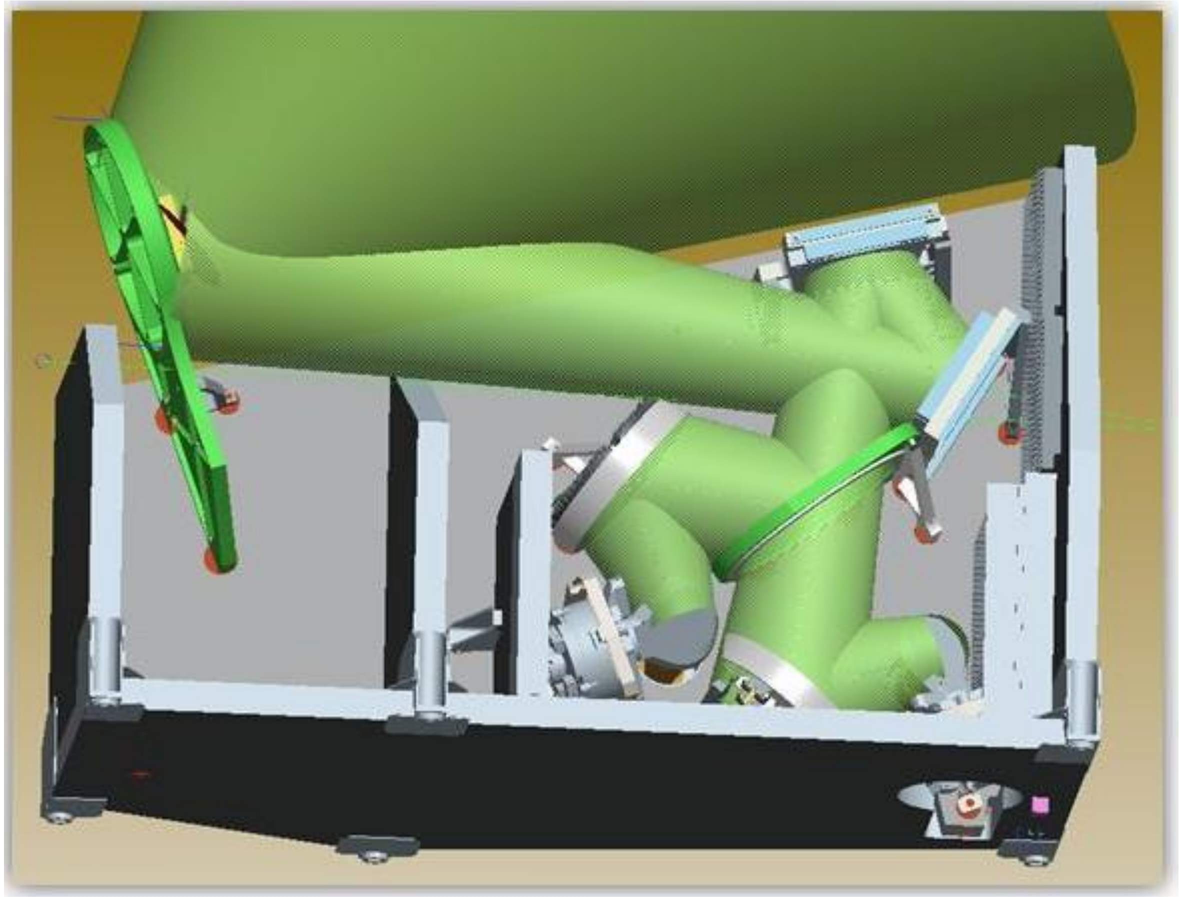
We need to have

- One-way Tx/Rx losses $\leq$0.5 dB
- Tx/Rx isolation >30 dB
- Tx-Rx Return loss >30 dB
- Tx-Rx Polarization purity >30 dB
- Transmit and receive polarisation CP
- Input polarisation to QO feed from transmit source is linear
- Output polarisation from QO feed to receiver also linear

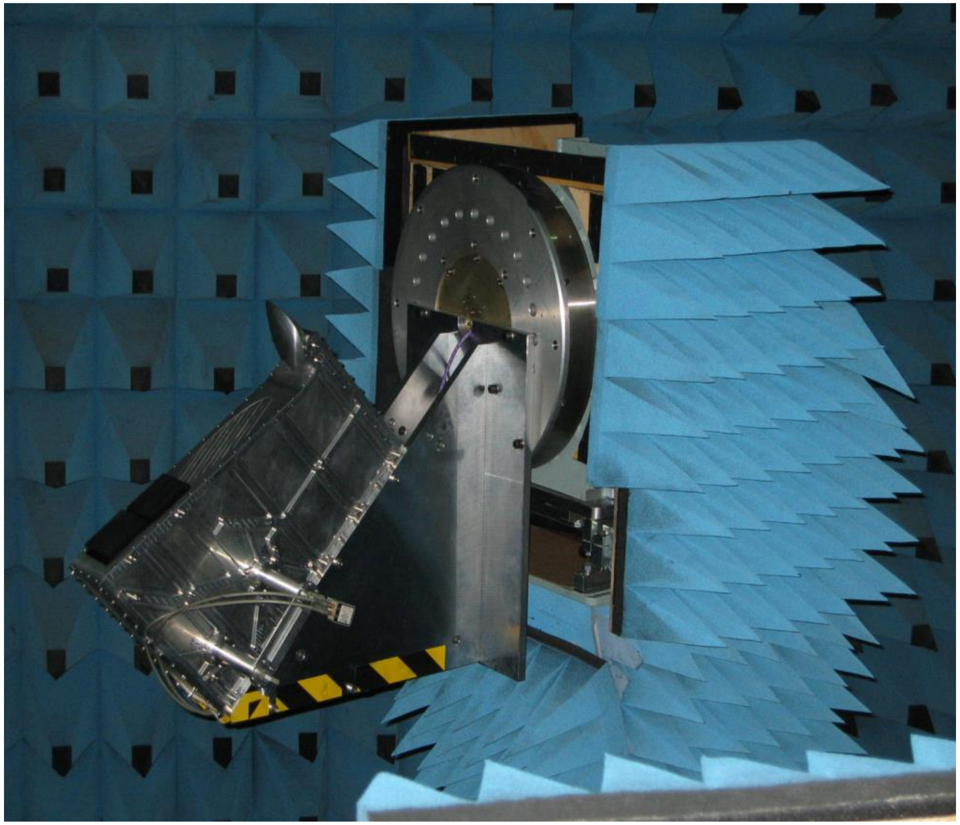
The QO scheme for EarthCARE's Radar



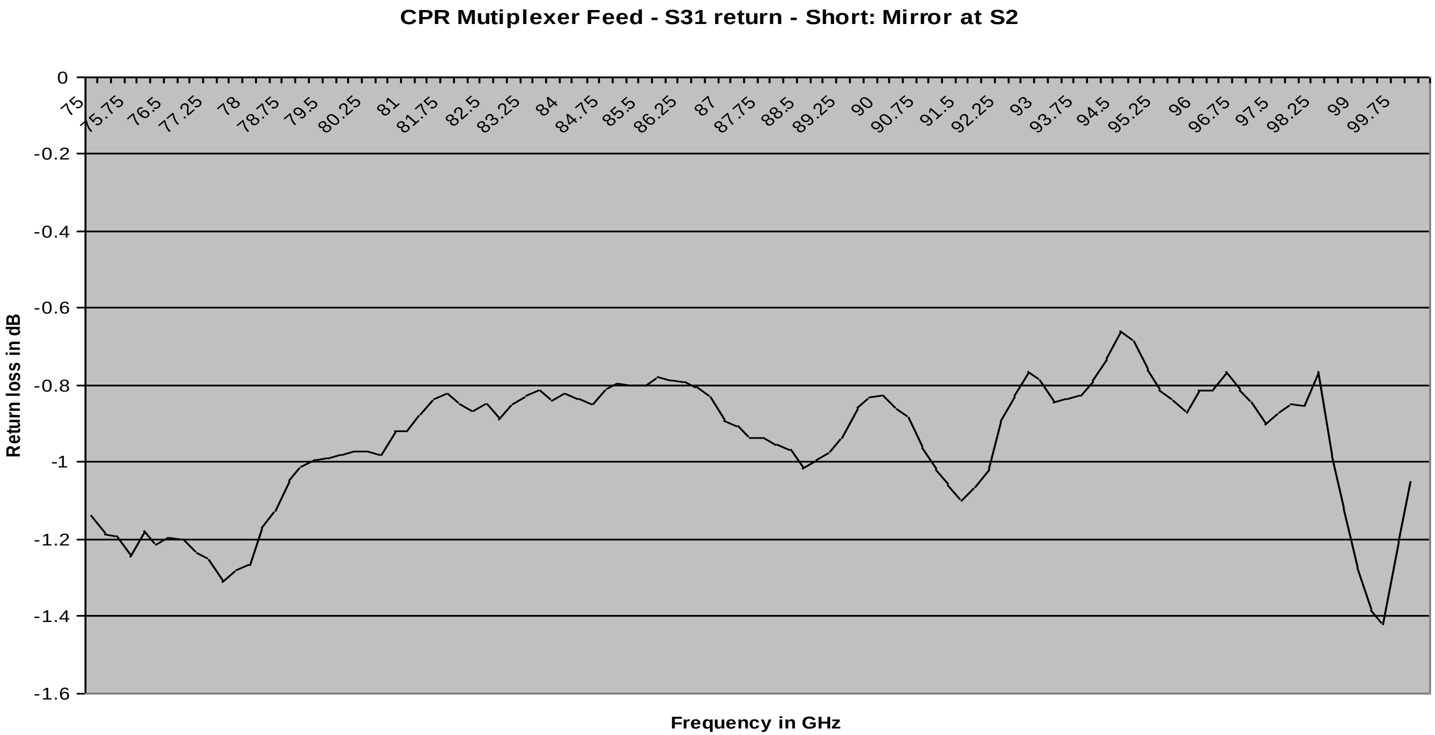
One of two corrugated horns attached to the sources transmits a beam to a mirror and is reflected up to a refocusing mirror following which it passes though an analyzing polarizing grid { and then though an Inatani-type Martin-Pupplet Diplexer acting as the CP polarizer . It then passes to the subreflectorand up to the main reflector .



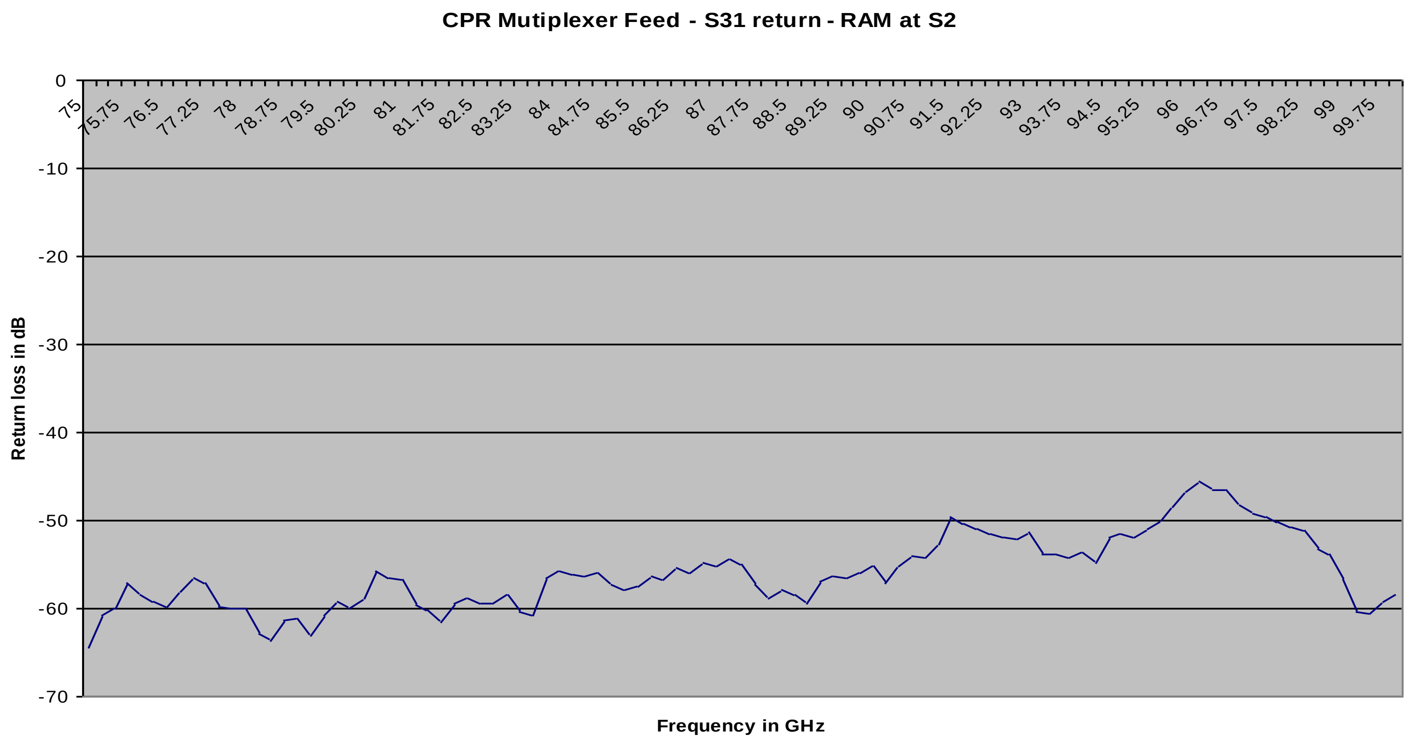
The green propagating beam shows the precise form of the beam moving though the optics and is a vital tool in insuring that there are no stray light problems within the structure



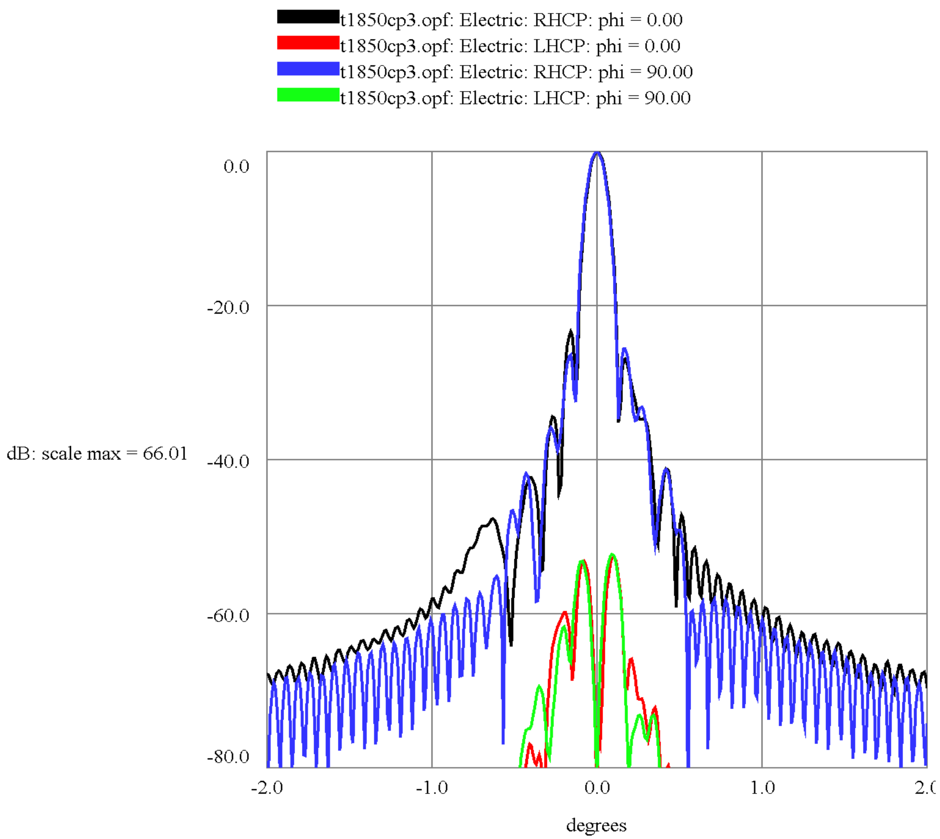
We have built a Breadboard/Engineering model of the CPR multiplexer, here mounted on the Calibrated Antenna range a the the UK's National Physical Laboratory in Teddington



Defining S1 as the source, S2 as the Sky and S3 as the Rx, this measurement show the transmit/receive losses are, at <0.8dB, well with the reguired single pass loss of 0.5dB

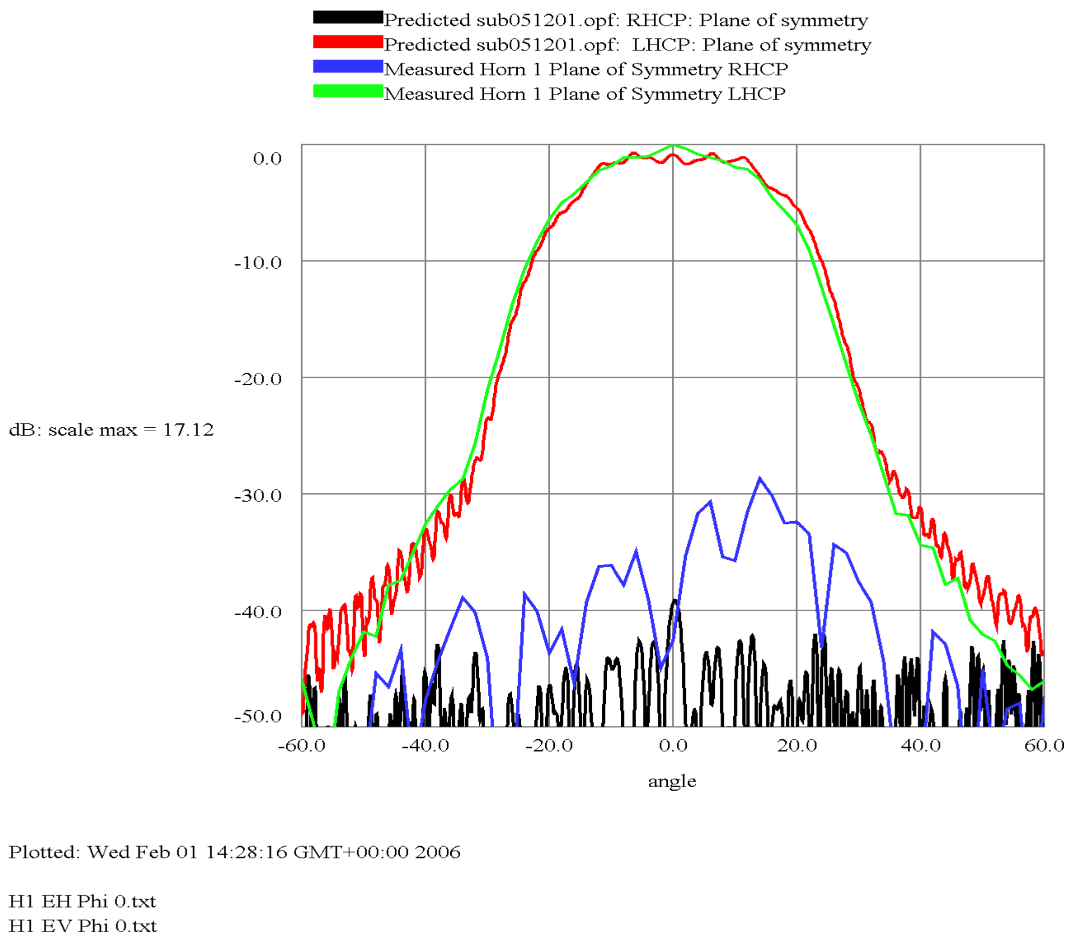


Now if we place good absorber at S3, rather than a matched reflector, the S13 transmission drops to less than -50dB, 20dB better than the specification



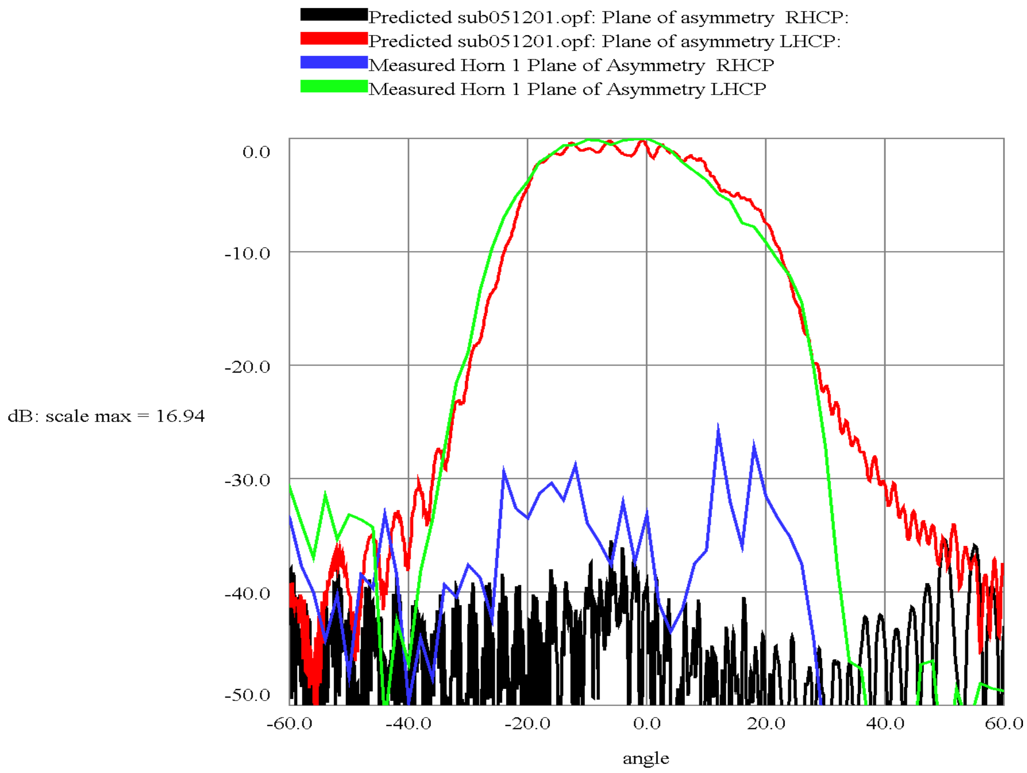
The multiplexer is also a the feed to an offset Cassegrain reflector based upon the Mitzugutch condition – the primary mirror has a focal length of 1850mm and is to provide a gain of 66 dB

Predicted full pattern of the CPR Antenna



These are predicted and synthetic measured CP patterns of the antenna – constructed from linear complex patterns – the NPL range has good enough stability to do this successfully.

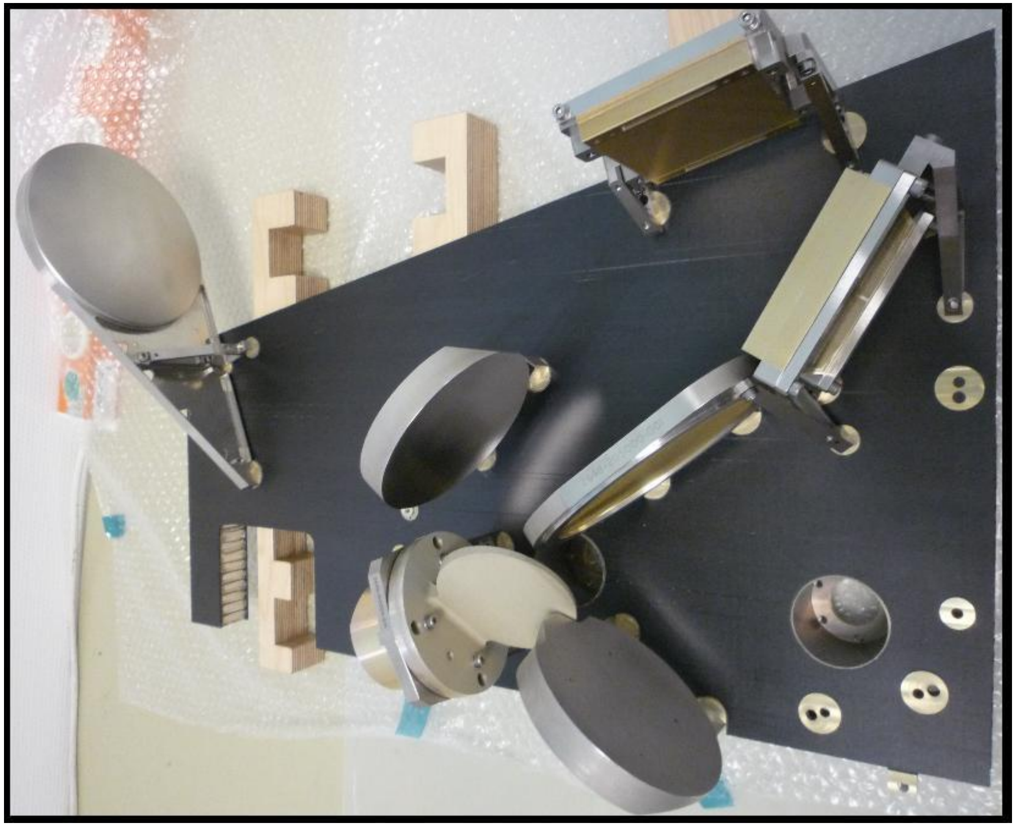
A good match is obtained, here in the plane of symmetry



Plotted: Wed Feb 01 14:29:34 GMT+00:00 2006

H1 EH Phi 90.txt
H1 EV Phi 90.txt

And here is the orthogonal pattern, in the plane of asymmetry, also showing good match



The TK Quasi-Optical Feed has been assembled by Astrium in Germany from TK supplied INVAR optics and is currently under test in Japan.

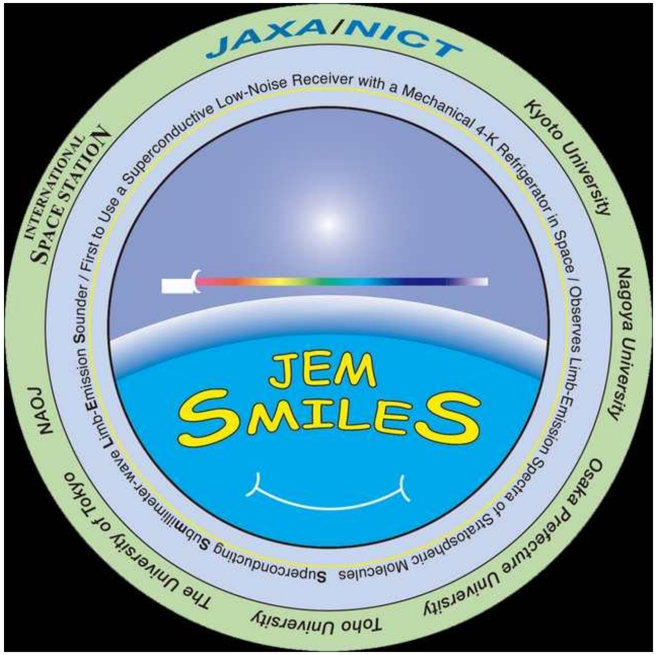
How to measure the atmosphere from space... or why Californian wine may be bad for you

Quasi-Optics used to sense BrO in the Stratosphere

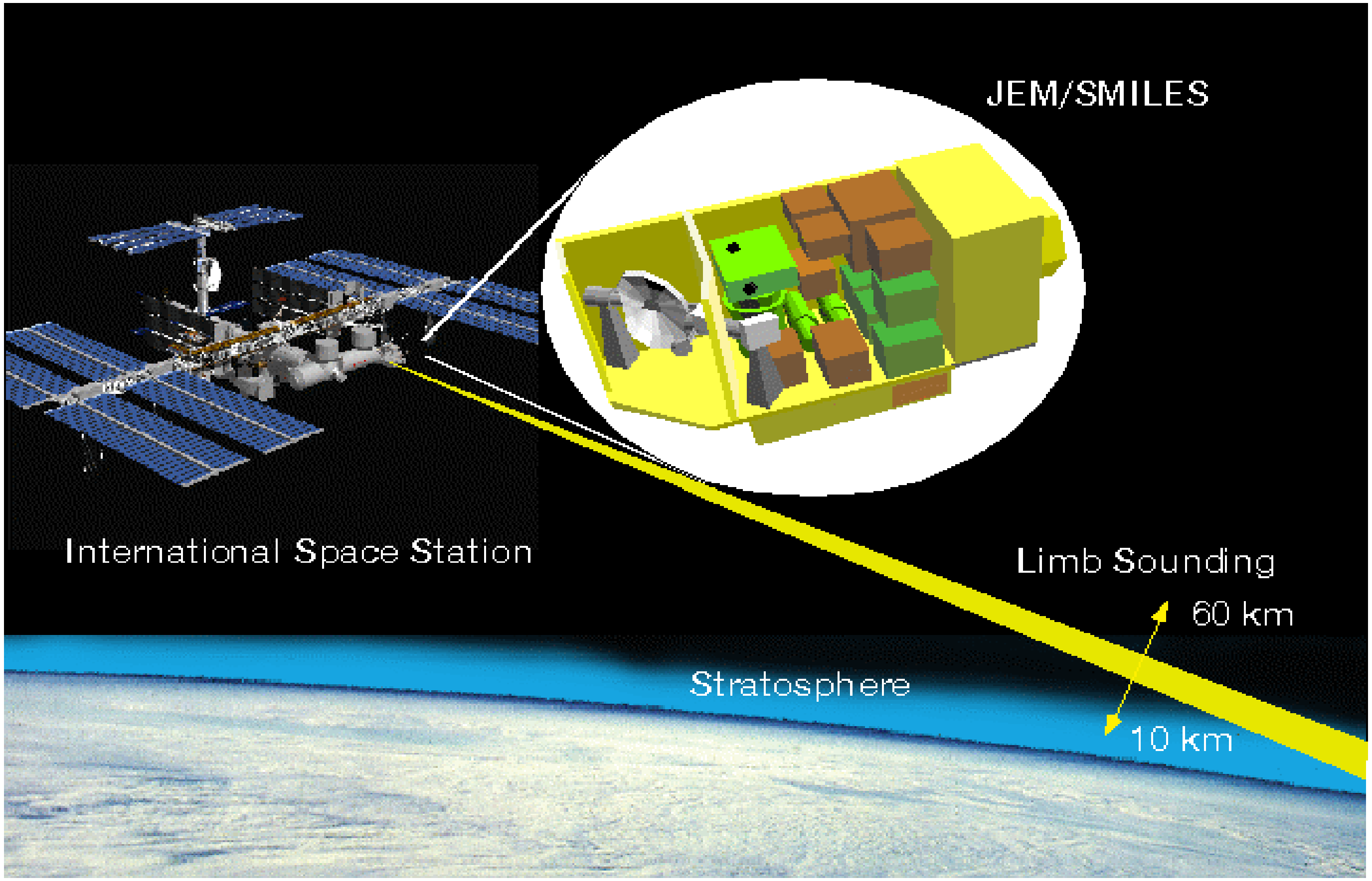
It is very important that we understand what Natural and Man generated processes are affecting the Atmosphere

Remote sensing in the THz region from Space is a powerful way to gather the information we need.

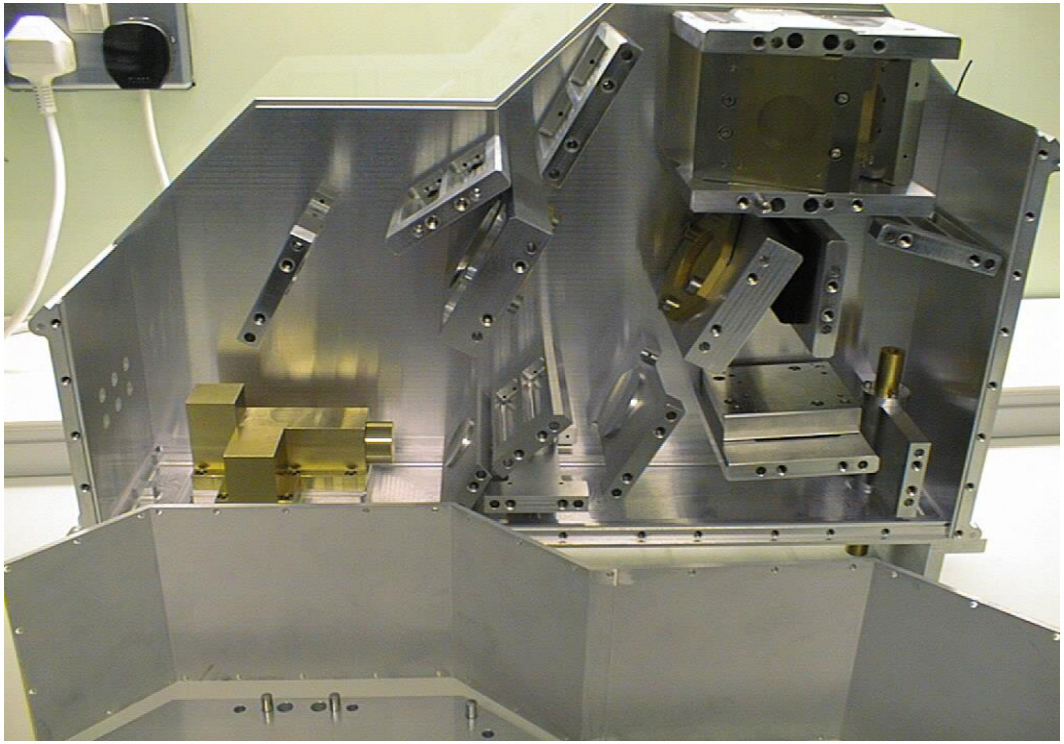
JEM/SMILES – the first SIS Receiver flow in Space looking at Ozone related Chemistry – including illusive BrO – which has a very weak signature in comparison, say, with ClO.



From the ISS at around 640 GHz



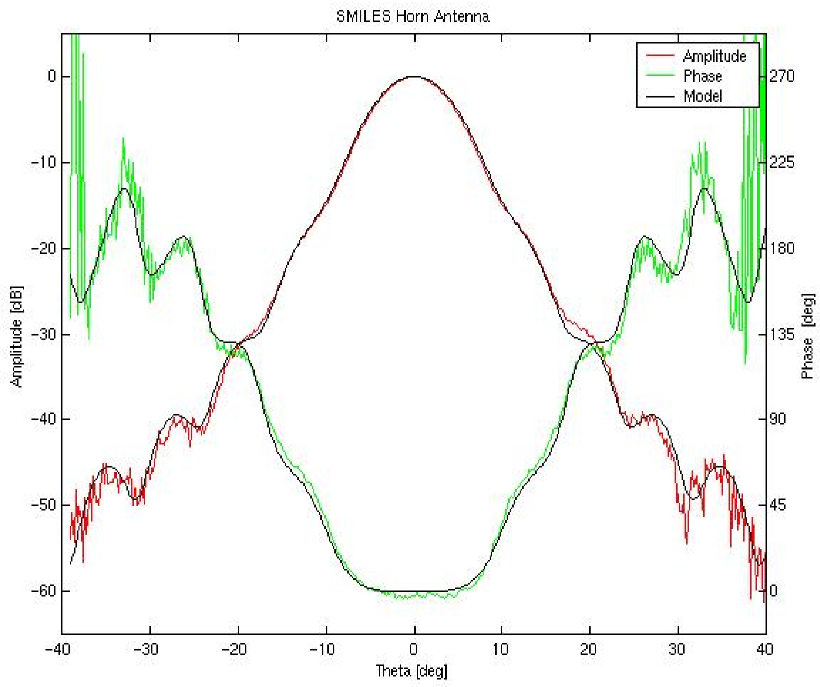
This is the EM of the Ambient temperature optics – where LO is injected and Single sideband filtering is applied



Work done in the IAP, Bern, by Axel Murk

Corrugated Horn manufacturing technology

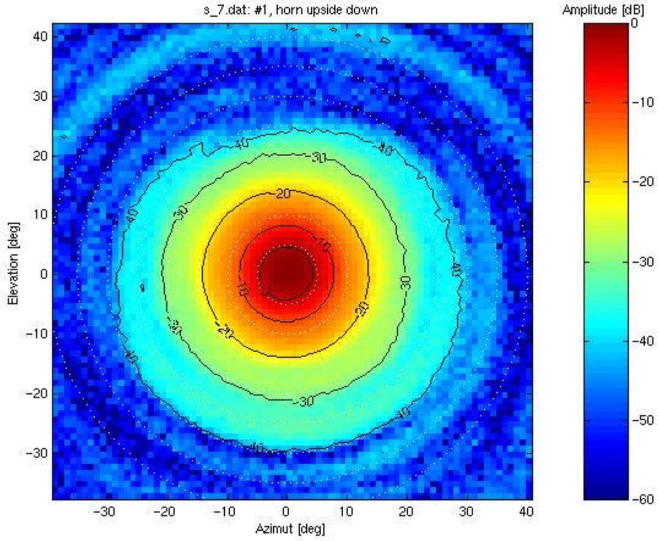
The ability to form and receive nearly pure fundamental Gaussian-beams, from signals generated / detected in single mode waveguide, is crucial to this QO technology: Corrugated horns do this -



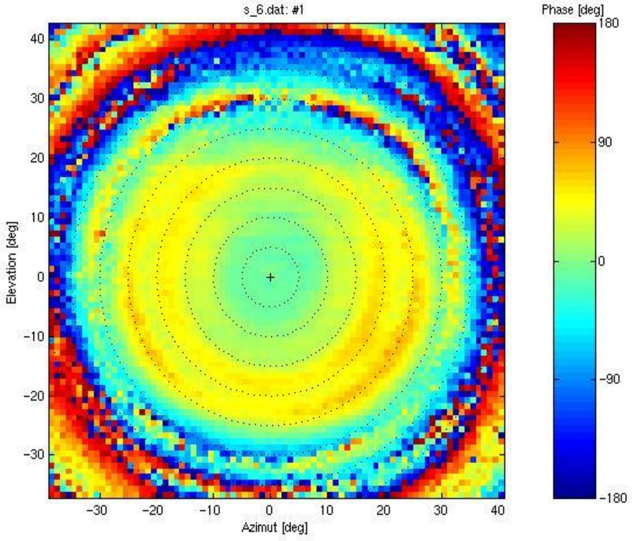
Theory and measurement of a Corrugated horn at 600 GHz

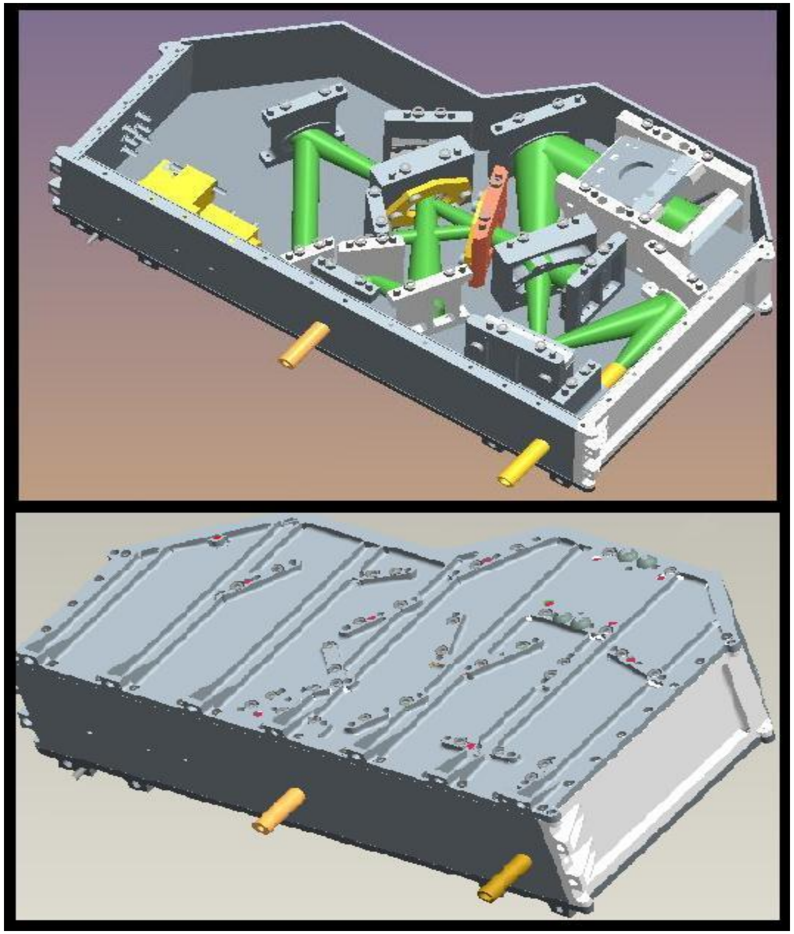
98% of the Energy leaving a corrugated horn is in the fundamental Gaussian Beam-Mode:

Amplitude



Phase

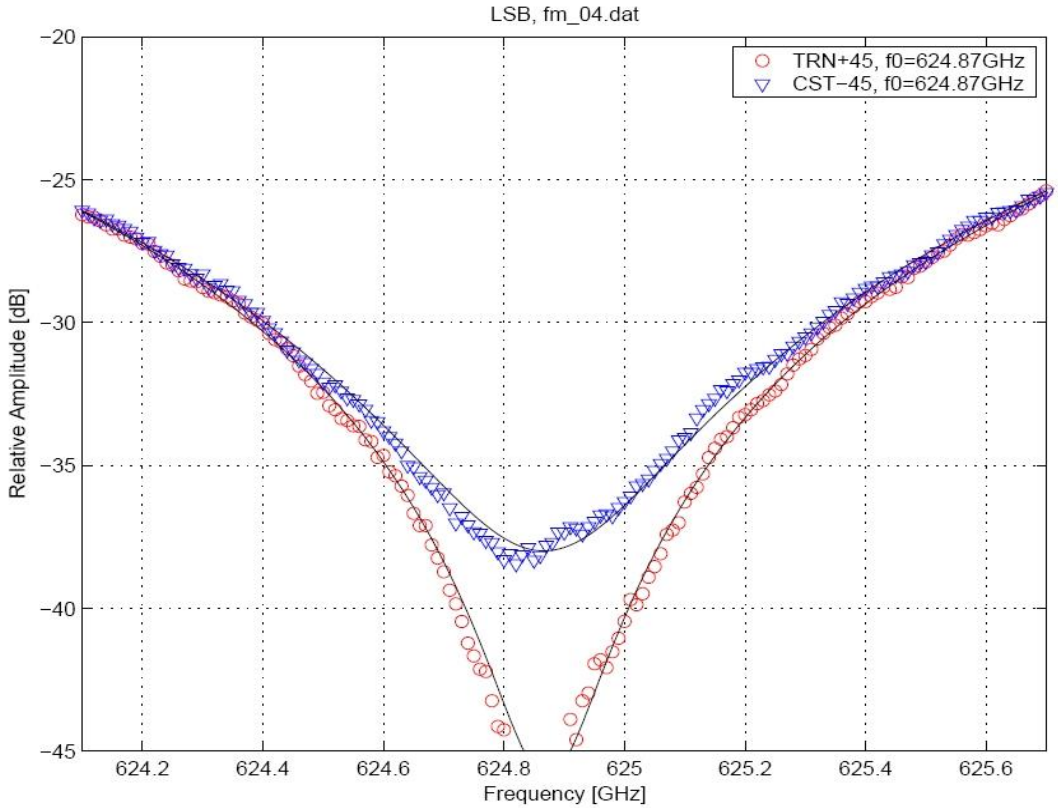




Upper image shows Gaussian beam modes propagating in the TK developed Pro/Engineer CAD design tool.

This tool allow rapid evaluation of Quasi-optical designs within an exact mechanical environment

AB VNA Measurements of SSB performance



AB VNA Measurements of SSB performance

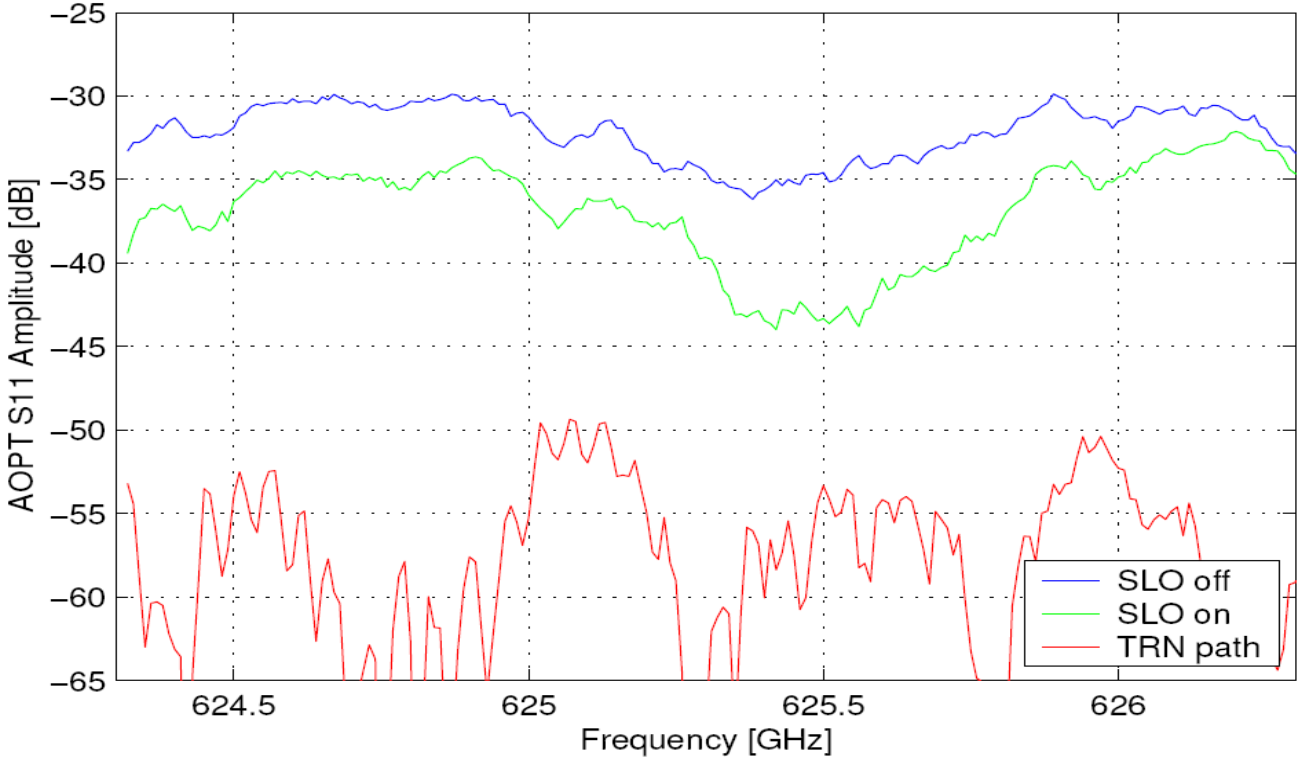


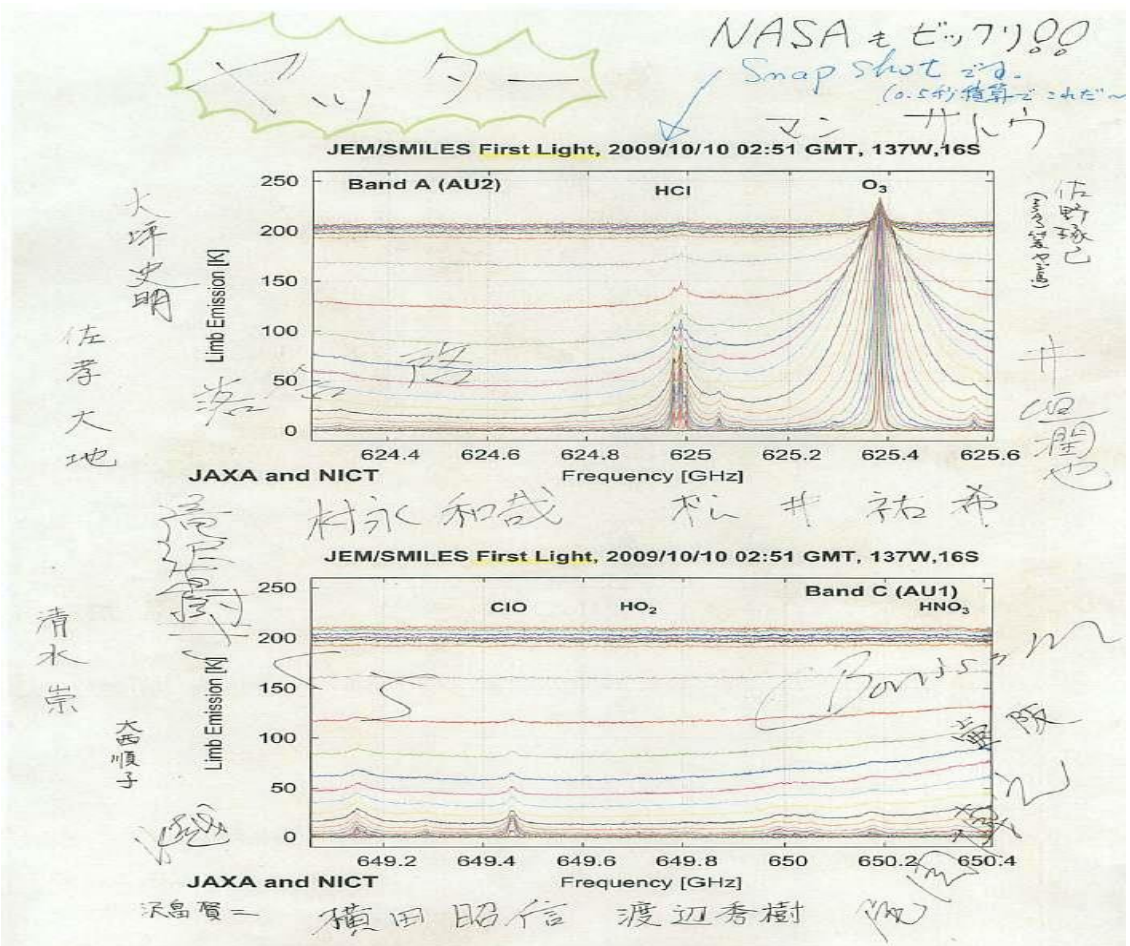
Figure 8: LSB Reflection measurements of the TRN path (red) and of the CST path when the SLO is switched off or on (blue and gree).

SMILES is at lower right on this picture of the ISS (Credit: NASA)

Smiles WWW Log 7th Oct 09

The initial checkout is still going on.
Today JEM/SMILES opened its "eye". As a part of the end-to-end checkout, JEM/SMILES observed Submillimetre signal through the primary antenna aiming the antenna toward deep space.
Today's checkout was fine, and interesting technically. In addition to 3-Kelvin radiation from the deep space, JEM/SMILES sometimes received strong signal when the ISS's huge solar paddle partially blocked the view of JEM/SMILES.

First Light results from JEM/SMILES



The results obtained from SMILES - given the orbit of the ISS - provide unique information on the changing levels of trace gasses during the daily (diurnal) cycle – information not available from instruments in Polar orbit

BrO at 650 GHz from JEM/SMILES

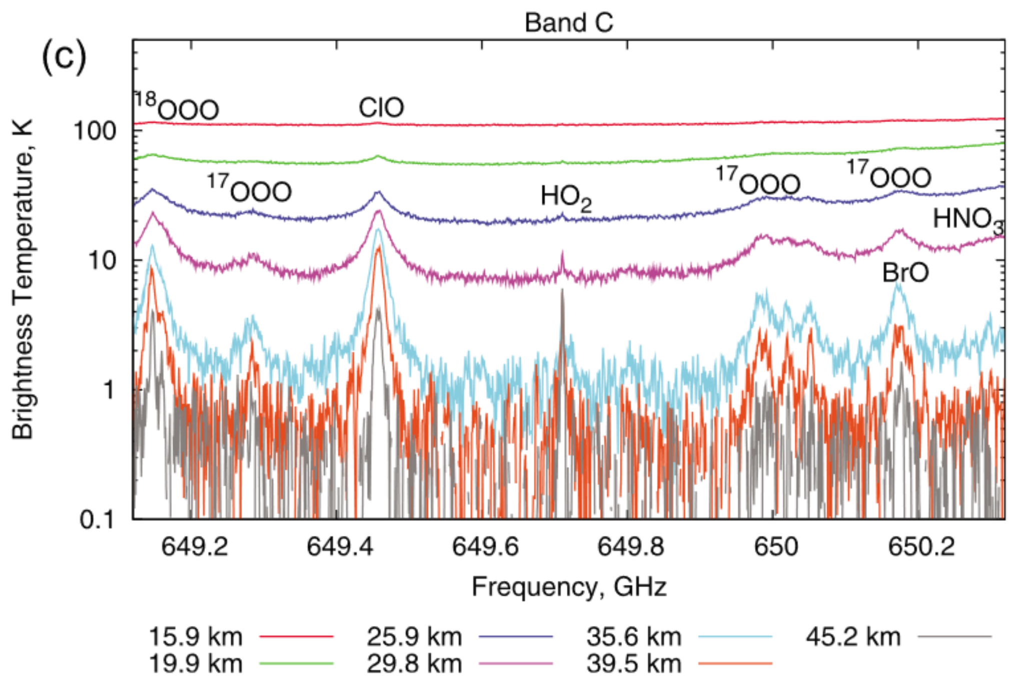
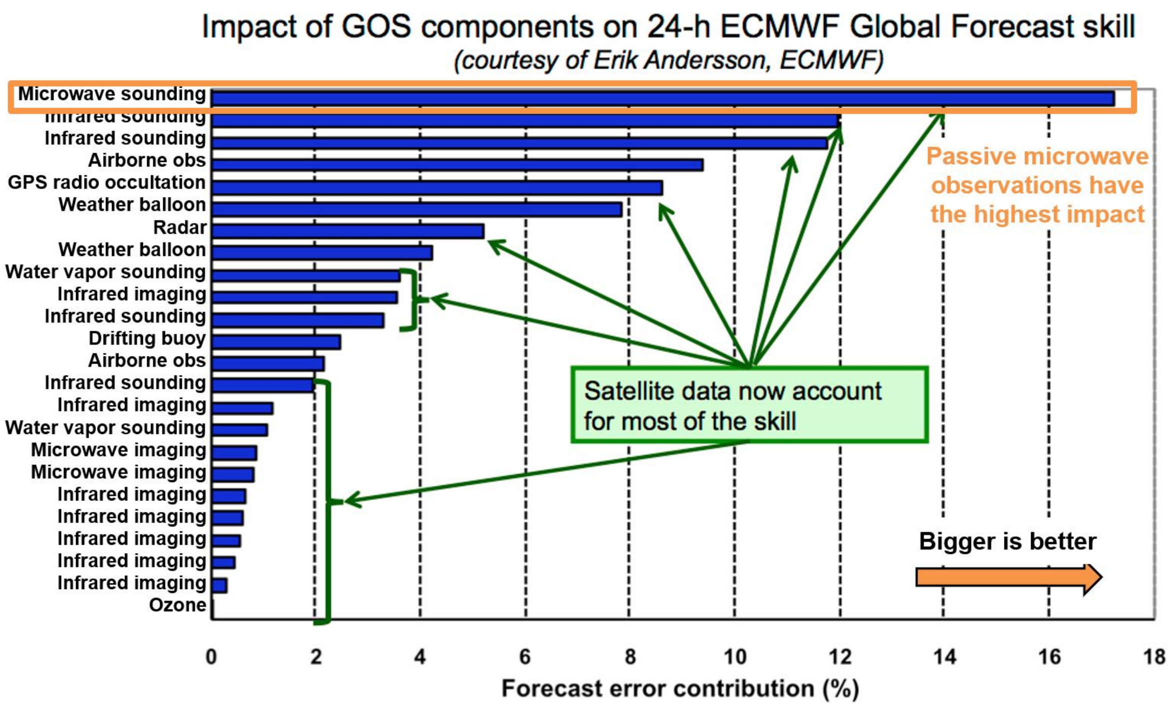
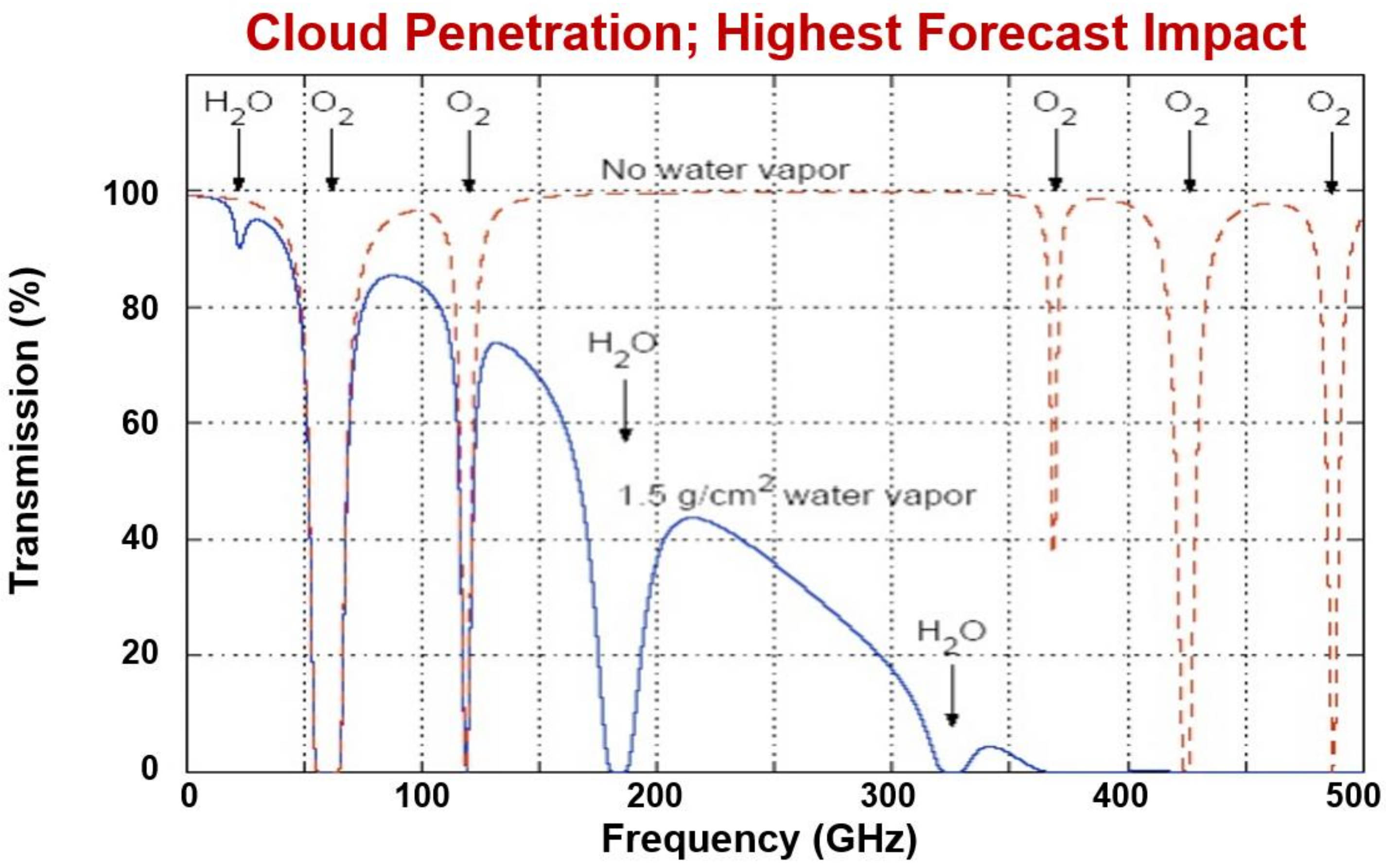


Figure 4. Observed spectra at several altitudes for (a) Band A, (b) Band B, and (c) Band C. Band A and C measurements were done at 03:22:14 UT on 12 October 2009 at 23.30°N and 173.83°E. Band B measurements were made at 00:53:32 UT on 17 October at 21.52°S and 138.83°E; latitude/longitude and time information is defined at 30 km along the scan.



Microwave instruments provide much of the data for short term forecasting


Cloud Penetration; Highest Forecast Impact
H2O
O2
O2
O2
O2
O2
No water vapor
H2O
1.5 g/cm2 water vapor
H2O
100
80
60
40
20
0
0
100
200
300
400
500
Transmission (%)
Frequency (GHz)

Now moving to operational instruments – Sat A of Metop-SG

EumetSAT MetOP-SG Micro Wave Sounder

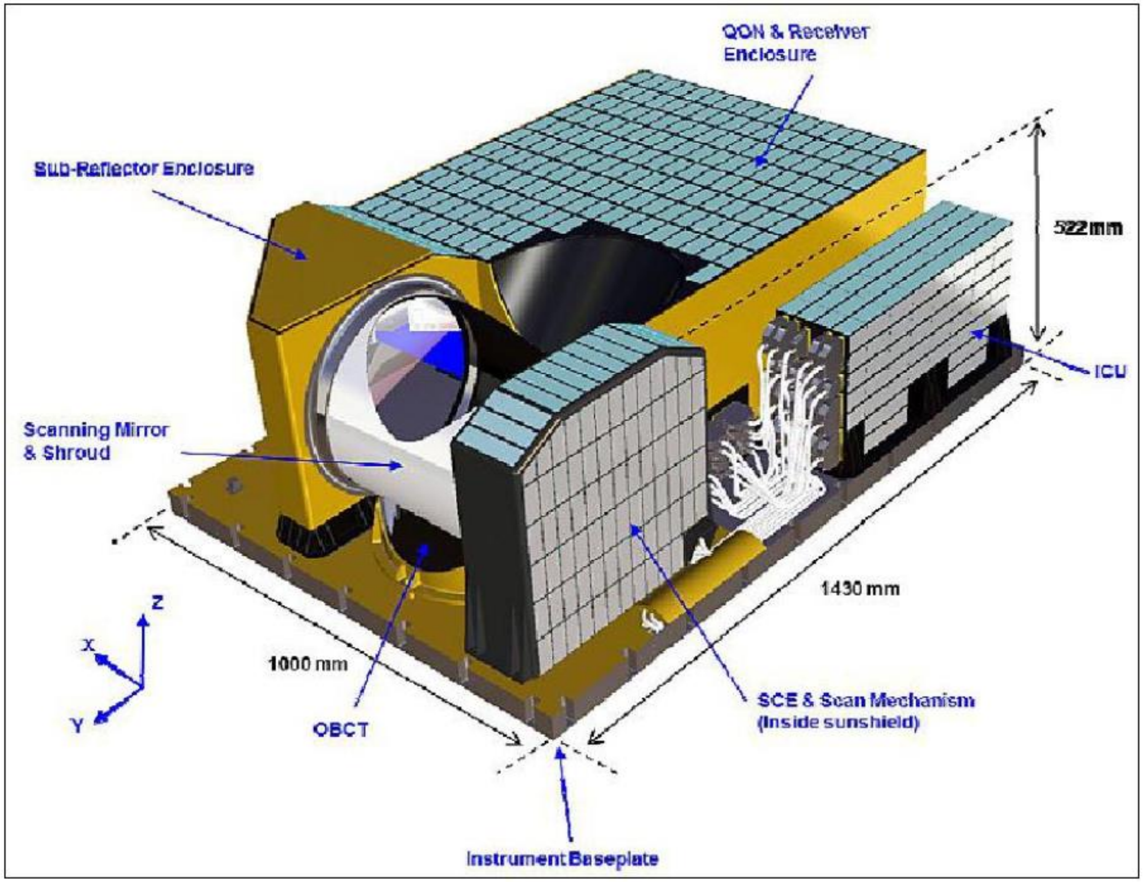
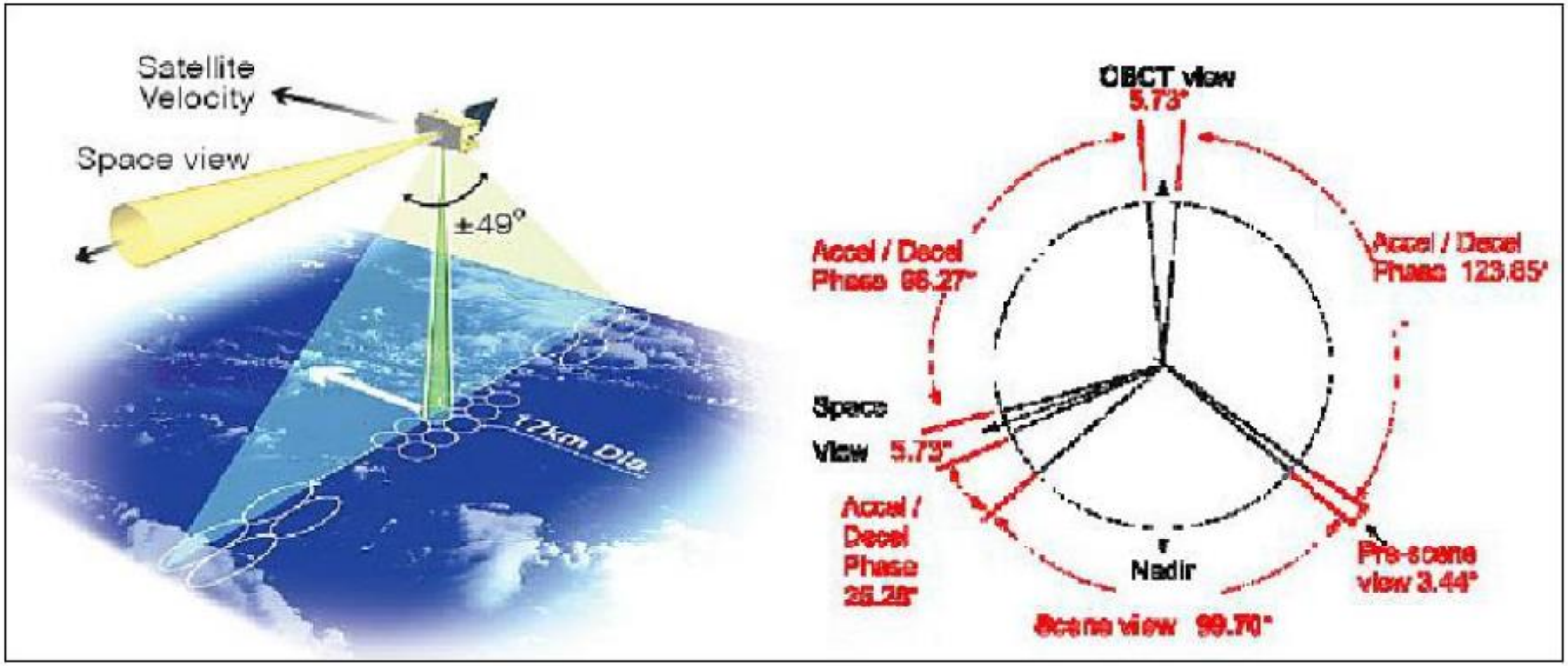


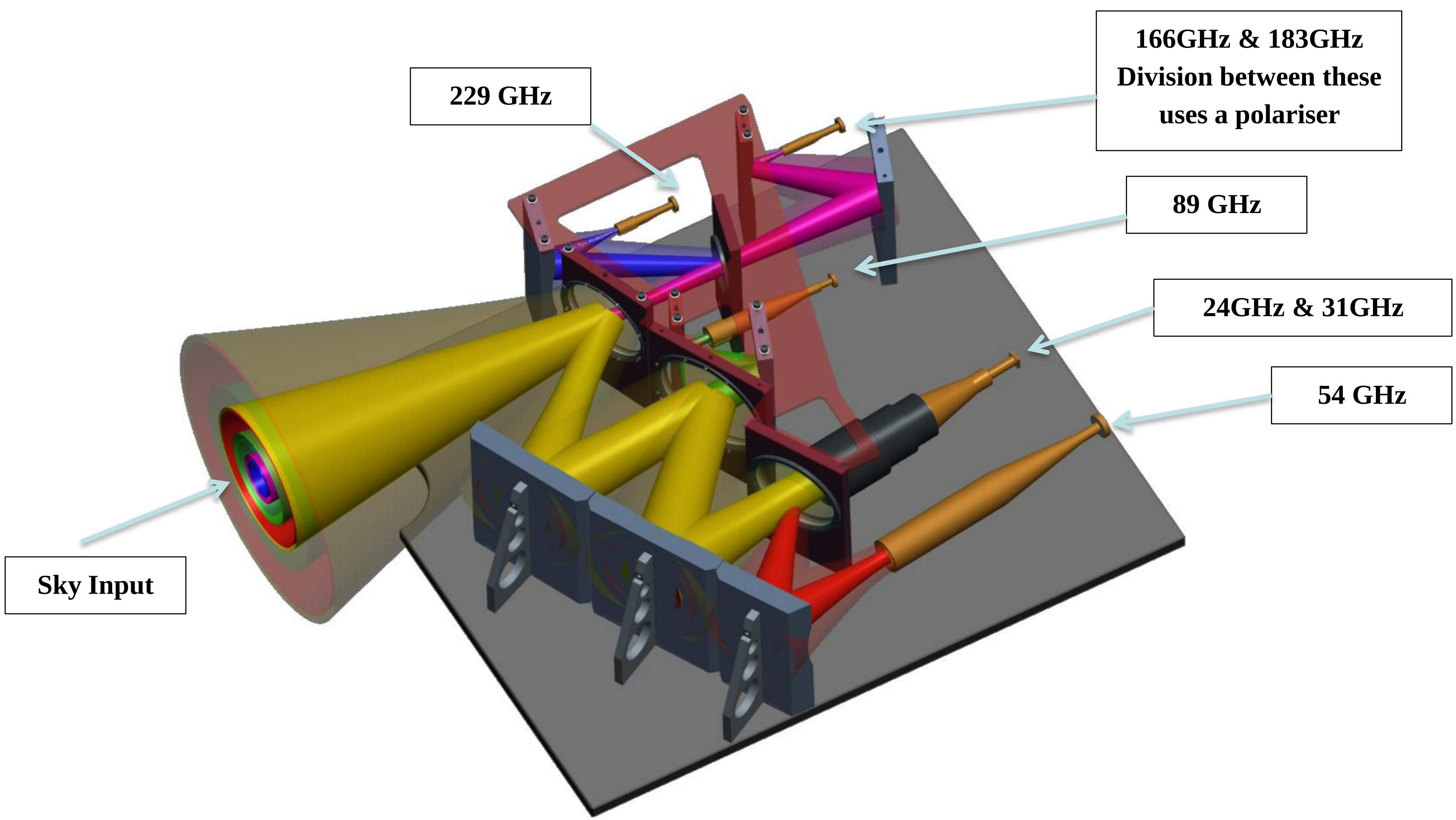
Figure 15: Configuration of the MWS instrument (image credit: Airbus Defence and Space)

The MWS is an cross-track scanning microwave radiometer, measuring the total power, atmospheric brightness temperature in 24 channels over the frequency range from 23.8 GHz up to 229 GHz. The instrument provides measurements of temperature and humidity (water vapor) profiles and total liquid water columns.

EumetSAT MetOP-SG Micro Wave Sounder



Quasi-Optical Concept



Very detailed Structural and Thermal Analysis needed

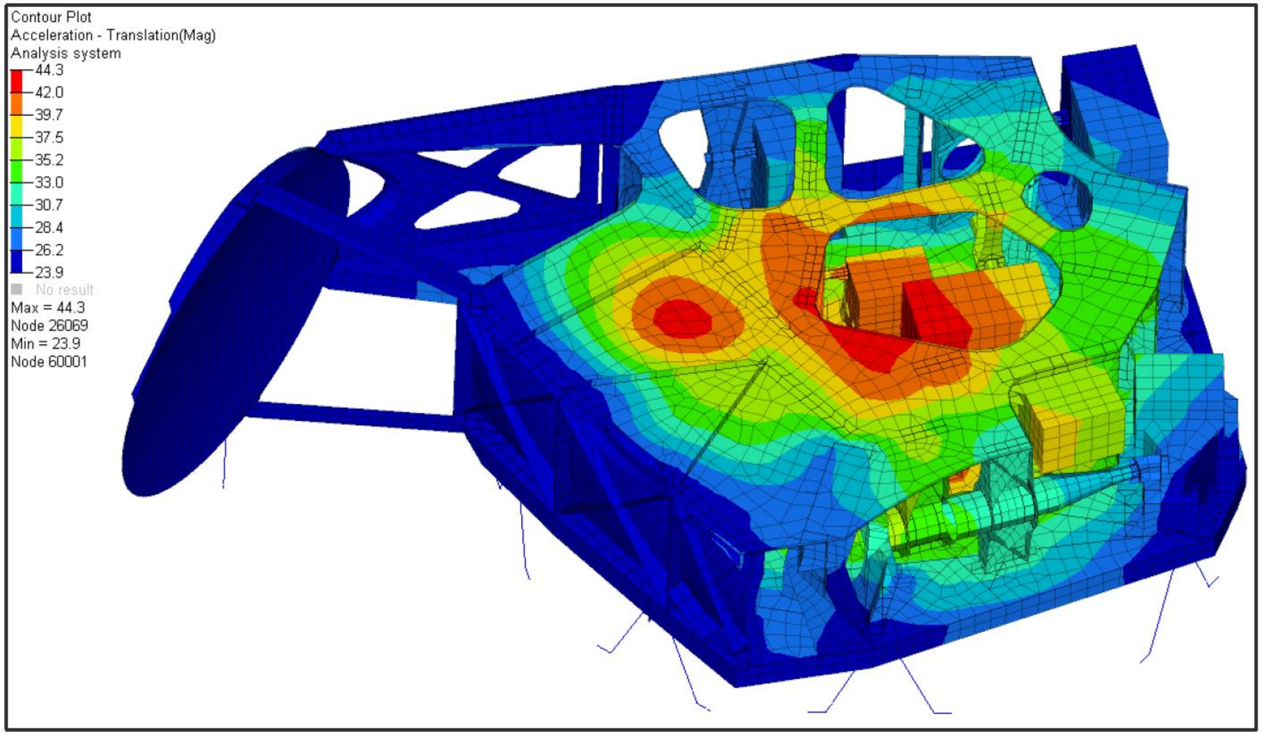
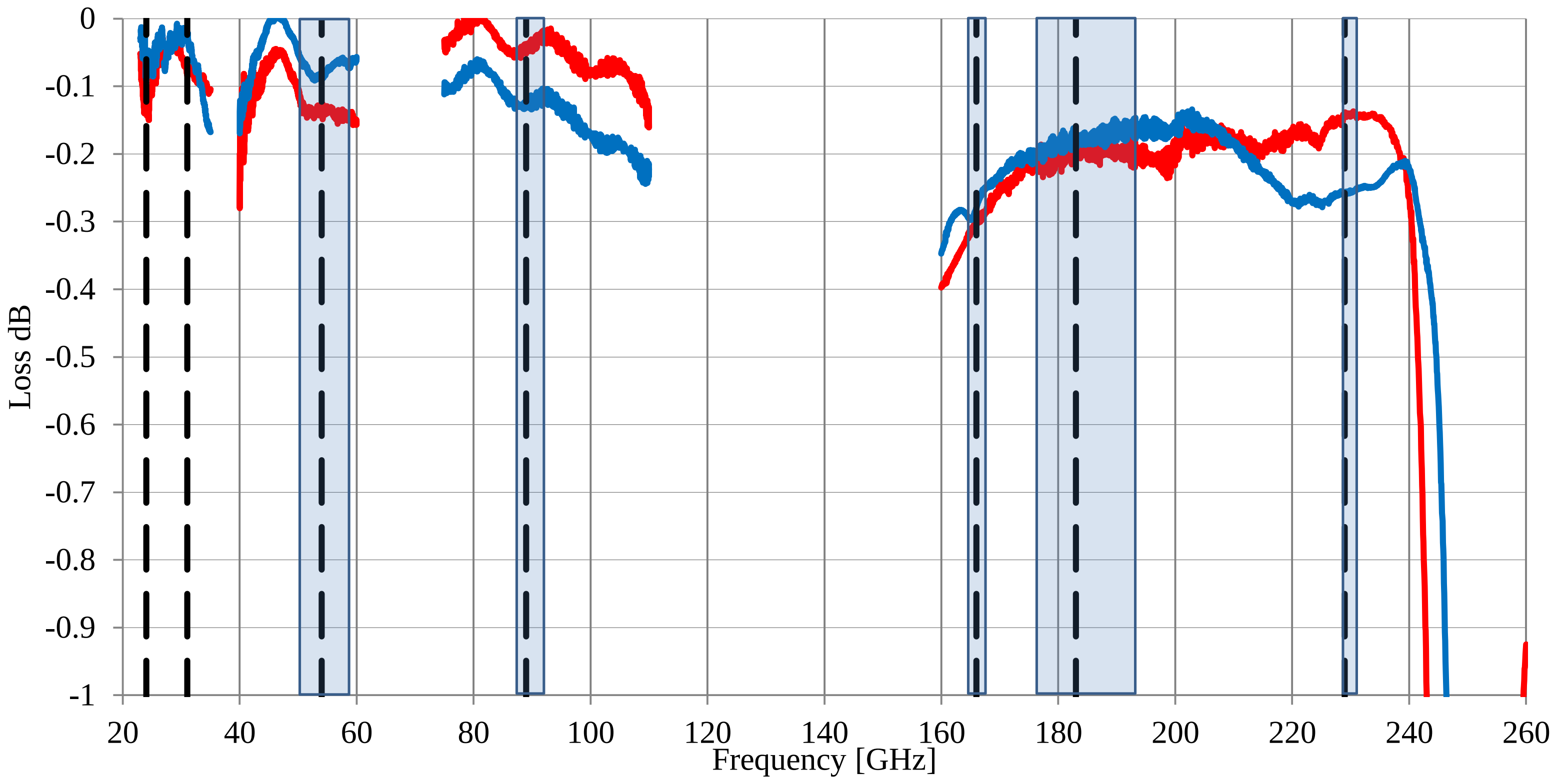


Figure 6-15: Sine Vibration, Acceleration Response (in g) to Z-Direction Excitation

Dichroic D1 – High Pass at 128GHz

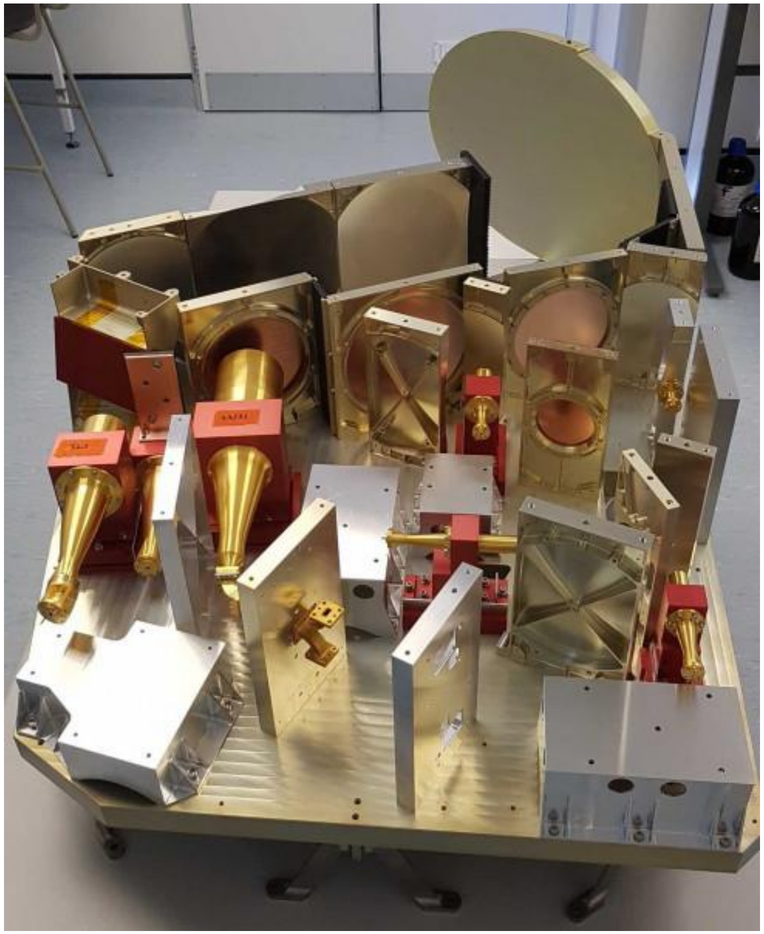


P state polarisation - **red lines**, **S** state polarisation - **blue lines**

Summary – Dichroic Performance within requirements

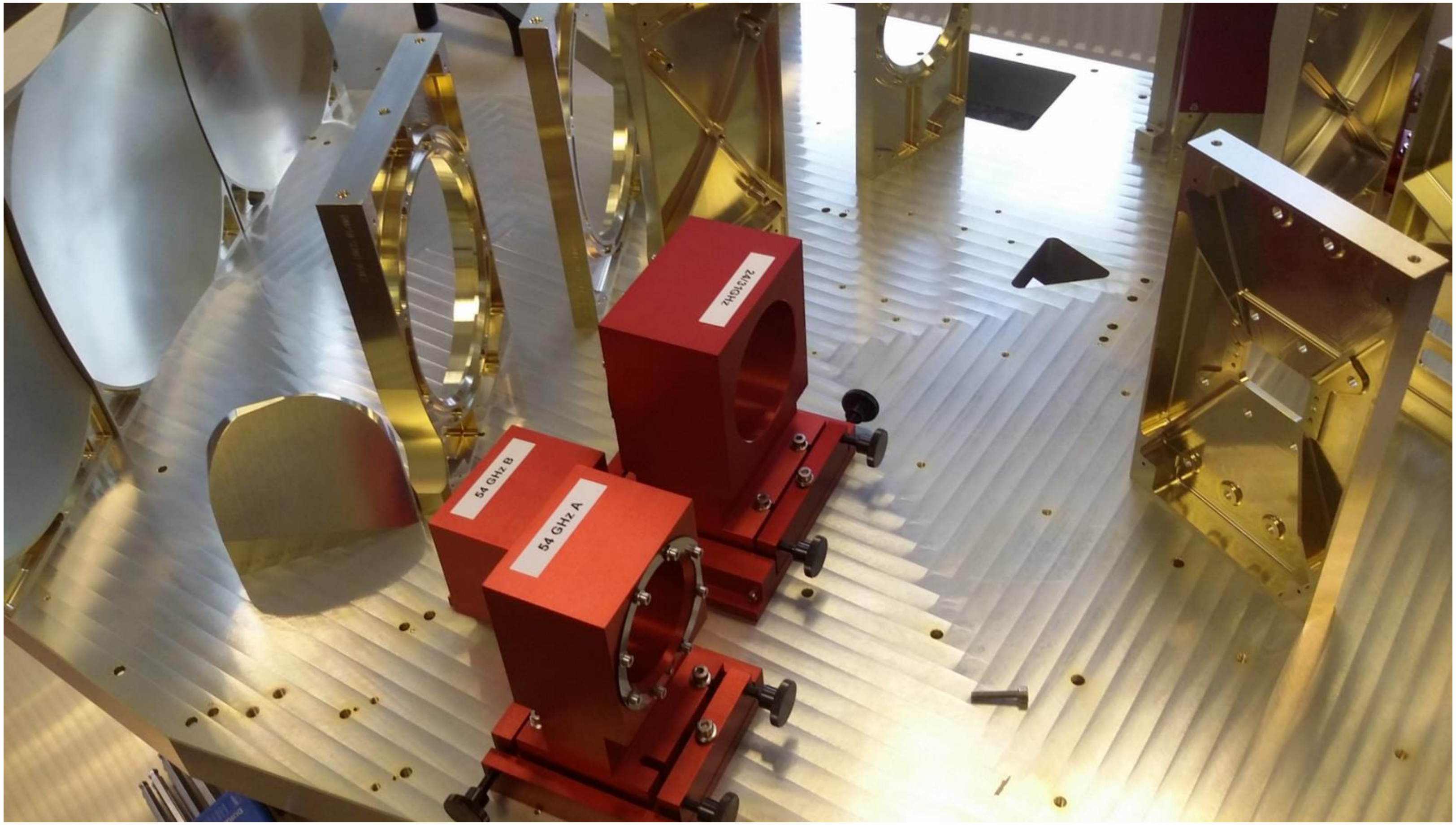
Dichroic	ID	24GHz	31GHz	54GHz	89GHz	166GHz	183GHz	229GHz
D1	W2236	0.13	0.07	0.13	0.13	0.30	0.20	0.26
D2	W2234	0.08	0.05	0.07	0.25	0	0	0
D3	W2238	0.01	0.09	0.09	0	0	0	0
D4	W2222	0	0	0	0	0.10	0.15	0.20
Total dichroic Loss		**0.22**	**0.21**	**0.29**	**0.38**	**0.40**	**0.35**	**0.46**
QON Loss		0.35	0.335	0.2	0.18	0.16	0.16	0.40
Total QON + Dichroic Loss		0.57	0.545	0.49	0.56	0.56	0.51	0.86
Total QON + Dichroic Loss in Proposal		**0.77**	**0.77**	**0.68**	**0.60**	**1.41**	**1.42**	**0.67**
Specification		**< 0.87**	**< 0.87**	**< 0.94**	**< 1.2**	**< 1.5**	**< 1.5**	**< 1.2**

MetOP-SG MWS EQM

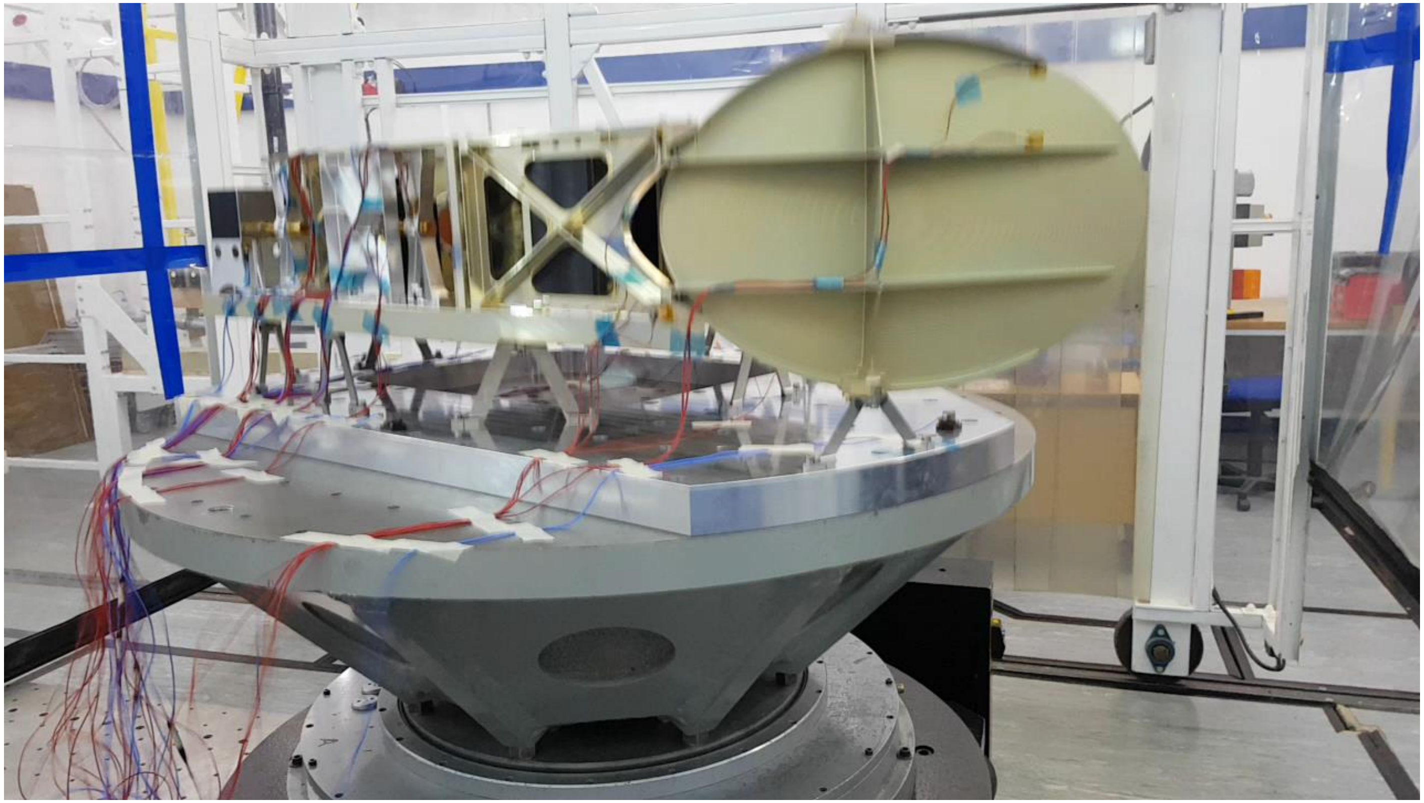


MWS is part of an ESA funded programme, with TK's customer being AIRBUS in the UK. The views expressed herein in no way be taken to reflect the opinion of the European Space Agency.

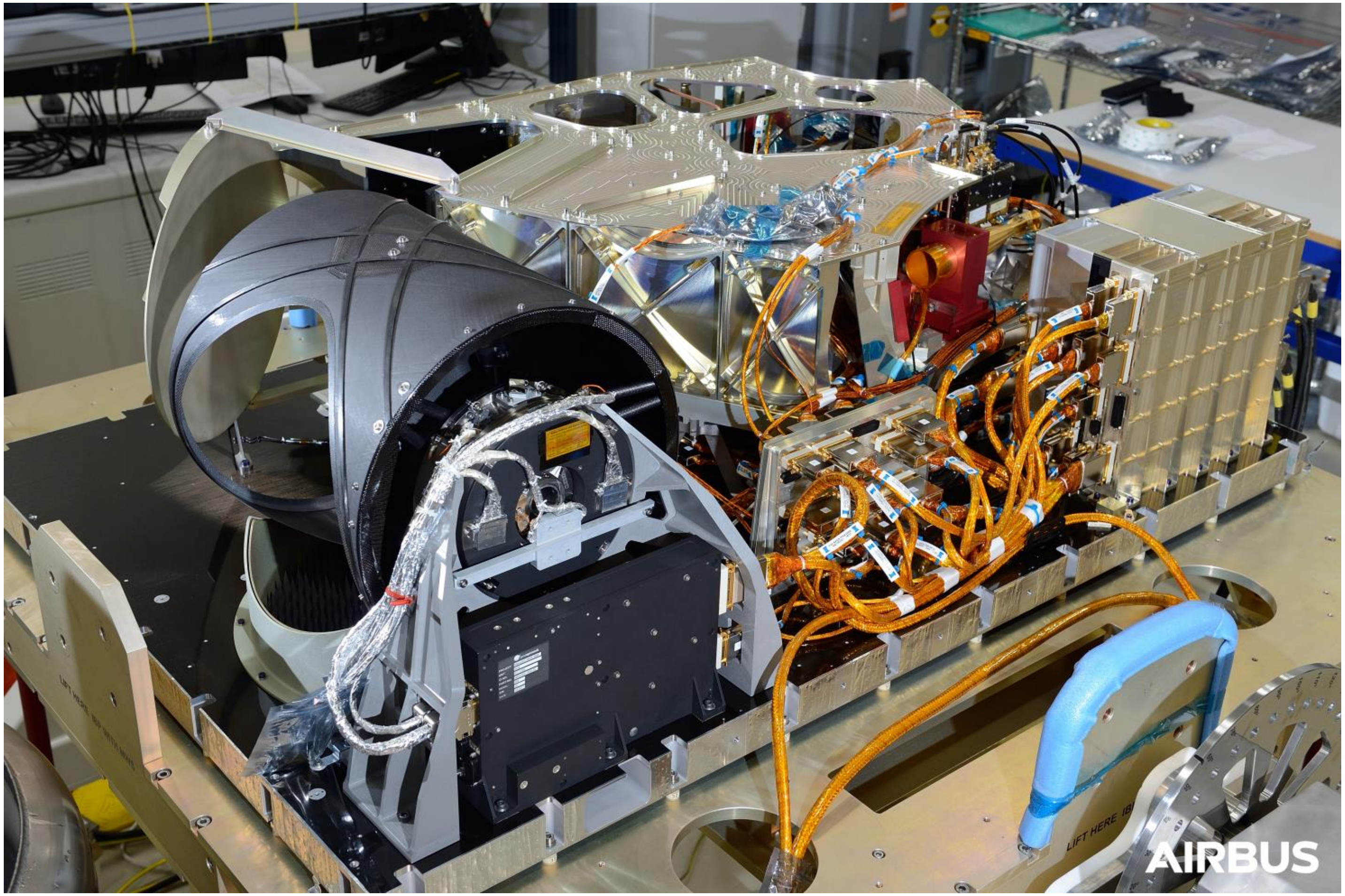
EQM hardware – Red bits are not to fly



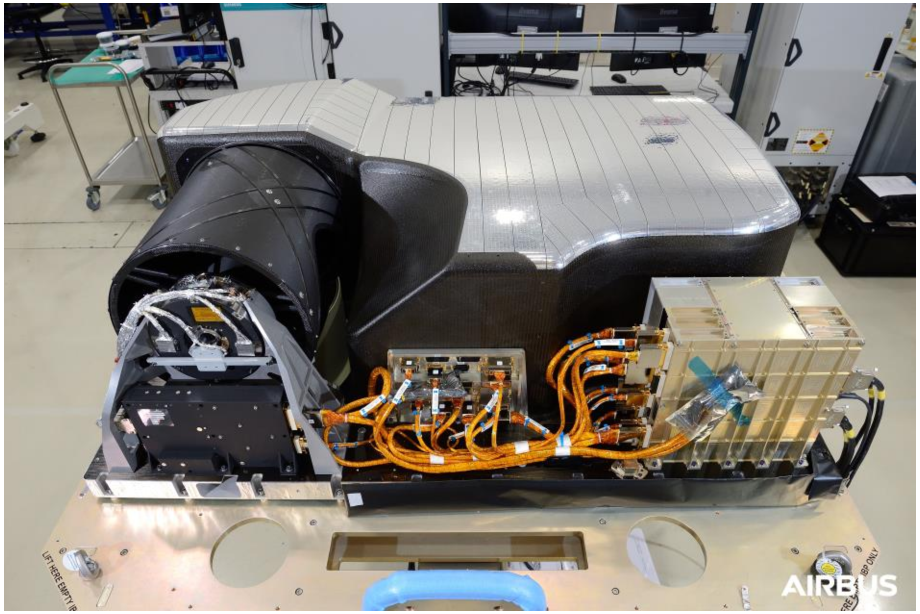
MetOP-SG MWS EQM – 24g RMS

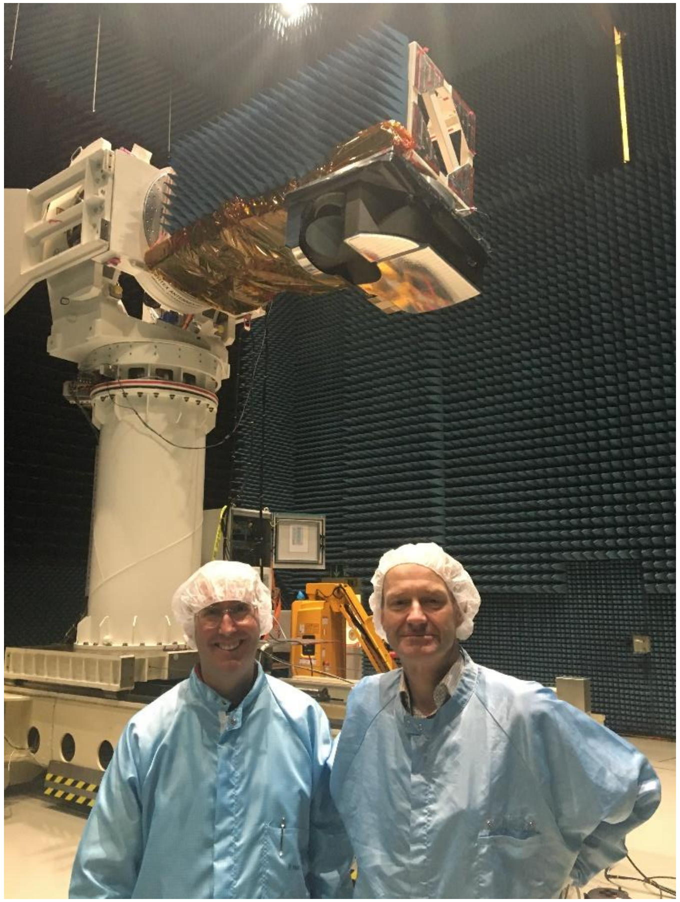


MetOP-SG MWS EQM

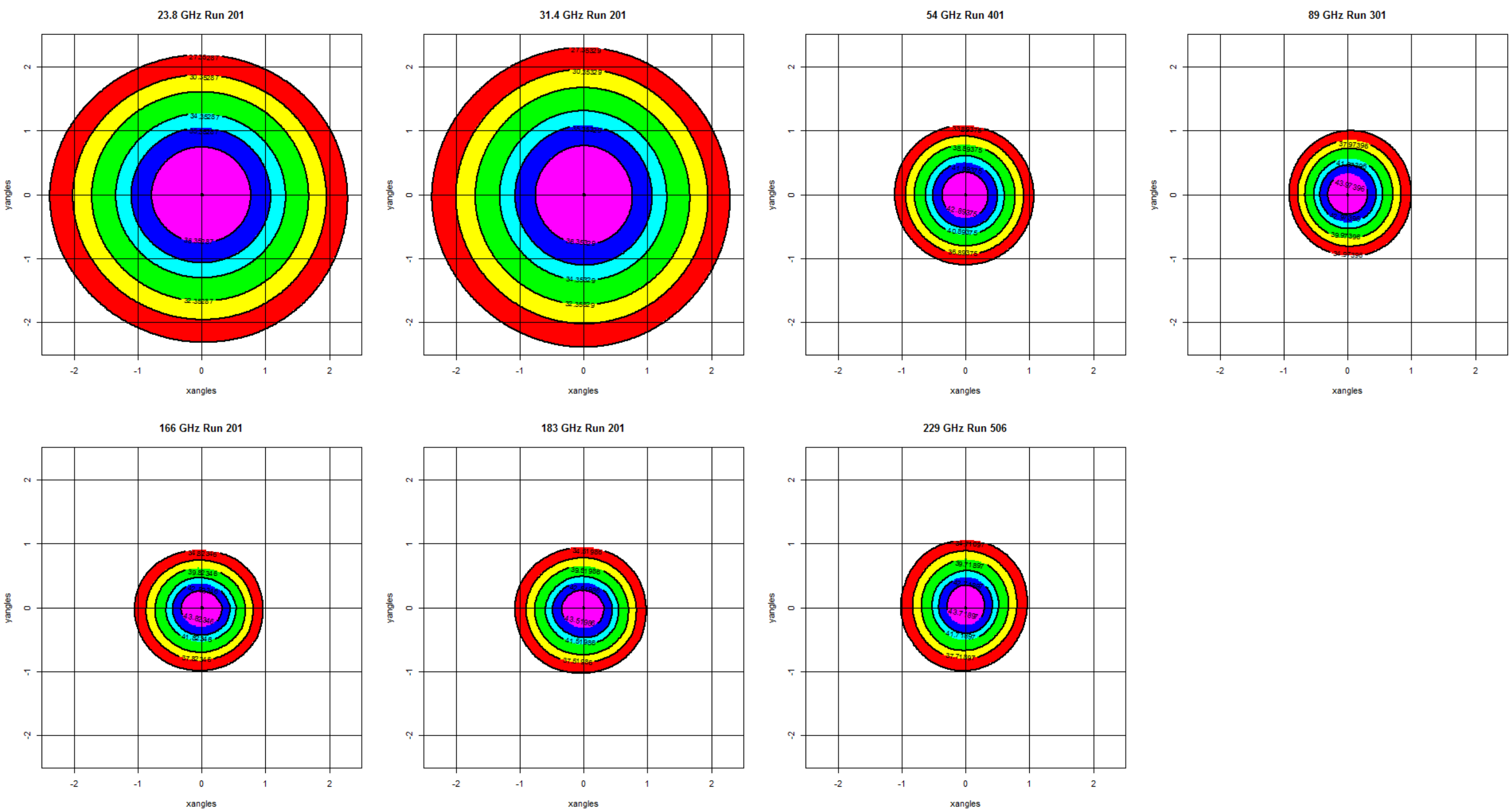


MetOP-SG MWS EQM – On the AIRBUS Ottobrunn Antenna range





And – Beam Performance within requirements



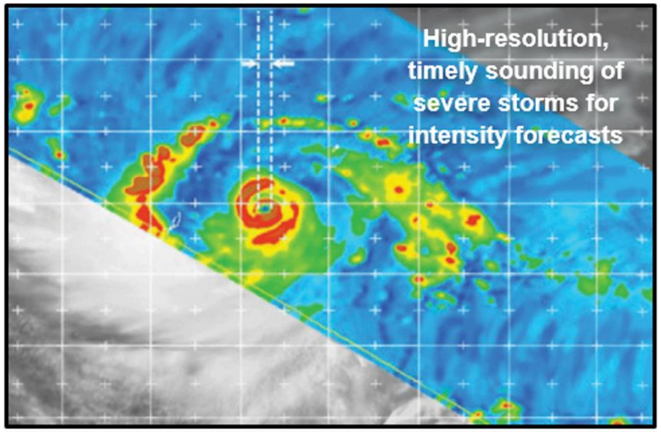
Contours are at (approximately) -1, -2, -3, -5, -7 and -10 dB.

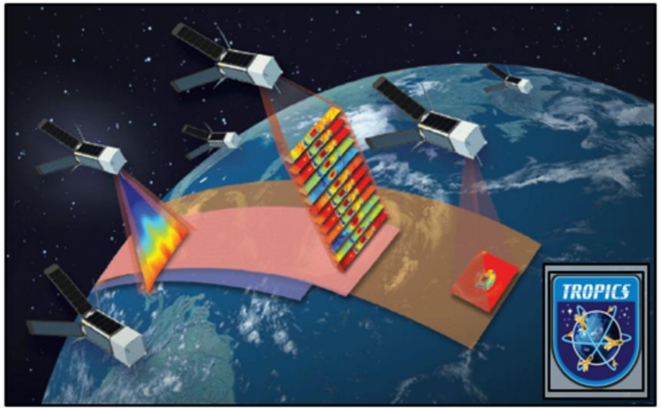
TROPICS

Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats

TROPICS – a NASA Earth Venture Instrument program – awarded March 2016

- **Innovative solution to provide data for severe storm intensity forecasts**
  - **Timely: 30 minute data update**
  - **Cost-effective: $30M + launch**
  - **Improved performance: all-weather retrievals of temperature, water vapor, precipitation, and cloud properties**
- **CubeSat constellation**
  - **4.5 kg, 10 Watts, 34cm x 10cm x 10 cm (each cubesat)**
  - **MIT LL 12-channel passive compact microwave radiometer**
- **Three 2020 launches provided by NASA to populate the constellation**

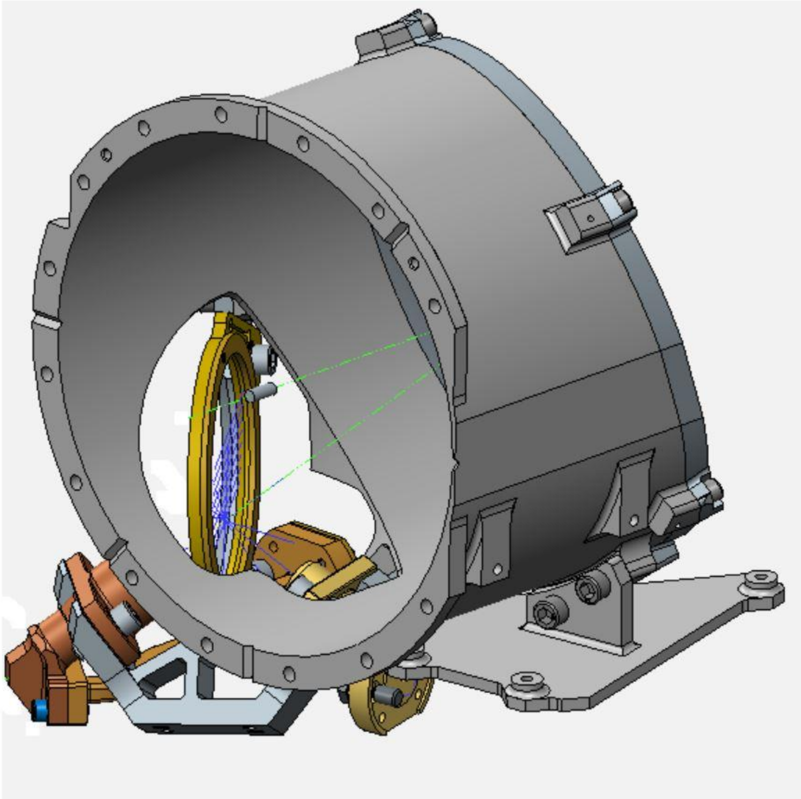




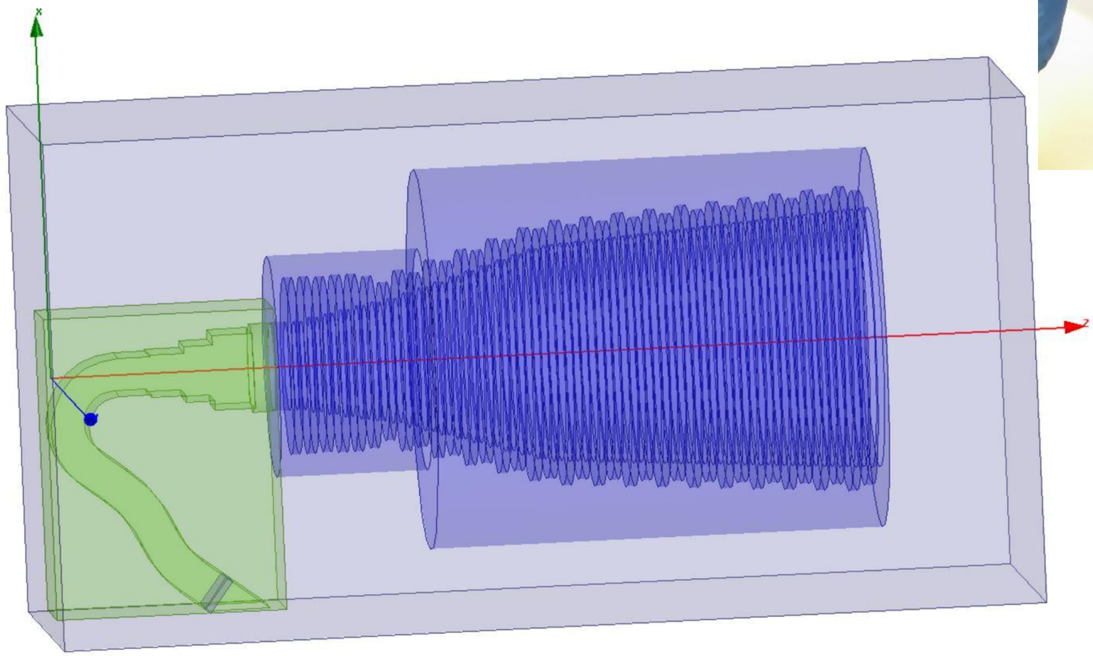
TROPICS

3U box --- with the radiometer housed in 100 by 100 by a little more tan 100mm spinning cube…

TK contracted to provide the Antenna



TROPICS



Grid based circuit to multiplex 89/115 and 183 channels using two very strange corrugated horn designs

TROPICS

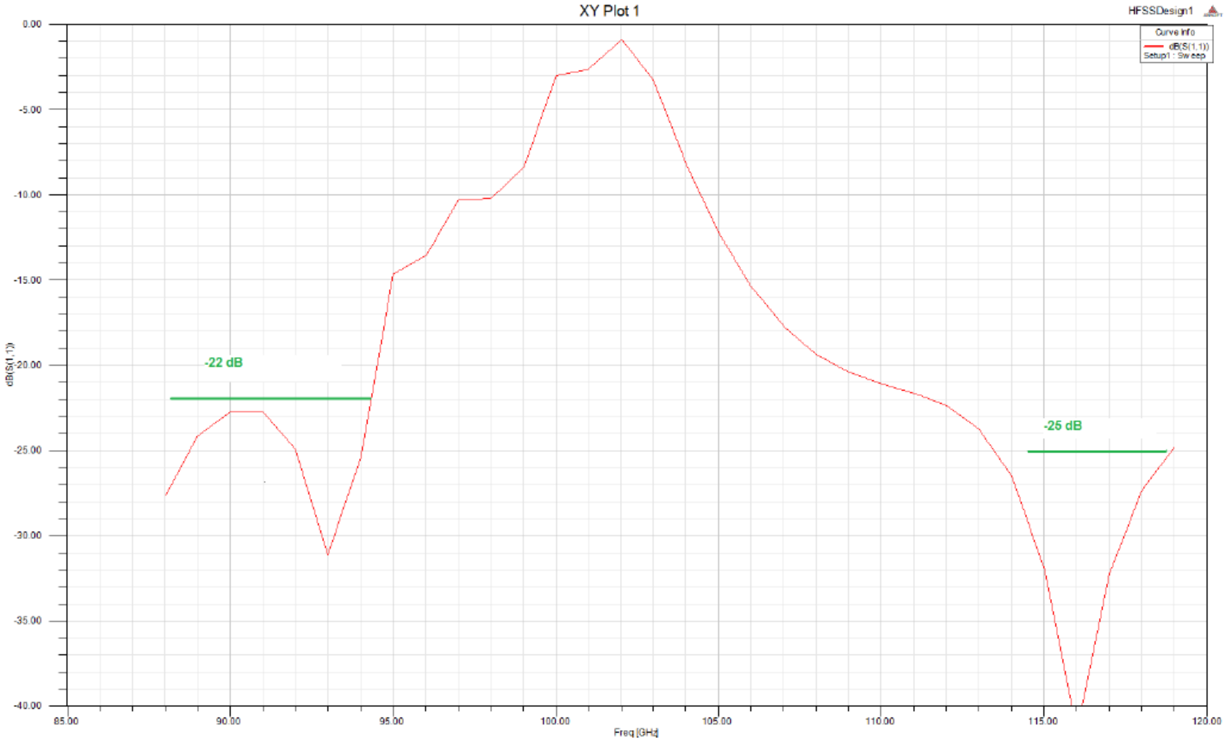
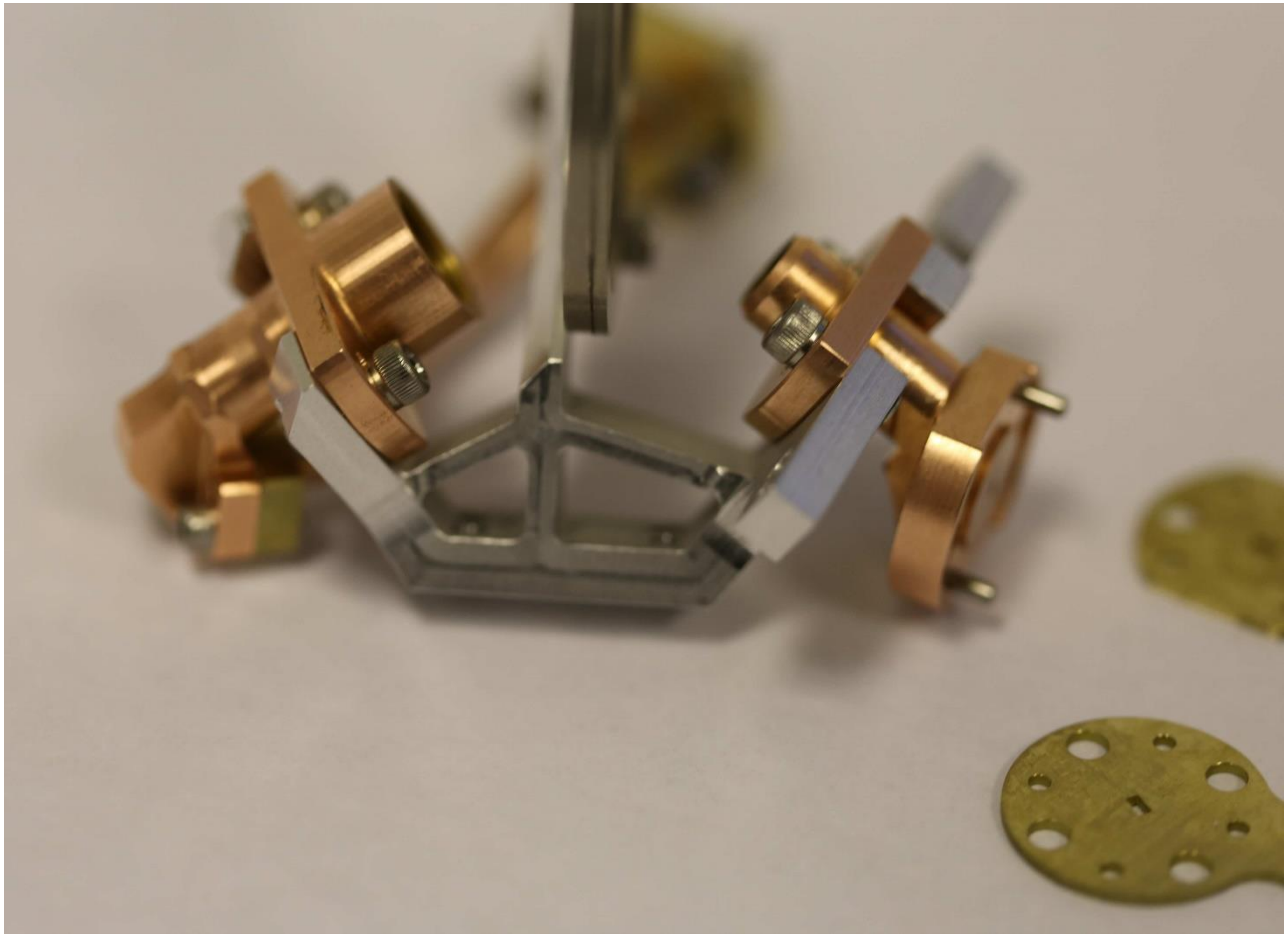
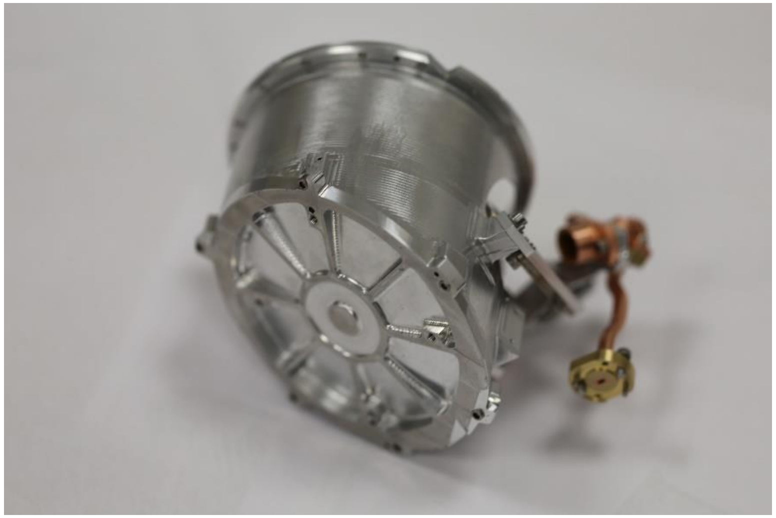


Figure 4-6: S11 over both bands.

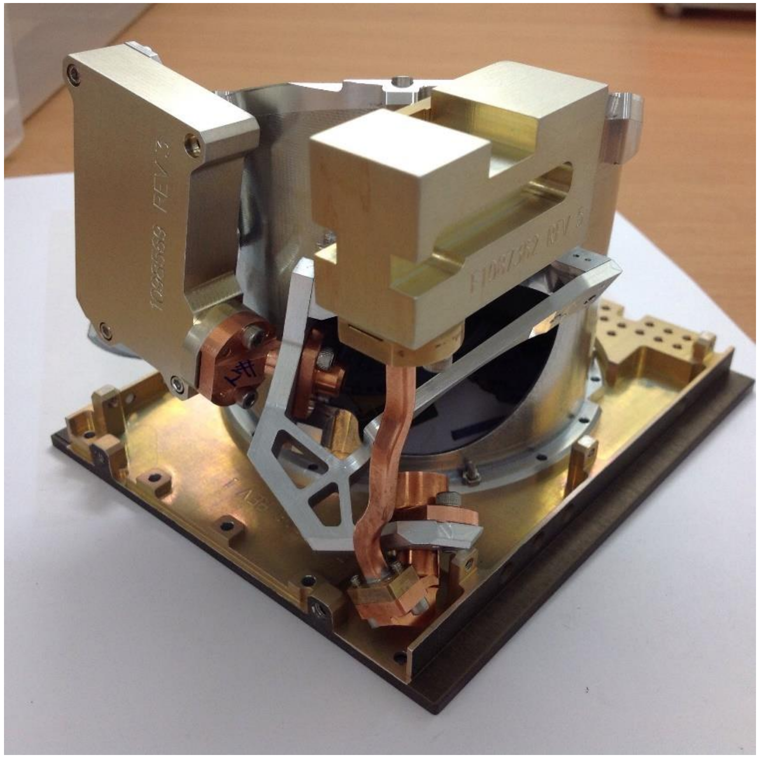




TROPICS

3U box --- with the radiometer housed in 100 by 100 by a little more tan 100mm spinning cube…

Every mm counts!



Plasma Fusion: Joint European Torus Experiment

`

HE11 guide & QO Feed –
Same need and techniques to give low loss and well defined beams

In-vessel 6 channel ECE and reflectrometry antenna using a double window (Tritium containing) QO plasma wall feed.

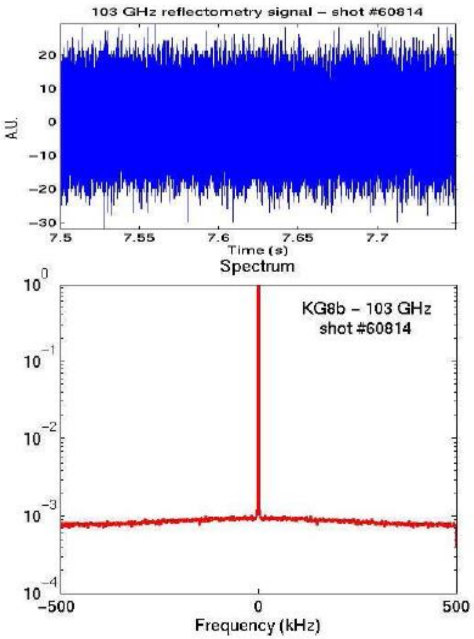
QO gives much higher signal levels

New MWA JET EP Projet

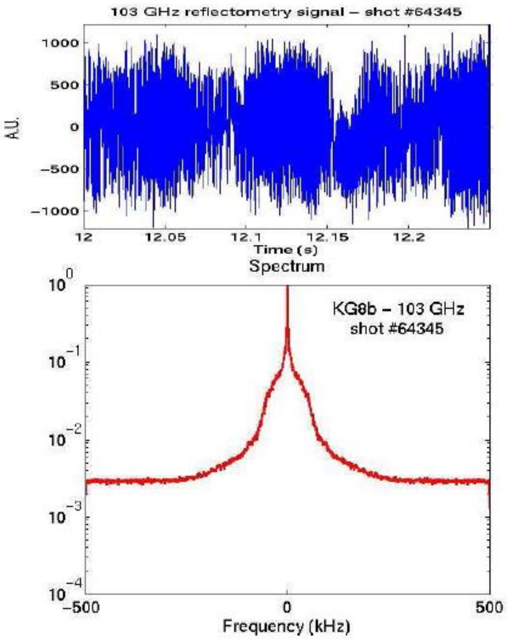
=> significant improvement of S/N for KG8b reflectometer data !

before new MWA

with new MWA



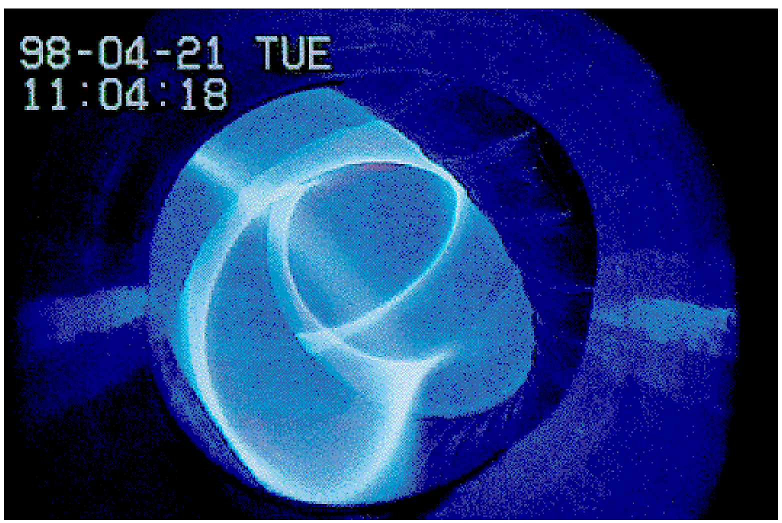
Amplitude of reflected signal increases from ±20 up to ± 1000 *i.e. + 17 dB !*

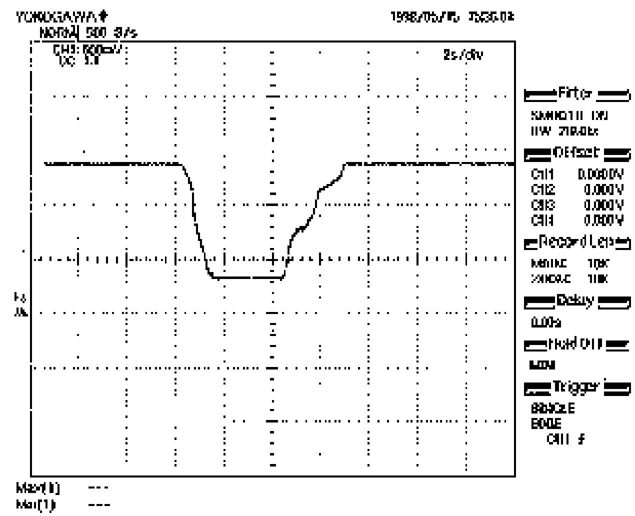


Clear dynamic is now observed on the spectrum suggesting a **S/N of about 20 dB !**

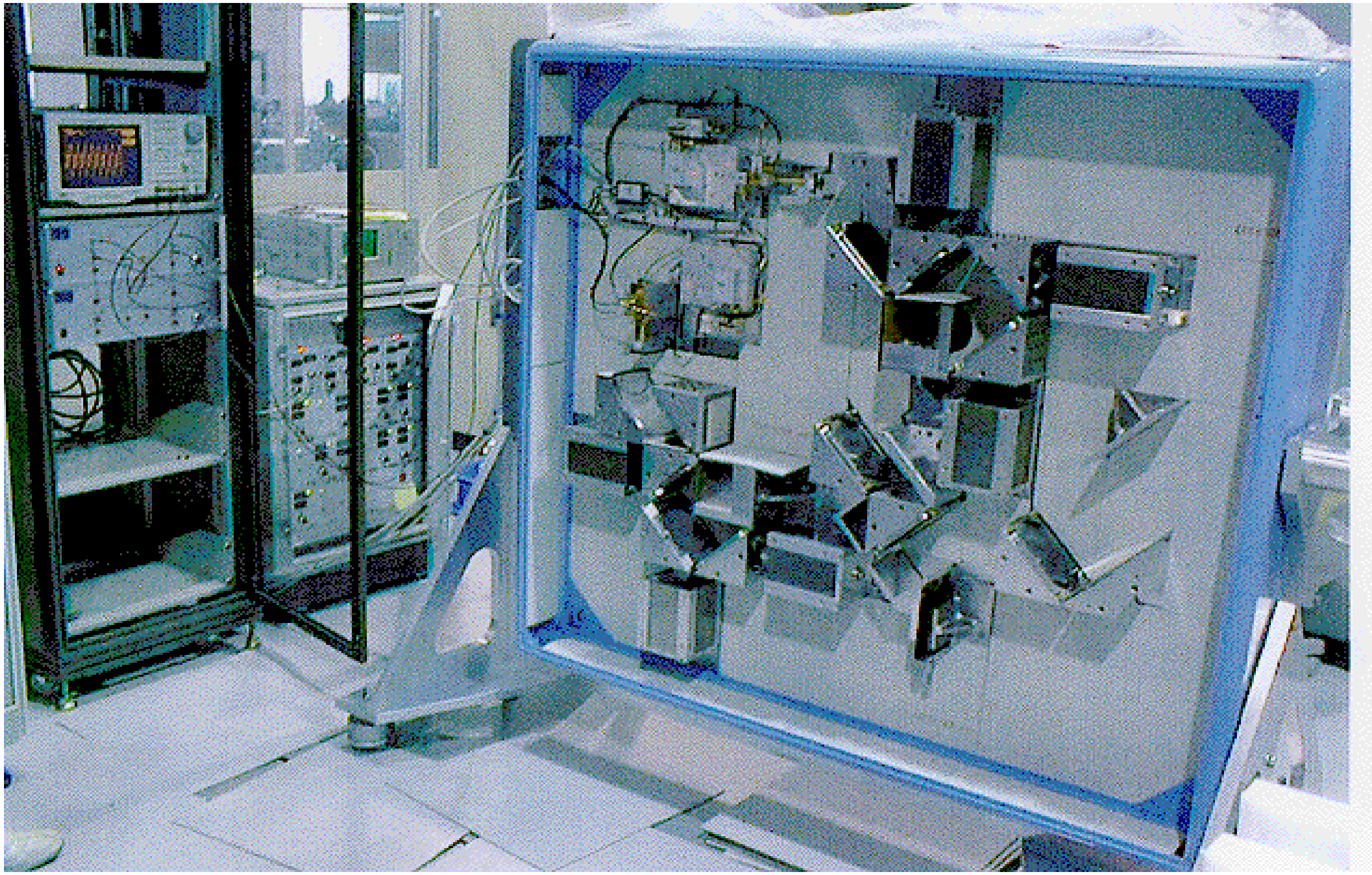
Determining electron density in a plasma

Here is an example of measurements from a Two Colour 140 and 285 GHz interferometer measuring electron line density in the NIFS Large Helical Device in Japan.





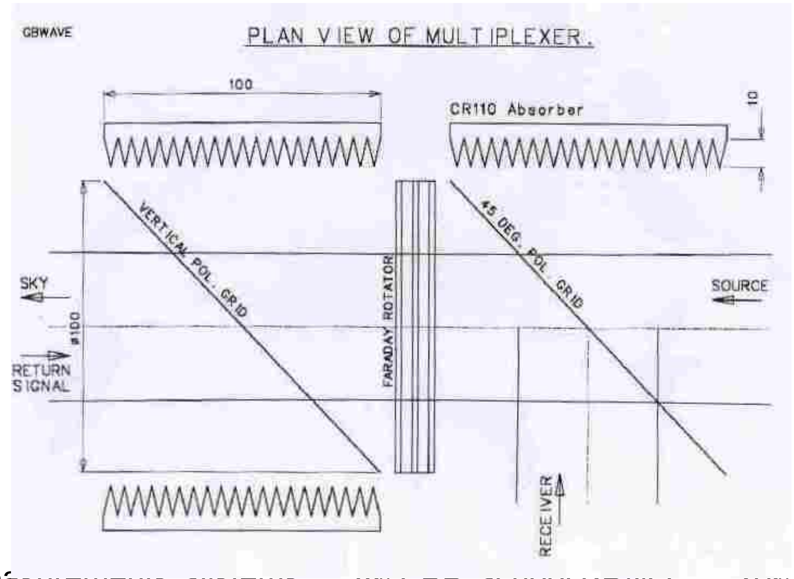
The Transmit side of the Interferometer



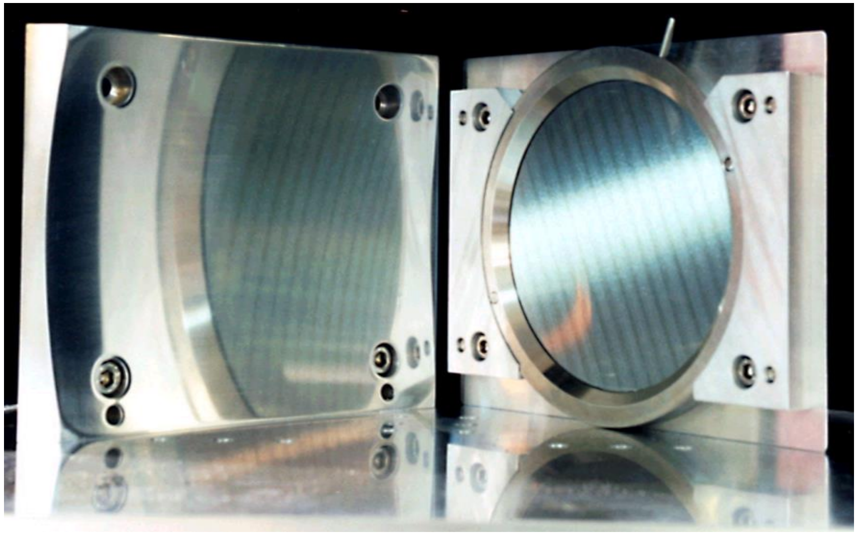
Suppressing Standing waves in Quasi-Optics

Standing waves within the instrument must be low enough not to compete with the very small signals which have passed through the lossy plasma. QO Isolators can be used to suppress these.

Quasi-optical Isolators used impedance matched hard ferrite to provide non-reciprocal Faraday rotation of the polarization of the beam and polarizing wire grids to analyse the signal



Polarizing wire grids, using fine Tungsten wire wound onto a metal frame are the main signal processing component in this and other QO systems, allowing polarization coded splitting and recombination of beams.

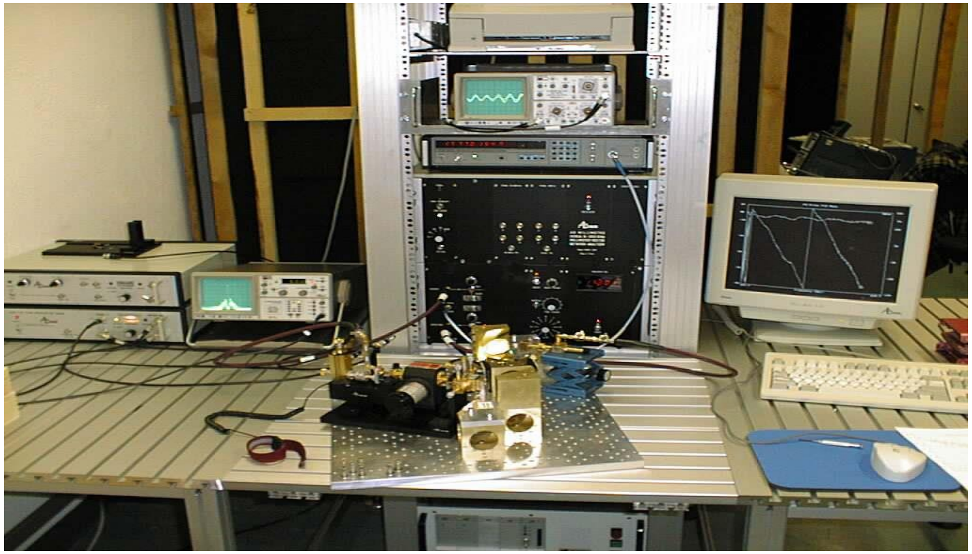


A non-reciprocal device is needed to rotate the beam.

Measuring Ferrite Parameters

Transmission as a function of frequency for four polarization states, for a given thickness of Ferrite, can be predicted from the ABCD matrix: The can be compared against measurement, and four parameters – *complex permittivity (two parameters) as well as Omega_m, Omega_o* – adjusted to fit.

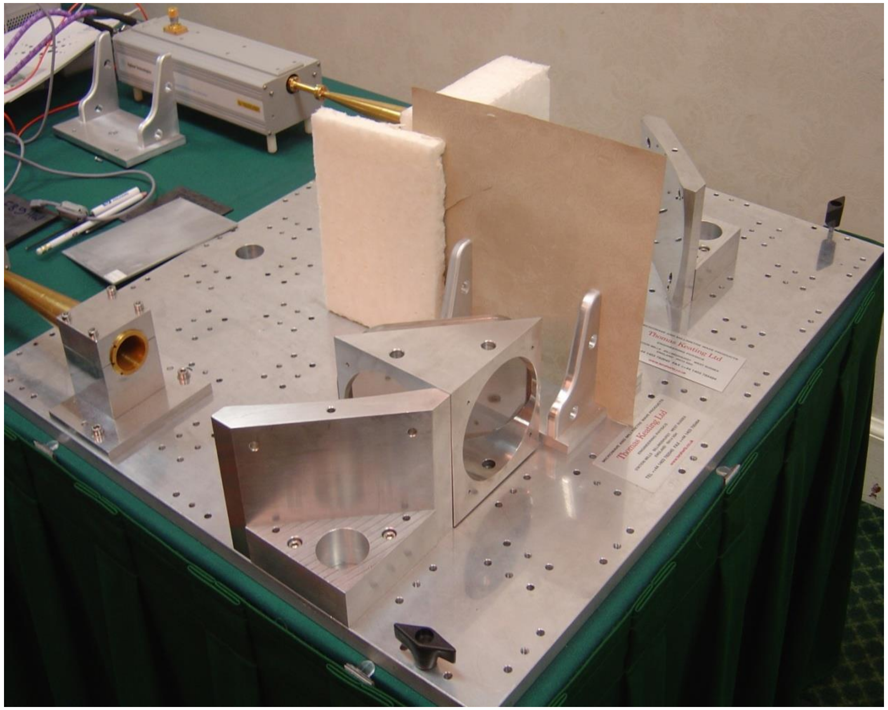
The fit can be very good – as the following four sides show:



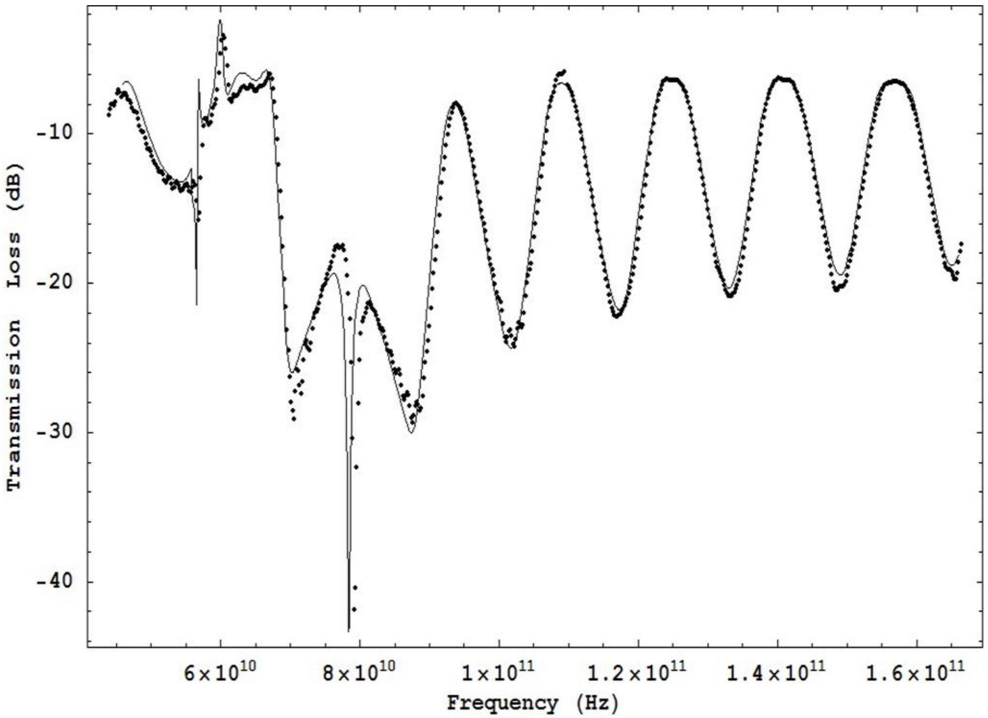
AB Vector Network Analyser

Ferrite sheets must be impedance matched

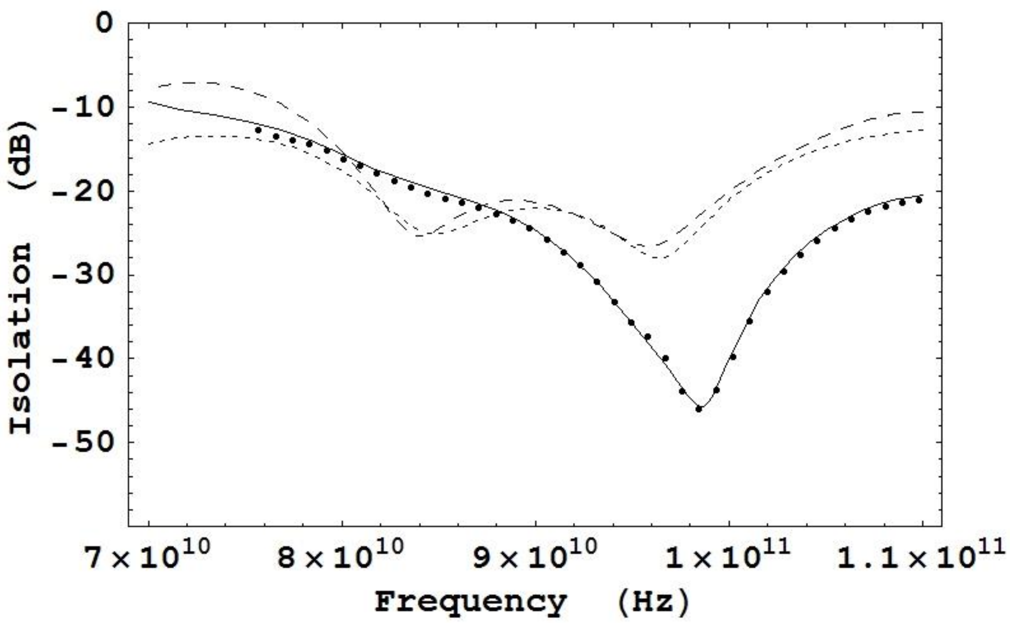
These dielectric layers on either side of the Ferrite allow a beam to enter and leave the Ferrite with little reflection



These tools - QO bench and VNA allow us to generate a transmission spectrum of the Ferrite material. It is complicated, but, amazingly, we can fit it with fit it with four parameters. Dots are measurements & line the model. Notice in dB! This fit is very precise, and give us strong comfort that our model is a good one

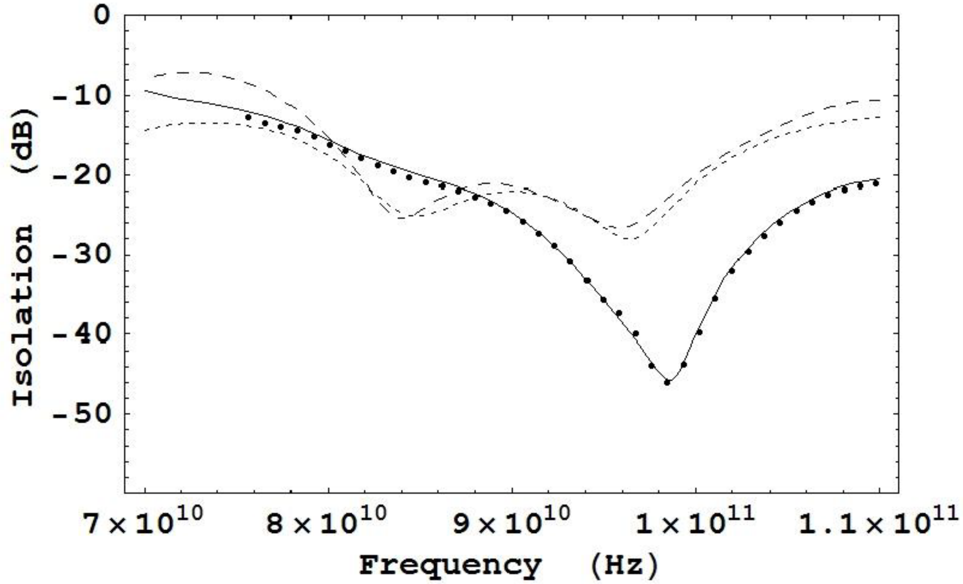


94 GHz Isolation – Theory and Experiment



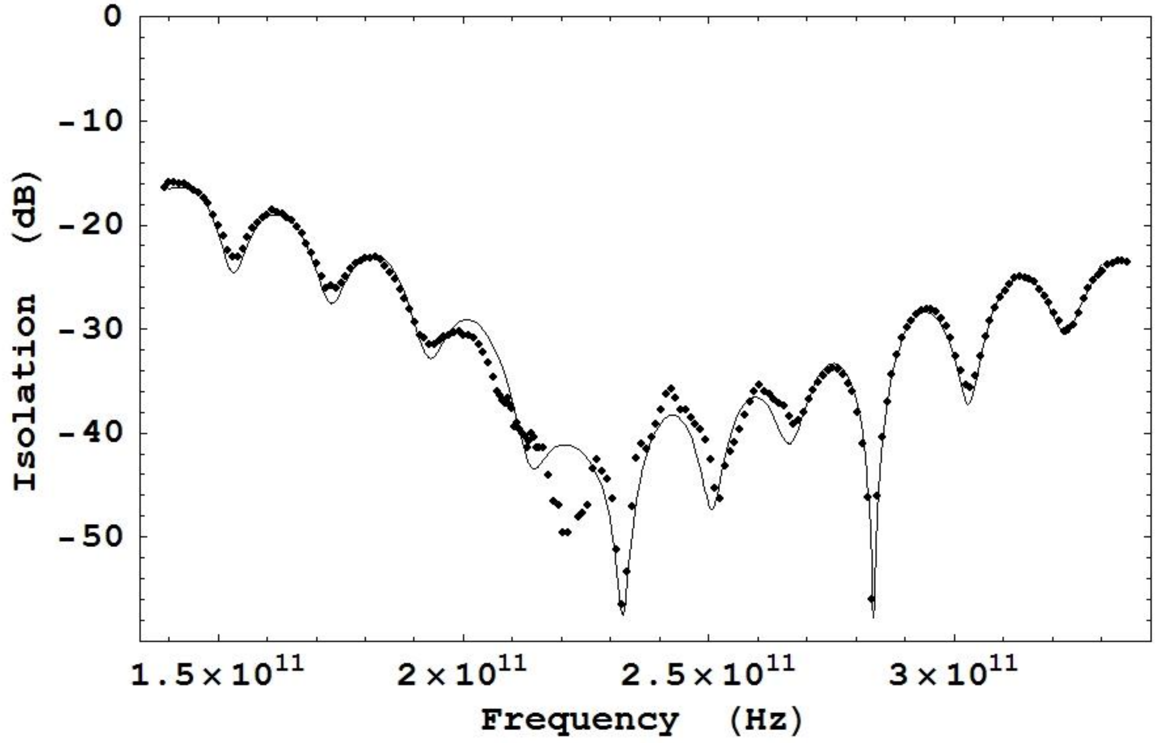
The predicted isolation (the continuous line) and back-reflectances (co-polar: long-dash line; cross-polar: short-dash line) for a circulator designed to give optimum performance at 100 GHz. The points are measured isolations

94 GHz Insertion loss – Theory and Experiment



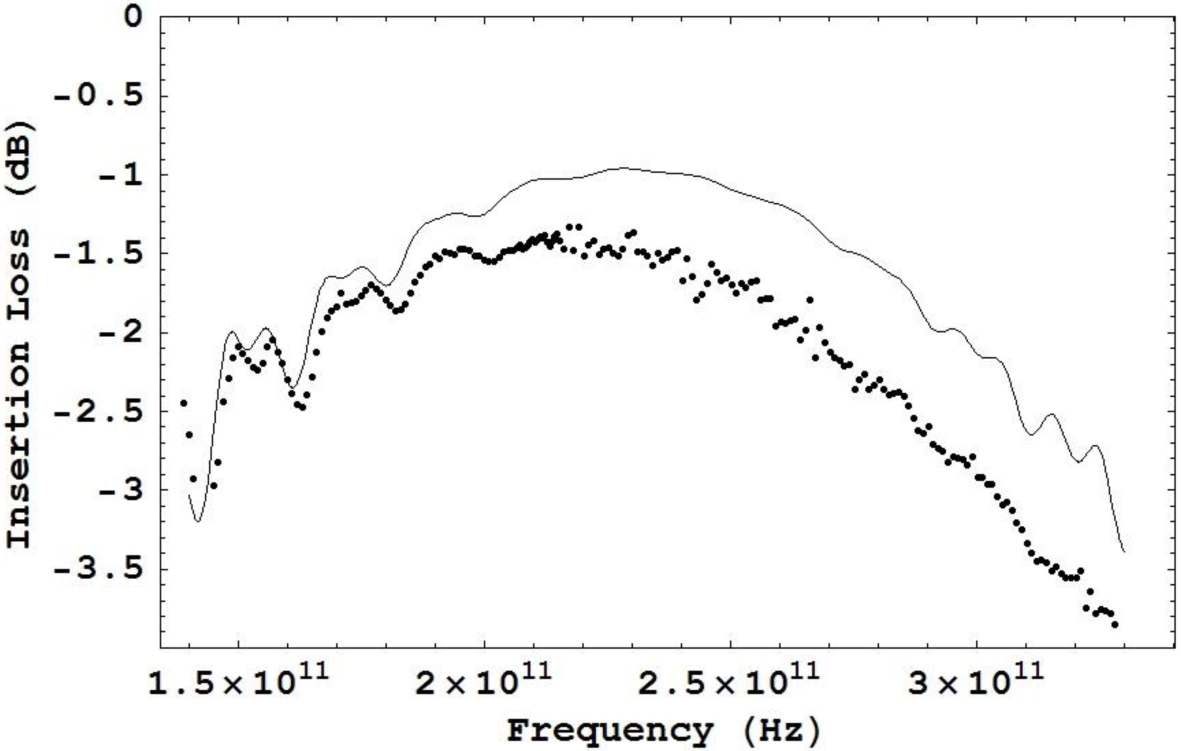
The predicted isolation (the continuous line) and back-reflectances (co-polar: long-dash line; cross-polar: short-dash line) for a circulator designed to give optimum performance at 100 GHz. The points are measured isolations

Isolator - Wideband performance >100 GHz



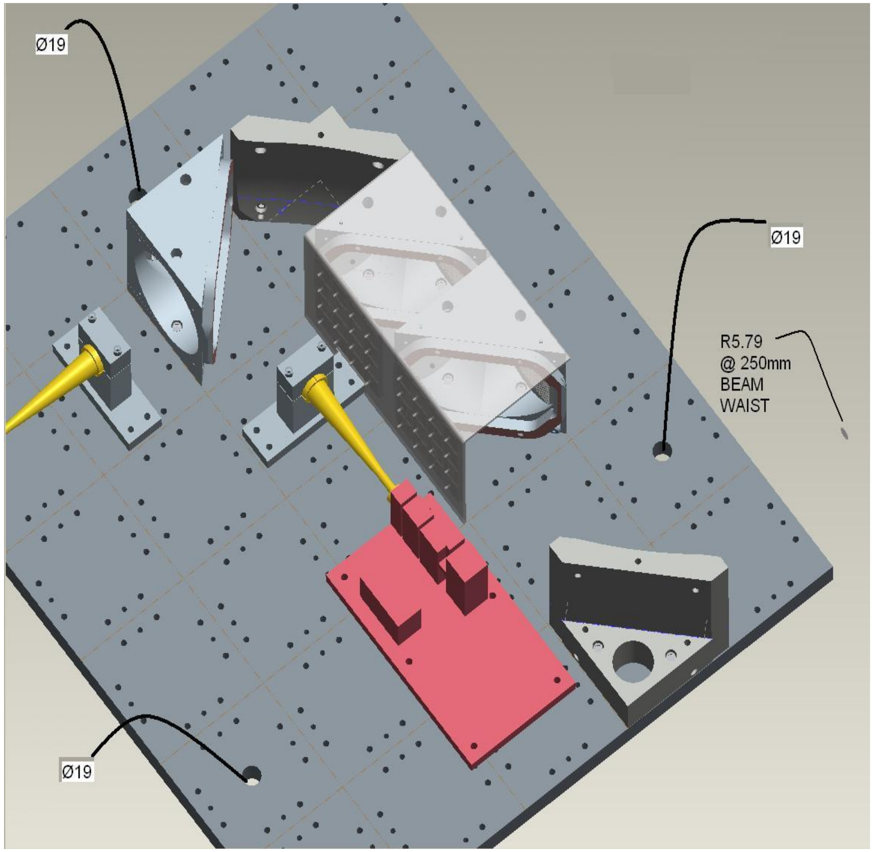
The isolation of a circulator designed for optimum performance at 240 GHz. The line is the predicted performance and the points are the measured values.

Insertion loss rising a bit >100 GHz – but still very good

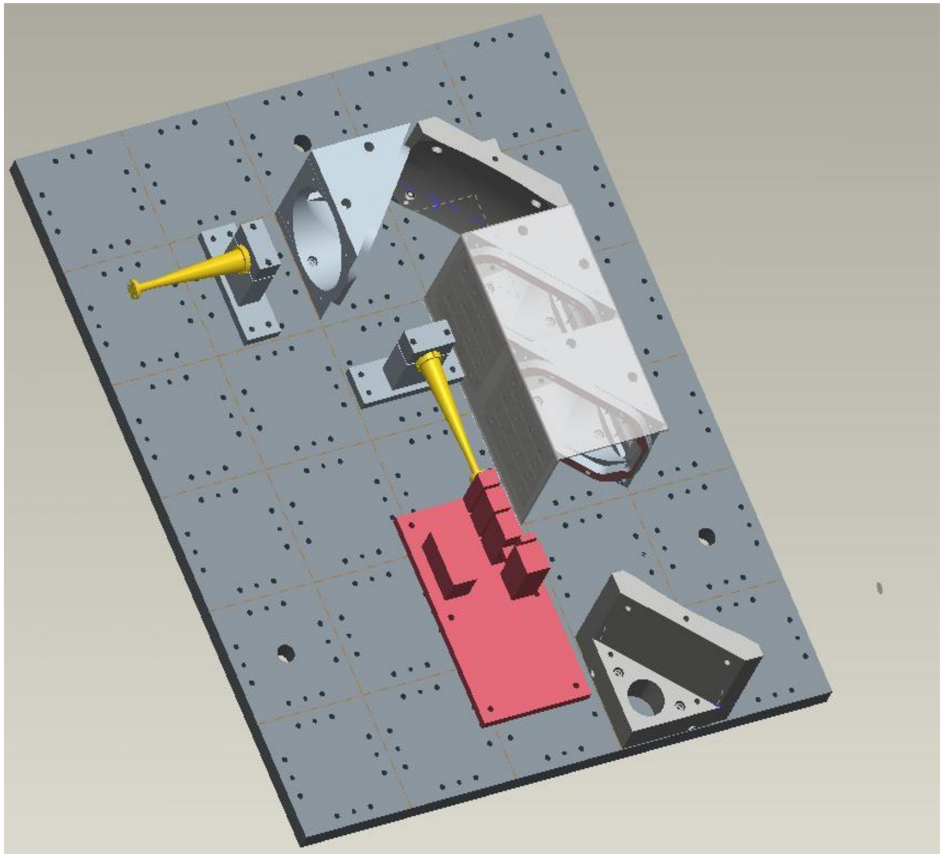


The insertion-loss of a circulator designed for optimum isolation at 240 GHz. The thin line is the predicted performances and the points are the measured values.

Quasi-optics used to make an FEL single moded

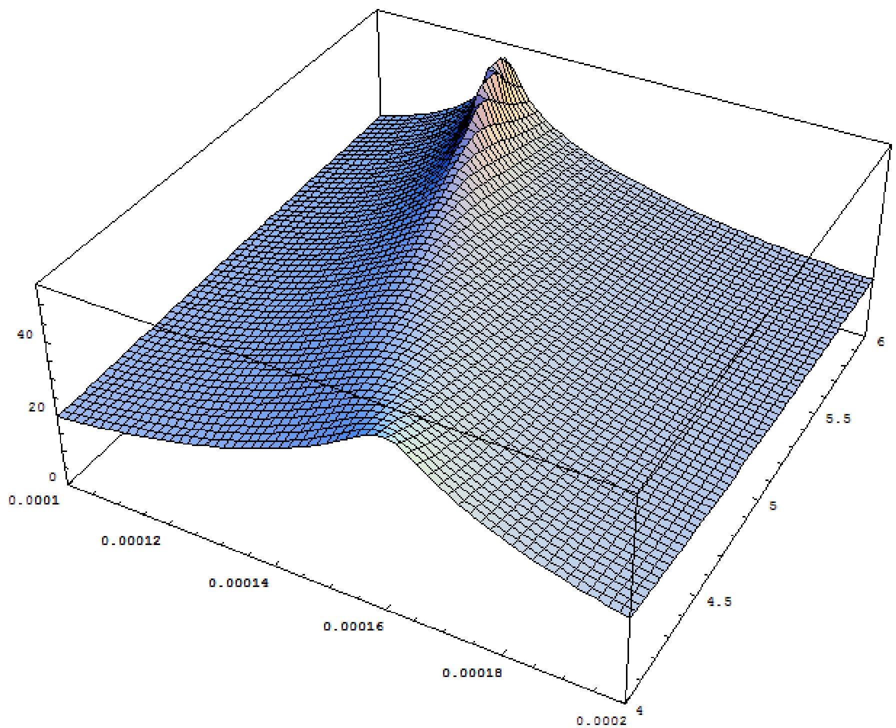


This is a Quasi-optical circuit, using two Faraday rotators currently being delivered to UCSB in California allow a high power Free Electron Laser to be “seeded” by a phased locked mW solid state source – Once the FEL fires up, the multiplier must be protected from the FEL's power!



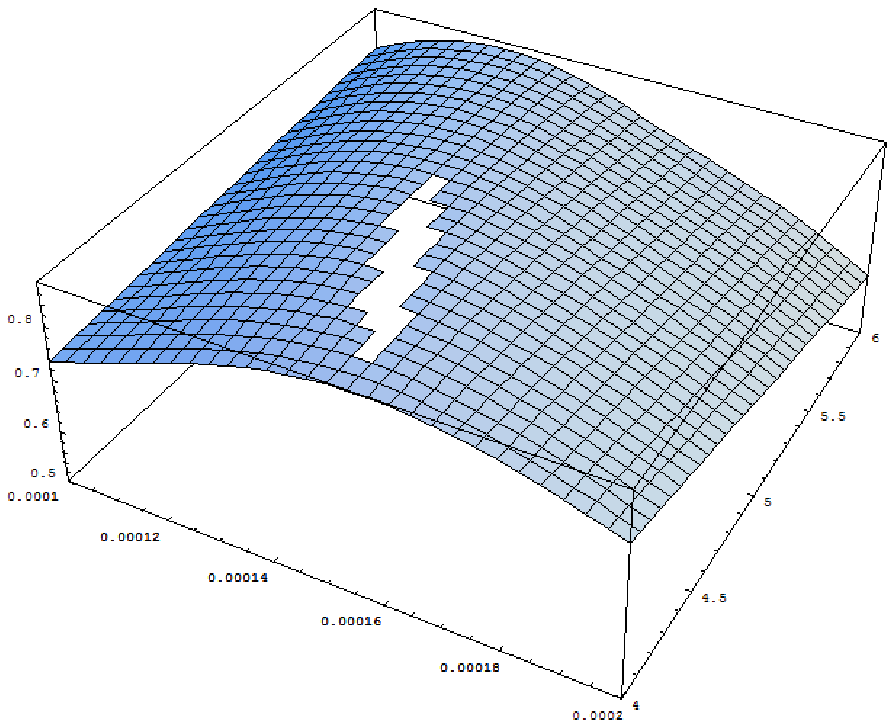
Such an isolation, with sensible insertion losses, would not be possible without better, lower loss ferrites and good modelling.

Predictions of isolation and insertion losses can be made using parameters for Ferrite used to match transmission measurements.



Predicted isolation in dB as a function of blooming layer thickness and blooming layer Refractive index – we use a material with a RI of about 5.14

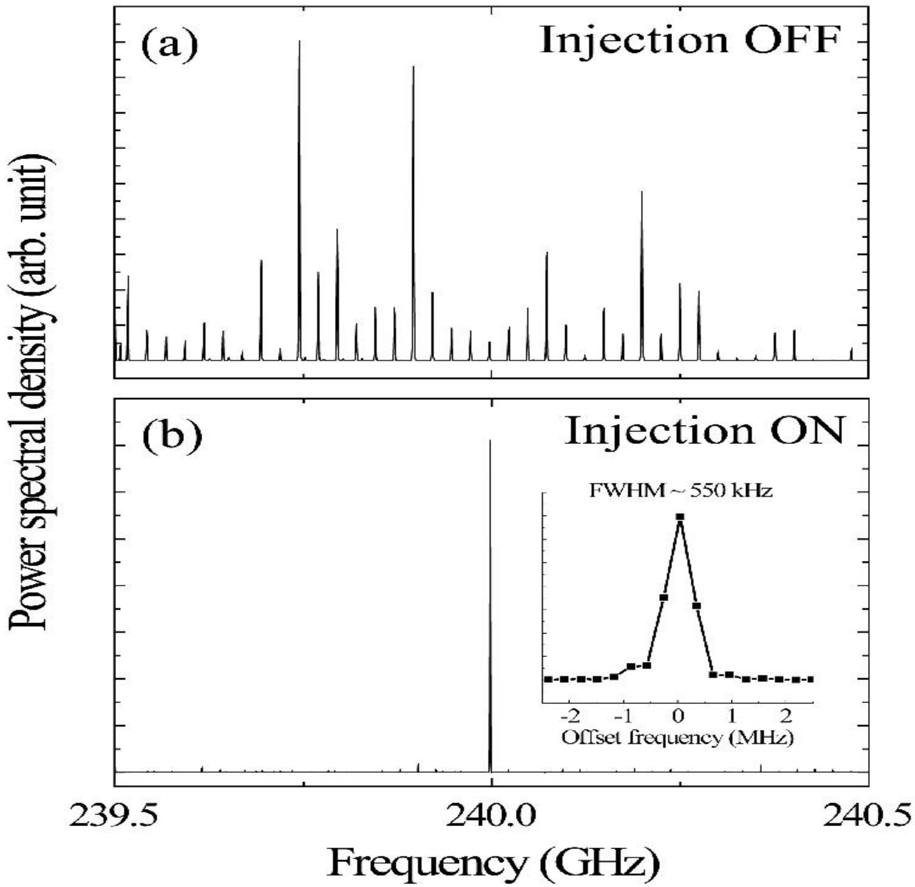
We are hoping to achieve isolation >30dB at 240 GHz



Predicted insertion loss as a function of blooming layer thickness and blooming layer Refractive index – we use a material with a RI of about 5.14

We are hoping to achieve insertion losses
of about 1.4dB at 240 GHz

FEL multiple resonance suppression

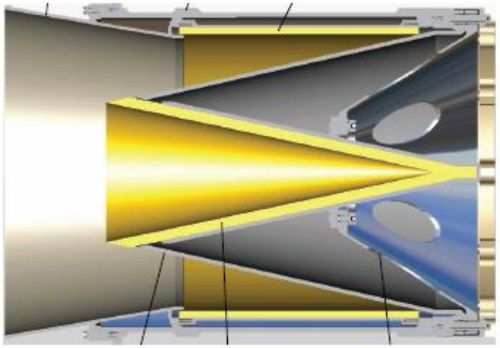


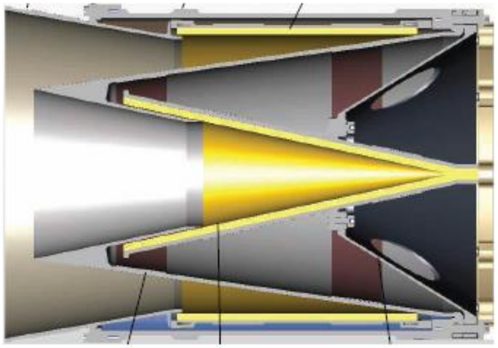
The multimode structure of a 240 GHz pulse from the UCSB FEL with no injection-locking signal.
(b) The single high-power line obtained with injection–locking (the insert shows the extremely narrow width of this line

Astronomy - Calibrating ALMA

ALMA Calibration targets – 67 Pairs

Folded Cone Geometry of ACL and HCL





ACL

- Central absorber cone
- Secondary cylindrical absorber
- Reflecting baffle to reduce spillover

HCL

- thinner absorber layers
- additional heated reflecting shroud reduces gradients
- degraded RF performance in Band 1+2

Specification		Ambient Calibration Load	Hot Calibration Load
Design frequency range		31 – 950 GHz (ALMA bands 1–10)	84 – 950 GHz (ALMA bands 3–10)
Radiometric accuracy design goal		±0.3K	±1K (at 70°C)
Backscatter design goal		-60 dB	-56 dB
Measured backscatter (S11)	Band 1 (31 – 45 GHz)	Average -55 dB (at nominal 2.5° tilt)	-30 to -45 dB †
	Band 2 (67 – 84 GHz)	Below -55 dB	-50 dB †
	95 – 150 GHz	Mostly below -60 dB	Mostly below -60 dB
	150 – 720 GHz	Mostly below -60 dB ‡	Mostly below -60 dB ‡
Maximum set temperature		NA	90°C *
Typical mass		5.4 kg	5.6 kg

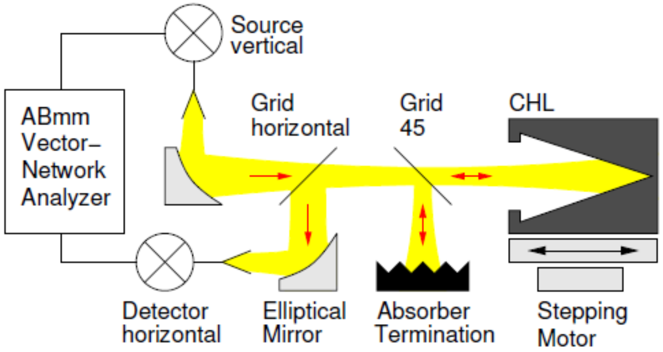
† *Performance not specified for this load and frequency.*
‡ *Results from prototype calibration loads.*
* *Read-out temperature may settle a few degrees below this.*

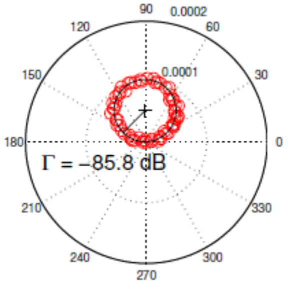
Table 1: Summary of the design goals and measured performance of the calibration loads.

Backscatter Test Setup

- S11 measurement with an ABmm VNA
- Directional coupler and ALMA feeds for Band 1+2, quasi-optics above.
- Test object measured at different distances *d* to calibrate directivity of the test setup
  $\Rightarrow$ phase changes, fit of a circle to the complex data
- Determines coherent S11, not total scattering!

Credit – Axel Murk at6 the IAP, Bern

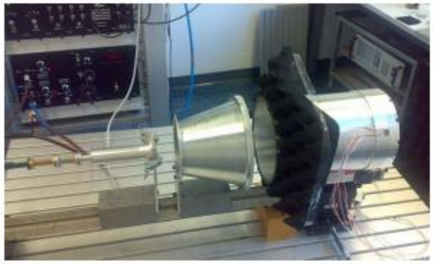


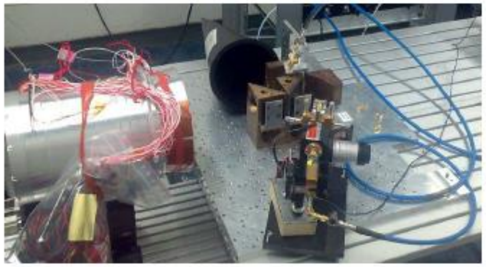


Backscatter Test Setup

Credit – Axel Murk at6 the IAP, Bern

Experimental setup for isolated cone prototypes
$\Rightarrow$ no interferences from secondary absorber or reflector.





Experimental setup with ACL and HCL in Band 1 and 4

S11 Reflectivity

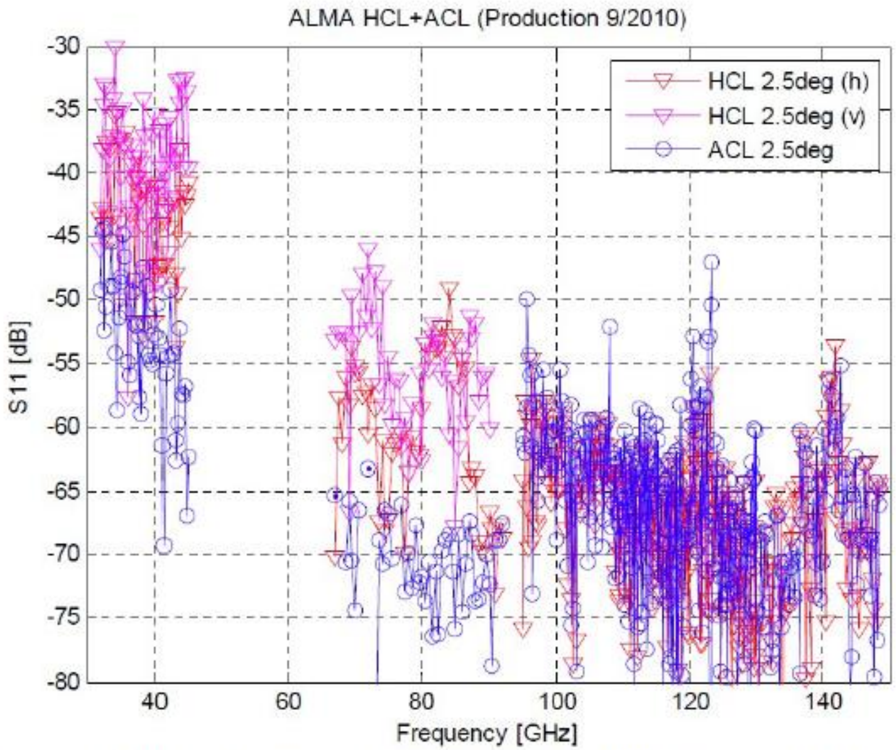
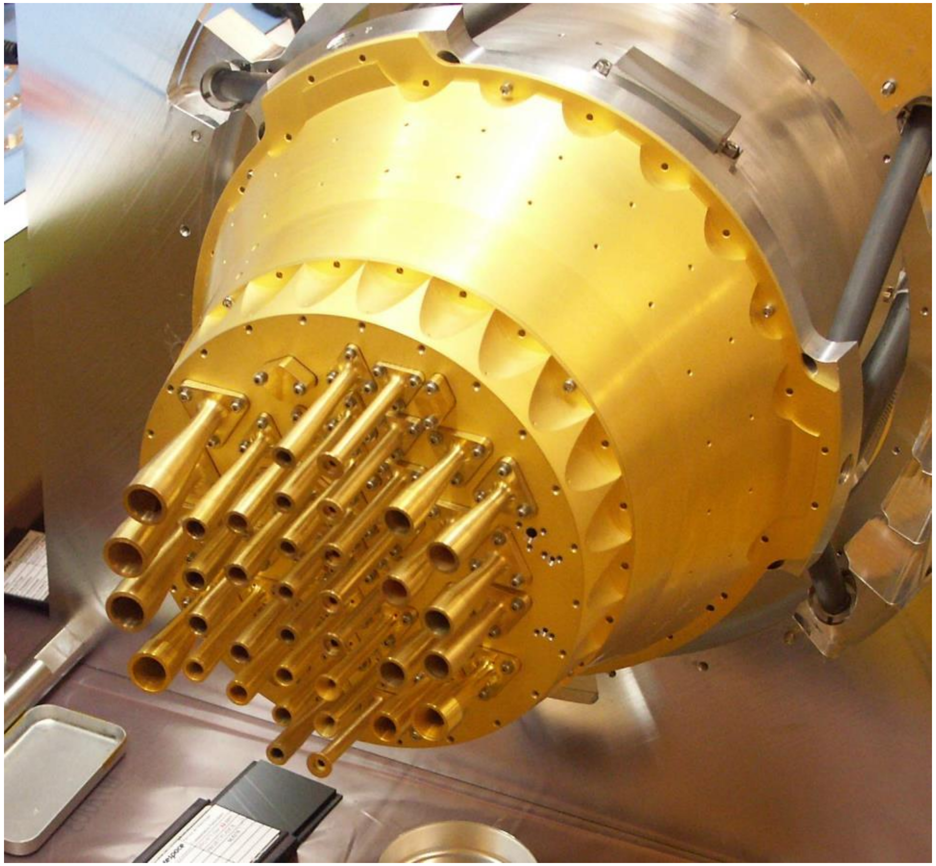


Figure 4: S11 performance of production calibration loads, from [RD3]. Spikes at 120 and 140 GHz are test artefacts due to reduced VNA sensitivity at these frequencies.

Credit – Axel Murk at the IAP, Bern

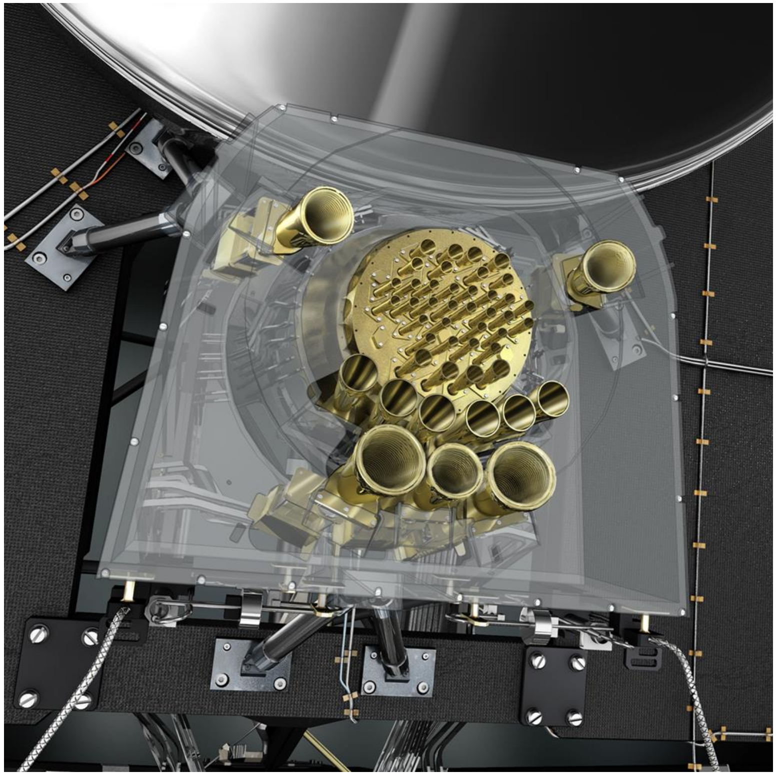
Last Application from Cosmology



Using the same techniques, ESA's Planck mission has further refined the major cosmological parameters – flatness of the Universe, and the fractions of visible, dark matter and dark energy.

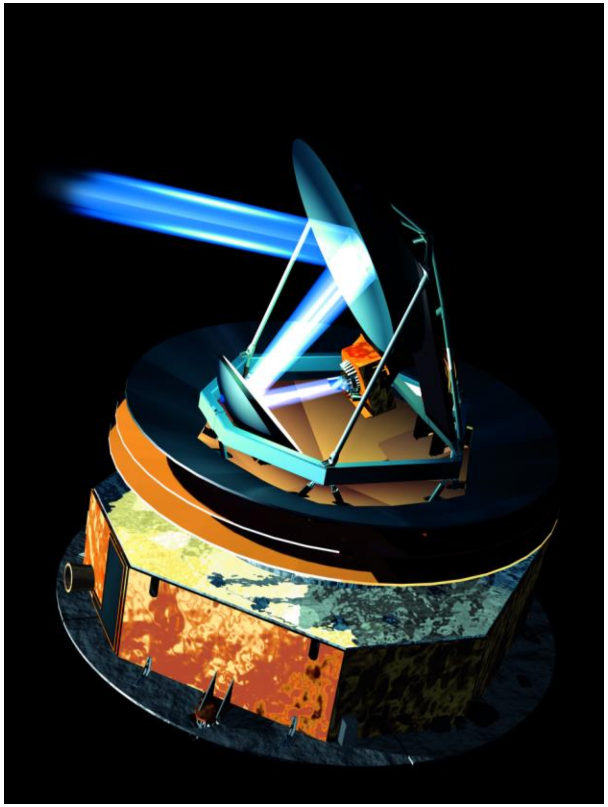
HFI Focal plane array showing front feed horns – each pixel has two more, hidden from view.

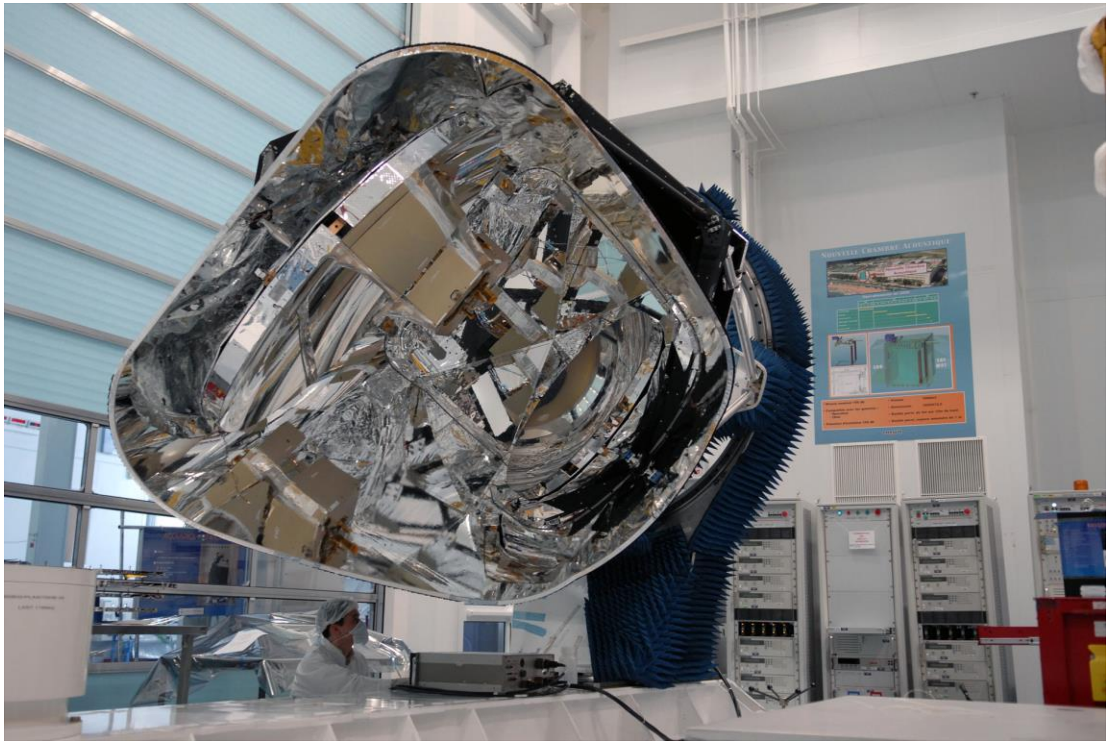
Both the High Frequency (HFI) and Low Frequency (LFI) antenna arrays



Planck Optics – the full antenna

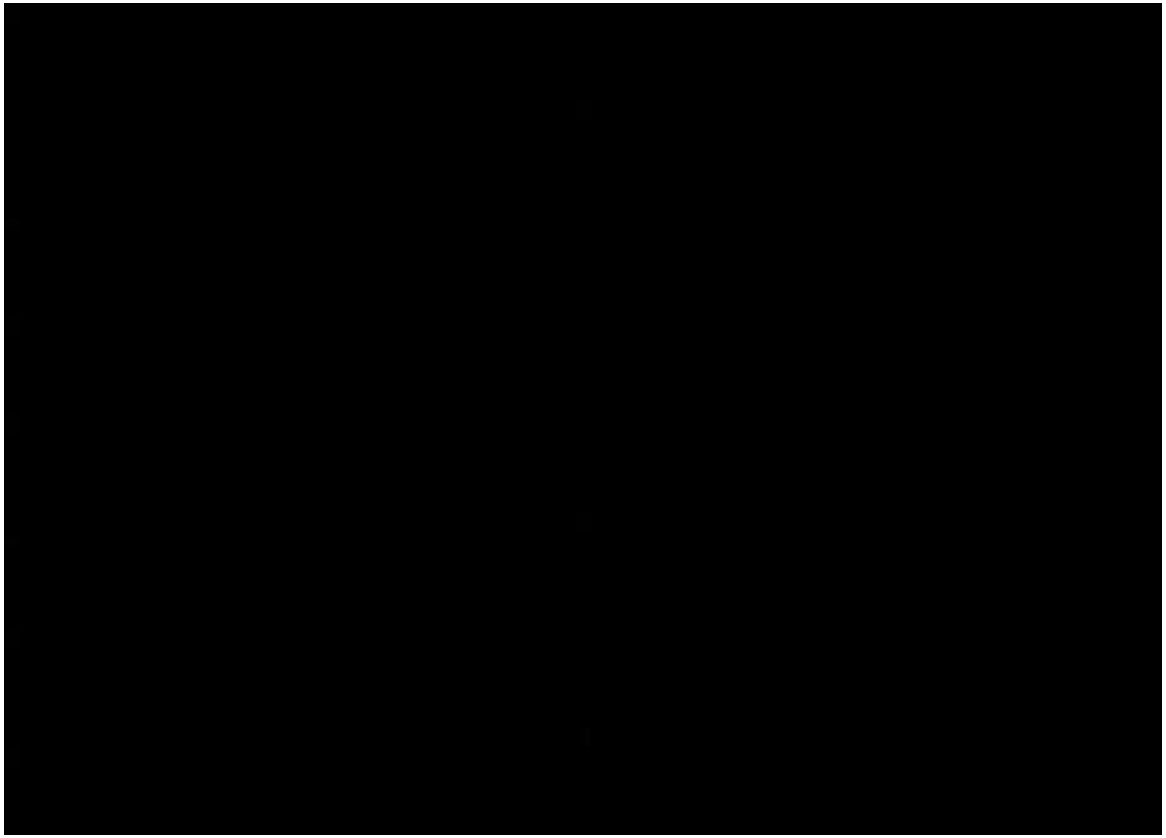
Dual
Offset
Reflector
feeding
the array
of horns





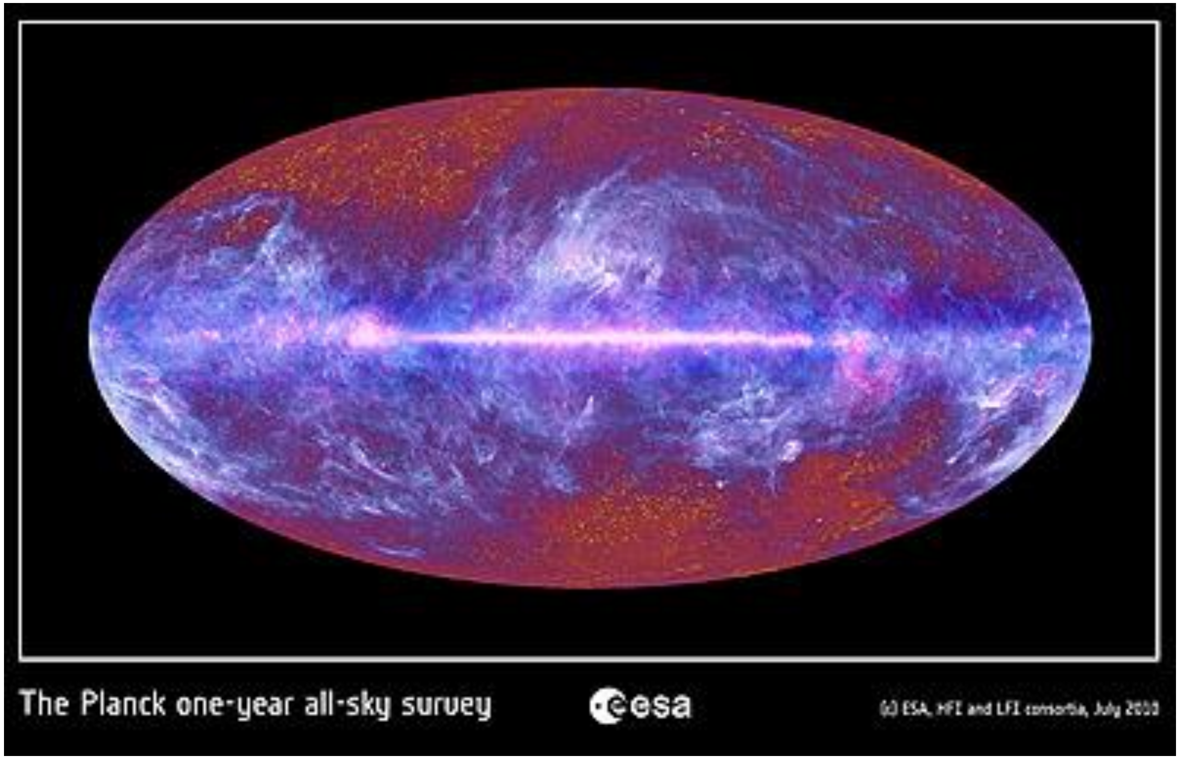
The whole FM structure being assembled in Alcatel's clean room in Cannes; the TK supplied feed horn array can just be made out in gold in the centre of the image.

Planck's spun to scan the sky

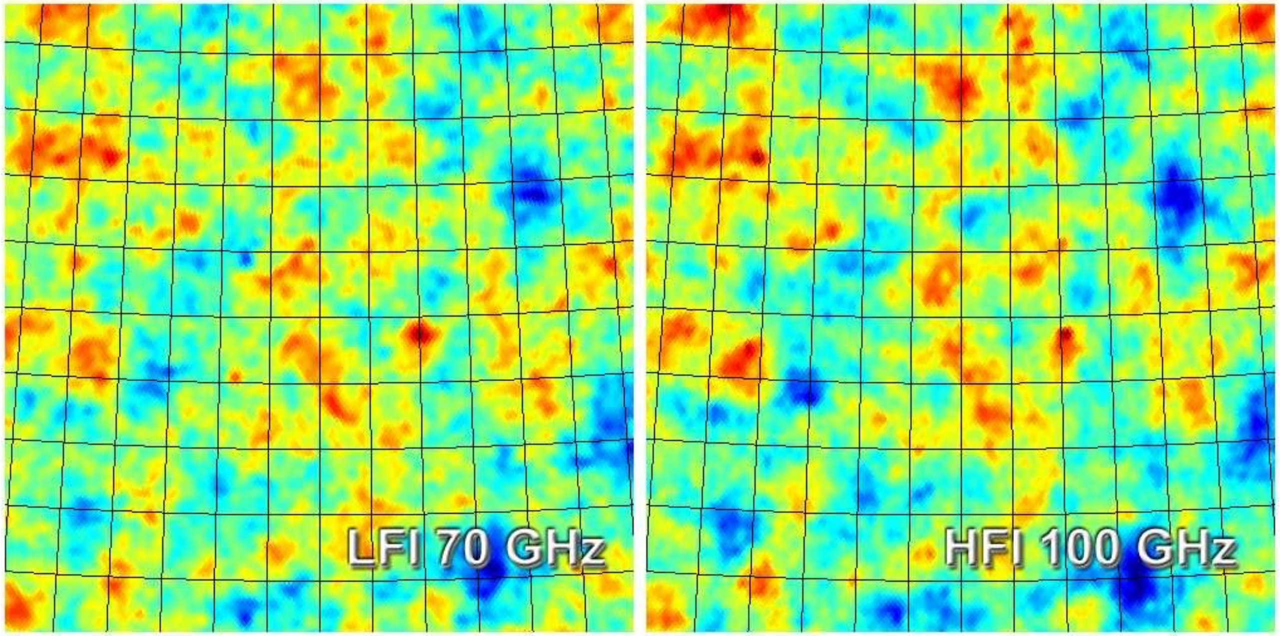


From its orbit around the second Lagrange point (L2) of the Sun-Earth system, Planck performs a continuous scan of the sky. The spacecraft spins at 1 rpm causing the telescope's field-of-view to trace out approximate great circles on the celestial sphere.

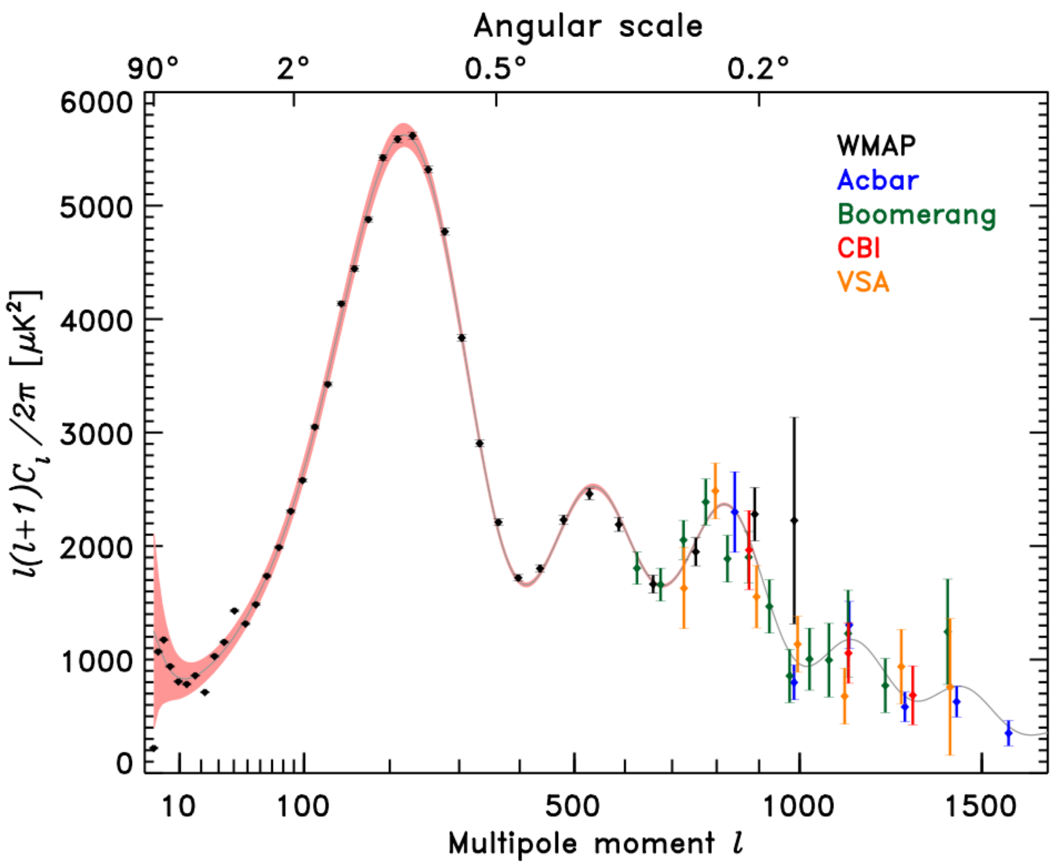
Results published by ESA captured by Planck as it orbits L2 some 1.5M Km from the Earth – spinning at about 1 RPM



LFI and HFI 10 degree square section out of the galactic plane – away from contaminating radiation from dust and synchrotron emission – good match



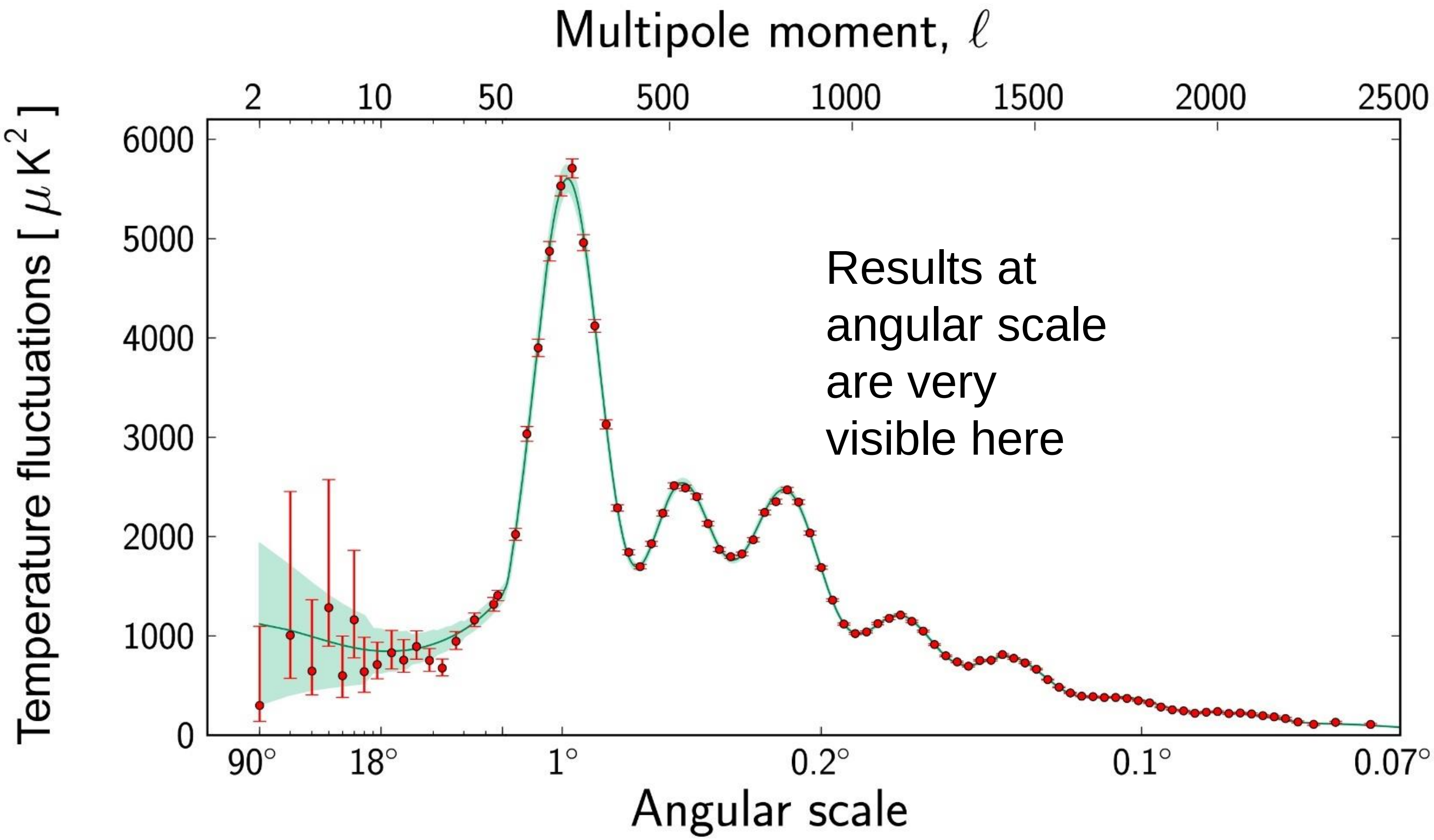
Conclusion



Planck aim was top improve on the previous measurements of the power spectrum of the cosmic microwave background radiation temperature anisotropy

(Image from NASA)

Conclusion


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK²]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale
Results at angular scale are very visible here

Why use Quasi-Optics rather than conventional waveguides to build HF ESR Spectrometers?

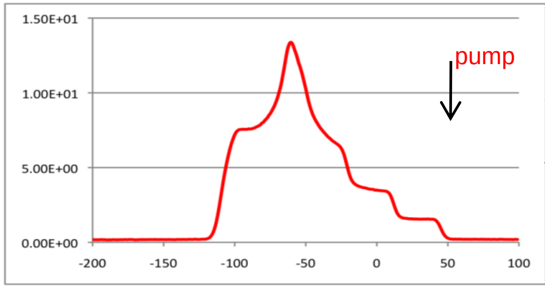
- Extremely low loss and non-dispersive transmission. Insertion loss waveguide to waveguide through a quasi-optical system is typically of the order of 1dB, including losses in the corrugated feeds.

- Systems can be designed using frequency independent reflecting optics (off-axis mirrors). These are only limited at the low frequency end by the size of the optics. Compared to lens-based optical systems, standing waves are negligible and cross-polarisation levels are very small.

- The ability to use both orthogonal polarisation states (both linear and circular) in signal processing.

St. Andrews’s HiPER Spectrometer

One nS Pi/2 and dead time 1 kW Pulsed ESR Spectrometer generating a step change in performance in Orientational Selective DEER for Structural Biology

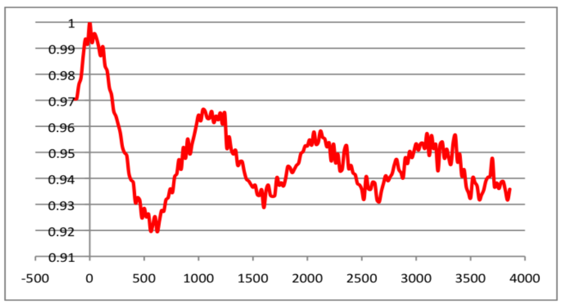


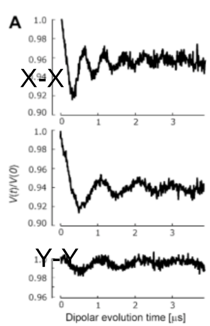
pump
probe
probe

T=50K, 1.2kHz rep rate

Z-Z

6 minutes

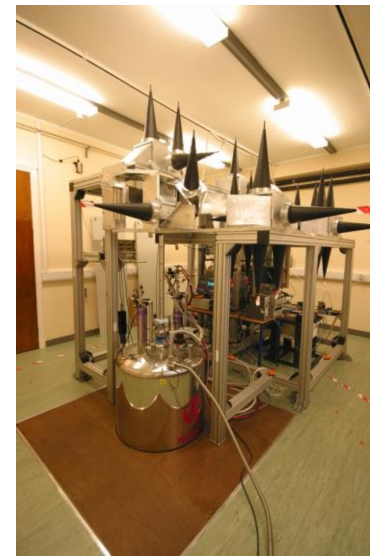


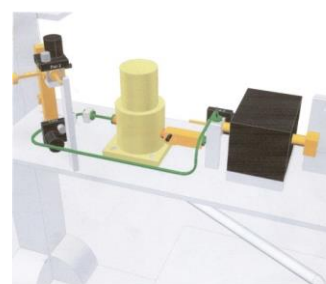


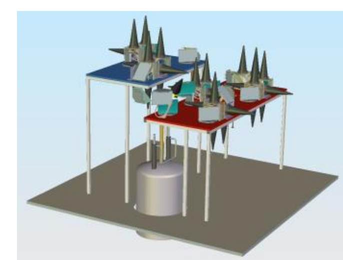
Comparison:

Conventional Instrument takes 50 Hours

Polyhach, Godt, Bauer, Jeschke JMR, 185 (2007), pp.118-129

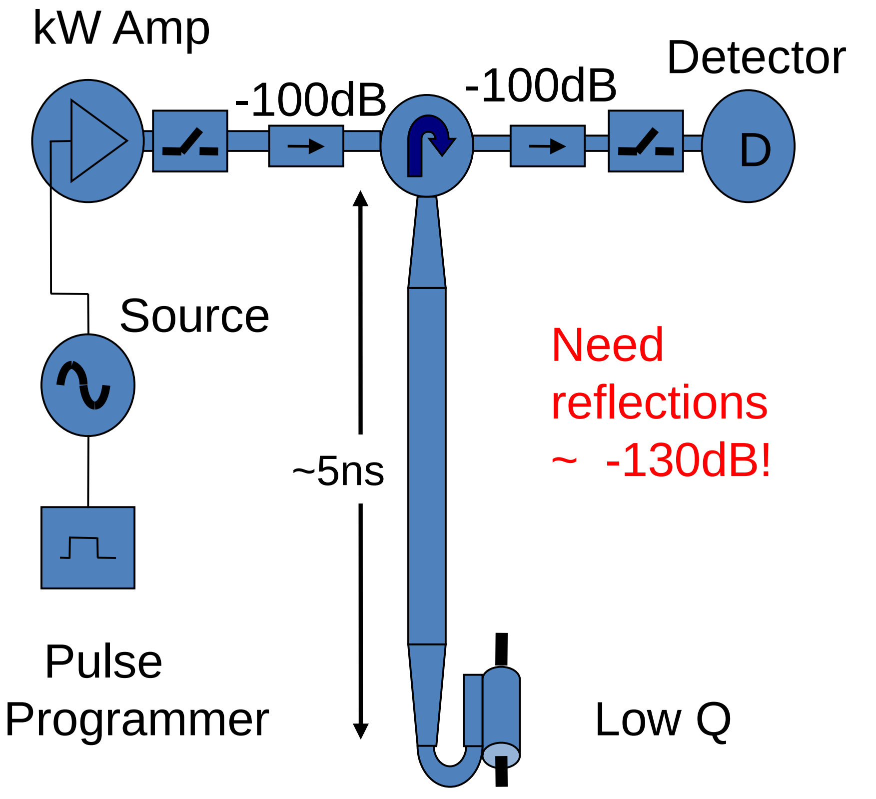




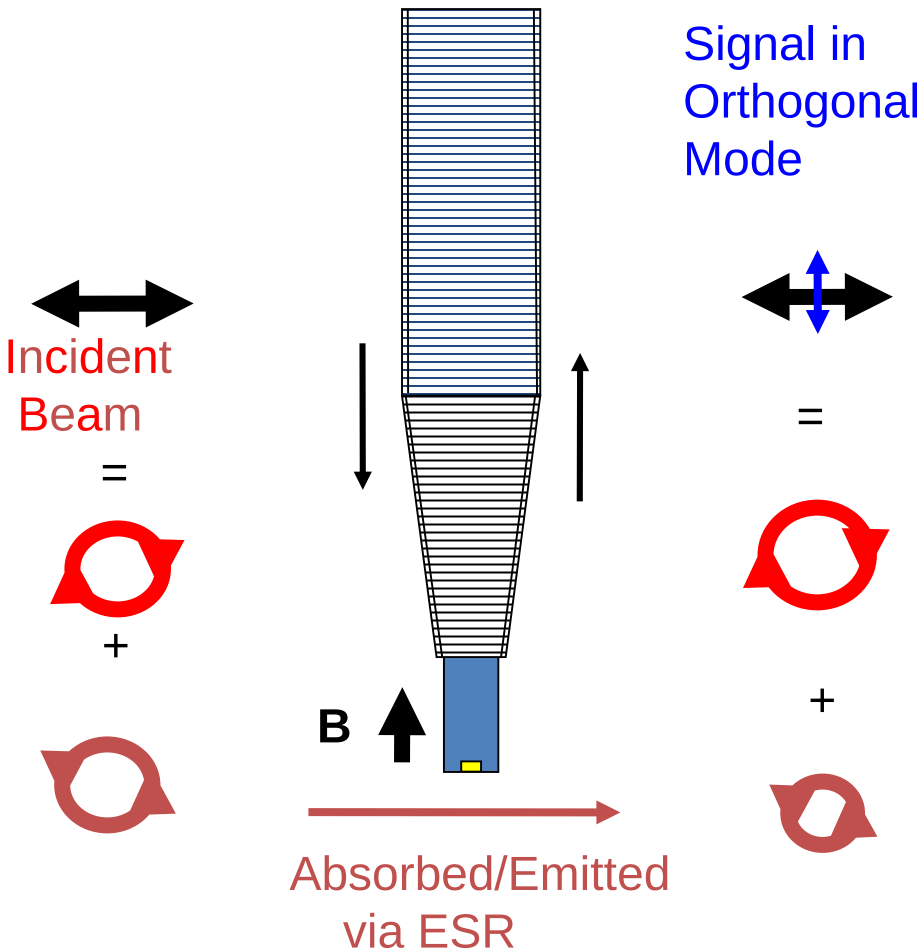


What are the challenges?

- Generating very short high power pulses with nanosecond phase and amplitude control
- Using high performance components with high average and peak power handling
- Constructing a low loss spectrometer without reflections



Use of Induction Mode – not possible in rectangular waveguide



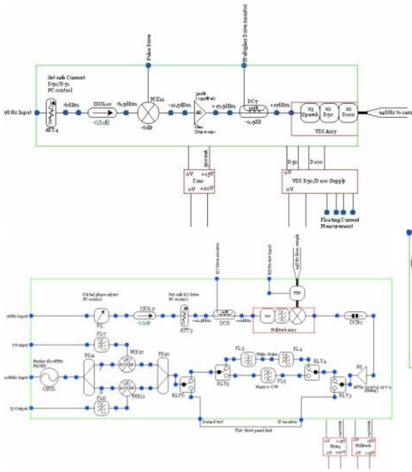
Detect reflected orthogonal polarisation

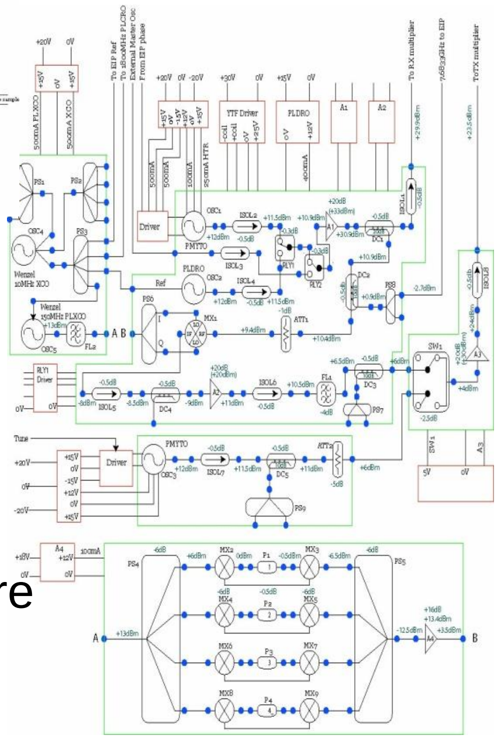
Regularly achieve 50dB+ X-polar isolation

HE11 Corrugated Guide

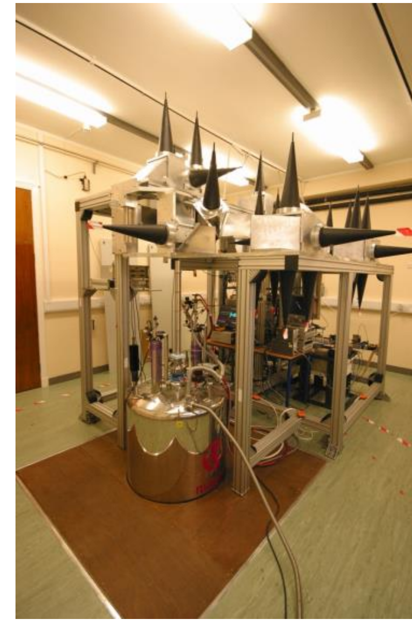
- Extremely low loss propagation (~0.01dB/m)
- Very high operational bandwidths
- Very high coupling efficiency to both fundamental Gaussian beams and single mode waveguide systems
- Allows both orthogonal polarisation states to be transmitted - permitting polarisation encoding, induction operation and illumination with circularly polarised radiation.
- Low levels of mode coupling and rotation of polarisation with tube distortion
- Cryogenic operation - low heat loss and similar levels of thermal contraction to stainless steel.

How to build a system without reflections

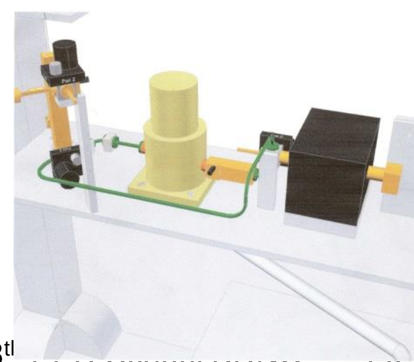


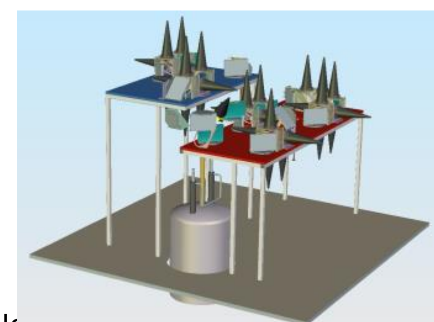


750K receiver noise temperature

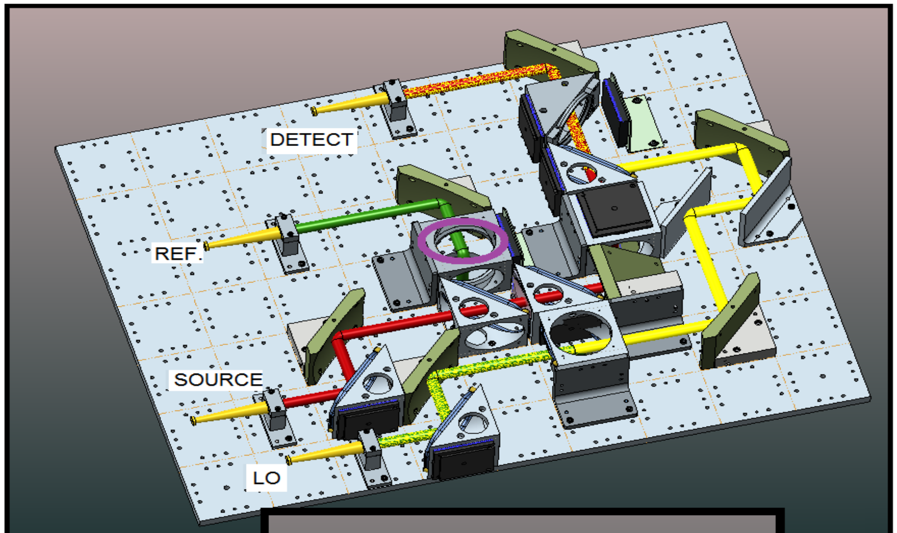


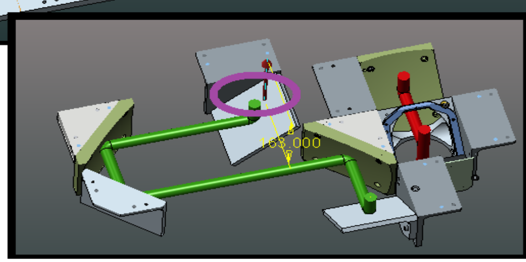
Lots of mechanical and electrical and software integration





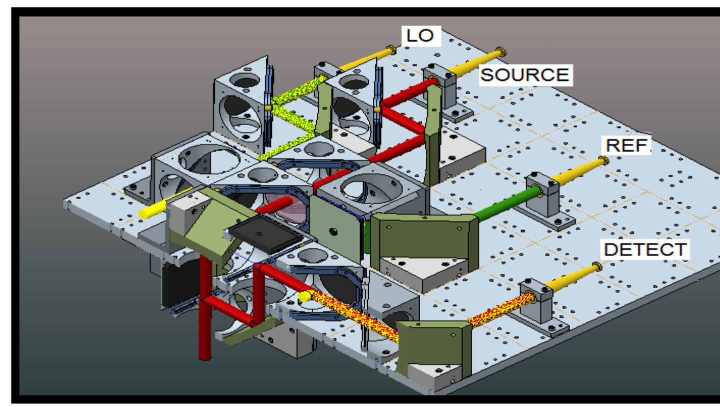
The Optics of HiPER

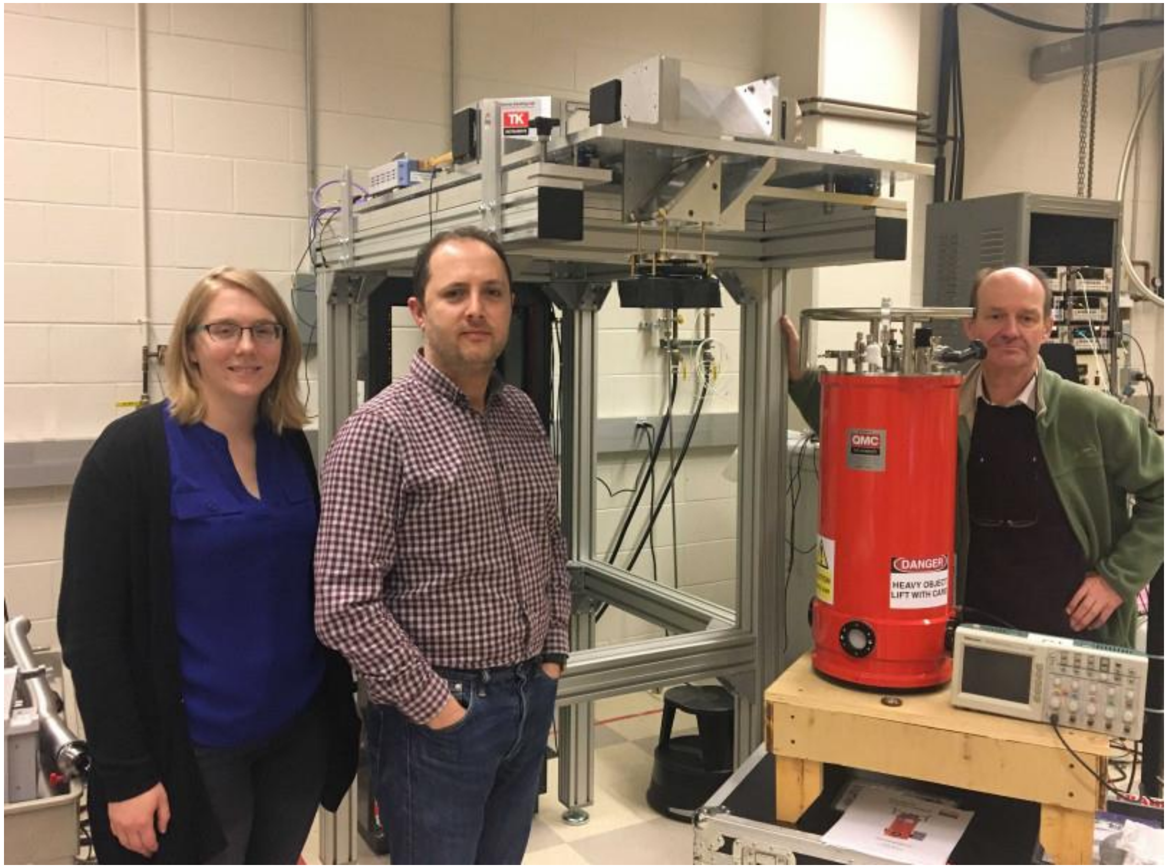




For: CEITEC Brno University of Technology

EPR QO Bridge

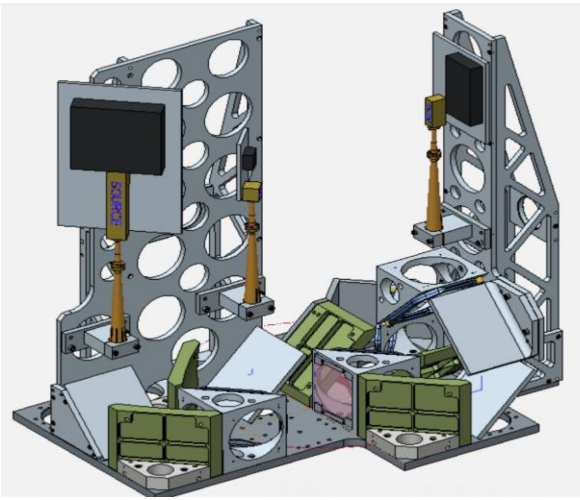




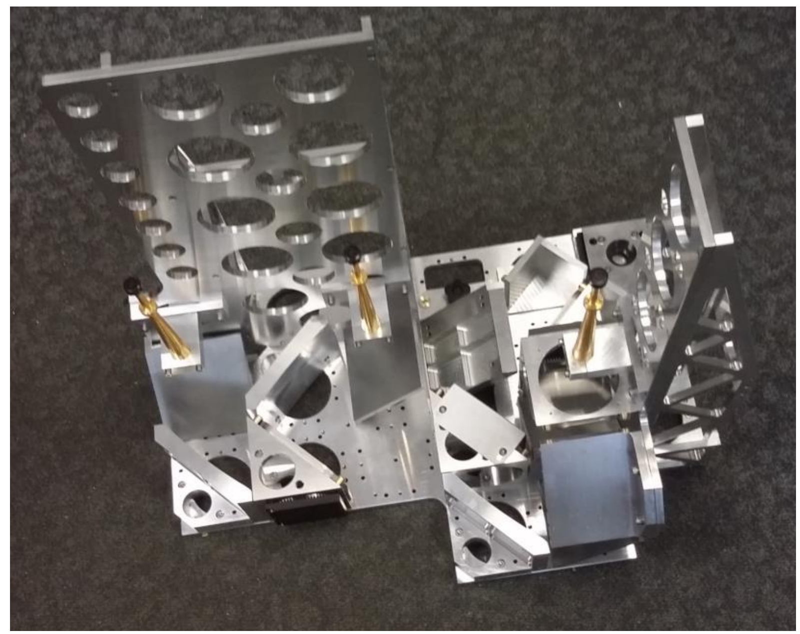
HF ESR instrument come in all shapes and sizes – depending upon frequency range and the form of the magnet

This one in Ohio

HF EPR enabled by Quasi-Optical Components



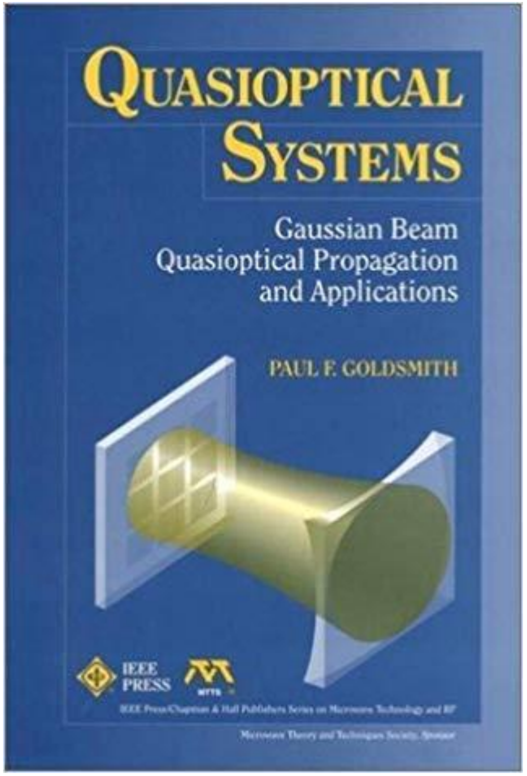
All of these appear in our HF EPR Bridges – and many other Instruments besides

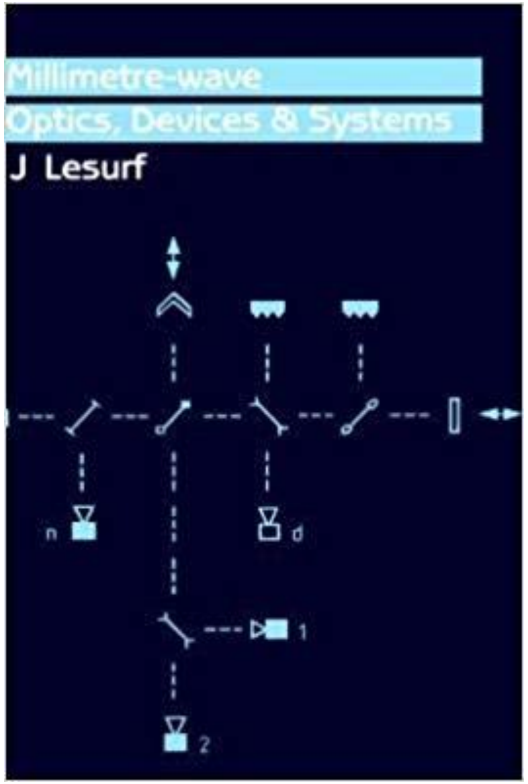


100 & 200 GHz ESR Bridge for Neutron Scattering Experiments

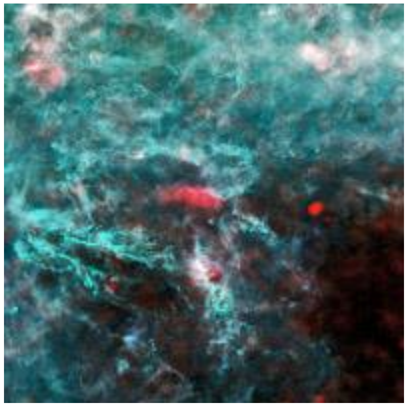
Collin Broholm – Johns Hopkins

Further Reading

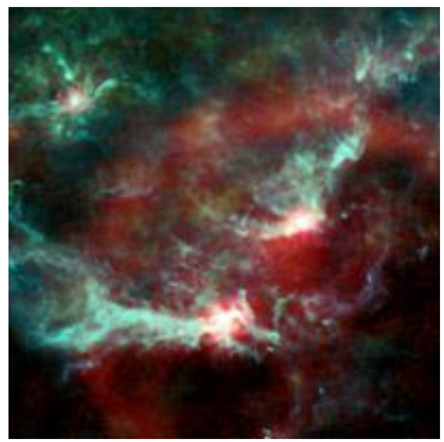


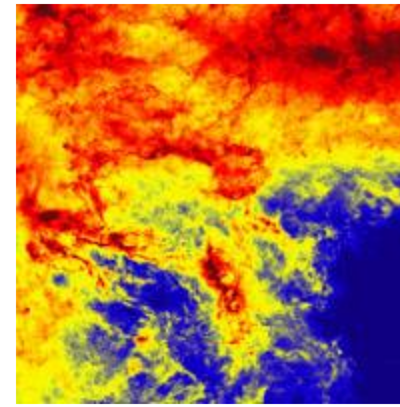


Planck Images – thanks to ESA



Leave you with some stunning THz images from Planck





Composite image from 30, 353 and 857 GHz measurements of a section of Perseus

An active star formation region in the Orion Nebula

ISM in Perseus at 857 GHz – low level of start formation