Quasi-Optical Design
A Short Tutorial …..

CEOI Training Workshop

Passive Microwave

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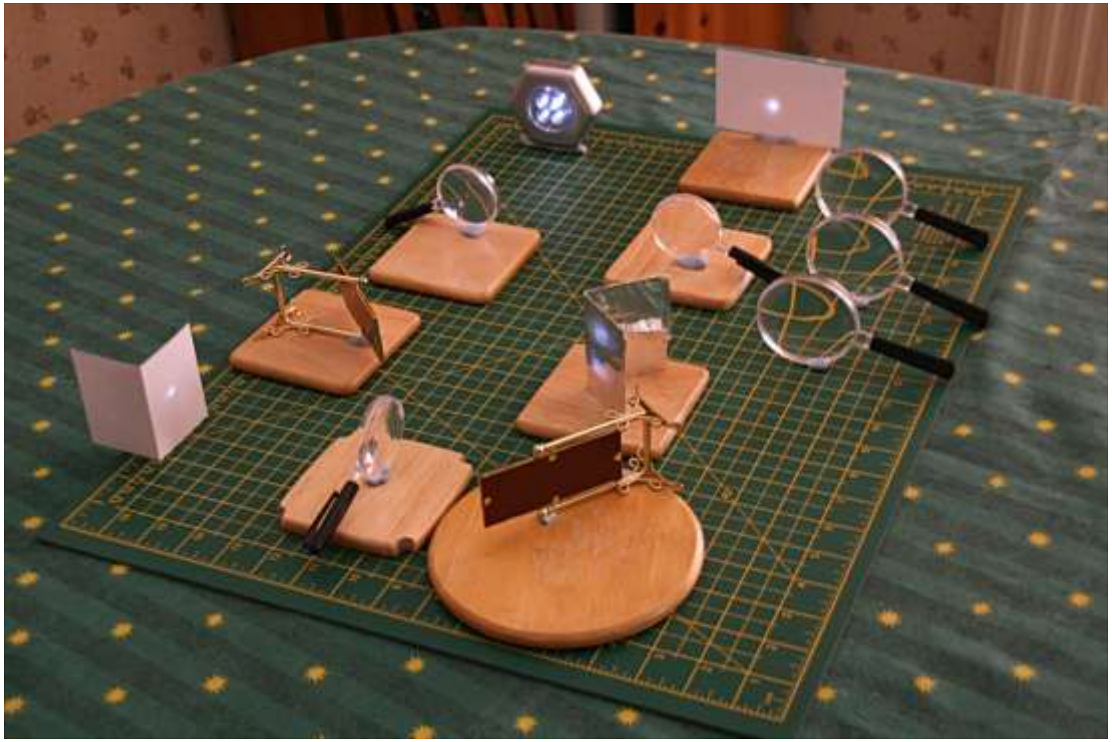
Design In-sight

What is Quasi-Optical (QO) Design / Analysis?

- Complimentary mixture of Optical and Microwave design
- Applicable in the THz region (0.01 -1 THz) !
- A means of visualising the feed system in a microwave radiometer (*microwaves aren't generally visible* …)
- The basis of a design of a microwave radiometer system before MW field analysis
- A means of analysing the radiometer performance

Quasi-Optics?



KEY	
Base Plate	Hobbycraft
Mirrors (adjustable)	Hobbycraft
Lenses	B&Q
LED Array	B&Q
Roof Mirror	Tesco (Alcan)
Detector Planes	Ryman
Optical Support	Habitat
Adhesives	WH Smith

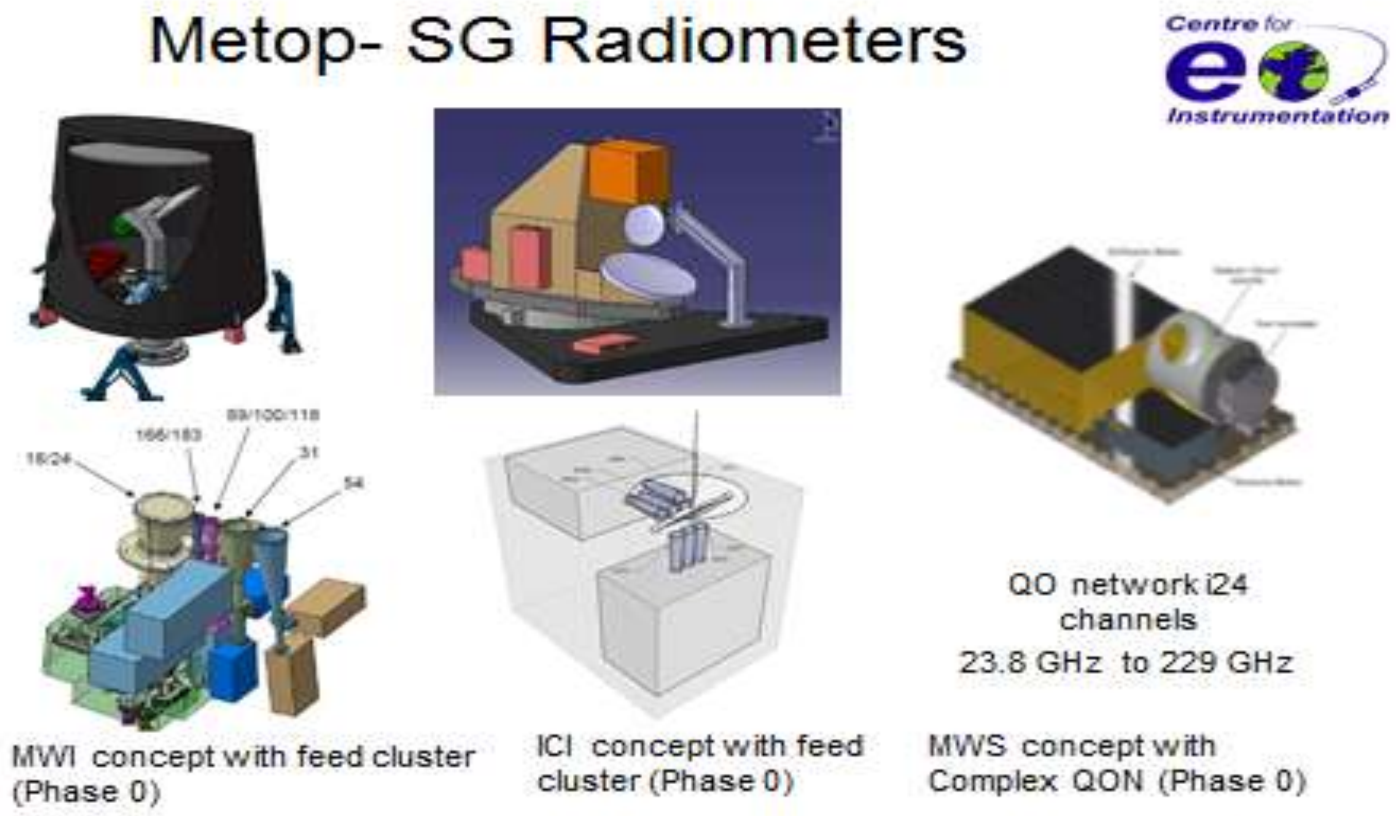
Straw Cutter Lite ! (2007)

- Demonstrates the microwave system built on CEOI Straw Cutter program for STEAM-R using light sources and multi-focus system
- Note the Beam splitting

Focus of Attention

- Context: Microwave Radiometers for Space
  - e.g. AMSU-B, MHS and now Eumetsat MetOp –SG MWS, MWI and ICI
- Requirements
  - Footprint on ground
    - Extent in km depends on satellite height
    - Pattern angle (1º- 5º from LEO)
  - Frequency bands and channels needed
    - 23 - 229 GHz (for MWS) 10:1 frequency ratio !
  - Radiometer sensitivity defined and leading to requirements on:-
    - RF Losses in feed system
      - Ohmic losses in components (current flow in surfaces)
      - Spillover losses (field levels outside components)
      - Reflection and scattering losses (edges and corners of components)

MetOp–SG Radiometers



Design Approach

- Main Mirror (reflector) defines footprint
  - Mirror will generally be scanned
- Reflector geometry (Parabolic, spherical) defines :
  - focal length (position of feed system)
  - cross-polar radiation (polarisation purity)
- QO chain to the Mirror defines illumination properties of the reflector
  - Beam size and foot print
  - Sidelobe levels and beam efficiency
  - In addition shares focal region with multiple feeds

Function of QO network

- Basic functions of the Quasi-Optical Network (QON)
- The QON design needs to translate beamwaist at the shared common focus of the Main Reflector to each feed horn in each band
- The beamwaist may be magnified or diminished by the optics to match the feed pattern
- The purity of the beam shape at the beam waist needs to be maintained to ensure the correct illumination of the main reflector and the farfield pattern performance (ground footprint)

Field at the Focus of a reflector

- In an **Optical System** (where apertures are many 100's or 1000's of wavelengths in extent), generally an image consisting of many points would be considered at a focal plane. Each point in the focal plane has a finite PSF (Point Spread Function).
- In a **Microwave System** (of maybe 10-100 wavelengths or less), the PSF is the image in a single beam system. This is the **antenna beam, or foot print**.
- Classically, in antenna system design terms, the focus would be considered as a point where you placed your feed (with known angular pattern) to form the antenna pattern from the reflector
- In QO, and gaussian beam optics, the focus is considered to be a finite beamwaist, with associated radius and phase centre, defining how the field radiates from the point.
- In QO this beamwaist is expanded round the QO system, between components (e.g. mirrors, filters, grids, dichroics and lenses)
- This expansion can be achieved in many ways:
  - Gaussian beam expansion
  - Physical Optics expansion
  - Ray Traced expansion
  - And combinations of all of these

Analysis Techniques

Large range of properties can be used to analyse a QO system

- Light travels in straight lines! (Geometric Optics, GO)
- Light reflects and refracts at a surface (Snell's Law)
- Light is an electromagnetic EM wave !
- EM Waves propagate (Huygens expansion)
- EM fields can be represented by Gaussian Beams (Single mode and multi-mode Gaussian Beam analysis)
- EM fields in a horn feed can be represented by cylindrical modes or spherical modes (HE11, which is a gaussian like mode)
- EM Waves are produced by currents on surfaces (Physical Optics, PO)
- Currents are induced by EM fields and reradiate (Diffraction, GTD)

Wave Particle Duality Paradox ! The QO system can be thought of in terms of Rays or Waves

All these properties are used in QO analysis

Beam Expansion Techniques

- Geometrical Optics (GO) – Light rays in straight lines
- Non-Sequential Ray Tracing (NSRT) – Interfering multiple rays
- Gaussian Beam Expansion (GBE) -(Single mode or multimode)
- Physical Optics (PO) – Surface currents produce fields
- Geometrical Theory of Diffraction (GTD) – Induced currents on edges expand as fields (Keller cones)
- Beam Propagation Synthesis (BPS) - Selective field expansion around ray bundles
- Method of Moments (MOM) – Field coupling between components
- Finite Element (FE)- expansion of current elements on complete system

Computer Codes

- CODE-V General Optical analysis (Sequential), GO, PO, Gaussian Beam propagation. Also Fourier Transform
- Zemax Sequential and Non-Sequential Ray Tracing, GO,PO between QO surfaces
- GRASP Reflector GO, PO and GTD on multiple reflectors
- QUAST QO Gaussian beam front end to GRASP
- CHAMP Cylindrical Mode analysis of corrugated conical horns

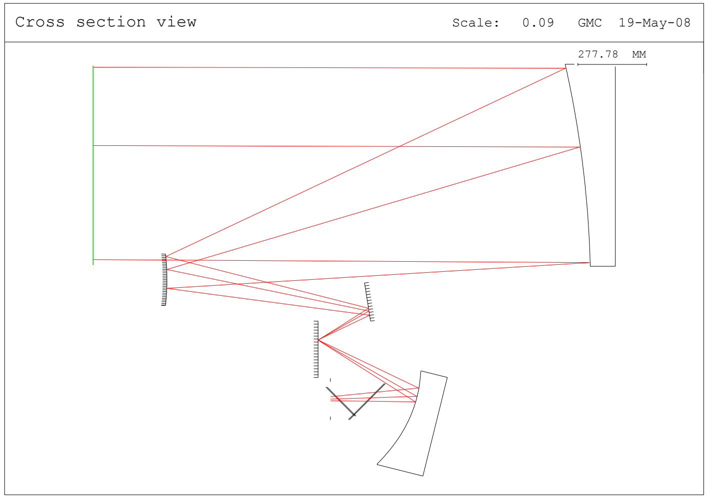
  Integrated MOM for horn outer profile and sub-reflector (or lens combination (TBC))
- CST,HFSS Frequency and Time domain analysis (FDTD) of microwave structures and systems
- FEKO General EM analysis of multiple reflector and dichroic plates and filters (PO, FE, MOM, GTD)

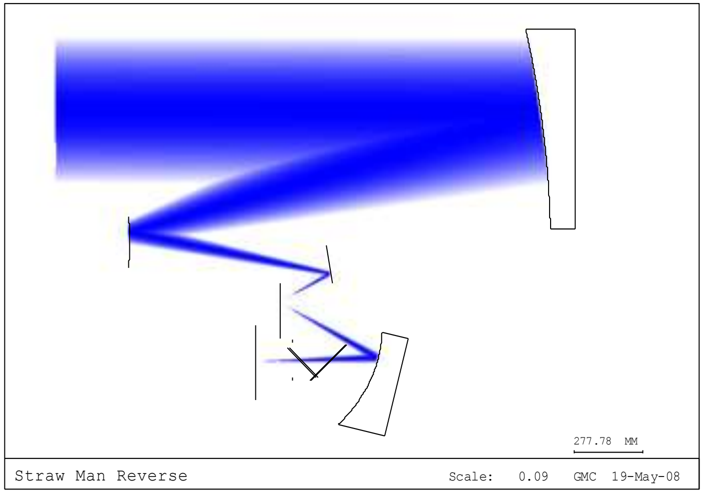
Gaussian Beam Propagation

Centre for eo Instrumentation

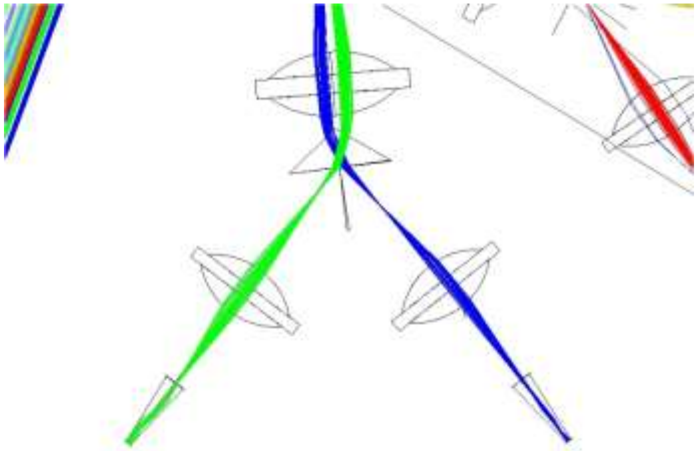
Propagation through the system

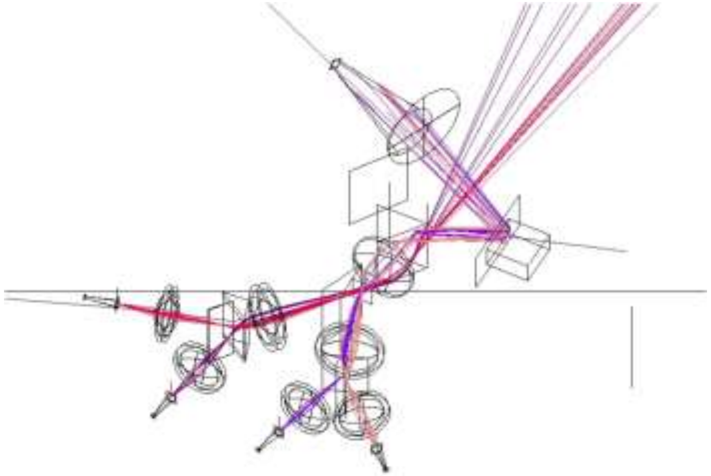
- Example from STEAM-R QO system (CEOI 340 GHz 2008)
- CODE-V mode (GO) – Source horn (bottom left) feeds main reflector via mirrors
- Sequential QO system **– no multiple paths possible**
- Same system with Gaussian Beam expansion from feed
- Non-Sequential Ray Tracing (NSRT, zemax) may be used to analyse this system - **multiple paths possible**

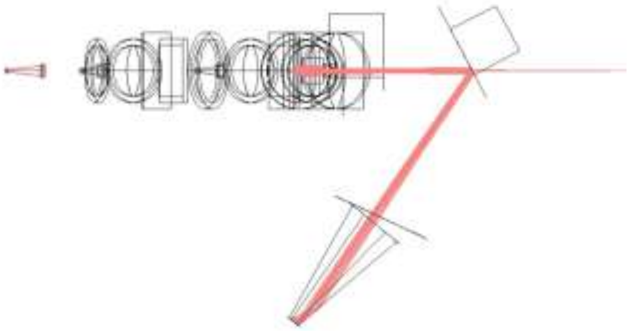




NSRT example (CEOI STEAM-R)







- Analysis of Beam Splitter with calibration load
- 3D component model
- Horn feeds, mirrors, prisms and lenses described in model
- Ray Traced QON in zemax 340 GHz
- Beams traced by colour per feed

Feed Horn Design

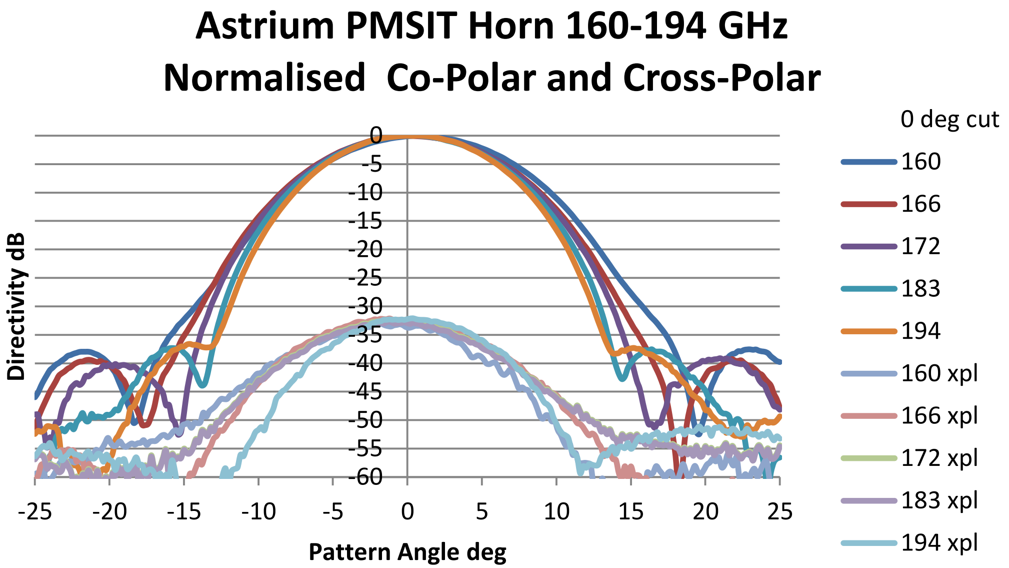
- Basic design of feed horn in QON aims
  - Wide bandwidth (e.g.16% at 183 GHz needed)
  - Very Good beam efficiency (low sidelobes , 1^{st} -35 dB to -40 dB)
  - Gaussian shaped beam (HE11 mode likely)
  - Good polarisation Purity (good cross-polar performance <-30 dB)
  - Good return loss at throat (-30 dB)

- Solution is a hybrid pattern horn
  - Potter stepped horn (1% bandwidth)
  - Linear or profiled Corrugated horn (20%)
  - Ultra Gaussian Horn (UGH) (very low sidelobes -40 dB) but long length
  - Modified profile corrugated horns (higher sidelobes, but shorter in length)

- Not essential to have a gaussian beam, and in fact horn patterns are only gaussian shape to a given power level (typically -20 to -40 dB)
- Ultra Gaussian Horn may be characterised by a simple beamwaist near the horn aperture and fairly constant in position (phase centre)

166/183 GHz Ultra Gaussian Horn

- 166/183 GHz corrugated horn (CEOI PMSIT development)
- High Performance Ultra Gaussian low sidelobe (-40 dB) design
- Beamwaist radius 3.7 mm 183 GHz



Measured co-polar and cross-polar Radiation patterns

Mirror / Reflector Design

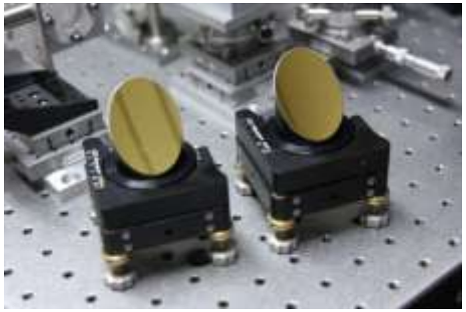
Just a few points about mirrors !

- F/D ratio should be kept high (>0.5) long focal lengths, but
  - In microwave systems a long focal length mirror leads to a large feed horn with small pattern angle needed to feed it
  - A short focal length leads to high cross-polar levels

    (F/D=1, -23 dB and F/D=0.5, -17 dB)
  - Beam symmetry is important for good mode matching in horn so spherical aberration needs to be minimised
  - Long focal length and illumination close to mirror normal is best

Good mirror to use is the 90º offset parabola – no spherical aberration !

- Single focus mirror – collimated beam in nearfield
- Surface finish <0.01λ rms (<10 microns)
- Aluminium or Gold (>1 micron) plating on aluminium (mainly because it protects aluminium)



Microwave Lens Design

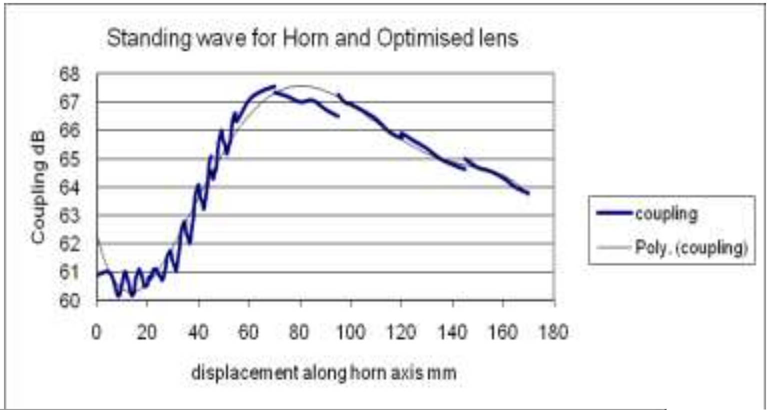
- Standard dielectric lenses are problematic!
  - Use to transfer beamwaist from one place to another in QON
  - Or scale the beamradius size and translate beam
  - Matching attempted with quarter-wave blazing on surface
- Standing waves evident between Corrugated horn and lens due to a few factors
  - Higher order modes in a simple HE11 design do not match at edge of lens
  - Reflections occur between the horn rim and the lens
  - Lens suffers from internal reflections and high energy (focussed regions) within the lossy lens materials

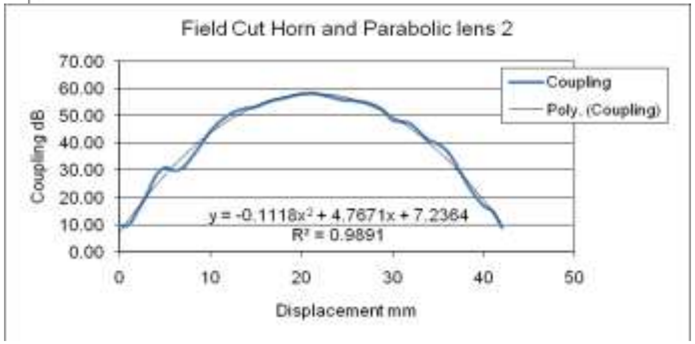
Solutions

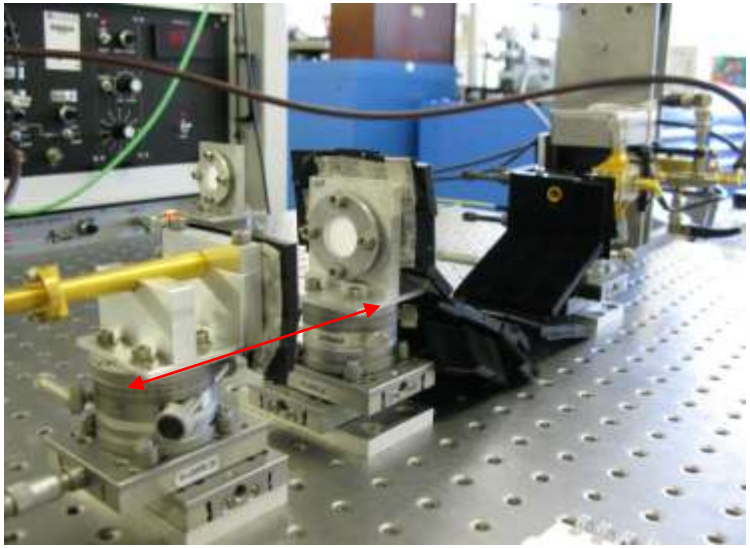
- Attempt to match fields in horn to a shaped lens
  - Analysis available (internal Astrium F) or CHAMP horn analysis (Ticra sometime soon!)
- **Develop an advanced lens design with low reflectivity**
  - **Astrium CEOI Metamaterial Study (2011) and Advanced GRIN lens design (AGLeD) (2012).**

Standing Wave in Lens / Horn

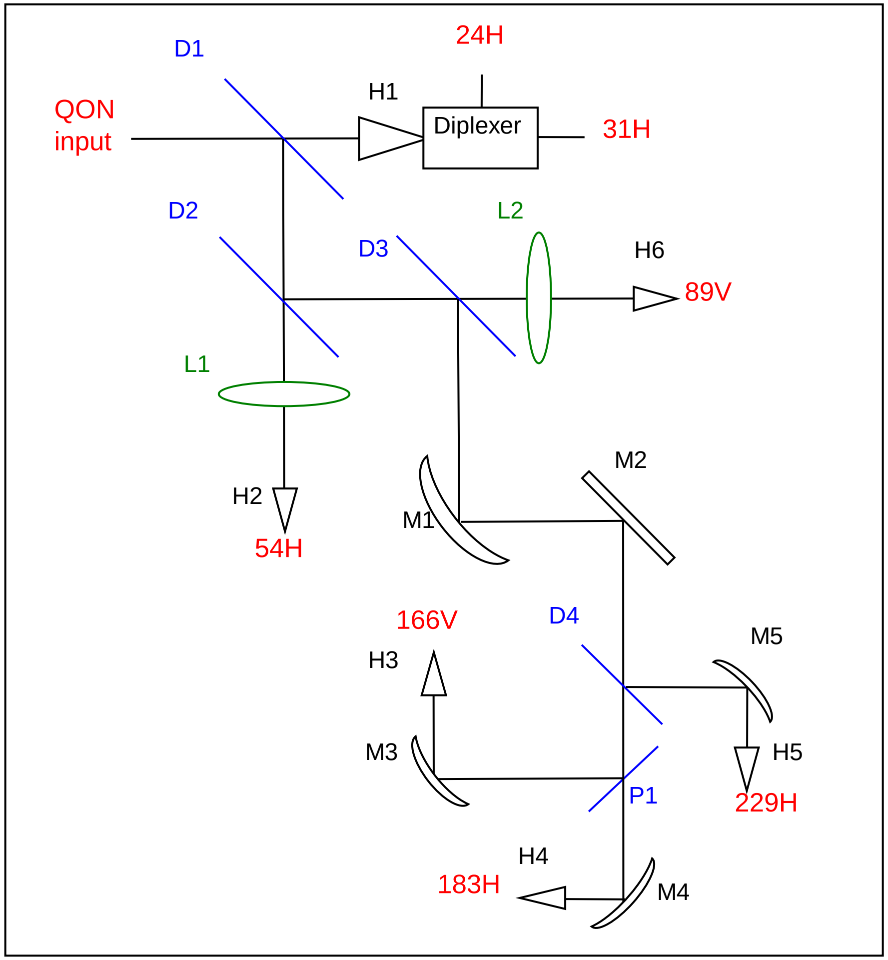
- Horn-Lens-Horn coupling 340 GHz
- Optimised lens shape with blazing
- Peak field at focus of lens
- 0.7 dB ripple in standing wave **along** the optical axis
- ~1 dB **across** optical axis





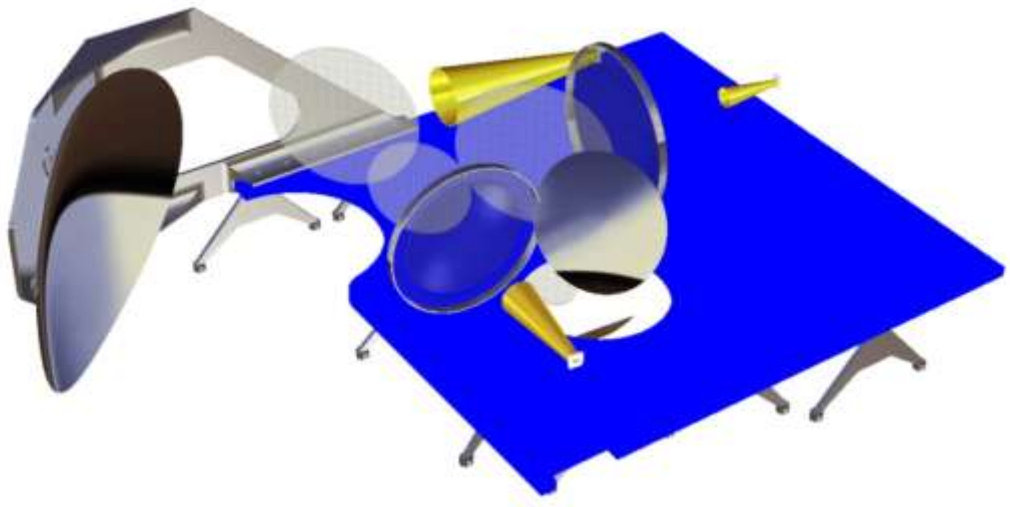


MWS QON Concept



- Complex QO network from MWS Phase A1 study for ESA
- QON includes focussing mirrors, lenses, dichroics beam splitters, polarisation grids and feed horns
- Main Mirror off top LHS
- Multichannel 24 GHz to 229 GHz
- Scheme is only a concept – Not here a detailed design
- Working Zemax model available
- PO analysis of reflector and feed system
- EM model of part of QO system (FEKO model)

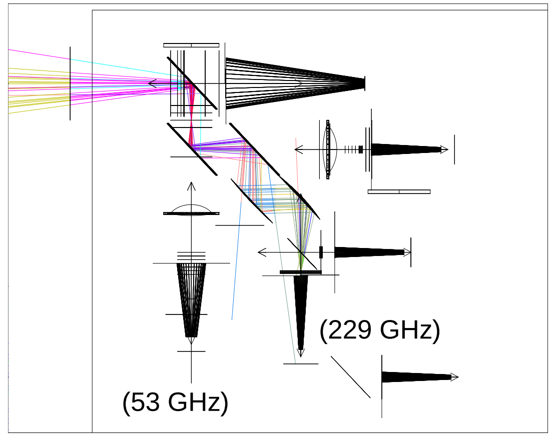
Instrument Concept with Reflector

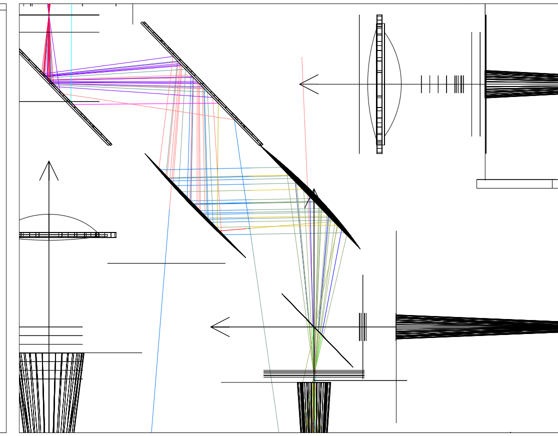


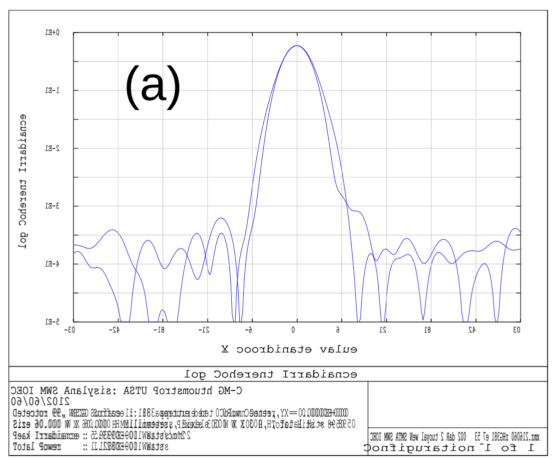
- QON concept for low frequency components
- Main reflector mounted to Instrument panel
- Horns, dichroics and mirrors shown

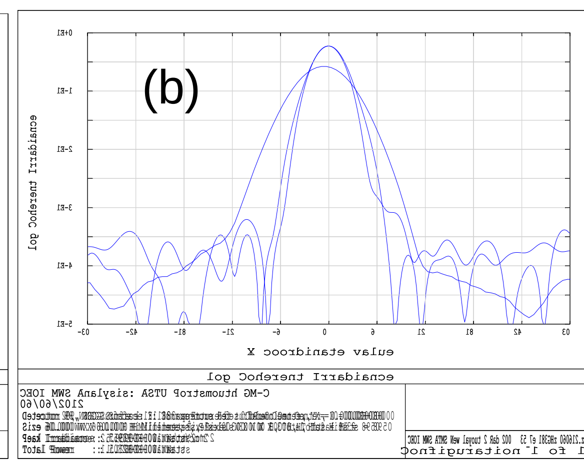
Non-Sequential Ray Tracing (zemax)

- Example Ray Traced layout using Non-Sequential Ray Tracing **(NSRT) in zemax** using detector planes
- Multi-feed QO system off single main reflector (off top LHS)
- Predicted beams in QO system at 229 GHz
- Dissimilar mirrors in Beamwaveguide (200 and 100 mm FL)
- **(a)** Two orthogonal cuts of field at Common Focus off main reflector system
- **(b)** Field magnification at horn (x2)





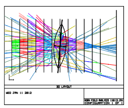


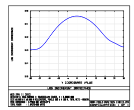


Lens Tilt effect on Beam Shape

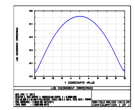
NSRT applied to dielectric lens (53GHz)

- Gaussian Source LHS (a)
- Zemax Detector planes set around lens with Huygens expansion of field

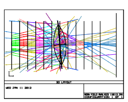


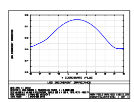


(b)



(a)





(c)

Source field on LHS modified by reflection from lens

a) Source with No lens +0° (-40dB)

b) Lens Tilt +5°   (-20 dB skirts)

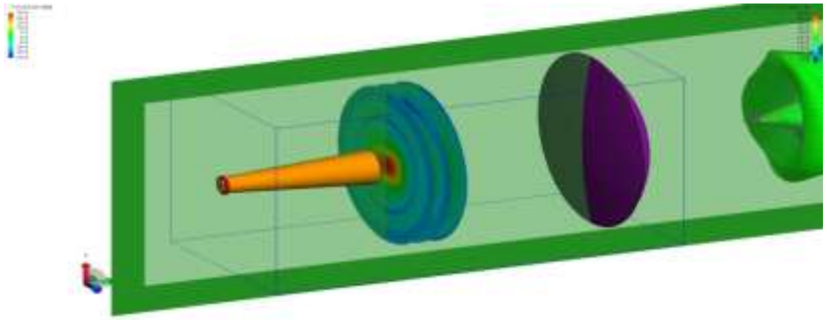
c) Lens Tilt -5°

Note the Optical focus on RHS

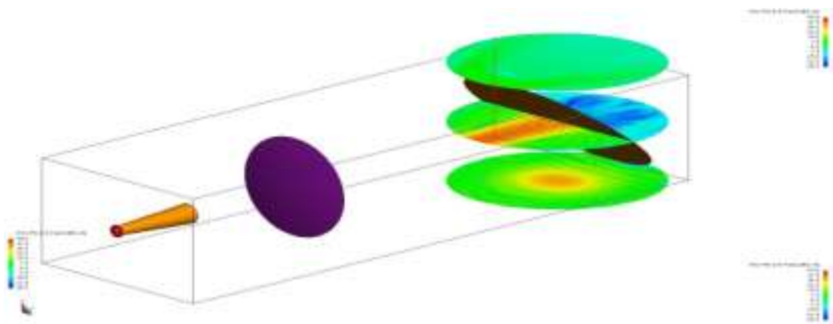
Two other foci are on the LHS near to and in the lens)

FEKO Analysis of QO system

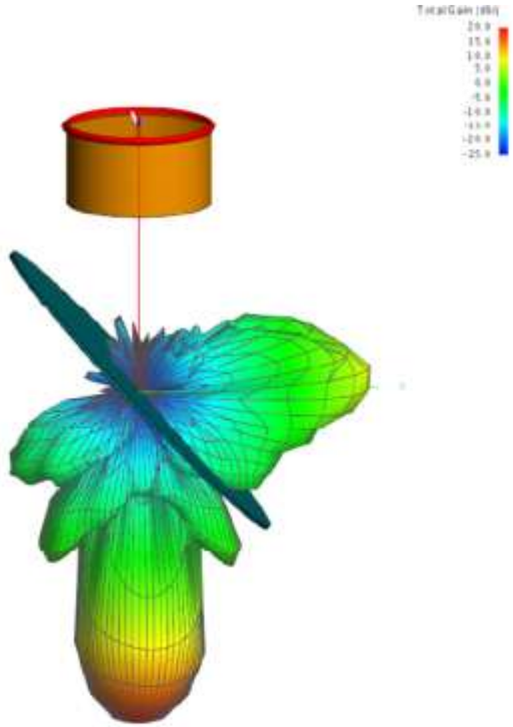
- Examples plots 53 GHz (CEOI MSQS program 2011)



Horn and dielectric lens

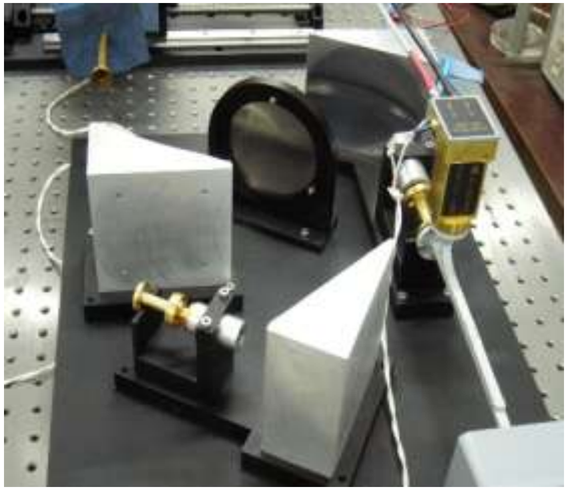


Horn lens and dichroic plate

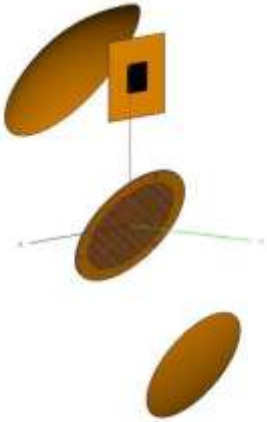


Horn aperture and dichroic plate showing transmitted and scattered fields

QO system analysis in FEKO

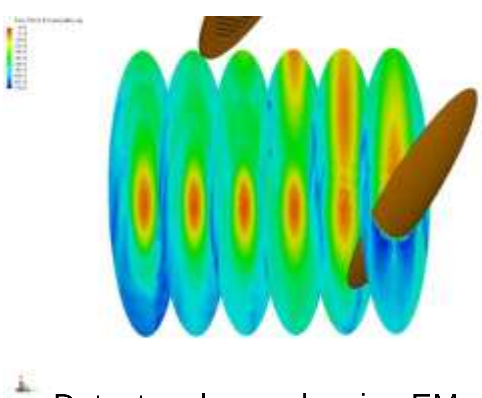


QMUL QO system CEOI MSQS program (54 GHz) – spin-off

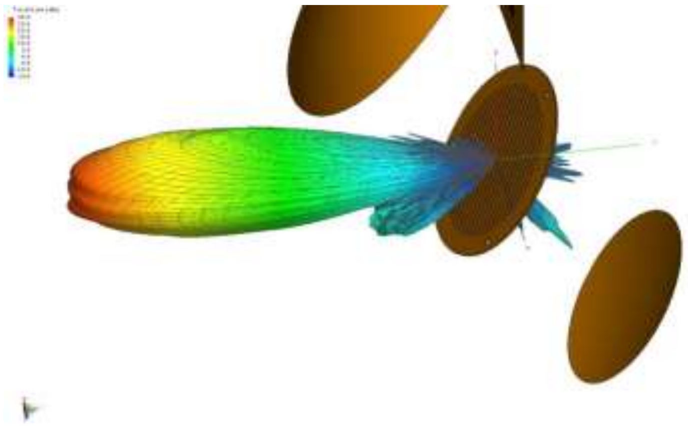


FEKO surface model

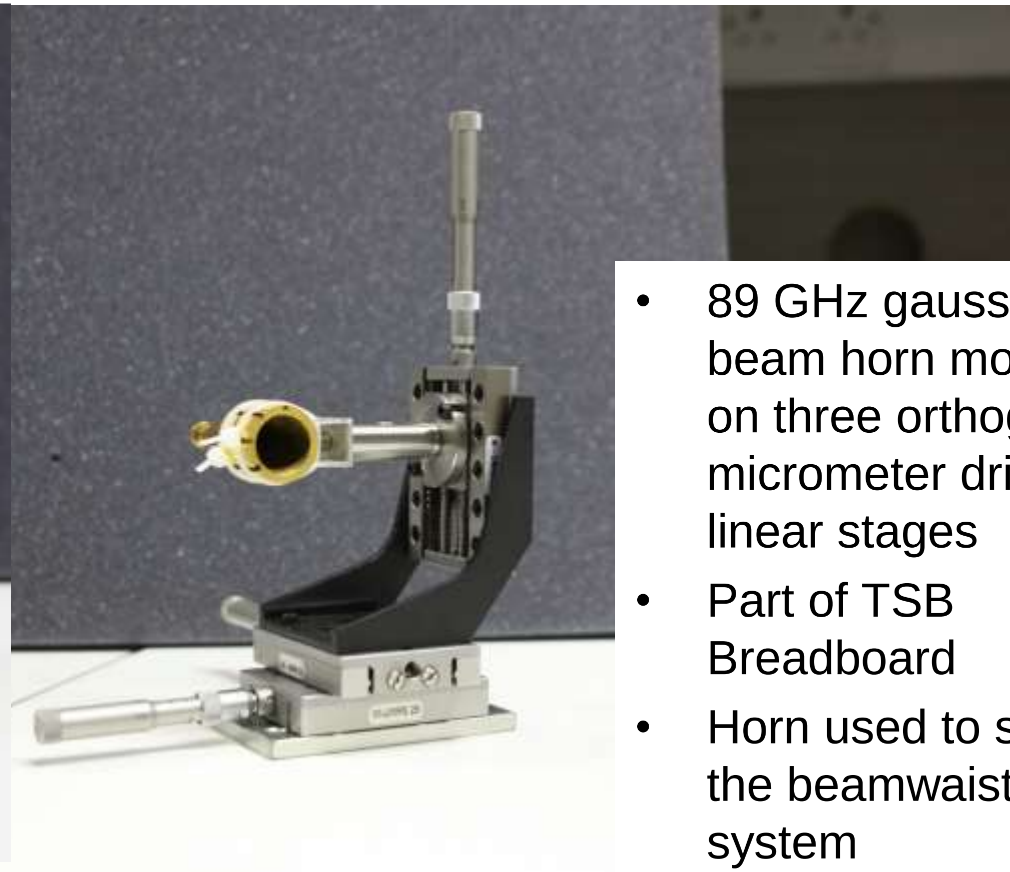
- System contains a Gaussian horn, two elliptical mirrors and dual layer FSS
- FEKO analysis with fields analysed on planes
- Sidelobes and scattering from back of FSS evident
- Complementary model to NSRT



Detector planes showing EM incident and reflected fields



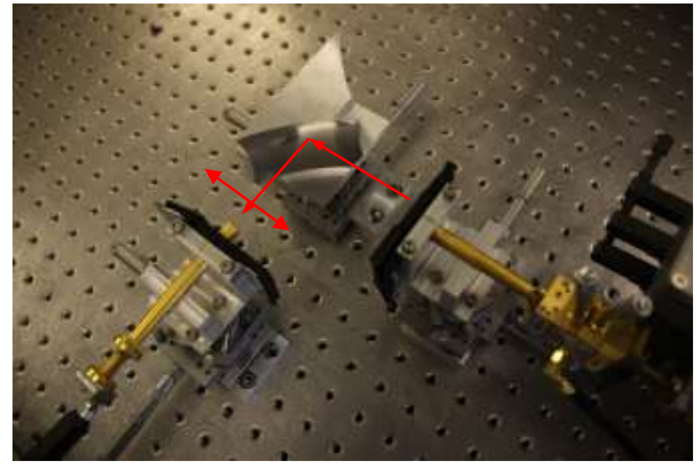
QO Field probe 89 GHz

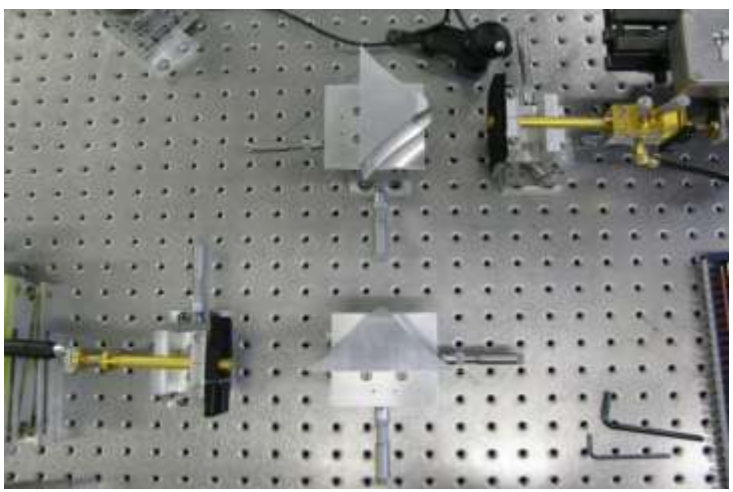


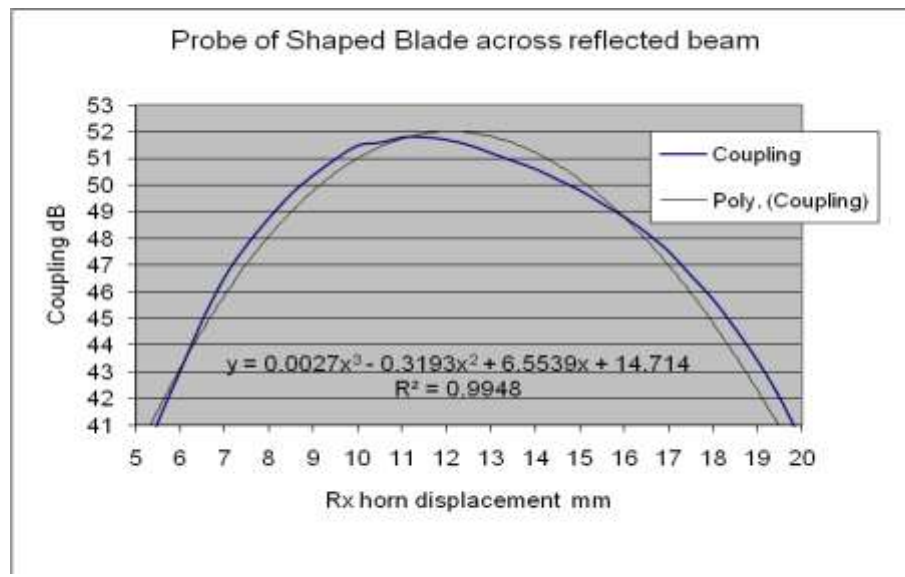
- 89 GHz gaussian beam horn mounted on three orthogonal micrometer driven linear stages
- Part of TSB Breadboard
- Horn used to sample the beamwaist in QO system
- 1 micron sensitivity <1/100λ

Quasi-Optical measurements

- Optical test bench example showing fields from horns and mirrors being measured (340 GHz) (CEOI STEAM-R - Straw Cutter project 2008)
- Horn probe is mounted on linear adjustment base to scan field from reflector.
- Some beam distortion can been seen in the probe scan from edge reflection and diffraction
- TSB BB 183/229 GHz work will have 2D scans across the beam

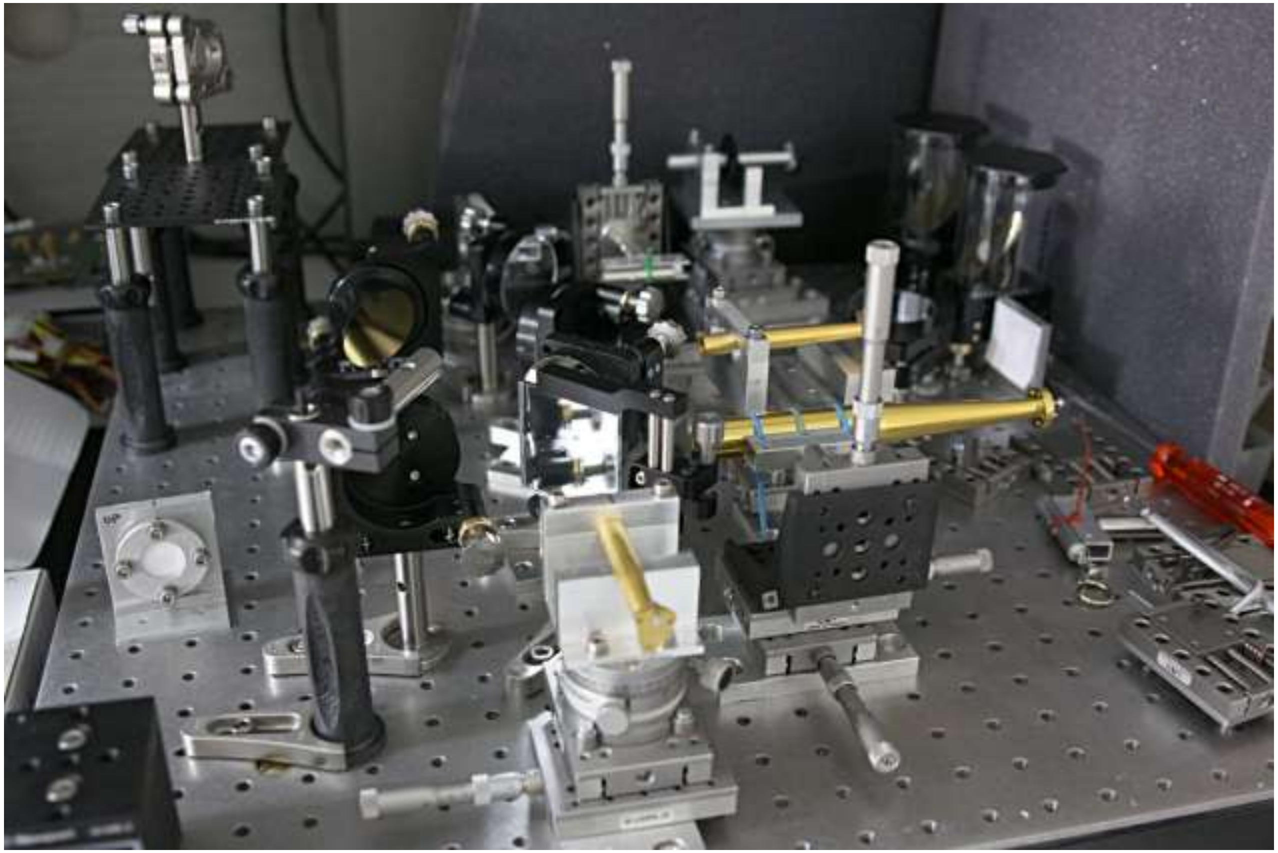






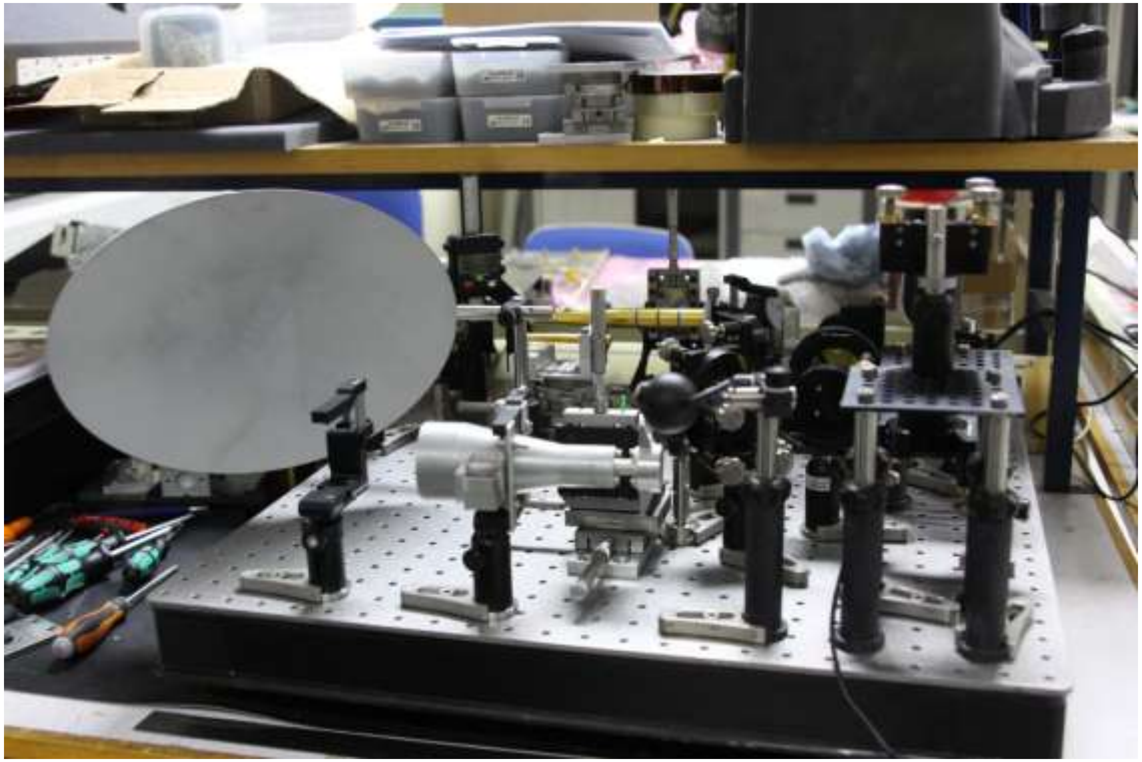
Graham Maxwell-Cox, Astrium Ltd

TSB Breadboard MWS



- TSB 166/183/229 GHz QO breadboard
- Design as per MWS Radiometer requirements
- Horn feeds on 3D micrometer stages for field probing

Main Reflector on TSB Breadboard



Initial Integration and alignment of main reflector on TSB breadboard

- 53 GHz corrugated horn may be seen in the foreground
- COTS optics supports and mirrors (Newport Spectra Physics)
- Work in progress!