Optics and Beam Forming: A Review

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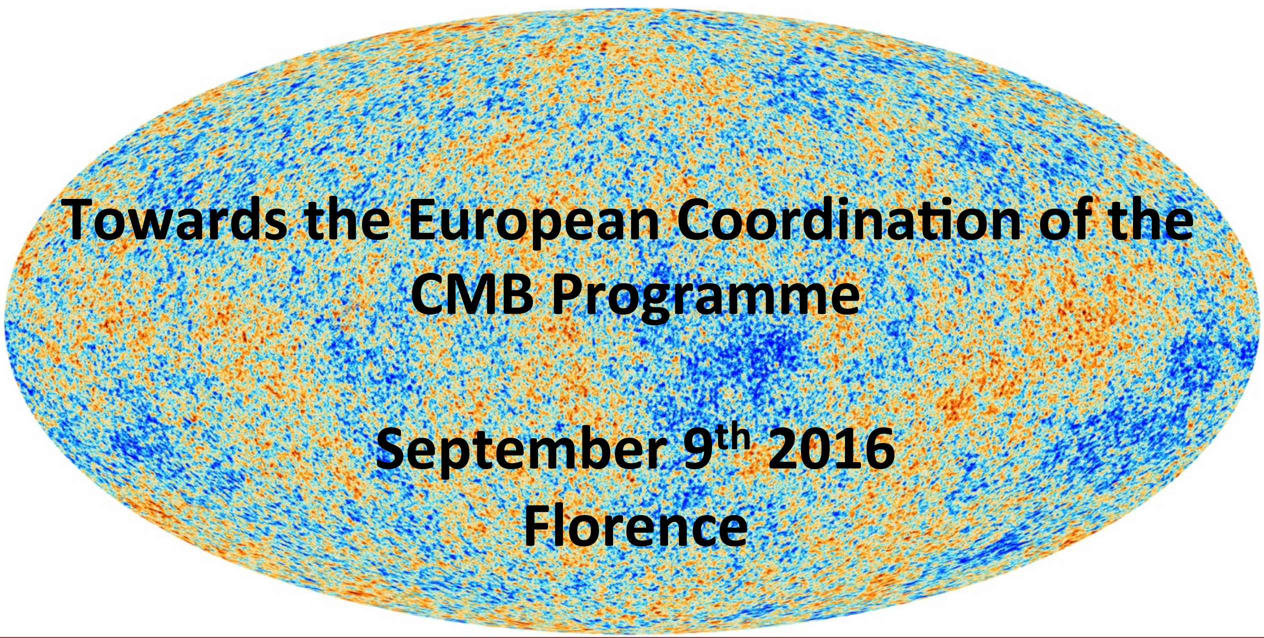


Towards the European Coordination of the CMB Programme

September 9th 2016
Florence

Introduction

- Building on the strong heritage and success of missions such as COBE, WMAP and Planck, we are now aiming to build instruments capable of detecting the B-mode component of the CMB anisotropy

- This will require the telescopes and focal plane architectures to realise much higher levels of sensitivity and systematic control than were achieved by previous instruments (anisotropies in the temperature, E-modes and B-modes are respectively at the levels of 160, 8 and 0.1 μK, the B-mode figure being an upper limit)

- Require all sky survey with sufficient angular resolution to remove lensing signatures, with approx 2.5 μK.arcmin pixel noise on the final maps. Detectors have realised necessary NEP – now must design an instrument that can exploit this

- To fully constrain the B-mode measurements, we must also observe the foregrounds. This means that we require many frequency channels from 60 GHz up to perhaps 1 THz
- These requirements make for a significant technological challenge

Specificities and Requirements of Platforms (from an optical perspective)

Ground based

- Relaxed requirements on dimensions, mass, cooling power
- Need to worry about ground pick-up→ stringent requirement on ground spillover
- Need a thick window and more thermal filters: higher thermal loading and need for low emissivity / low loss components
- Effects of atmosphere + above components → additional systematics
- Components can be changed / modified

Balloon

- Requirements of mass, dimensions and power not as stringent as space but limits still
- Existence of cryostat window (even if thin)
- Residual atmosphere

Space

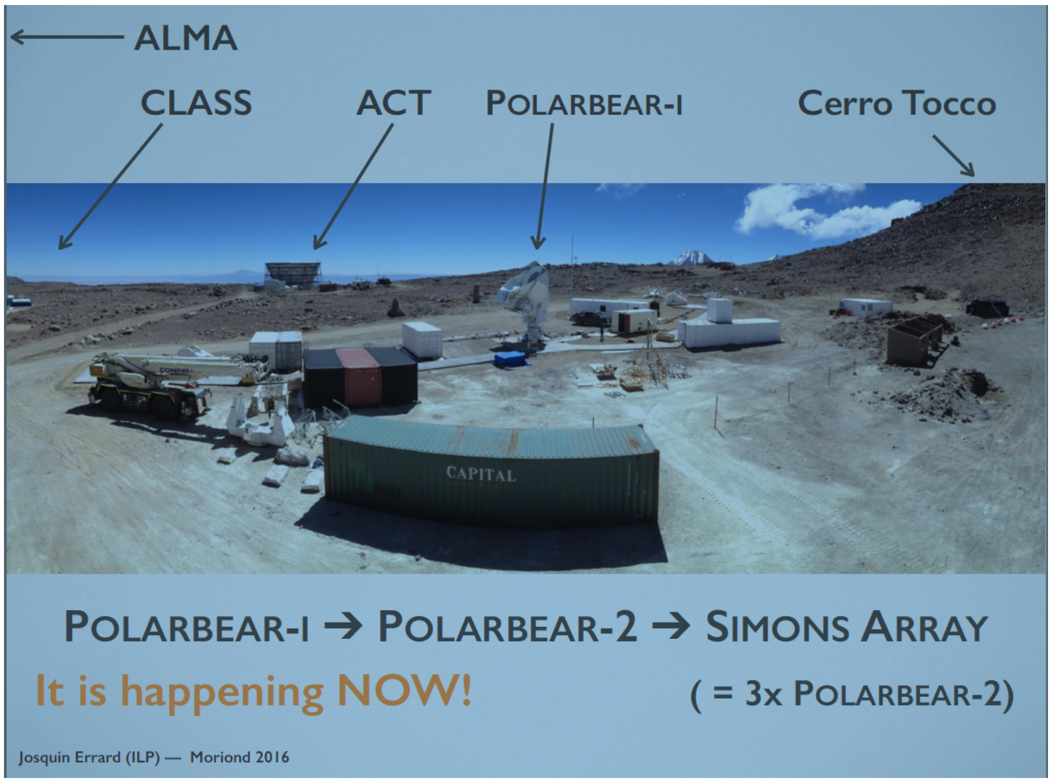
- Strong requirements on mass, dimensions, power and cooling power
- Strong requirements on spillover due to contamination source
- No window, atmosphere, fewer filters: beams can be cleaner → higher specs for beam formation

Some Representative Projects

Instrument		Beam Forming	Technology	Detector	Comment
QUIET	Ground based	Corrugated Horn Arrays	Horn platelet arrays	Split Block OMT HEMT amplifiers	Used novel platelet techniques to manufacture horn array
ACTPOL receiver	Ground based	Silicon platelet horn array	Horn Platelet arrays	TES array	Multichroic operation (90 and 150GHz) in one horn
BICEP 2	Ground based	Phased array of 512 TESs	Phased array technique to define beam	TES array for each polarisation	Array of double slot antennas
POLARBEAR 2	Ground based	Lenslets with sinuous antennas (multichroic)	Silicon lenslets	TES array	Multichroic operation with sinuous antennas coupled via lenslet
LiteBIRD	Future space mission	Silicon lenslets	Planar	MKID array	Next generation mission
CoRE+	Future mission proposal	Flat lens coupled antenna array with 1.2 m telescope	Flat lens coupled antenna array	MKID array	Next generation mission

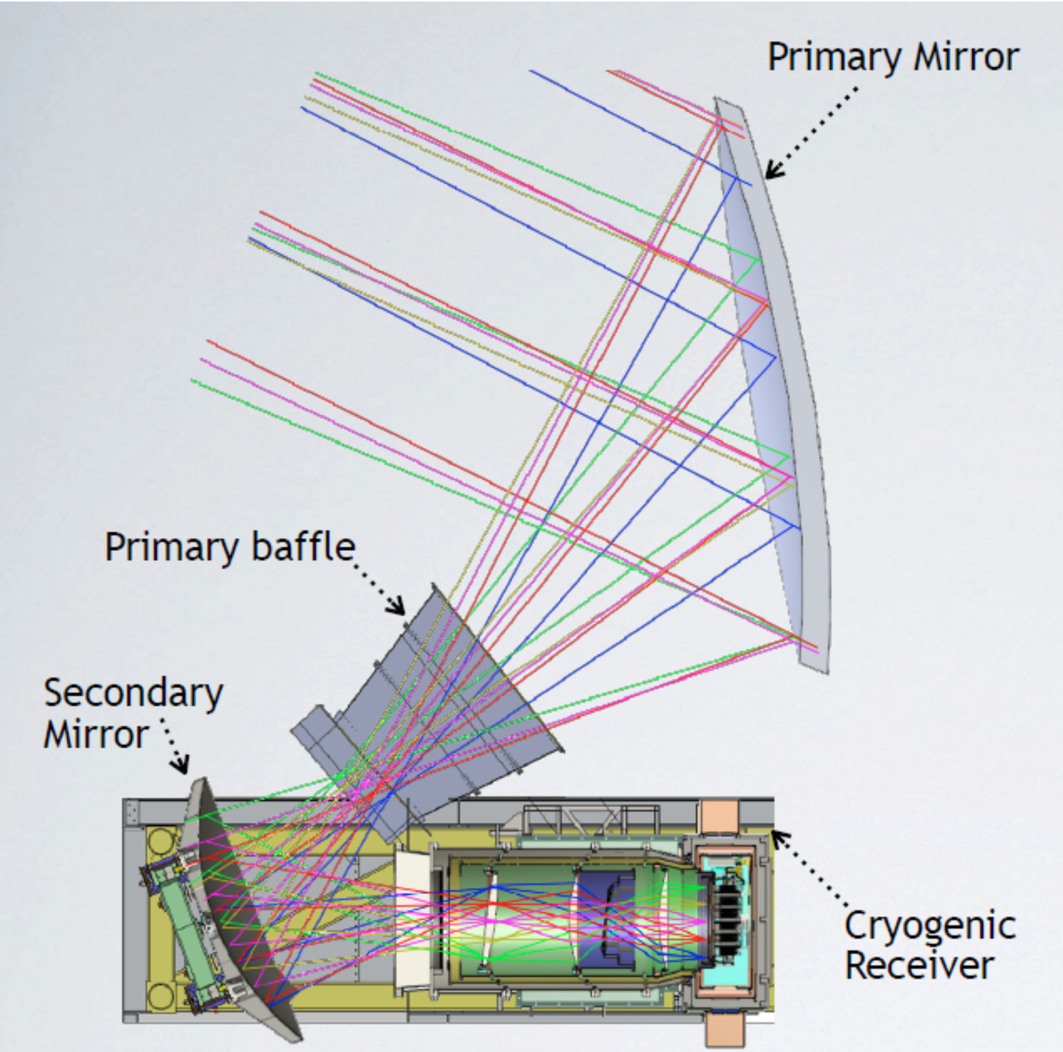
Polarbear – 2 and the Simons Array

- James Ax observatory at an altitude of 5200 m in the Chilean Atacama Desert
- Allows cross-correlation with other experiments, and access to 80% of the sky



Future CMB polarization observatories in the presence of foregrounds and gravitational lensing: POLARBEAR-2 and the SIMONS ARRAY, Josquin Errard, Moriond 2016

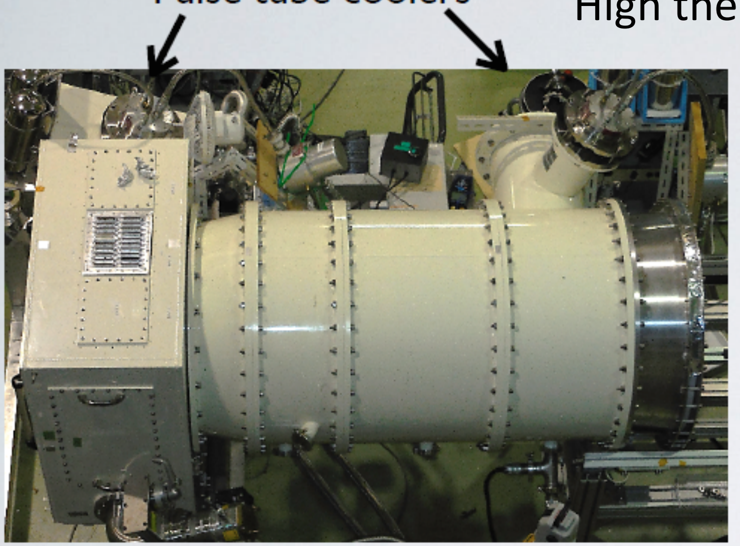
Polarbear – 2 and the Simons Array

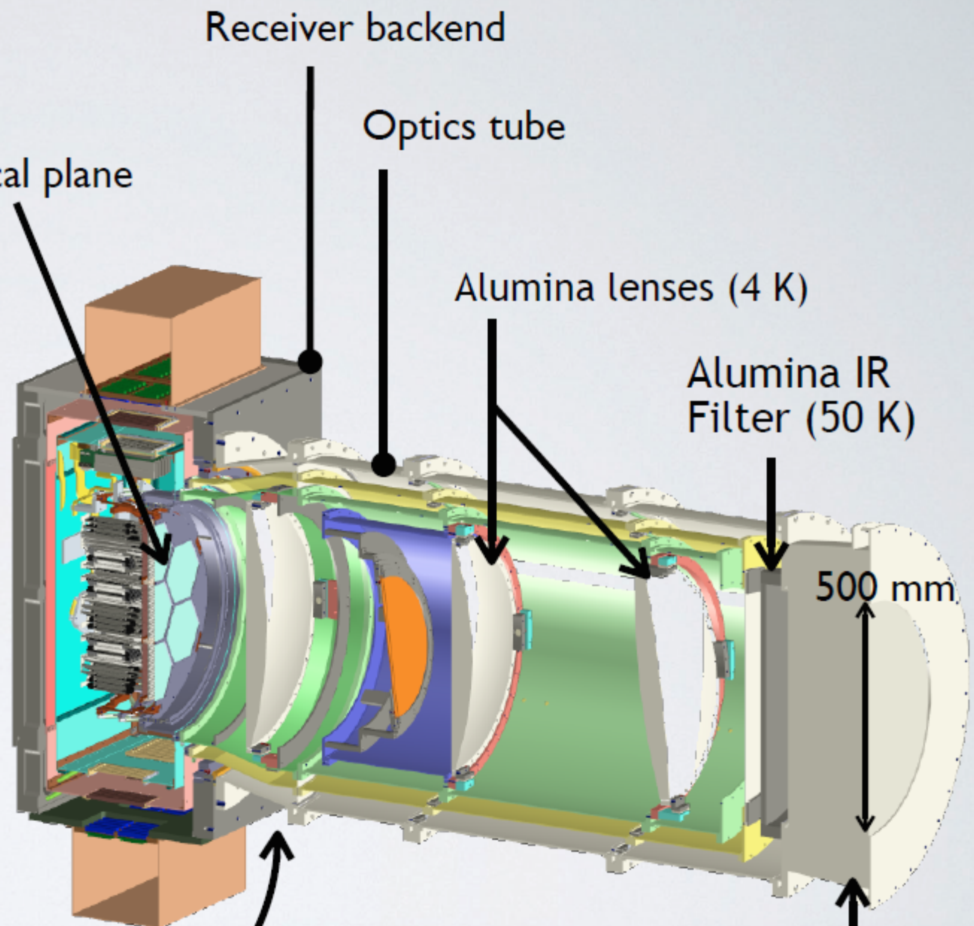


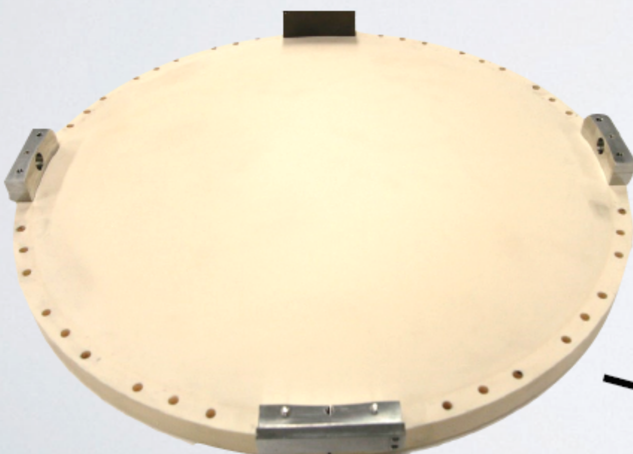
- 3.5 m offset Gregorian (high polarization fidelity, low sidelobe levels, high TRL, high aperture efficiency and easy to baffle)
- 3.5 arcmin resolution @ 150 GHz
- Receivers cover 95 and 150 GHz simultaneously
- Two more receivers (95+150 GHz and 220+280 GHz) will be rolled out soon on additional telescopes, forming the Simons Array
- Aim is to maximise sensitivity and control systematics

POLARBEAR-2 Receiver

Lenses/filter made from Nihon Ceratec's 99.9% purity alumina
N=3.1 minimises optical aberrations. Low loss tangent
High thermal conductivity.







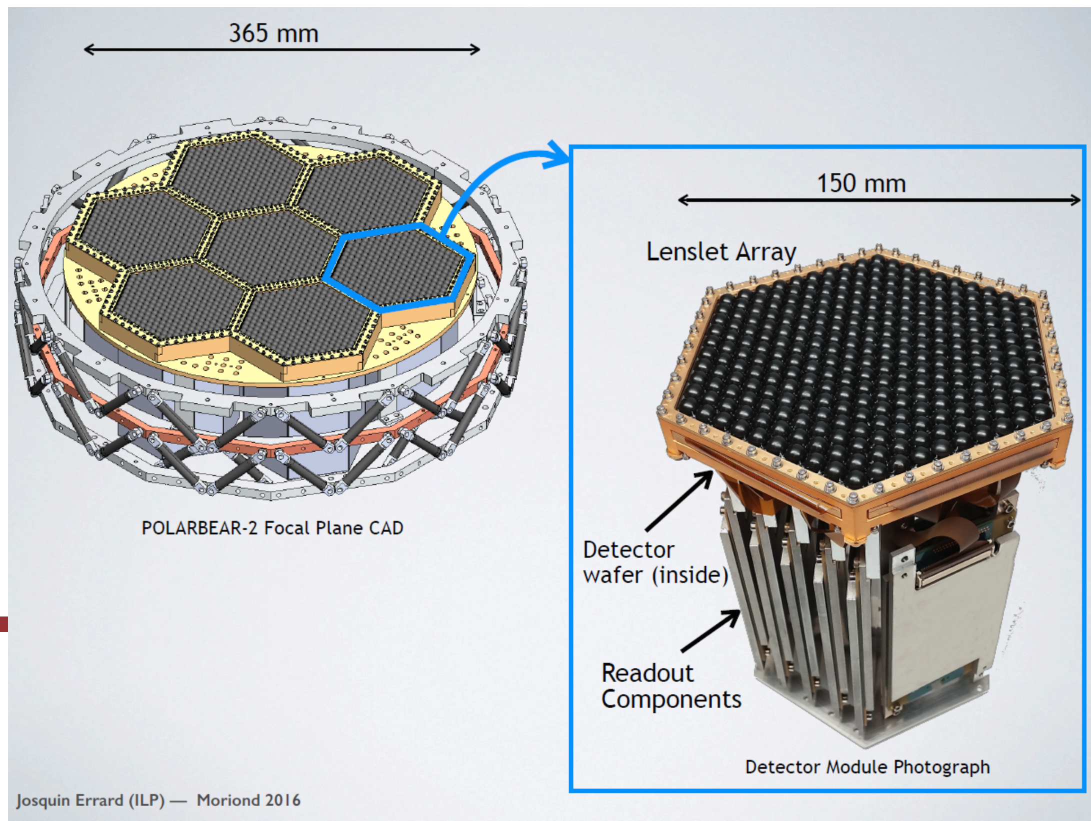
Josquin Errard (ILP) — Moriond 2016

AR coating minimises losses. (Two layer epoxy coating, thermal sprayed ceramic coating and expanded kapton coating)

Polarbear 2 Focal Plane Architecture

- Focal plane houses seven detector array modules, each containing 271 dual linear polarised pixels that are multichroic, detecting at 95 and 150 GHz simultaneously. This gives 7588 individual detectors (TES bolometers) on the focal plane

- This optical system achieves a Strehl of greater than 0.9 across the entire 365 mm diameter focal plane – this gives very high levels of optical quality



Polarbear 2 Beam Forming

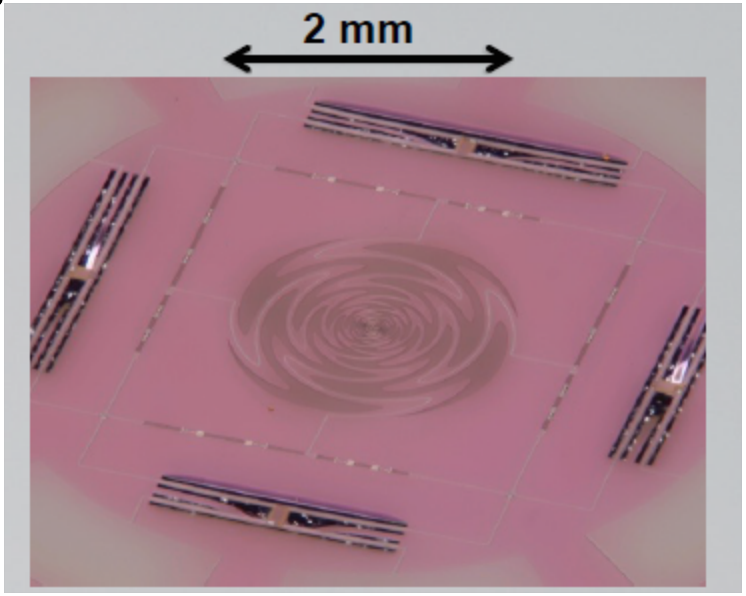
- Each pixel uses a sinuous antenna to couple the optical signal to the RF detector regieme

- These antennas are inherently broadband and dual polarized, meaning that one antenna can provide multichroic operation and measure both polarizations, meaning that a more densely packed focal plane can be realised – critical for increasing sensitivity

- Antenna is a continuous winding structure that emits long wavelengths from the exterior regions and short wavelengths from the interior regions

- For antennas coupling to linear polarisation, the opposing arms separated by half a wavelength act as a two element array

- Continuous broadband operation from 60-240 GHz



Polarbear 2 Beam Forming

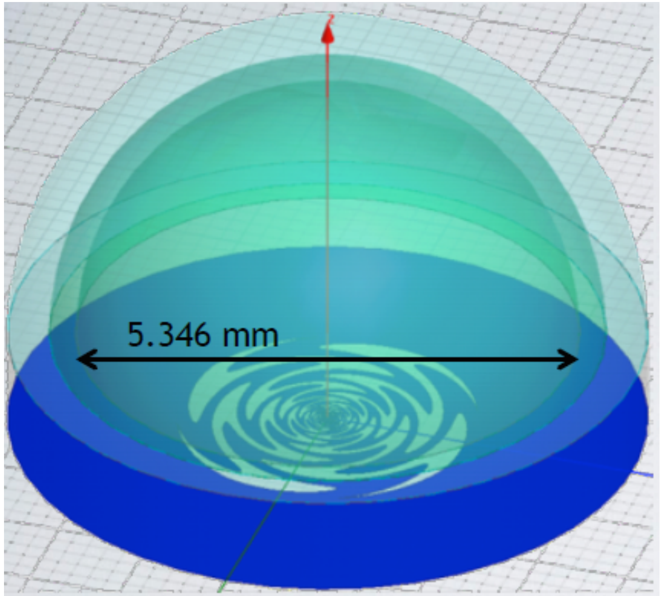
- Such antennas have a very broad beam pattern as their size is comparable to the wavelength in question

- Beam pattern is controlled using hemispherical silicon coated lenslet with broadband AR coating

- The high dielectric constant silicon means that the antenna receives approx 90% of the power from the lenslet – low losses

- The silicon lenslet array is coated with two layers or epoxy based coating

- The sinuous antenna is printed on a 6 inch wafer that couples into an RF circuit also printed on the wafer

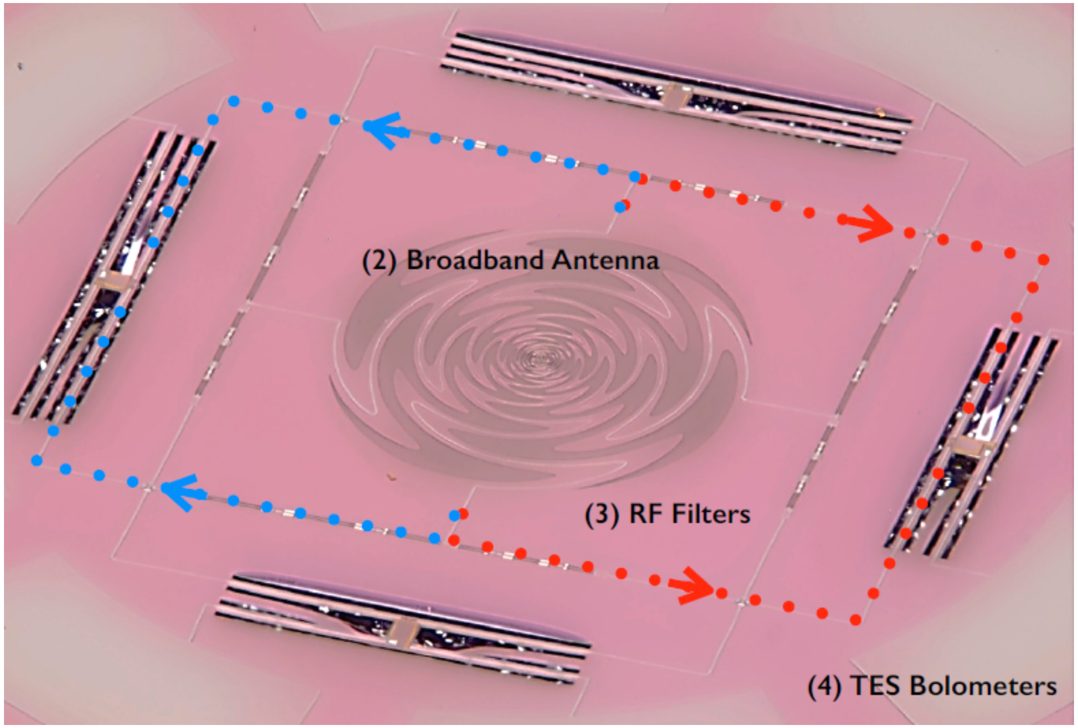


(I) Si Lenslets with anti-reflection coating

Polarbear 2 Detection

- Bandpass filters split the signal into 95 and 150 GHz channels

- Signal is terminated on a load resistor, with the heat dissipated in a superconducting absorbing layer. This is coupled to a TES bolometer that gives the temperature at a given frequency/polarization. Multiplexed SQUIDs are used to read out each pixel



Lenslets with Planar Antennas

Advantages

- Standard lithographic techniques can be used to produce such pixels
- Dielectric lenslet handles beam-forming AND maximises the optical coupling to the detector over a wide bandwidth
- One pixel can measure several spectral bands/polarisations – focal planes can be more densely populated

Disadvantages

- Silicon lenslets must be precisely aligned with the antennas
- Free space coupling is dominated by the reflection losses at the surface of the lenslets. Silicon lenslets therefore need AR coating that is A) Broadband (multi-layered) and B) is uniform across the lens surface. These are both technological challenges
- Polarisation rotates with frequency, across the band you can get a cross-polar power of up to 1% depending on the bandwidth

Planar Mesh Lenses

- Planar mesh lenses are currently being developed as part of an ESA TRP: “Next Generation Sub-millimetre Wave Focal Plane Array Coupling Concepts ”. The project is lead by Maynooth, in collaboration with APC Paris, Cardiff, Chalmers, La Sapienza and Manchester

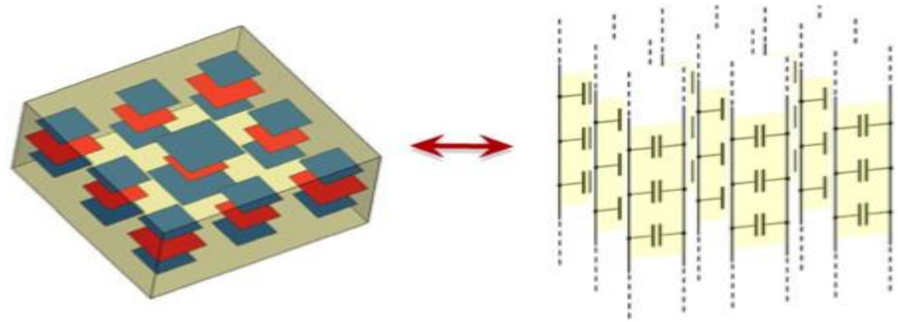
- This aspect of the project is driven by Giampaolo Pisano – has already spoken about these lenses

- It is based on an inhomogeneous metal mesh device can be modelled with a two-dimensional array of different TLs [Pisano et al, Applied Optics 52,n.11, (2013)]

- In order to achieve the appropriate transmissions and phase delay across the lens surface, a specifically developed code is used which can optimise more than one thousand TLs to simulate the action of a traditional “thick ” dielectric lens

- This planar thin mesh lens is very robust, and can be used cryogenically as well as in space environments as normal mesh filters.

- Very thin and robust
- Very light and low loss
- No Anti Reflection Coatings required



Inhomogeneous metal mesh devices can be modelled with a two-dimensional array of different TLs [Pisano et al, 2013].

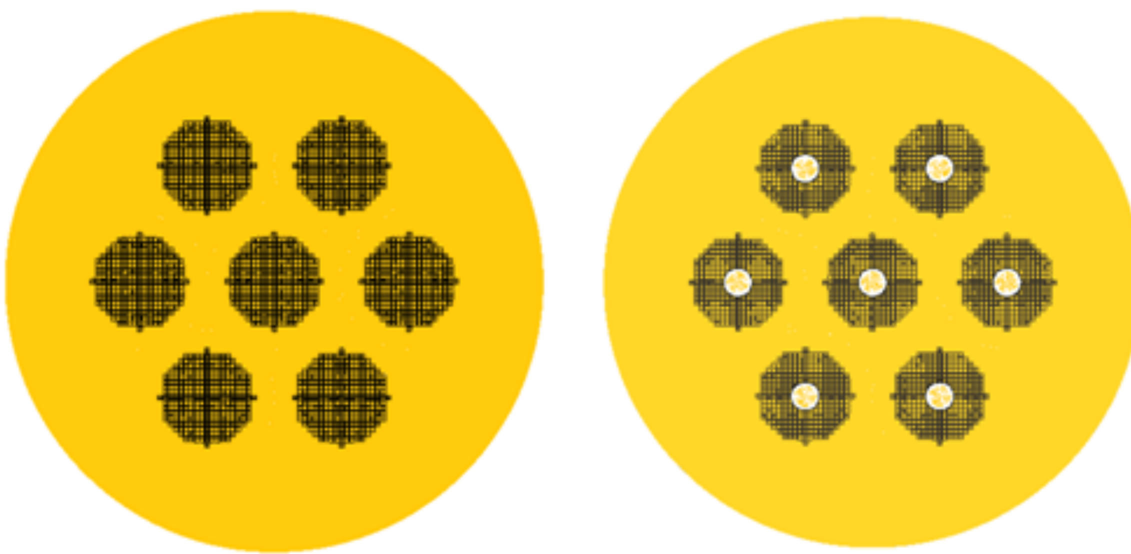
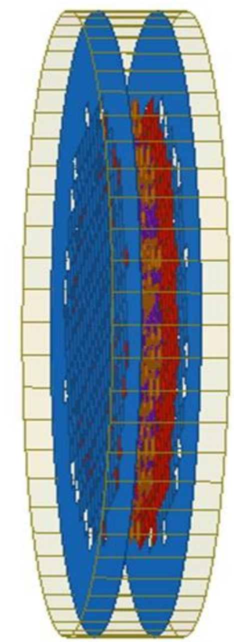


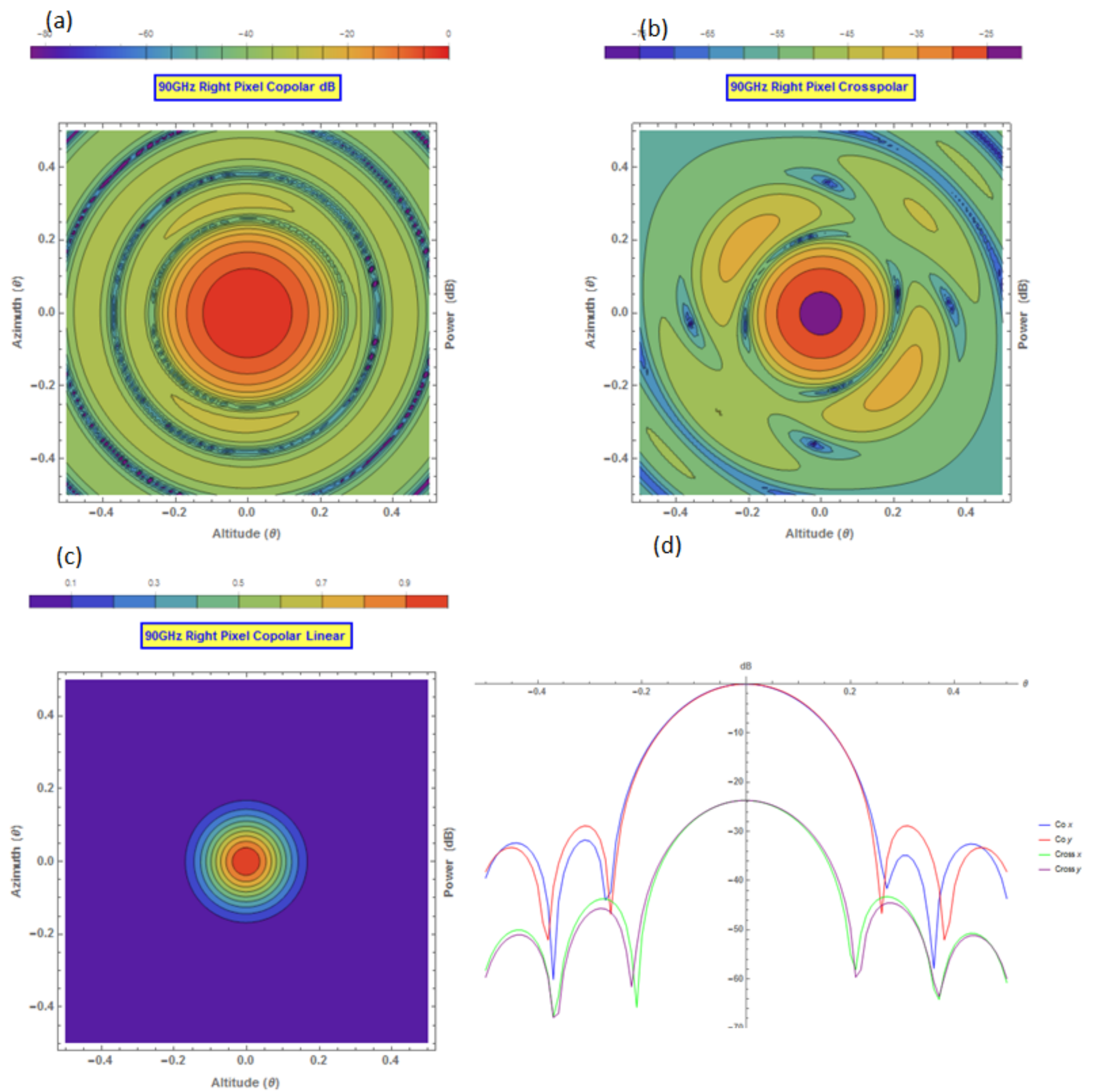
Figure 1: A plan view of the prototype mesh lens focal plane array showing the front and back of the seven element array.



90 GHz beams on the sky

This is a 90 GHz beam propagated through a 1.2 m crossed Dragone from a mesh lens coupled with a sinuous antenna projected onto the sky.

N. Trappe et al, SPIE Astronomical Telescopes and Instrumentation 2016



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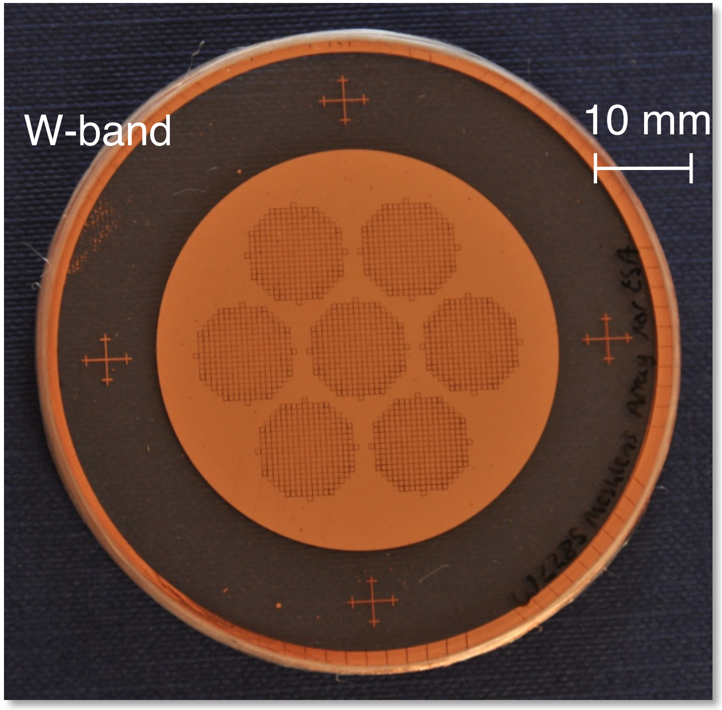
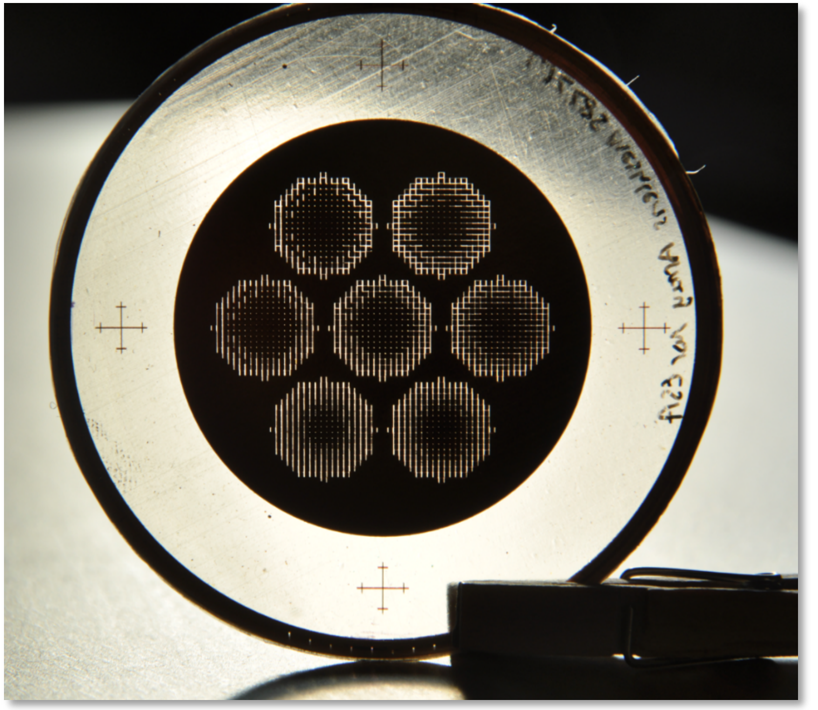
Flat Mesh Lens Array: Focal plane detector/antenna integration

ESA TRP collaboration: Maynooth (PI), Manchester, Cardiff, Rome, Paris APC and Chalmers

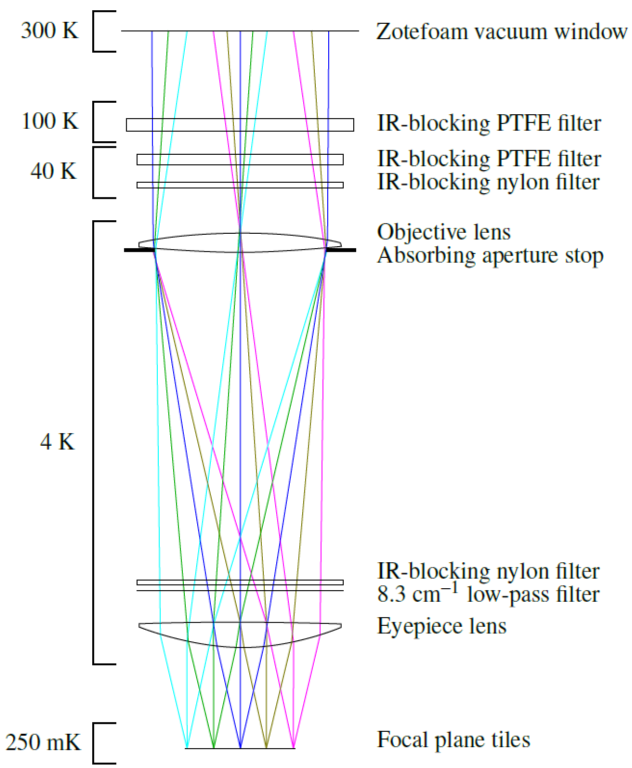




- Mesh lens miniaturisation for large focal plane arrays
- Usual manufacturing processes, accurate alignment required
- A single flat device includes all the lenses

BICEP 2 Optics

- Was located in the South Pole on the Antarctic Plateau
- 26 cm aperture telescope, utilising cold, on-axis refractive optics optimised for 150 GHz

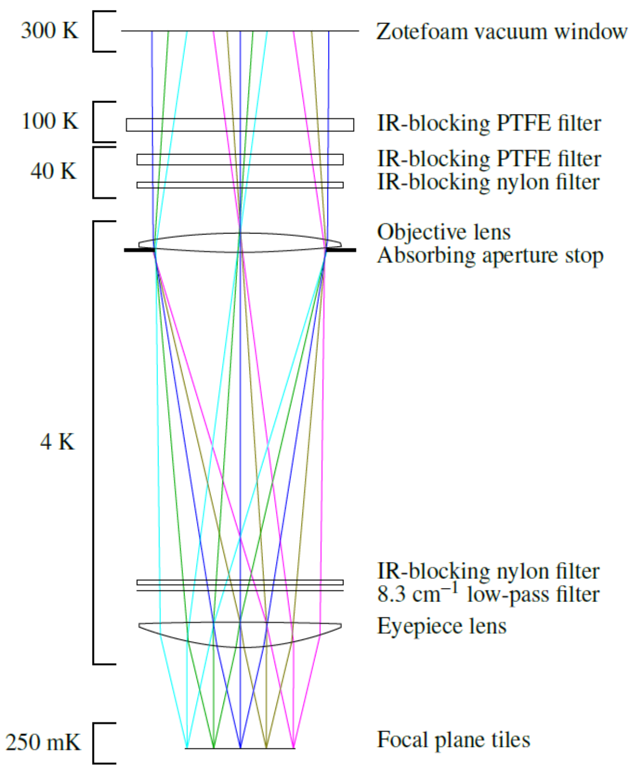


BICEP2 II: EXPERIMENT AND THREE-YEAR DATA SET, 2014

- Cheaper than reflective optics…significantly smaller aperture though
- HDPE lenses are 30 cm in diameter and optimised to give an f/2.2 design that minimises aberrations and maximises telecentricity

BICEP 2 Optics

BICEP2 II: EXPERIMENT AND THREE-YEAR DATA SET, 2014



- Sensitivity maximised using heat sunk IR filters and 4 K optics to minimise optical loading on the focal plane

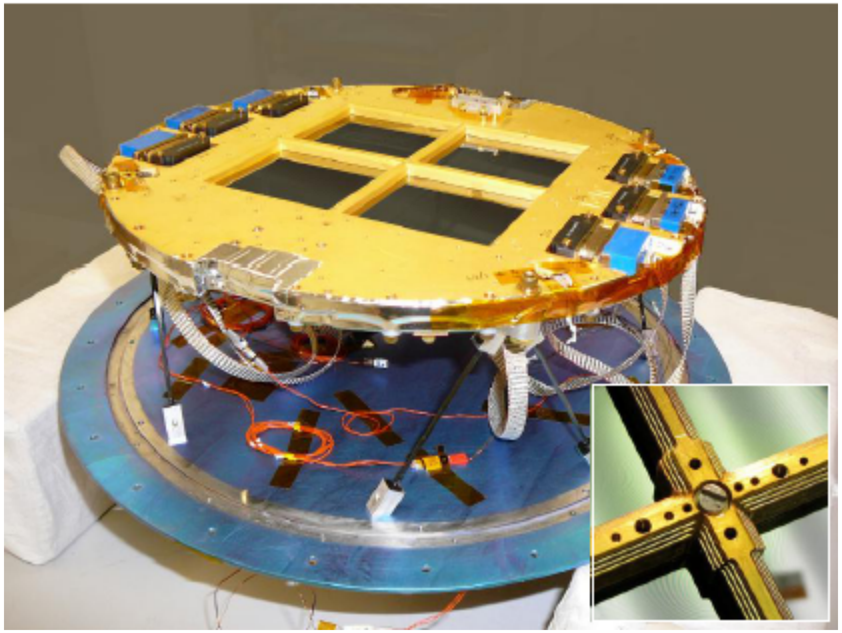
- Stray light control achieved using an aperture stop just behind the objective lens (Eccosorb). This also assists in reducing the optical loading

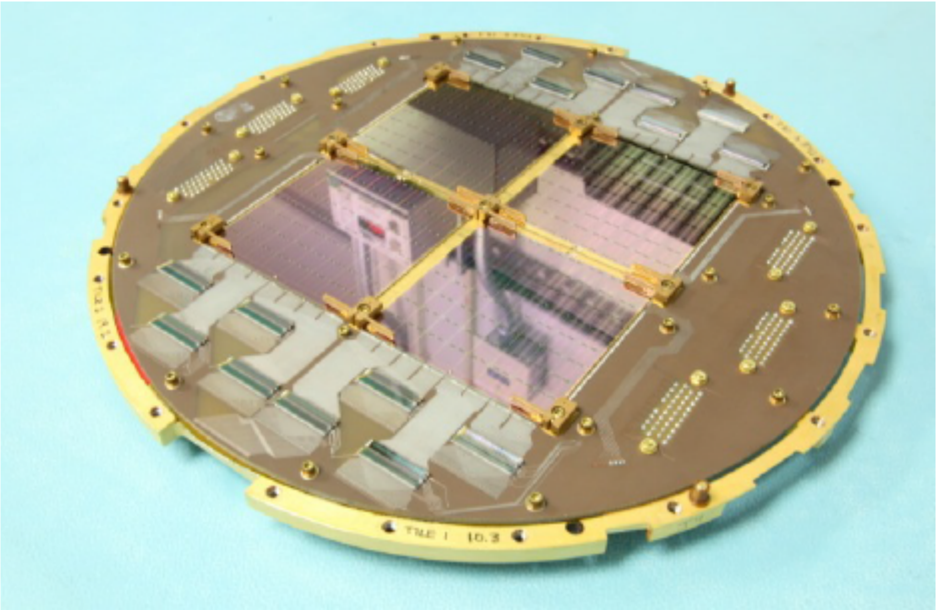
- A low pass mesh edge filter was placed in front of the eyepiece lens to reflect any coupling to sub-mm radiation not absorbed by the IR filters

- This relatively simple system works very well in terms of maximising sensitivity, but complications could arise for more broadband systems – broadband AR coatings

BICEP 2 Focal Plane

- Focal plane populated with integrated arrays of antenna coupled bolometers
- Combines beam defining planar slot antennas, inline frequency-selective filters and TES detectors in a single monolithic package
- Unit has four flat tiles, each containing an 8x8 array of dual polarization spatial pixels
- This gives 128x4 bolometers
- In total there are 500 optically coupled antennas and 12 dark (no antenna) TES detectors



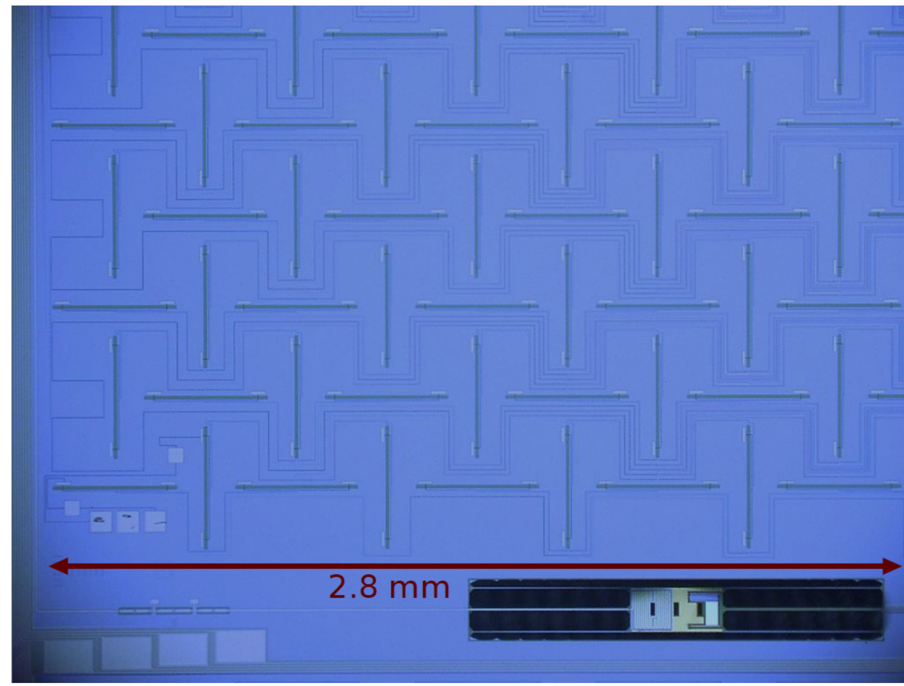


BICEP 2 Beam Forming

- Integrated planar phased-array antenna
- Sub-radiators are slot antennas etched into a superconducting Nb ground plane
- Orthogonal polarizations found using orthogonal, co-located sets of 288 slots
- Silicon substrate was used to supply the power, as the active side was face down on the focal plane – a backshort machined in the Nb reflected the backlobe onto the slots
- Very low cross-polarisation possible

- Currents from each slot are coupled to planar microstrip lines integrated on the array

- Done for both polarisations, each terminating on a different TES detector system via an RF filter



BICEP 2 Beam Forming

- Planar phased arrays achieve beam forming by coherently summing the contributions of the sub-antennas using a combiner network
- This coherent combination of antennas gives a higher forward beam directivity than one sub-antenna in isolation
- Shape of main beam is controlled by antenna size
- Eliminates the need for horns or coupling optics
- Flexible – can customise beams in terms of taper, directivity and generate overlapping beams in different bands

Planar Phased Arrays

Advantages

- Waveguide coupled bolometers require an absorber that is a wavelength in diameter, in antenna coupled bolometers like this, a resistive transmission line termination absorbs RF power – can be as small as lithographic techniques permit
- Can operate over a range of frequencies by scaling the antenna/filter – not the detector
- Overcomes limitation of bolometer technology in cavity coupled systems at lower frequencies
- No coupling optics and entirely lithographed – lends to large focal plane arrays
- No alignment issues/AR coating issues associated with lens-coupled systems
- Lack of feedhorns means mass savings and easier cooling systems
- Possible to use with non-telecentric optics due to the ability to control the beam patterns
- Differential beam ellipticity can be eliminated by controlling the x-y field distributions of the sub-antennas

Planar Phased Arrays

Disadvantages

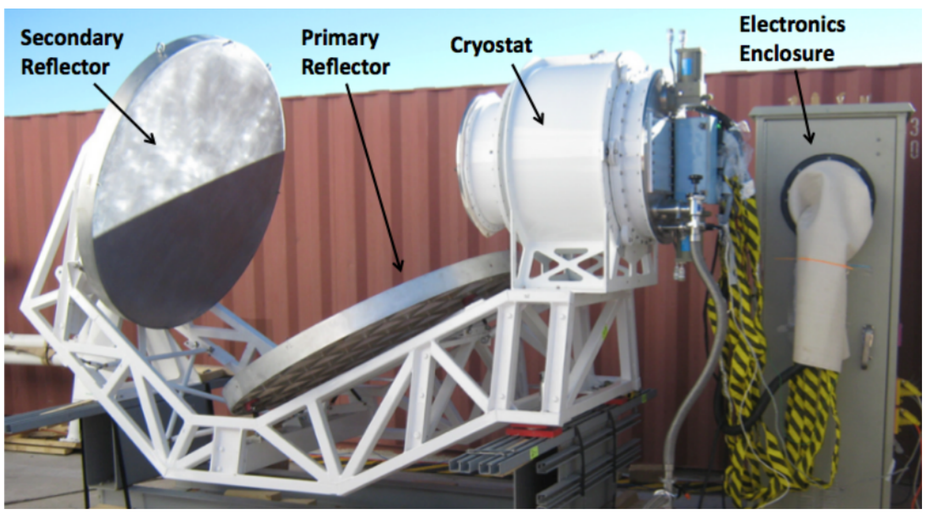
- Lower TRL than feed horns and lens coupled antennas
- Non-uniformity or dead pixels impact on the summing network – implications for beam formation
- A cold stop is required to terminate antenna sidelobes
- Grating lobes are an issue when sub-antennas are too close- minimum spacing
- Requires a quarter wavelength backshort to couple the backlobe to the detector for maximum efficiency

QUIET Instrument

- Q/U Imaging ExperimenT – Chajnantor Plateau in the Atacama Desert, Northern Chile

- Telescope requires wide field of view, excellent polarisation characteristics, minimal beam distortion, minimal spillover and low level sidelobes. The latter requirements are often met by offset Cassegrain and Gregorian antennas, but the wide field of view required is not easily offered using these designs

- Use a classical 1.4 m Crossed-Dragone design. This can also satisfy the Mizuguchi condition, which when combined with a low cross-polar antenna (e.g. corrugated horn), gives low instrumental polarisation. Also offers naturally flat focal plane with no tertiary optics



The crossed Dragone geometry offers a larger focal plane array than the open configuration, and so allows for more detectors – critical for sensitivity r equirements

Maynooth University
National University of Ireland Maynooth

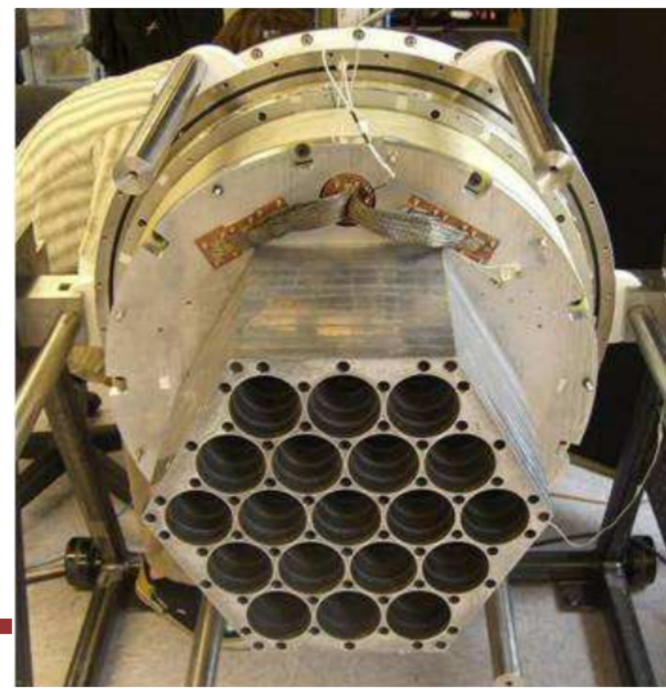
The QUIET Instrument- QUIET Collaboration- ApJ 2012

QUIET Beam Forming

- Feed requirements: highly symmetric beam, high efficiency, gain and bandwidth with low cross-polarisation and sidelobes
- 2 bands: Q band, 19 feeds, 39-47 GHz. W band, 91 feeds, 98-100 GHz
- Easily satisfied by conical, corrugated horns however the large number required makes the cost prohibitive (using standard manufacturing techniques)
- Alternative manufacturing process was proposed:

Array is manufactured as a series of thin platelets of aluminium 6061-T6, each platelet representing one corrugation. The platelets are attached using diffusion bonding, resulting in a block that contains an array of hexagonally packed, conical corrugated horns running through it

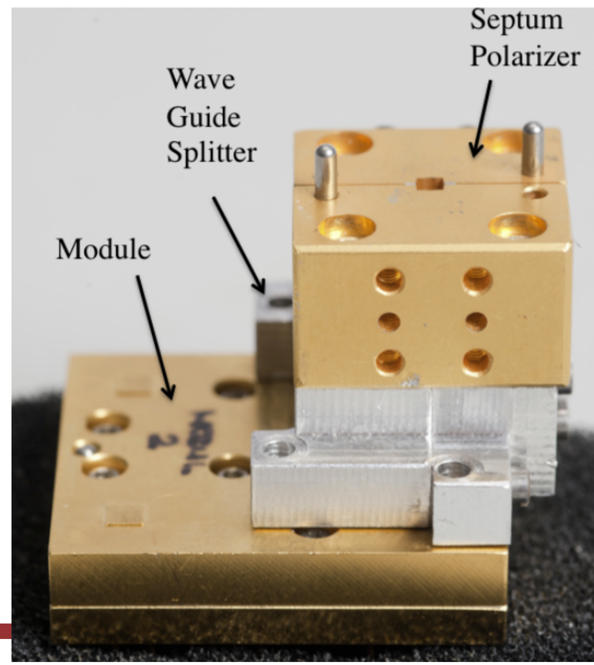
- These horns were found to achieve the required levels of performance, albeit with slightly increased cross-polar levels compared to 'traditional' horns



Monsalve, 2010

QUIET Detector

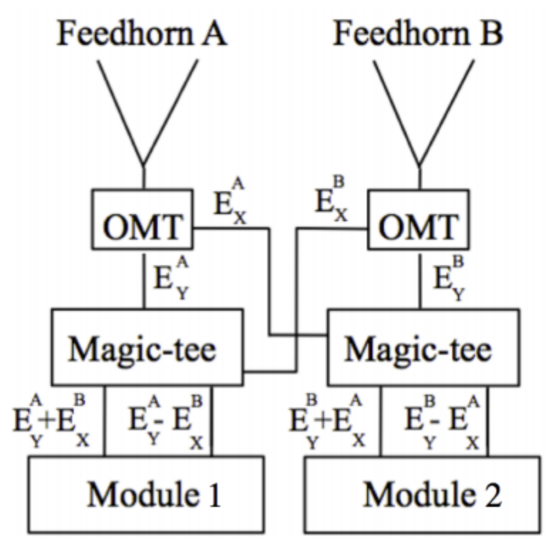
- Uses high electron mobility transfer (HEMT) LNAs detector regime
- Most pixels in the Q/W bands are polarisation sensitive and uses strip-line coupled monolithic microwave integrated circuit (MMIC) components with HEMT in lieu of waveguide devices
- Each polarimeter contains a septum polariser, a waveguide splitter and a module containing an integrated package of HEMT based MMIC devices



QUIET Detector

- Polariser contains circular-square waveguide transition, feeding a square waveguide with a septum, which is able to send left and right circularly polarised signals
- These signals step through a waveguide transition to match into the larger waveguides that feed the amplification modules. The results are read out using a diode detector operating in the square law regieme

- The differential temperature assemblies use orthomode transducers to output two linearly polarised beams from each horn. The x polarised component of each of the temperature horns is fed to the other and mixed with the y component via a 180 deg waveguide coupler, giving sums and differences which are fed to the LNA modules



OMTs

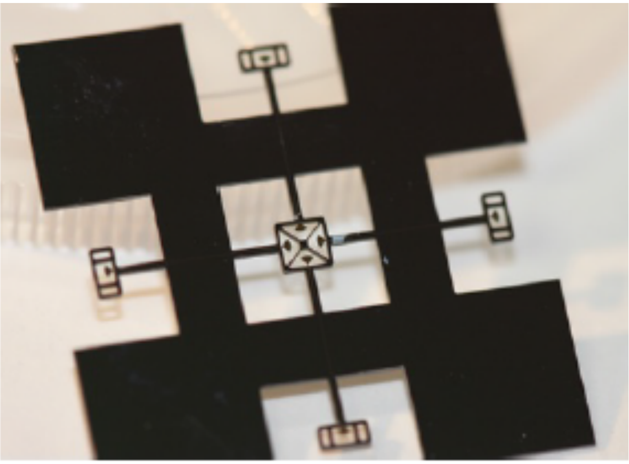
- QUIET uses them for temperature difference measurements. Two main types:
- Waveguide OMT – most mature realisation of OMTs, and well understood for W band operation. Have been successfully used in WMAP and Planck LFI, some ALMA bands, CARMA, ATNF and SRT ground based observatories for radio to mm-waves
- There are drawbacks: their use in large focal plane arrays, especially above 100 GHz is difficult and expensive (bulky, mechanical machining, feeding a detector)

Pisano et al, 2007

OMTs

- Planar OMT used by ACTpol, SPTpol and CLASS

- There are advantages to using this technology: they are directly integrated into corrugated feed horns and so can contribute to beam forming with low cross-polarisation and ellipticity
- Precisely fabricated using lithography – predictable performance
- Light and small, e.g. 2mm at 90GHz – good for monolithic integration in large detector arrays
- Designed to match desired waveguide modes – no refractive optics
- Multichroic: gives single mode operation over a wide band. This gives unprecedented polarization purity for such systems



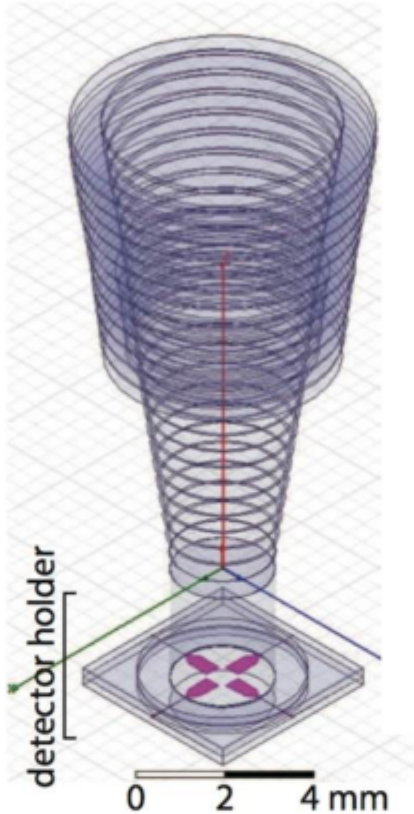
Bordier et al, 2012

PSBs

- Can also use Polarisation Sensitive Bolometers (PSBs)
- Two orthogonal, free-standing lossy grids displacement by tens of microns. They are mounted in a cavity and dissipate the current induced in them b the incoming beams producing a Joule heating effect measured by two thermistors
- Each grid sensitive to one polarisation. PSBs combine separation and detection
- Used by a generation of successful CMB instruments, Boomerang3, BICEP, QUAD, Planck HFI
- Very mature, but due to advances in TES technology, practically all large pixel number arrays use TES detectors. Few exceptions, PIXIE and MuSE

Silicon Platelet Horns

- ACTPol utilises silicon micro-machined feedhorns that illuminate bolometers
- Feedhorns, detectors and SQUIDs manufactured at NIST
- Three arrays, two contain 512 dual polarisation feeds at 148 GHz and the third contains 522 dual feeds operating at 97 and 148 GHz simultaneously. Each array is 15 cm in diameter
- The feedhorn arrays are assembled from stacks of silicon wafers with micro-machined circular apertures corresponding to a single corrugation of each horn
- Each platelet is etched, coated with a Ti/Cu layer on both sides and gold plated, forming the array
- Preserves the performance of corrugated horns without the manufacturing difficulties
- Planar OMT used to couple each polarisation to a TES bolometer



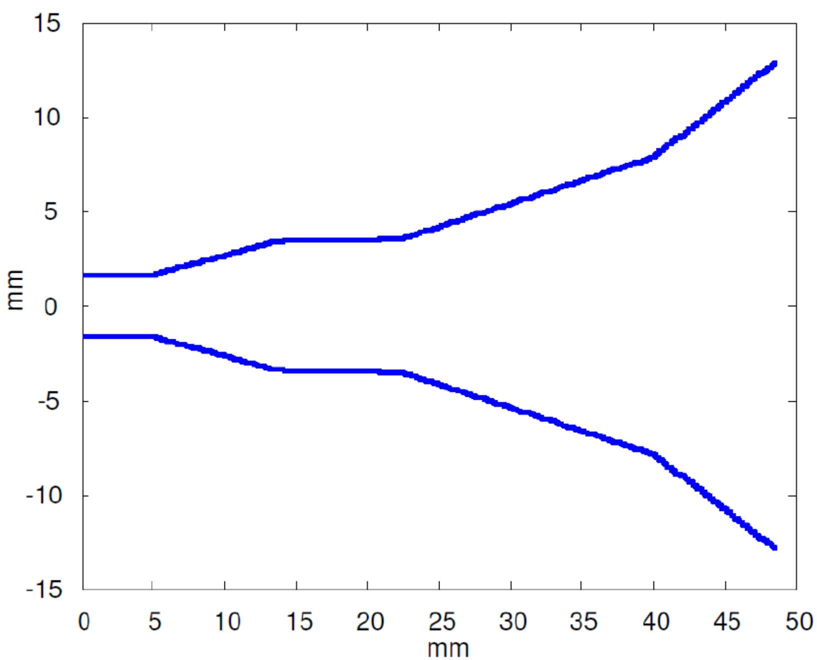
ACTPol Instrument, Thornton et al. 2016

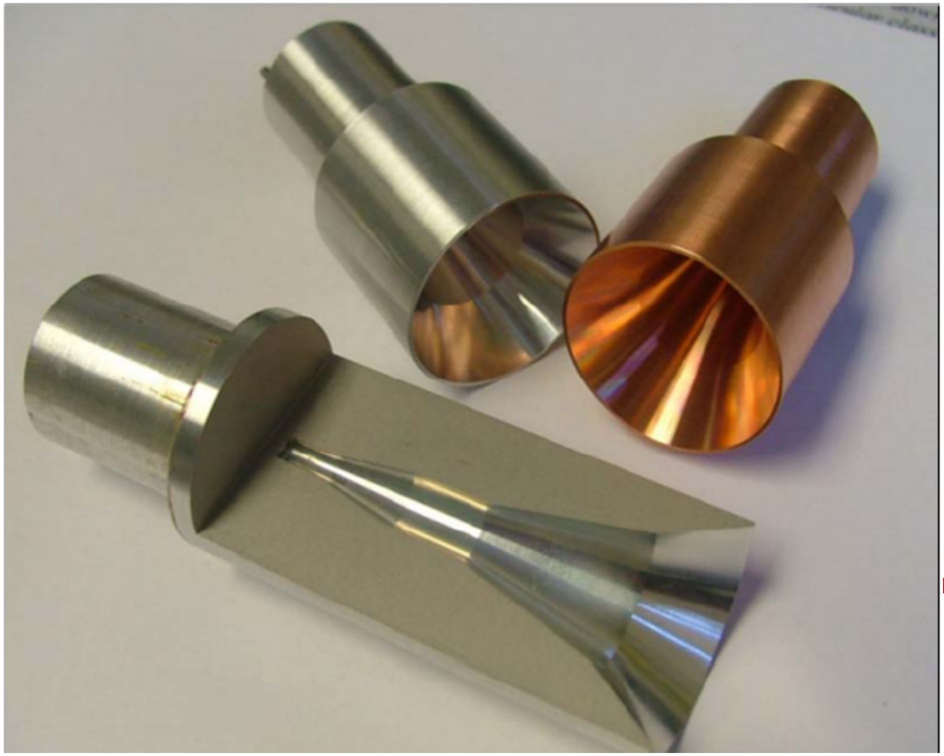
Some more words on horn technology

- Horns are excellent beam forming elements, as curved focal planes can be used…can use optimised telescope configurations with no tertiary optics
- Rings and platelets can realise cheaper arrays of horns, rivalling traditional arrays in terms of performance
- There are other horn alternatives: 3D printed RF antennas, waveguides and filters
- SwissTo12 currently working hard on this front. Enables complex RF designs, mono-block components (No assembly – good performance), weight reduction
- Several validation examples showing excellent performance, including a W band filter and a Ku band antenna containing, primary, secondary reflectors and feed antenna in one piece. Tested by ESA with success in March 2016
- Currently undergoing space/aerospace qualification testing, mostly with ESA
- Outgassing tests passed for all materials, thermal shock tests passed, thermal cycling tests, flammability ongoing, radiation/hardness and vibration tests under preparation

Some more words on horn technology

- There is also the possibility of a smooth-walled spline profile horn antenna – several groups have examined this possibility using varying approaches, including the Maynooth group (McCarthy et al, IR Physics and Technology, 2016)
- Works by defining the horn profile as a series of spline interpolated sections and optimising the length and radius of each section to maximise the performance with respect to the parameters of interest
- Meets typical CMB performance requirements at the expense of the parameters that aren't so important (retains the desired performance traits of a corrugated horn)
- Cheaper and lighter than corrugated horns, can be designed quickly





Some additional detectors

- **Microwave Kinetic Inductance Detectors (MKIDS):**
- Do not rely on thermal dissipation on a resistor. Rather, incoming radiation breaks Cooper pairs, creating a quasiparticle excess, increasing the kinetic inductance. Detector responds by coupling to the MKID inductors
- Used by NIKA2, A-MKID etc. Also used by SUPERSPEC, which was multichroic (195-310 and 320-520 GHz)
- **Cold Electron Bolometers:**
- These are coupled directly to an antenna and are advantageous in terms of size, loss and matching impedance. They have issues though in their effect on beam forming, filtering and polarisation separation

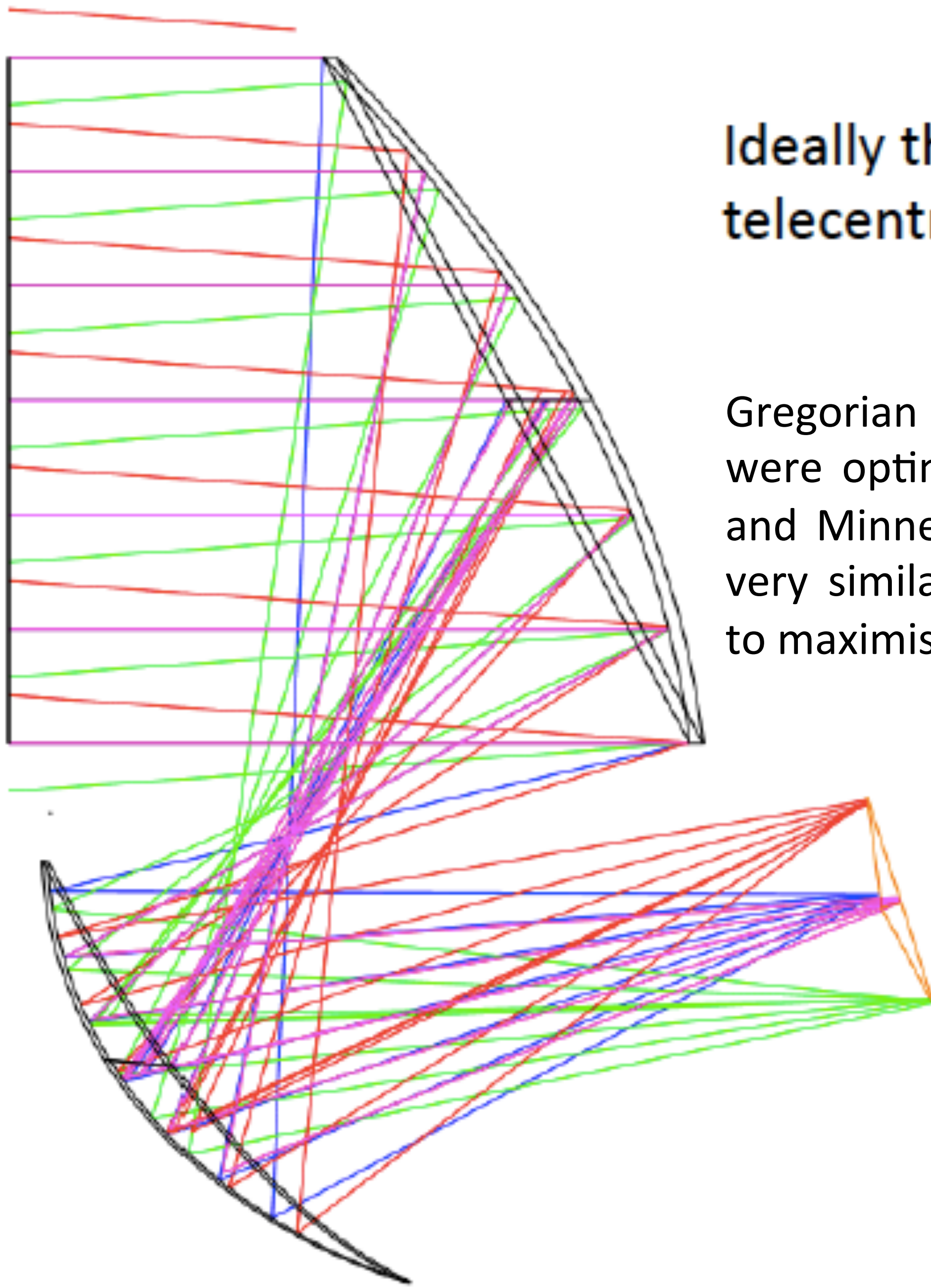
COrE+

- **COrE+ (Cosmic Origins Explorer) is a proposed mission currently being prepared for the upcoming ESA M5 call**

- Involves a large consortium preparing all aspects of the proposal

- Maynooth (Darragh McCarthy, Neil Trappe) and Minnesota (Shaul Hanany, Karl Young, Qi Wen, Chiou-Yang Tan) are working on the optical design and analysis of the telescope

- Requirements include high beam symmetry, large field of view, 1.2 m aperture, low cross-polarisation, high sensitivity -> drives requirement for a large densely packed focal plane containing several thousand detectors ranging from 60-600 GHz



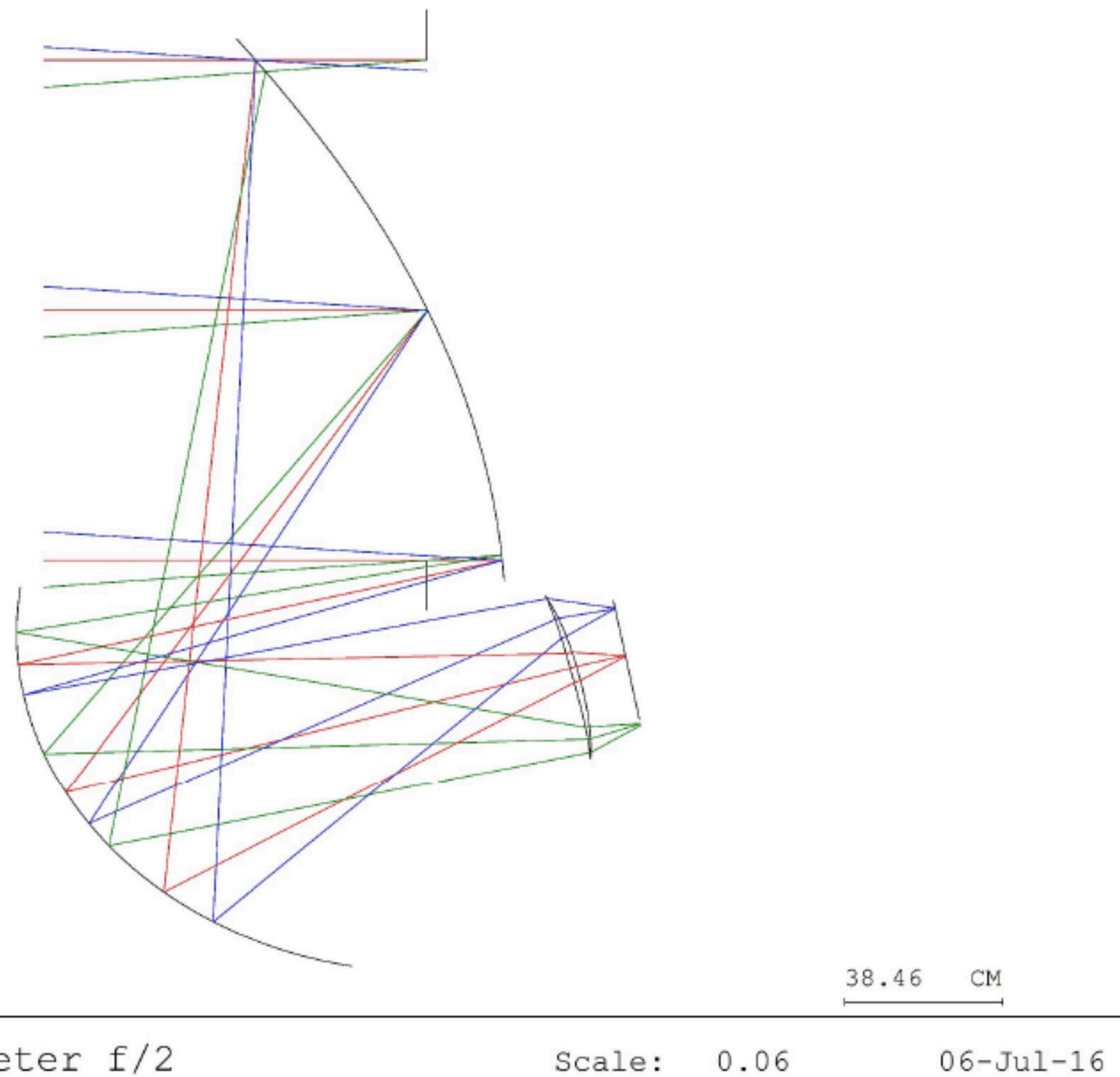
Ideally the telescope should be telecentric

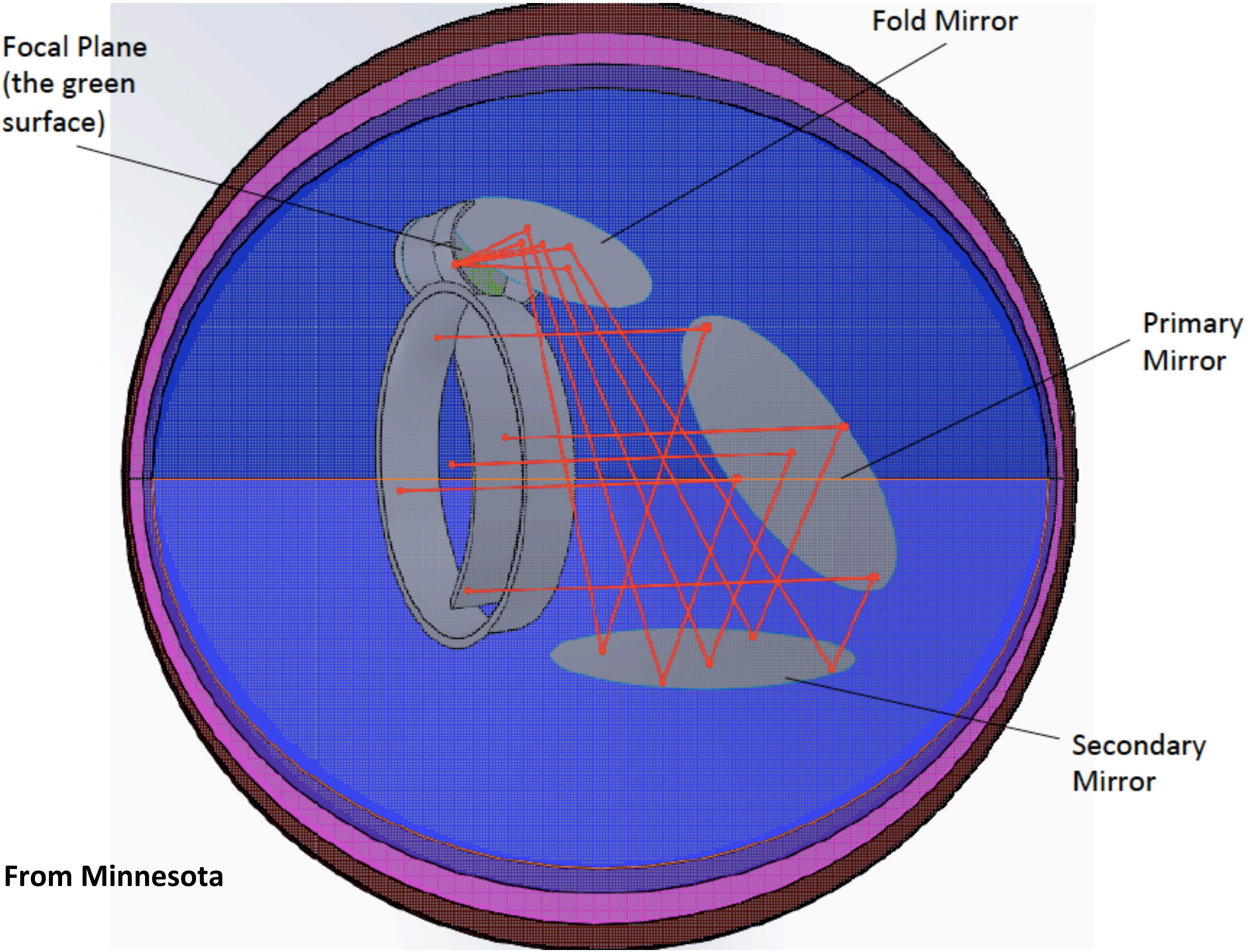
Gregorian design – separations and surfaces were optimised independently by Maynooth and Minnesota in Zemax and Code V, giving very similar designs/performance – aim was to maximise diffraction limited focal plane

Minnesota added an alumina lens to flatten the focal plane surface – can now use planar technology (flat mesh lens + MKIDS) instead of horns. Design is difficult to baffle though, and lens would need broadband AR coating – low TRL

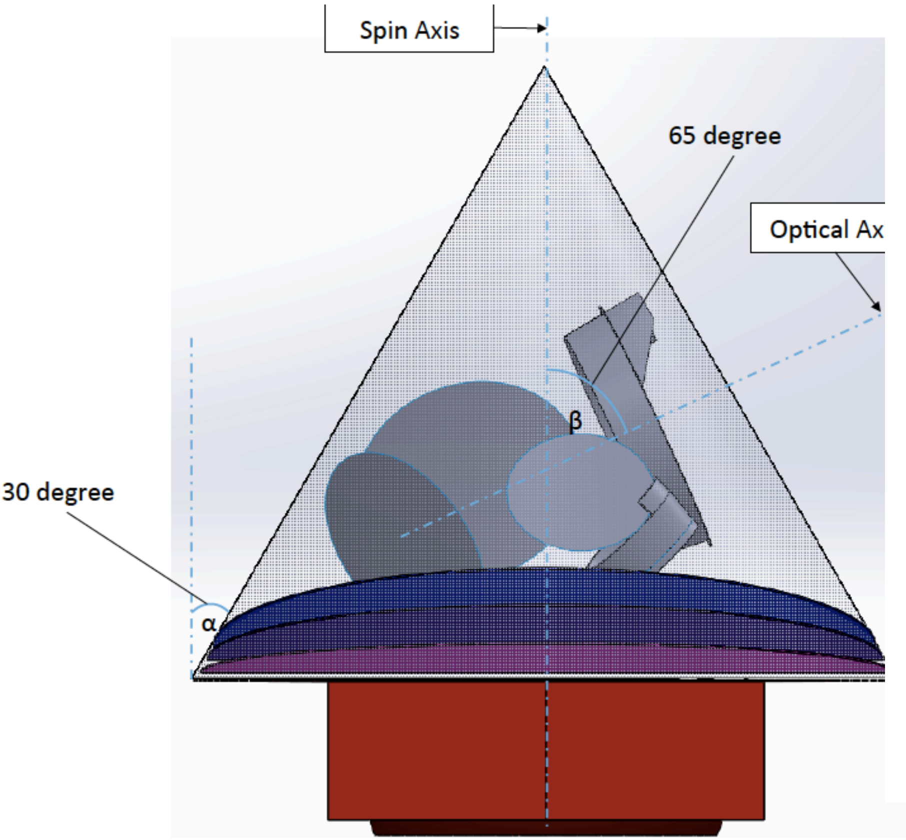
Gregorian Dragone with lens

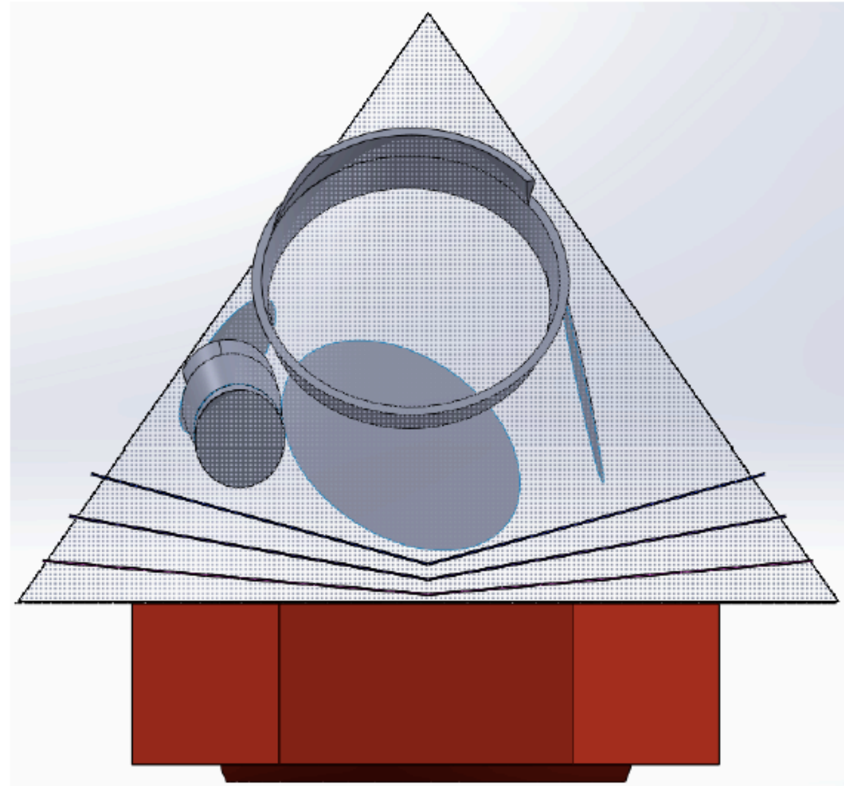
- F-number (at the center of the focal plane)= 1.88
- Aperture size = 1.2m
- Size of mirror
  - Primary = 1.5m * 1.3m (length*width)
  - Secondary = 1m * 0.7m
- Size of Lens = 0.4m
- Focal Plane Size = 1.1m
- Focal plane is flat and approximately telecentric.
- Mirror are conic sections.





From Minnesota



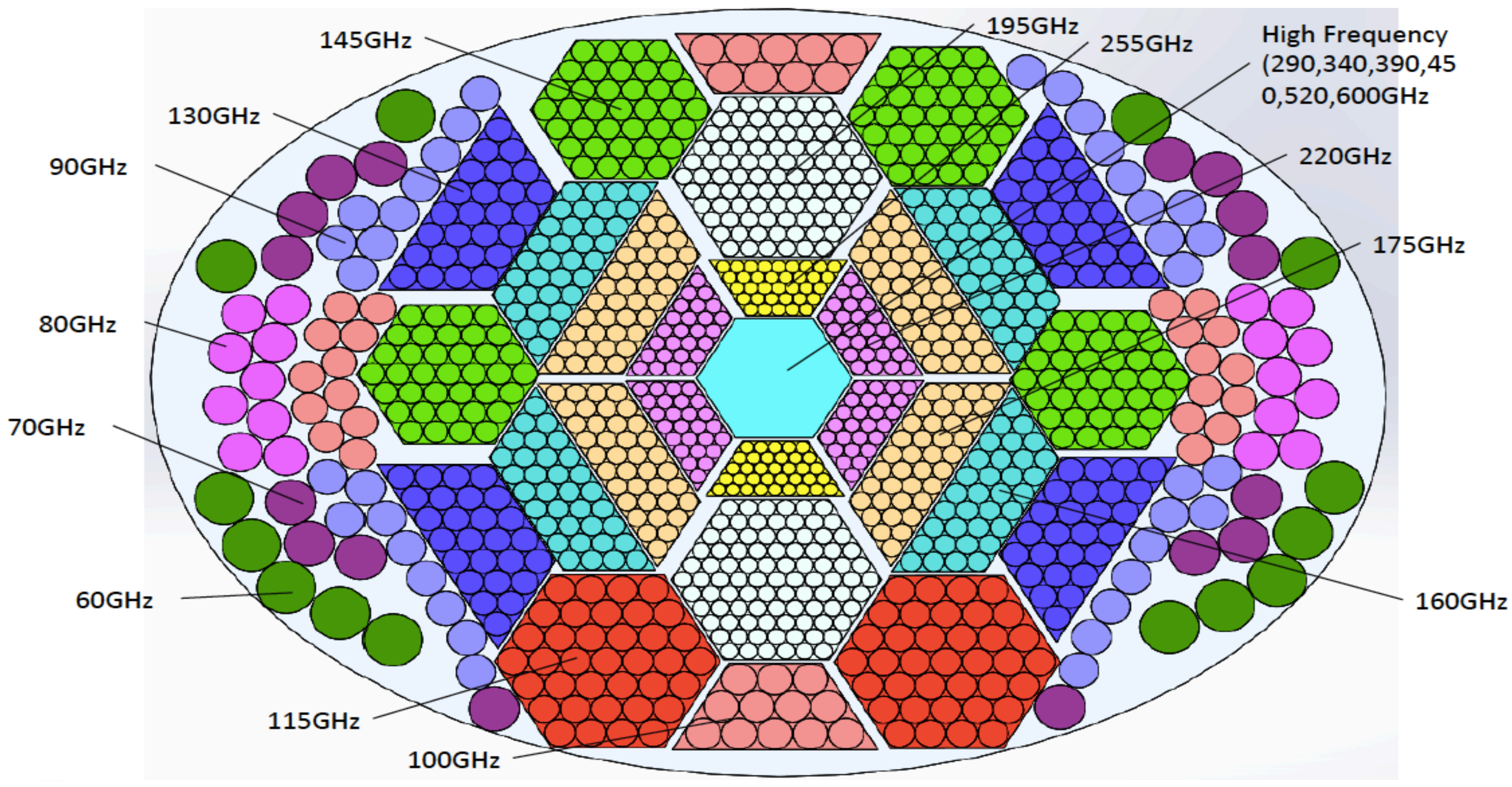


From Minnesota

- F-number (at the center of the focal plane) = 2.54
- Mirror Size:
  - Primary : 1.4 m * 1.3 m
  - Secondary : 1.4 m * 1.3 m
  - Fold Mirror : 0.85 m * 0.63 m
- Focal Plane Size :
  - In meter : 0.59 * 0.40
  - In 2.5 * F * Lambda at 150 GHz : 46 * 32

2100 detectors

From Minnesota



Conclusions

- Telescope type is determined by optical performance requirements (field of view, polarisation, beam shape etc)

- Beam forming technology is determined by a variety of factors including focal plane size, mass and thermal requirements, the shape of the focal plane surface, the presence of a cold aperture, precise beam requirements, detector technology being used

- Detector technology is determined by coupling regime, free space/planar/waveguide

- Must decide what the limitations and requirements are, and then proceed from there, as each step informs the rest!

Thank you for you attention

RF performance	Beam Forming					
Technology	Horn Antennas			Planar		
Type	Traditional electroform Corrugated	Platelet/silicon etched/Ring Technology	Smooth walled (optimised)	Lens coupled	Filled Array	Phased Array
# polarisations possible	2	2	2	2	2	2
Polarisation separation	OMT, Polariser, PSB	OMT, Polariser, PSB	OMT, Polariser, PSB	Antenna, Polariser	Antenna, Polariser	Antenna, Polariser
Frequency of operation possible	<600 GHz	<800 GHz	>1THz	>1THz	>1THz	>700 THz (Nb band gap)
Cross-Polarisation	<-30dB	<-30dB	<-20dB	<-25dB	<-25dB	<-20dB
Additional telescope requirements	None	None	None	Cold stop required	Cold stop required	Cold stop required
Beam directionality	High	High	High	Good	Low	Medium
Requires flat focal plane	No (curved FP possible)	No (curved FP possible)	No (curved FP possible)	Yes	Yes	Yes
Bandwidths	~30%	~30%	~20%	~60%	~60%	~60%
Multichroic operation possible	Yes	Yes	Yes	Yes	Yes	Yes
Scalability to large arrays	Difficult	Challenging	Challenging	Challenging	Challenging	Challenging
TRL	TRL high	TRL low	TRL high	TRL medium	TRL medium	TRL low
Other Advantages	Beam quality	Beam quality	Manufacturabili ty	Lithography, low mass	Lithography, low mass	Lithography, low mass
Other Disadvantages	Mass & scalability	Mass	Mass, lower beam quality	AR coating	Beam quality & sidelobes	Technically challenging
Other WPs Cross-link	WP1.2, 2.2,2.3,2.4	WP1.2, 2.2,2.3,2.4	WP1.2, 2.2,2.3,2.4	WP1.2, 2.2,2.3,2.4	WP1.2, 2.2,2.3,2.4	WP1.2, 2.2,2.3,2.4

Advantage		Disadvantage		Not usable		Investigated	by Task #

Maynooth University
National University of Ireland Maynooth

Manufacture	Beam Forming					
Technology	**Horn Antennas**			**Planar**		
Type	**Traditional electroform Corrugated**	**Platelet / silicon etched/ Ring Technology**	**Smooth walled (optimised)**	**Lens coupled**	**Filled Array**	**Phased Array**
Material	Copper/Gold	Silicon/metal/ plastic	Copper/Gold	Silicon, Nb, NbN, SiO2, Si3N4	Silicon, Nb, NbN, SiO2, Si3N4	Silicon, Nb, NbN, SiO2, Si3N4
Material availability	Yes	Yes	Yes	Yes	Yes	Yes
Mechanical robustness	Good	Lower TRL	Good	Good	Good	Good
Relative mass	High	Medium	High	Low	Low	Low
Relative dimensions	Large	Large	Large	Lower	Lower	Lower
Consortium Experience	High	High	High	Medium	Medium	Medium

Advantage		**Disadvantage**		**Not usable**		**Investigated**	**by Task #**

Cryo-mechanical	Beam Forming					
Technology	**Horn Antennas**			**Planar**		
Type	**Traditional electroform Corrugated**	**Platelet / silicon etched/ Ring Technology**	**Smooth walled (optimised)**	**Lens coupled**	**Filled Array**	**Phased Array**
Robustness to cooling cycles	High	Low TRL	High	Low TRL	Low TRL	Low TRL
Heat dissipation	None	None	None	None	None	None
Temperature gradient	Low	Low	Low	Low	Low	Low
Low Temp differential emissivity	Low	Low	Low	Low	Low	Low

Advantage		**Disadvantage**		**Not usable**		**Investigated**	**by Task #**