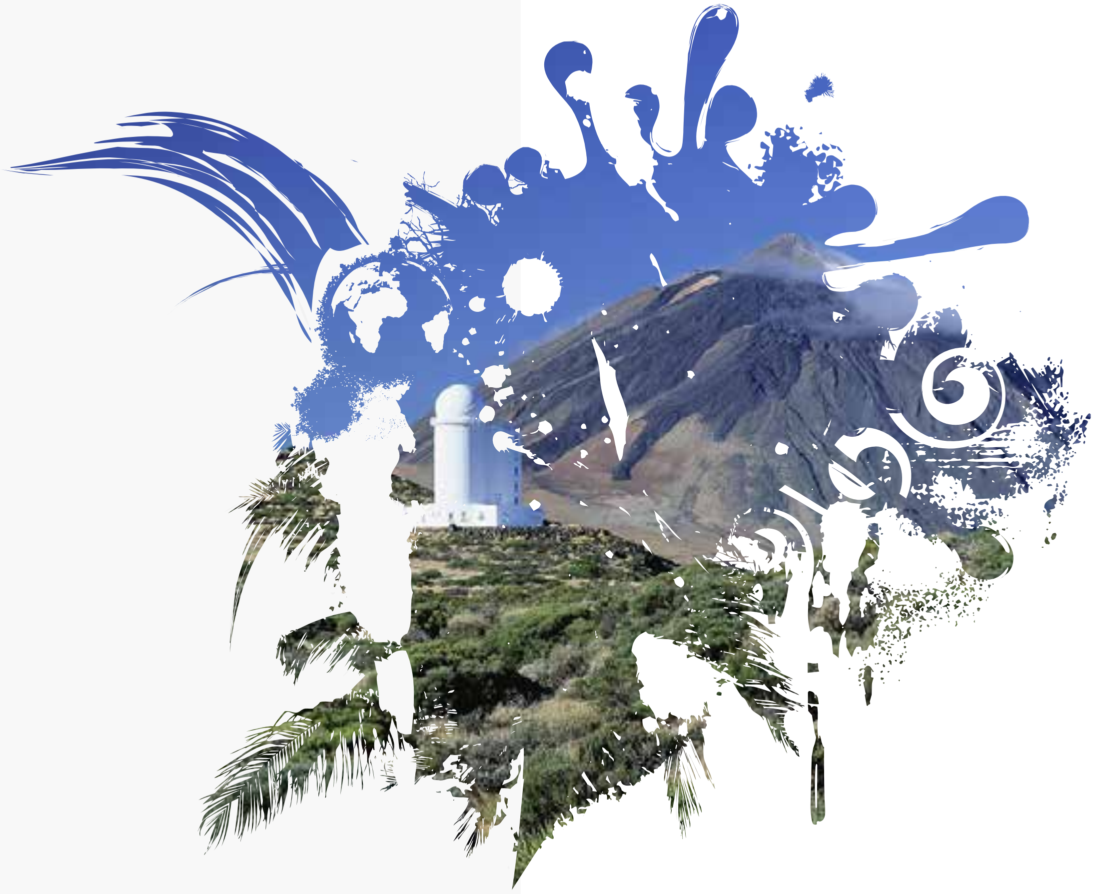
CMB systematics and calibration focus workshop

Kavli IPMU, Kashiwa, Japan

30 November - 03 December 2020

SABRINA REALINI

Università degli Studi di Milano



Characterization of the optical system of the LSPE-Strip instrument

THE LARGE SCALE POLARIZATION EXPLORER (LSPE)

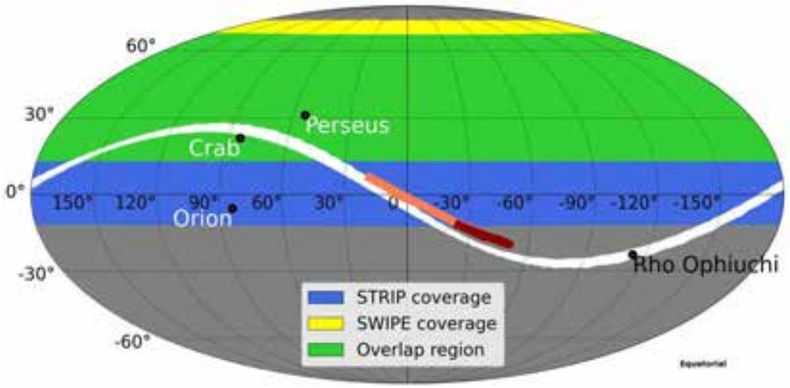
» Experiment funded by Agenzia Spaziale Italiana (ASI) and INFN

» Objectives

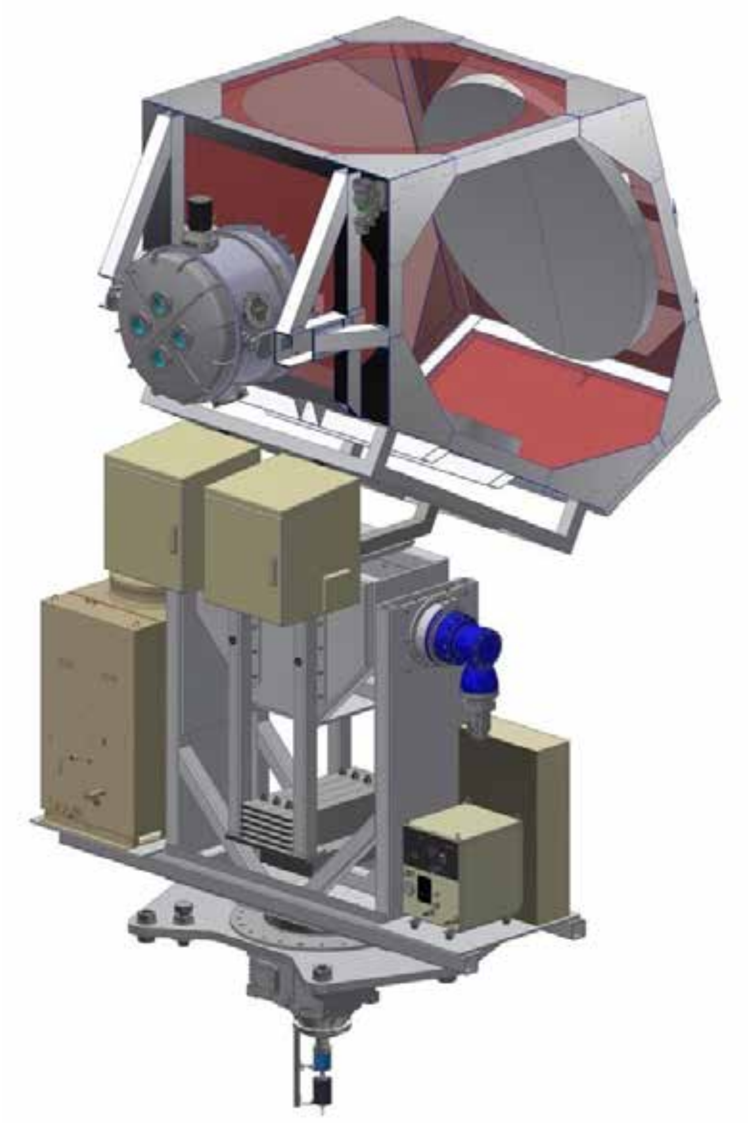
- Search for polarization B-modes of the Cosmic Microwave Background
- Produce wide maps of foreground polarization generated by synchrotron and interstellar dust emission

» Two independent instruments with the same sky coverage

- **SWIPE**: balloon-borne instrument (140 – 220 – 240 GHz)
- **Strip**: ground-based telescope (43 – 95 GHz)



The Strip Instrument



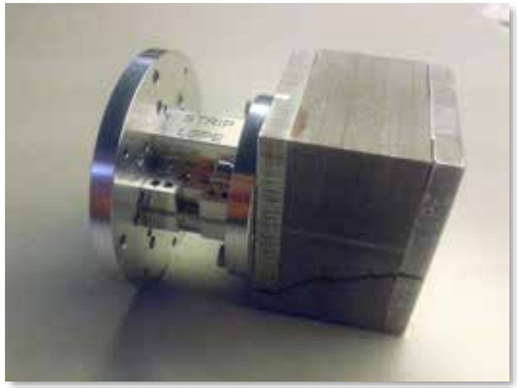
» Ground-based experiment in Tenerife
  - 2 years observation
  - 38% sky coverage

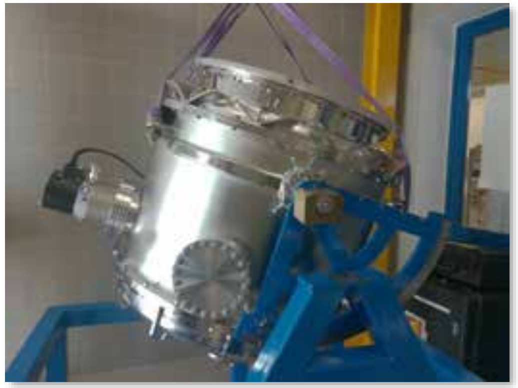
» Two arrays of coherent receivers
  - 49 polarimeters in the Q-band
    - Polarized synchrotron emission
  - 6 polarimeters in the W-band
    - Track amount of water vapour
    - Characterize atmosphere in Tenerife

The Strip Instrument

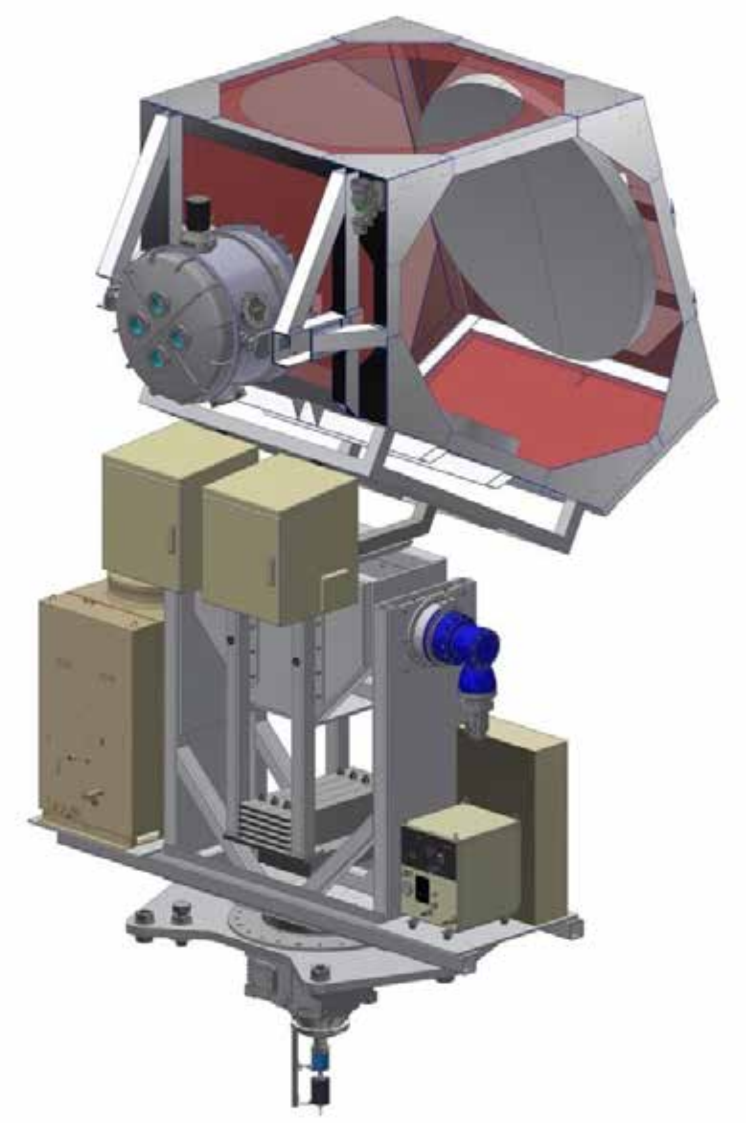
» Current status

- All instrument hardware is built or under construction
- System level test are ongoing at OAS-INAF Bologna





THE TELESCOPE



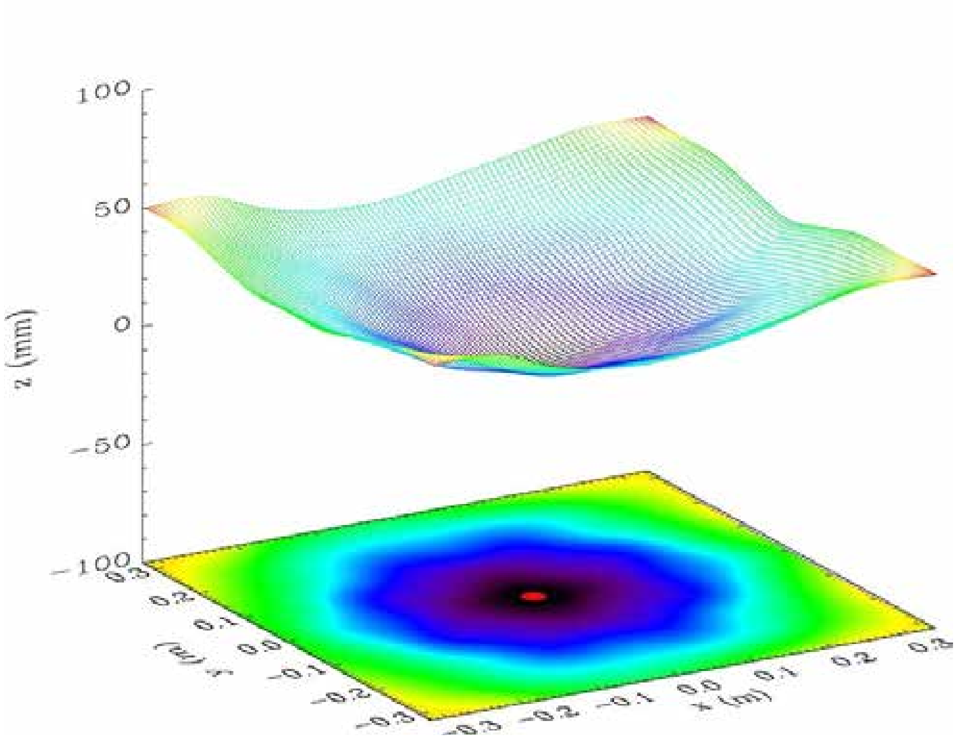
» Alt-azimuth telescope mount
  - Fully rotating azimuth axis at 1 r.p.m.
  - Elevation angles between 5° and 50°

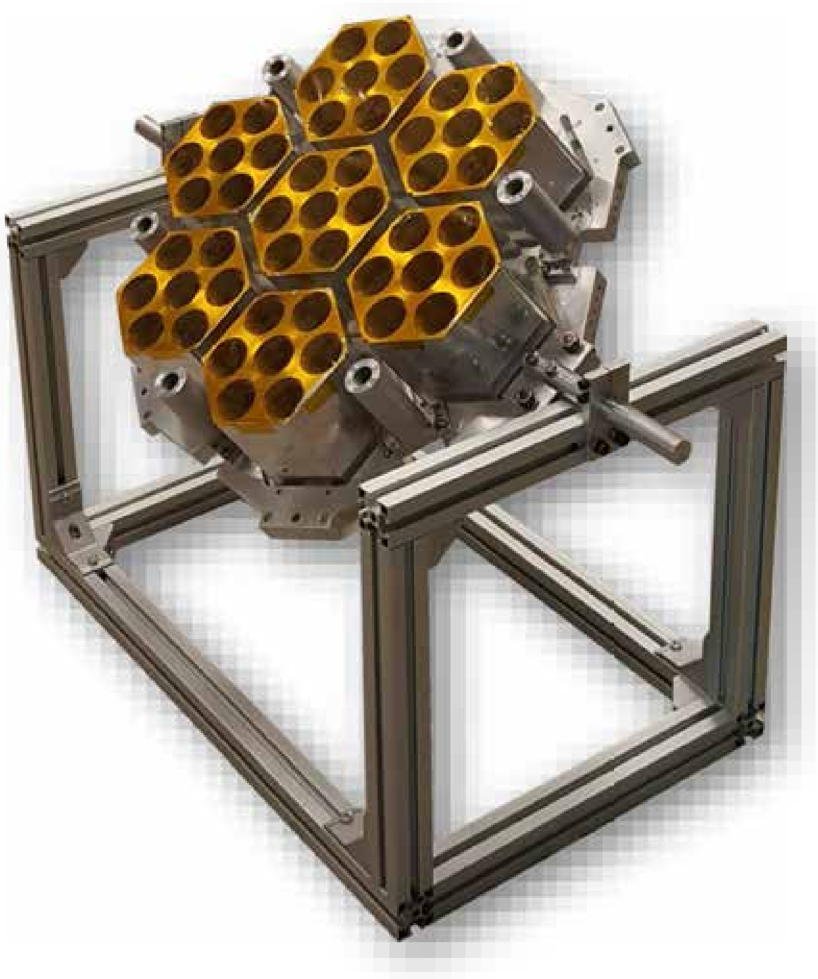
» Dual-reflector telescope
  - Crossed-Dragone configuration with 1.5 m aperture
  - F# = 1,8
  - Comoving baffle

THE FOCAL PLANE UNIT

» Focal surface evaluation

- Wavefront error minimization
- 600 × 600 mm focal surface





The Focal Plane Unit

» Q-band feedhorn modules
- Seven dual-profiled corrugated horns per module
- Platelet technique engineering

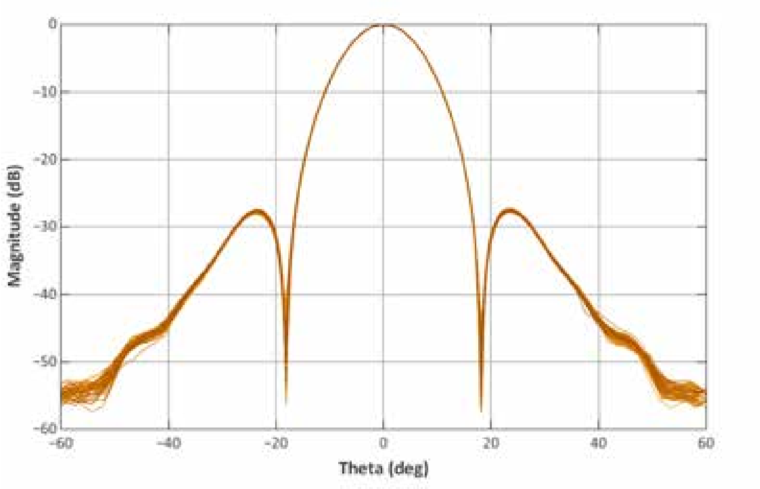
» W-band feedhorns
- Six dual-profiled single corrugated horns
- Platelet technique engineering
- Chemical etching cut

THE FOCAL PLANE UNIT

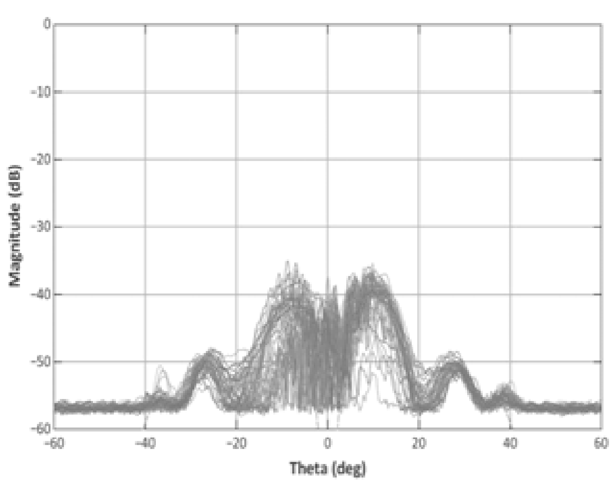
» Q-band measurements in the anechoic chamber at UniMi
  - Radiation patterns for 49 feedhorns *[Franceschet C., 2016]*

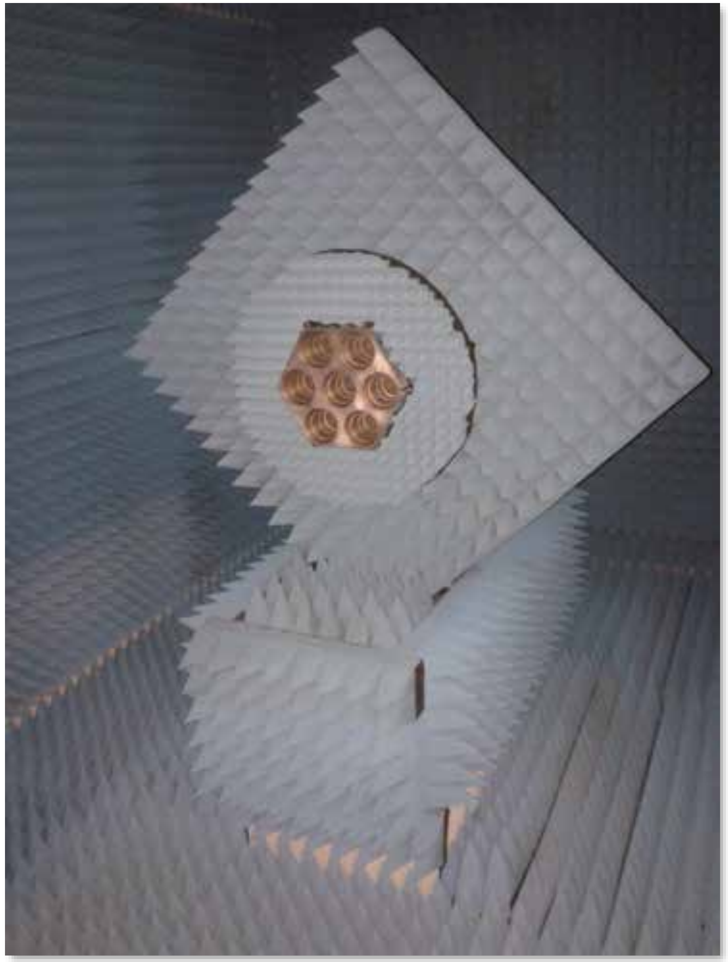
» W-band measurements in the anechoic chamber at UniMi
  - Radiation patterns for 7 feedhorns (6 nominal + 1 spare unit)
  - Return Loss

co-polar 45° plane



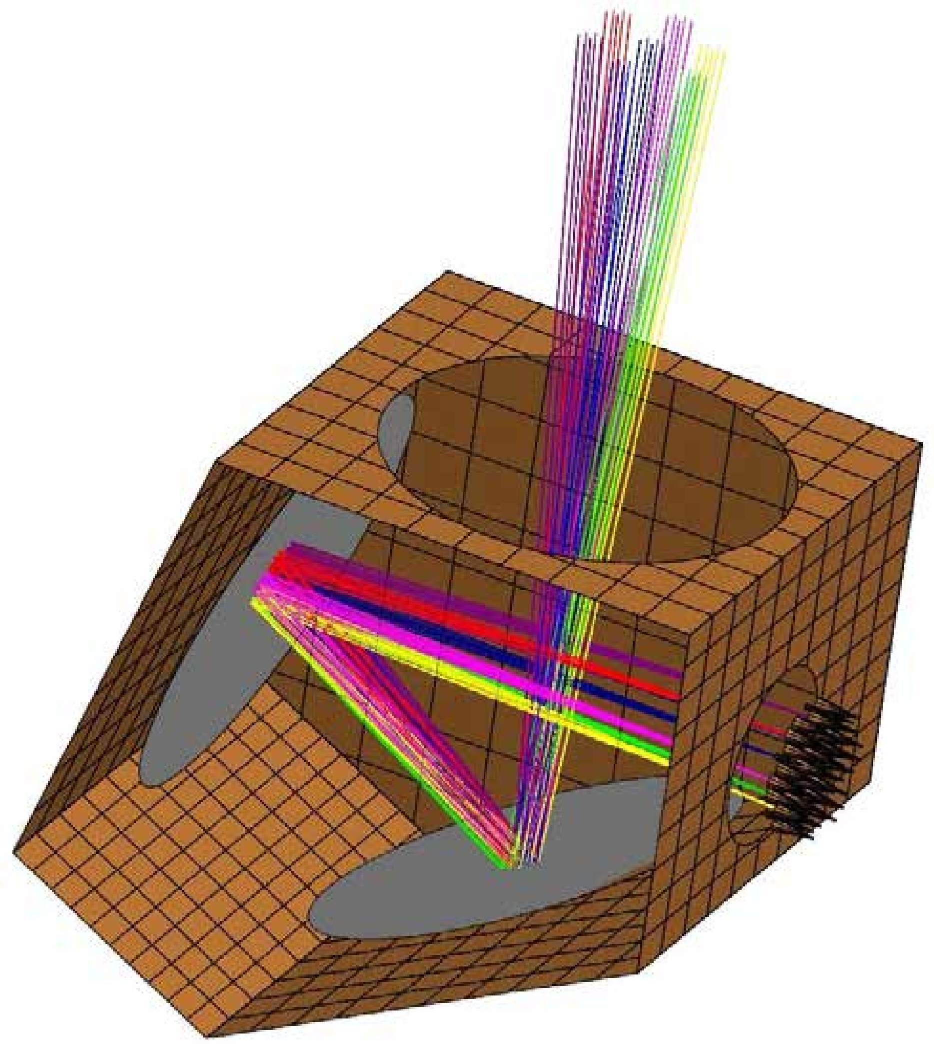
cross-polar 45° plane





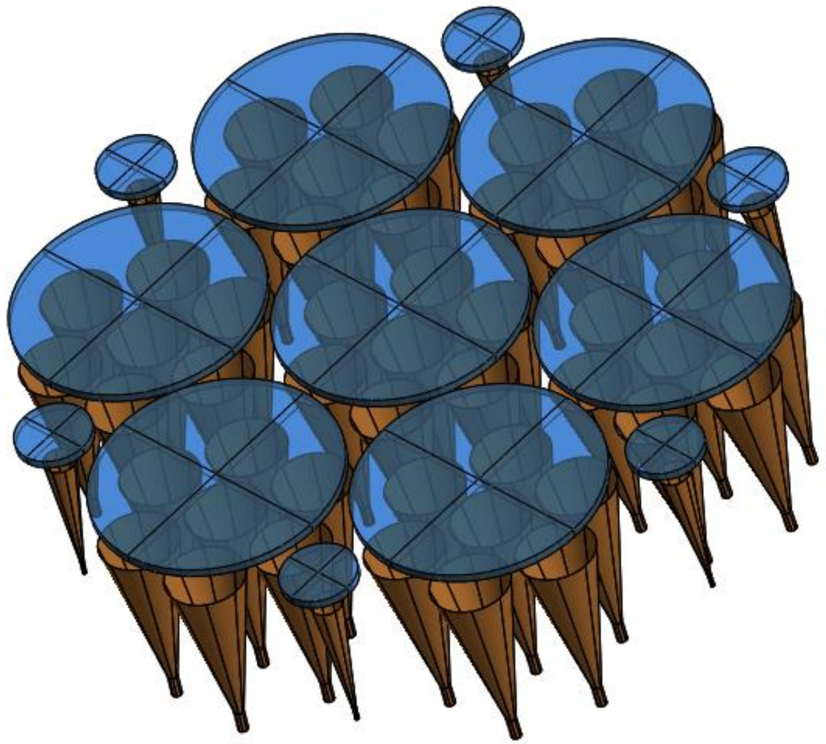
OPTICS MODEL WITH GRASP

- Focal Plane Unit
  - 49 Q-band corrugated feedhorns
  - 6 W-band corrugated feedhorns
- Main and sub reflector
- Comoving baffle



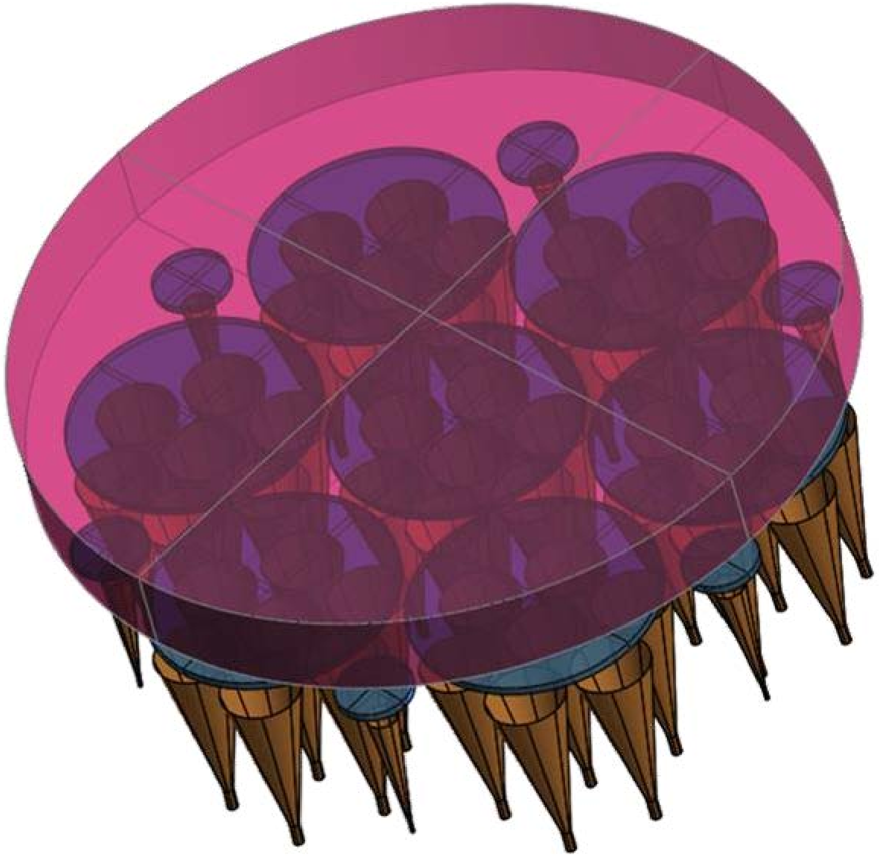
Optics Model with GRASP

- » Focal Plane Unit
  - 49 Q-band corrugated feedhorns
  - 6 W-band corrugated feedhorns
- » Main and sub reflector
- » Comoving baffle
- » 13 IR filters



OPTICS MODEL WITH GRASP

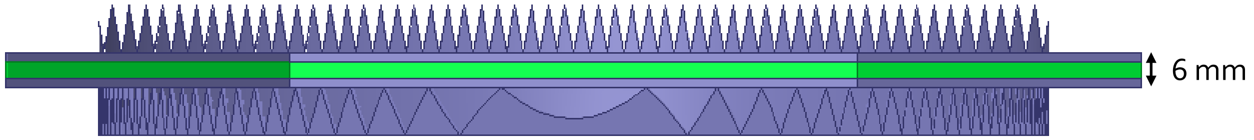
- Focal Plane Unit
  - 49 Q-band corrugated feedhorns
  - 6 W-band corrugated feedhorns
- Main and sub reflector
- Comoving baffle
- 13 IR filters
- Cryostat vacuum window



EFFECT OF FILTERS AND WINDOW

» Ultra-High Molecular Weight Polyethylene

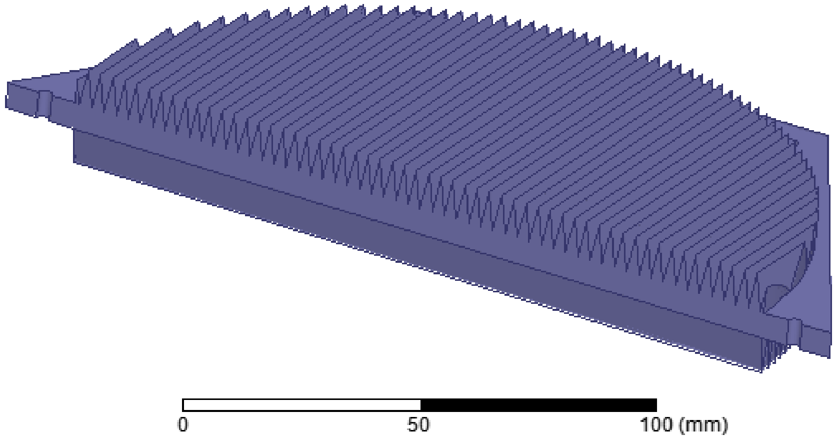
- ε_R ~ 2,32
- tan δ ~ 10^{-4} (Q-band)
- tan δ ~ $1{,}3 \cdot 10^{-4}$ (W-band)



» Designed at the Universidad de Chile (UdC)

- Geometrical and electrical parameters

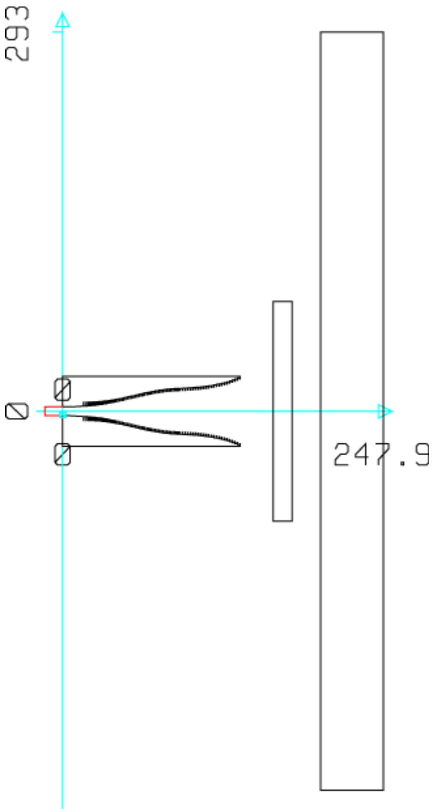
	Diameter	Thickness	RL
Q-band filter	170 mm	6 mm	<-31 dB
W-band filter	52 mm	17,32 mm	<-27 dB
Window	586 mm	43 mm	<-25 dB

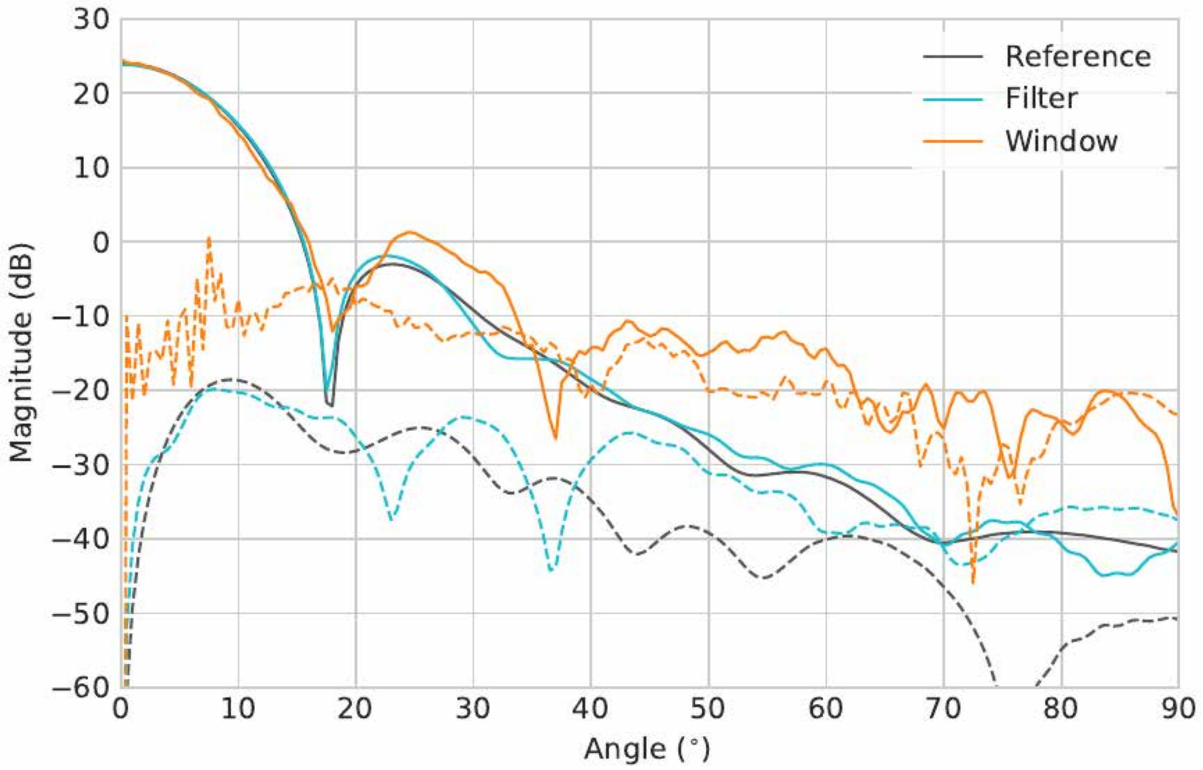


» Filter and window modify the nominal feedhorn radiation pattern

EFFECT OF FILTERS AND WINDOW

» Simulation neglecting the AR coating
  - Effect of the impedance mismatch and production of stationary waves

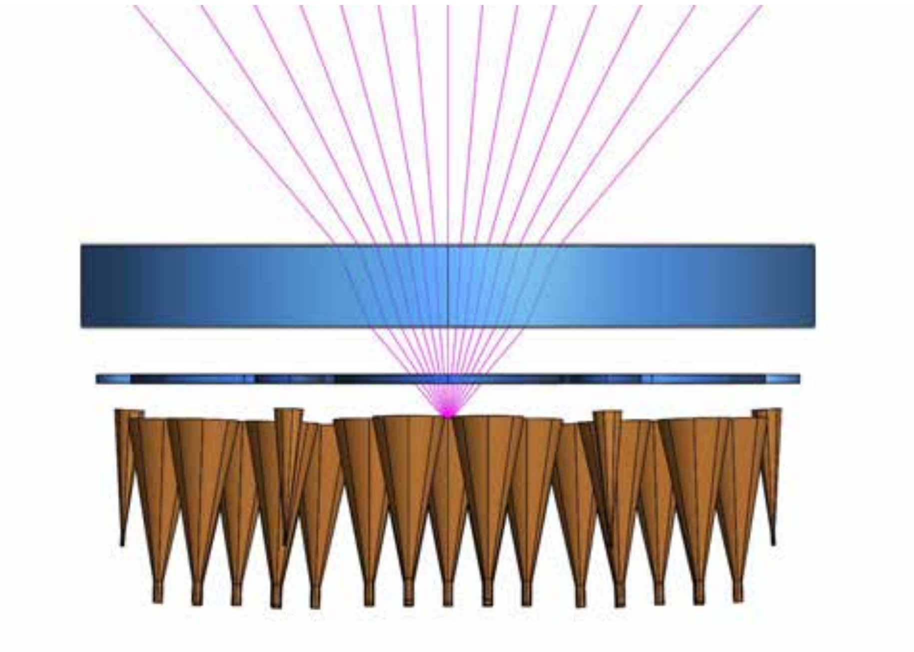


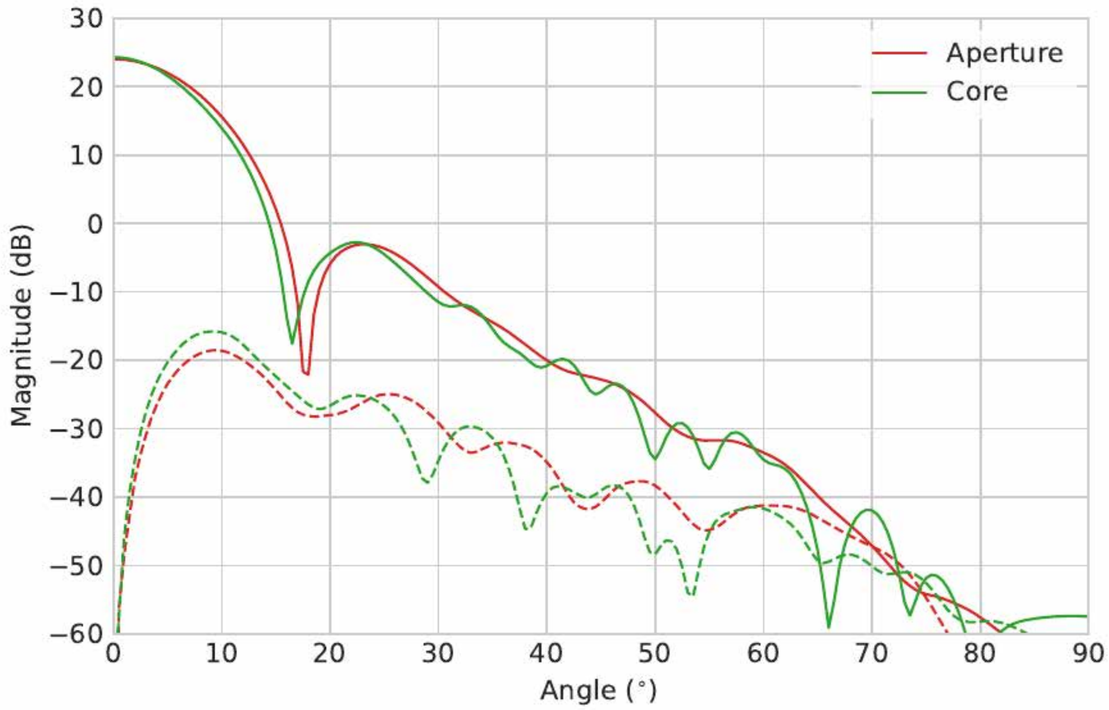


Effect of Filters and Window

» Simulation assuming perfect impedance matching, i.e. perfect AR coating

- Effect of the refraction
- Effect of the surrounding metallic structure
- Lens with the height of the central core





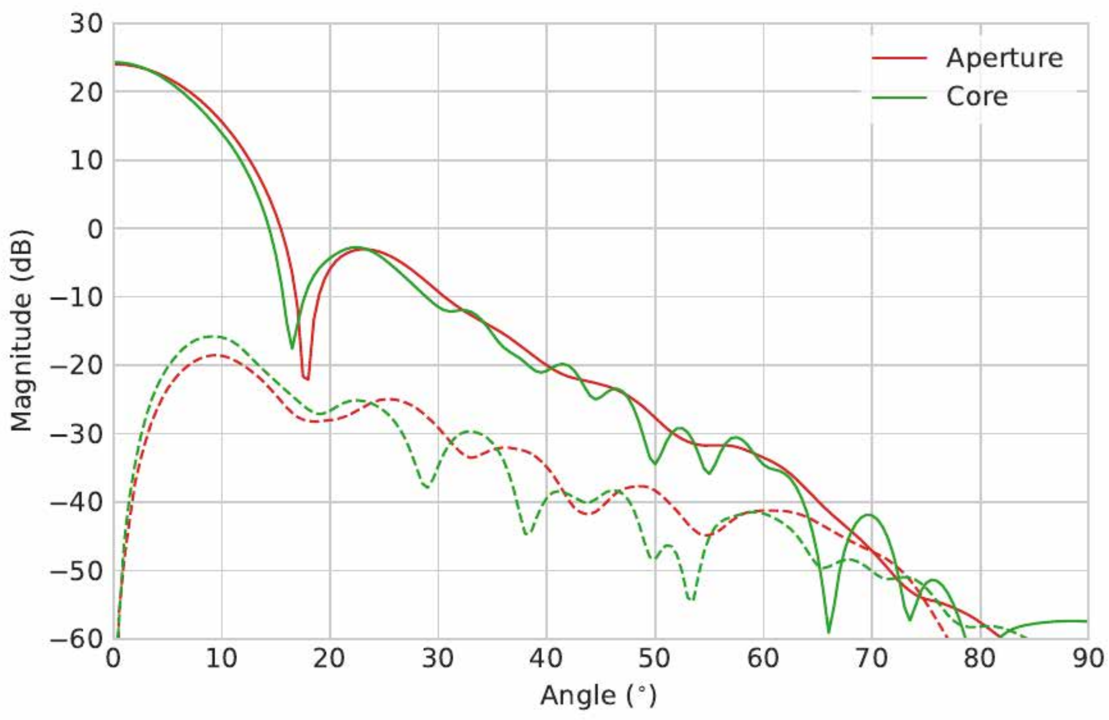
EFFECT OF FILTERS AND WINDOW

» Simulation assuming perfect impedance matching, i.e. perfect AR coating

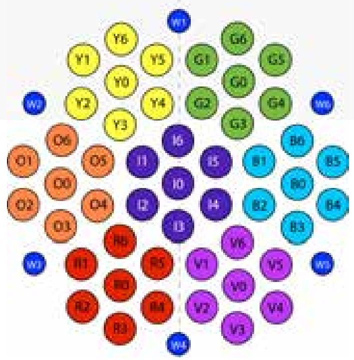
- Effect of the refraction
- Effect of the surrounding metallic structure
- Lens with the height of the central core

» Parameters at 43 GHz

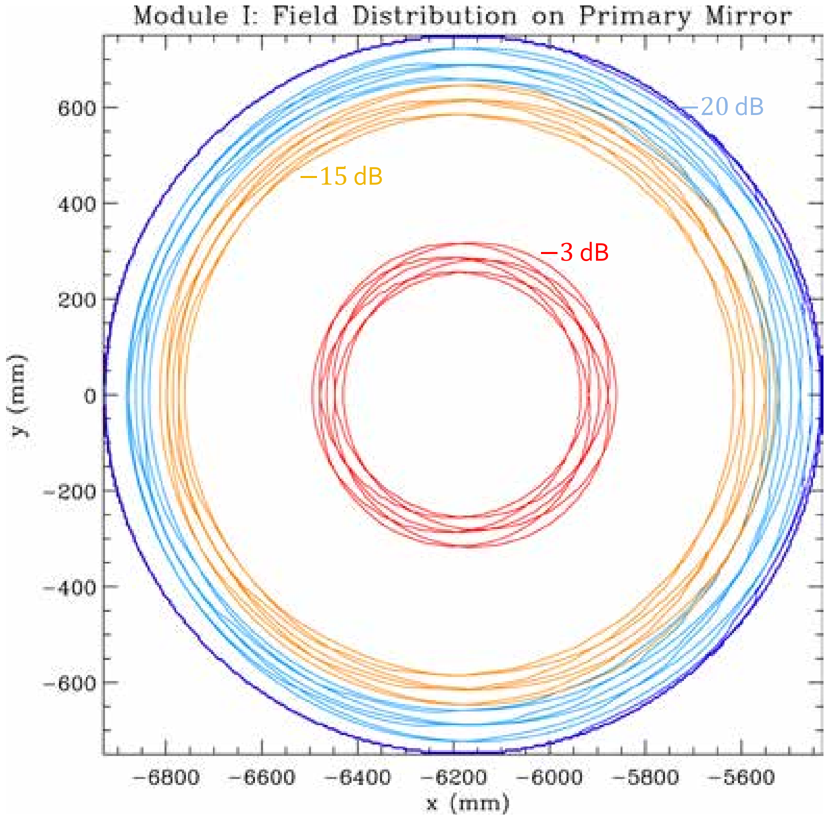
	Fwhm (°)	XPD (dB)
Beam	12,16	42,63
Filter	12,12	41,10
Window	10,07	40,08

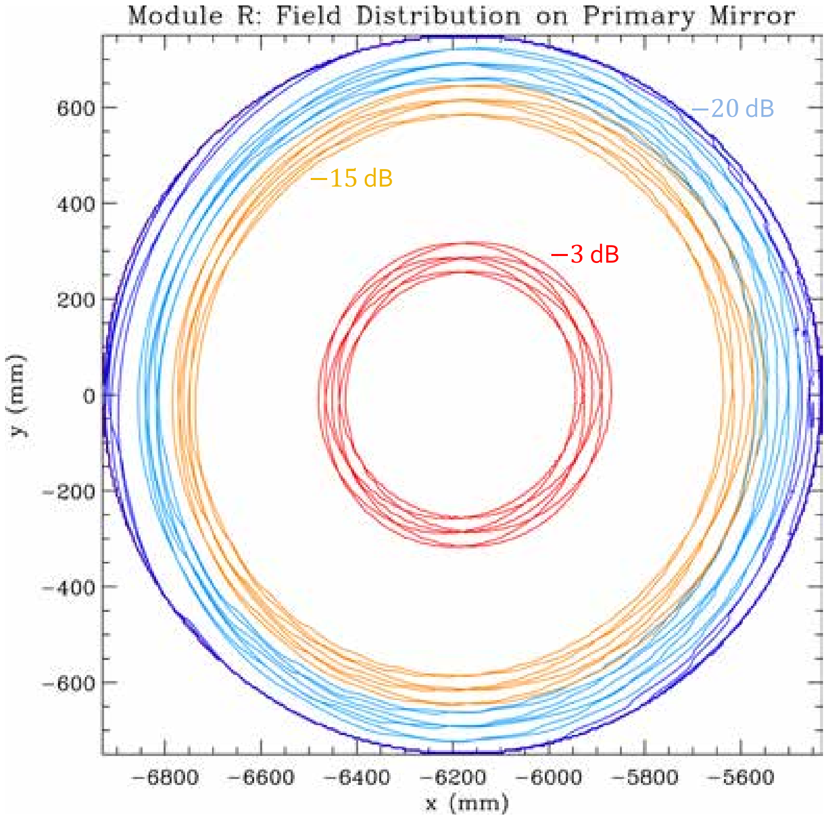


Field Distribution

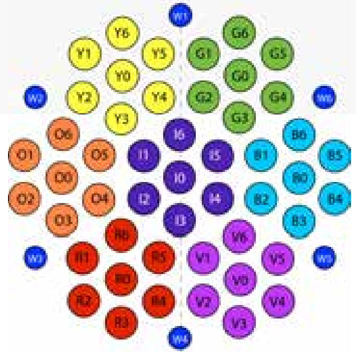


- Field distribution on main reflector
  - Illumination is centered on primary mirror, but is slightly elliptical for off-axis feedhorns



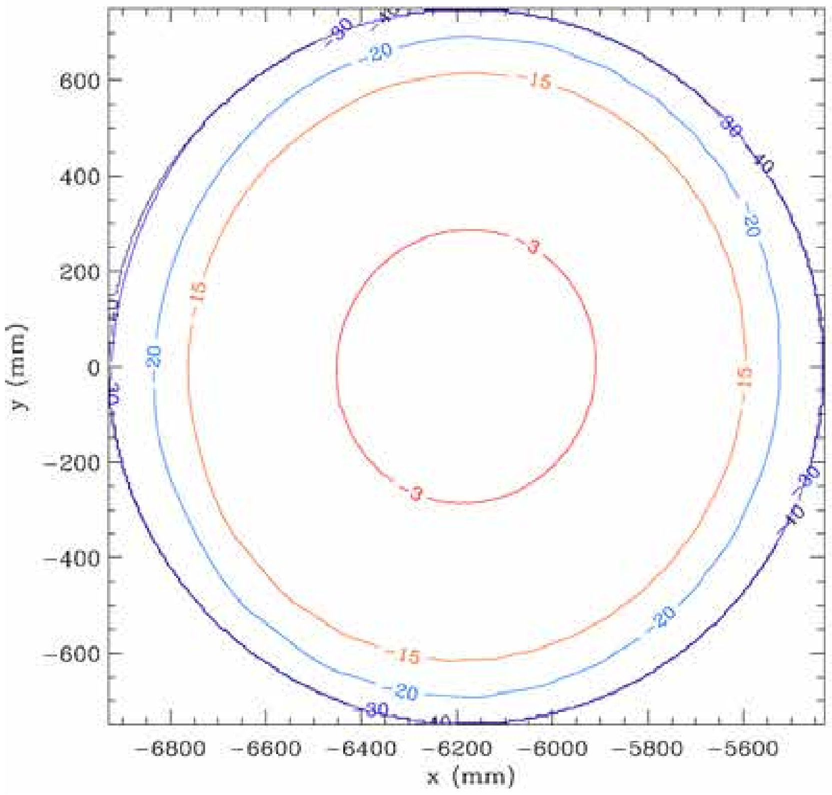


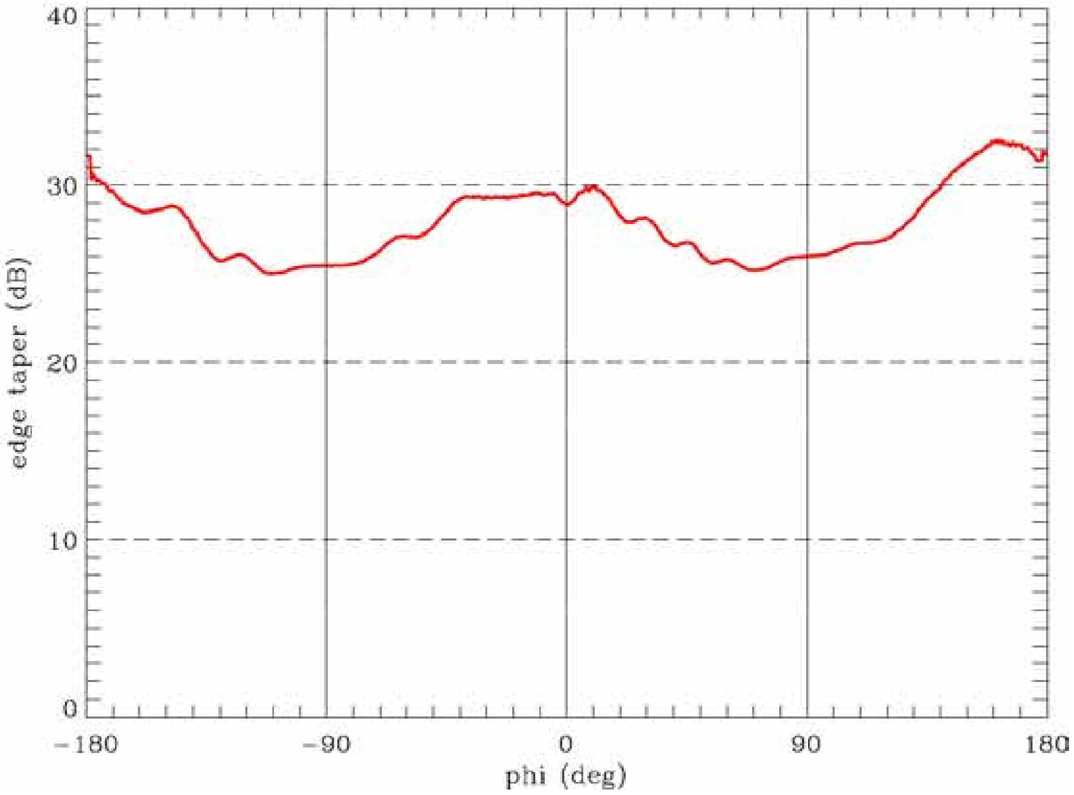
FIELD DISTRIBUTION



» Edge Taper evaluation

Feedhorn R_0





Main Beams

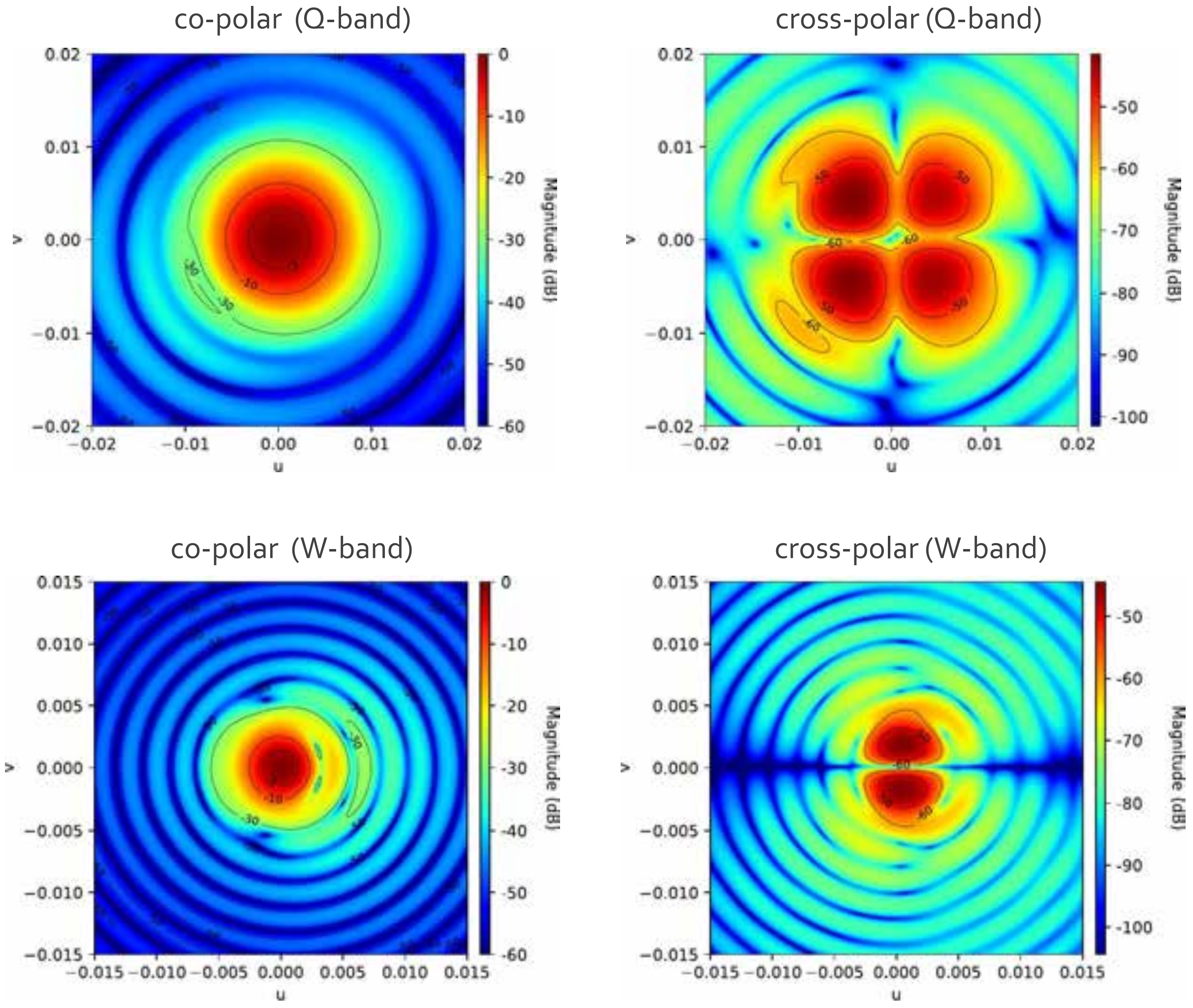
Main Beams

» Simulation technique
  - Physical Optics
  - Physical Theory of Diffraction

» 49 beams at 43 GHz

» 6 beams at 95 GHz

» Main beam parameters
  - Angular resolution (Fwhm)
  - Ellipticity
  - Directivity
  - Cross-polarization



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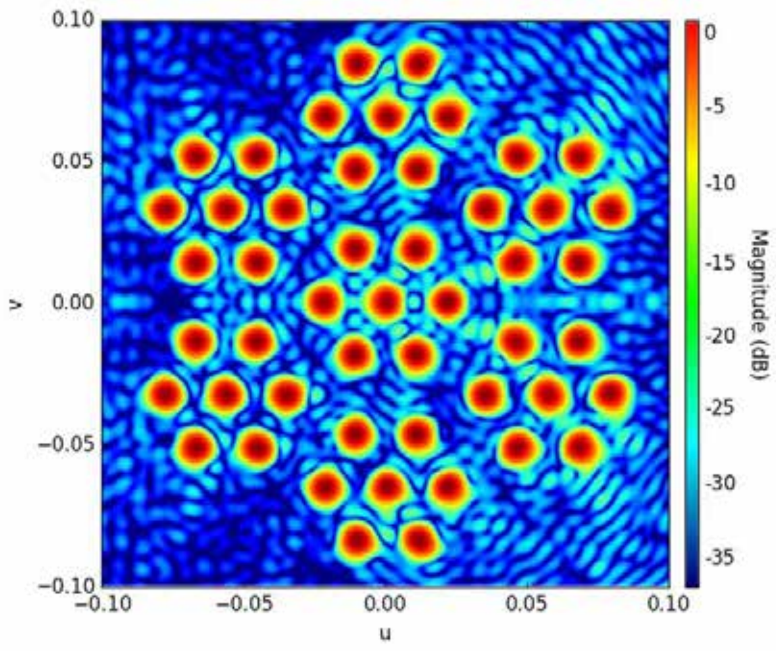

Beam	FWHM(')	e	D (dBi)	XPD (dB)
I0	22.28	1.0056	57.61	42.35
I1	22.32	1.0018	57.59	42.08
I2	22.35	1.0088	57.58	42.47
I3	22.37	1.0127	57.57	42.30
I4	22.35	1.0088	57.58	42.47
I5	22.32	1.0018	57.59	42.08
I6	22.30	1.0048	57.60	42.05
Y0	22.48	1.0034	57.48	41.50
Y1	22.67	1.0065	57.38	41.25
Y2	22.54	1.0046	57.46	41.75
Y3	22.40	1.0046	57.53	41.85
Y4	22.39	1.0062	57.53	41.94
Y5	22.52	1.0000	57.46	41.46
Y6	22.67	1.0040	57.38	41.32
O0	22.62	1.0138	57.41	42.42
O1	22.80	1.0169	57.32	42.32
O2	22.82	1.0195	57.31	42.49
O3	22.69	1.0161	57.38	42.22
O4	22.51	1.0092	57.47	42.26
O5	22.48	1.0100	57.48	42.15
O6	22.62	1.0112	57.41	42.27
R0	22.69	1.0252	57.40	41.78
R1	22.71	1.0221	57.39	42.11
R2	22.91	1.0271	57.29	41.60
R3	22.93	1.0278	57.29	41.48
R4	22.75	1.0243	57.37	41.50
R5	22.56	1.0220	57.47	42.09
R6	22.53	1.0222	57.48	42.17

Main Beams

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» Main beam parameters
- Angular resolution (Fwhm)
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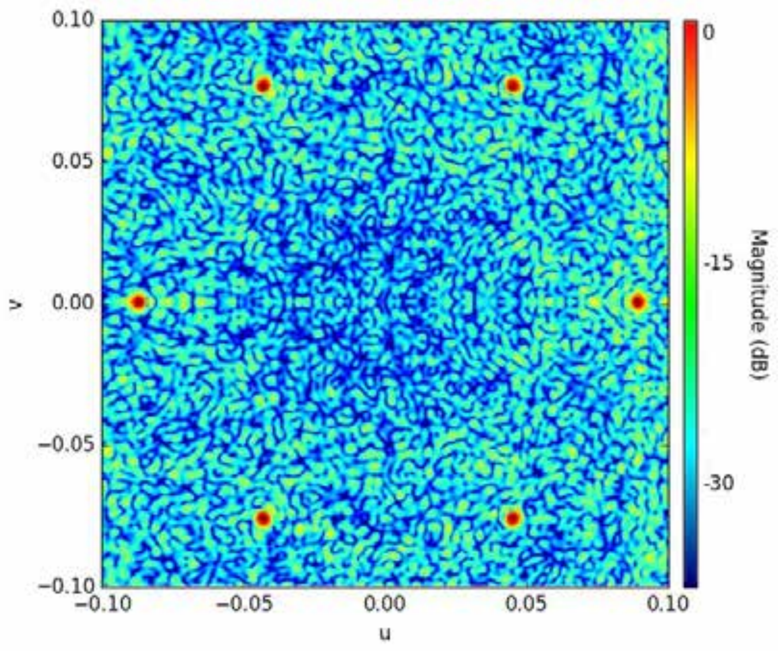
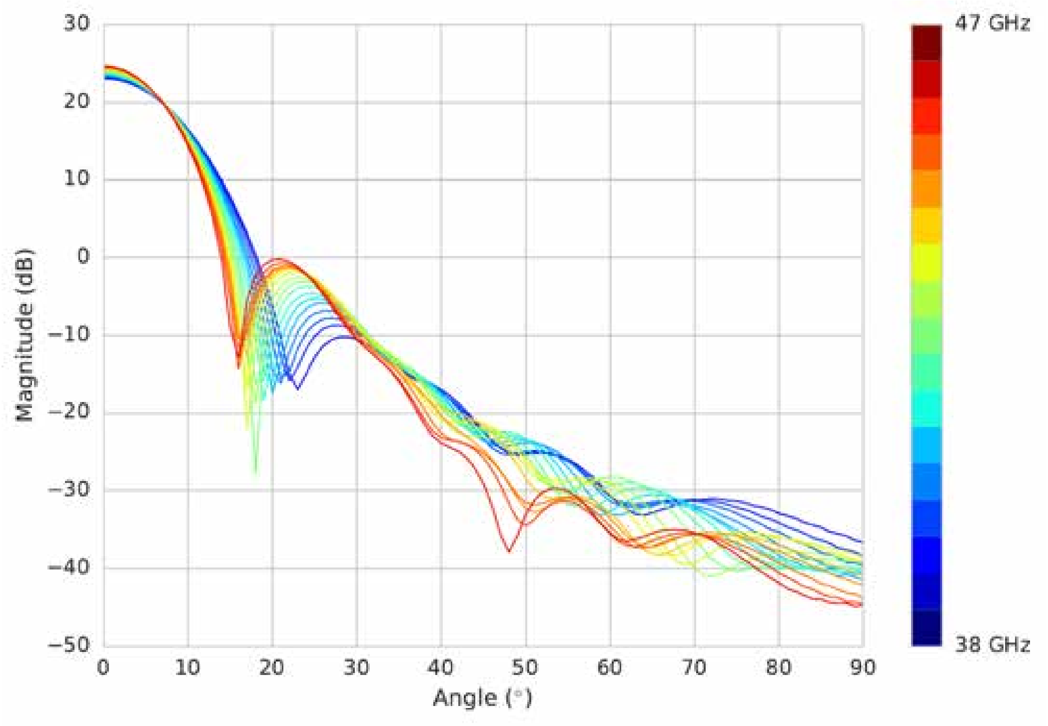
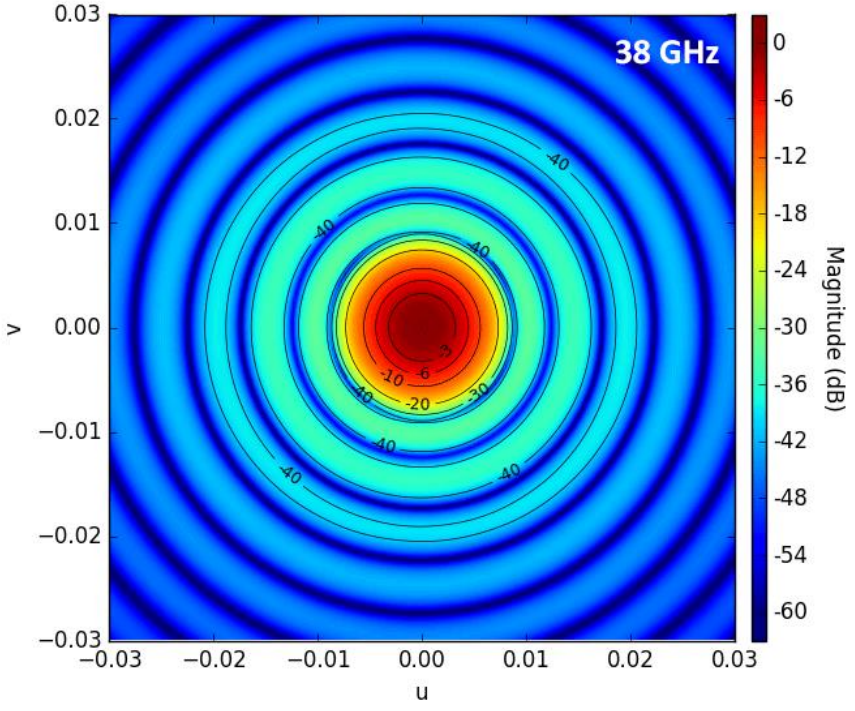


Beam	FWHM(')	e	D (dBi)	XPD (dB)
W1	9.41	1.0231	61.45	44.43
W2	9.34	1.0185	61.52	46.57
W3	9.32	1.0054	61.56	46.53
W4	9.49	1.0004	61.40	44.15

MAIN BEAMS

» Main beam shape is expected to be frequency dependent within the bandwidth
- Different response of feedhorns
- Different telescope diameter with respect to the wavelength





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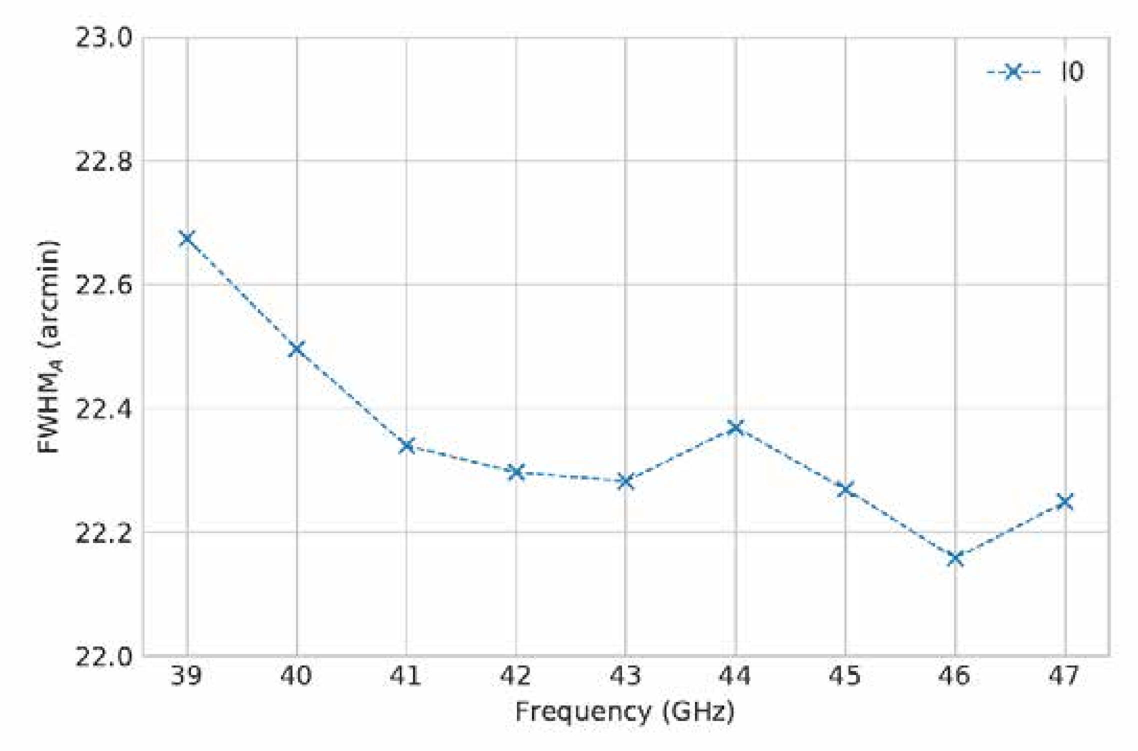


MIRRORS IMPERFECTION MODELLING

» Mirror surface distortions modelled with GRASP

» Effect on main beam parameters

Random distortions

- Effect of mechanical tolerances
- Regular grid with random z-values, specified by a correlation distance (c_x, c_y) and an amplitude
- A cubic interpolation function connects the grid points and yields a continuous surface between the random values at the nodes

$$\varepsilon_{rms} = 0{,}24\ \varepsilon_{PP}$$

Structured variations

- Effect of variations from structural analysis considering different loads acting on the telescope
- Weighted sum of Zernike polynomials with tabulated coefficients given by «BCV progetti s.r.l.»
- Analysis accounts only for the reflector stiffness, i.e. no optical enclosure, telescope mount and baseplate influence

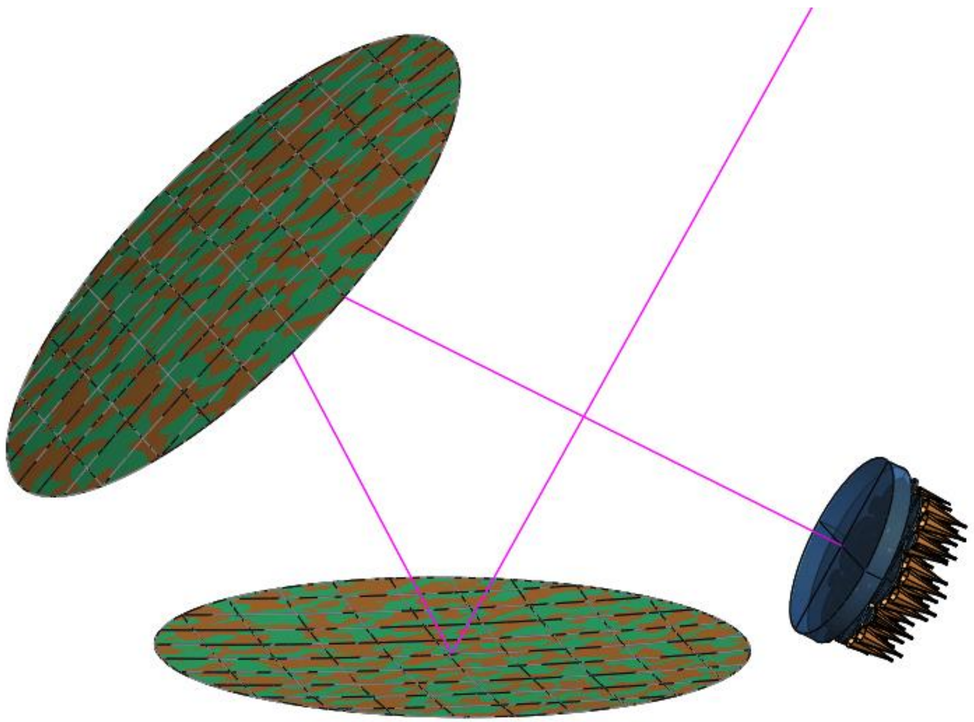
Mirrors Imperfection Modelling

» Random surface distortions

- STRIP mirrors are designed to have $\varepsilon_{PP} = \pm 50\mu\text{m}$

$$\varepsilon_{rms} = 0{,}24\ \varepsilon_{PP} = 23{,}5\ \mu\text{m}$$

- Analysis on 3 scales
  - Wavelength 7,46 mm
  - Telescope size 100 mm
  - Intermediate scale 500 mm



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  - Wavelength 7,46 mm
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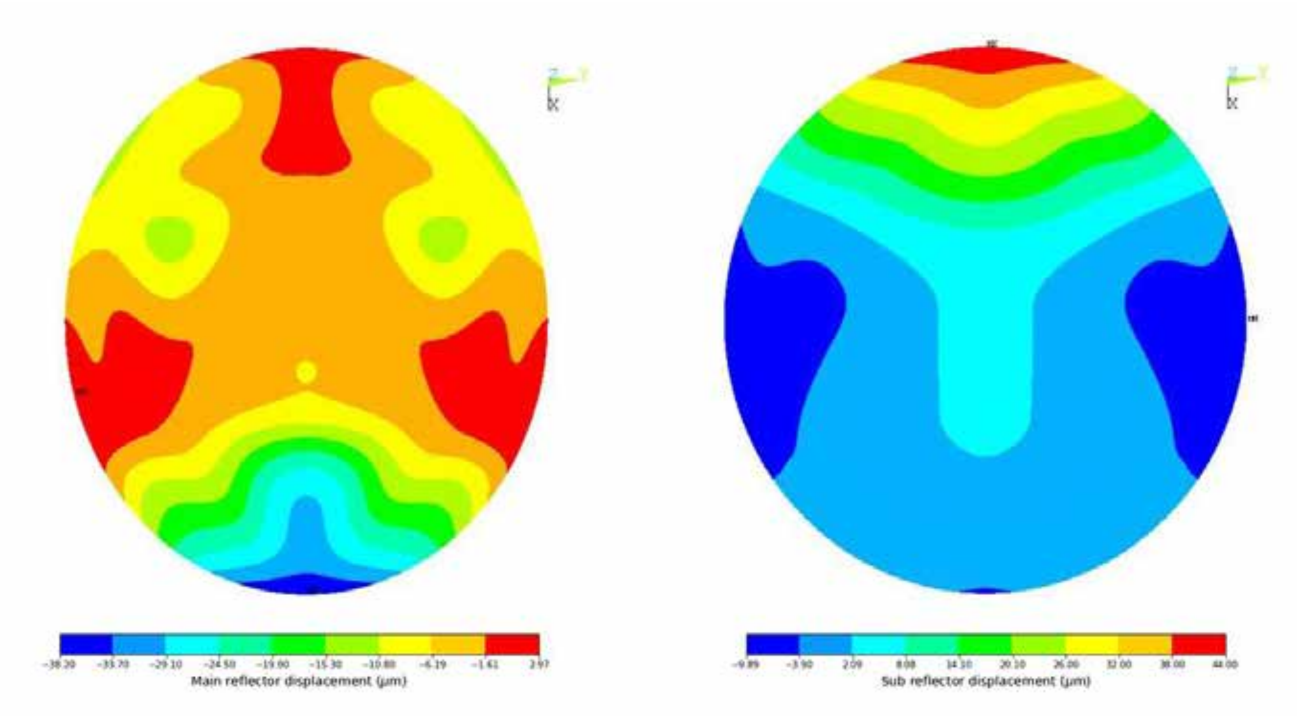
Horn	c_x (mm)	ΔFWHM (%)	Δe (%)	Δ$\mathcal{D}$ (%)	Δ XPD (%)
I_0	7,46	0,02	-0,02	0,09	0,02
	100	-0,16	-0,21	0,10	0,64
	500	0,31	0,04	-0,07	0,17
R_0	7,46	0,02	-0,03	0,09	0,10
	100	0,03	0,30	0,05	-0,43
	500	0,34	-0,38	-0,07	0,45

MIRRORS IMPERFECTION MODELLING

- Structured distortions expressed by Zernike polynomials expansion
- Analysis for different loads which may act on mirrors during telescope operative conditions
  - GRAVITY: six elevation angles from 35° to 90° (zenith angles)
  - TEMPERATURE: uniform variation, axial and lateral gradient
  - WIND: speed thresholds of 12,5 m/s and 24,0 m/s



[BCV progetti srl, 2020]

Mirrors Imperfection Modelling

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  - GRAVITY: six elevation angles from 35° to 90° (zenith angles)
  - TEMPERATURE: uniform variation, axial and lateral gradient
  - WIND: speed thresholds of 12,5 m/s and 24,0 m/s

- Results
  - Strong winds have a stronger effect on main beam parameters
  - Off-axis feedhorns are more affected by mirrors distortions
  - The effect of gravity is stronger for higher elevation angles

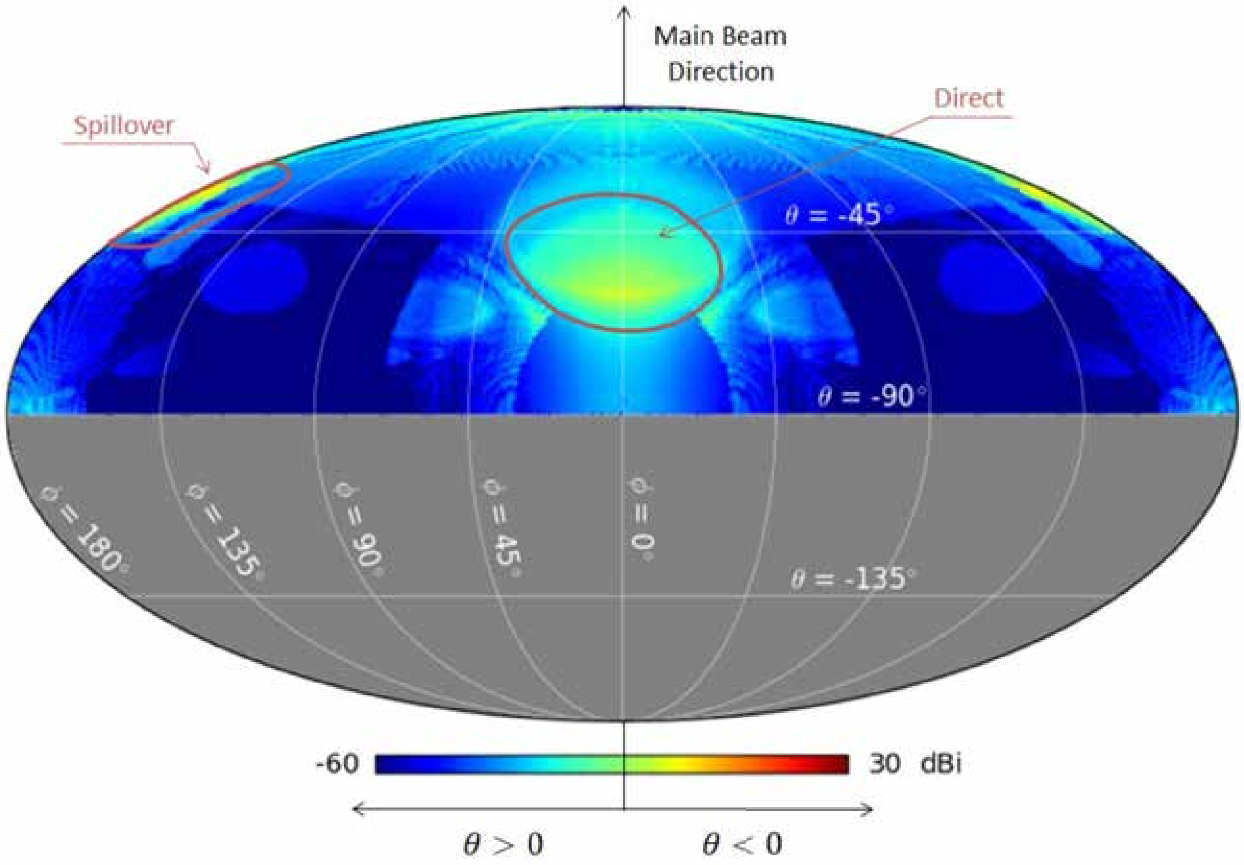
Sidelobes

SIDELOBES

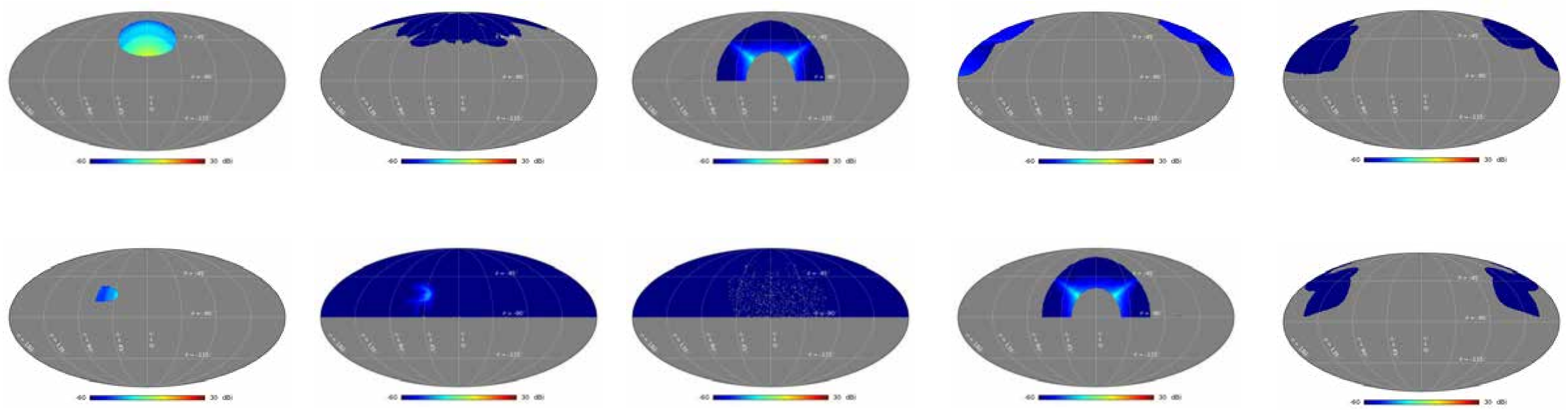
» Simulation technique
  - MultiReflector Geometrical Theory of Diffraction
  - Physical Optics for selected contributions

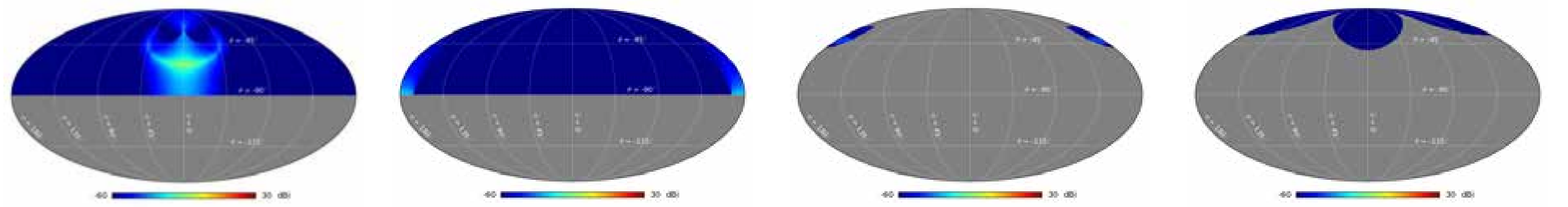
» 4π radiation pattern for 4 representative feedhorns up to the 2° order of interaction (reflection or diffraction)

» Requirement on far-sidelobes <-65 dB



SIDELOBES





and 224 more

SIDELOBES

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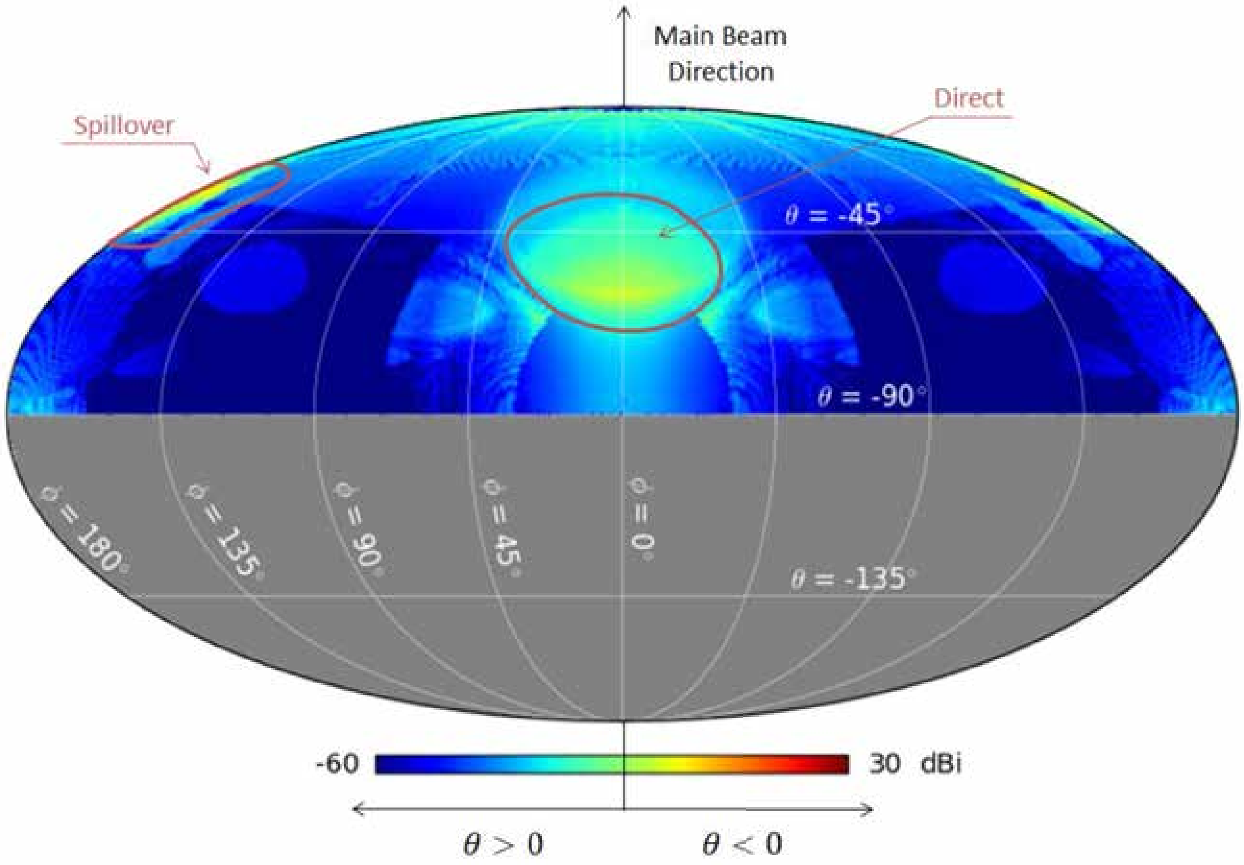
- » 4π radiation pattern for 4 representative feedhorns up to the 2° order of interaction (reflection or diffraction)

- » Requirement on far-sidelobes <-65 dB
  - Direct radiation from the horn [20°, 60°]
  - Double reflection inside shielding structure ~30°



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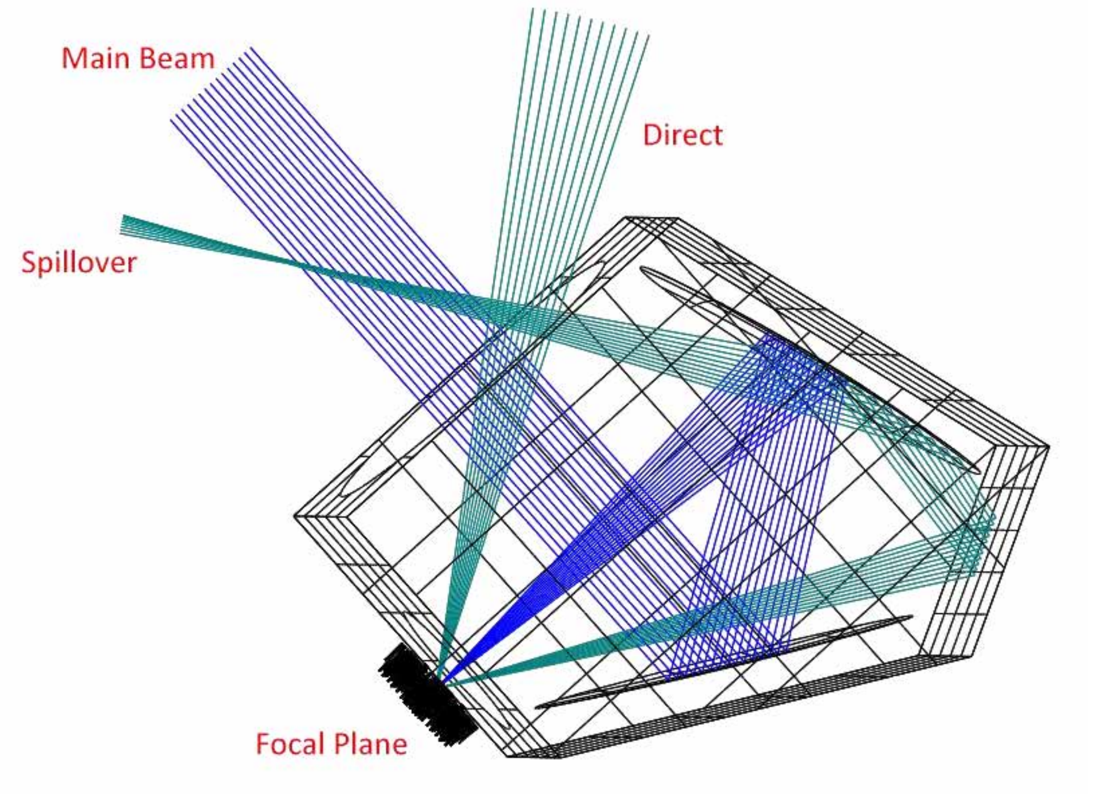
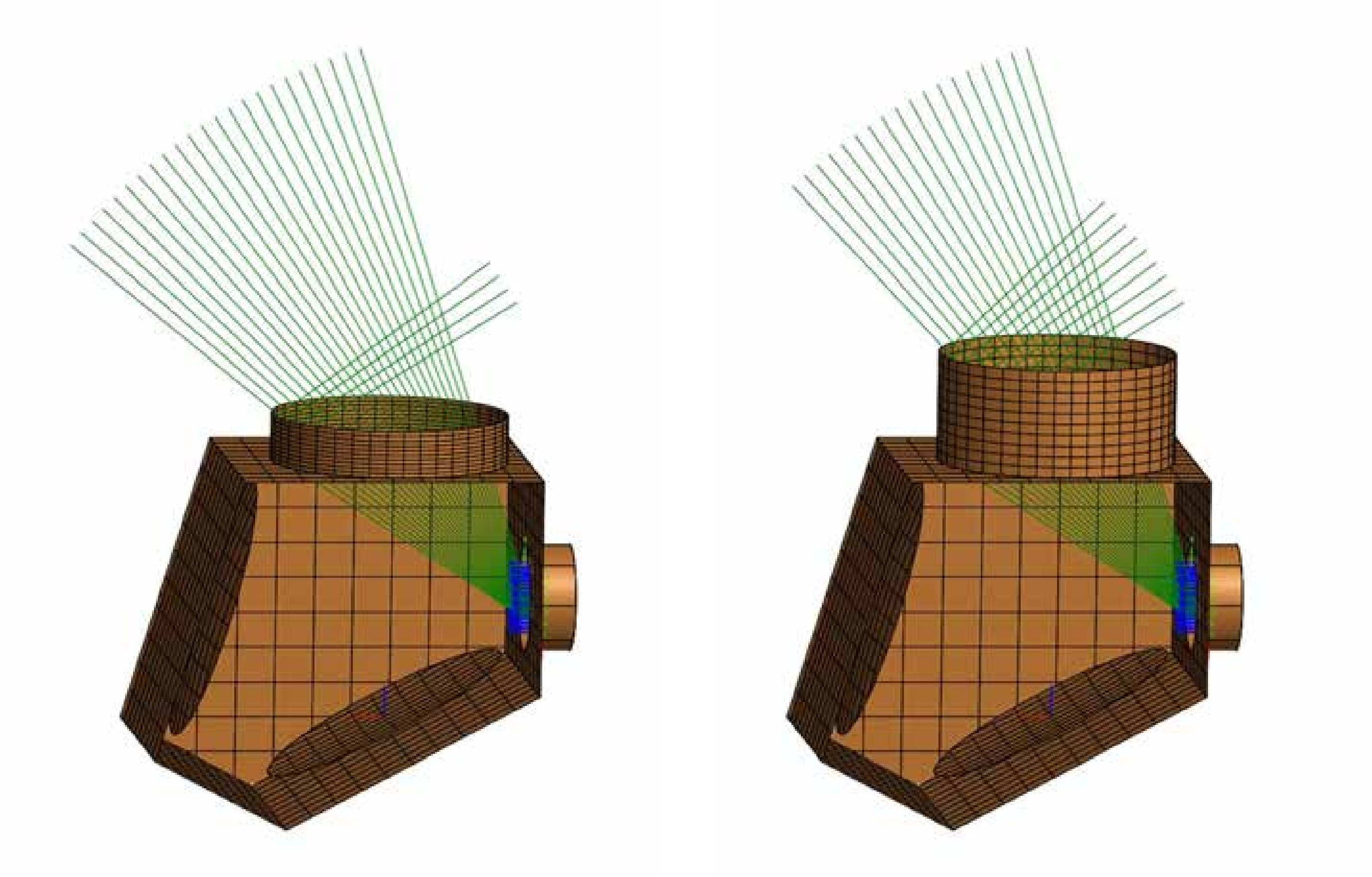


Forebaffle Analysis

- Forebaffle placed on top of the telescope aperture to reduce the sidelobe level
- Analysis of the direct contribution changing the height of the reflective baffle



Forebaffle Analysis

» Forebaffle placed on top of the telescope aperture to reduce the sidelobe level

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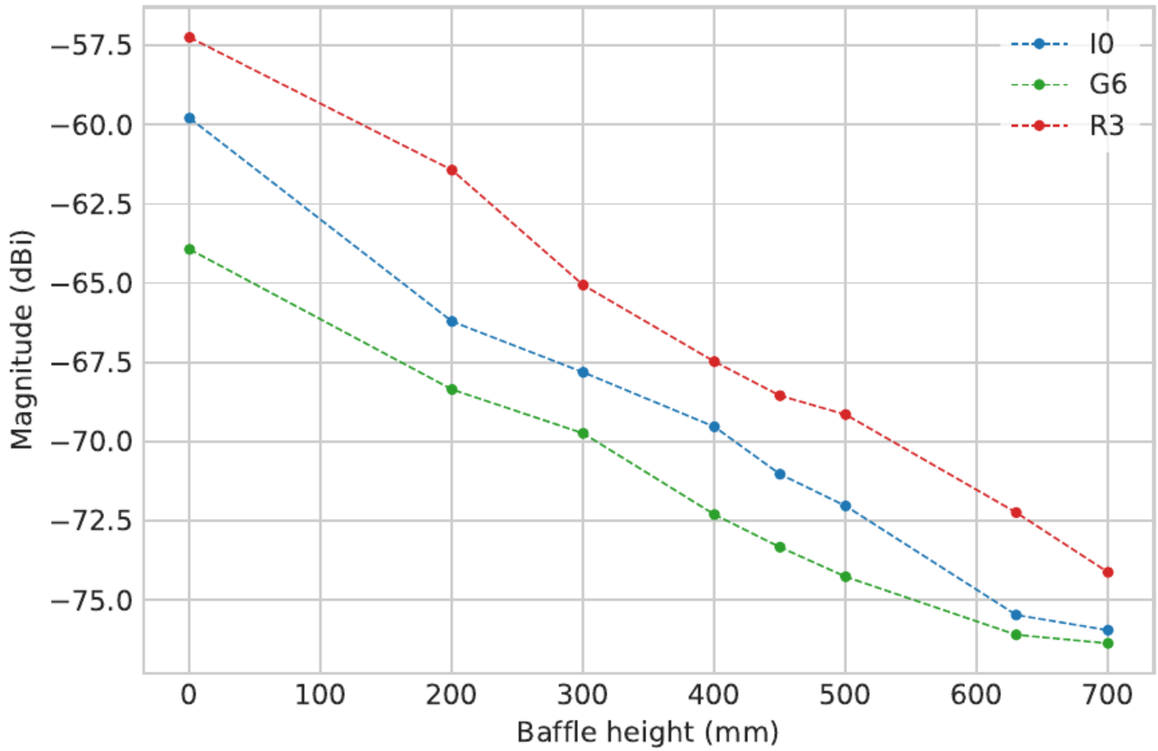
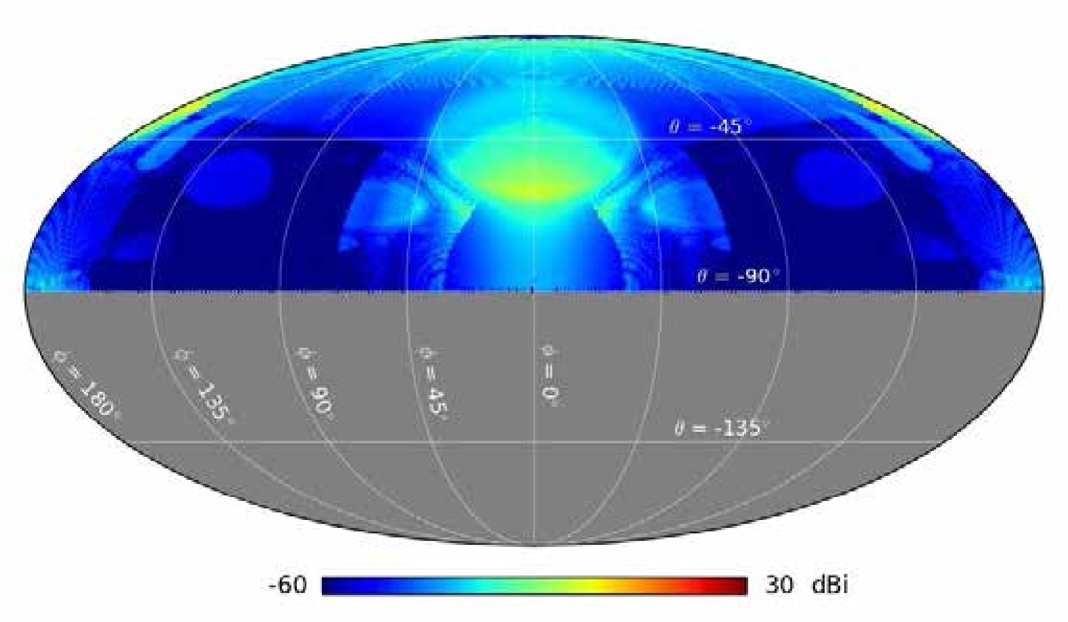
Stopping angles

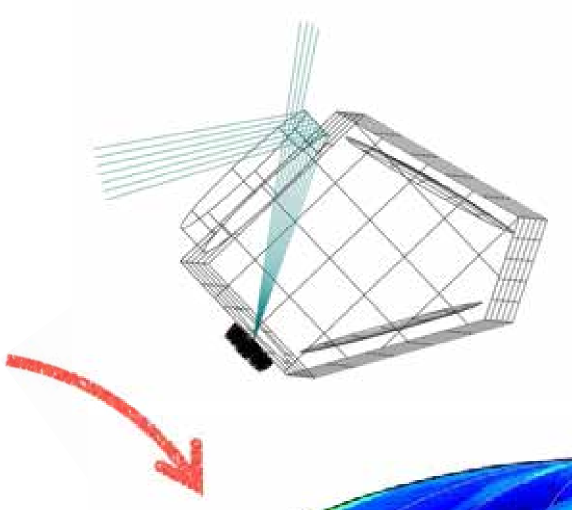
Height	I_o	R_3	G_6
0 mm	27,0°	21,5°	32,2°
200 mm	32,0°	27,0°	36,5°
300 mm	34,0°	29,5°	38,5°
400 mm	36,0°	32,0°	40,5°
450 mm	37,5°	33,0°	41,5°
500 mm	38,5°	34,0°	42,5°
630 mm	41,0°	37,0°	44,5°
700 mm	42,0°	38.5°	45,6°

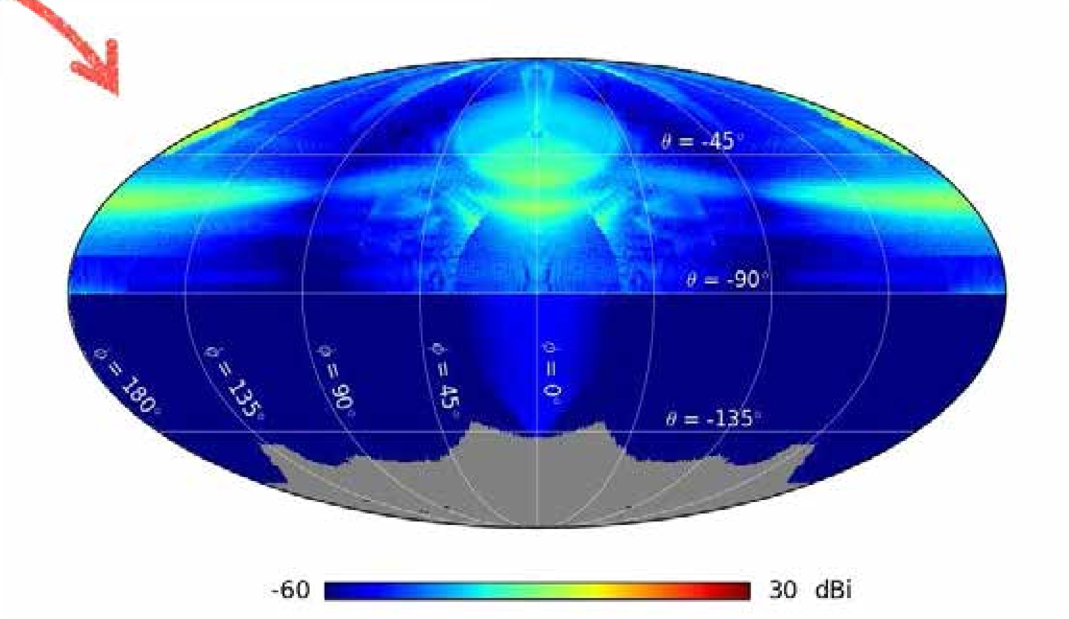


FOREBAFFLE ANALYSIS

» Increasing complexity of angular response



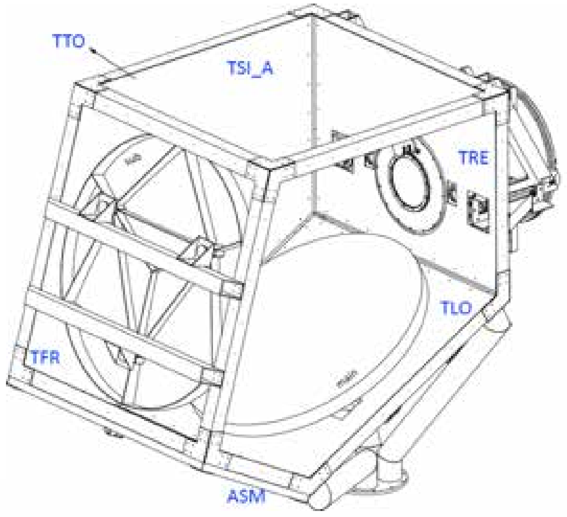


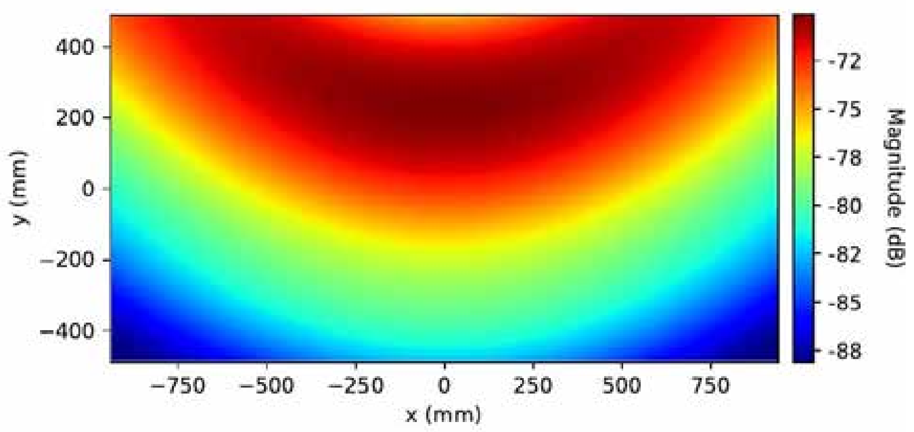


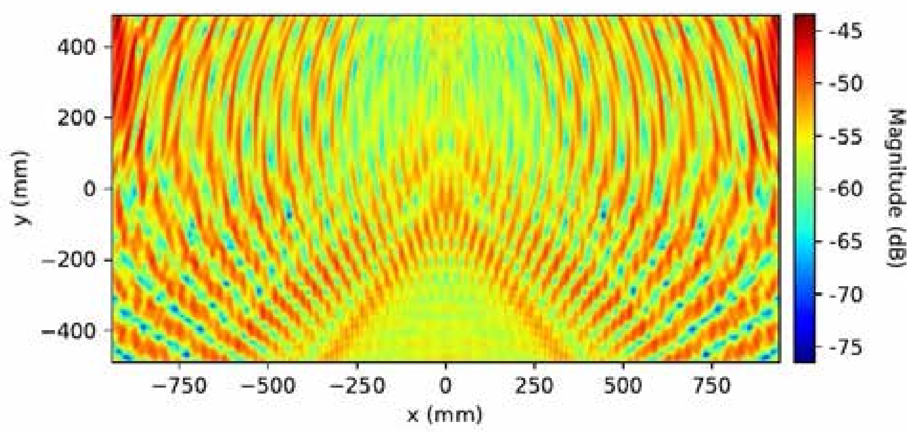
Field on the Panels

» Field on each panel of the shielding structure
- Analyse the amount of power that hits each panel
- Decision to cover the structure with an absorber

Panel	Reflection	Amplitude (dB)
ASM	direct	-70,13
	sub-reflector	-43,49
	main-reflector	-34,92



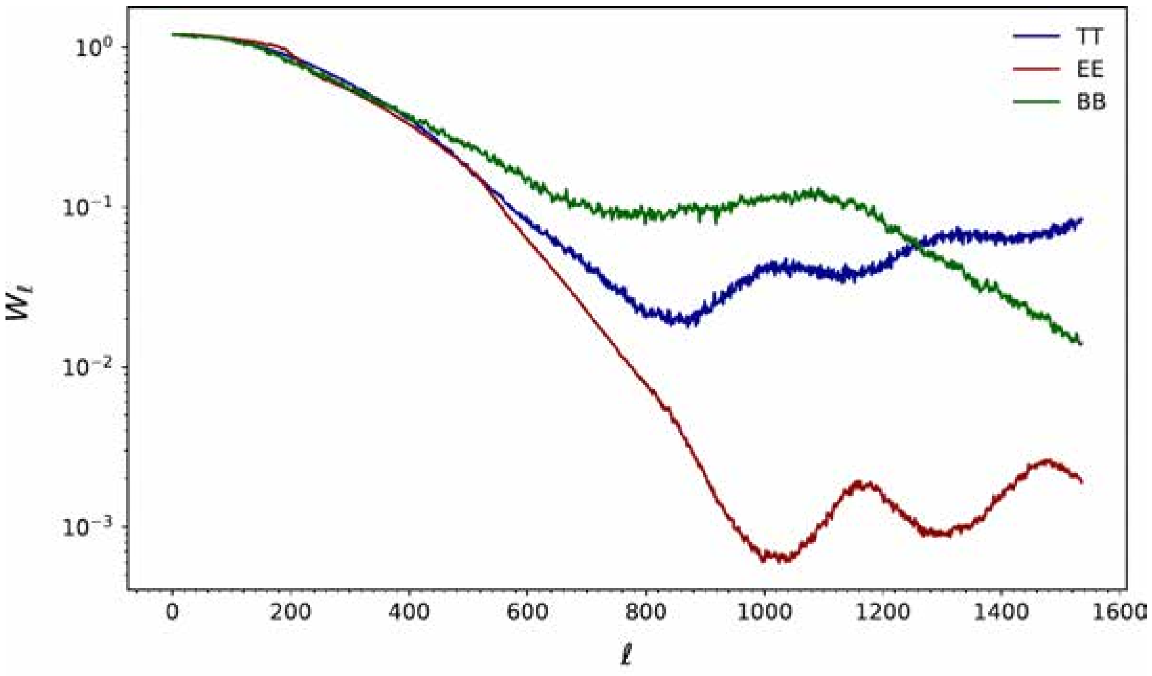




Impact on Observations

» Evaluation of beam window function

$$T_{obs}(\hat{n}) = \int b(\hat{n}, \hat{n}')T(\hat{n}')d\Omega \longrightarrow C_\ell^{obs} = W_\ell C_\ell$$

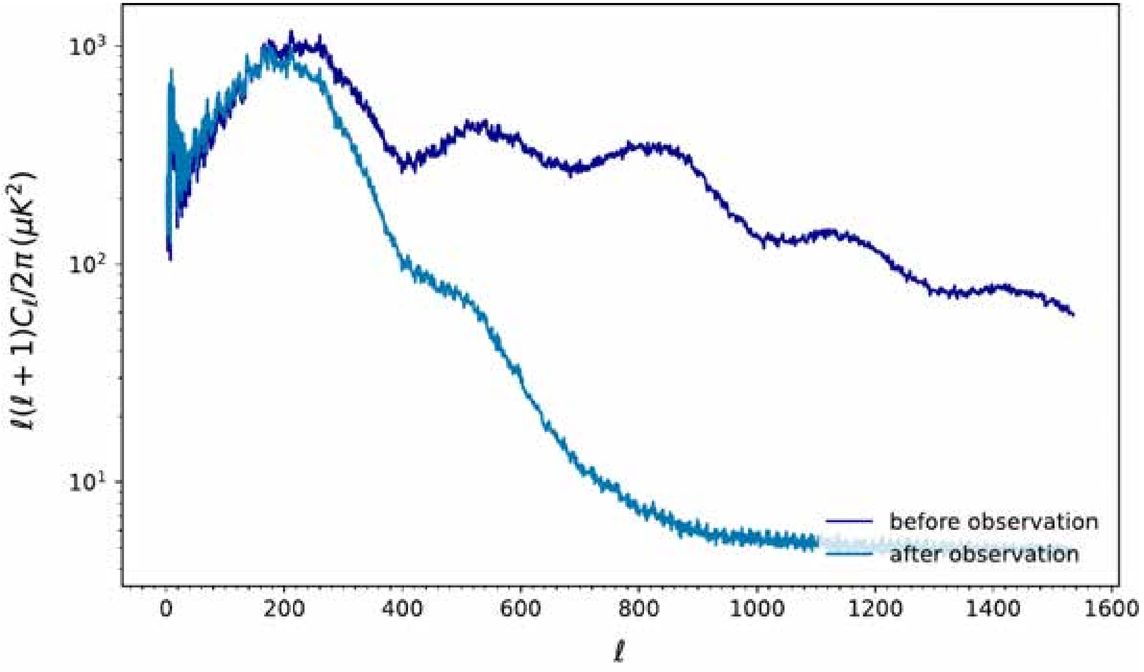


» Effective beam
- Average of all optical beams that cross a given pixel
- Its convolution with the true CMB sky produce the observed sky map
- Captures the difference between the true and observed angular power spectra

Impact on Observations

» Evaluation of beam window function

$$T_{obs}(\hat{n}) = \int b(\hat{n},\hat{n}')T(\hat{n}')d\Omega \longrightarrow C_\ell^{obs} = W_\ell C_\ell$$



» Comparison between the input power spectra and the spectra after the observation with the main beam of Io

» Smoothing effect of the main beam angular resolution

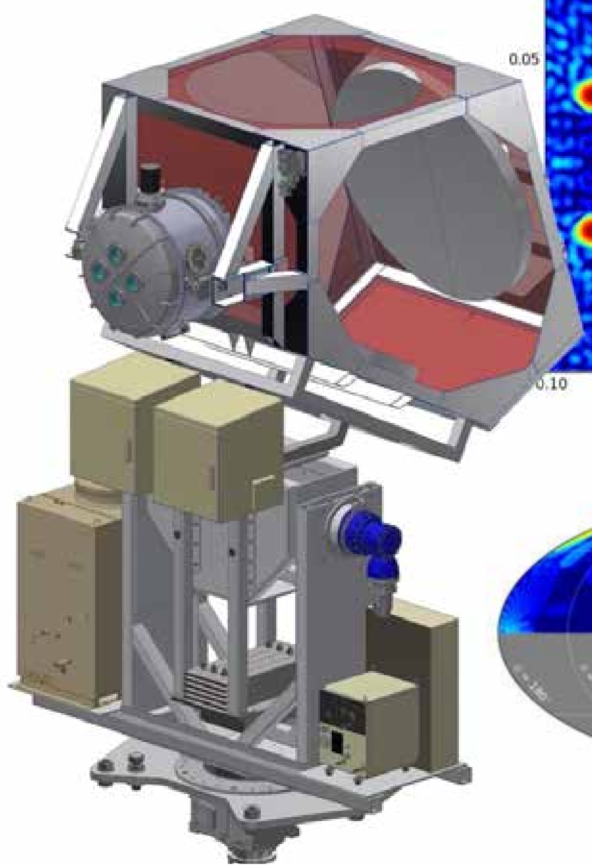
» Development of the convolution module in the Strip pipeline is underway

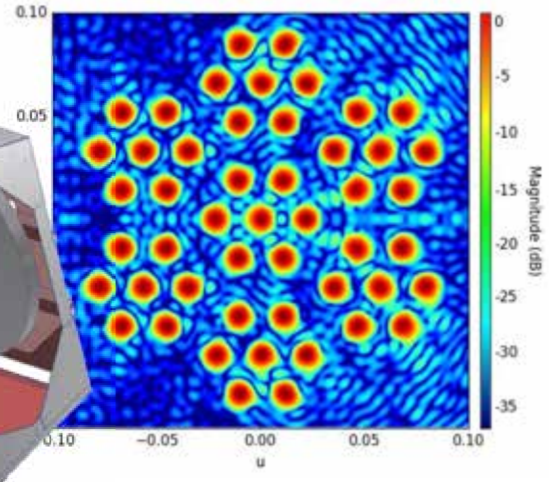
SUMMARY

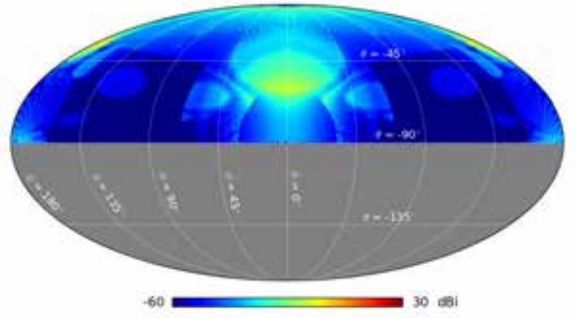
» Development of a detailed electromagnetic model of the Strip telescope
  - Feedhorns, mirrors, shielding structure with circular aperture, IR filters and cryostat window

» Main beams and sidelobes analysis including more realistic effects
  - Mirror surface distortions (random and structured)
  - Absorber

» Preliminary analysis of the impact of the optics on observations







Thank You

SABRINA REALINI

on behalf of the LSPE collaboration