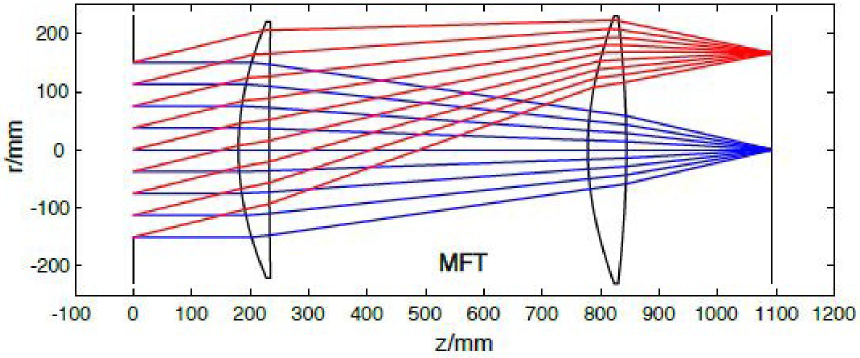
MHFT - Status of Optical/RF modeling

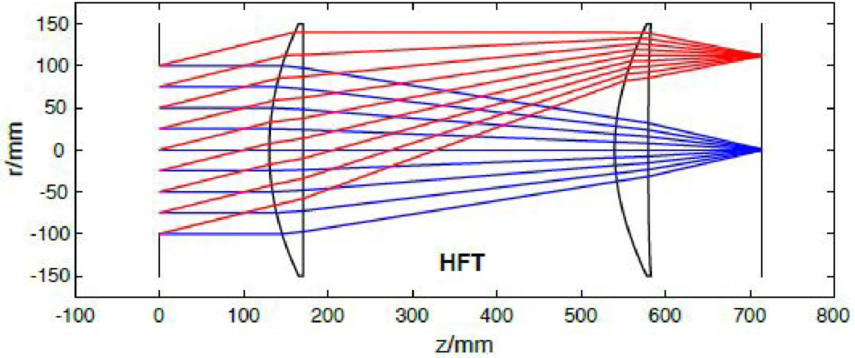
on behalf of and with contributions from the MHFT optics team
(Meeting LB Italia LNF 2023/05/23)

Reflective vs refractive tradeoff analysis conclusion (post ESA CDF 2018)

[BASELINE] - Option B: Fully transmissive solution

After the CDF, a new optical & mechanical design has been developed in order to fix some issues in term of volume and field-of-view. With this new design, the HFT field-of-view is not occulted by the V-groves anymore. It is also more compliant with the requirements in term of eigen frequency, mass and implementation on the PLM than the one studied during the CDF.



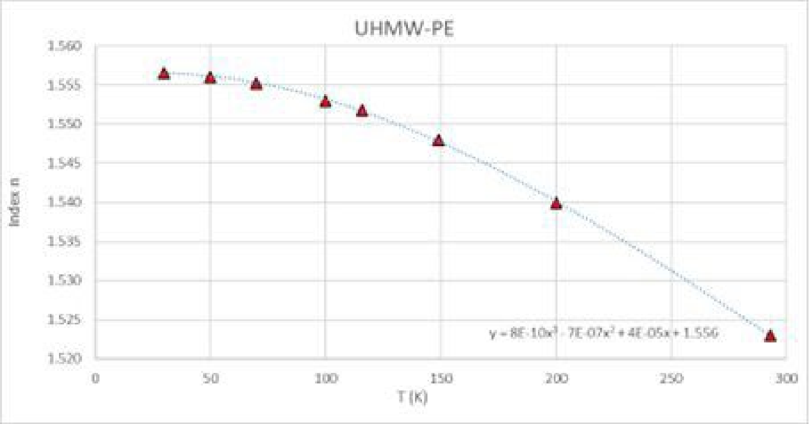


	MFT	HFT
Bandwidth	89 – 224 GHz	166 – 448 GHz
Multichroic detectors central frequencies	100/140/195, 119/166 GHz	195/280, 235/337, 402 GHz
Total n. of detectors	2074 (1098 + 976)	1354 (508 + 508 + 338)
Detector coupling	sinous antenna + Si lenslet	horn+OMT
Stop diameter	300 mm	200 mm
Field of view	28°	28°
Focal ratio	2.2	2.2
Min-Max Strehl ratio at 14°	0.95 - 0.99	0.91 - 0.98

Table 1. Summary of baseline configurations for the 2-lens assemblies of MFT and HFT. Strehl ratios are computed at the edge of the nominal field of view and the min-max range refers to the shift in value across the telescope band.

Proc. SPIE 11443, 1144370 (13 December 2020); doi: 10.1117/12.2579233
Proc. SPIE 12190, 121901R (31 August 2022); doi: 10.1117/12.2629271

Baseline update after cold UHMW-PE characterization



P. Hargrave's ESA TRP

Proposed MFT update (V2.0)

Filename = PH-PE-2lens-MFT-300x22-Nov-2022-V-2-0.zos

28° FoV, Focal plane radius = 167.1 mm, f/2.2, EFFL = 655.5 mm, EPD = 300 mm

Total tube length = 1091.8 mm

	Surface Type		Comment	Radius		Thickness	Material		Coating	Clear Semi-Dia		Chip Zone	Mech Semi-Dia	Conic		TCE x 1E-6
0	OBJECT	Standard ▾		Infinity		Infinity				Infinity		0.000	Infinity	0.000		0.000
1	STOP (aper)	Standard ▾		Infinity		180.000				150.000	U	0.000	150.000	0.000		0.000
2	(aper)	Standard ▾	L1	574.863	V	52.200	1.56,0...	M		220.000	U	0.000	220.000	-0.750	V	0.000
3	(aper)	Standard ▾		Infinity		545.400				220.000	U	0.000	220.000	0.000		0.000
4	(aper)	Standard ▾	L2	567.573	V	66.200	1.56,0...	M		230.000	U	0.000	230.000	-3.710	V	0.000
5	(aper)	Standard ▾		-1661.3...	V	248.000				230.000	U	0.000	230.000	-52.082	V	0.000
6	IMAGE	Standard ▾		Infinity		-				166.481		0.000	166.481	0.000		0.000

Proposed HFT update (V2.0)

Filename = PH-PE-2lens-HFT-200x22-Nov-2022-V-2-0.zos

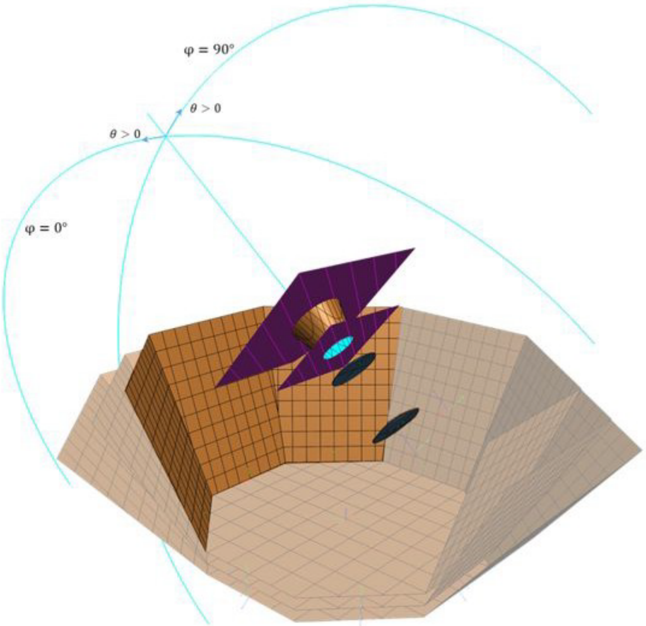
28° FoV, Focal plane radius = 112.3 mm, f/2.18, EFFL = 433.5 mm, EPD = 200 mm

Total tube length = 714.7 mm

Note that surface 5 is now constrained to be planar, to avoid concave surface (trickier for coating).

	Surface Type		Comment	Radius		Thickness	Material		Coating	Clear Semi-Dia		Chip Zone	Mech Semi-Dia	Conic		TCE x 1E-6
0	OBJECT	Standard ▾		Infinity		Infinity				Infinity		0.000	Infinity	0.000		0.000
1	STOP (aper)	Standard ▾		Infinity		130.0...				100.000	U	0.000	100.000	0.000		0.000
2	(aper)	Standard ▾	L1	349.624	V	40.000	1.56,0...	M		150.000	U	0.000	150.000	-0.763	V	0.000
3	(aper)	Standard ▾		Infinity		369.4...				150.000	U	0.000	150.000	0.000		0.000
4	(aper)	Standard ▾	L2	288.419	V	40.000	1.56,0...	M		150.000	U	0.000	150.000	-3.697	V	0.000
5	(aper)	Standard ▾		Infinity		135.2...				150.000	U	0.000	150.000	0.000		0.000
6	IMAGE	Standard ▾		Infinity		-				111.641		0.000	111.641	0.000		0.000

GRASP (Physical Optics)



MFT model includes

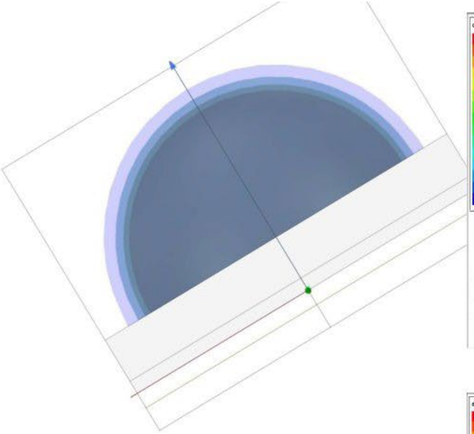
- *PH-PE-2lens-MFT-300x22-frozen-april2019* by Pete, Apr. 2019
  - HDPE lenses (n = 1.52)
  - Aperture stop ⌀300 mm
- *Pattern of sinuous antenna + lenslet* by Greg J., Apr. 2022
- Forebaffle aperture ⌀421 mm
- Perfect absorber (tube, forebaffle) and lens ARC
- V-groove: three panels in front of the telescope

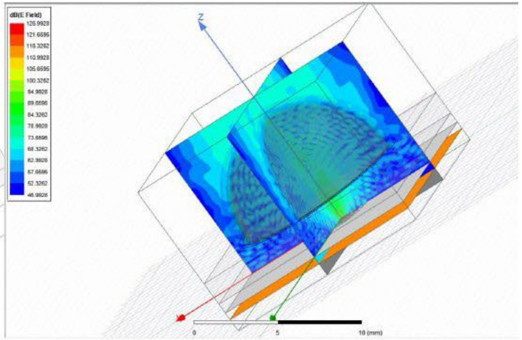
Simulation summary

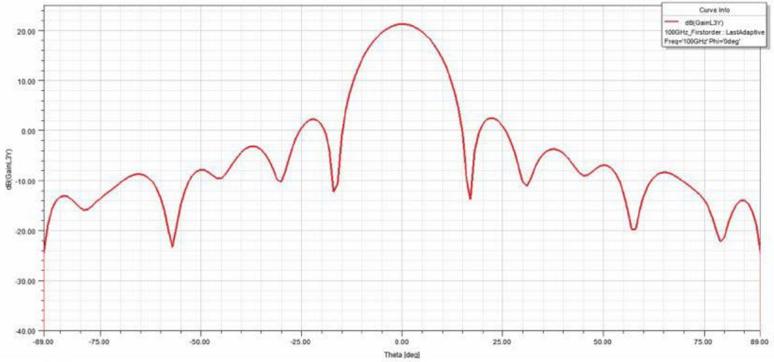
- Method: GRASP Physical Optics
- 49 pixels of the FPU (IMo 1.3)
  - 119 sims at 100, 119, 140, 166 and 195 GHz
- Beams calculated in their MB coordinate system

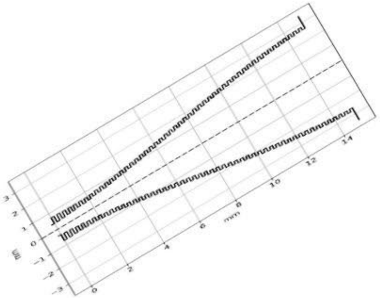
(Faster than MoM, more efficient for design implementations and iterations)

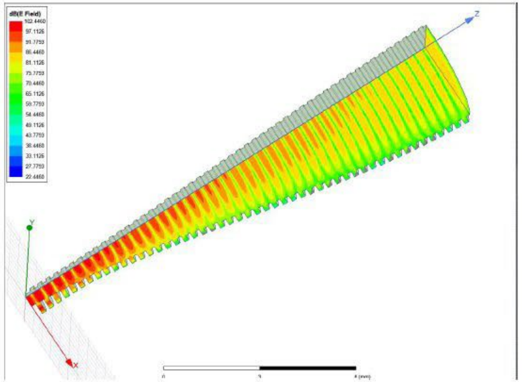
GRASP (Physical Optics+HFSS feeds sims vs freq)

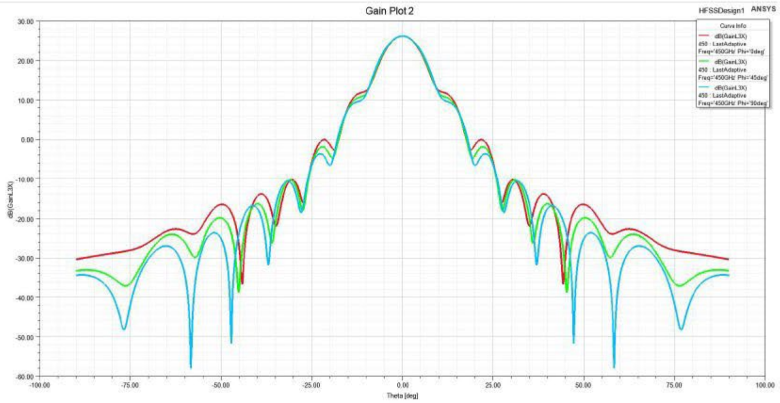












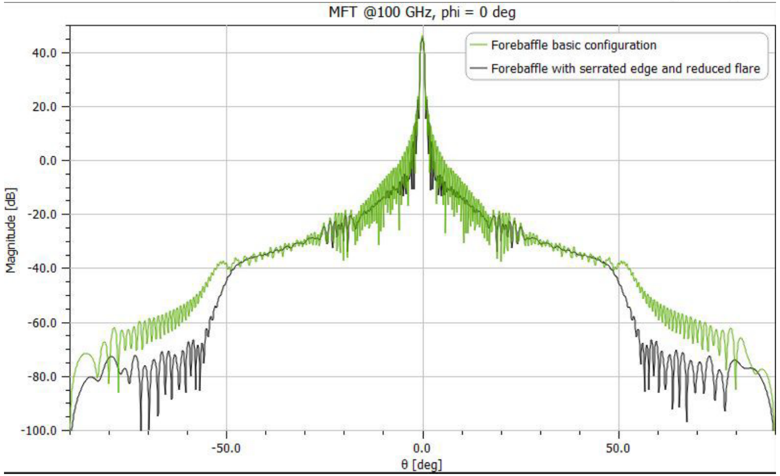
GRASP (forebaffle w/ flared edge)

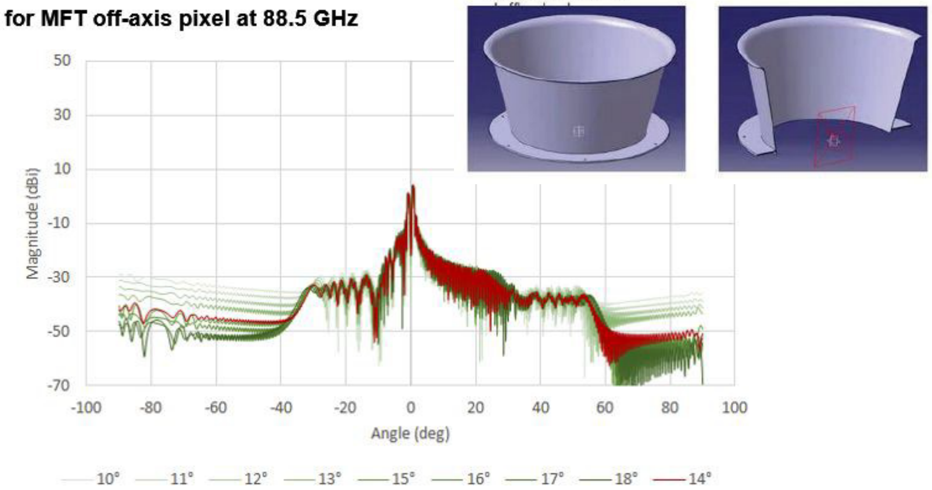
- Study of the impact of forebaffle on optical response
  - Preliminary study of the FB **flare angle** performed at MFT frequencies (100 to 195 GHz) for on-axis and off-axis pixels (both co-polar and cross-polar)
  - Modeling with MoM and PO is on-going, including:
    - “Real” beam former response (HFSS sims for MFT, SRSR sims for HFT)
    - Rolled-edge FB design vers. “Cone 3” by Berend W.

MHFT Entrance Cone 3

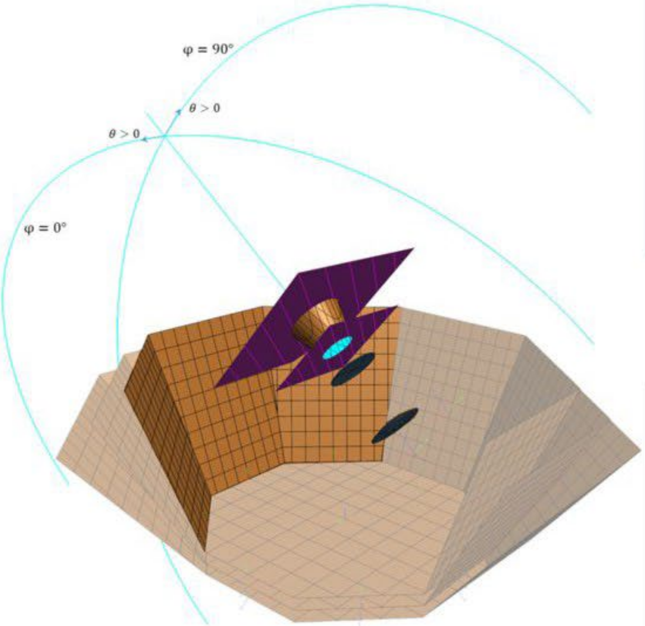
• To avoid diffraction on

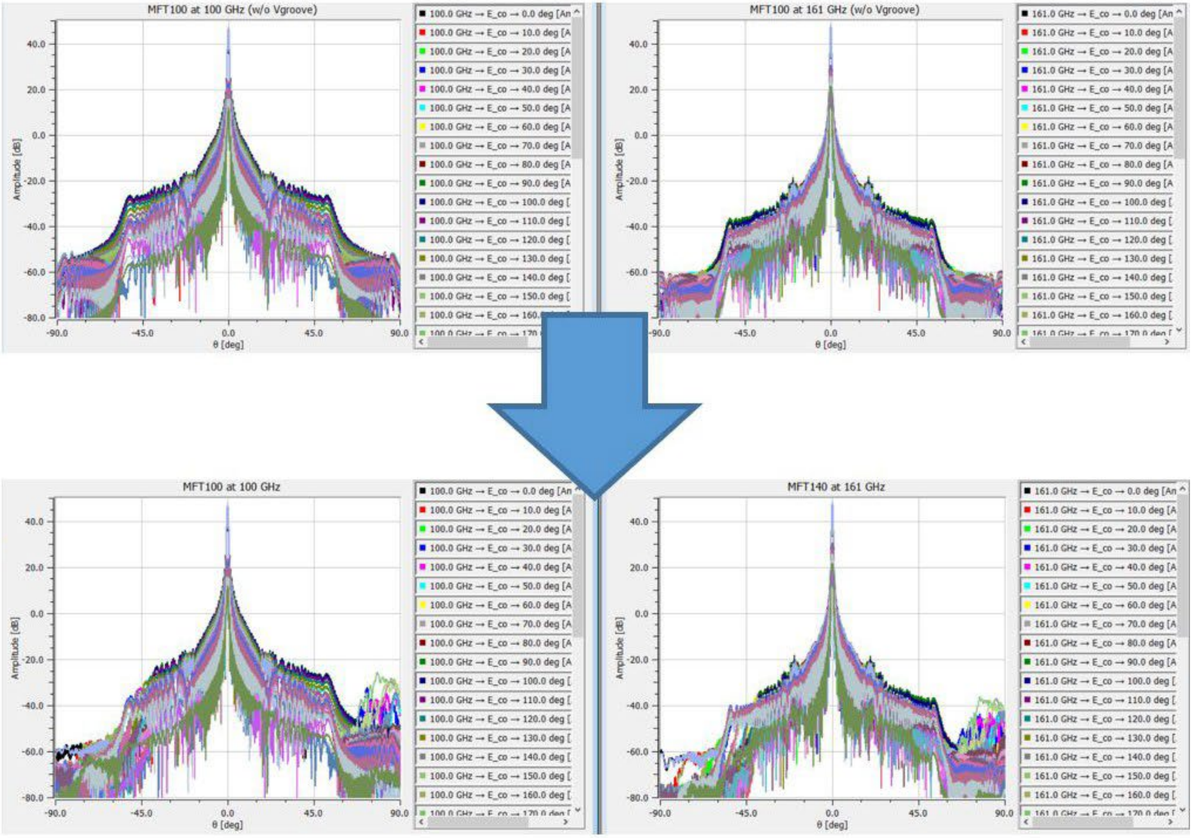
Example of FB flare angle impact for MFT off-axis pixel at 88.5 GHz





GRASP (V-groove closest panels)

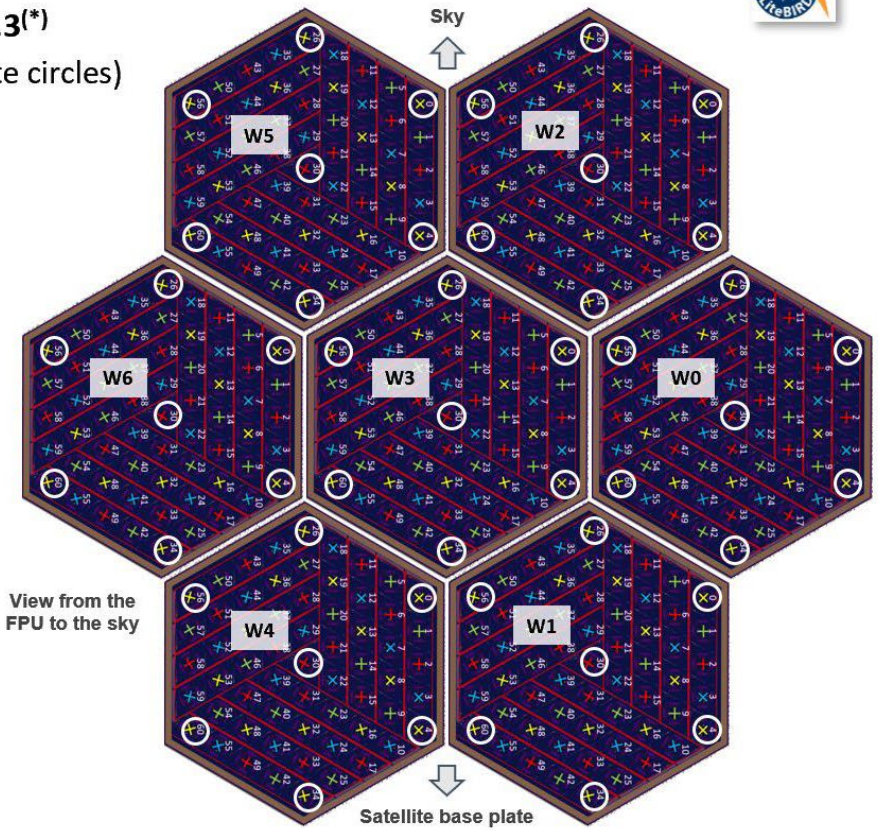




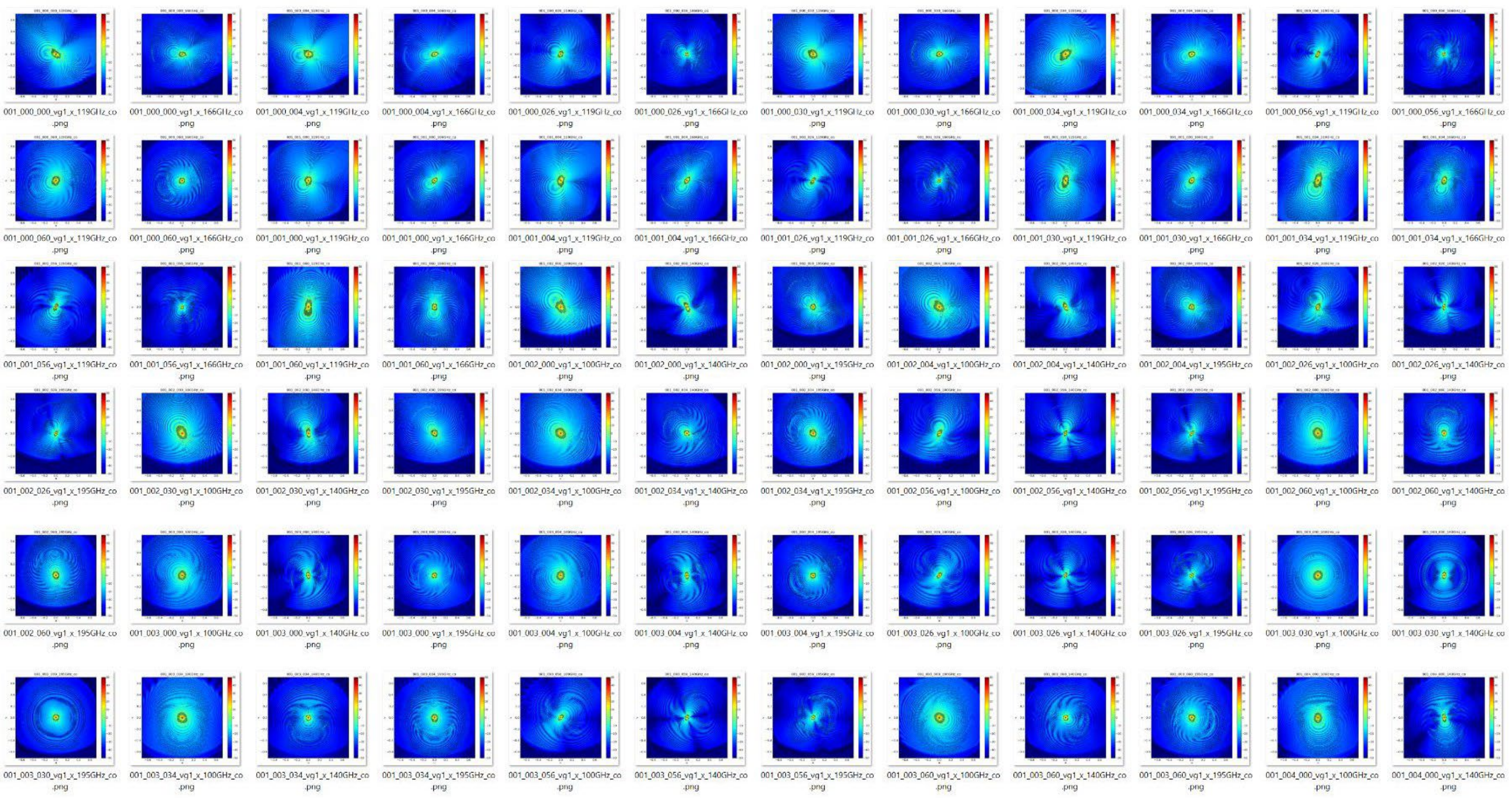
GRASP (beams and illumination across FP)

MFT focal plane configuration

- **FPU configuration reported in IMo version 1.3(*)**
  - 7×7 pixels sampled on the focal plane (white circles)
    - 001_00X_**000**_YYY
    - 001_00X_**004**_YYY
    - 001_00X_**026**_YYY
    - 001_00X_**030**_YYY (center pixel of the wafer)
    - 001_00X_**034**_YYY
    - 001_00X_**056**_YYY
    - 001_00X_**060**_YYY
  - X = wafer number, YYY = frequency
- **Di-chroic and tri-chroic channels**
  - **W0** : 119 – 166 GHz
  - **W1** : 119 – 166 GHz
  - **W2** : 100 – 140 – 195 GHz
  - **W3** : 100 – 140 – 195 GHz
  - **W4** : 100 – 140 – 195 GHz
  - **W5** : 119 – 166 GHz
  - **W6** : 119 – 166 GHz



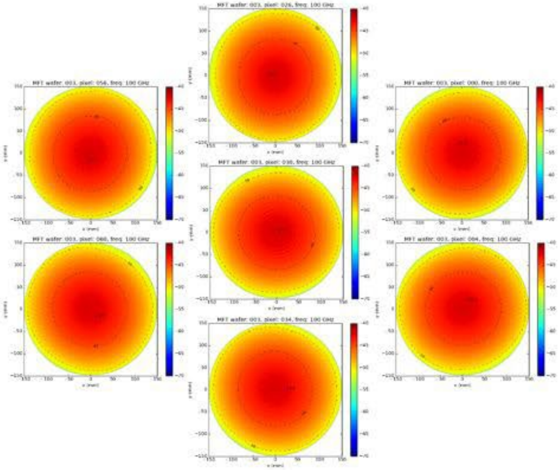
GRASP (beams and illumination across FP)



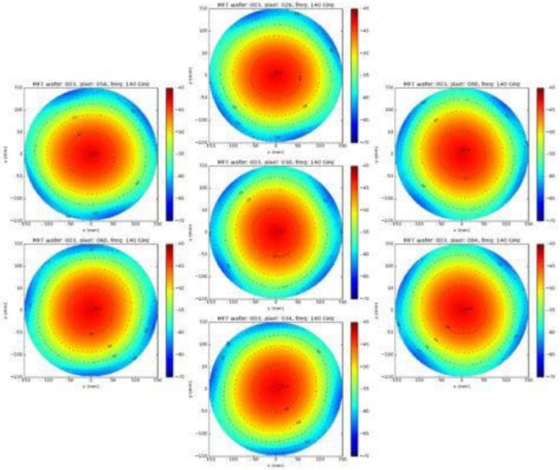
Evaluation of the aperture efficiency

- **Comparison between pixels of the same wafer W3 (center wafer)**
  - "Illumination" does not greatly depend on the position of the pixel on the wafer

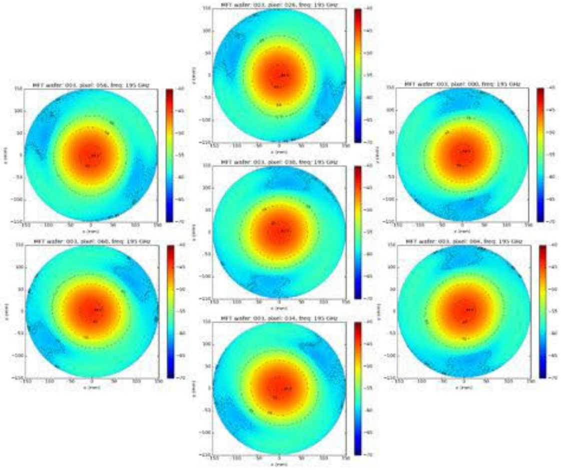
100 GHz



140 GHz



195 GHz



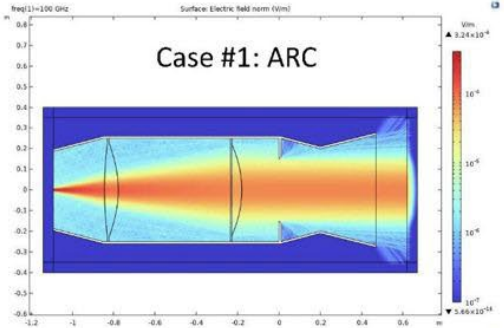
  - Similar comparisons can be done between pixels across different di/tri-chroic wafers
  - Frequency has major impact on the illumination of the aperture stop

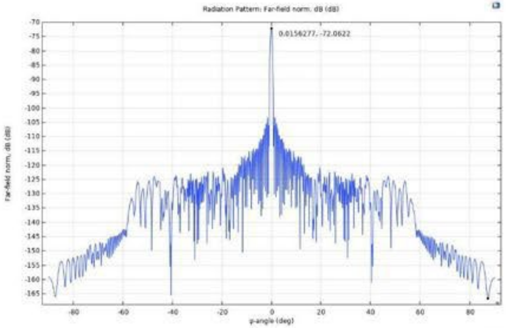
COMSOL 2D Model Simulations

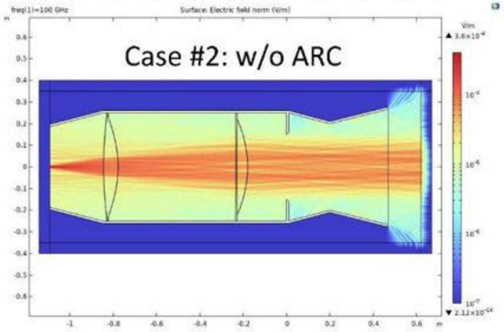
- **2D model implemented with Comsol MultiPhysics (Alexey)**
- **Optical simulations combined with thermal-mechanical modeling**
- **Study of several features and characteristics of the MFT optics:**
    - Optical response for on-axis and off-axis pixels (to be validated/compared with/to GRASP)
    - Forward illumination
    - Effect of lenses ARC
    - Temperature-dependent refractive index *n*(T)
    - Effect of tube walls absorber
    - Effect of forebaffle
- **Study of the "cold optics"**

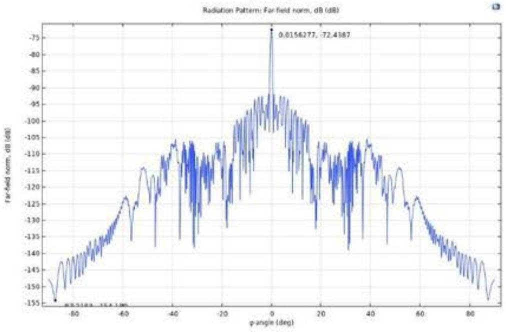
COMSOL 2D Model Simulations

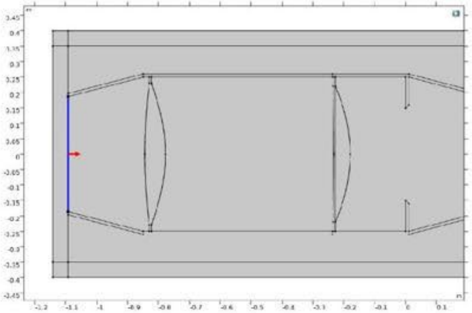
WO Simulations: FP Reflection +/- ARC





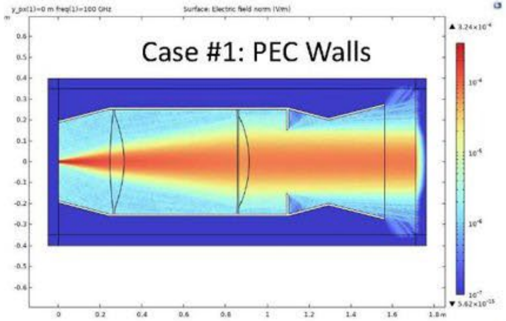


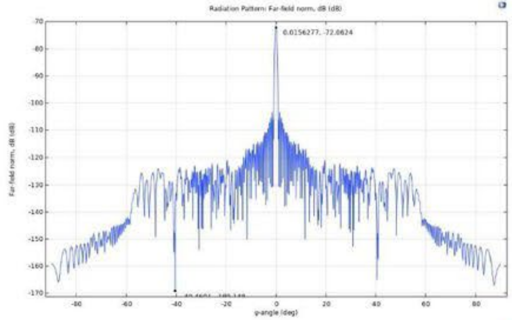


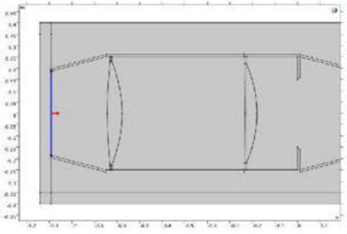


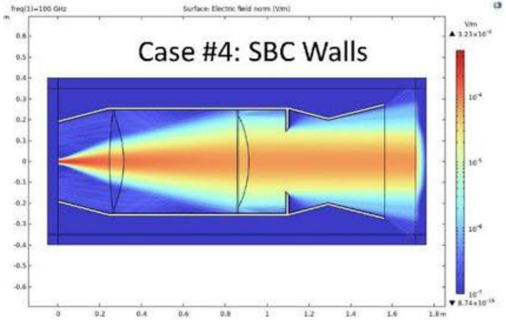
COMSOL 2D Model Simulations

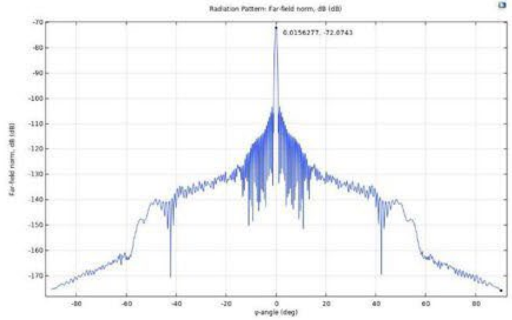
WO Simulation: Wall Absorber (SBC)











FWHM beamwidth:

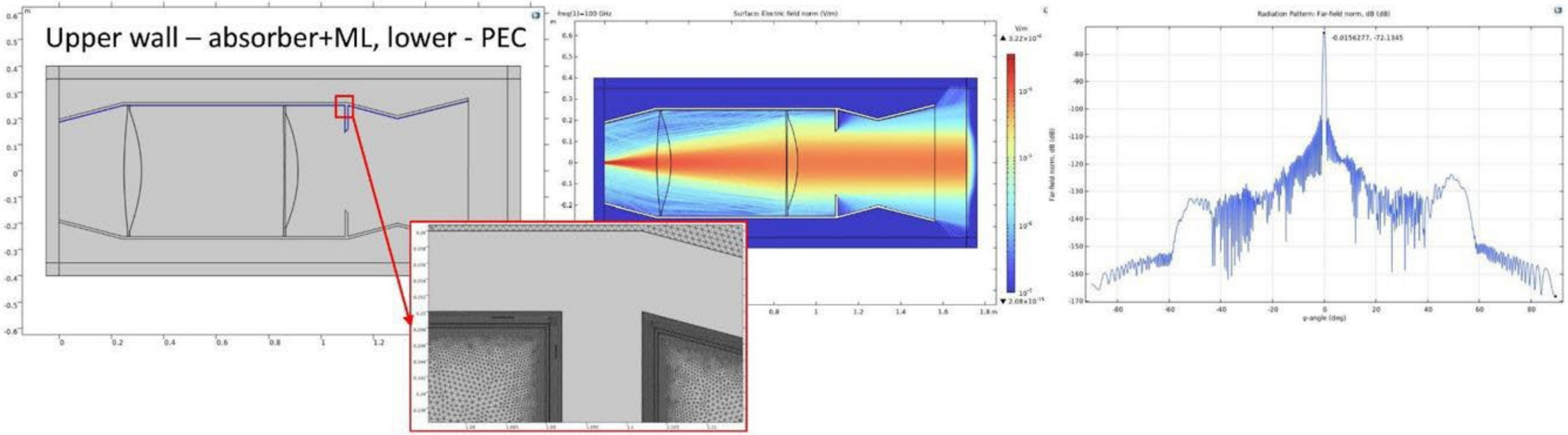
- Case #1 = 0.6690;
- Case #4 = 0.6665.

COMSOL 2D Model Simulations

WO Simulation: Wall Absorber - I

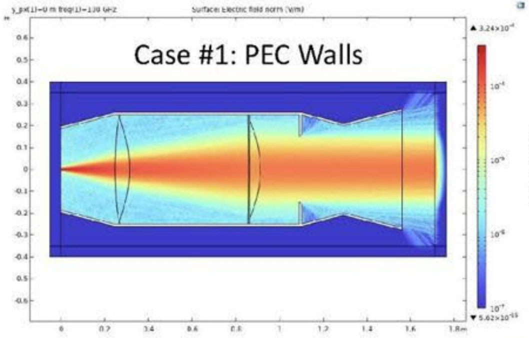
Absorber model (Bin Xiao, et al., "Epoxy-Based Ceramic-Polymer Composite with Excellent Millimeter-Wave Broadband Absorption Properties by Facile Approach," Adv. Eng. Mater. 2019, 21, 1900981):

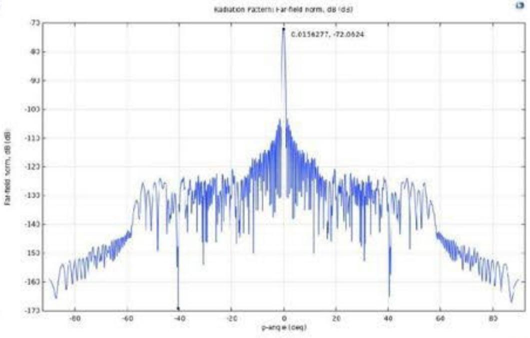
- Wall absorber (epoxy + 60% BNFO): ε_a=6.3+i1.5; μ_a=0.82+i0.5; $t_a=5*\lambda_0/4/\mathrm{SQRT}(|\varepsilon_a||\mu_a|)\approx$ 1.5 mm (subopt.);
- Wall absorber matching layer: $n_{aML}=\mathrm{SQRT}(\mathrm{SQRT}(|\varepsilon_a||\mu_a|))$; $t_{aML}=\lambda_0/4/\ n_{aML}\approx$ 0.48 mm (subopt.).



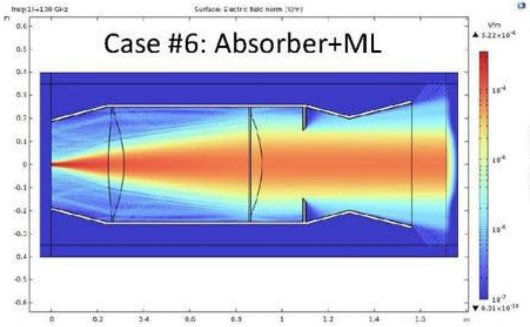
COMSOL 2D Model Simulations

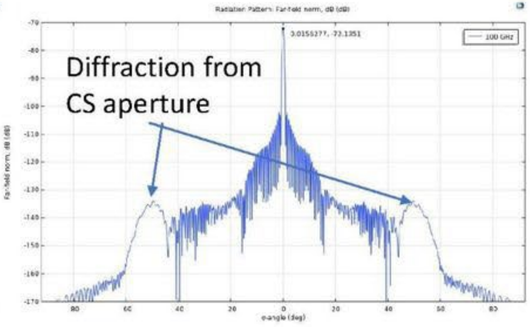
WO Simulation: Wall Absorber - II



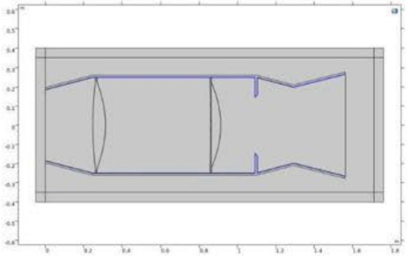


Beamwidth 0.669 deg.



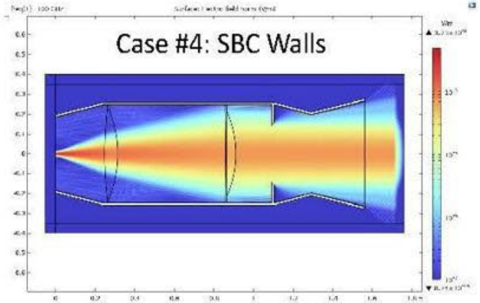


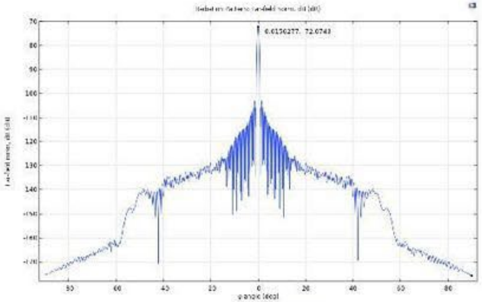
Beamwidth 0.678 deg.



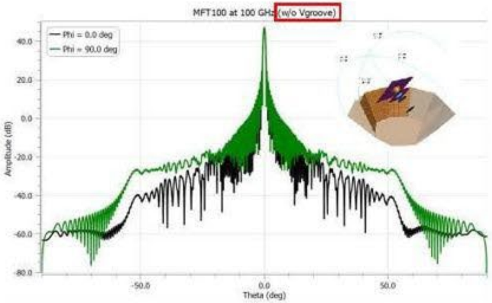
COMSOL 2D Model Simulations

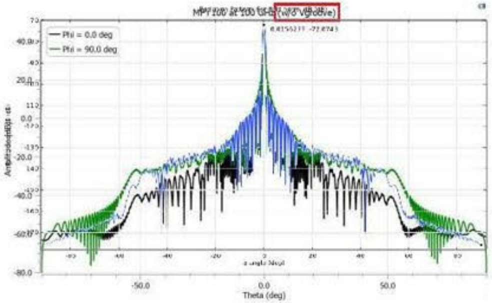
WO Simulation: Comparison with PO (I)





This work, E-plane beampattern at 10GHz with SBC walls





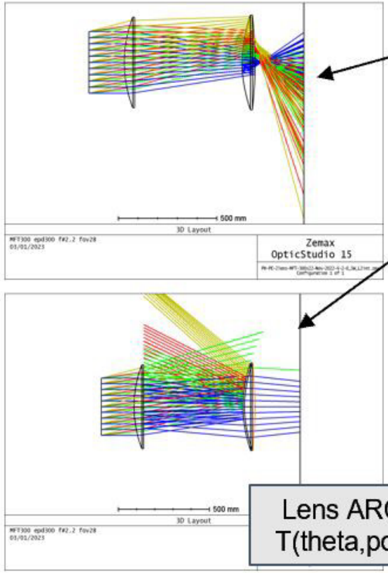
Lamagna, L., et al. "Optical modeling for the LiteBIRD Medium and High Frequency Telescope", Proc. SPIE 2022

Other on-going activities

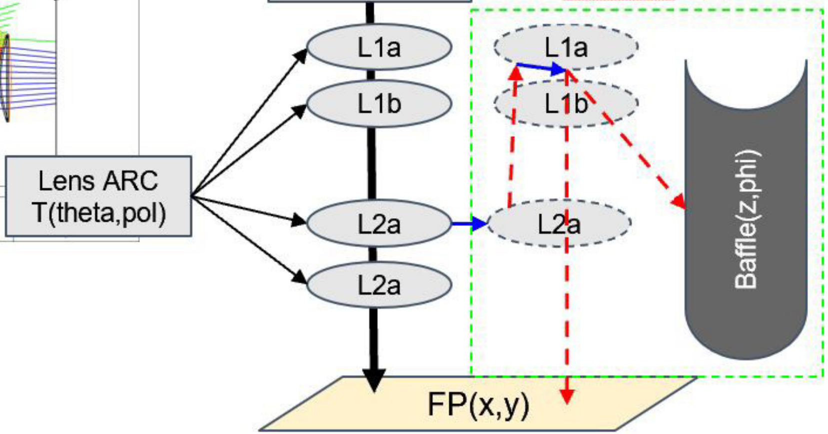
- **Analysis of expected spectrally-weighed optics-induced straylight and unwanted reflections**

Utility and Relevance:

- Ghost analysis from double reflections within optics
- Straylight mitigation importance mapping of optics baffle tube
- Estimation of straylight and ghosts as a function of filter-positions
- Preliminary estimation of optics chromatic aberration (distribution with FP)
- Multiple-reflection induced far-side-lobes
- First order side-lobe frequency dependence



G.Savini – UCL – Started on 10th January 2023



- **Reprise and expand first iteration independently done by MarcoDP**
- **Formalism consolidation underway.**
- **Some numerical machinery to develop.**
- **Inputs and confirmation needed about filter locations, ARC spectral efficiencies, etc.**

MHFT - Status of RF calibration studies

on behalf of and with contributions from the RF-cal team
(Meeting LB Italia LNF 2023/05/23)

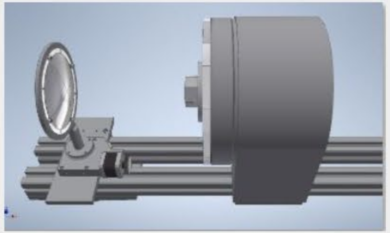
Breadboard models (CF, MDP, BrunoM, ++)

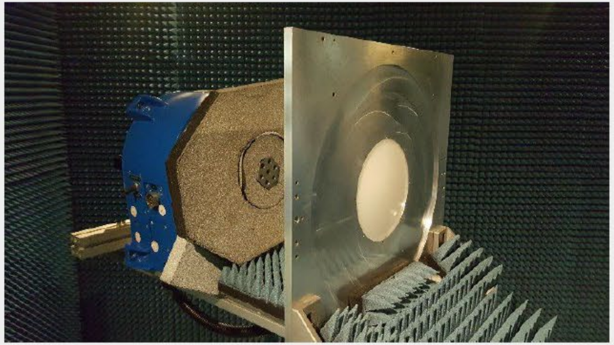
- Purpose of the breadboards
  - LiteBIRD MHFT optics is based on refractive optics
    - Modeling is not as understood/accurate than reflective optics
    - Additional parameters (losses, refractive index, higher reflections) affecting the beams
  - Need to check the accuracy of simulations & measurements agreement
  - Getting used to such measurements
  - Which measurement method is best?
  - Which accuracy can be achieved?
  - Define a validation/calibration strategy for the future models (EM, QM, FM) for warm and cold measurements

MHFT RF Breadboard models: simple → more complex

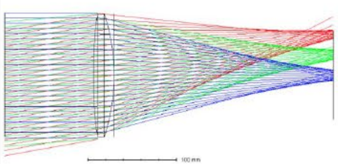
BreadBoard 1

- W-Band (75 - 110 GHz)
- Horn + lens system (recycled)
- 2 different corrugated horns used
- Lens ⌀ = 138.7 mm
- Effective Focal Length = 210.4 mm
- HDPE without anti-reflection coating





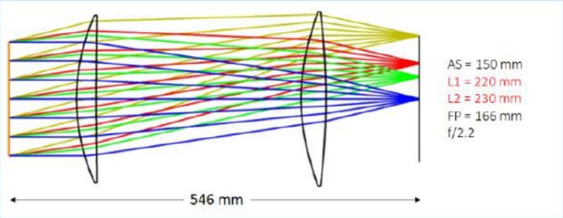
BB1 model with Zemax

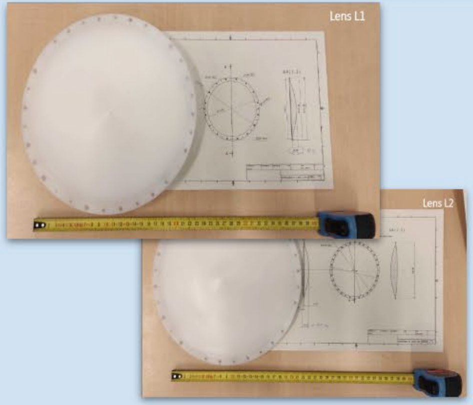


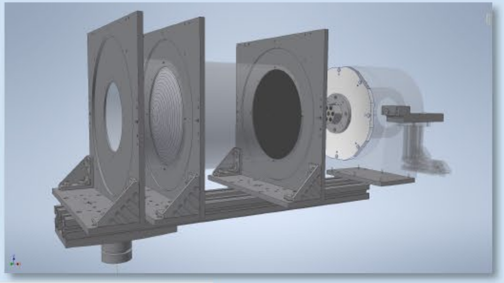
BB1 model with GRASP

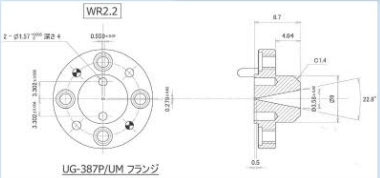
BreadBoard 2

- 2 lens system
- Scaled version of the MFT optics by a factor ½
- 180 - 440 GHz
- Lenses (HDPE without A/R coating)







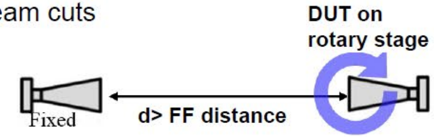


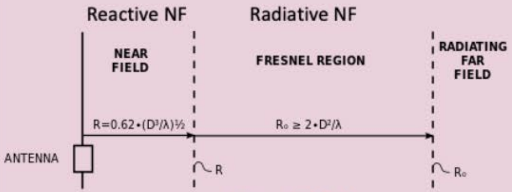
Feedhorns on order to cover the full band

Measurement facilities and Methods at Uni-Milano and IAS

Method 1: Direct Far field measurement

- For small apertures only
- Beam cuts

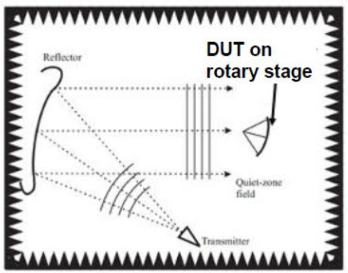


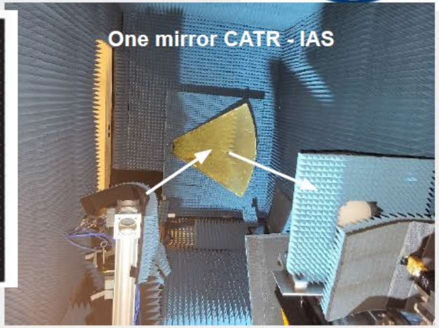


For BB1

Freq.	Reactive / Radiative NF	Near Field / Far Field
75 GHz	52 cm	9.95 m
90 GHz	57 cm	11.94 m
110 GHz	63 cm	14.59 m

Method 3: Far field with CATR:

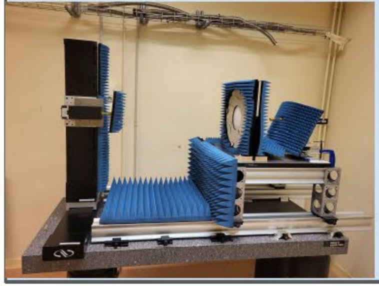


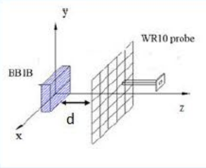


Creation of collimated beam and Quiet Zone for DUT

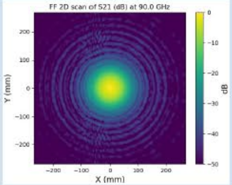
All measurements are based on the use of VNAs (Vector Network Analyser)

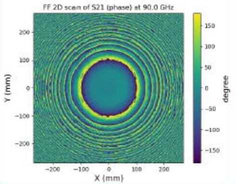
Method 2: Near Field measurement to Far Field transformation: needs amplitude AND phase

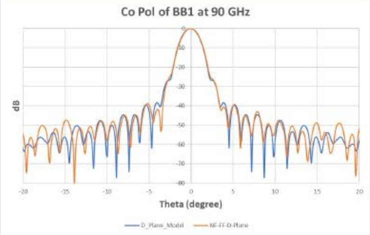




Map of the beam (Amp & Phase)







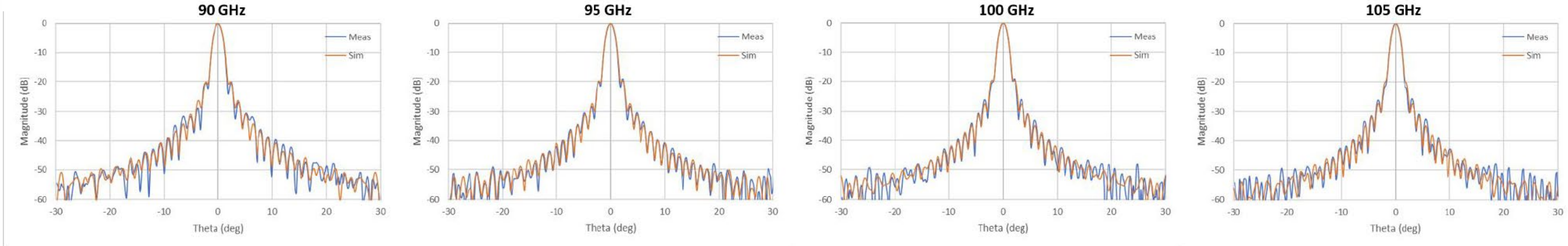
Planarity check at the base (Δs < 3 μm)

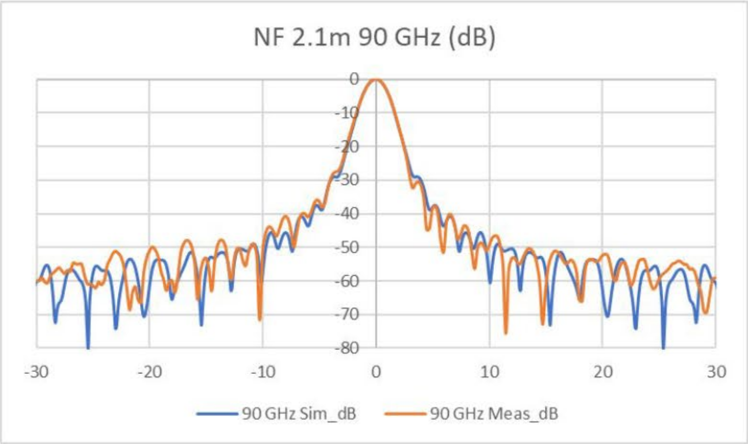
Near-Field scanner

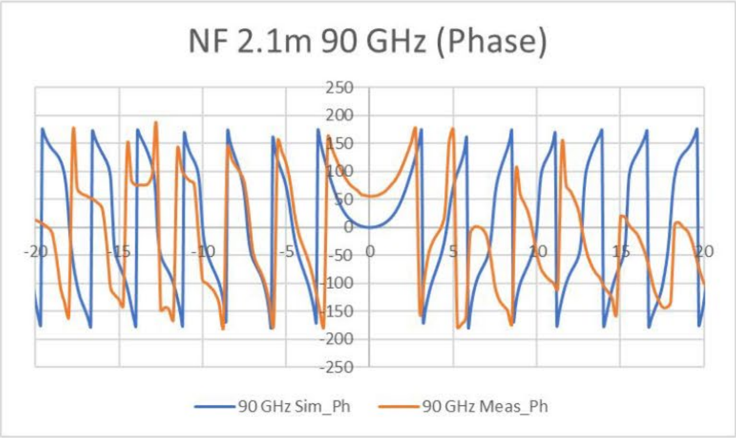
CNES KP, 23rd March 2023

Summary of results so far - Method 1: (intermediate field)

- BB1 test campaign in the "intermediate" field (about ⅓ of the far field distance)



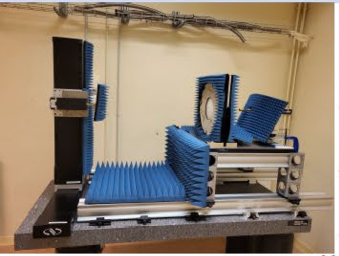


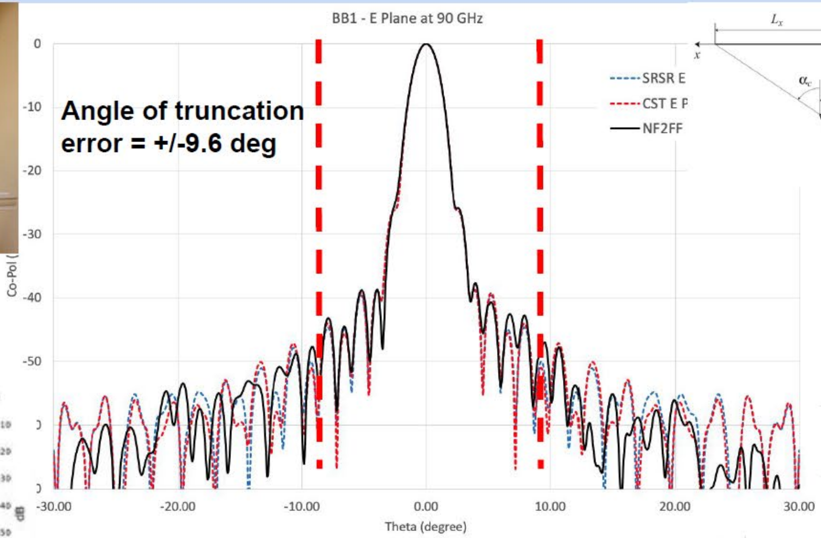


Results for

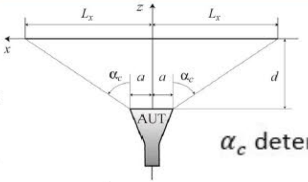
- 2 configurations
  - different horns
- 2 different facilities
  - UniMilano & IAS

Summary of results so far - Method 2: Near Field





Angle of truncation error = +/-9.6 deg

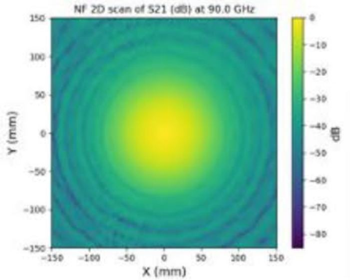


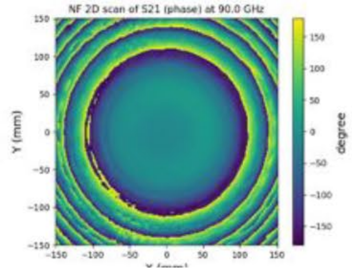
$$-\alpha_c \le \alpha \le \alpha_c$$

$$\alpha_c = \tan^{-1}\left(\frac{L_x - a}{d}\right)$$

α_c determine the angular zone that is free of truncation error

- < ±0.1 dB from 0 dB down to -20 dB
- Up to a few dBs from -20 dB down to -40 dB
- Up to +/- 3 dB from -40 dB down to -60 dB



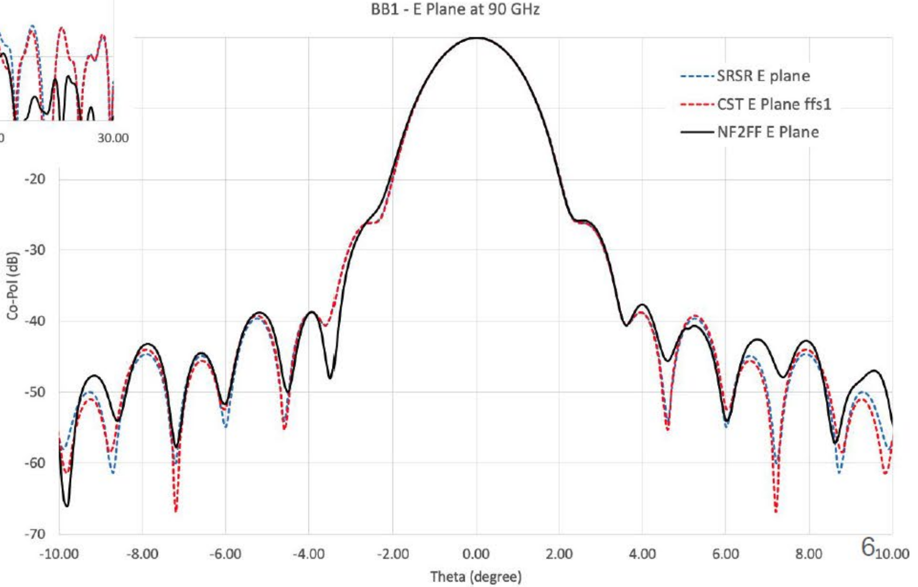


NOTE for refractive system:

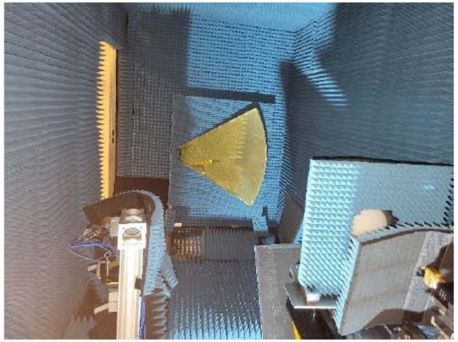
- Differences between models
- Beam shape very sensitive to refractive index
- Beam shape very sensitive to misalignment

For the future:

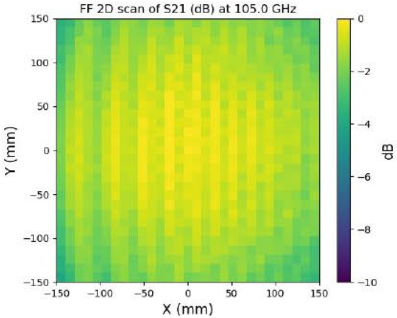
alignment needs to be better



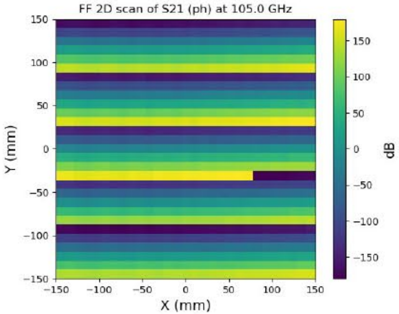
Summary of results so far - Method 3: CATRs

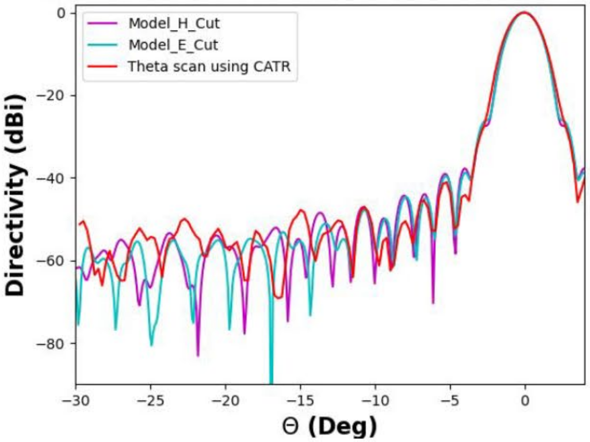


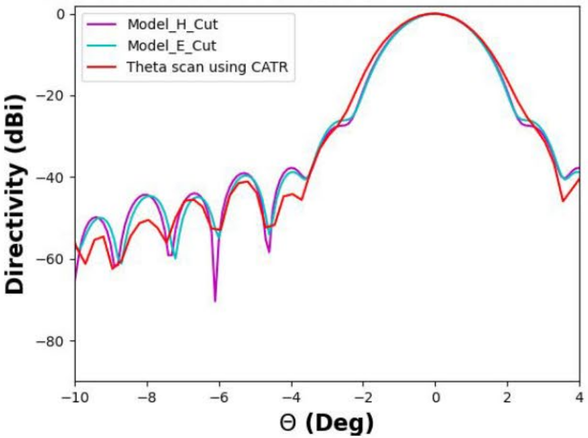
Quiet zone characterisation



Alignment to be improved

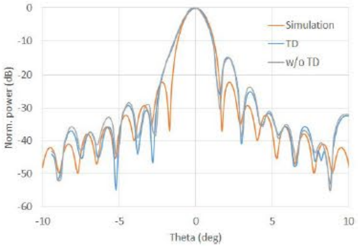






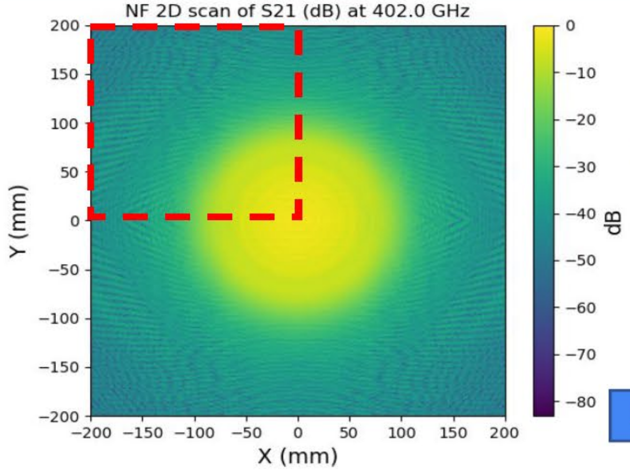
<u>CATR at UniMi</u>

- R.m.s. accuracy of the reflectors surface does not allow measurements at BB1 frequencies
- We measured the BB1 but several artifacts are shown even at the main beam level



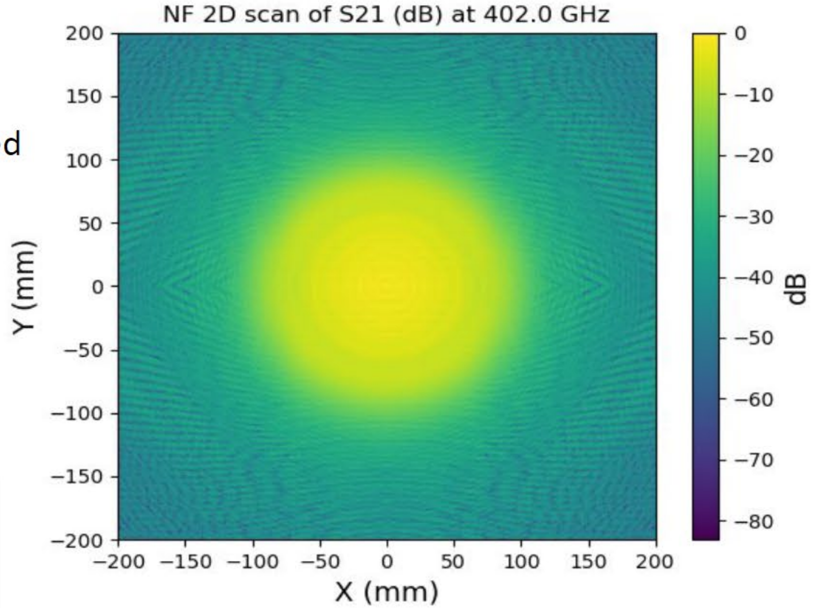
- A new CATR (~ 2m x 2m) is being developed for high frequency operation up to 500 GHz

CNES Antenna Near Field measurement (Preliminary)

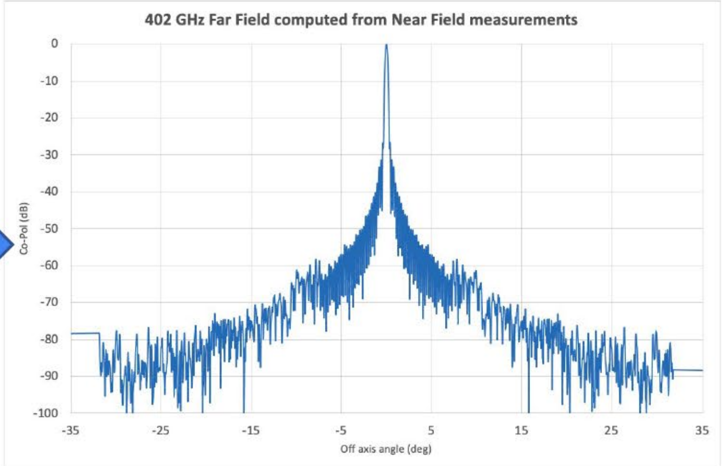


¼ of the beam measured

Full map extrapolation



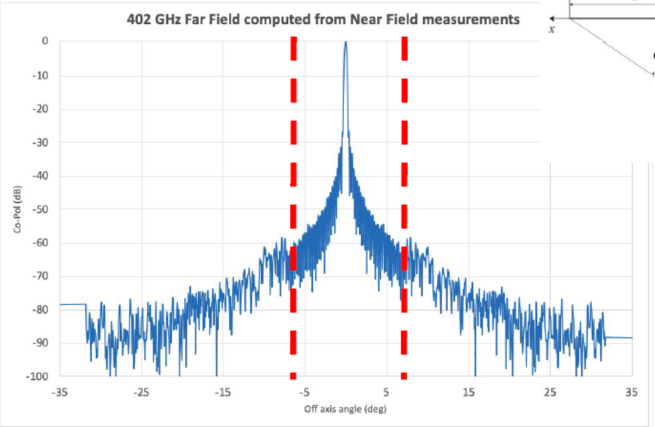
FF map reconstruction

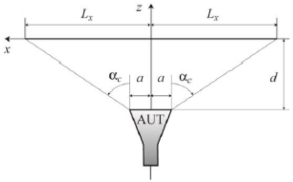


- **Sampling of 1mm > λ/2 (under sampled)**
- **λ /2 = 0.37 mm**
- **Degradation of accuracy**
- **Future meas. with better sampling**

CNES KP, 23rd March 2023

From Near Field measurement to FF reconstruction

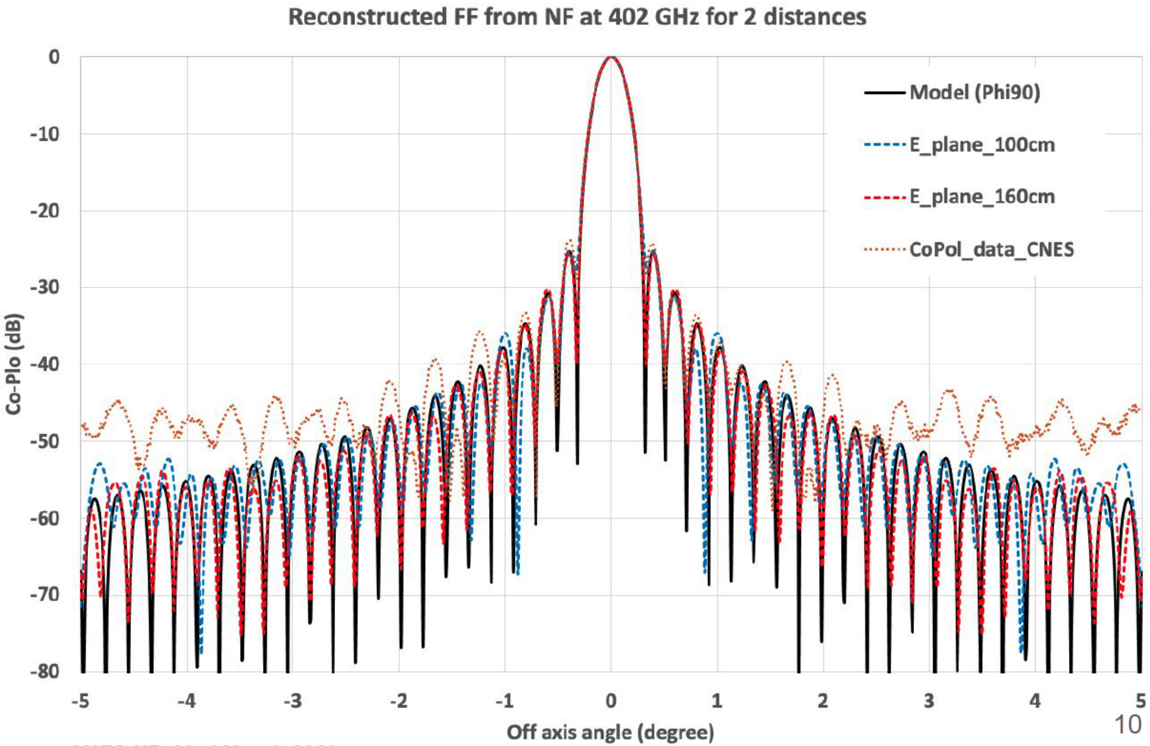




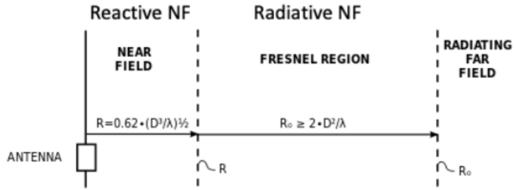
$-\alpha_c \leq \alpha \leq \alpha_c$

$\alpha_c = \tan^{-1}\left(\frac{L_x - a}{d}\right)$ α_c determine the angular zone that is free of truncation error

Limited scan span → Truncation error → +/- 5.7 deg



- **Measurements performed in the reactive field instead of the radiative field**
  - 2 distances (1m and 1.6 m)
  - Reactive/radiative limit = 2m
- **Next meas. further away**



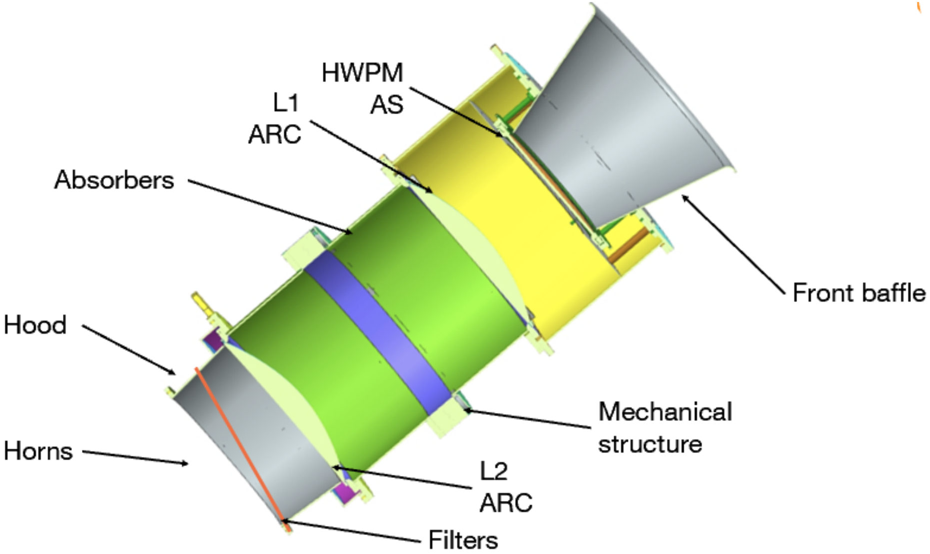
ORFPM (a.k.a. the HFT warm prototype)

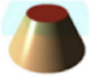
=> Focus on the high frequency telescope (HFT) as:

1/ this is where the requirement on the beam knowledge is the more stringent

2/ the CNES CATR has been tested once at those frequencies with a simple beam former (small reflective optics), so that full instrument testing requiring a larger quiet zone has to be demonstrated

=> ORFPM has to be “optically” representative of the HFT



	Front Baffle 	HWP 	HWPM 	Cold Stop	L1 	L2 	Hood 	Filters	Horns 	Detectors 	Mechanical structure 	Absorbers	Cold readout 	Warm readout 	HWPM Drivers	DPU	HK
Prototype	DM / Proto	DM / Proto	Dummy ?	DM / Proto	DM / Proto + ARC	DM / Proto + ARC	DM / Proto	DM / Proto	Dummy of beam former	Not in a first time	Limited to the tube	DM / Proto	Not in a first time	Not in a first time			

Validation of holographic beam characterization→ORFPM?

There is an international effort on various CMB experiments to develop alternative techniques for beam measurements based on **near field radio holography**, for example see: LFT (**), LAT for Simons Observatory (*)

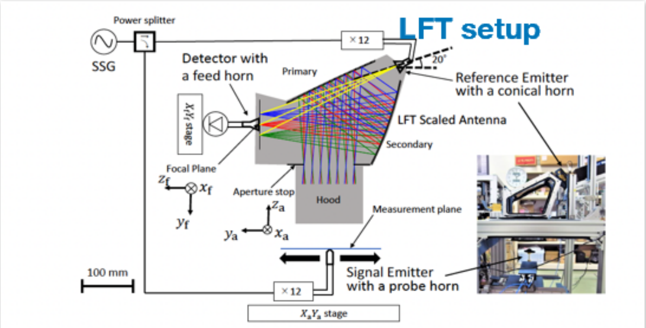


Fig 2 Experimental setup for holographic phase-retrieval near-field measurements for a 1/4-scaled antenna of the LiteBIRD LFT. The continuous wave from a SSG is split and multiplied to feed the signal and reference emitters. The signal emitter with a probe horn scans near the aperture. The reference emitter with a conical horn emits coherent signals toward the focal plane to create a hologram. The reference emitter is fixed between the primary and secondary mirrors, $(x_f, y_f, z_f) = (0\,\mathrm{mm}, -125\,\mathrm{mm}, -260\,\mathrm{mm})$. For this study, we used a vector network analyzer as the SSG and the detector so that we can compare the retrieved phase with vector-measured one.

R. Nakano, H Takakura, Y Sekimoto, et al., Proc. SPIE 12190 (https://doi.org/10.1117/12.2627582)

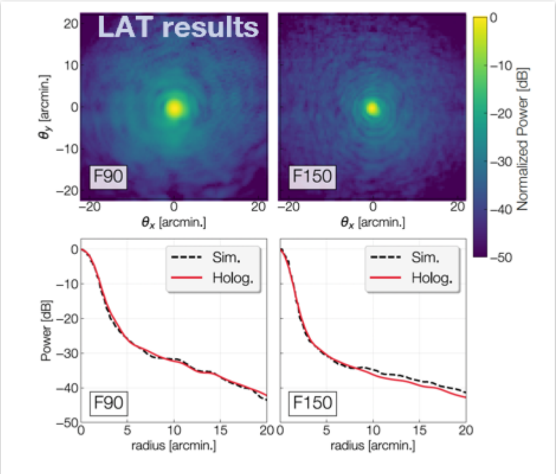


Fig. 7. Top row: Using FD, the LATRt measurements are propagated through the LAT from the near-focal plane, to the far-field. Bottom row: Radial profile of the measured(simulated) far-field beams in the F90 and F150 bands, plotted in red(black). The lack of diffraction rings in the ra-

Promising way forward for LiteBIRD, needs to be demonstrated at high frequencies

Tests planned in ISAS on LFT setup (400GHz) as soon as possible

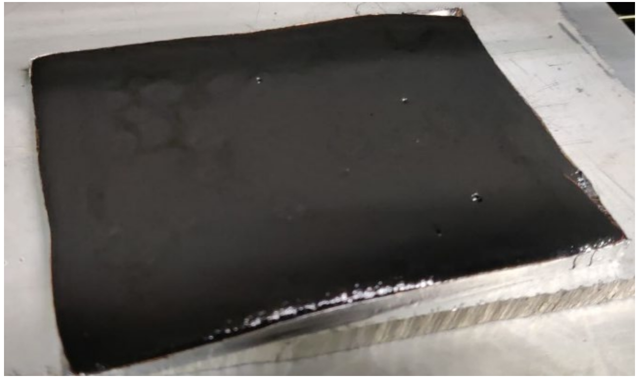
(*) Characterizing the Large Aperture Telescope Receiver with Radio Holography : https://arxiv.org/abs/2207.07040

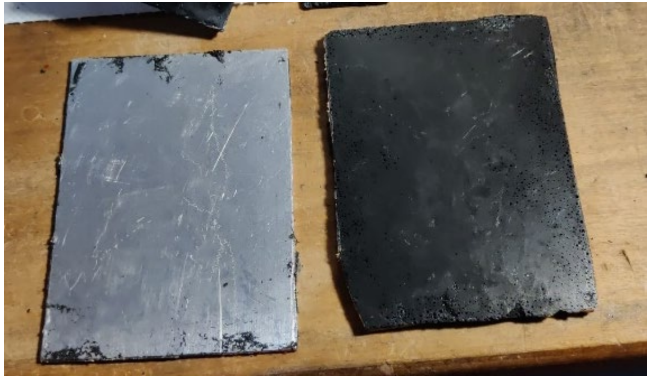
(**) A holographic phase-retrieval method of near-field antenna pattern measurement for bolometer-array-equipped millimeter-wave telescopes (Ryo Nakano et al.)

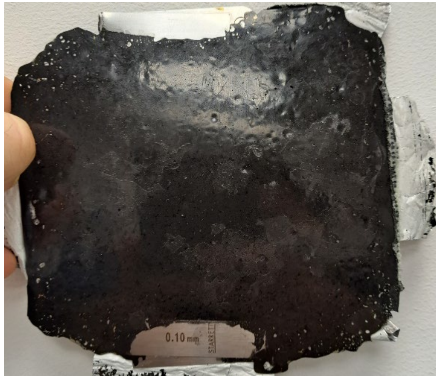
ORFPM absorber plates production and characterization at UniRM1

Recipes: Eccosorb CR110: pure, +carbon grains 500um, + carbon grains fine.
Outgassing: outgassing 10-30 minutes at 20 mbar
Curing: 65° C to 90 ° C as per datasheet curing times. **NEED TO TEST LOWER TEMPERATURES TO COMPLY WITH PLA ENVIRONMENTAL SPECIFICATIONS FOR ORFPM FOREBAFFLE.**
Detachment: huge progress with dedicated off-the-shelf silicone-free epoxy detaching wax.

- Also trying thinner (100um) controlled thickness layers to inspect mechanical robustness and repeat transmittance (loss) measurements.
- Tuned molding procedures on curved surfaces to cover ORFPM tube tiles
- Tiles delivery started. Waiting for Eccosorb CR PtB re-supply to complete the large plates.







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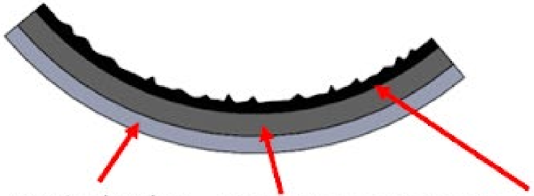
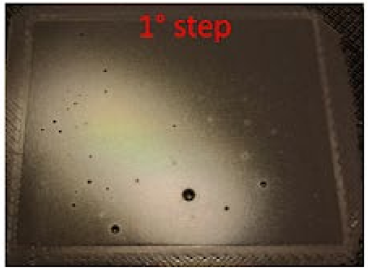
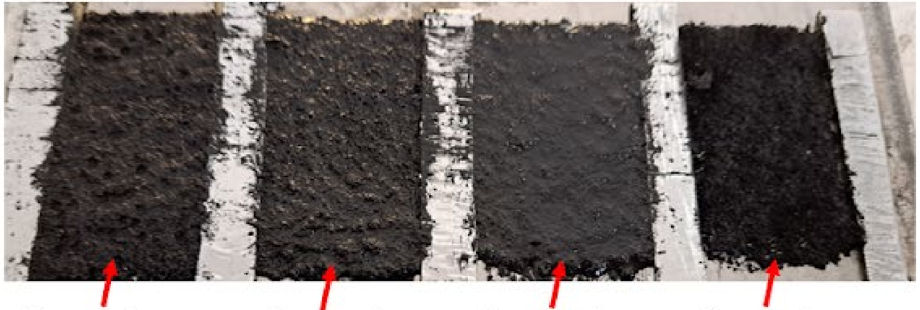
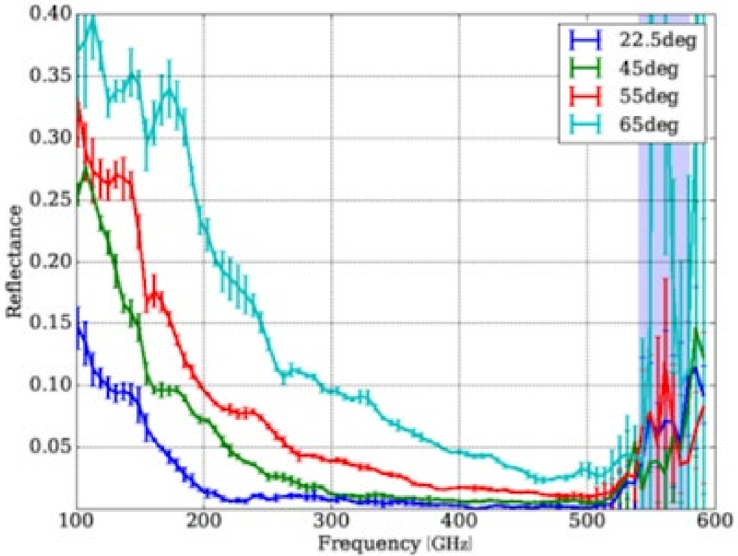






- Double layer: 2mm Pure Eccosorb + 1mm Doped Eccosorb;
- 1st Step: Produced a flat prototype (11x8cm) with first layer of Eccosorb CR110 2mm thickness;
- 2nd Step: Deposited the second layer of doped Eccosorb with 40% in weight of Carbon Black grains;
- ARC based on the surface roughness of the second layer;
- Expected low specular reflection and high scattering over a wide span of angles .

ORFPM absorber plates production and characterization at UniRM1



- Reflectance measurements for different angles: 22.5°, 45°, 55°, 65° ;
- Scattering measurements: work in progress…

Double layer: 2mm Pure Eccosorb + 1mm Doped Eccosorb;
1st Step: Produced a flat prototype (11x8cm) with first layer of Eccosorb CR110 2mm thickness;
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