Super-Resolving Toraldo Pupils for Radio Astronomical Applications

L. Olmi (INAF - OAA)

on behalf of the “PUTO” team

http://www.ifac.cnr.it/PUTO

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Physical effects limiting the resolving power of a telescope

- Optical aberrations (can be minimized by design)
- Atmospheric "seeing" (space or adaptive optics)
- **DIFFRACTION** (intrinsic to EM propag.)

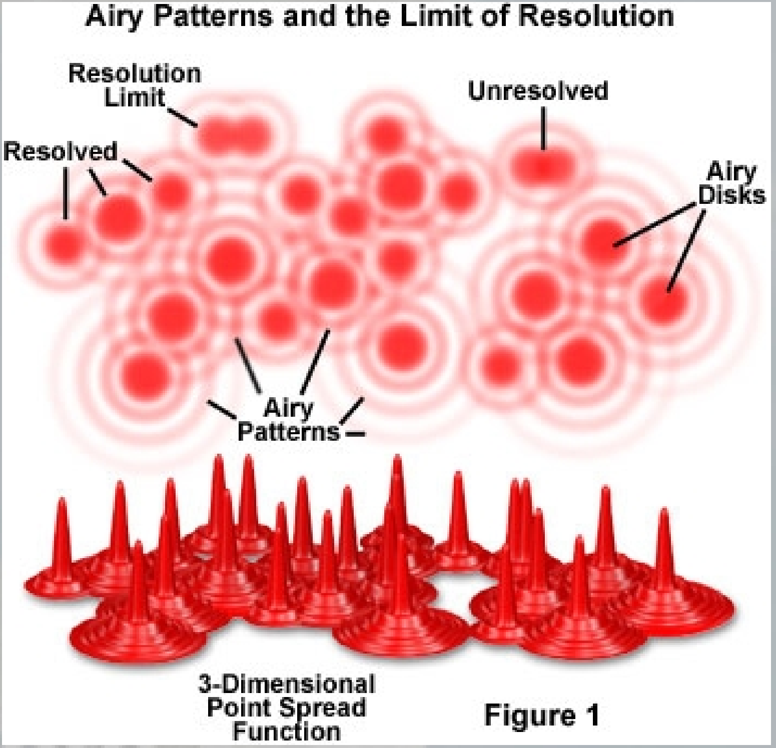

Figure 1

SUPER-RESOLUTION aims at achieving a PSF narrower than the classical diffraction limit.

Super-Resolution: active field

The Nobel Prize in Chemistry 2014
Eric Betzig, Stefan W. Hell, William E. Moerner

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The Nobel Prize in Chemistry 2014

Photo: A. Mahmoud
Eric Betzig
Prize share: 1/3

Photo: A. Mahmoud
Stefan W. Hell
Prize share: 1/3

Photo: A. Mahmoud
William E. Moerner
Prize share: 1/3

The Nobel Prize in Chemistry 2014 was awarded jointly to Eric Betzig, Stefan W. Hell and William E. Moerner *"for the development of super-resolved fluorescence microscopy".*

4. Conclusion

Petrin (2010)

In this chapter it was proved the fundamental result of diffraction theory: *for any focusing system the existence of singularity at image point of a point source is impossible in principle.* The result was illustrated for the important focusing system consisted of a layer of material with negative refraction (the superlens).

Published online 8 July 2011 | Nature | doi:10.1038/news.2011.406

News

Soft-drink cans beat the diffraction limit

To focus sound to a point, all you need is a thirst for fizzy drinks.

Jon Cartwright

Sound, like light, can be tricky to manipulate on small scales. Try to focus it to a point much smaller than one wavelength and the waves bend uncontrollably — a

A&A 561, A118 (2014)
DOI: 10.1051/0004-6361/201322665
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Astronomy & Astrophysics

Beating the diffraction limit in astronomy via quantum cloning

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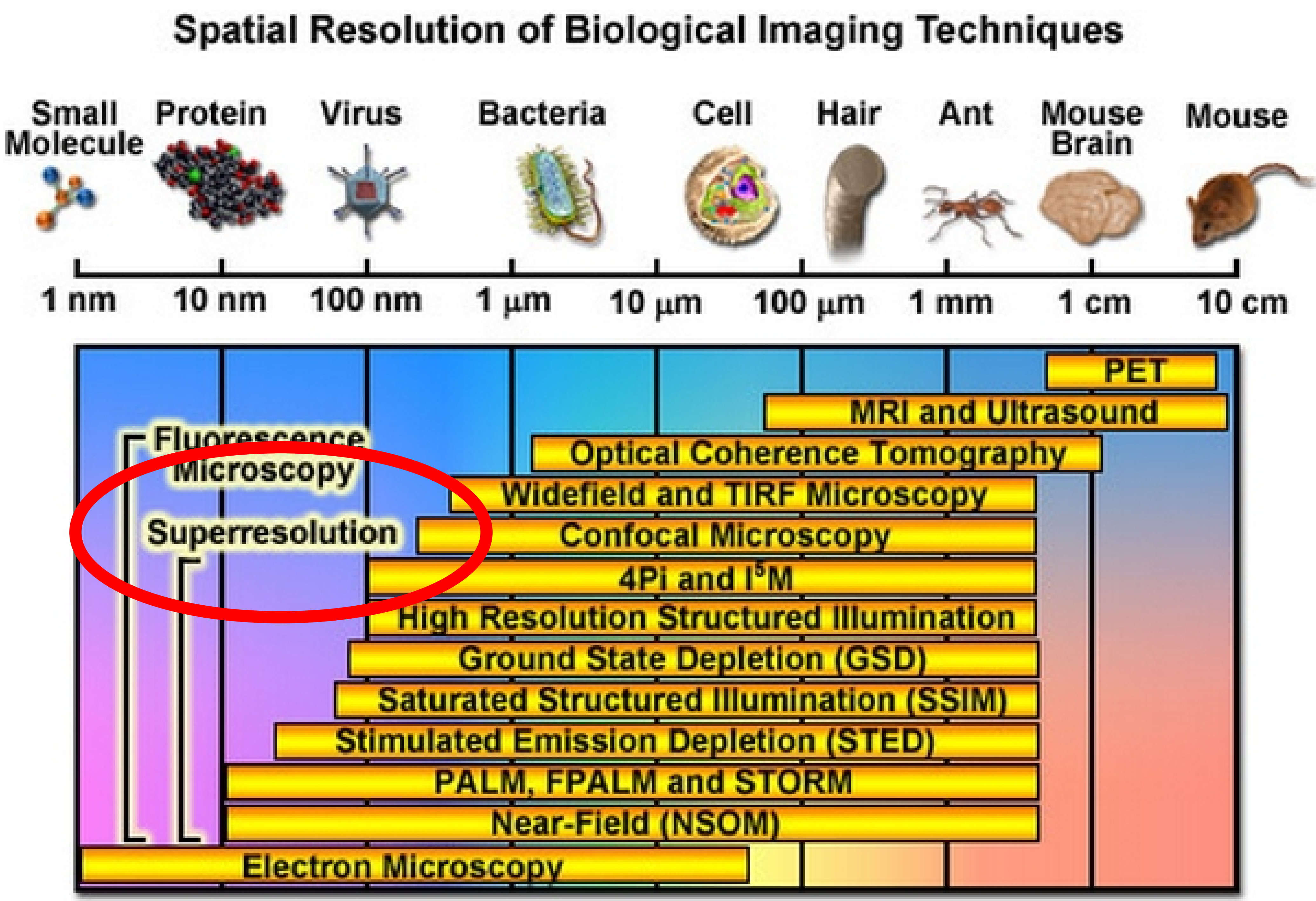
SCIENTIFIC REPORTS

OPEN

Super-resolution optical telescopes with local light diffraction shrinkage

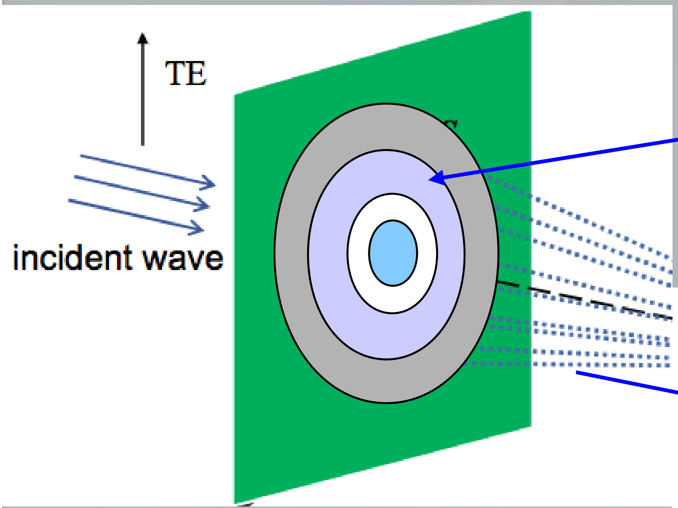
Changtao Wang[1,*], Dongliang Tang[1,2,*], Yanqin Wang[1,*], Zeyu Zhao[1], Jiong Wang[1], Mingbo Pu[1], Yudong Zhang[1], Wei Yan[1], Ping Gao[1] & Xiangang Luo[1]

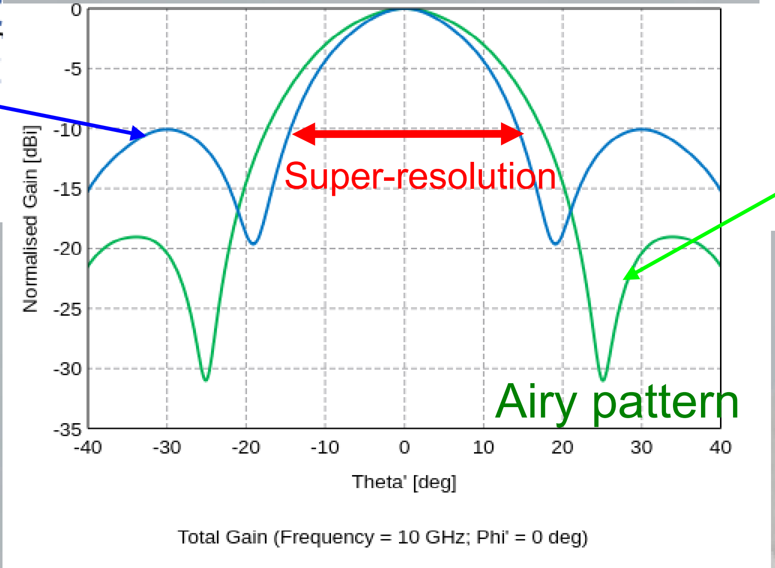


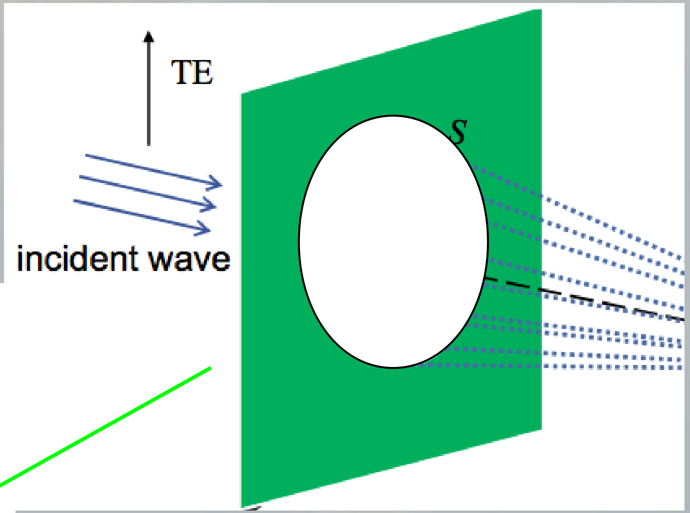
Spatial Resolution of Biological Imaging Techniques
Small Molecule
Protein
Virus
Bacteria
Cell
Hair
Ant
Mouse Brain
Mouse
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
PET
MRI and Ultrasound
Optical Coherence Tomography
Fluorescence Microscopy
Widefield and TIRF Microscopy
Superresolution
Confocal Microscopy
4Pi and I⁵M
High Resolution Structured Illumination
Ground State Depletion (GSD)
Saturated Structured Illumination (SSIM)
Stimulated Emission Depletion (STED)
PALM, FPALM and STORM
Near-Field (NSOM)
Electron Microscopy

Toraldo Pupils

G. Toraldo di Francia (1952) recognized that an array of concentric finite coronae (providing 0º or 180º phase delay) can sharpen up the central lobe of the PSF at the expense of increased side-lobe strength.

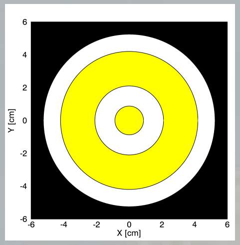






Clear aperture

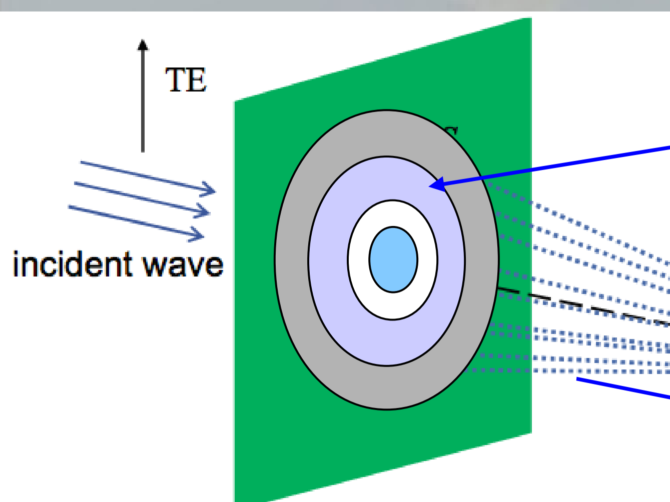
Multiple coronae (binary phase mask)



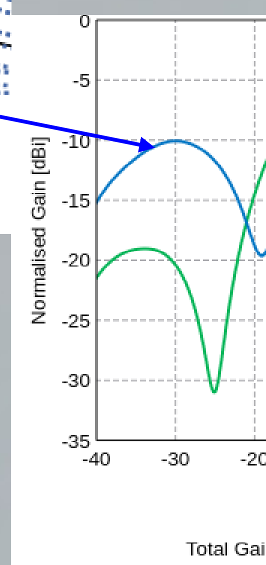
TP4

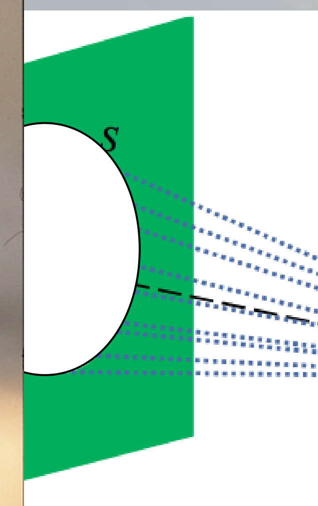
Toraldo Pupils

G. Toraldo di Francia (1952) ... oncentric finite coronae (providing 0º or ... n up the central lobe of the PSF at ... side-lobe strength.



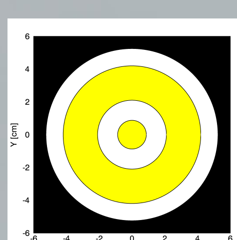
Complex





erture

Multiple coronae
(binary phase mask)



TP4

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Toraldo Pupils in the Microwave Frequency Range

2003: First laboratory demonstration of super-resolution achieved with Toraldo Pupils in the microwave range (Mugnai et al., *Phys. Lett. A*, 2003).

2015: Start project "PUTO" devoted to study the implementation of Toraldo Pupils on radiotelescopes:

- EM numerical simulations (Olmi et al., SPIE vol. 9906, 2016) (Olmi et al., *Appl. Opt.*, subm.)
- Laboratory measurements (Olmi et al., *Exp. Astr.*, 2017)
- Prototype fabrication and test (in progress)
- Development of metamaterial-based TPs

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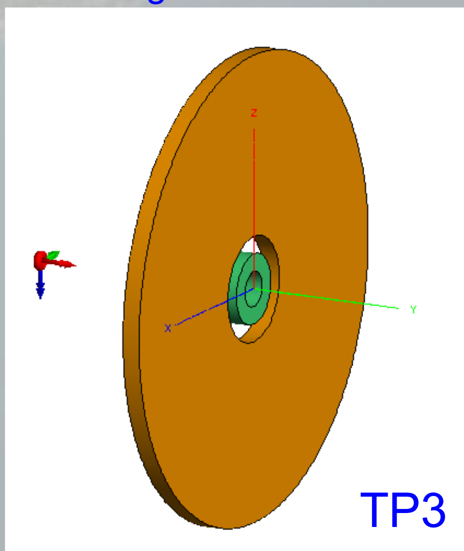
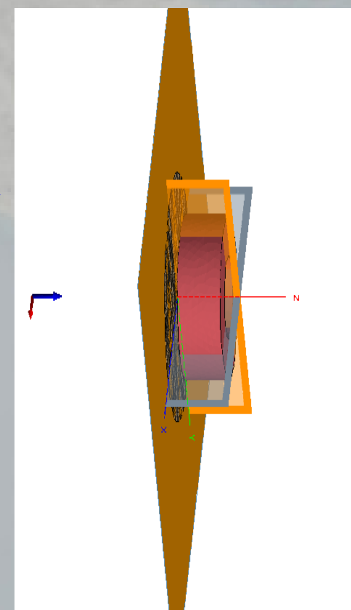
Toraldo Pupils: FEKO* EM simulations

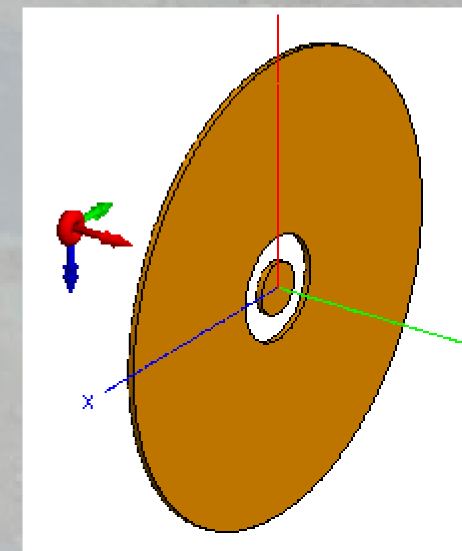
Conducting finite screen & dielectric

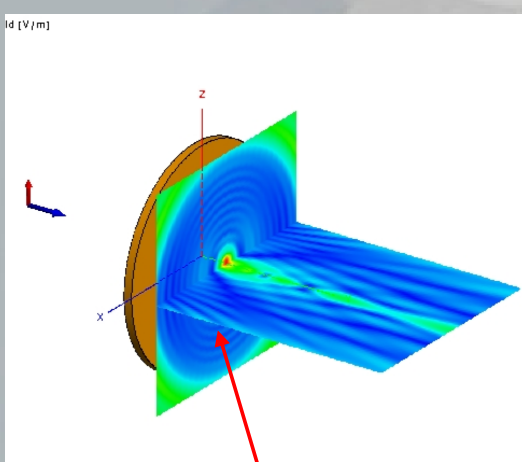


PMLS & dielectric



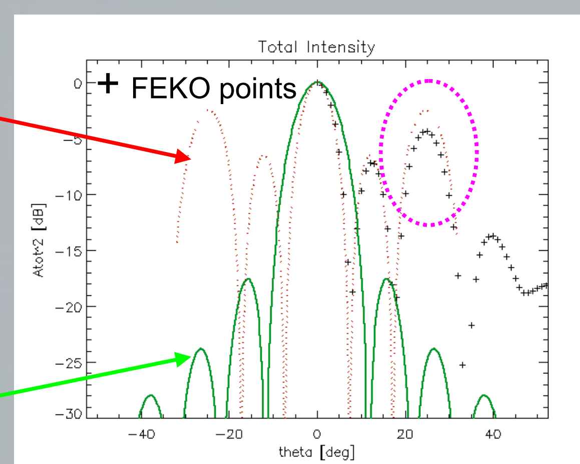
Overlapping individual fields

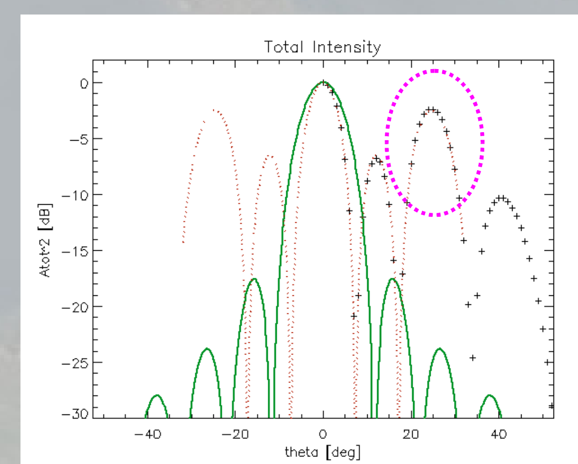




TP3 Analytic model

Clear aperture





* https://www.feko.info/

(Olmi et al., SPIE vol. 9906, 2016)

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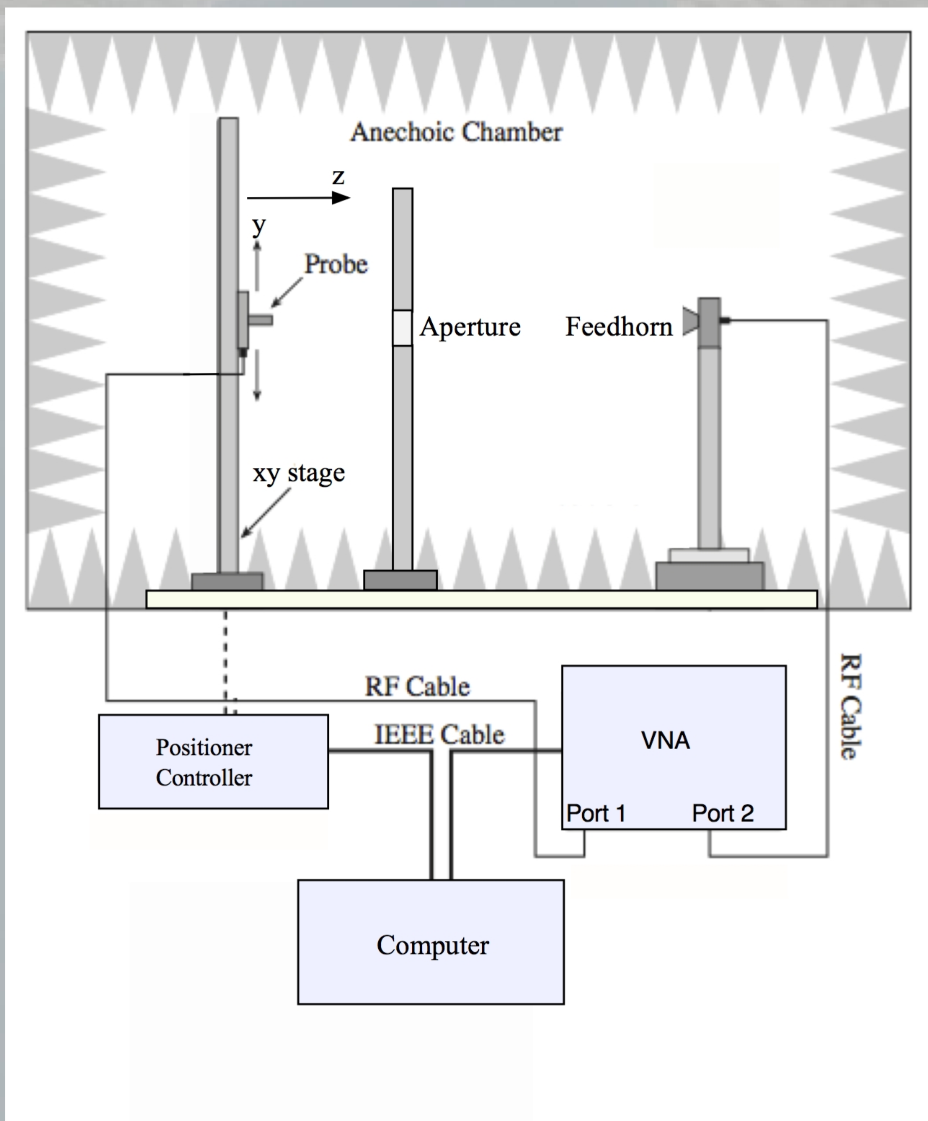
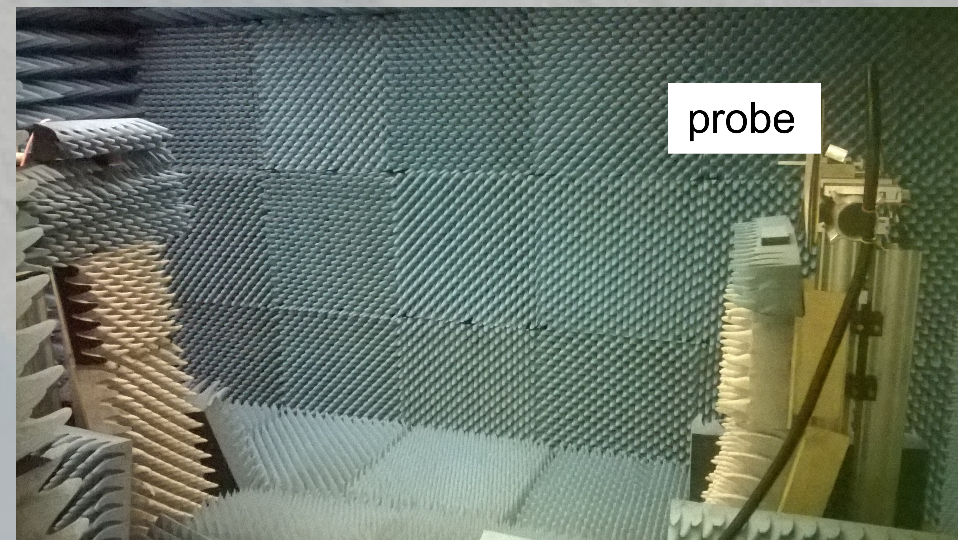
Laboratory Measurements

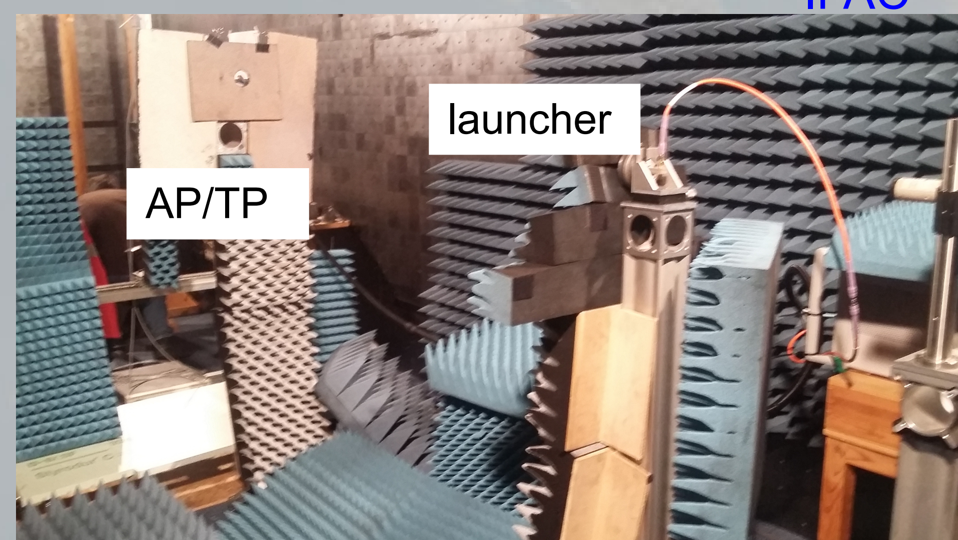


(Olmi et al., *Exp. Astr.*, 2017)

Arcetri



IFAC



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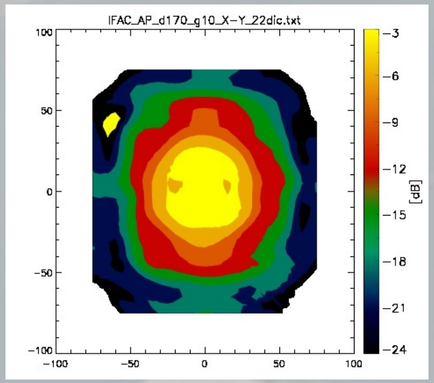
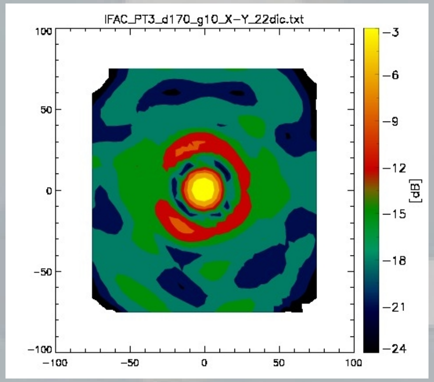
Laboratory Results

Near field

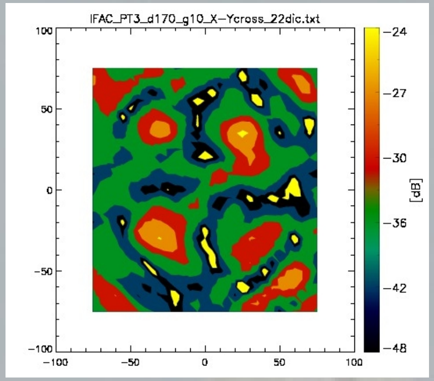
AP



TP3
Co-pol



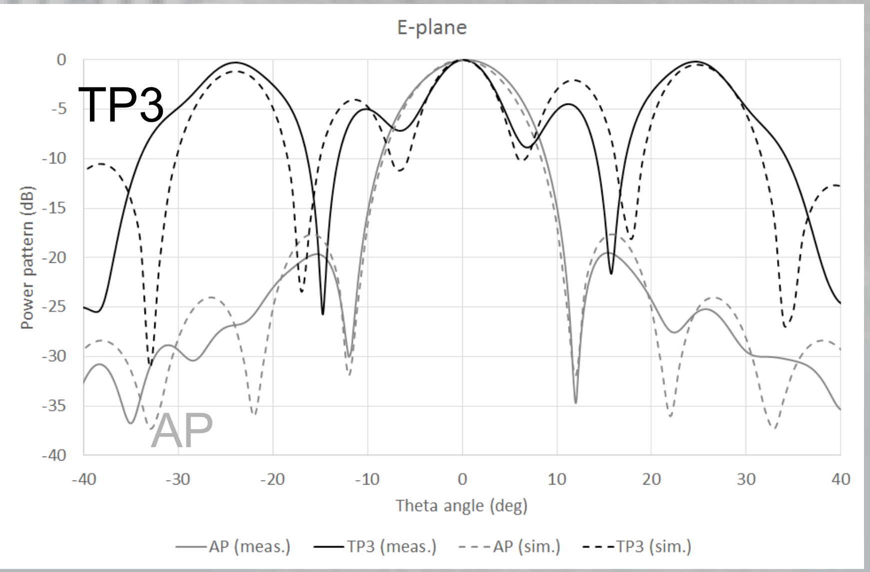
TP3
Cross-pol

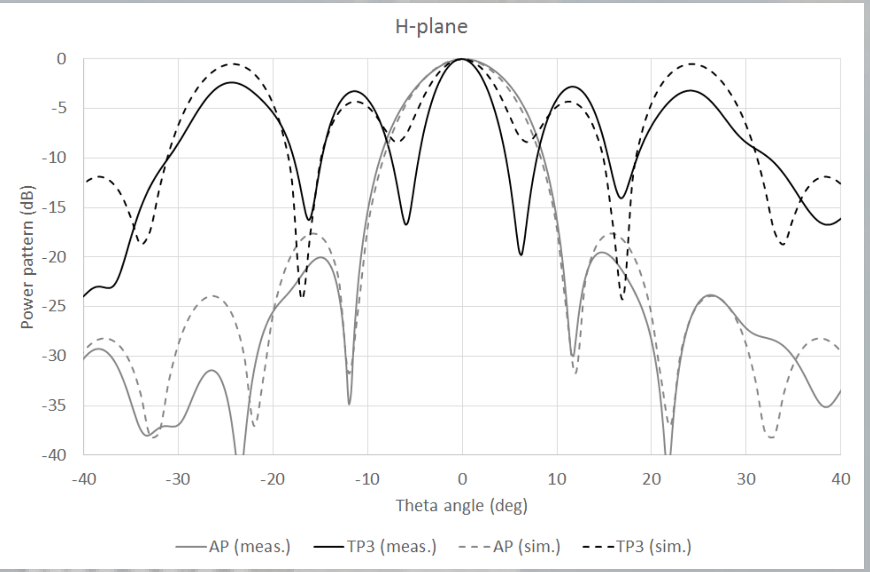


X (mm)

NF-to-FF
conversion

Far field

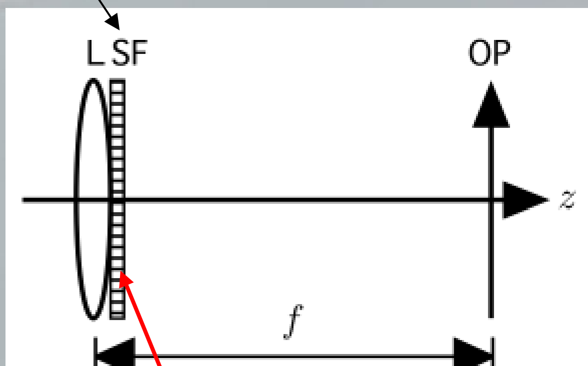




(Olmi et al., *Exp. Astr.*, 2017)

Implementation on (Radio) Telescopes

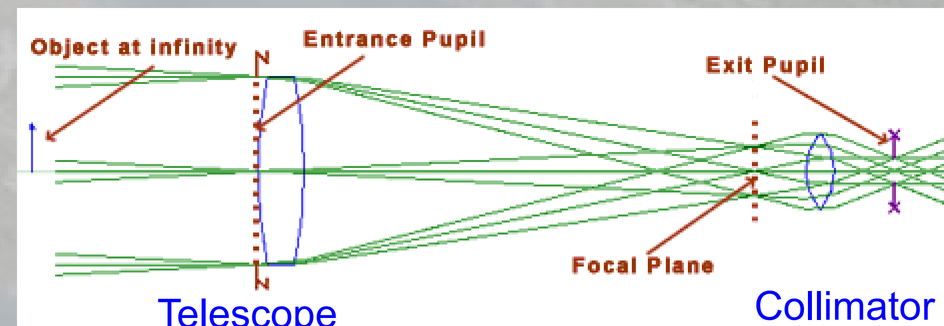
Ideally, place TP on entrance pupil

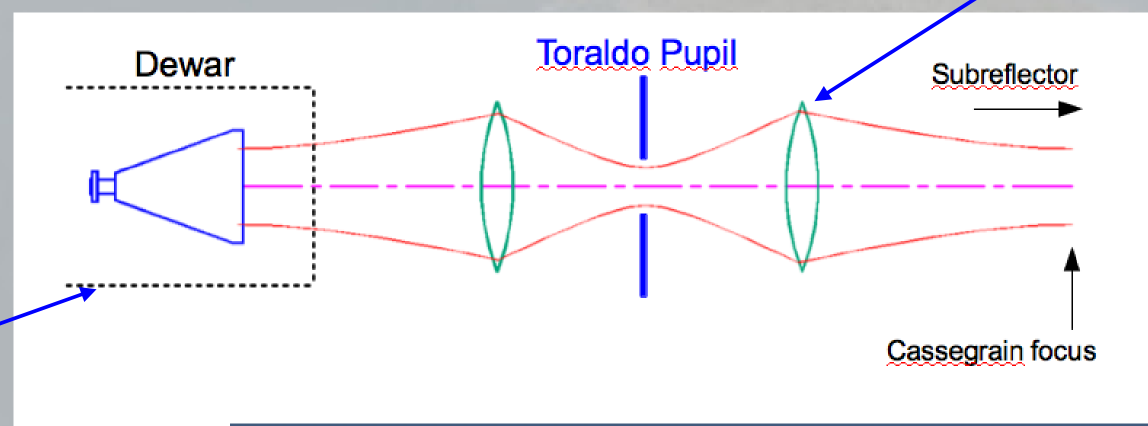


$$U_f(u,v) = \frac{A \exp\left[j\frac{k}{2f}\left(1-\frac{d}{f}\right)(u^2+v^2)\right]}{j\lambda f} \times \iint_{-\infty}^{\infty} t_A(\xi,\eta)\exp\left[-j\frac{2\pi}{\lambda f}(\xi u+\eta v)\right] d\xi\, d\eta.$$

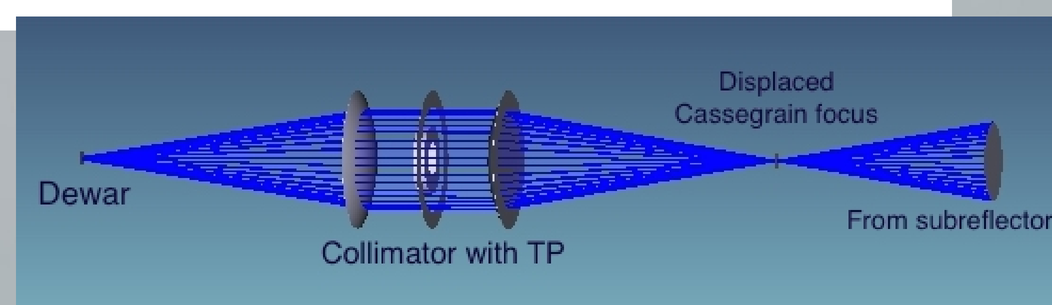
Transparency function

Acting on wavefront at **exit pupil** is equivalent as acting on it at entrance pupil of telescope.

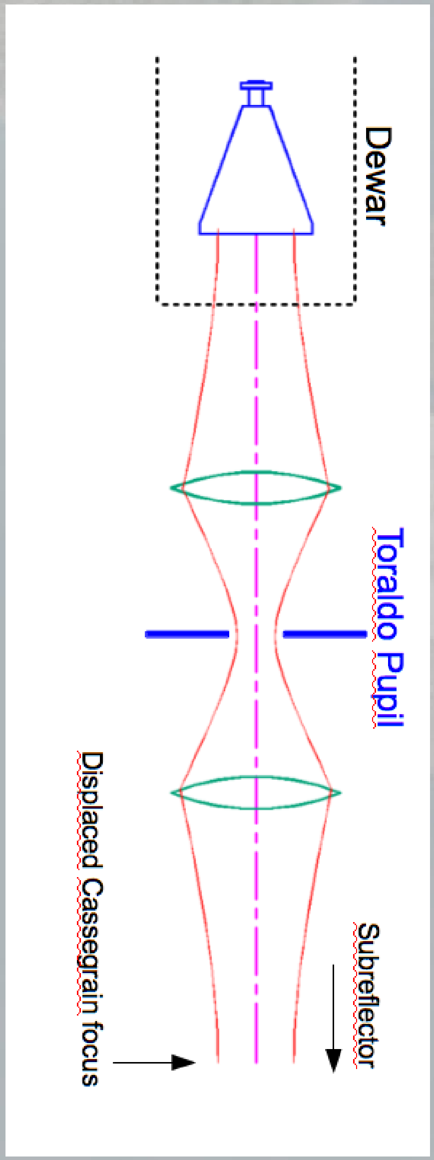


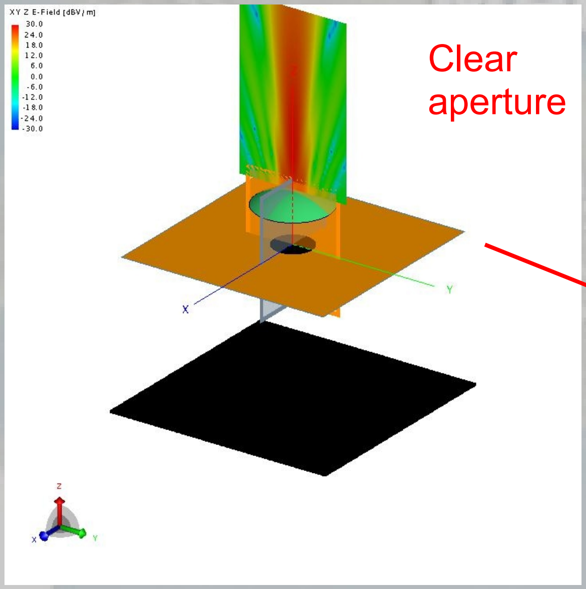


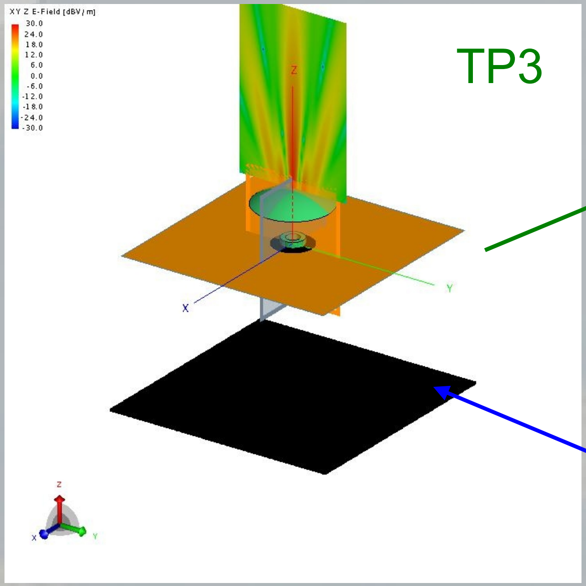
Dewar should be moved backward



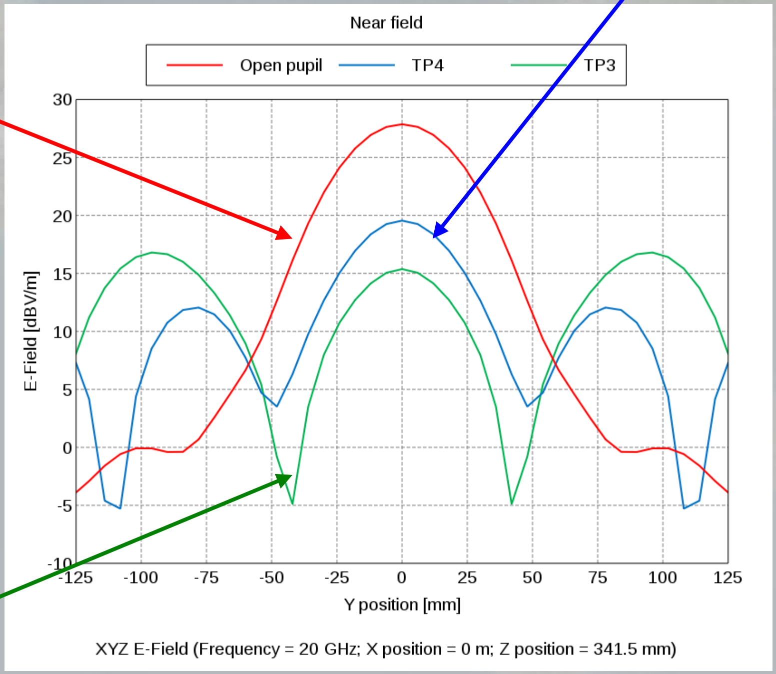
Collimator Design





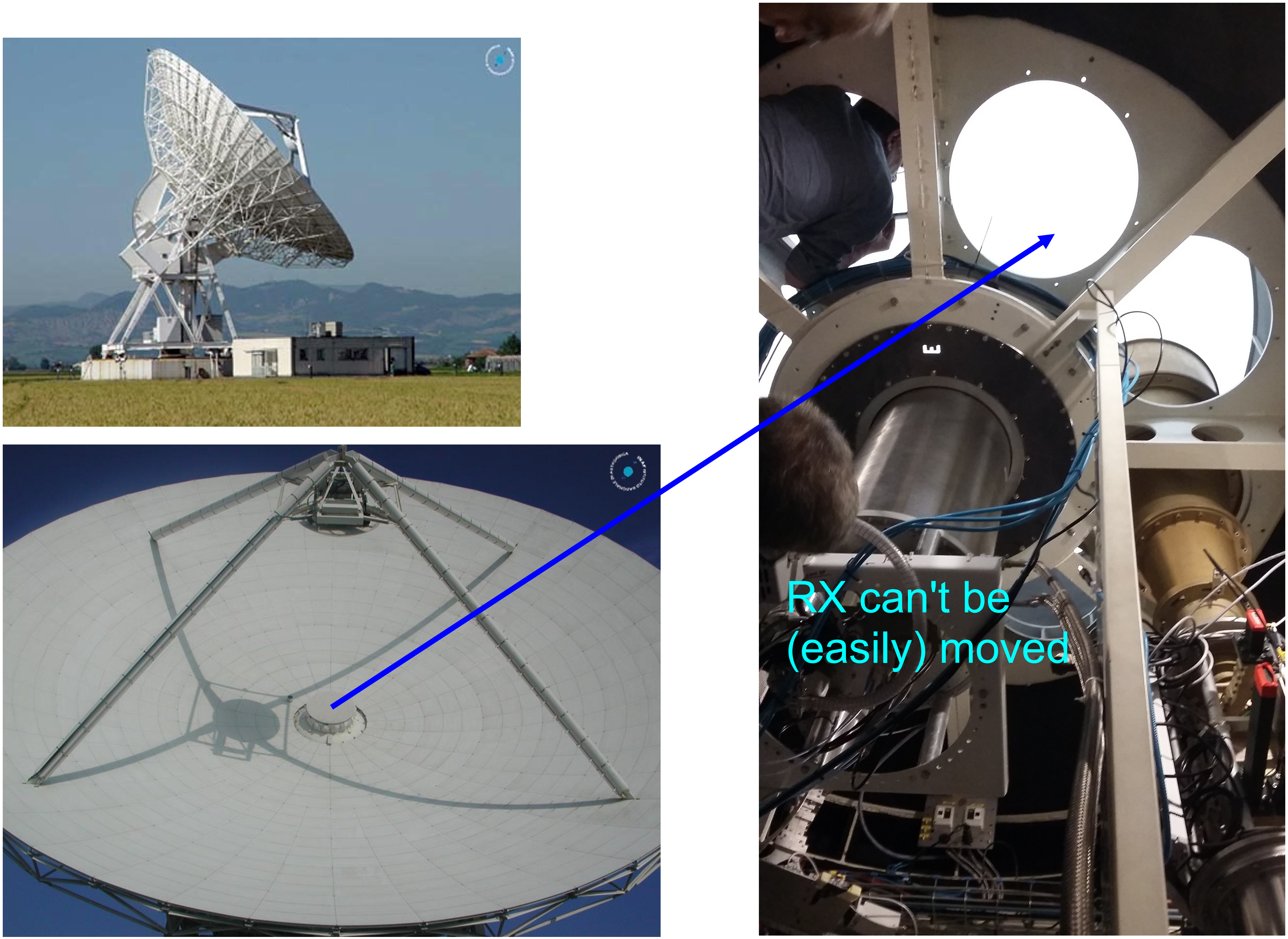


TP4

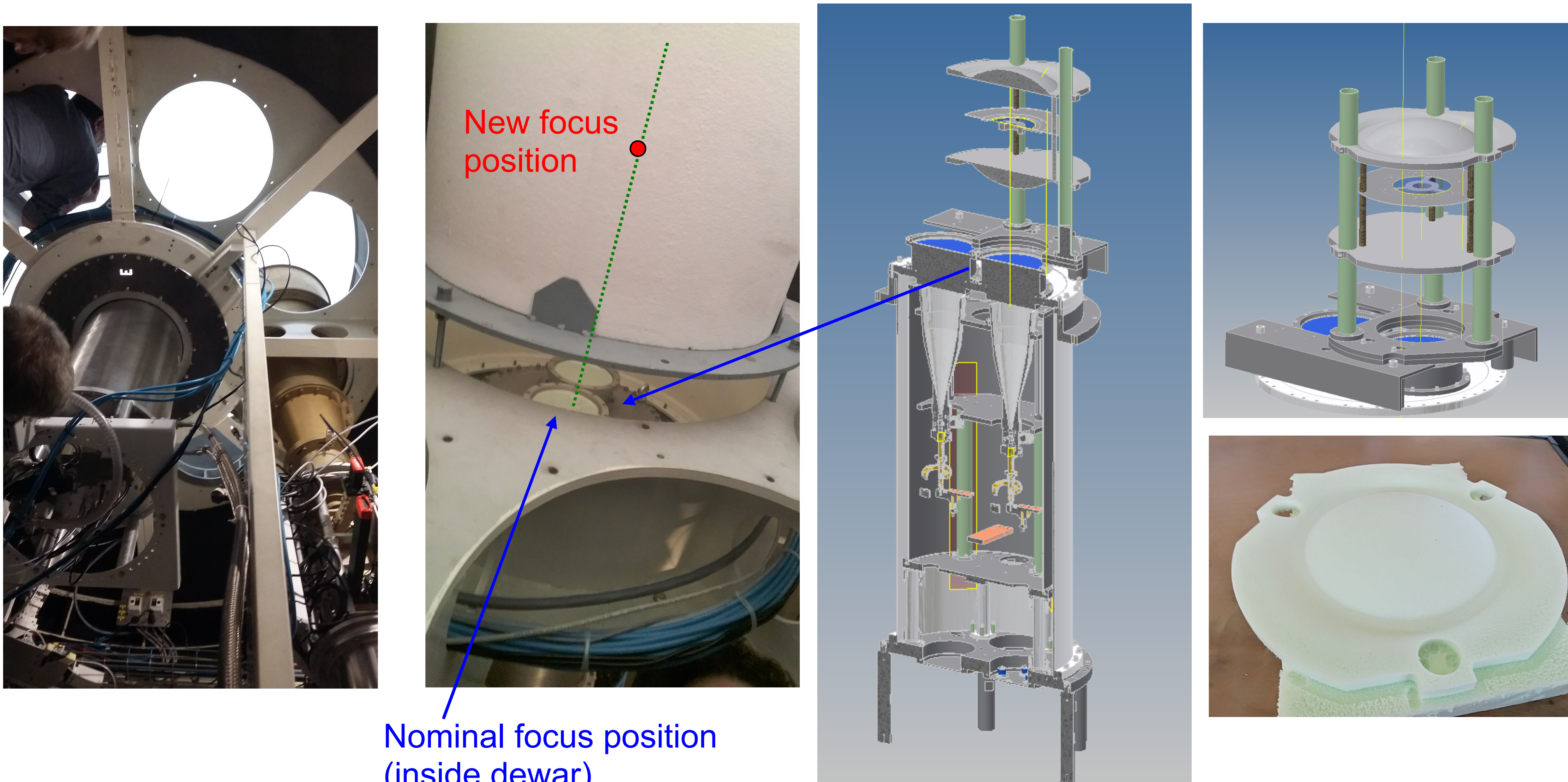


"Aperture plane excitation" simulates Cassegrain focus of Medicina telescope

Mounting on the Antenna



Implementation on 32m Medicina Telescope



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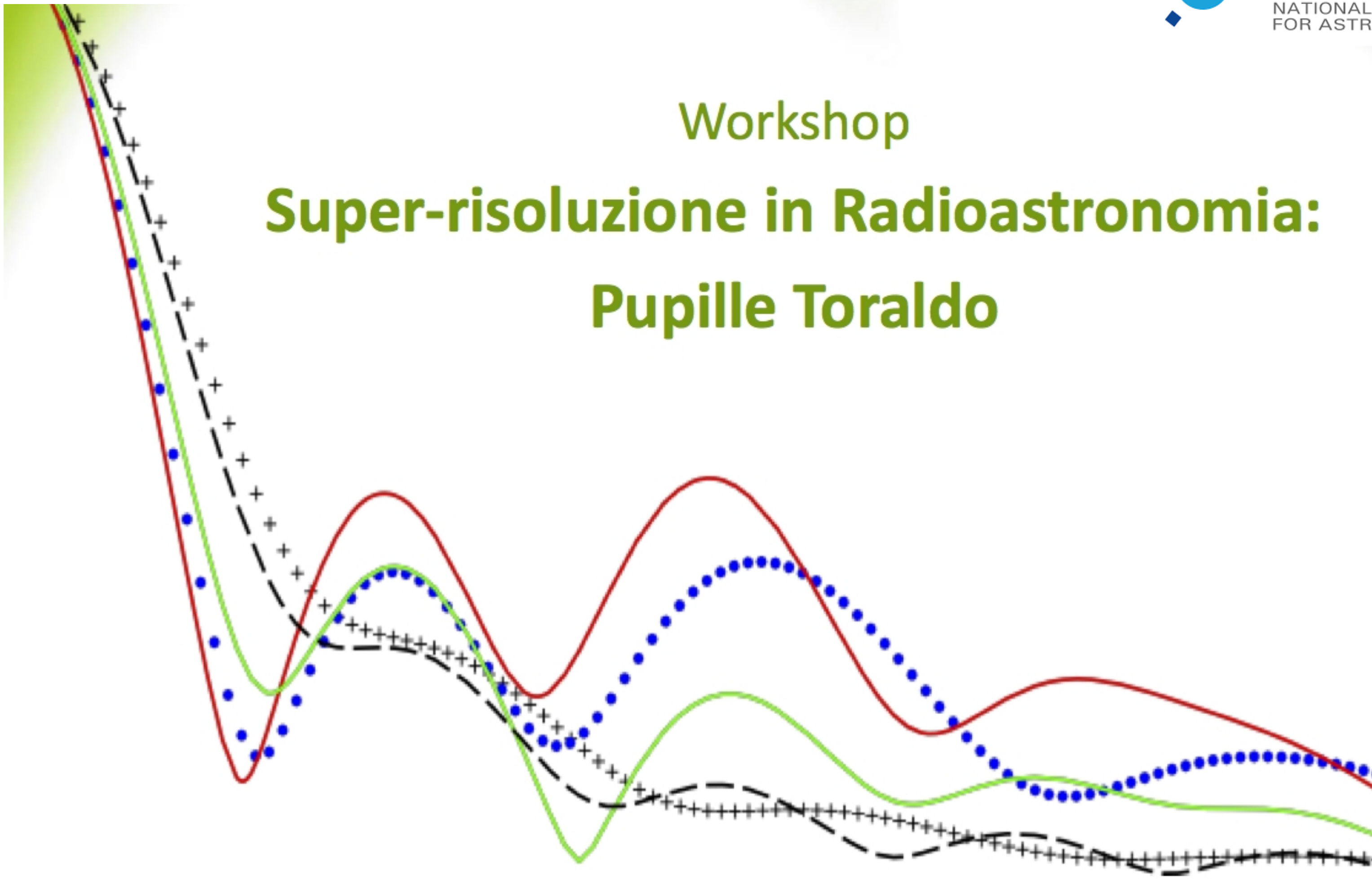


Workshop

Super-risoluzione in Radioastronomia: Pupille Toraldo

Villa Galileo

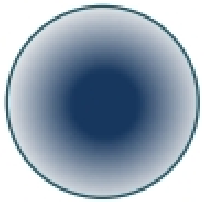
Firenze

12 ottobre 2017

By G. Pisano

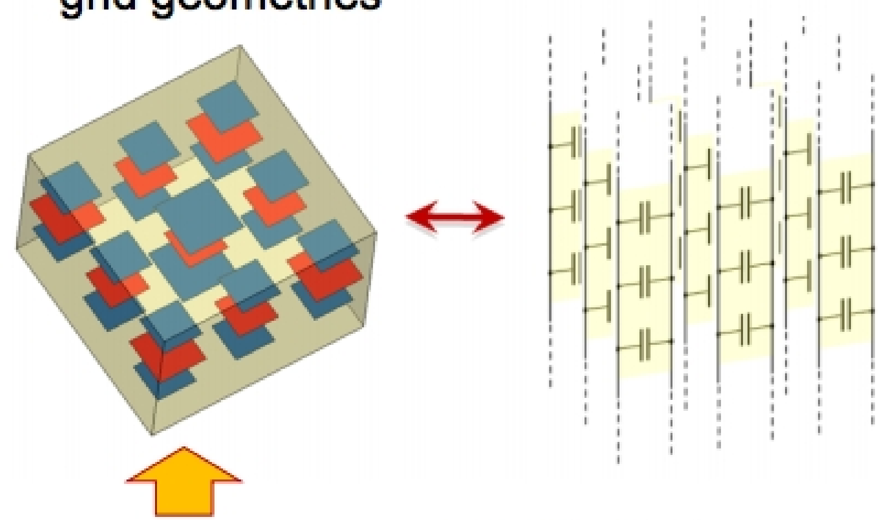
Flat Mesh Lens: Inhomogeneous Phase Delays

G. Pisano et al.
Applied Optics **52**,n.11, (2013)

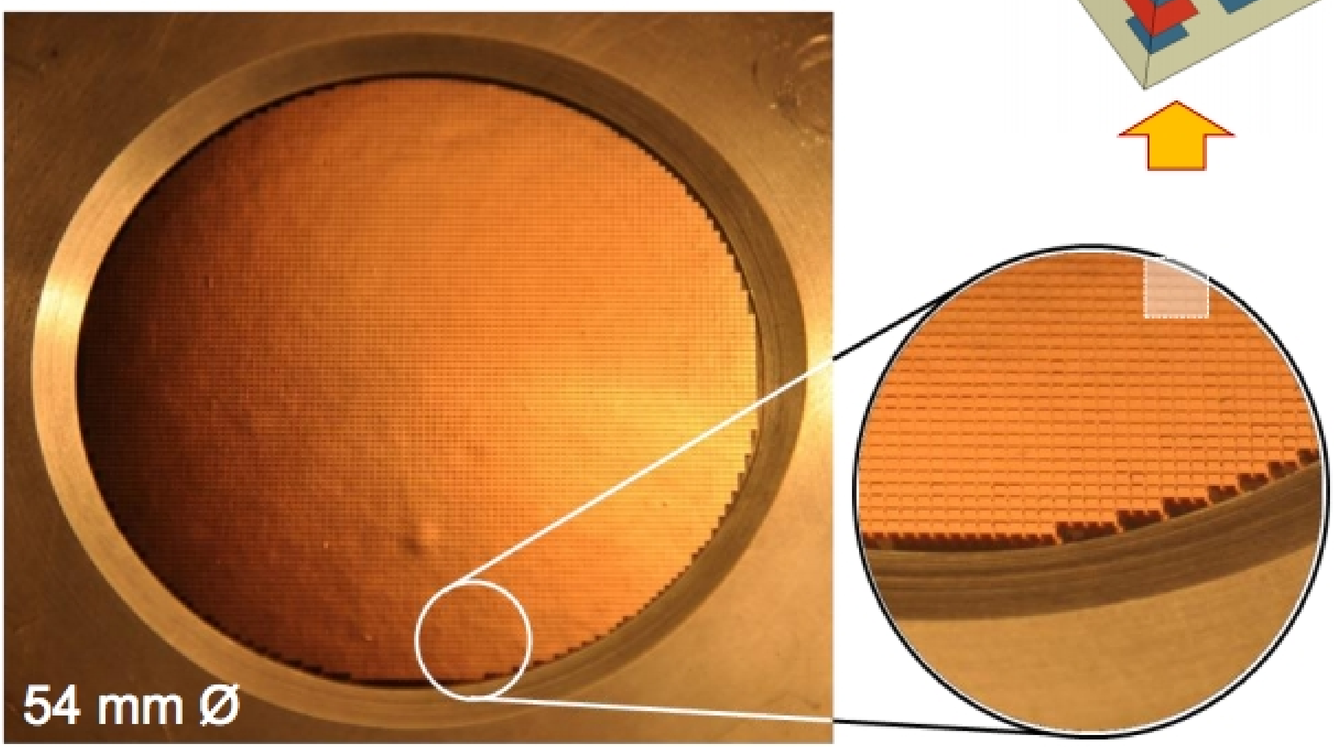


Inhomogeneous grids

Locally variable grid geometries



Multiple transmission lines



W-Band f/3 lens prototype (1.4mm thick)

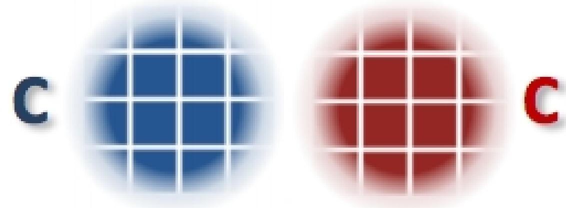
- Very thin and robust
- Very light and low loss
- No Anti Reflection Coatings required

Metamaterial based Toraldo Pupils: Option 1

By G. Pisano

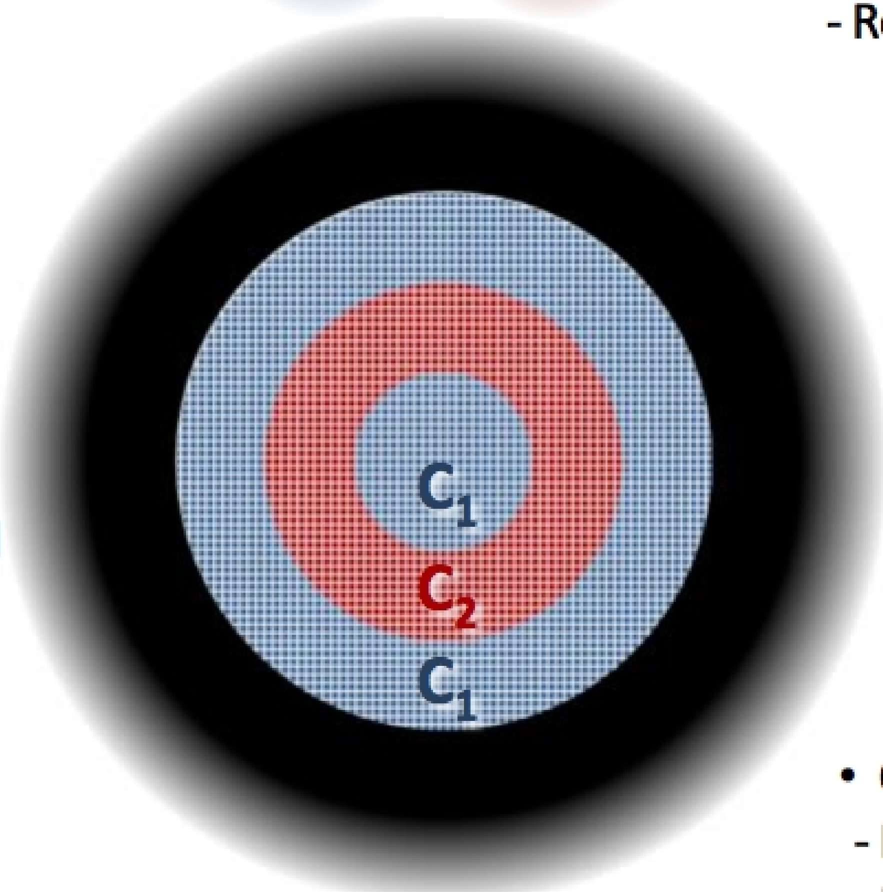
Mesh-lens type TP

(3-coronae)



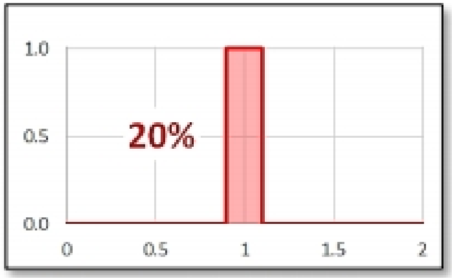
- **Pros:**
  - Easy manufacture
  - Requires only 2 filter designs

- **Working principle:**
  - Differential phase-shift from different capacitive filters
  - Similar to mesh-lens but with flat differential phase requirement



- **Bandwidth**

  $\Delta\phi = 180° \pm 20°$



- **Cons:**
  - Narrow bandwidth
  - Large number of grids required so far (~20)

- **Structure:**
  - Metal aperture
  - Transparent Capacitive grids – Phase shift ϕ
  - Transparent Capacitive grids – Phase shift $(\phi + \pi)$

Summary

simulations and laboratory measurements confirm performance discrete TPs.

v-efficiency (and to a lesser extent high-sidelobes) need further alysis and optimization.

dicina field-tests (in preparation) are required to fully characterize eal TP "plug-in" optical module.

ntinuum TPs and/or metamaterials could be used to improve EM formance.

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