Beamforming
(and LOFAR)

Andreas Horneffer

(Using Material from J. Anderson and M. Kuniyoshi)

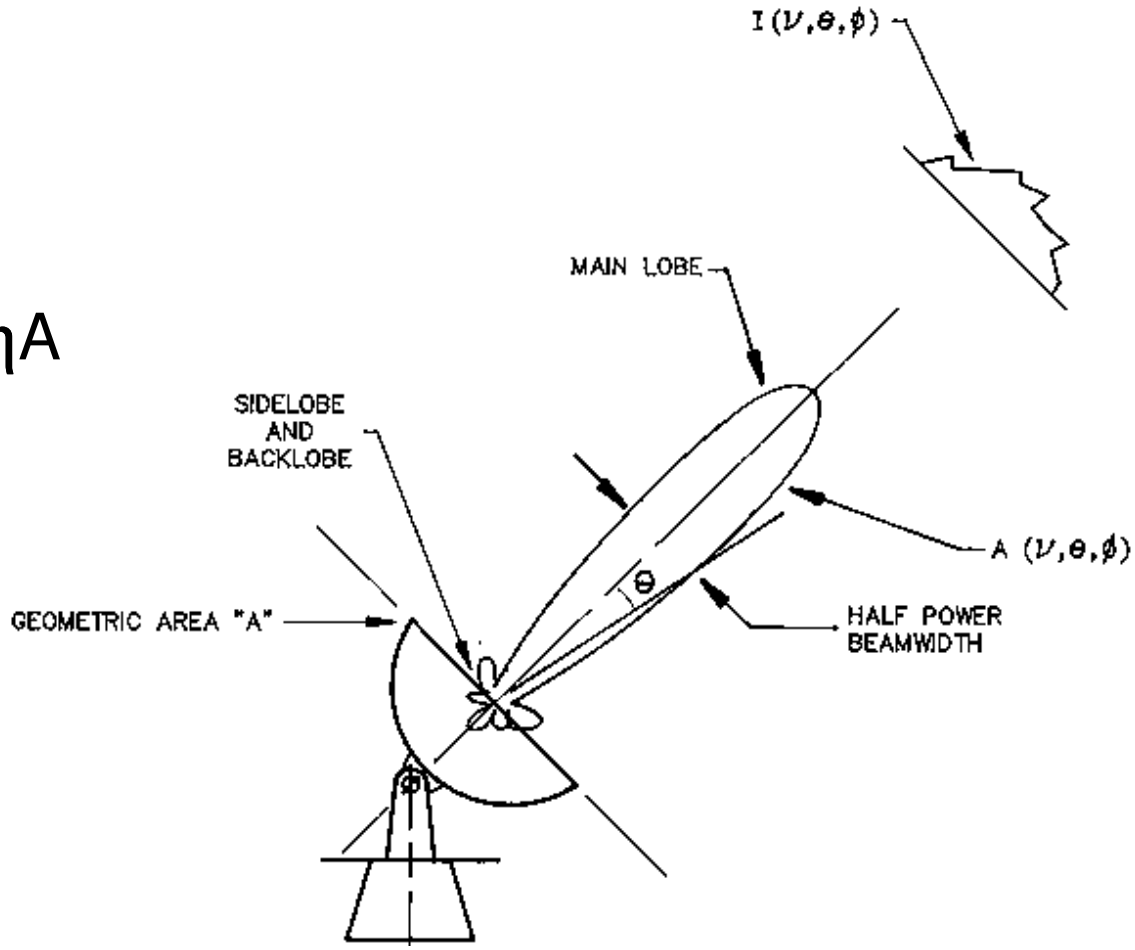
Basic Antenna Parameters

Effective collecting area $A(\nu,\theta,\phi)$ m^2

On-axis response $A_0 = \eta A$
η = aperture efficiency

Normalized pattern (primary beam)
$\boldsymbol{A}(\nu,\theta,\phi) = A(\nu,\theta,\phi)/A_0$

Beam solid angle
$\Omega_A = \iint_{\text{all sky}} \boldsymbol{A}(\nu,\theta,\phi)\, d\Omega$

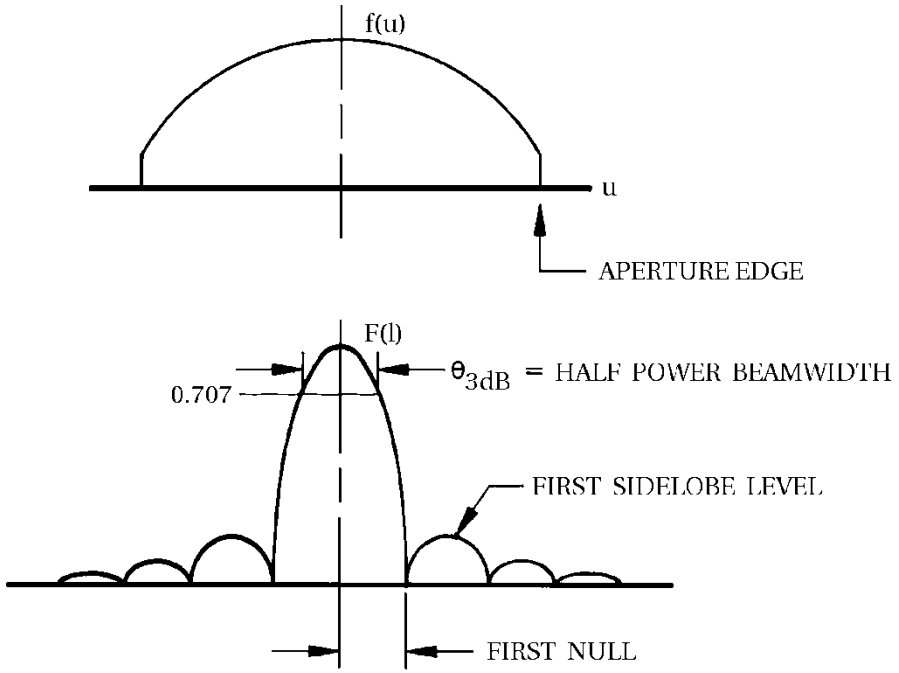


$A_0\,\Omega_A = \lambda^2$ $\quad$ λ = wavelength, ν = frequency

Aperture-Beam Fourier Transform Relationship

f(u,v) = aperture field distribution
u,v = aperture coordinates
(in wavelengths)

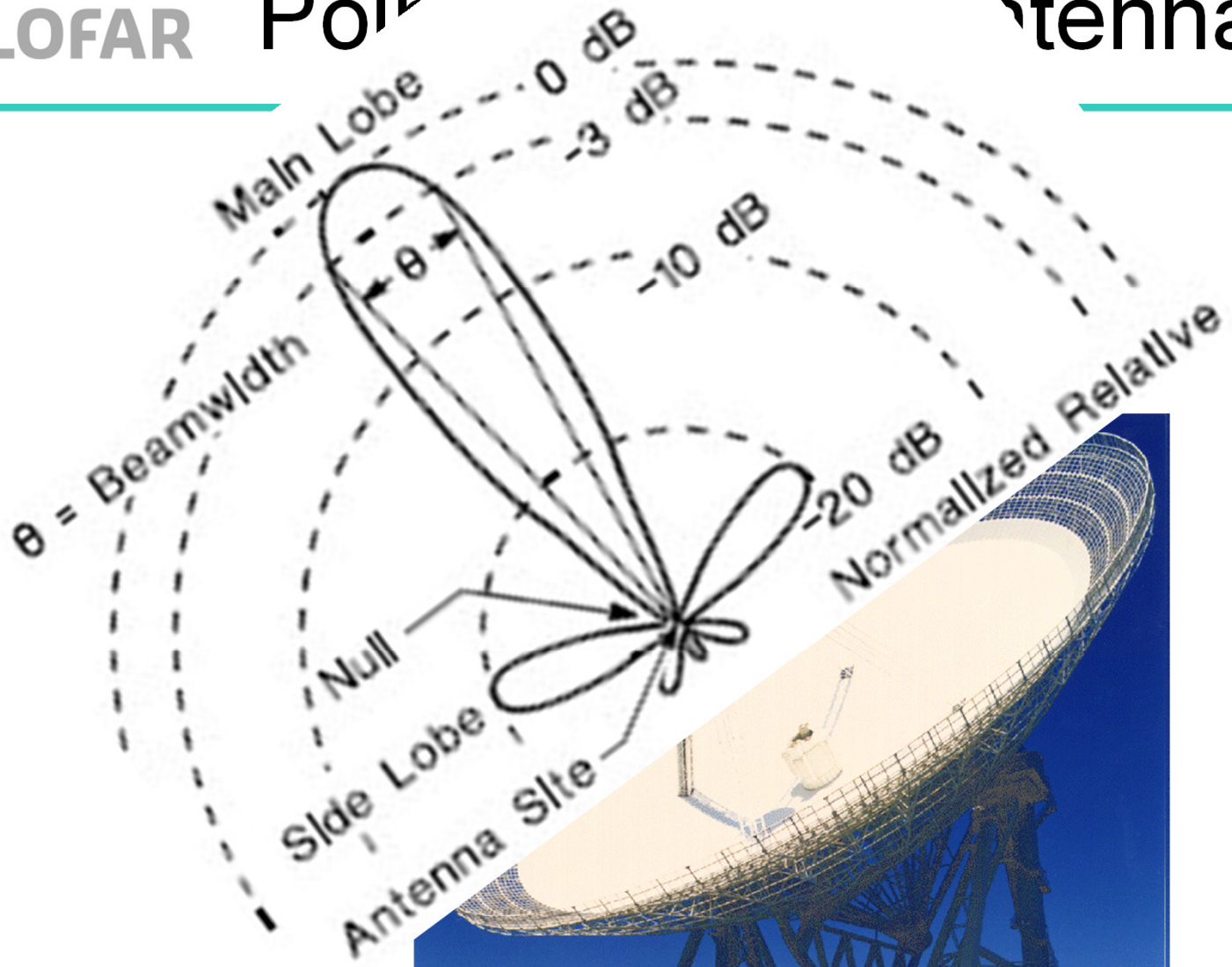
F(l,m) = far-field voltage pattern
l = sinθcosϕ , m = sinθsinϕ



$$F(l,m) = \iint f(u,v)\exp(2\pi i(ul+vm))\,du\,dv$$

$$f(u,v) = \iint \mathrm{F(l,m)}\exp(-2\pi i(ul+vm))\,dl\,dm$$

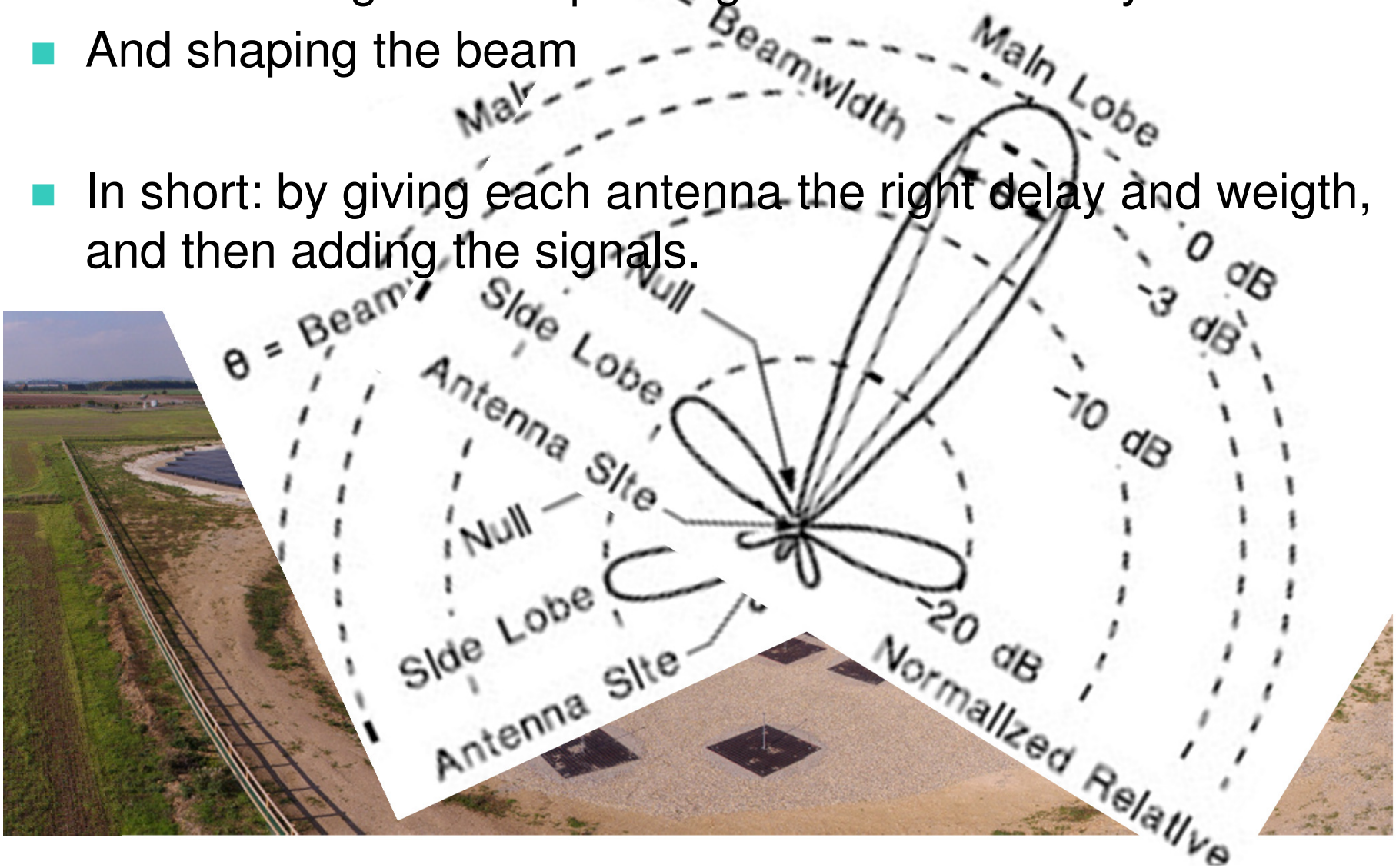
Poi[illegible]tenna


Main Lobe
0 dB
-3 dB
-10 dB
-20 dB
θ
θ = Beamwidth
Null
Side Lobe
Antenna Site
Normalized Relative

LOFAR Pointing Antenna Arrays?

- Beamforming means “pointing” an antenna array
- And shaping the beam

- In short: by giving each antenna the right delay and weigth, and then adding the signals.



Pointing Antenna Arrays?

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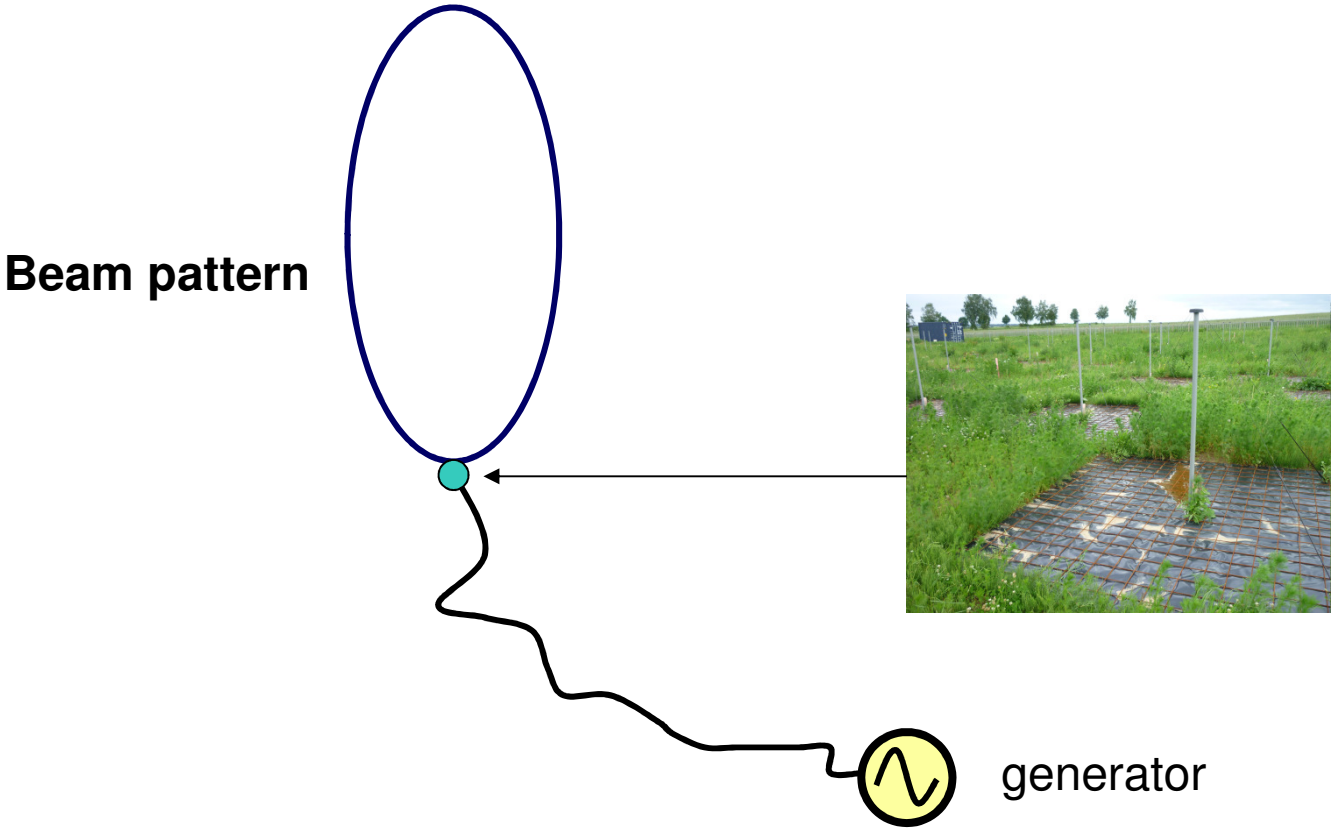
The Principle of Beamforming

Note: Antenna patterns are the same when transmitting or receiving. Thus receiving works the same as the transmitting case shown here.



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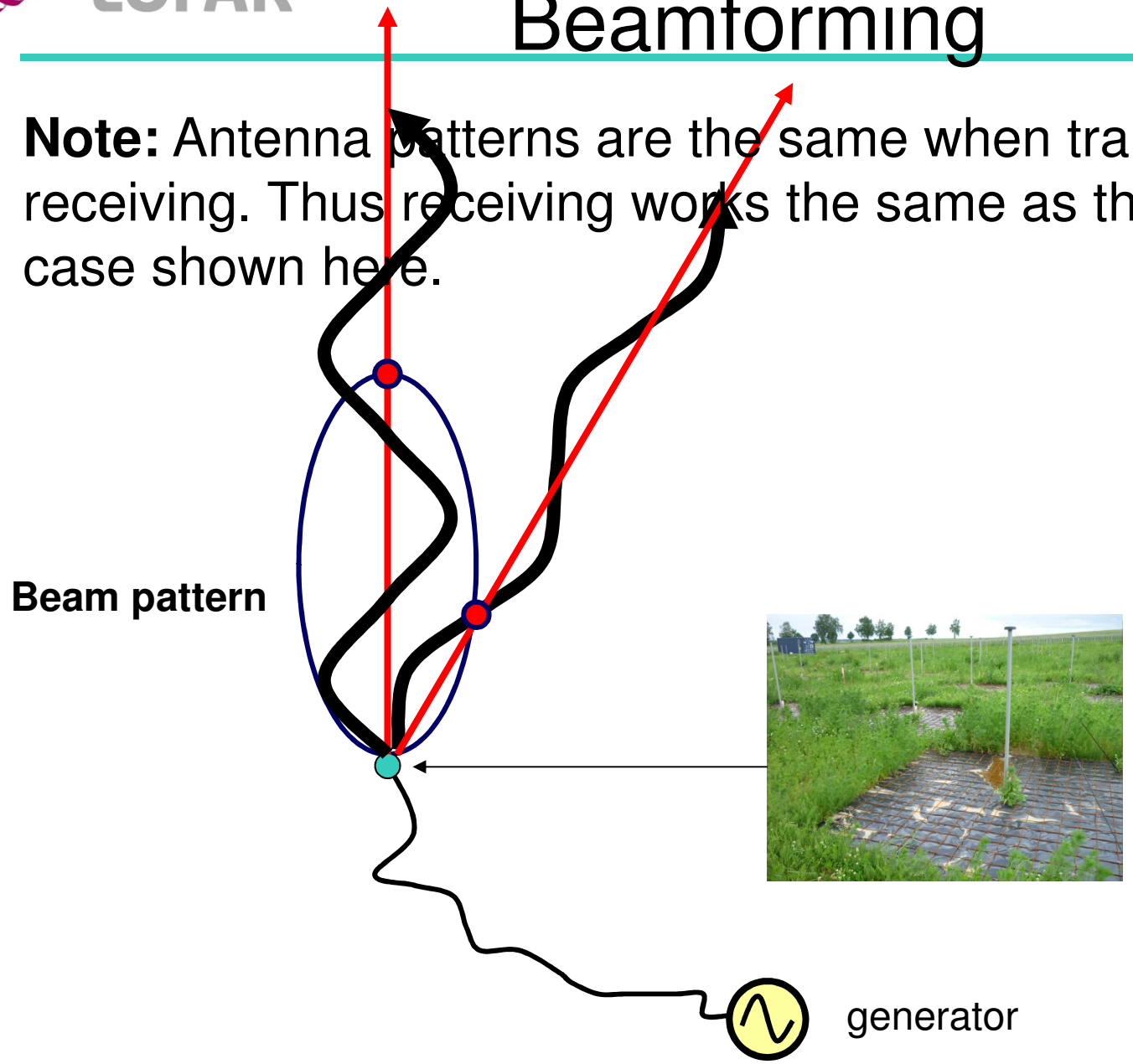

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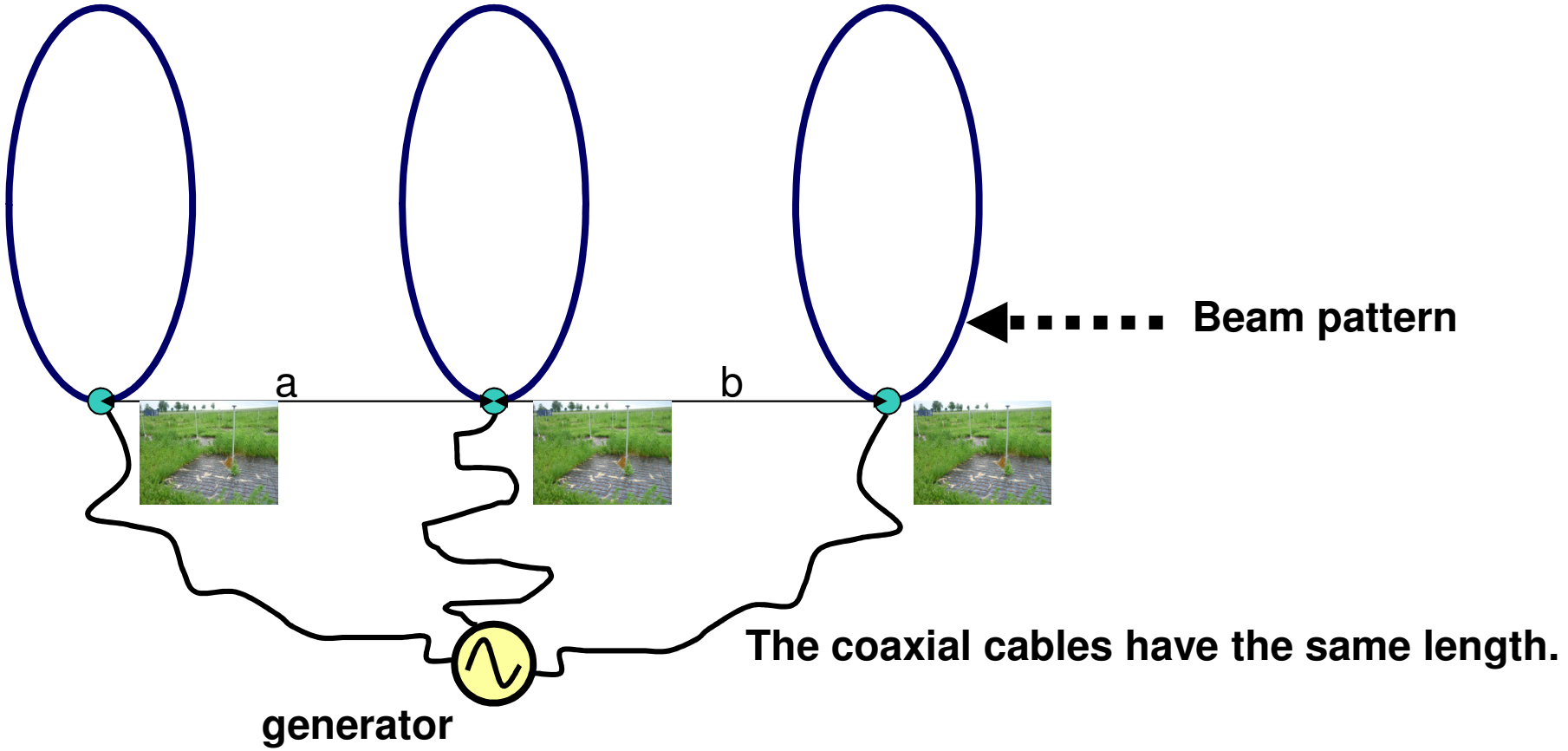
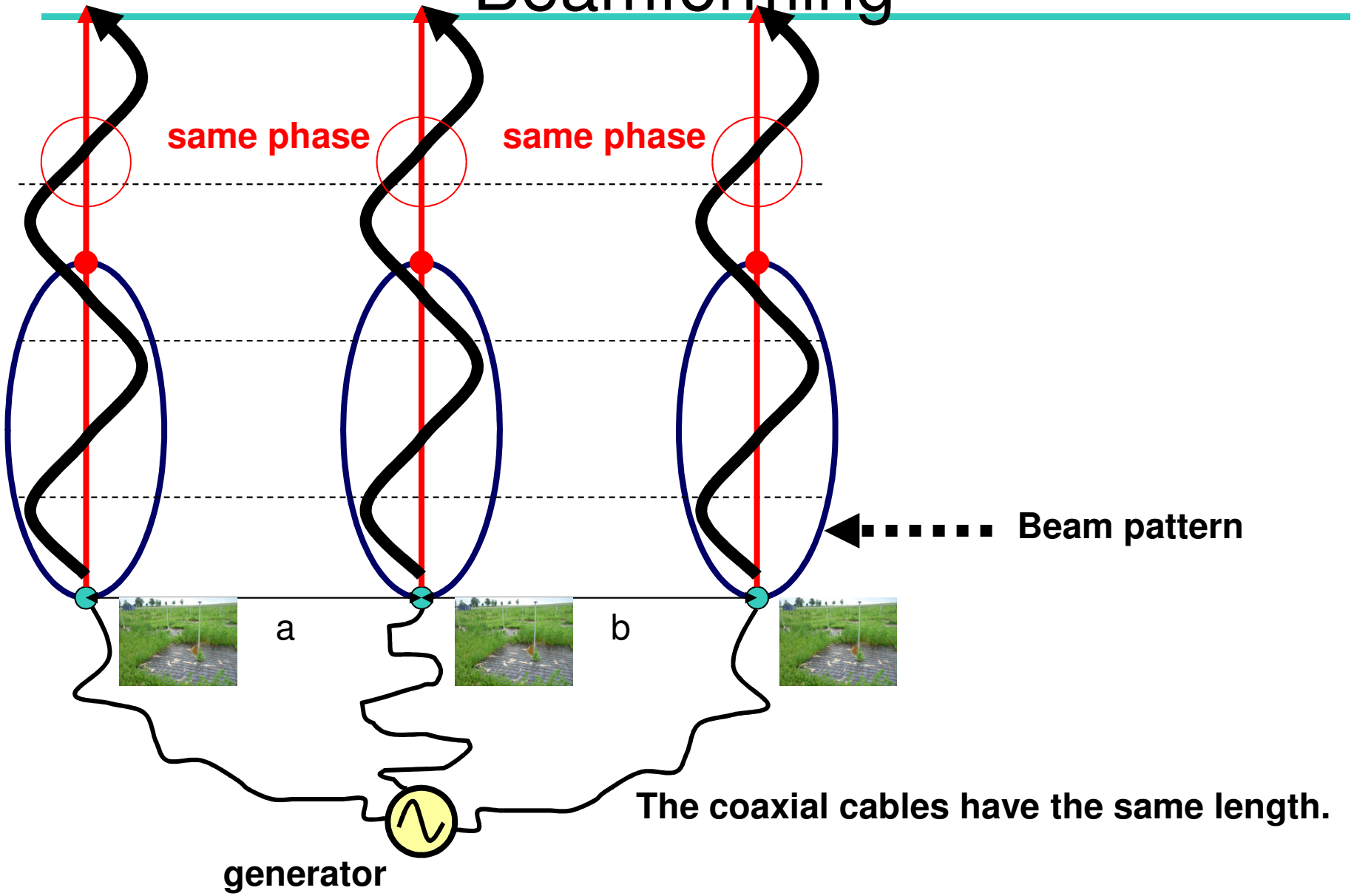
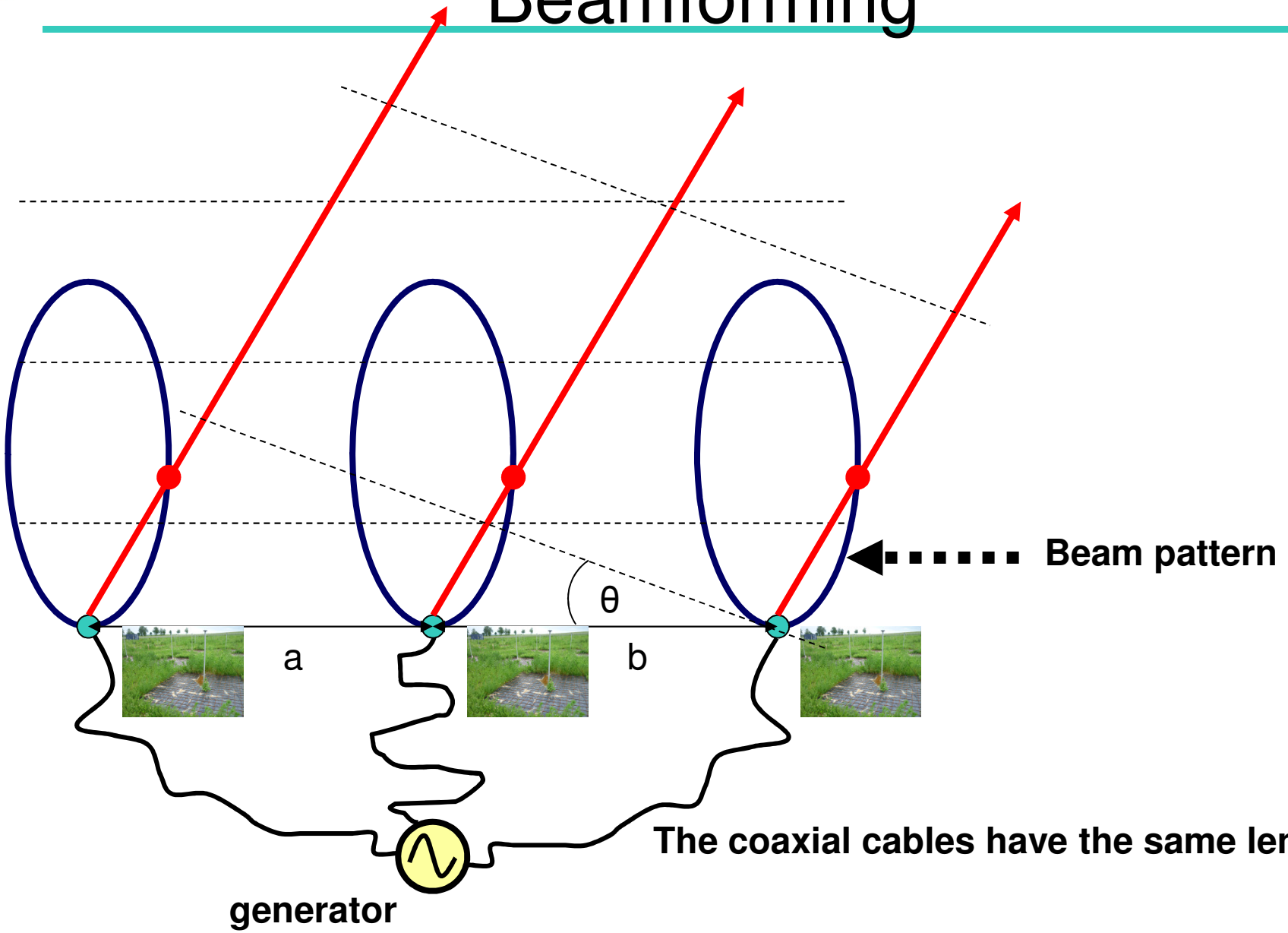


The Principle of Beamforming



The Principle of Beamforming



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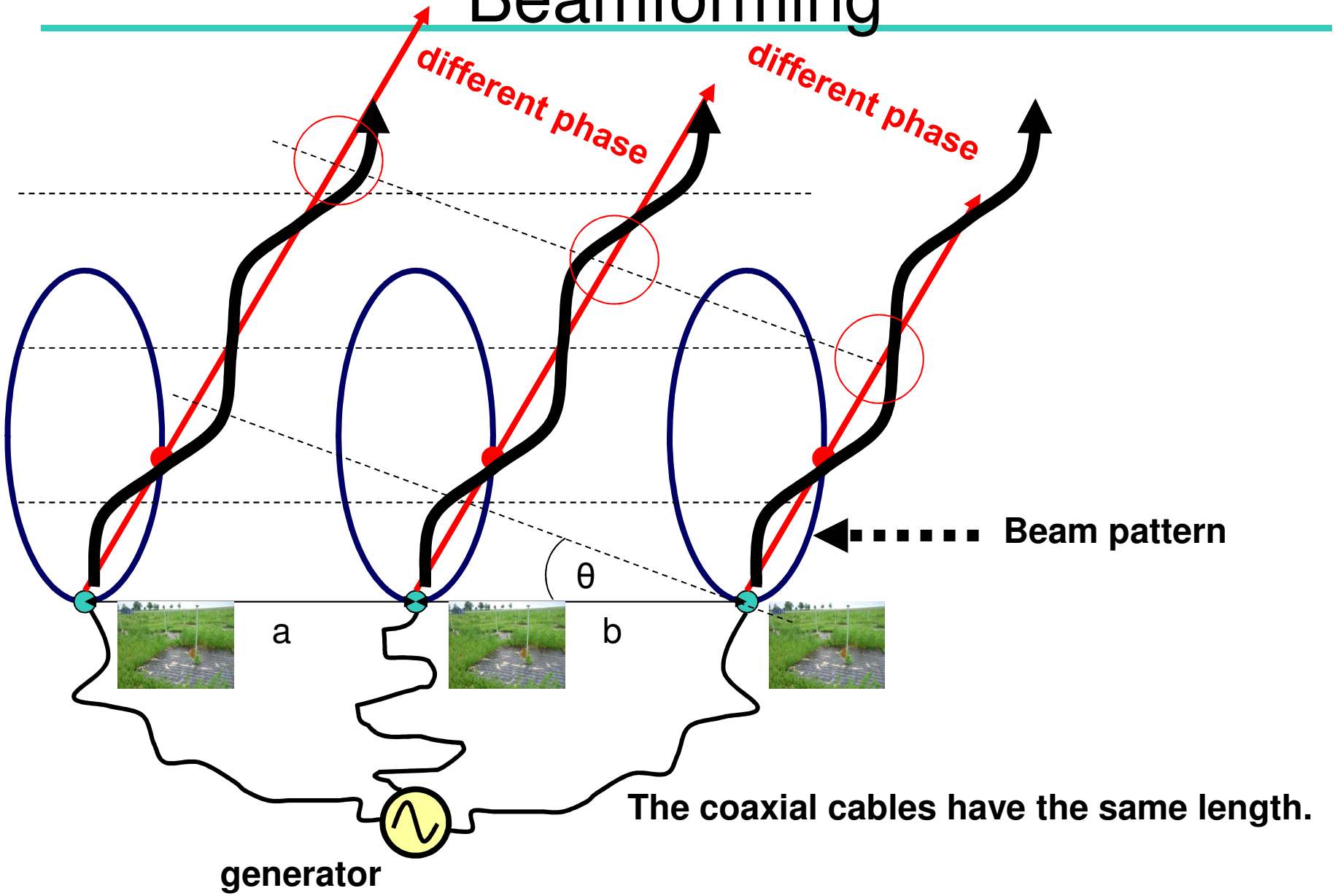

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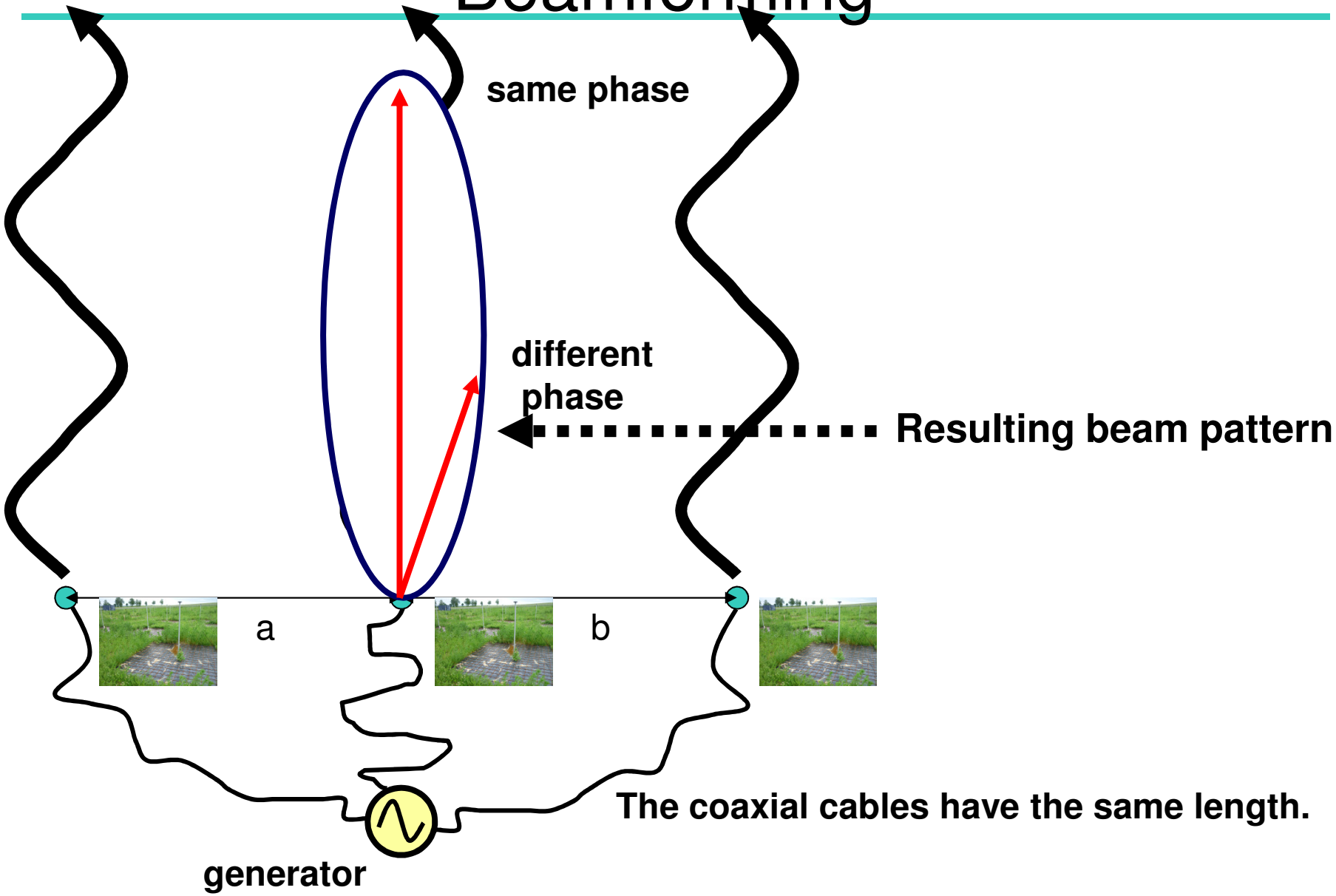

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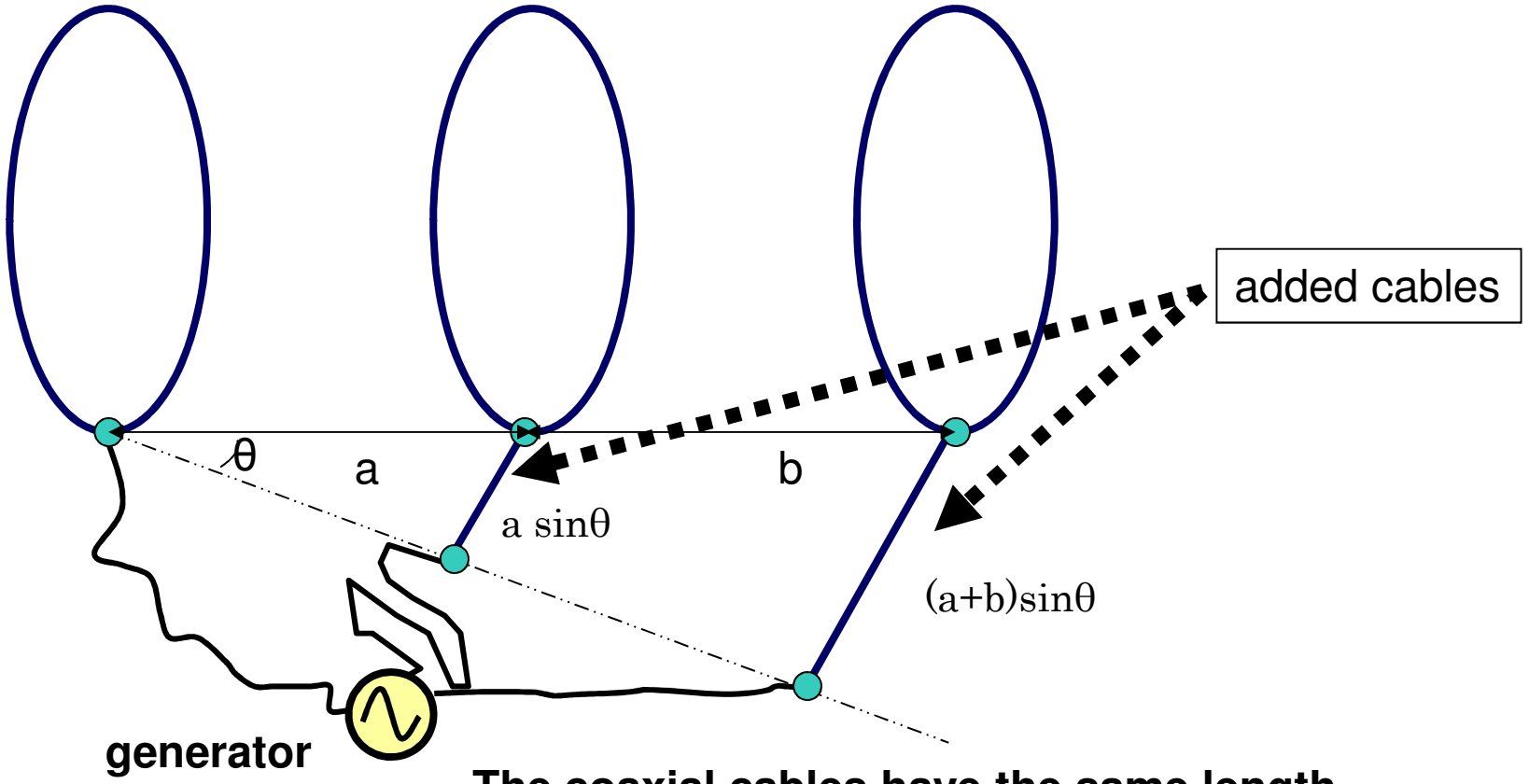
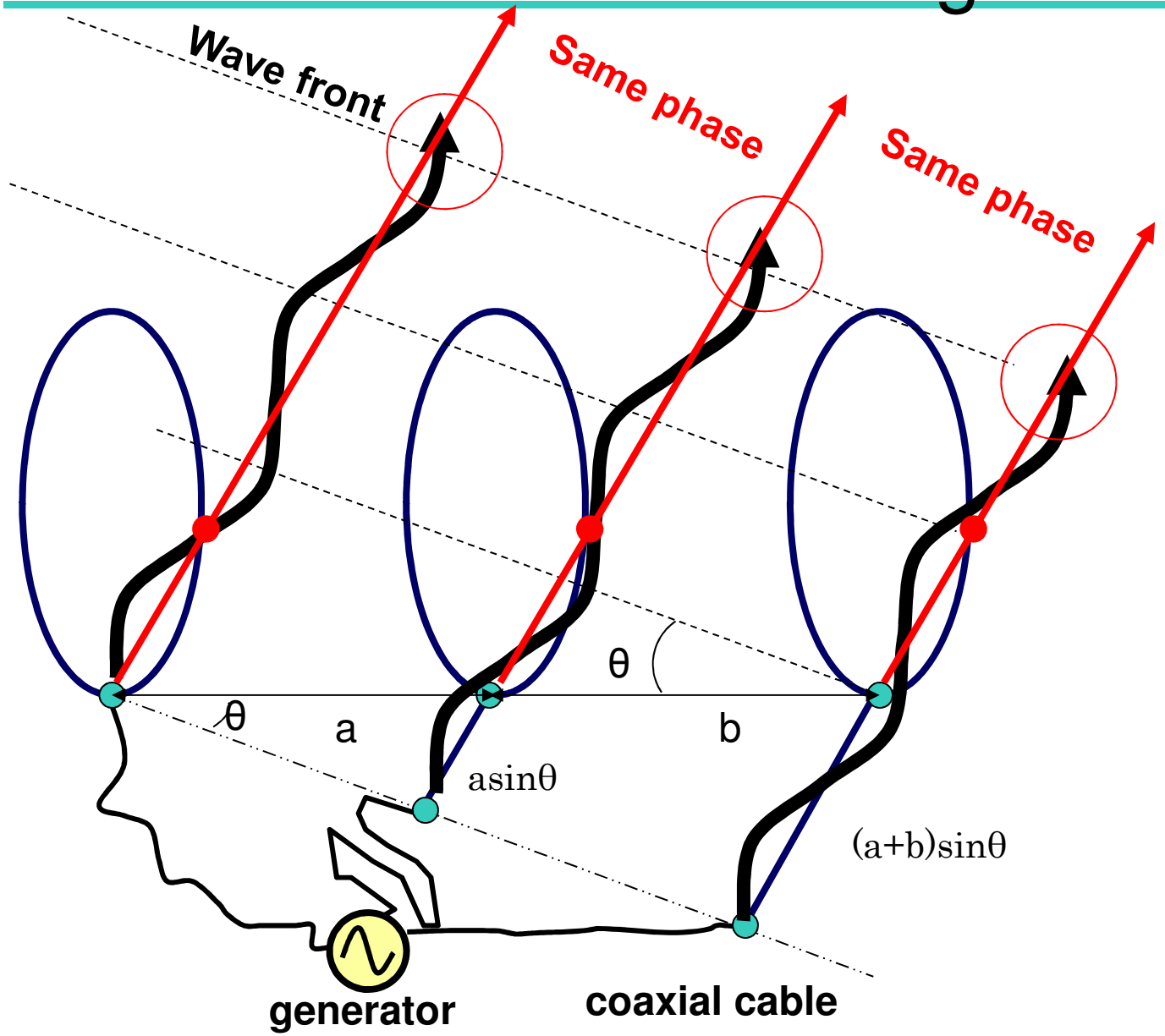


The coaxial cables have the same length.

The Principle of Beamforming



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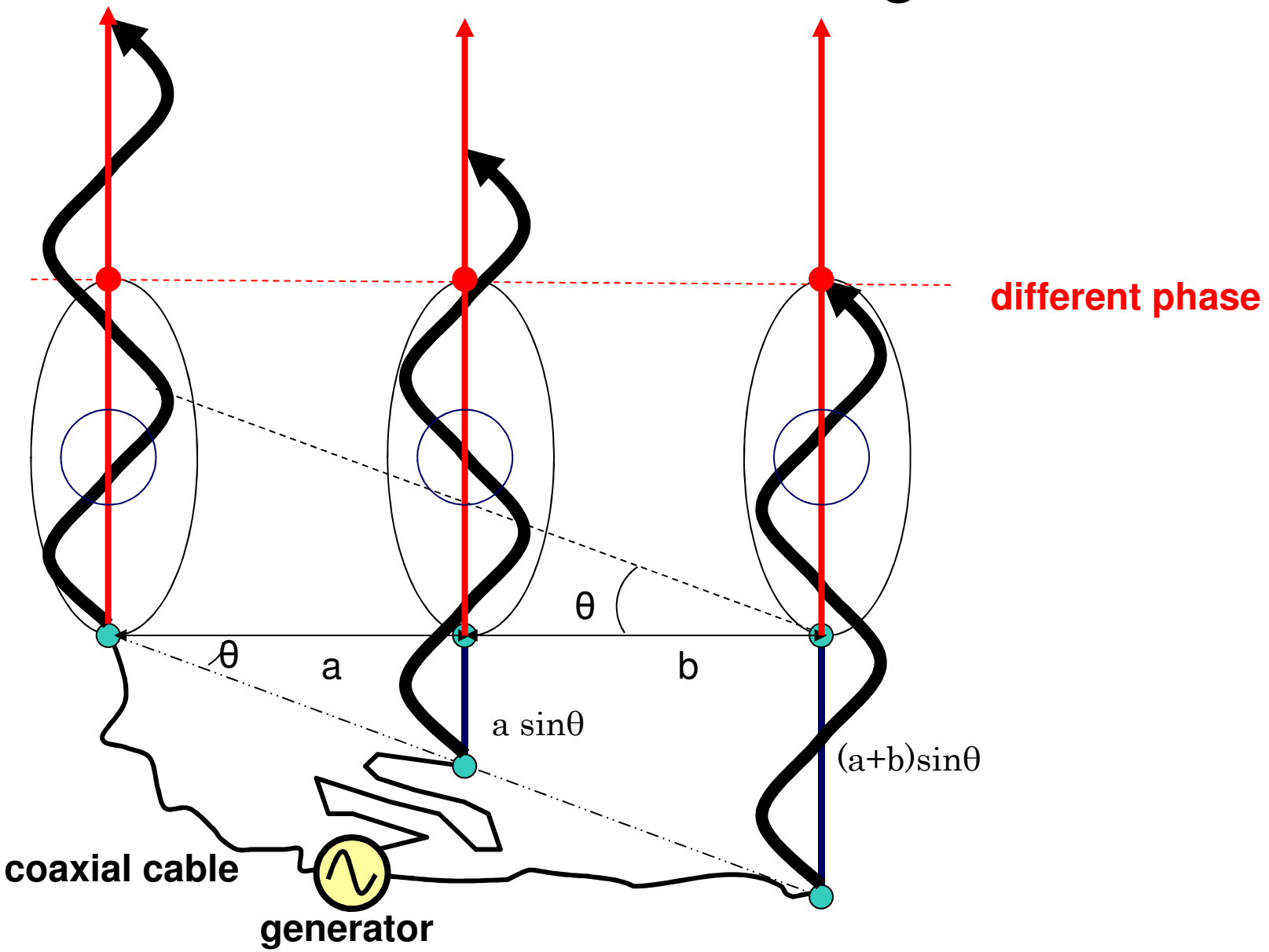

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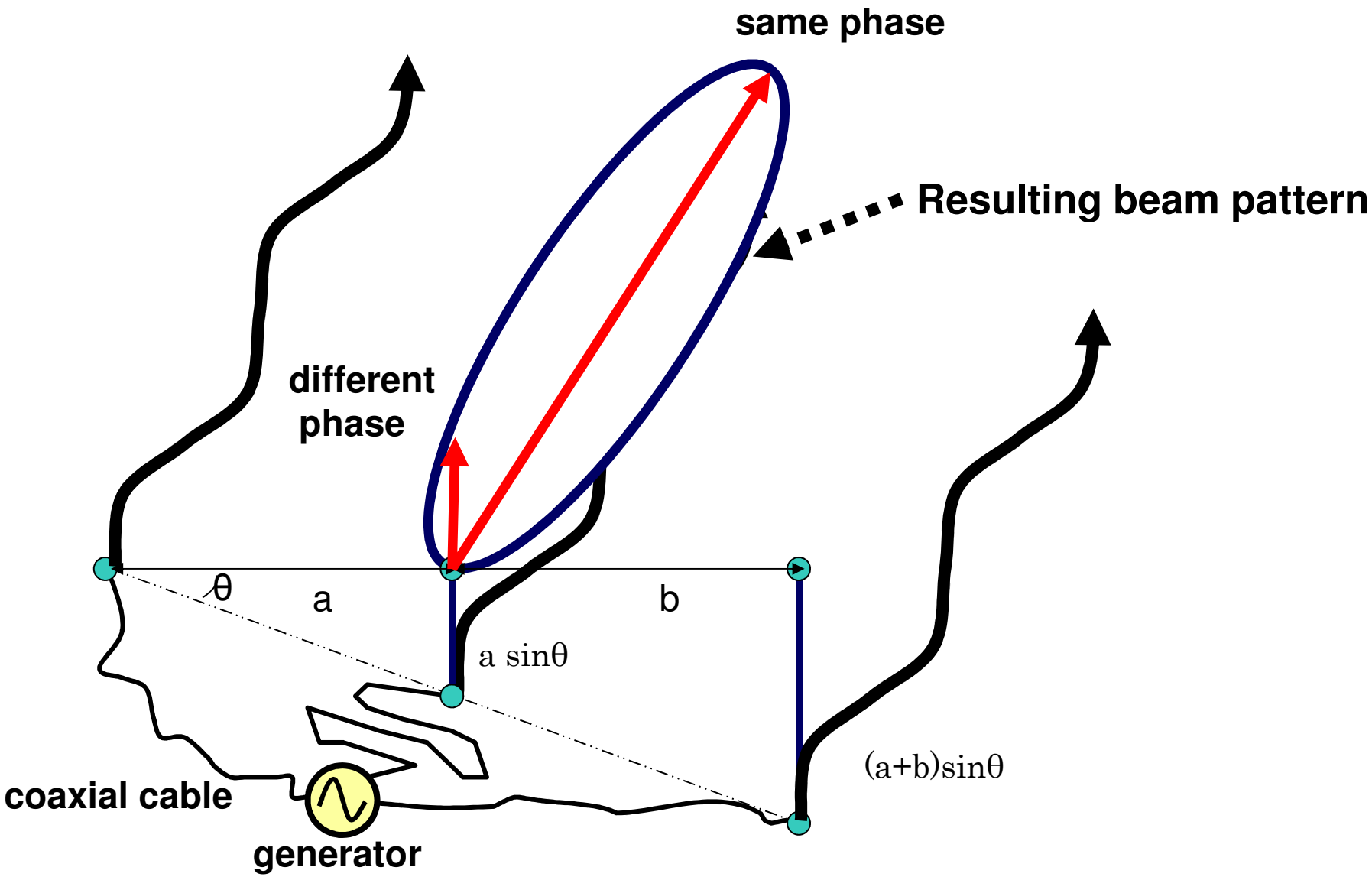

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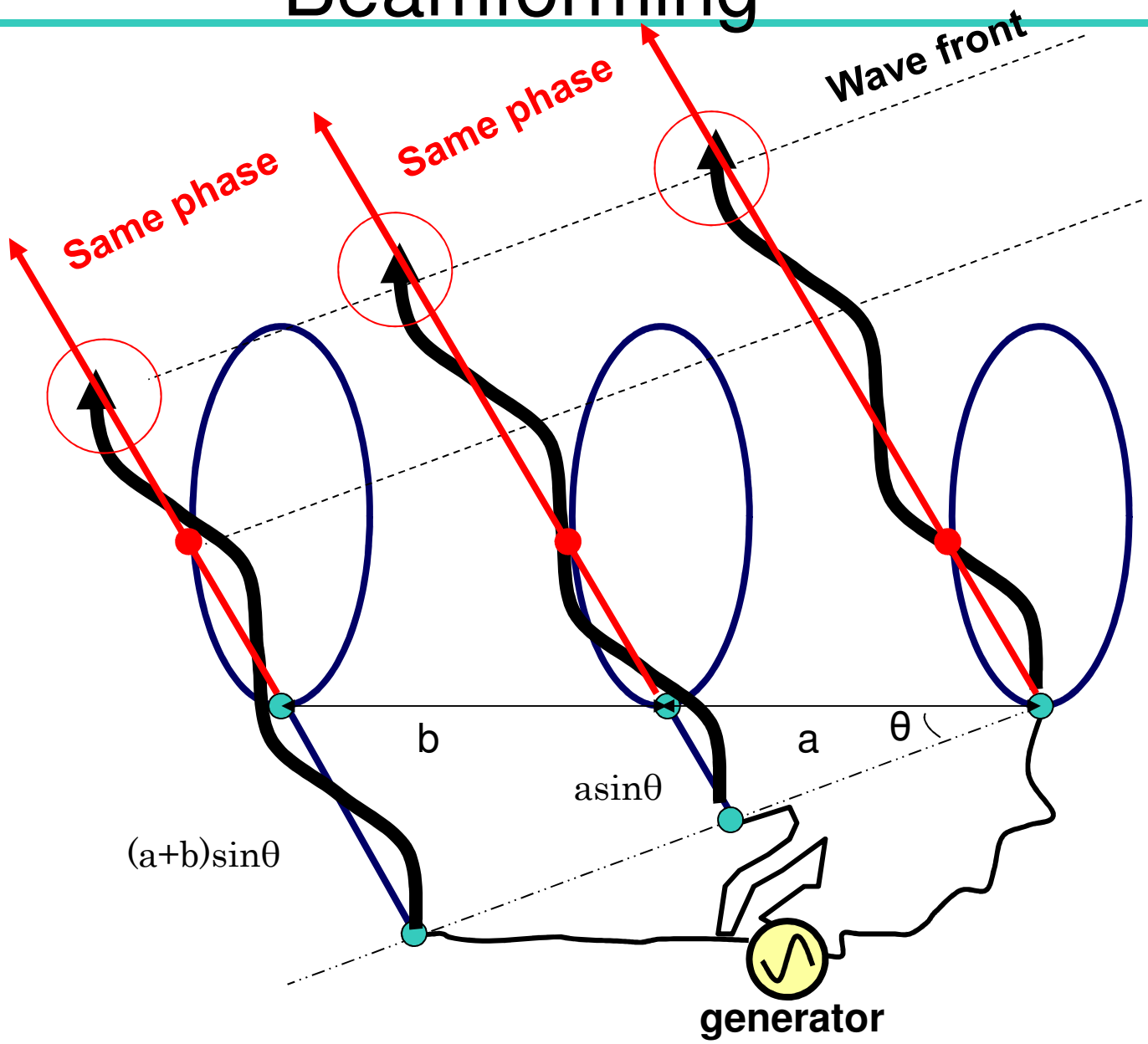

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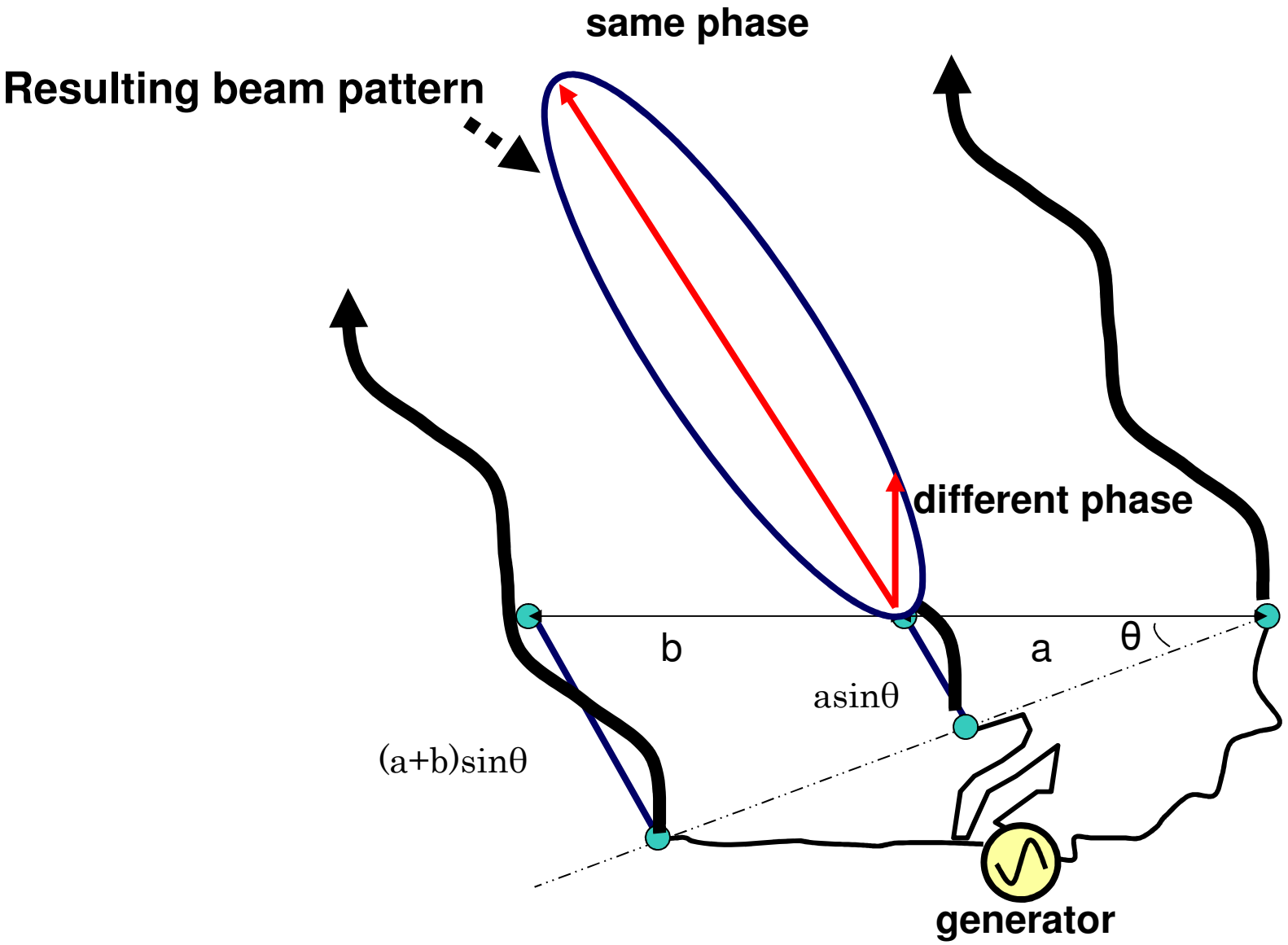
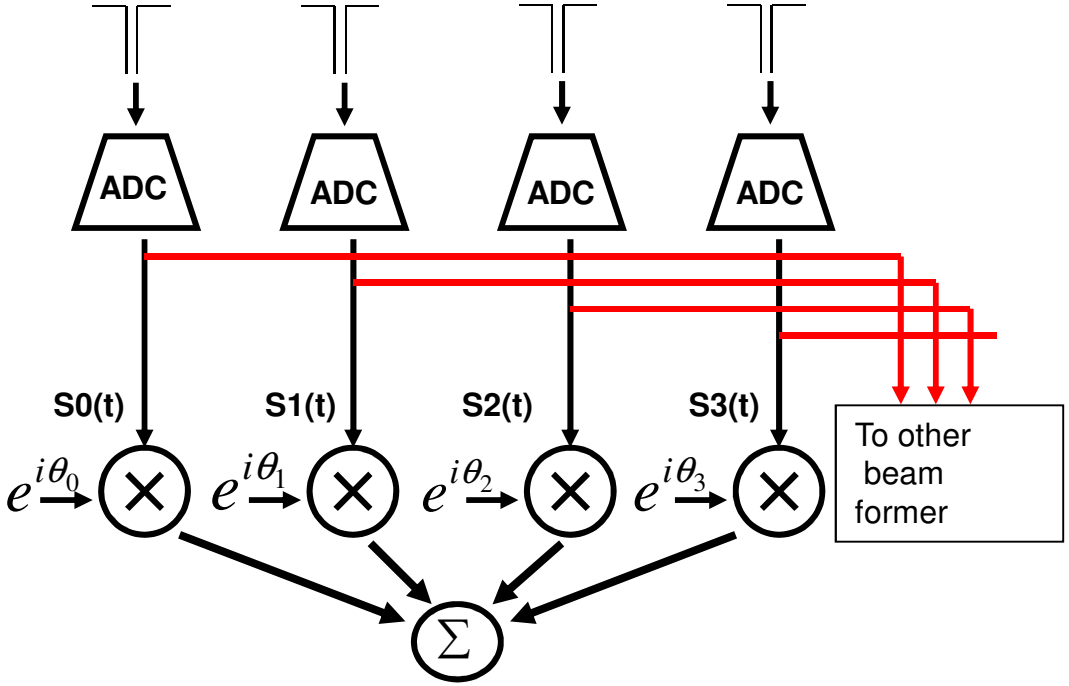


Digital Beamforming

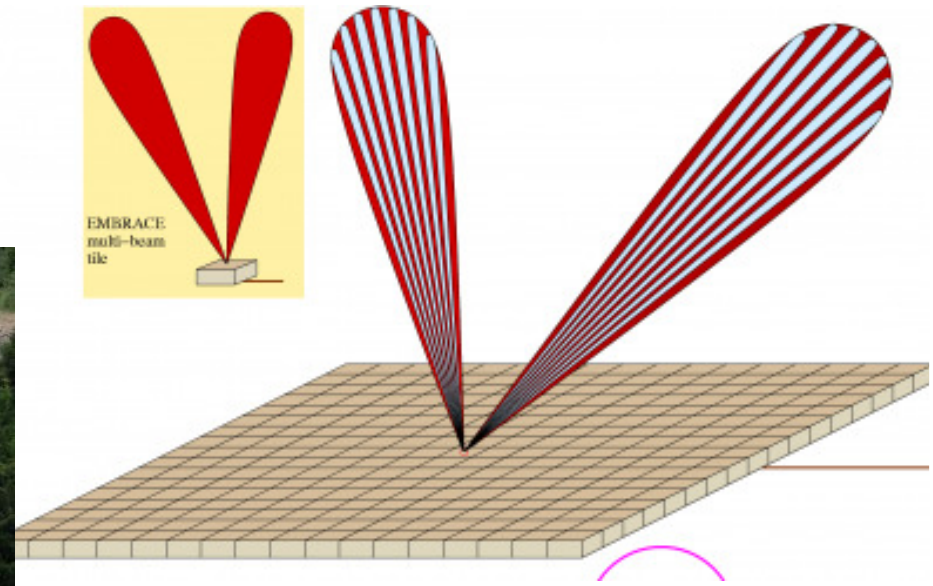
- A shift in time is a multiplication with a phase gradient in frequency

  (Fourier shift theorem)

- If Δv is small then the phase gradient is a phase factor



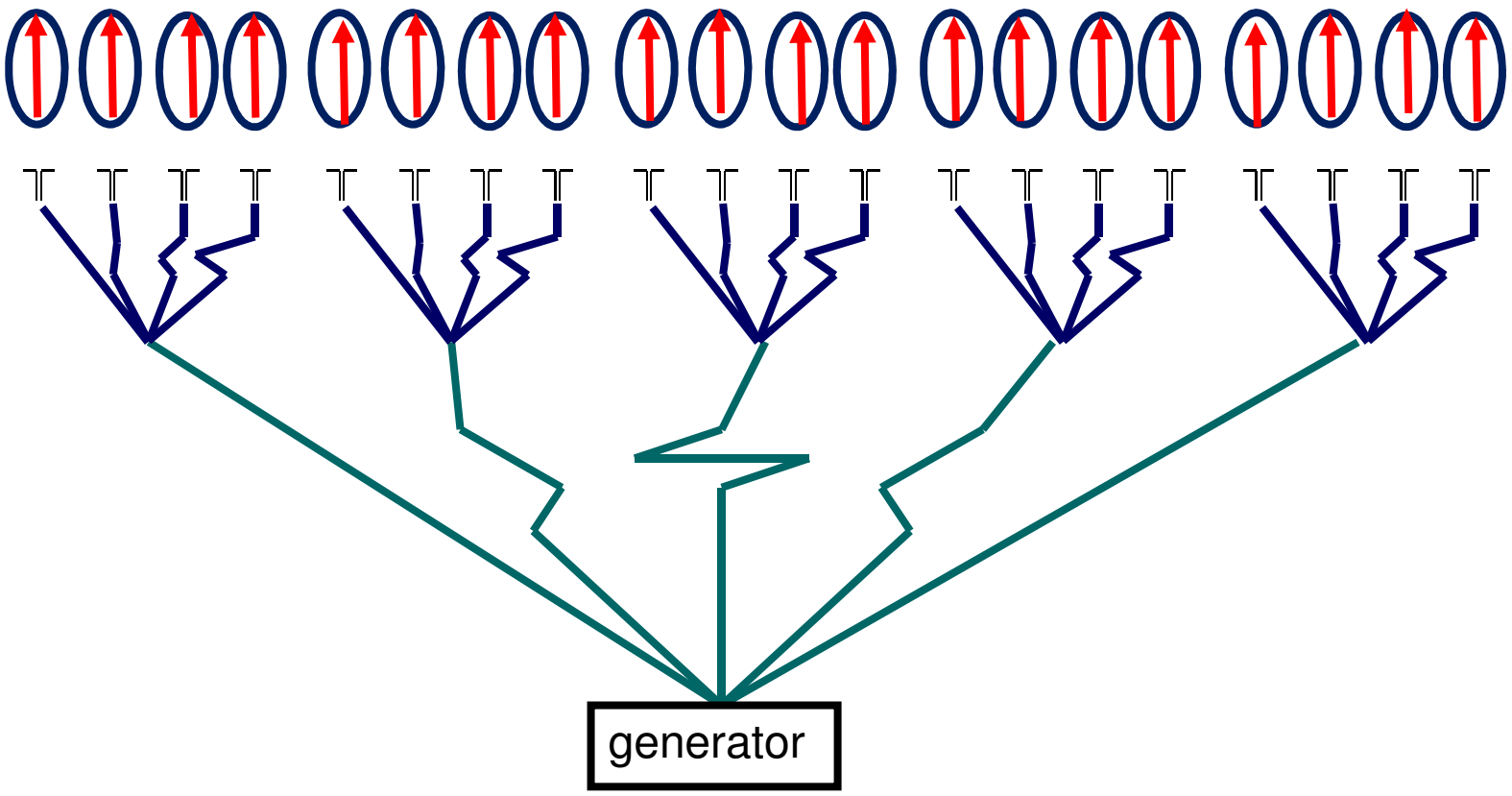
LOFAR High Band Antennas



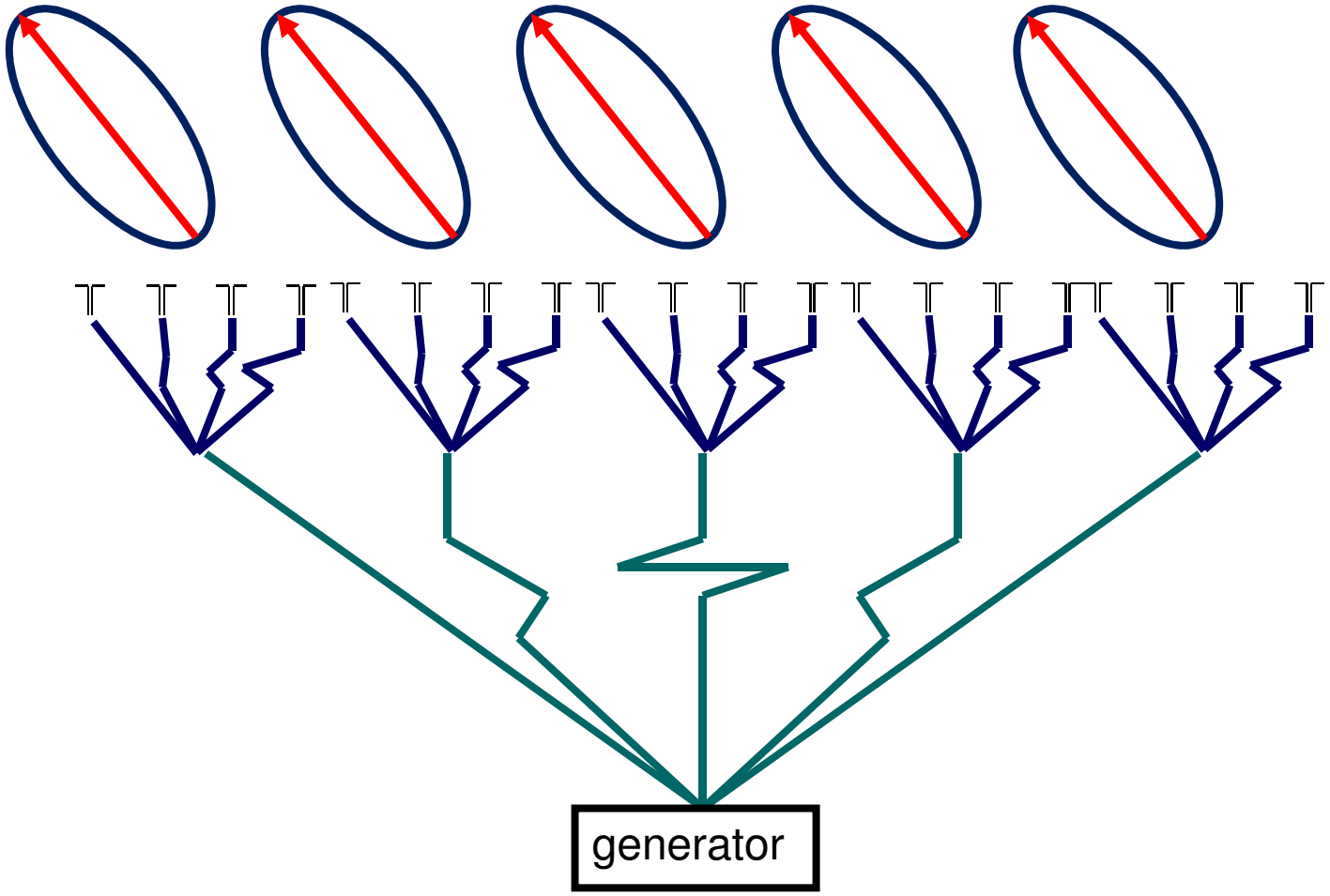
(ASTRON)

http://www.astron.nl/~devoscm/rd-wiki/doku.php?id=report_projects_2008

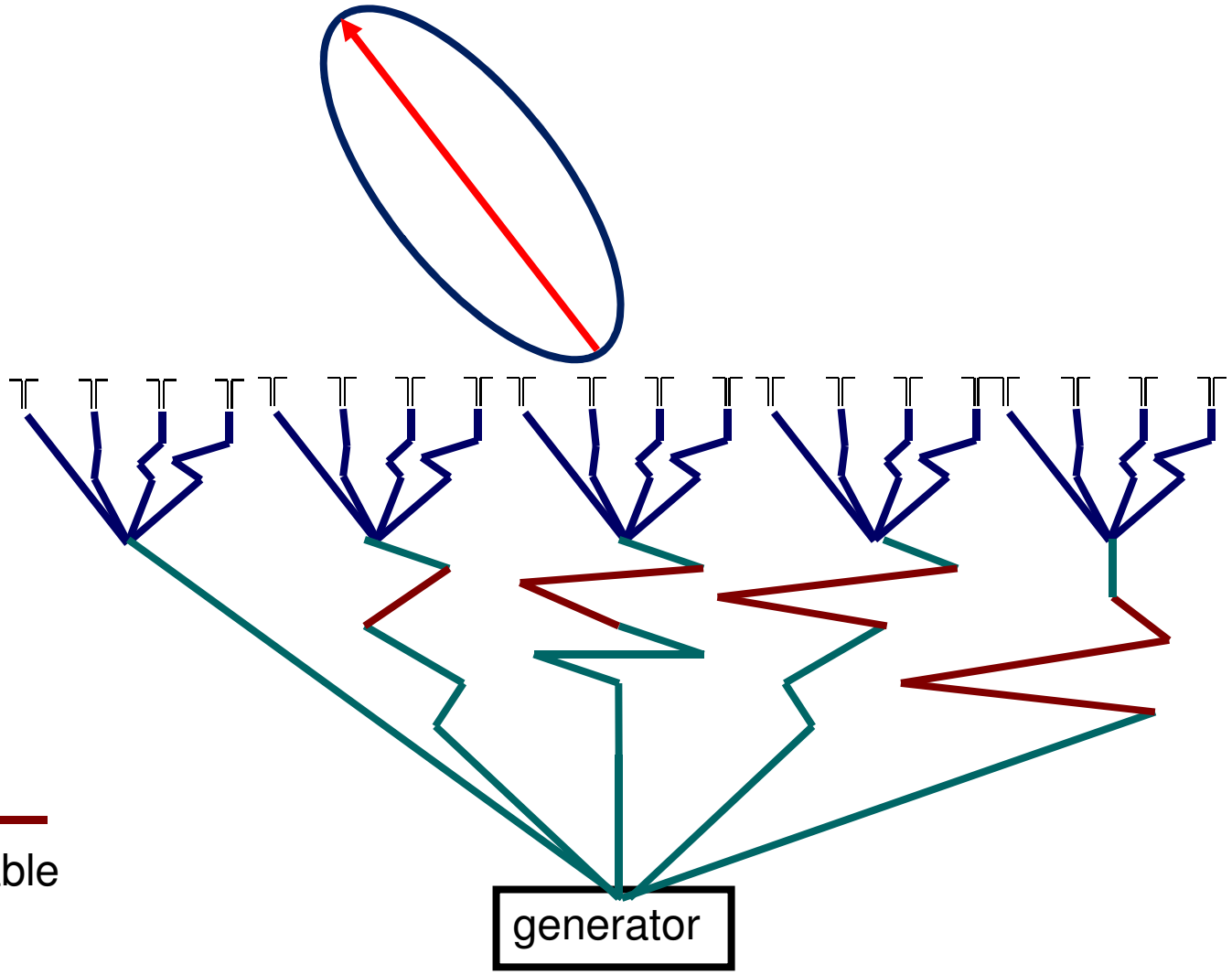
HBA Tiles
Dipole Beam



HBA Tiles
Tile Beam



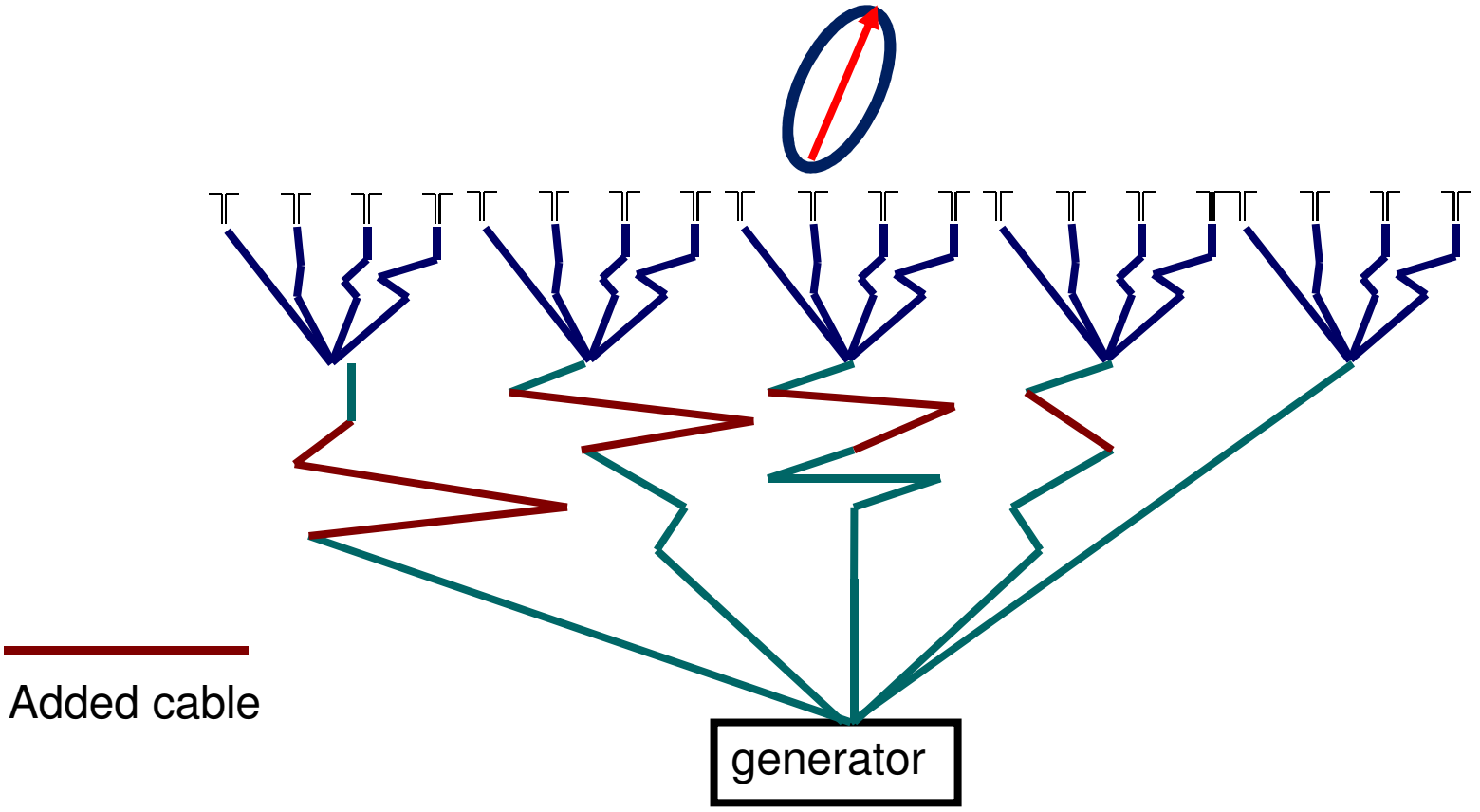
HBA Tiles
Station Beam 1



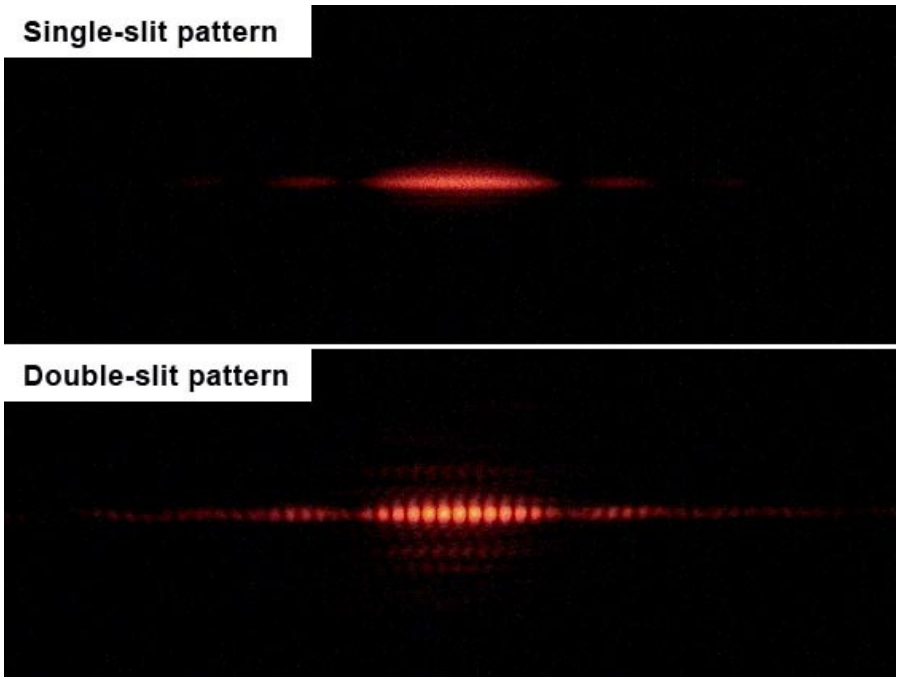
Added cable

HBA Tiles
Station Beam 2

- Station beam outside the tile Beam



Single- and Double-Slit Experiment

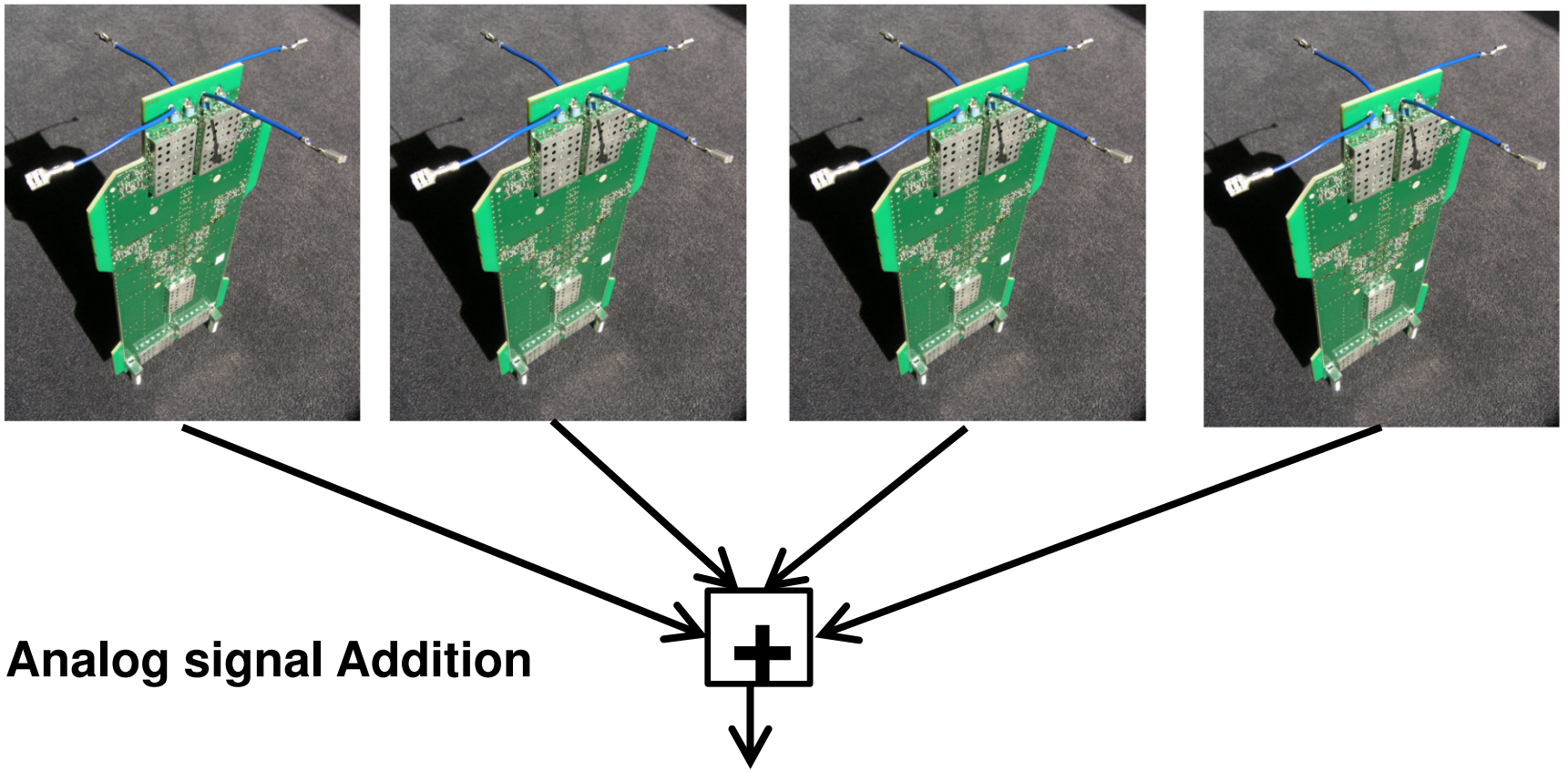


- You see the main pattern from the single slit
- In the double slit experiment the brightness of the double-slit maxima is modulated with the single-lit pattern
- See same effect when forming a station beam within a tile-beam

Images from Wikipedia

LOFAR Tile Beamformer

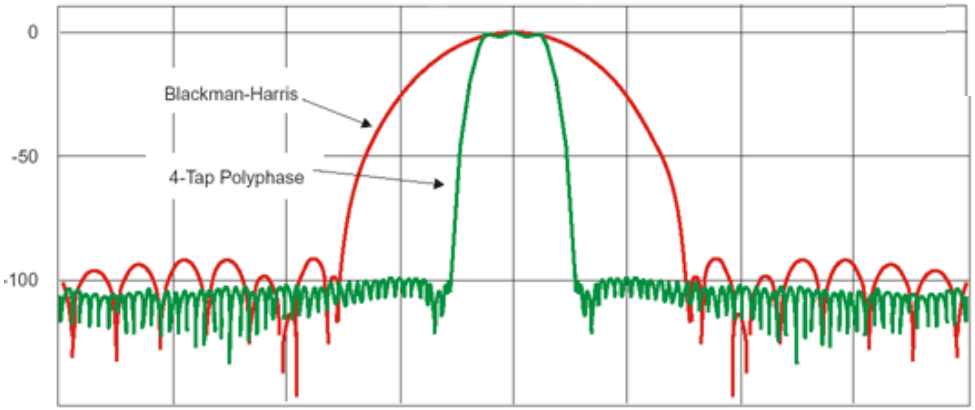
1) **Delay Lines on Frontend Boards**
   5 bit (32 steps); 0.5 ns resolution



2) **Analog signal Addition**

LOFAR Station Beamformer

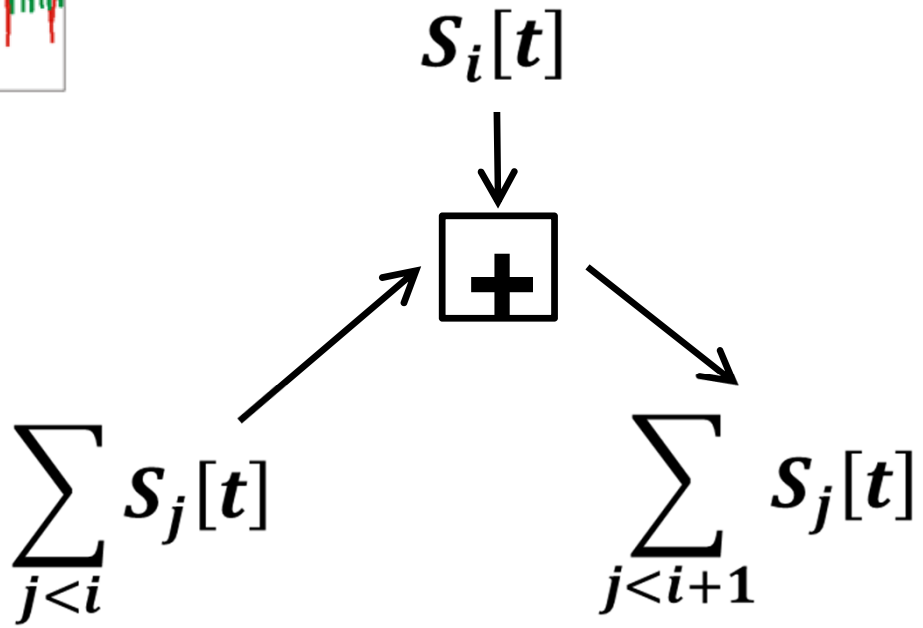
1) Polyphase Filterbank



2) Multiply with phase weigth

$$S_{f,out}[t] = S_{f,in}[t] * A_f e^{i\theta_f}$$

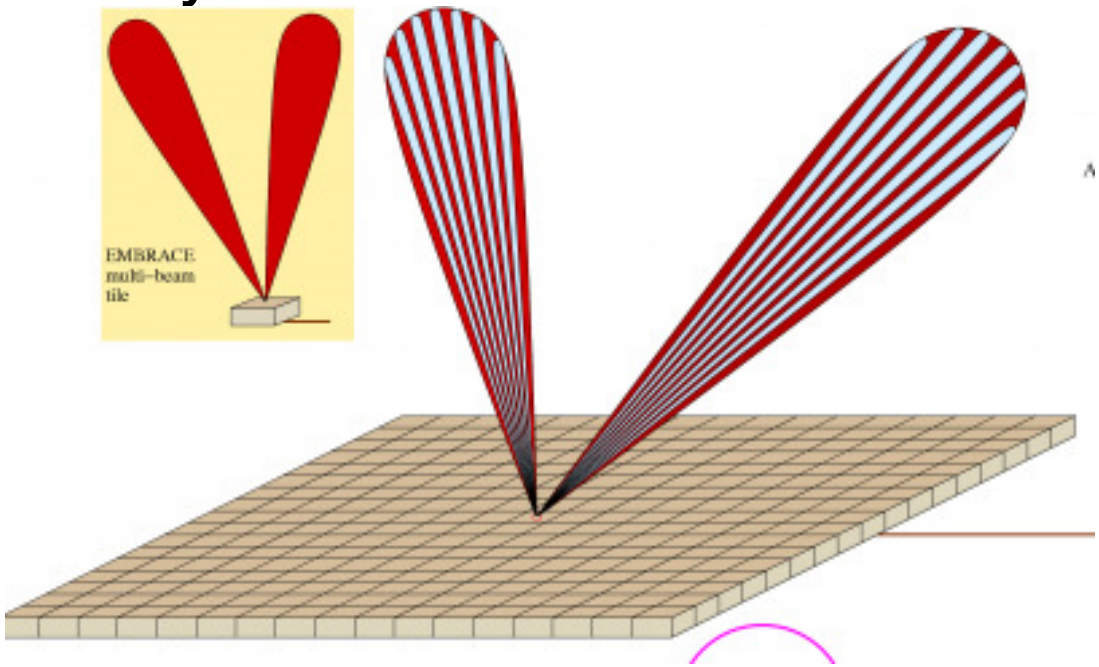
3) Add to data on ring



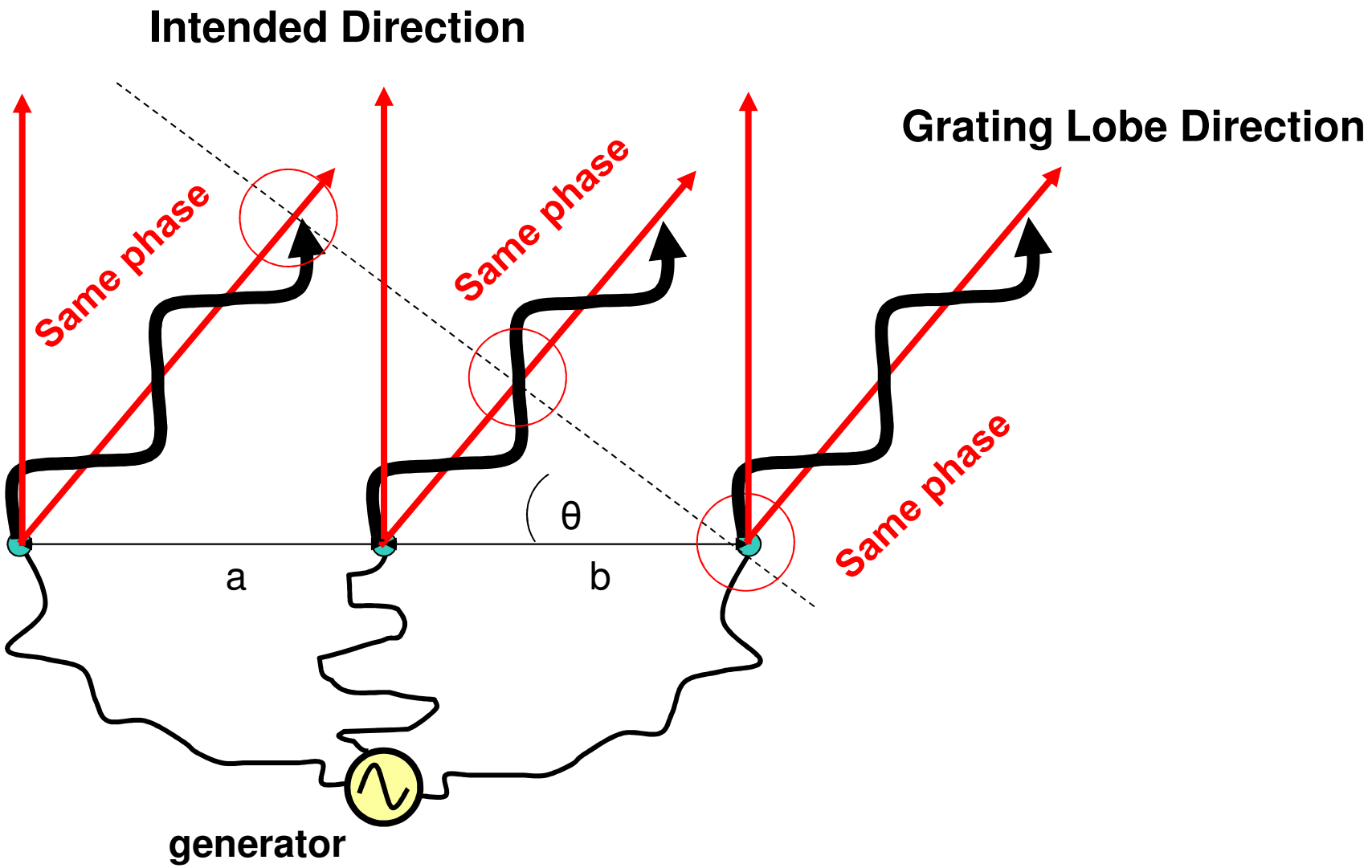
Remote Station Processing board

HBA Multi-Beaming

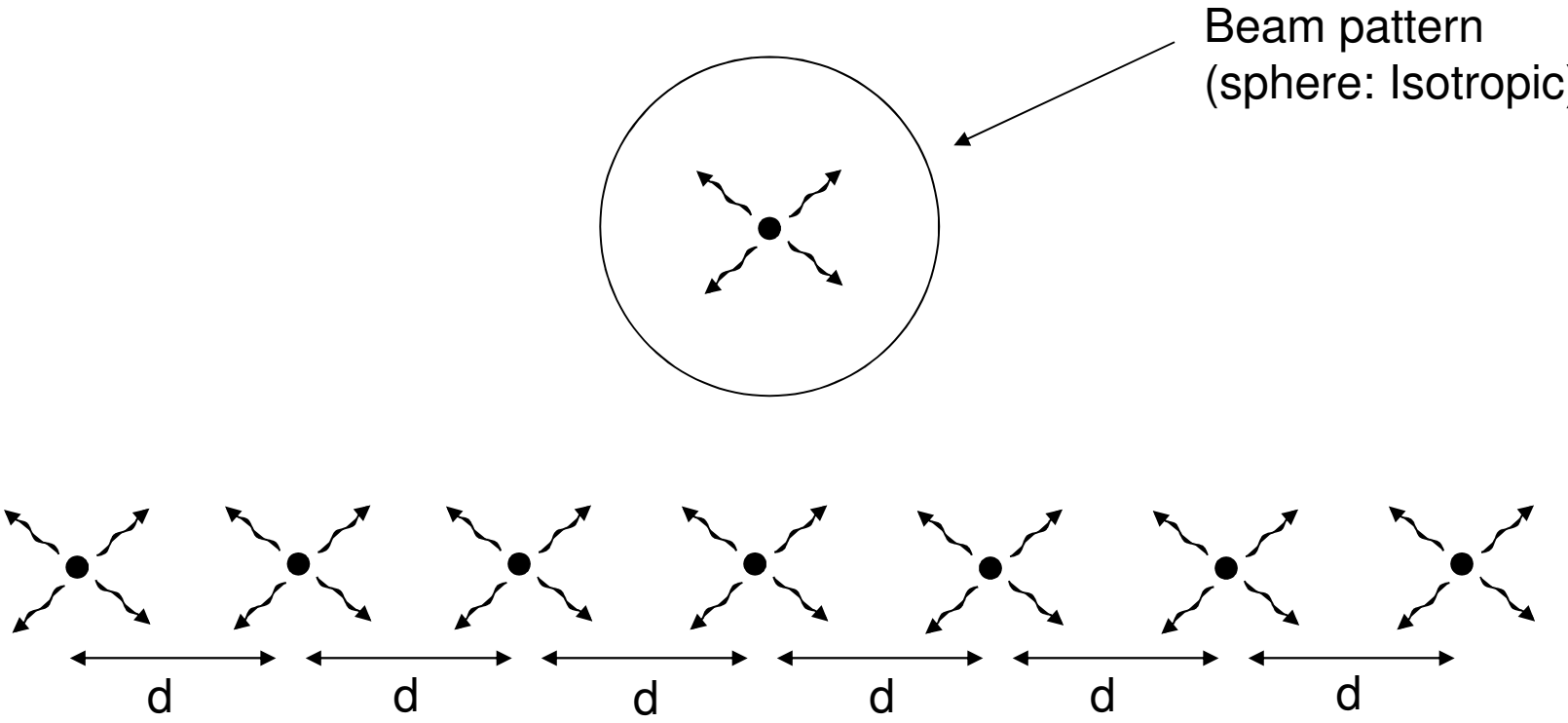
- Only one tile beam!
- Can point several stations beams within the tile beam.
- Can point station beam outside the tile beam, but with reduced sensitivity.



Grating Lobes

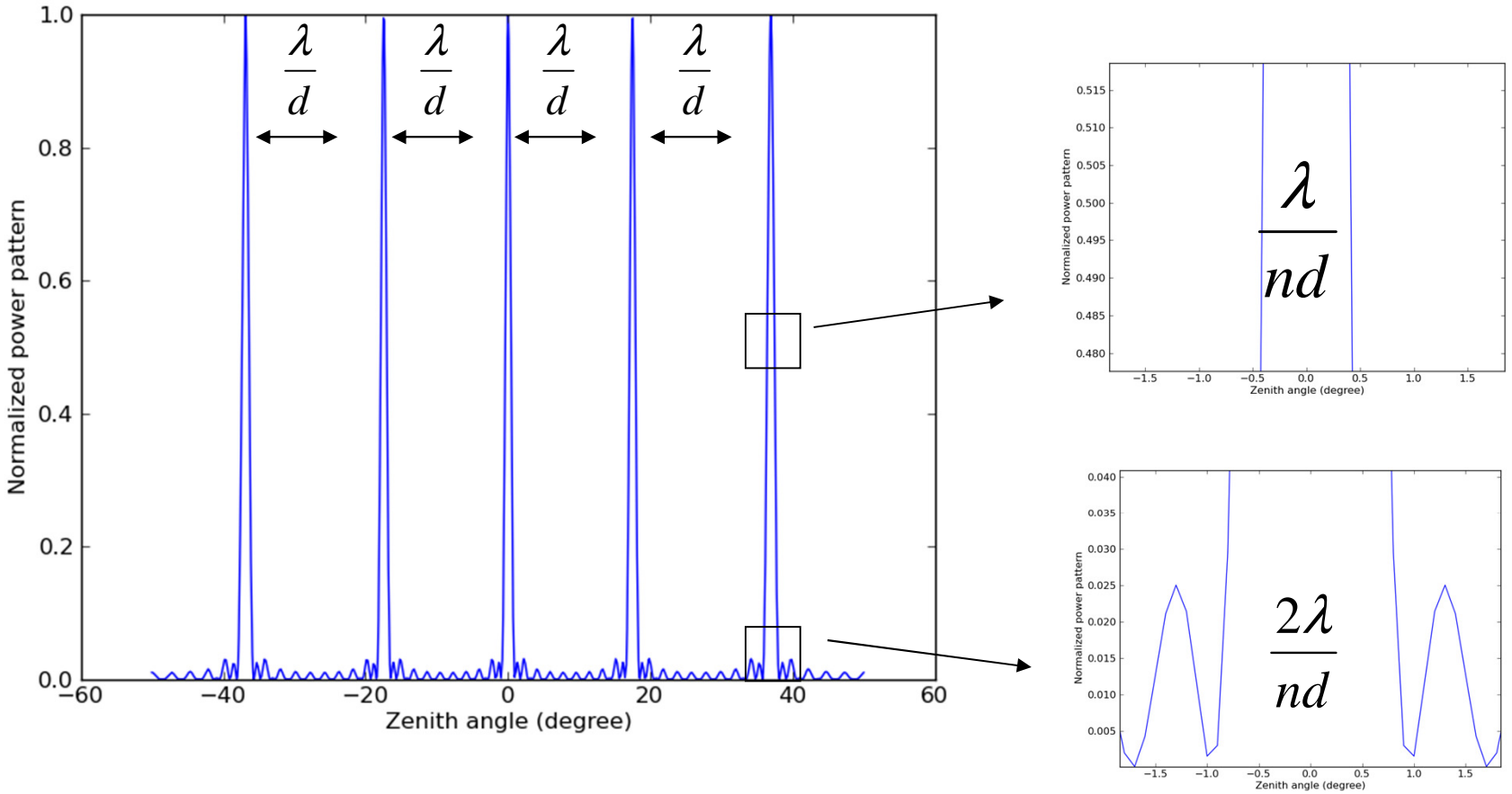


Grating Interferometer with Isotropic Sources

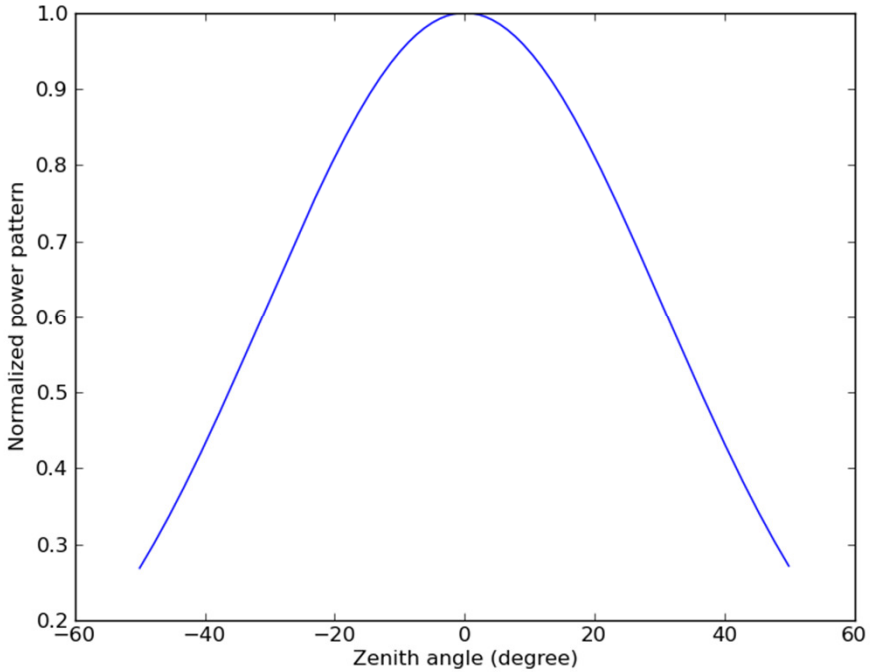


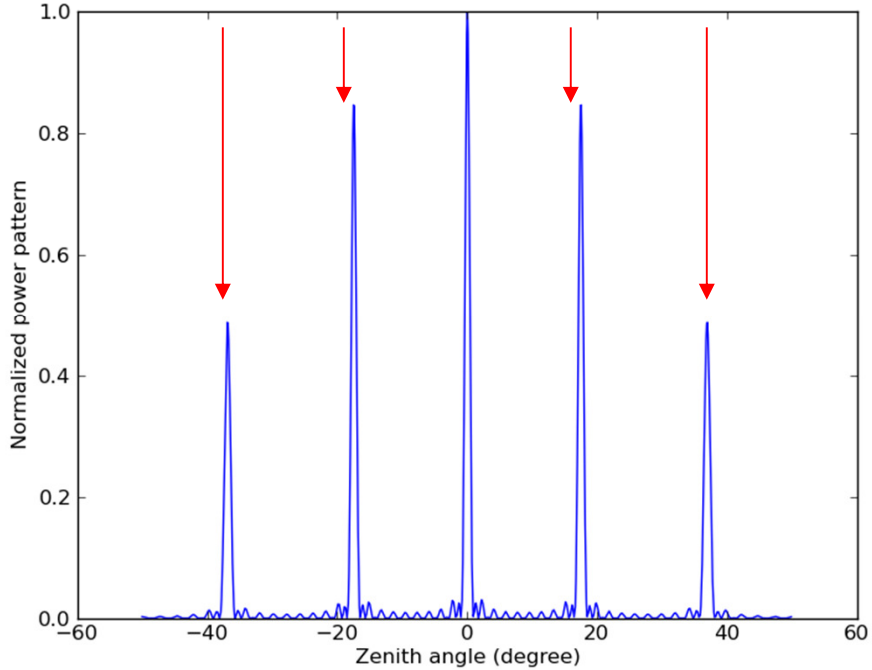
Array of n isotropic sources of equal amplitude E_0 and spacing d

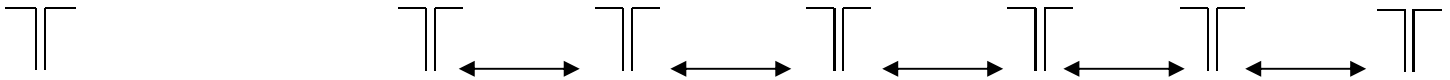
Grating Interferometer with isotropic sources



Grating Interferometer with Dipoles

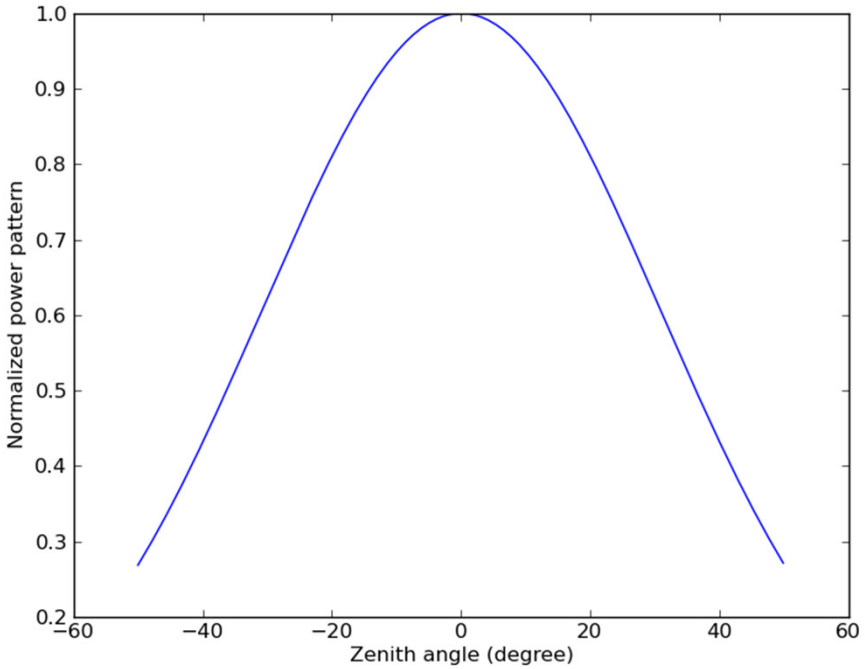


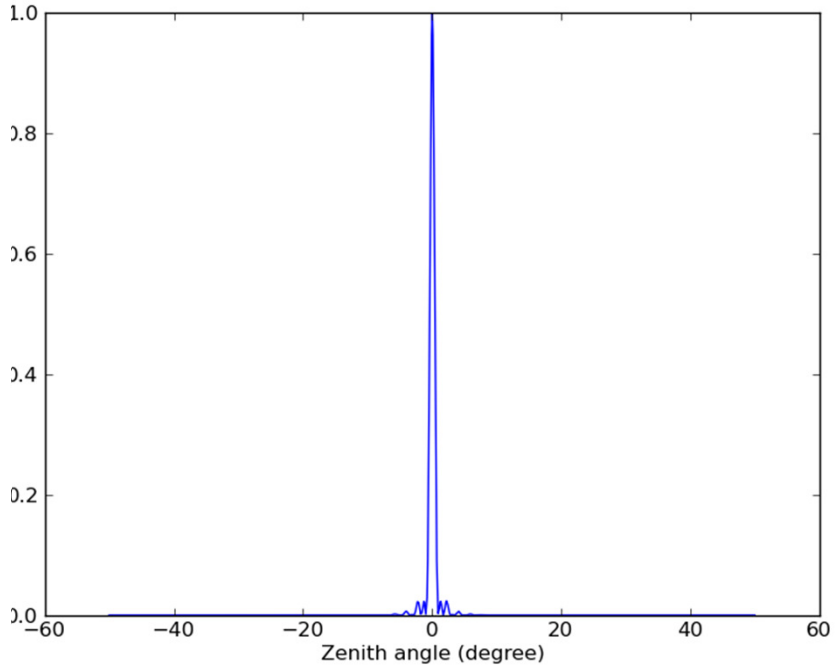


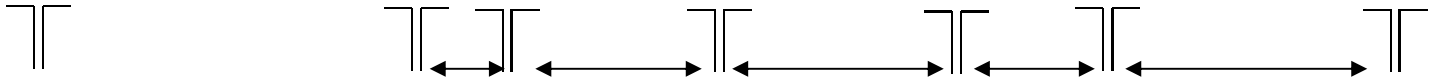


Array of the same spacing

LOFAR Pseudorandom Spacing

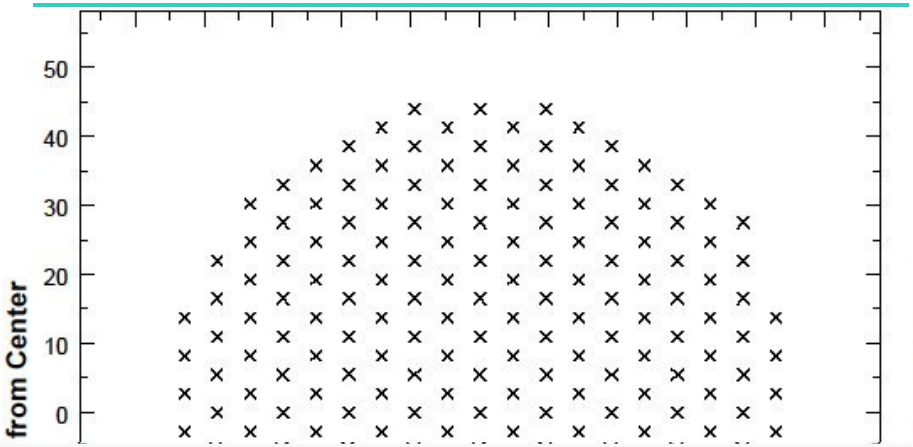


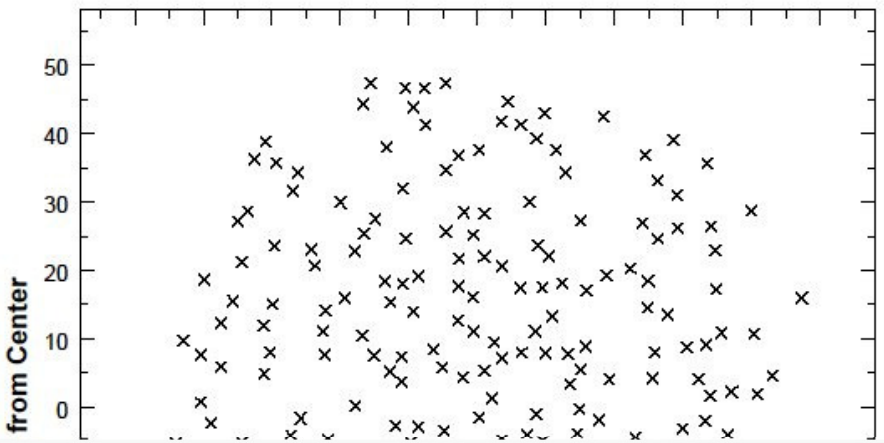


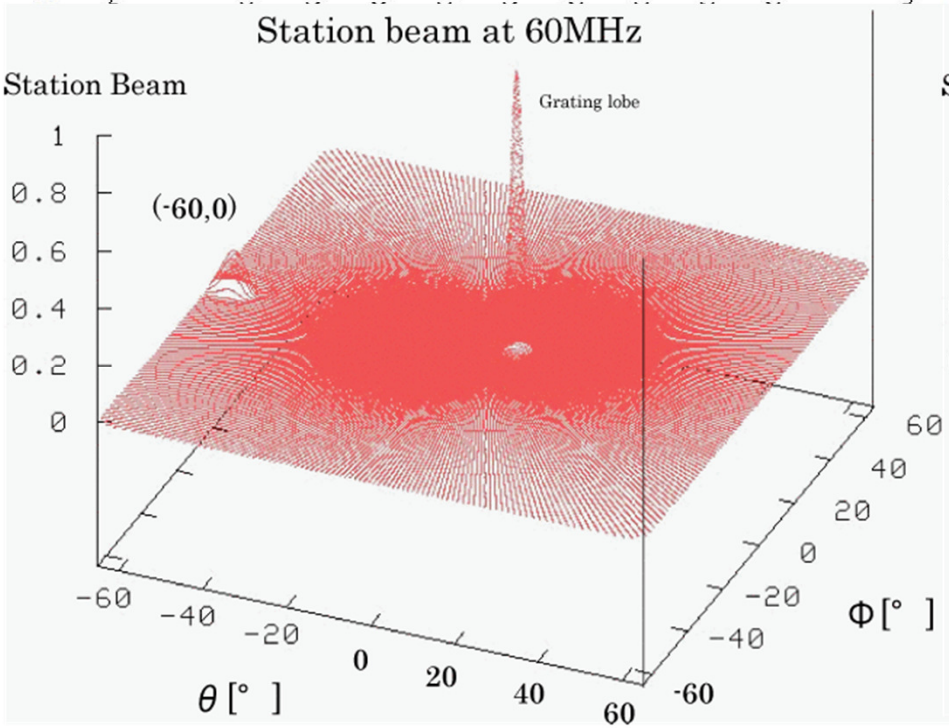


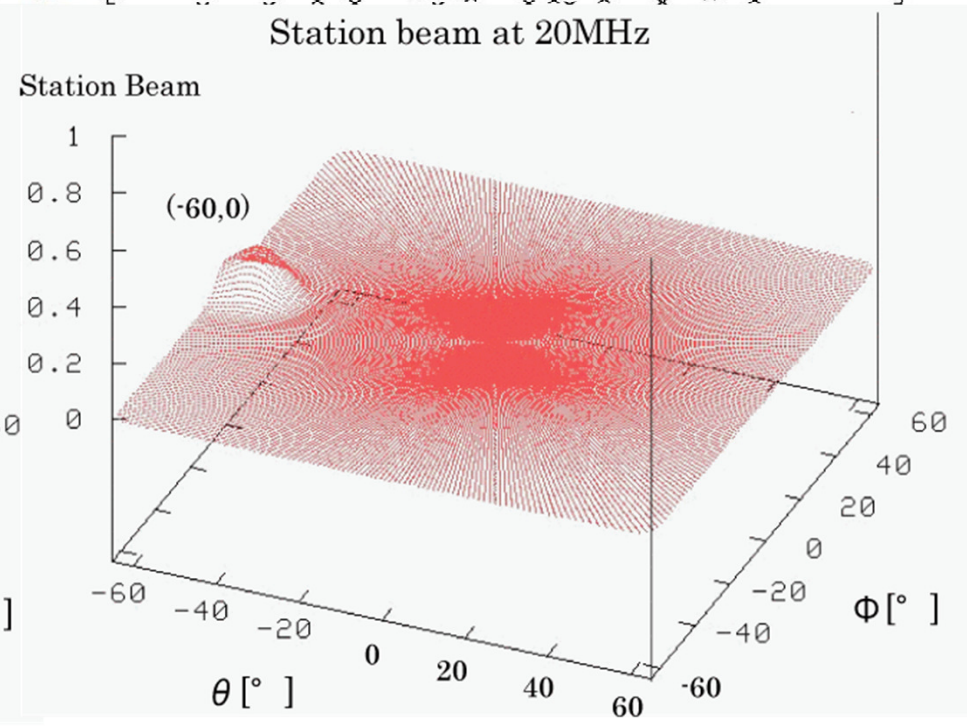
Array of pseudorandom spacing

LOFAR Grating vs Pseudorandom



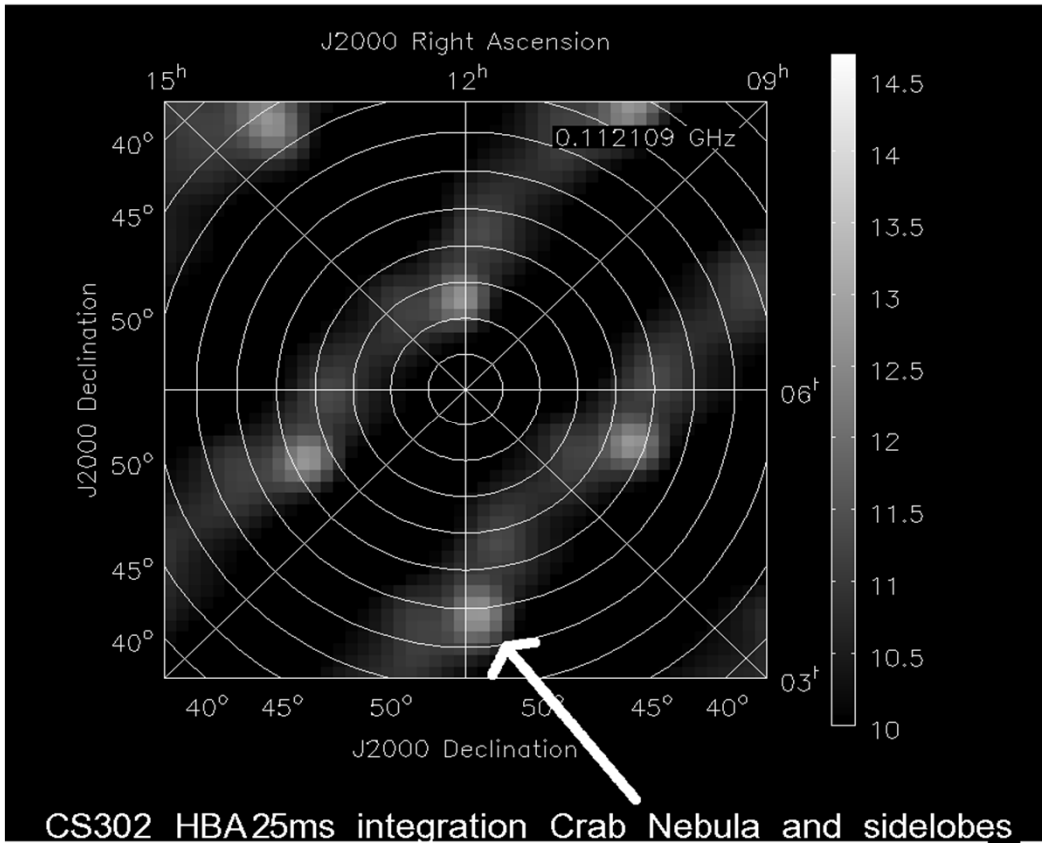






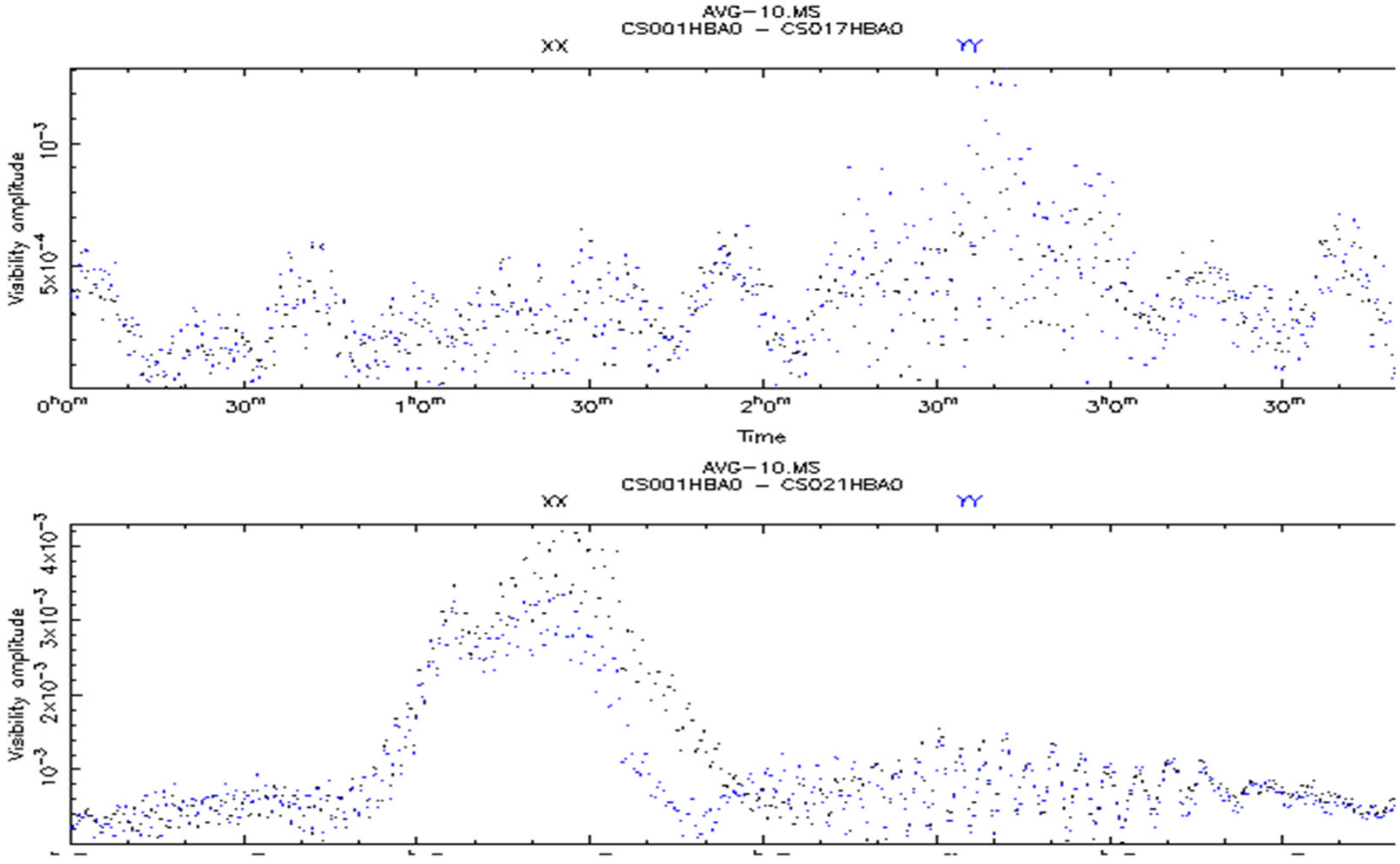
Crab Nebula

- regular HBA spacing creates grating lobes
- Position of grating lobes changes with frequency



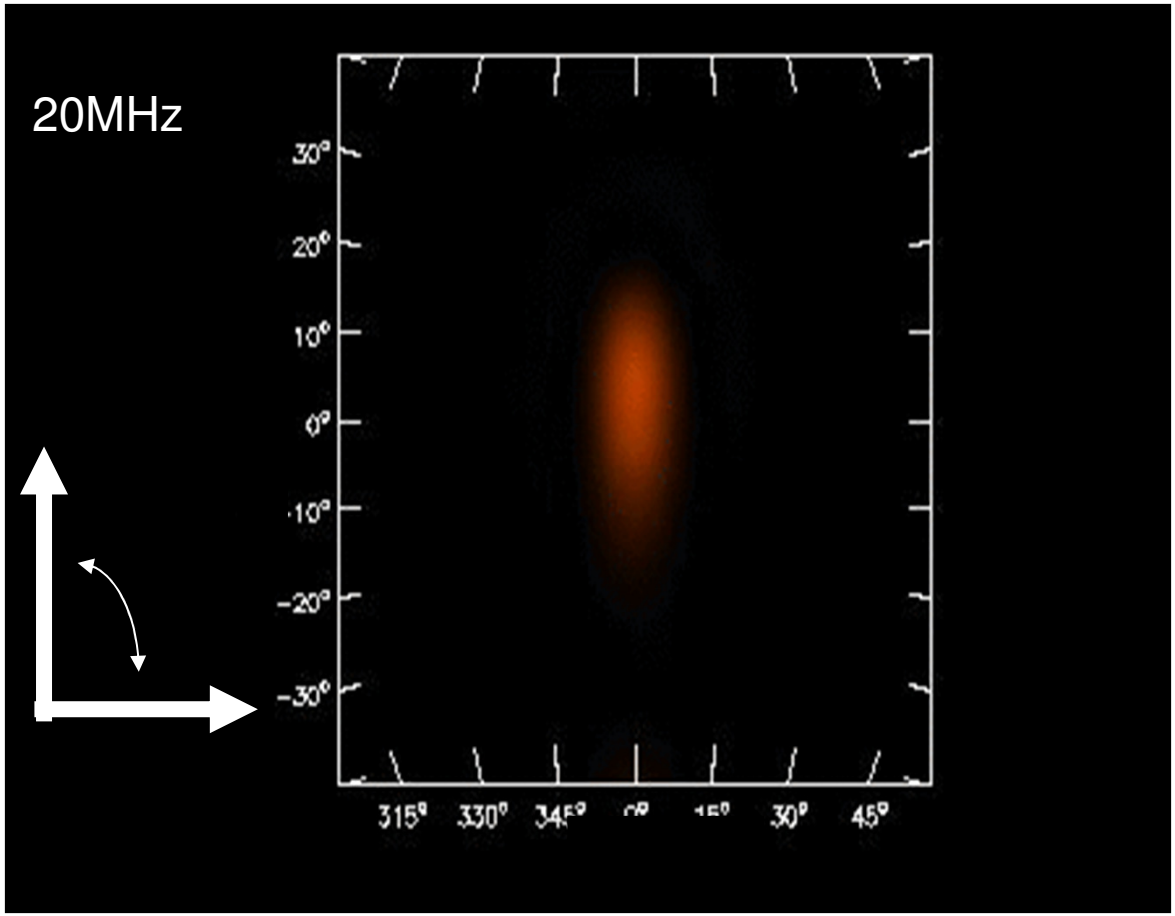
by S. ter Veen

Grating Lobes in LOFAR Visibilities



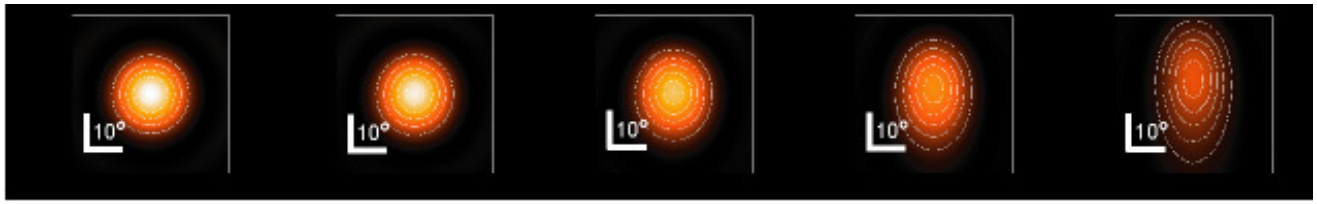
- Two Baselines
- One of the stations of the second baseline had a grating-lobe on a strong source.

LOFAR Station Primary Beam



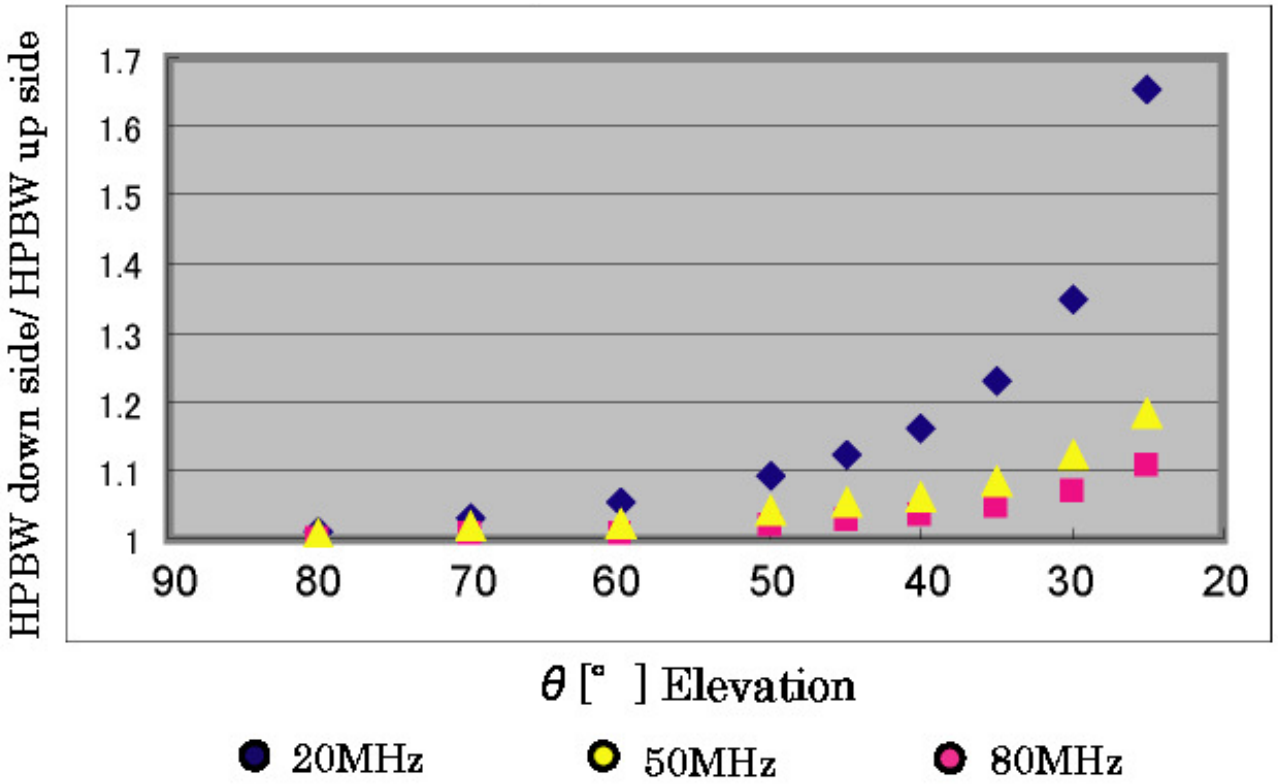
That's actually a LWA simulation.

Asymmetric Station Beam



20MHz

The ratio of the HPBW of down side to up side



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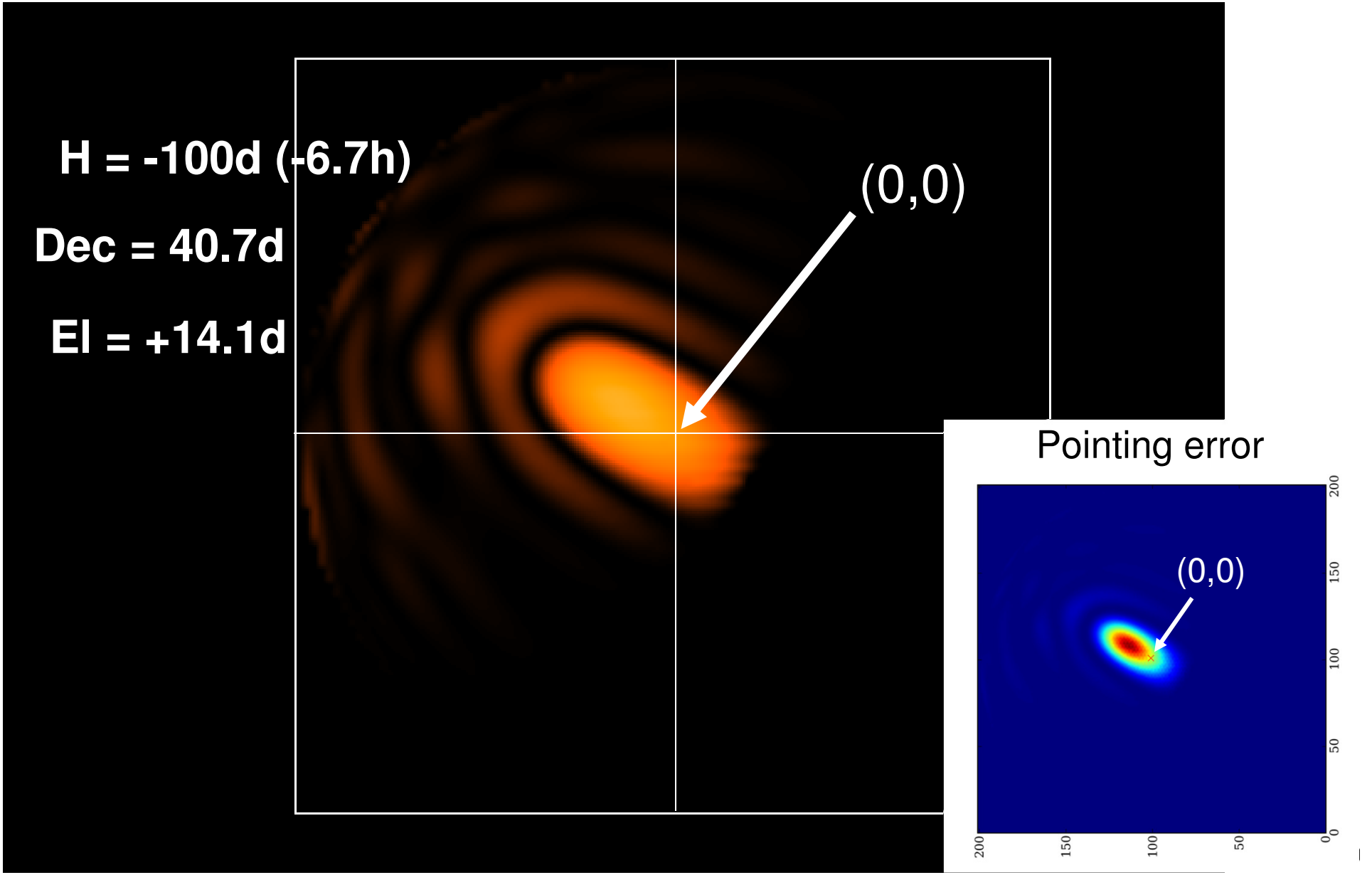
Pointing error



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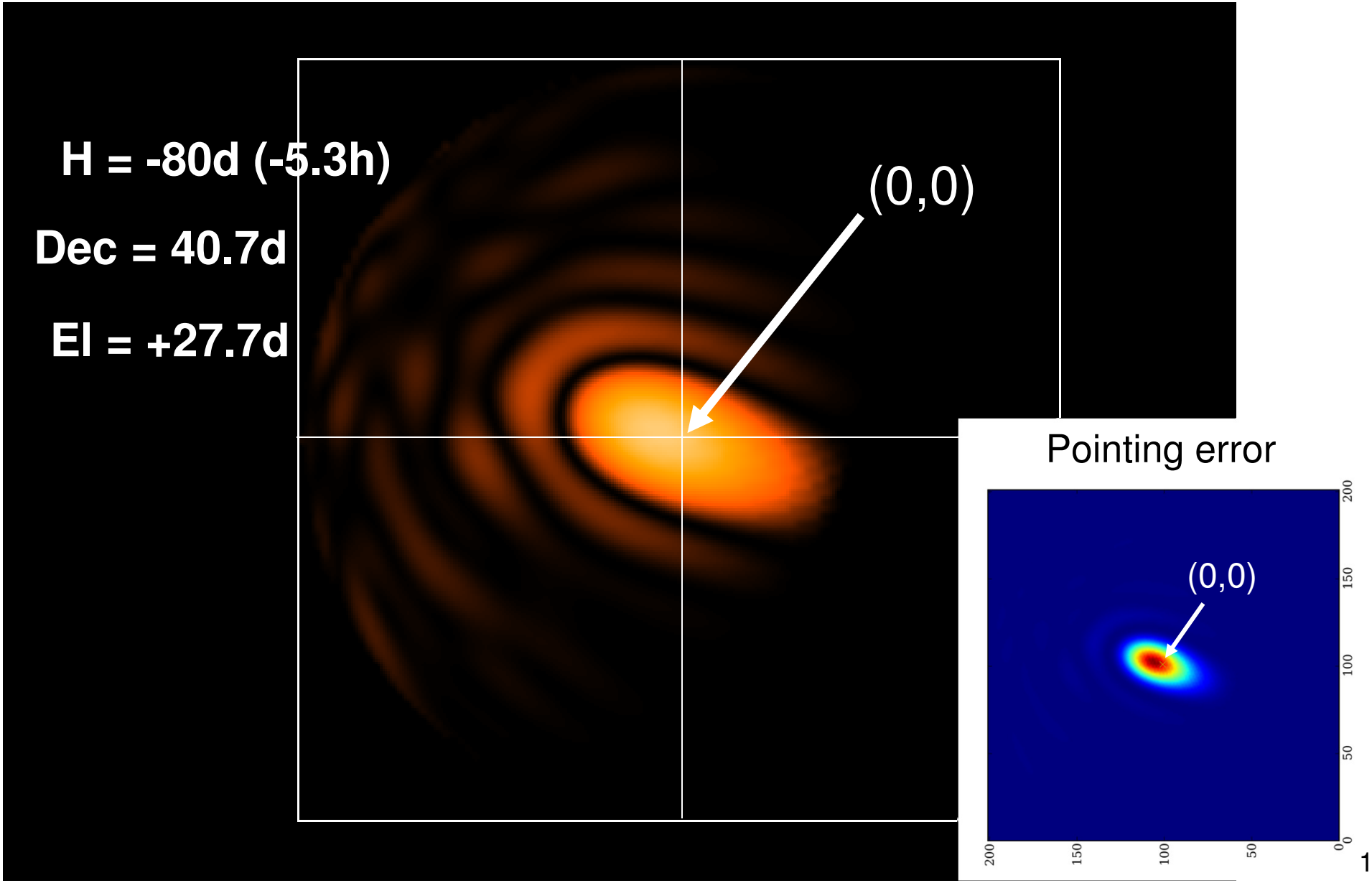

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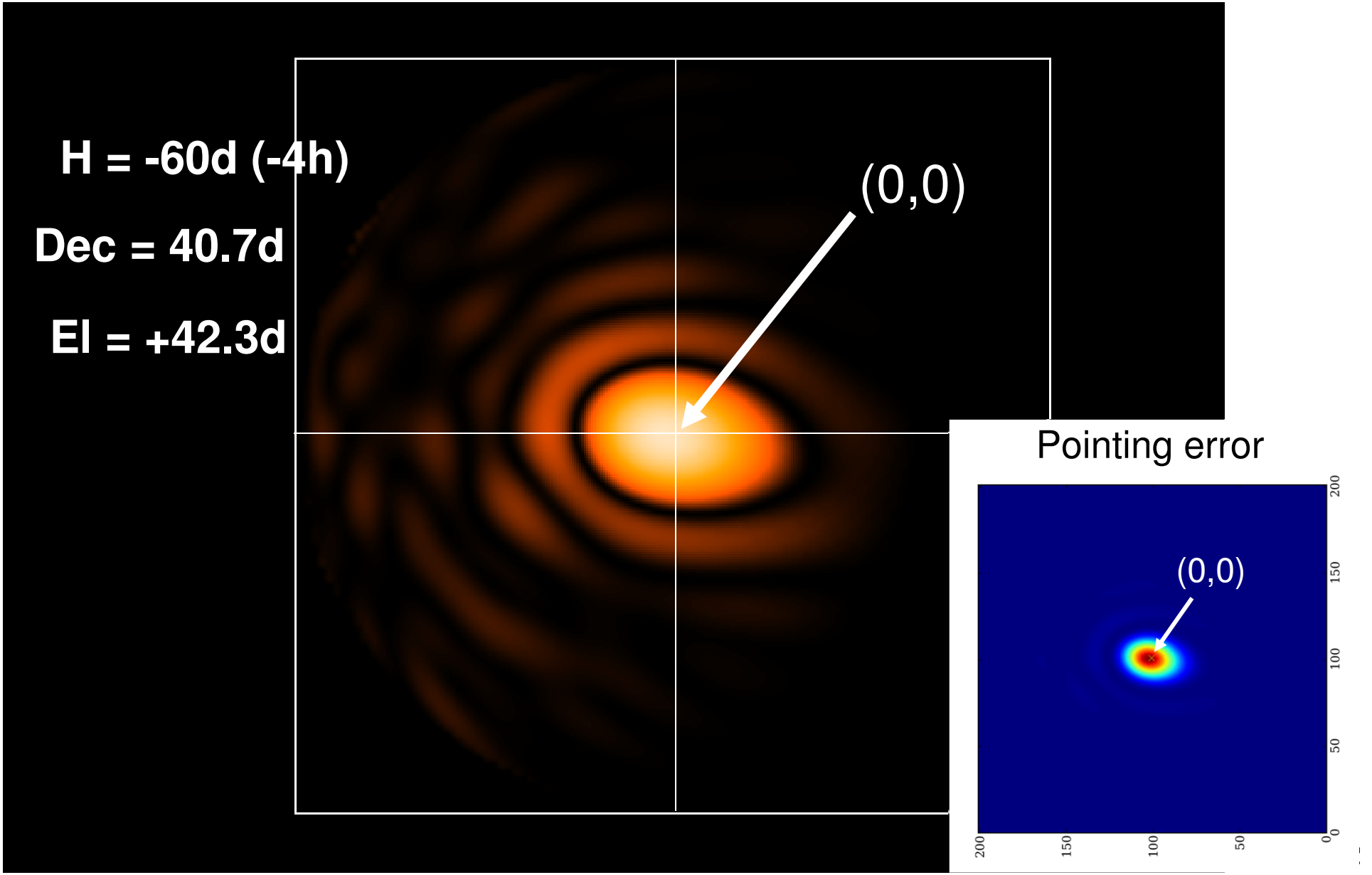

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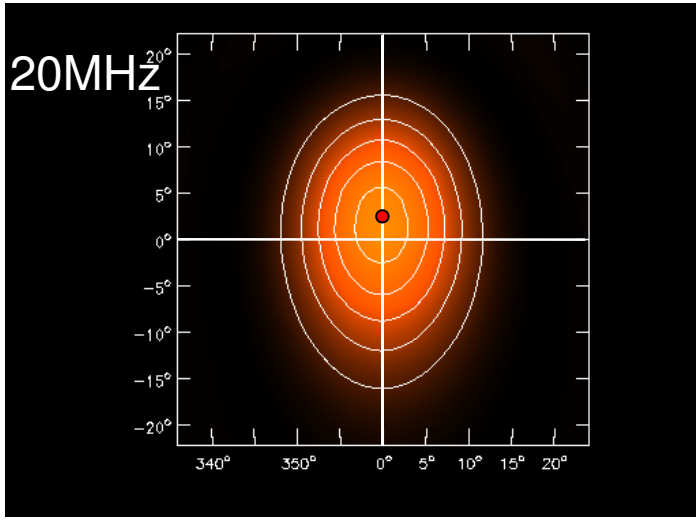
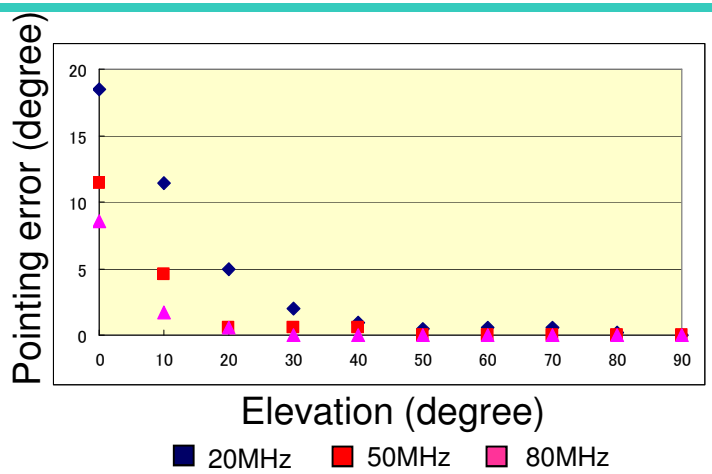
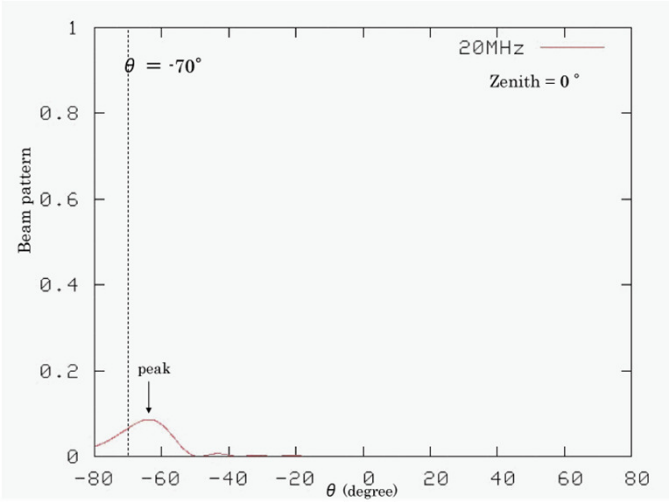
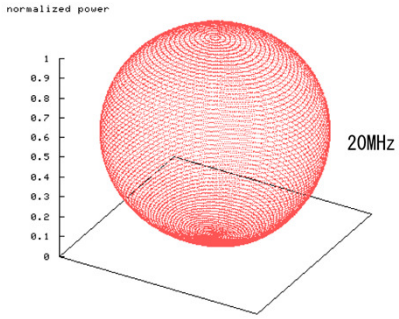




Pointing error as a function of elevation angle (degree).



Pointing error

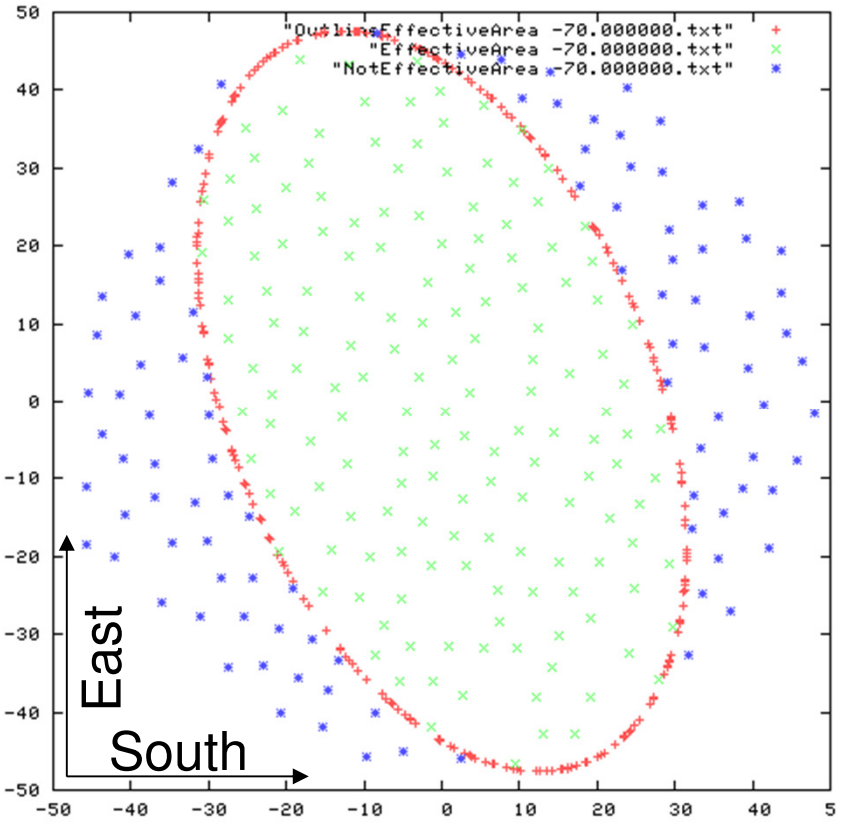


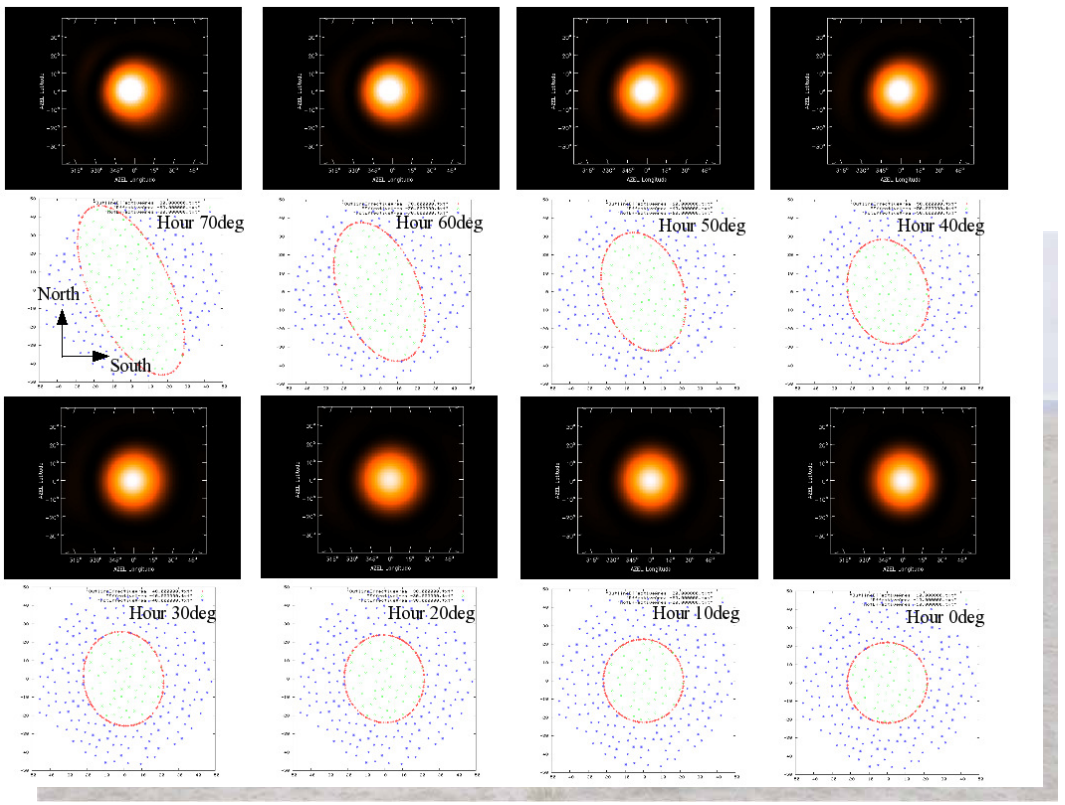
antenna reception patterns

That's actually a LWA simulation.

Shaping the Beam

- Shape the beam by giving different weights to the elements
- In this case: get a circular beam at all elevations

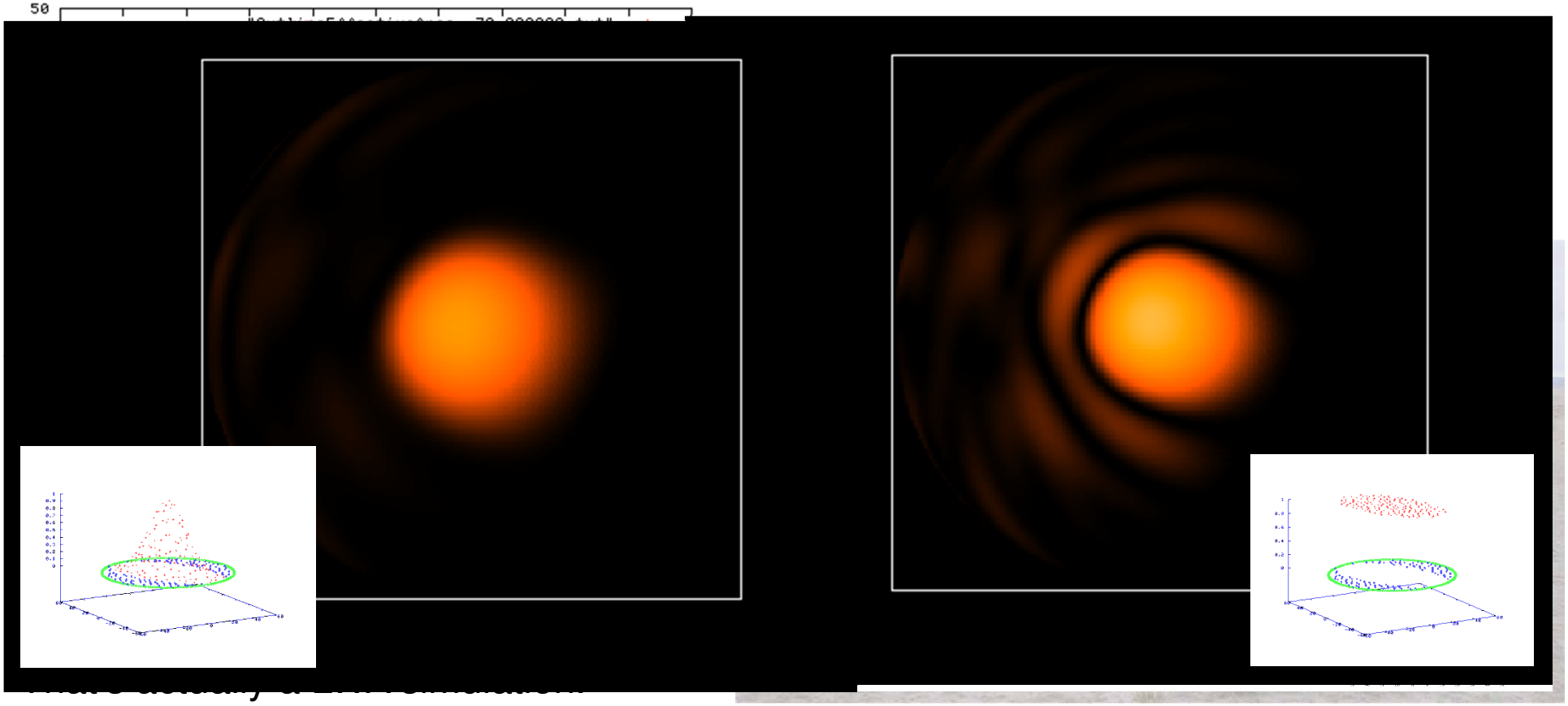




That's actually a LWA simulation.

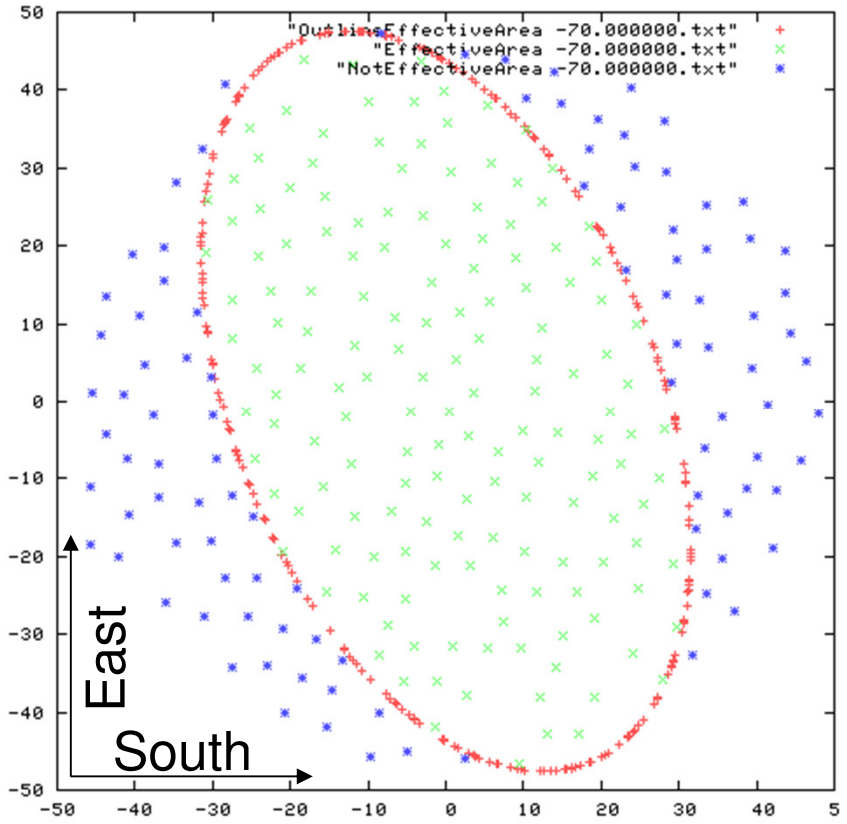
Shaping the Beam

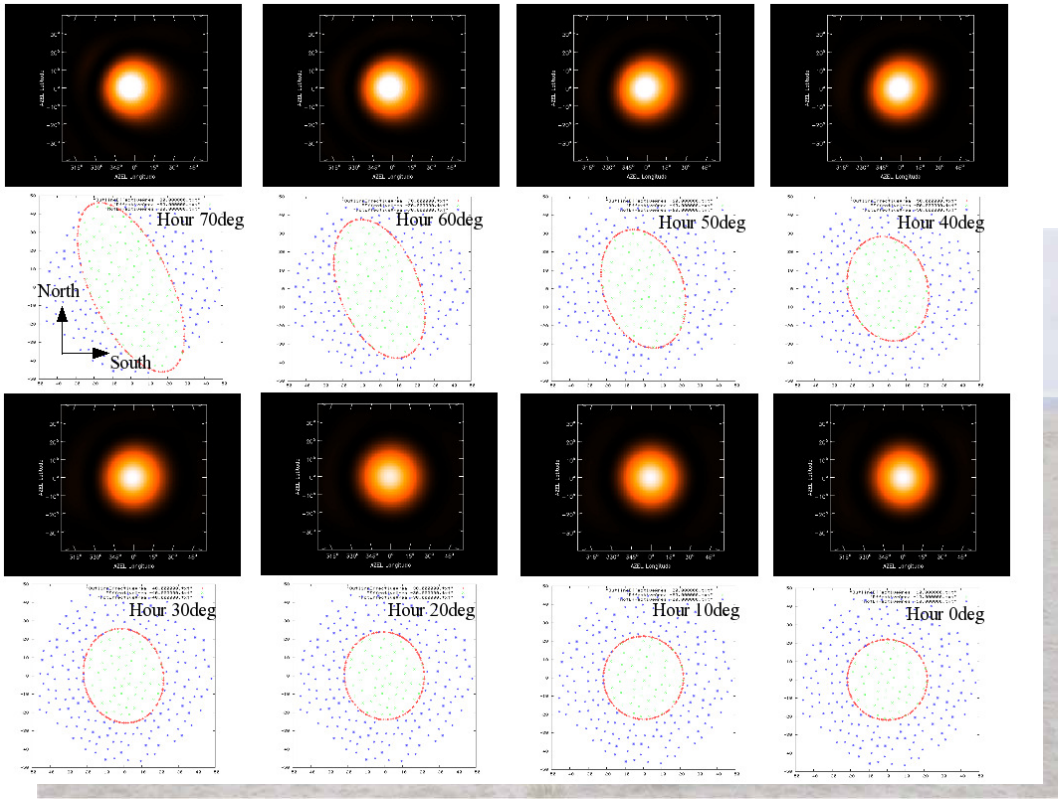
- Shape the beam by giving different weights to the elements
- In this case: get a circular beam at all elevations



Shaping the Beam

- Disadvantage: loose a lot of sensitivity!



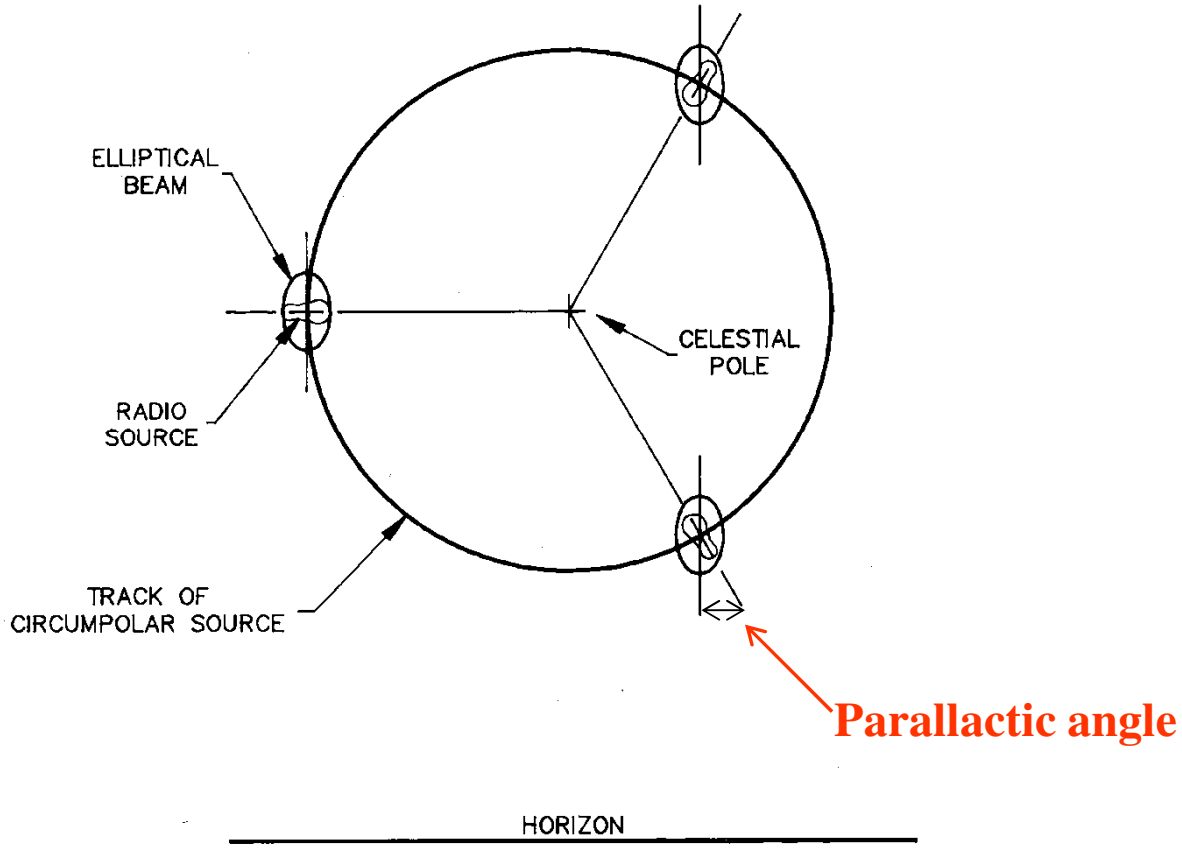


That's actually a LWA simulation.

LOFAR

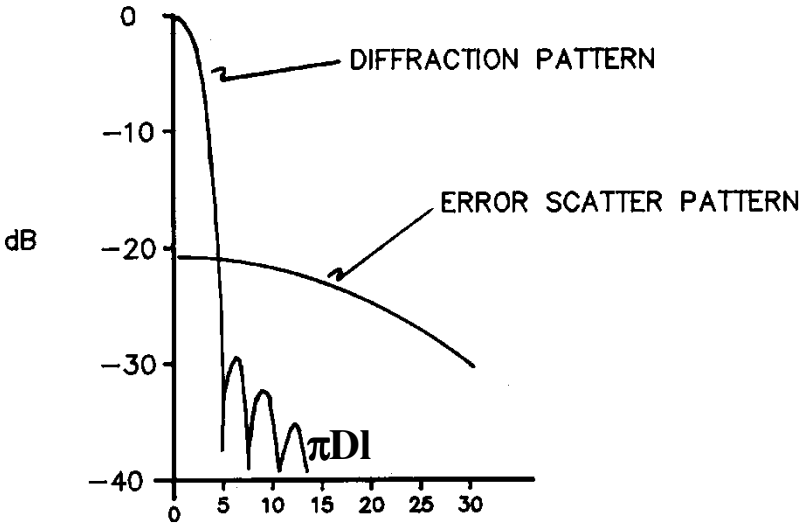
The End!

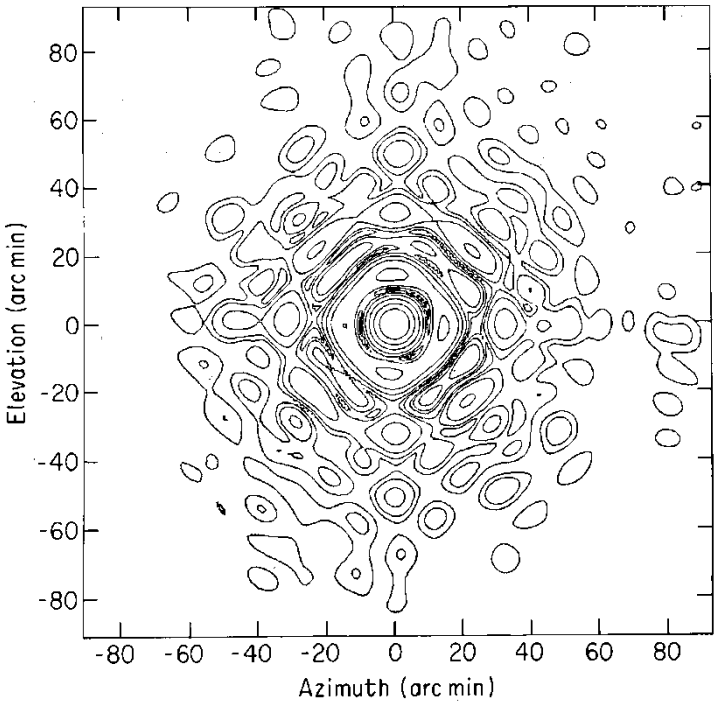
LOFAR Beam Rotation on the Sky



Antenna Performance Parameters

Primary Beam Shape





Antenna Performance Parameters

Pointing Accuracy

$\Delta\theta$ = rms pointing error