LOFAR

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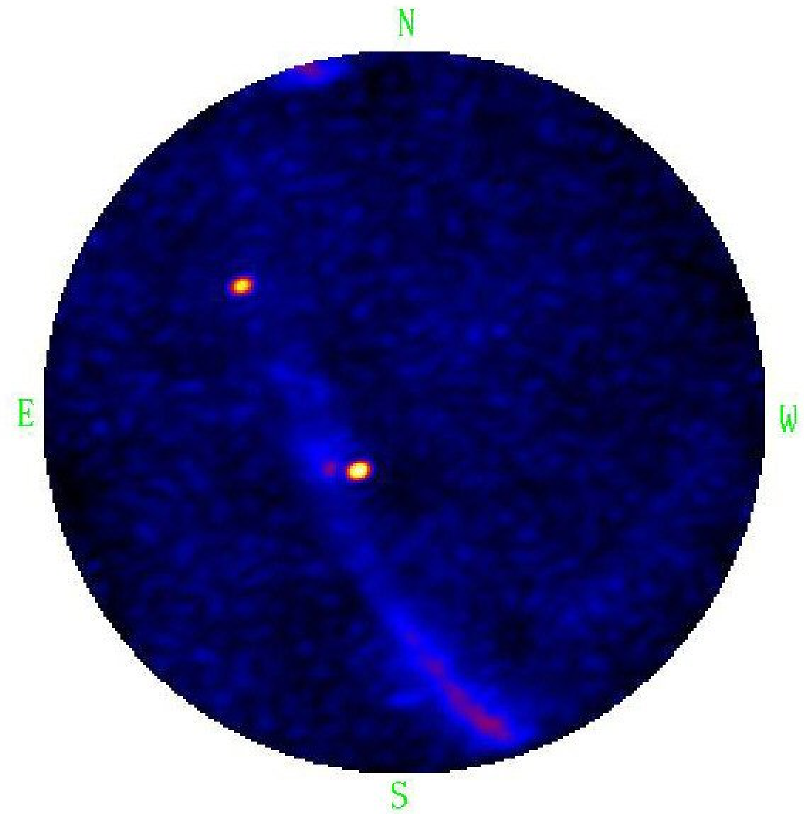


On behalf of the LOFAR collaboration

Max-Planck-Institut für Radioastronomie

LOFAR

MAX-PLANCK-GESELLSCHAFT

Acknowledgements

- LOFAR development is performed by a very large community
- Some of the slides in this presentation have been stolen from the antennas and receiver talks of Peter Napier (2006 school) and Mark McKinnon (2010 school)
    - See http://www.aoc.nrao.edu/events/synthesis/2010/
      http://www.aoc.nrao.edu/events/synthesis/2008/
      http://www.aoc.nrao.edu/events/synthesis/2006/
- Many other slides explaining how aperture arrays work were taken from M Kuniyoshi
    - http://www.astro.rub.de/glow_school_2010

What Is LOFAR?

- Dutch propaganda film
  - http://www.lofar.org/sites/lofar.org/files/u3/lofar.swf

Effelsberg and LOFAR

What Is "Single Dish Radioastronomy"?

- Obviously, it is what you do if you only have a single (big) dish
  - But not everything you do with a single dish is really single dish radioastronomy
  - The single of single dish is not really the important part
  - Nor is the dish, for that matter
- Single dish radioastronomy is what you do when you don't want to do radio interferometry
  - Interferometry: multiplying cosmic signals
  - Non-interferometry: adding cosmic signals, multiplying a cosmic signal only by itself or by a frequency standard (mixing)
    - Note that additive interferometry for centimeter and longer radioastronomy is really used for what we think of as "single dish" techniques to the astronomer today

Typical Single Dish Applications

- Flux density monitoring
  - I don't care what it looks like, I just want to know how bright it is and whether or not that brightness changes
- Spectral measurement
  - I don't care what it looks like, I just want to measure part of the spectrum
- High time resolution
  - I don't care what it looks like, I just want to measure the brightness to look for really fast changes
- Total power measurement/imaging
  - I do care what it looks like, and my interferometer does not measure (part of) what I need
  - Zero-spacing measurement

LOFAR Can Do All of These Things

- At the individual element (dipole) level
- At the station level
  - A single International Station is equivalent to a ~55 m diameter dish
  - The sensitivity of a single station is useful for many interesting science applications
- At the multiple-station level
  - What LOFAR calls tied-array mode, often called phased-array mode in other parts of the world
- Future instruments (read SKA) will also be able to do these things
- To be fair, many existing interferometers can do many of these things, and some can do all of them
    - You have to look carefully at the performance properties of individual instruments, and choose the instrument which best suits your scientific goals

“Single Dish LOFAR” By LOFAR KSPs

- Cosmic Magnetism
  - Zero-spacing information
- Deep Extragalactic Surveys
  - Zero-spacing information
- Epic of Reionization
- Solar Physics and Space Weather
  - High time resolution spectral monitoring of the Sun for Solar flares
  - Flux density monitoring of interplanetary scintillation
- Transient Sources
  - High time resolution observations of pulsars and planets
- Ultra High Energy Cosmic Rays
  - High time resolution observations of cosmic-ray induced radio pulses

So, What Is LOFAR and Why?

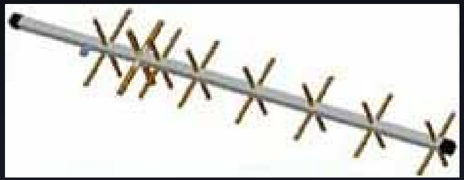
General Antenna Types

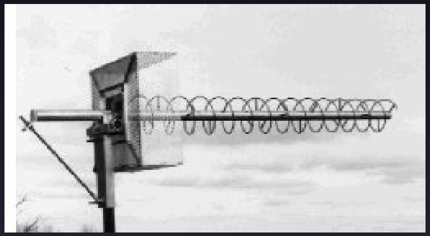
Wavelength > 1 m (approx)

Wire Antennas

Dipole

Yagi



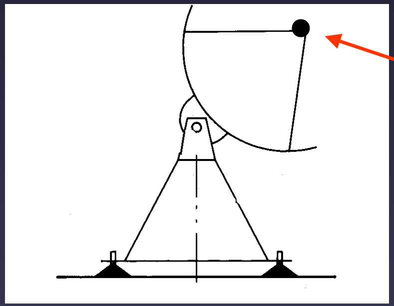


Helix

or arrays of these

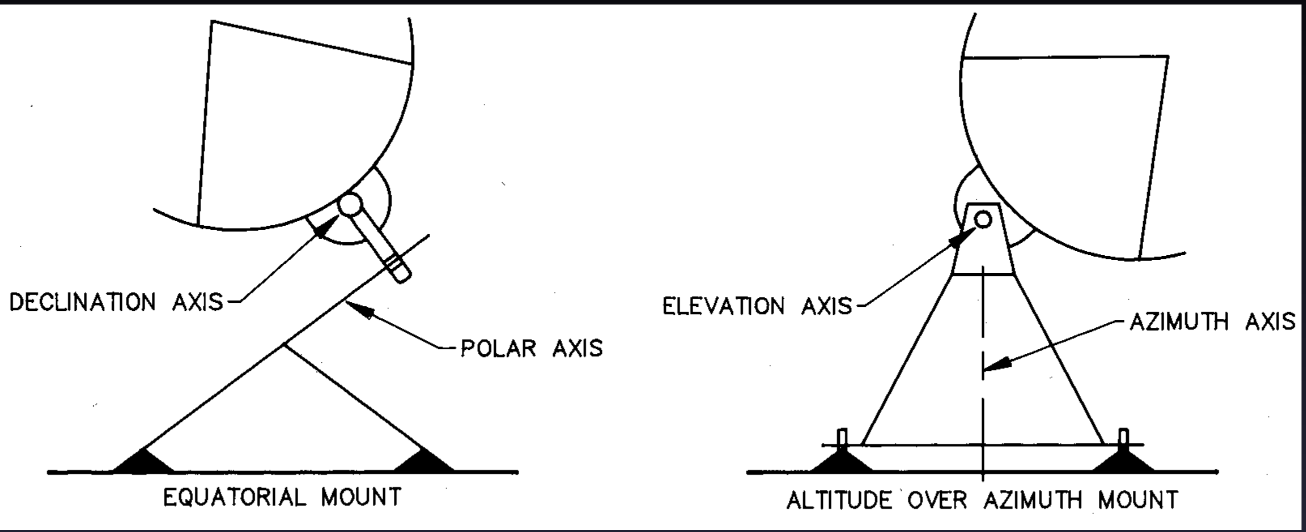
Wavelength < 1 m (approx)

Reflector antennas



Wavelength = 1 m (approx) Hybrid antennas (wire reflectors or feeds)

Types of Antenna Mounts

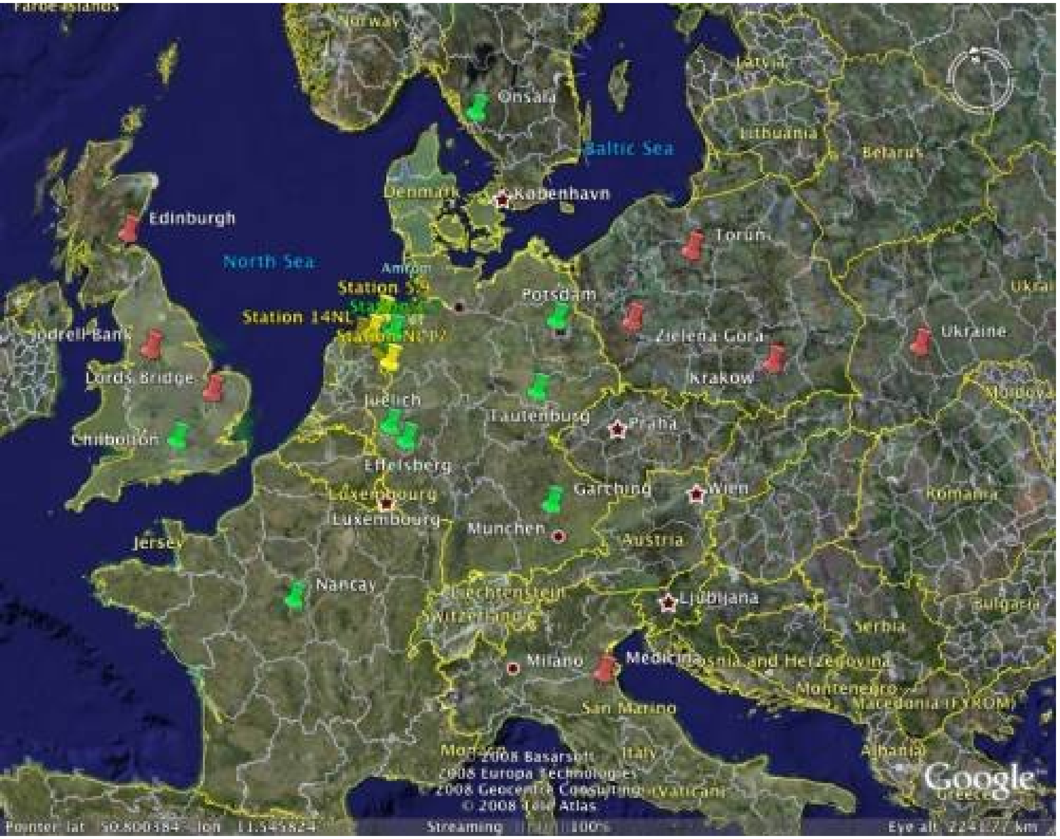


+ Beam does not rotate
+ Better tracking accuracy
– Higher cost
– Poorer gravity performance
– Non-intersecting axis

+ Lower cost
+ Better gravity performance
– Beam rotates on the sky

+ Cheap material cost
+ Constant gravity performace
– Beam does not point at target
– Station beam different for all directions on sky
– Gain different for all directions on sky
– Pushes most of the problems into software

LOFAR: The Low Frequency Array



- Aperture array technology
  - digital processing
- Low Band (LBA)
  - normally 30 to 80 MHz
  - can do 10 to 80 MHz
- High Band (HBA)
  - 120 to 260 MHz
- 3rd input
  - open at International stations
  - extra LBA inputs for Dutch stations (better performance < 30 MHz)

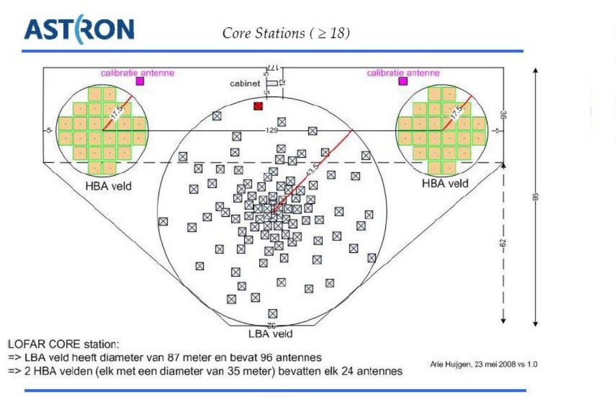
- Core (2 km diameter)
- Remote (inside NL)
- International (outside NL)

Orginal LOFAR

Current LOFAR

Core

- Core area will be a nature reserve
- 96 LBA antennas (48 observing at a time) & 2 x 24 HBA tiles

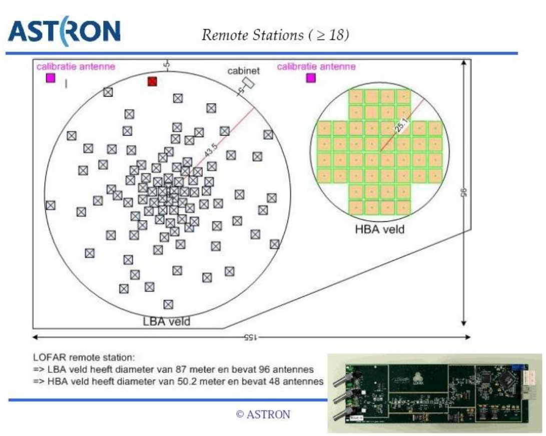


- 2 km diameter
- Micky Mouse design
- Station Beam FWHM
  - 8.7 6.6 5.3 2.6°
  - 30 75 120 240 MHz
- Synthesized beam
  - 800 300 200 100”
  - 30 75 120 240 MHz

Remote

- Up to 130 km baselines
- Circular-pair half-design
- Station Beam FWHM
  - 8.7 6.6 3.7 1.9°
  - 30 75 120 240 MHz
- Synthesized beam
  - 20 8 5 3”
  - 30 75 120 240 MHz

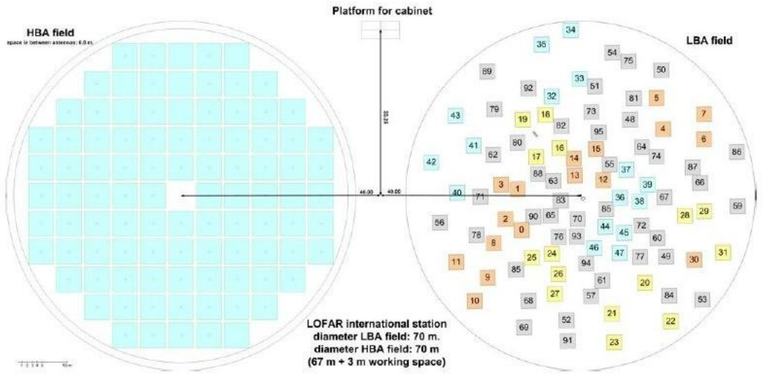
- 48 HBA tiles & 96 LBA (only 48 at a time used for observation)
- Station field rotation as well



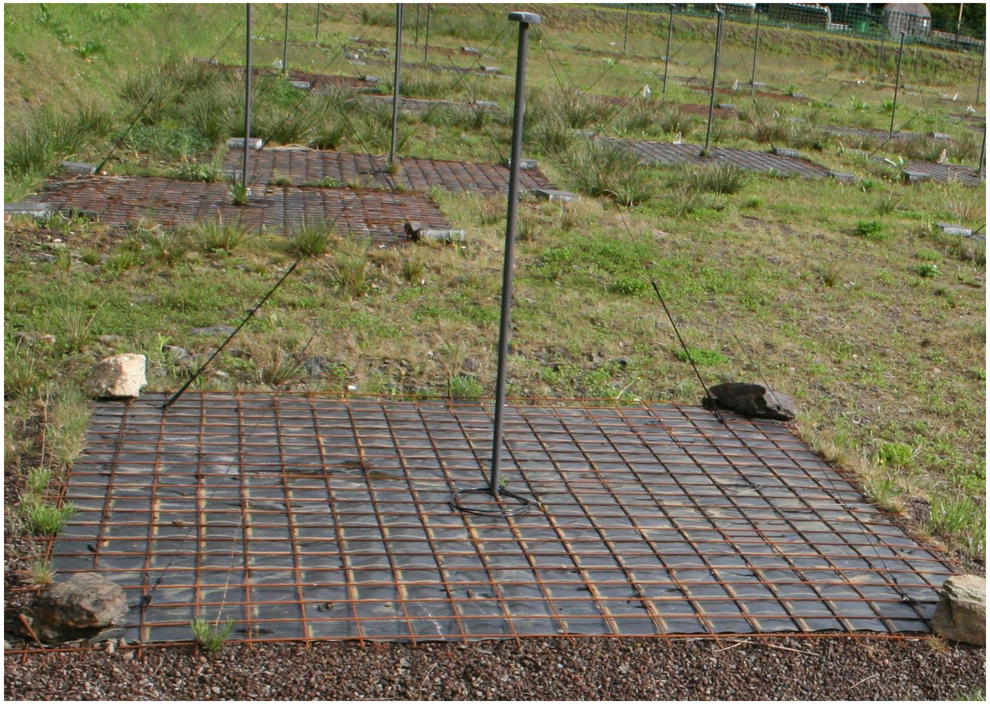
International

- ~1000 km baselines
- Original station design
- Station Beam FWHM
  - 9.9 4.0   2.5 1.2°
  - 30   75   120 240 MHz
- Synthesized beam
  - 1.7   0.7   0.4 0.2”
  - 30   75   120 240 MHz

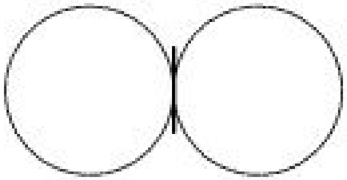
- 96 LBA and 96 HBA tiles
- Station rotation also applied

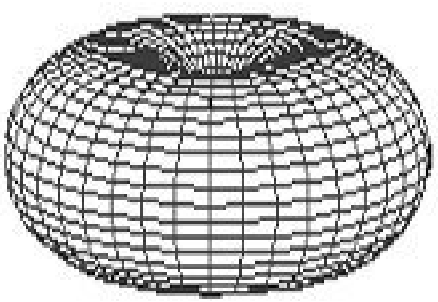


LBA



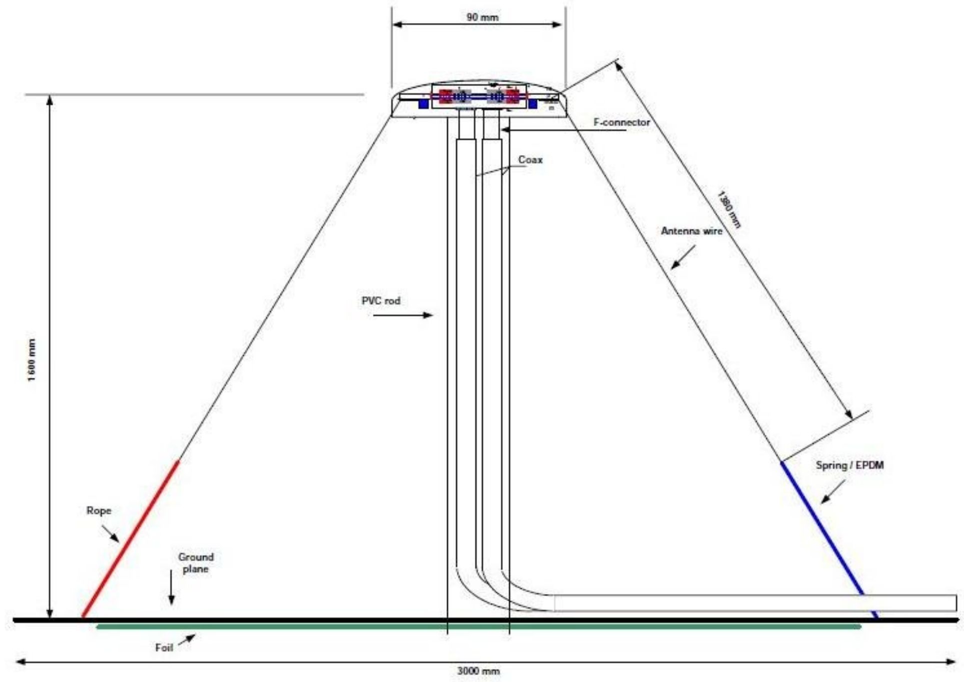
- Low Band Antenna
- 10 to 80 MHz
- Peak response ~56 MHz
- Normally filter out RFI below 30 MHz
- Bent dipole design





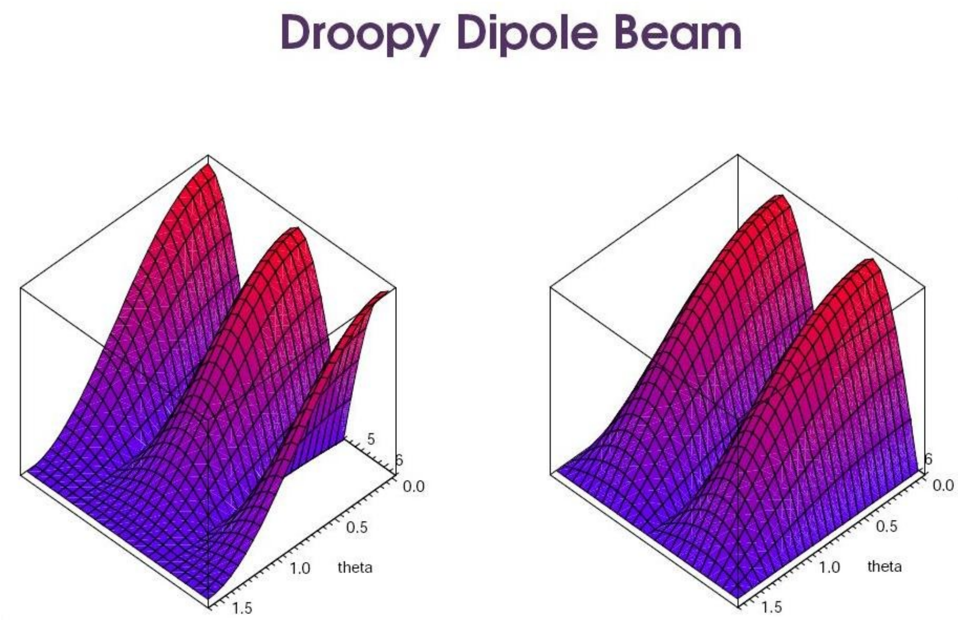
Dipole radiation patterns from Wikipedia

LBA



- Head contains connectors for dipole wires
- Ambient temperature amplifiers

LBA Antenna Beam

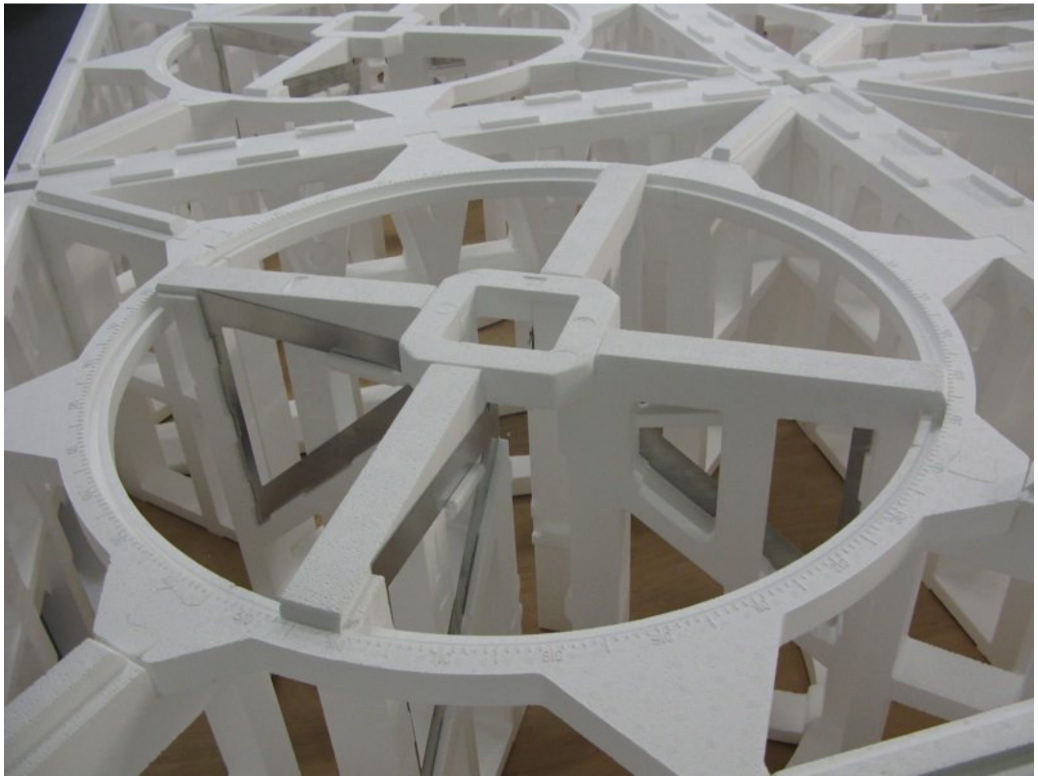


Analytic LBA dipole model by Yatawatta

- Because of high leakage terms, need to achieve effectively just as high dynamic range as Stokes *I*
  - Don't win because true *Q*, *U*, and *V* are small

- Linear polarization dipoles
- Sensitivity strongly depends on azimuth and elevation angle
- Strong polarization leakage off-axis
  - Antennas fixed to ground, so nearly everything is off-axis
  - Leakage typically 50%
- Little polarization sensitivity at low elevations
- Strong frequency dependence

HBA



- High Band Antenna
- 120—260 MHz
- Roughly uniform gain across band
- 4x4 dipole "tiles"

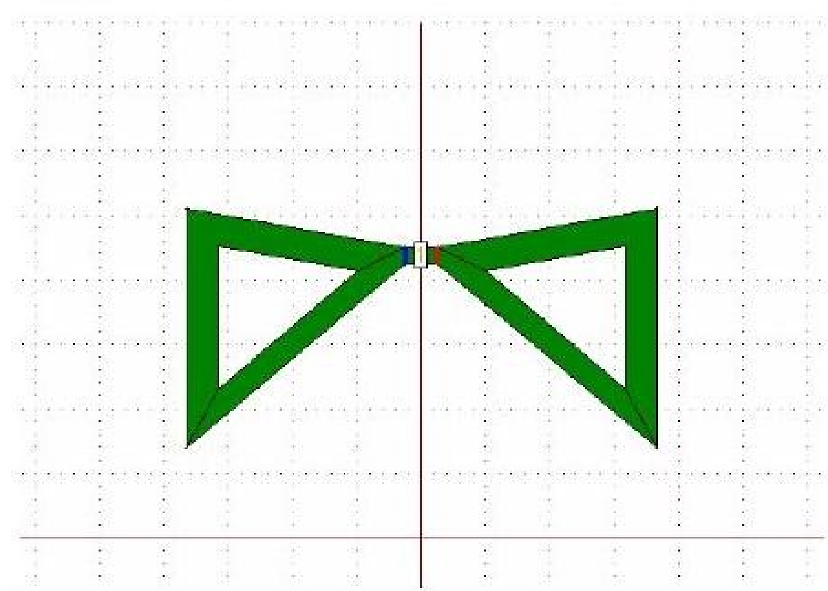
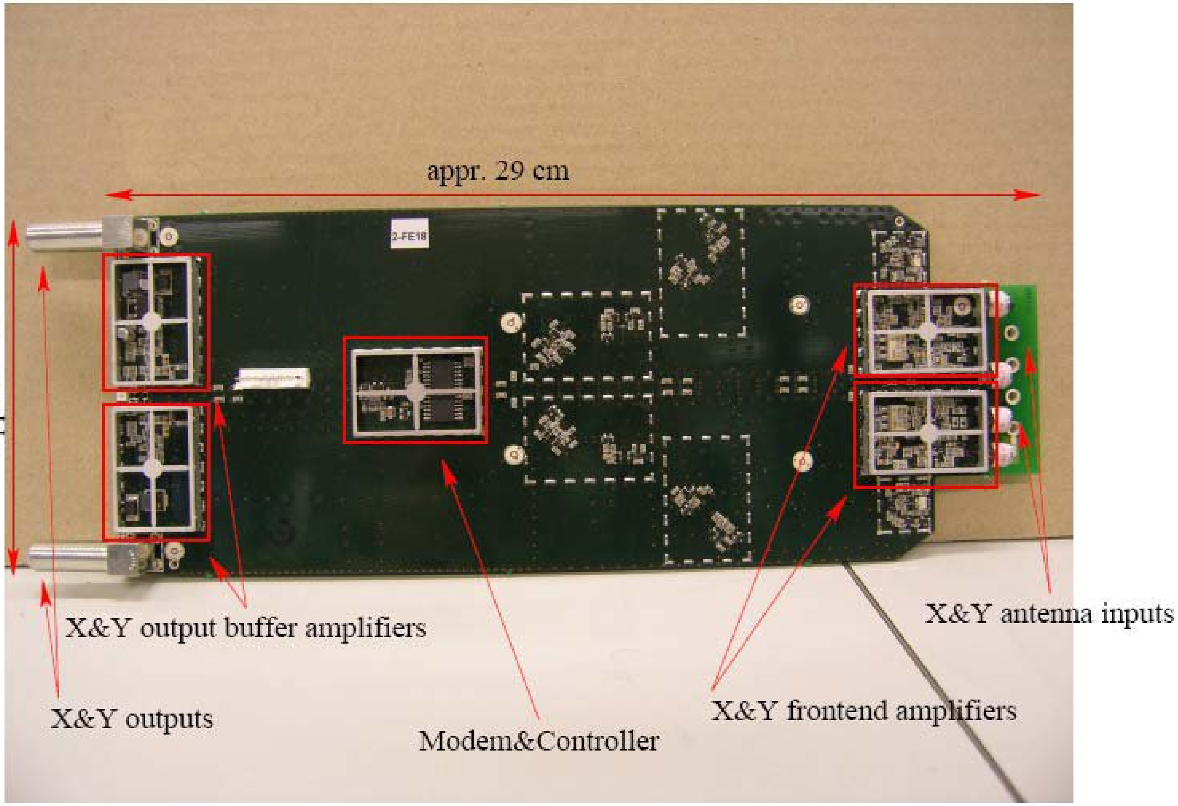
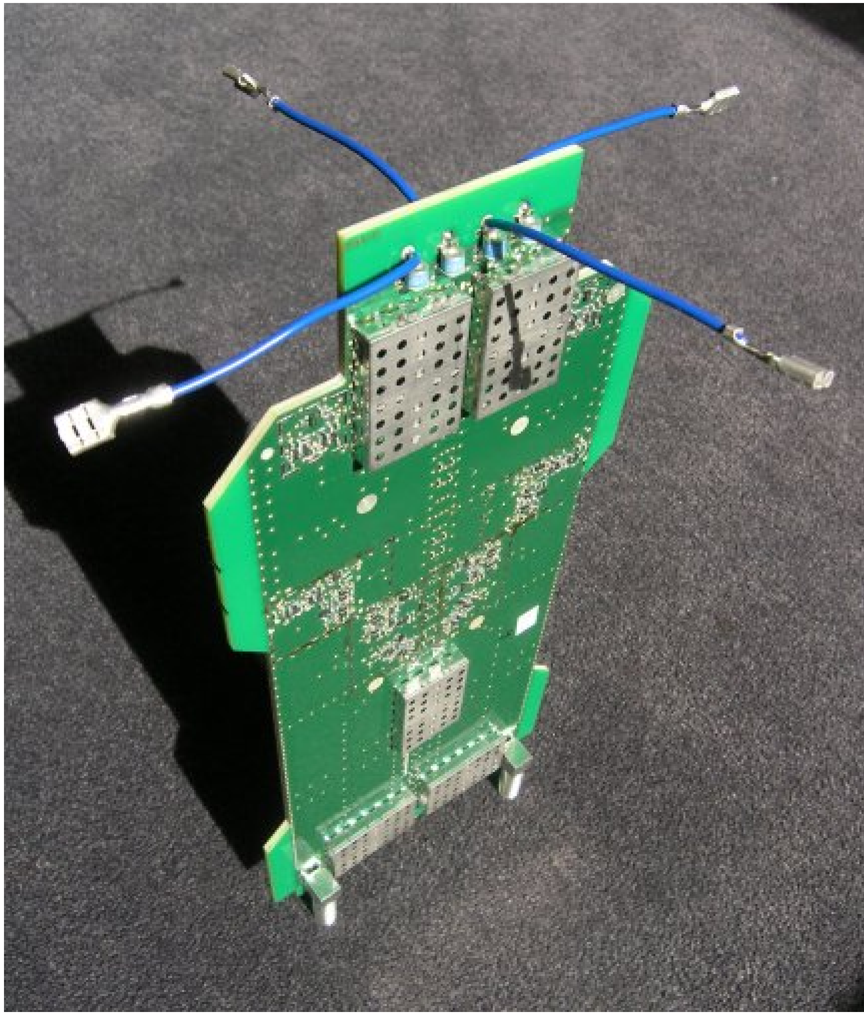


Figure 17 *A sketch of a HBA antenna element*

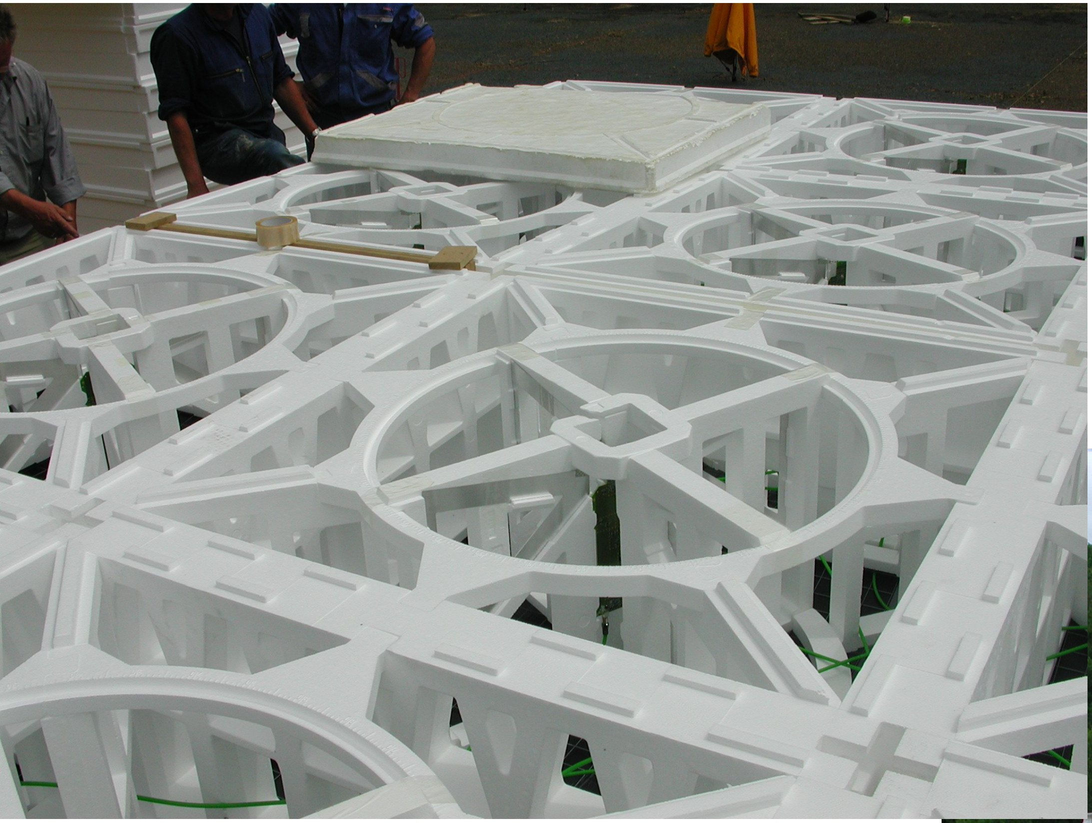
HBA

- HBA frontend board
- Connects to the 4 triangular blades of the antenna system
- Ambient temperature amplifiers





HBA Dipoles in 4x4 Tiles



Example LOFAR Stations

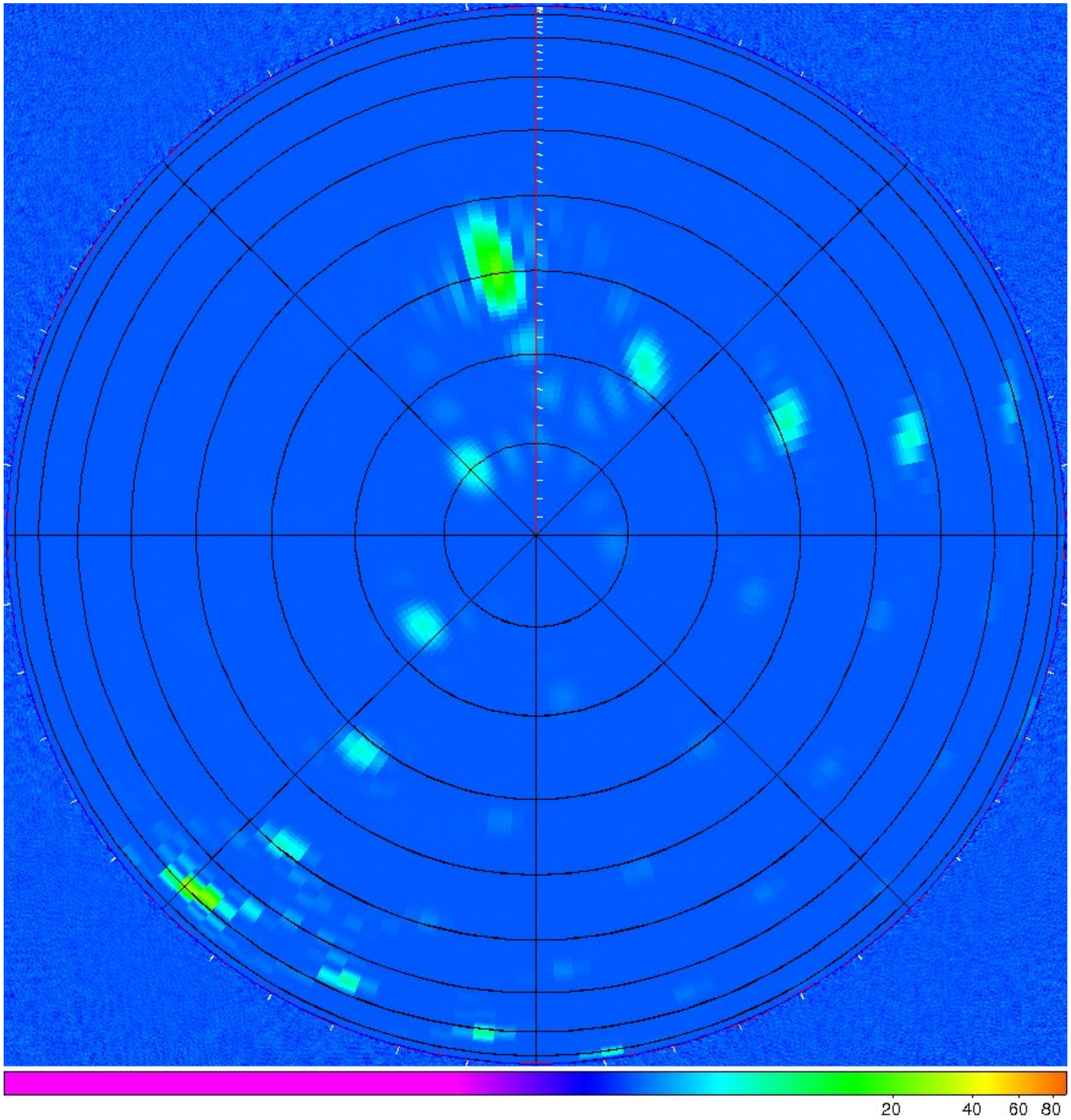
Vocks

Thueringer Landessternwarte/Eisloeffel

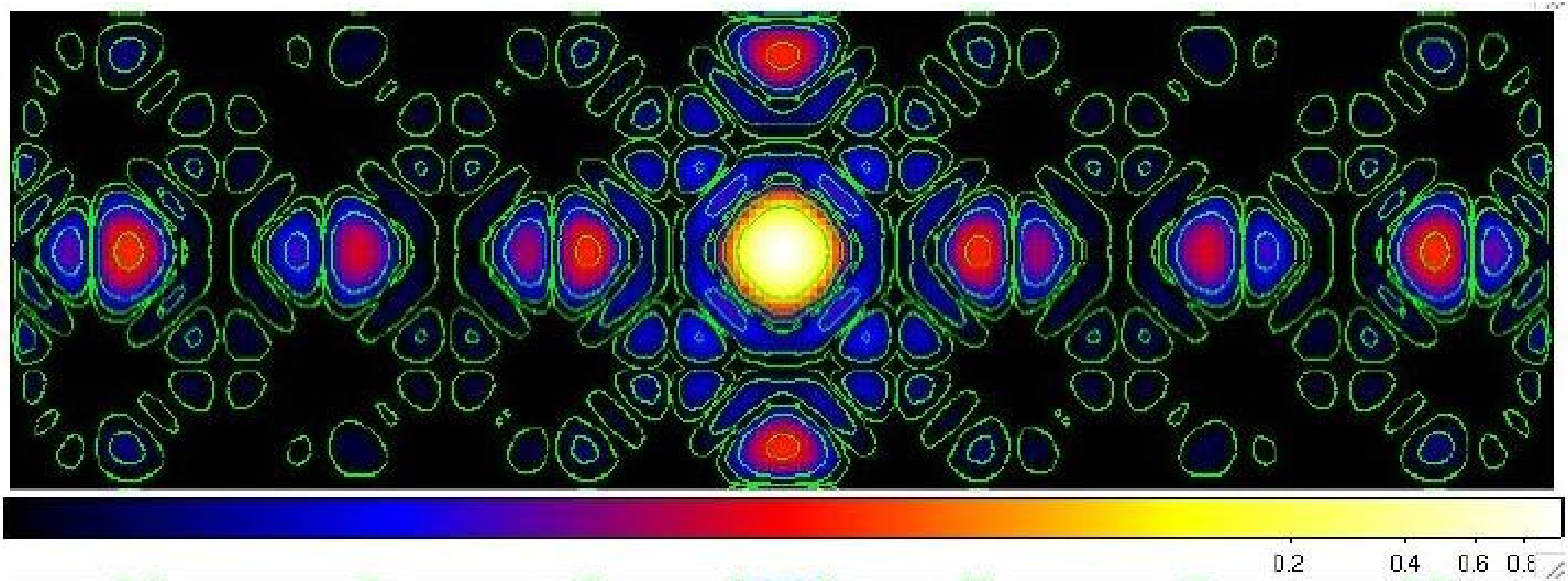
Thueringer Landessternwarte/M Pluto

Your Destination Tomorrow

Grating Lobes



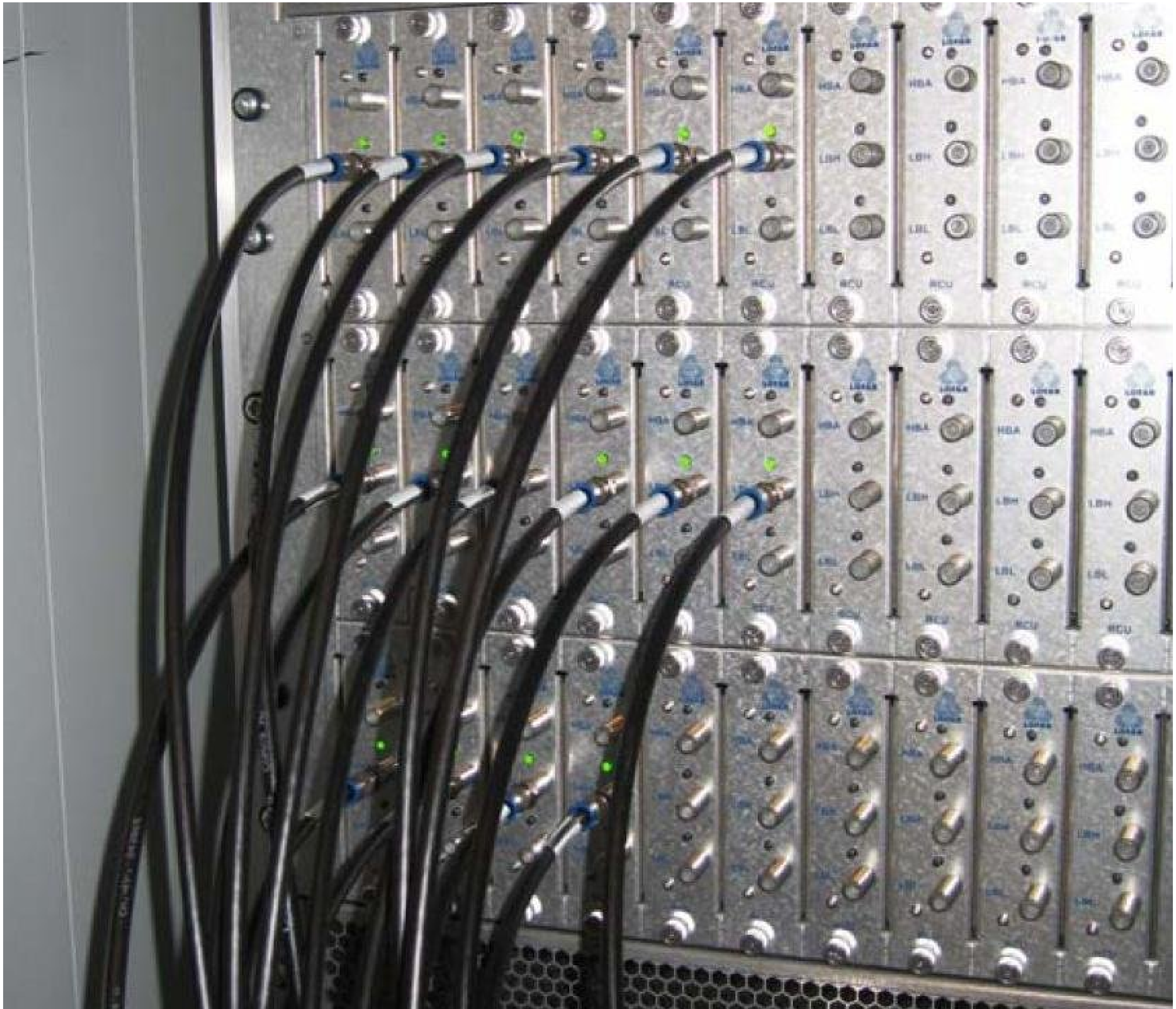
Station Beam Pattern



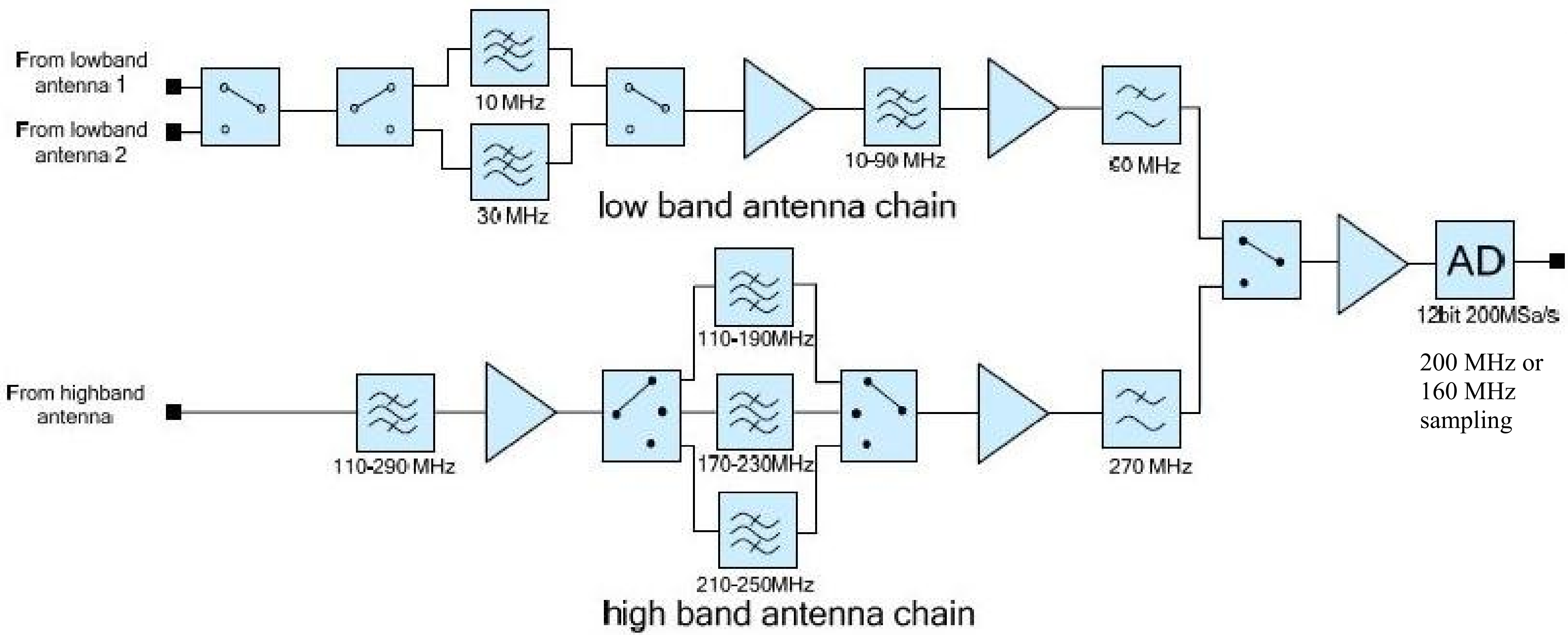
- Primary beam and sidelobe pattern not as clean as a circular filled aperture
  - HBA grid makes an especially bad grating response
- Have to pay attention more than other telescopes to beam pattern

LOFAR Station Hardware

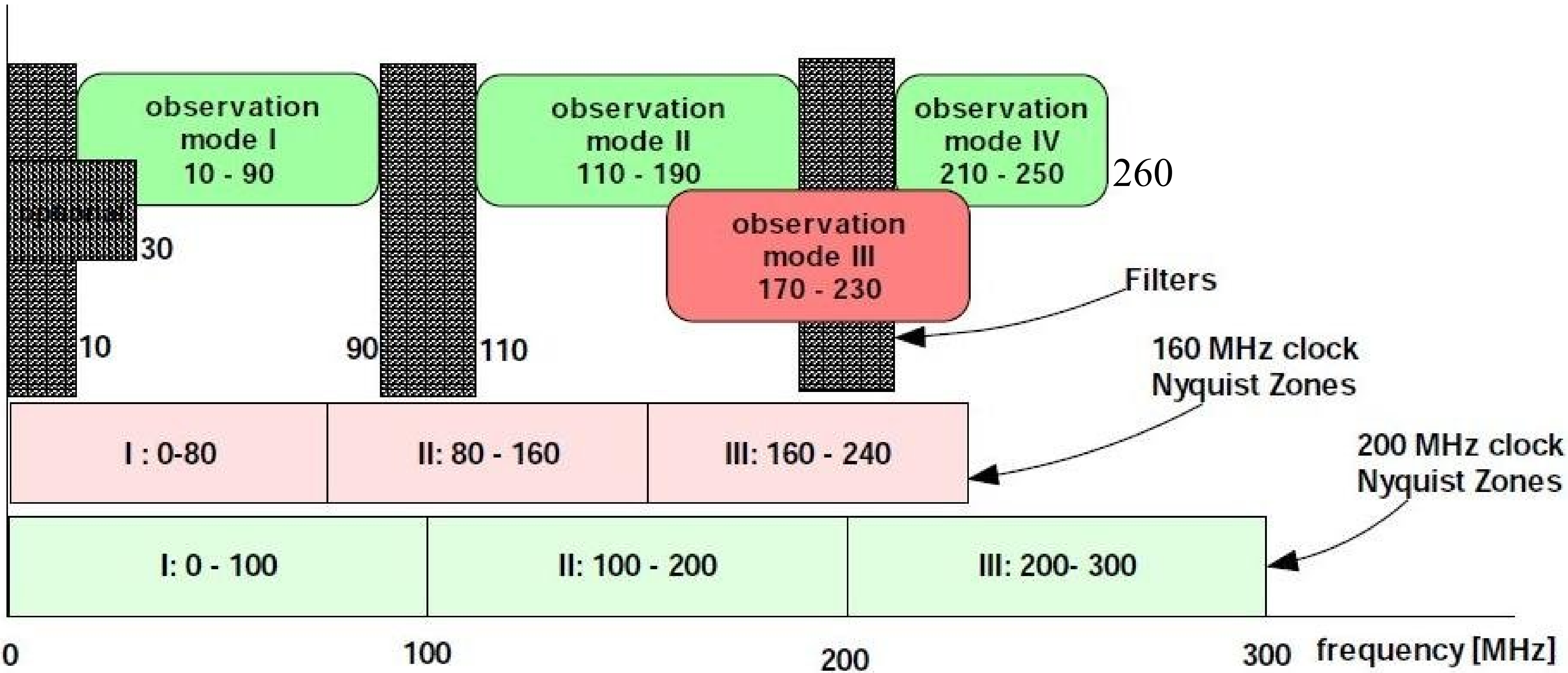
RCU — Receiver Unit

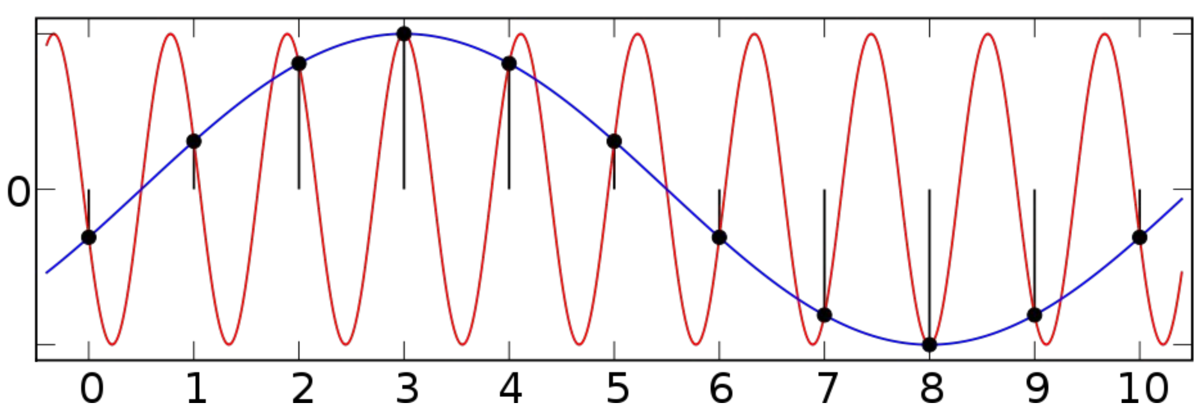


LOFAR Frequency Selection



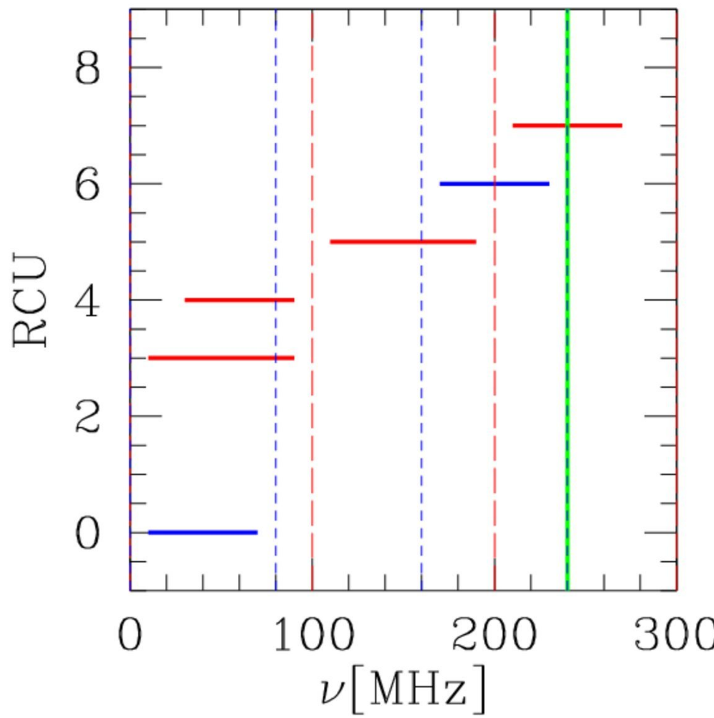
LOFAR Band Selection





Station Electronics: Gory Details 1

- Bandpass filter
  - 10—90 MHz
  - 30—90 MHz
  - 110—190 MHz
  - 170—230 MHz
  - 210—270 MHz



- 12 bit A/D converter
  - 200 MHz or 160 MHz clock
  - Forms 100 MHz or 80 MHz bands
- RCU modes: common combinations of antenna inputs, bandpass filters, and clock rates assigned special RCU codes
  - But LOFAR can observe with any antenna input, bandpass filter, and clock rate combination
    - Low band observations with 160 MHz clock potentially important for full frequency coverage for RM synthesis and spectral line work
  - Each antenna/polarization input can chose own antenna and bandpass
    - Must use the same clock frequency

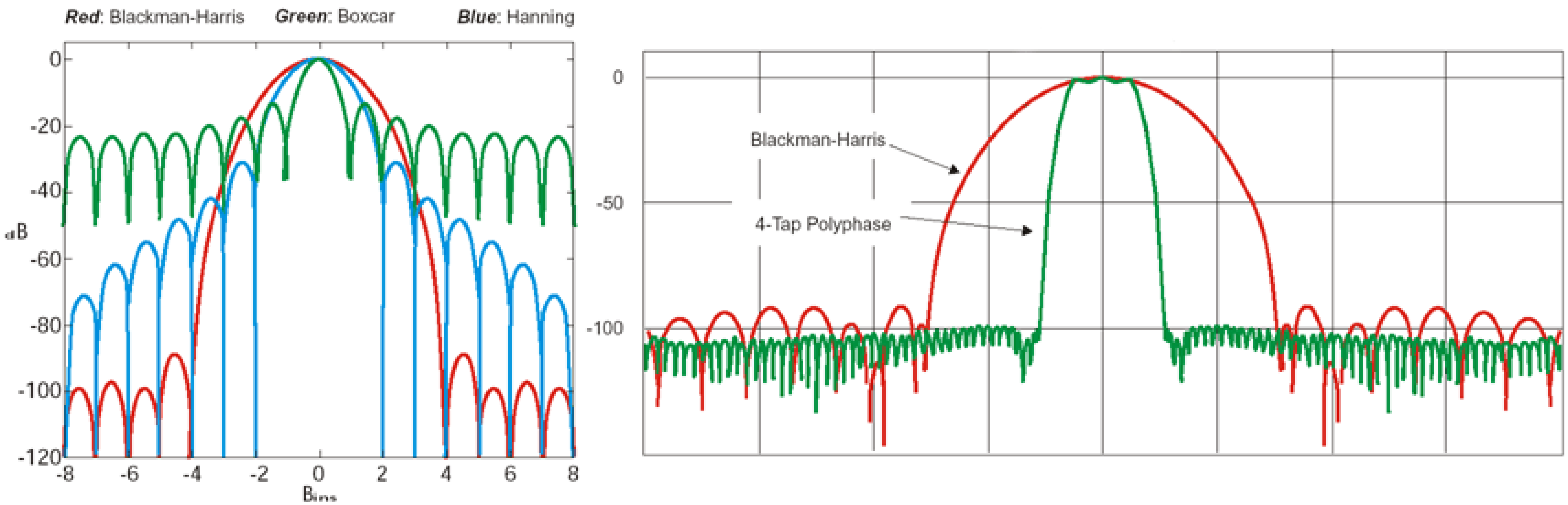
Station Electronics: Gory Details 2

- Polyphase filterbank converts the time series data from each dipole/tile into 512 (513) frequency subbands
    - 195.3125 kHz subbands for 200 MHz clock
    - 156.2500 kHz subbands for 160 MHz clock
    - 16 bit complex number (16 bit real, 16 bit imaginary) for each subband every 5.12 μs (200 MHz) or 6.40 μs (160 MHz clock)
- Beamformer hardware processes up to 248 beamlets
    - A beamlet is one subband beamformed for a specific direction
    - 248 beamlets determine maximum bandwidth available to beamformer
        - 48.4375 MHz for 200 MHz clock
        - 38.7500 MHz for 160 MHz clock
  - **Arbitrary** subband selection by astronomer
  - **Frequency coverage** not required to be contiguous
  - Calibration will work best in full production system with wide **frequency coverage**

Station Electronics: Gory Details 3

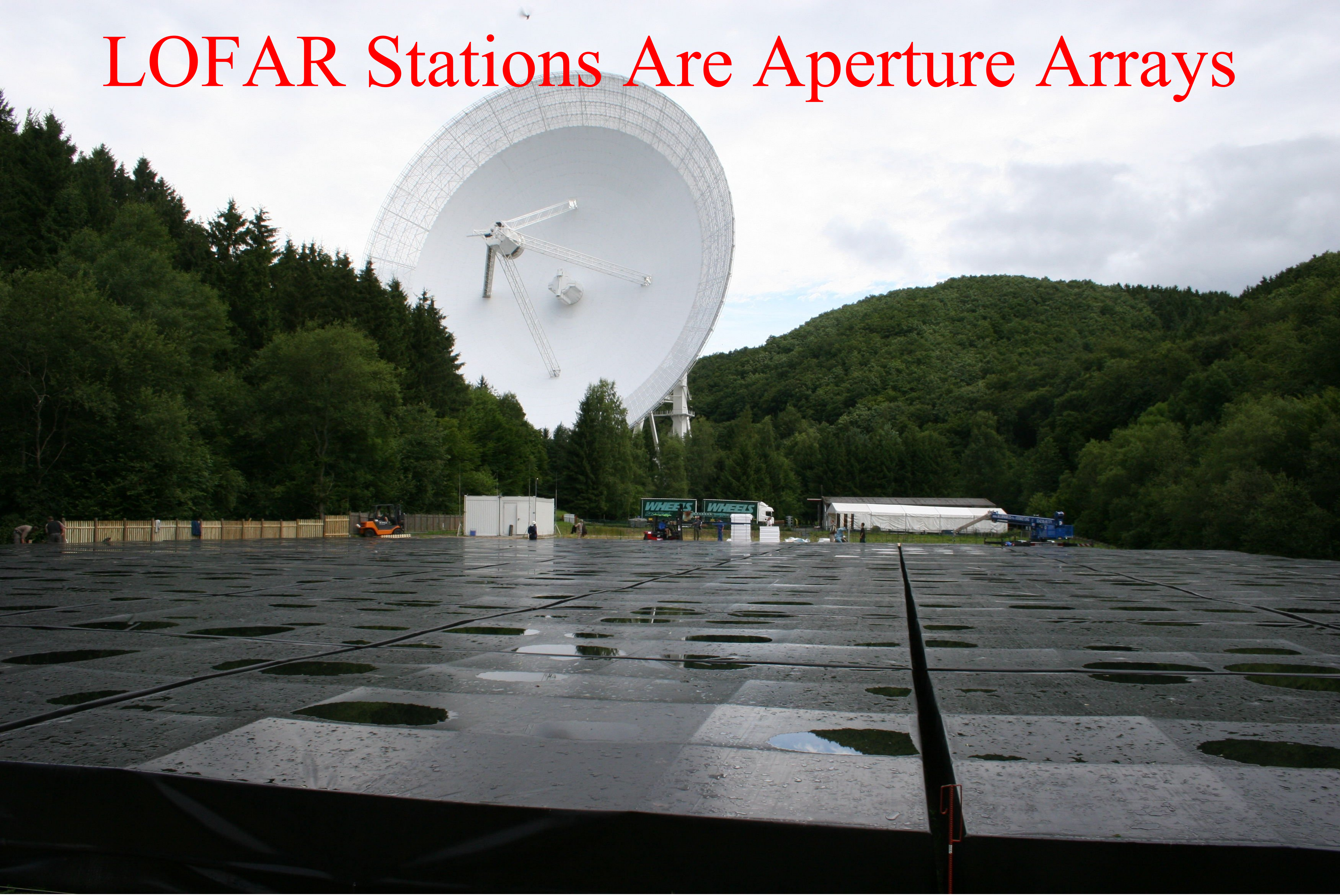
- 16 bit complex samples — total bandwidth 48.4375, 38.7500 MHz
  - 1 beam $\leq$ 248 subbands (48.4375, 38.7500 MHz for 200, 160 MHz clock)
  - 2 beams $\leq$ 124 subbands each (24.22, 19.38 MHz), may reuse subbands across beams
  - 4 beams $\leq$ 62 subbands each (12.11, 9.69 MHz), may reuse subbands across beams
  - 8 beams $\leq$ 31 subbands each (6.05, 4.84 MHz), may reuse subbands across beams
  - 8 beams, arbitrary subband allocation (248 subbands total, 48.4375, 38.7500 MHz total), may reuse subbands across beams
- 8 bit complex samples — total bandwidth 96.875, 77.500 MHz
  - 2 beams of 248 subbands each (48.44, 38.75 MHz), all subbands reused
  - 4 beams of 124 subbands each (24.22, 19.38 MHz), from original 248 subband selection, may reuse subbands across beams
  - 8 beams of 62 subbands each (12.11, 9.69 MHz), from original 248 subband selection, may reuse subbands across beams
- 4 bit complex samples — total bandwidth 193.75, 155.00 MHz
  - 4 beams of 248 subbands each (48.44, 38.75 MHz), all subbands reused
  - 8 beams of 124 subbands each (24.22, 19.38 MHz), from original 248 subband selection, may reuse subbands across beams
- 3 x 1 GE network bandpass limits observations to ~ 30.5 (61, 122) MHz for 16 (8,4) bit modes, but full bandwidth available for all 10 GE stations

Polyphase Filterbank

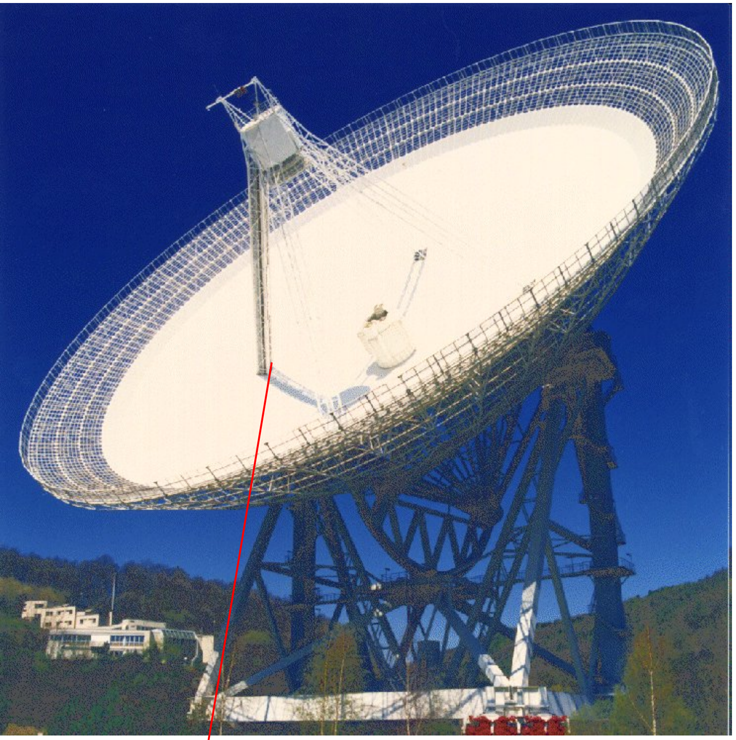


- Similar to a discrete Fourier transform (think of the FFT)
- But uses more datapoints in the transform, weighting the points differently
- Reduces sidelobe levels in frequency-space
  - Important for RFI mitigation
- Spectral dynamic range is normally greater than 80 dB for standard LOFAR data processing

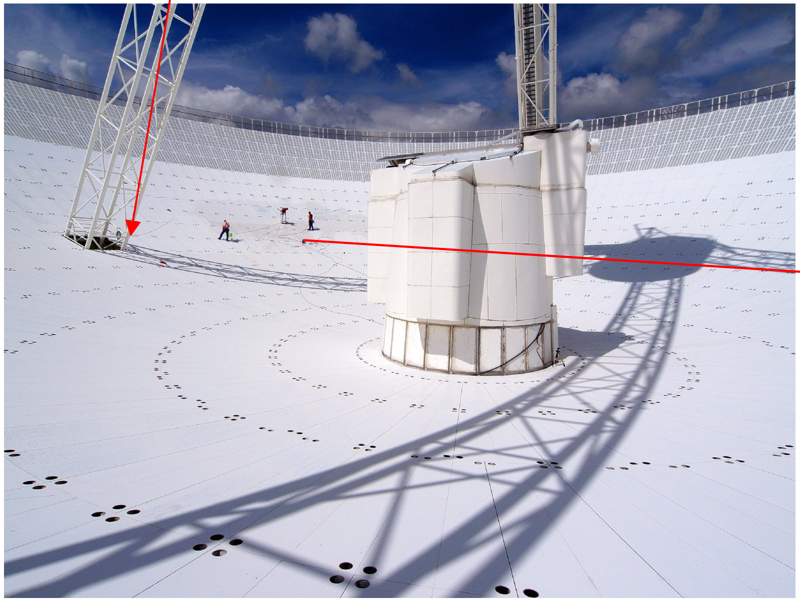
LOFAR Stations Are Aperture Arrays

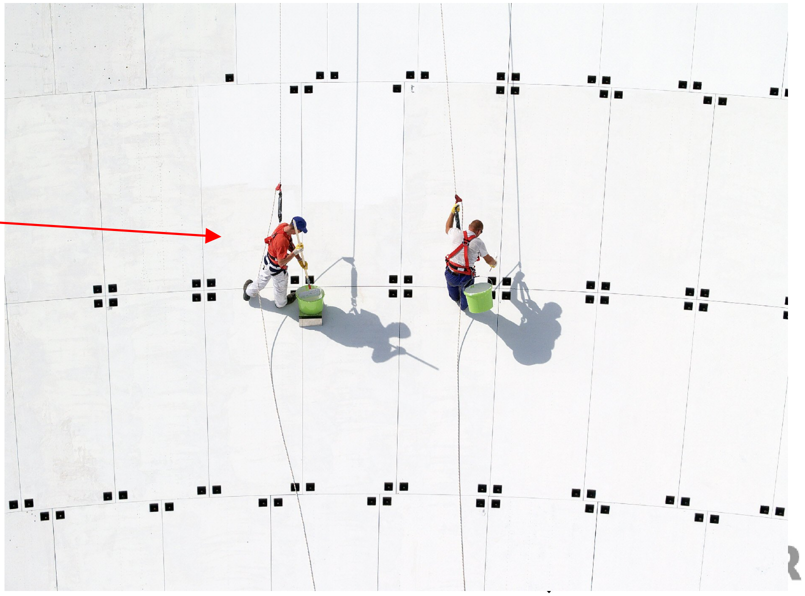


Effelsberg 100 m



- A large dish such as the Effelsberg 100 m has many adjustable panels
- The panels are manually adjusted to phase up the dish





GBT

Rachel Rosen, NRAO/AUI

- The GBT has a metrology system to monitor the positions of its panels and make continuous adjustments to keep the panels phased up (the GBT active surface)

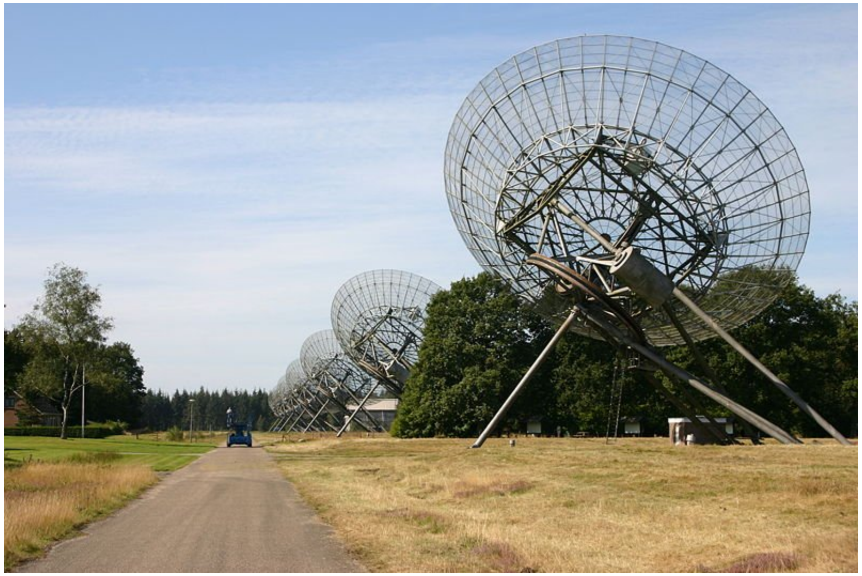
Optical Equivalents

ESO/Y. Beletsky

NASA

- Optical astronomy uses adjustable segmented mirrors, deformable mirrors, and adaptive optics to phase up the telescopes

Phased Arrays



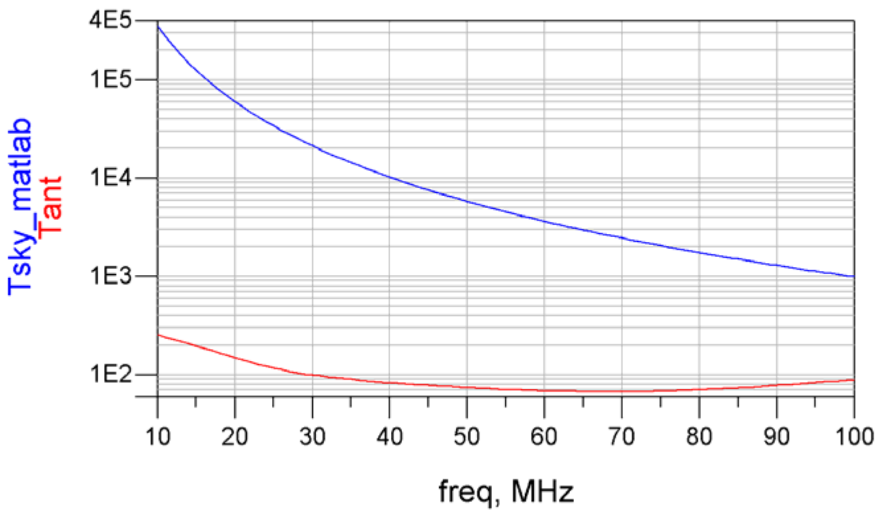
Adriaan Renting

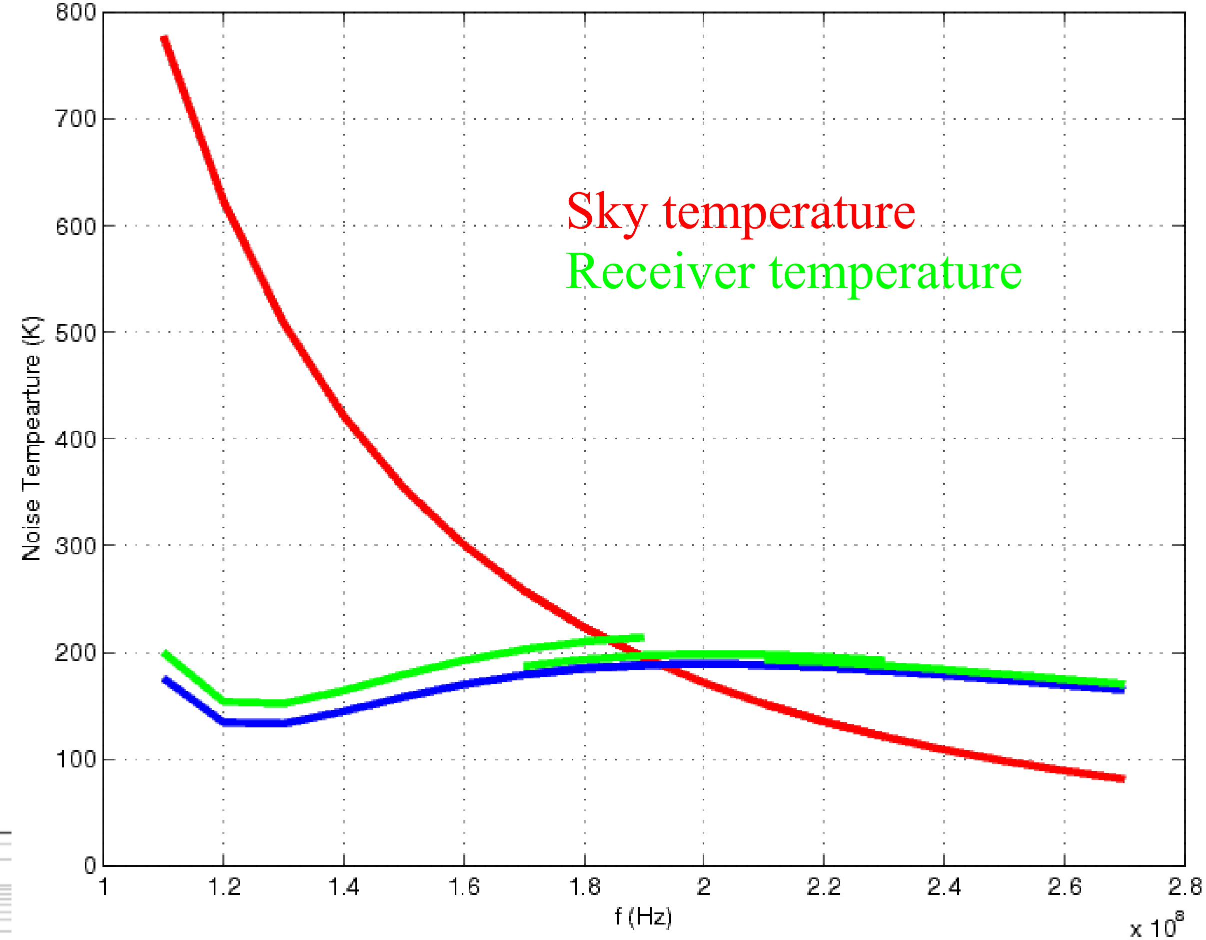
CSIRO

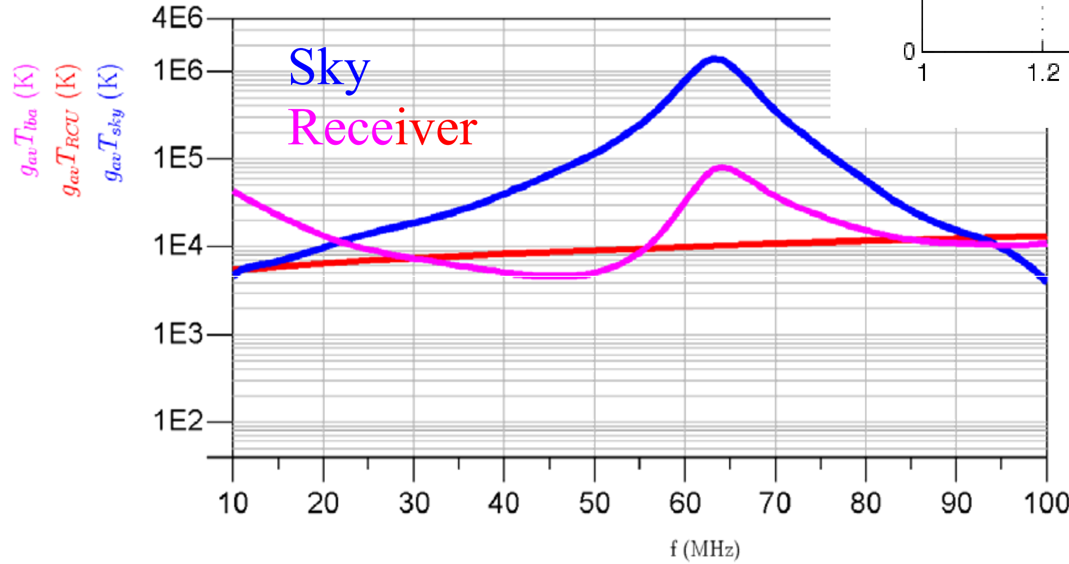
LOFAR Approach

- Rather than phasing up the telescope mechanically, LOFAR phases up a station electronically
- Instead of adjusting the position of each element of the station, the delay from each element is electronically adjusted
- Cheap hardware costs — no moving parts :)
- Everything drive by software :(

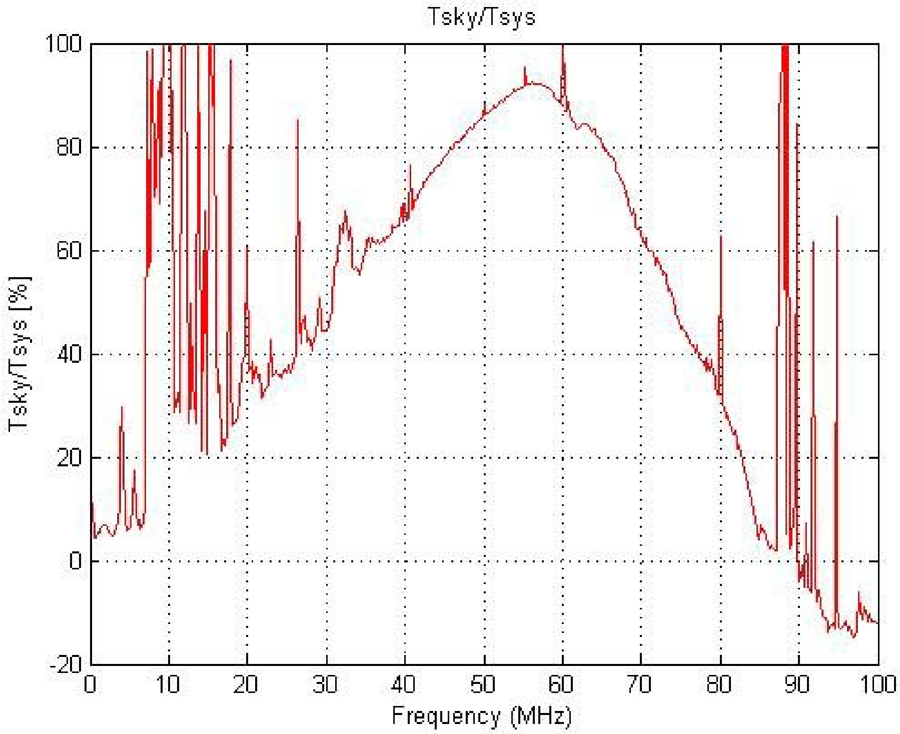
LOFAR System Temperatures







LOFAR and RFI



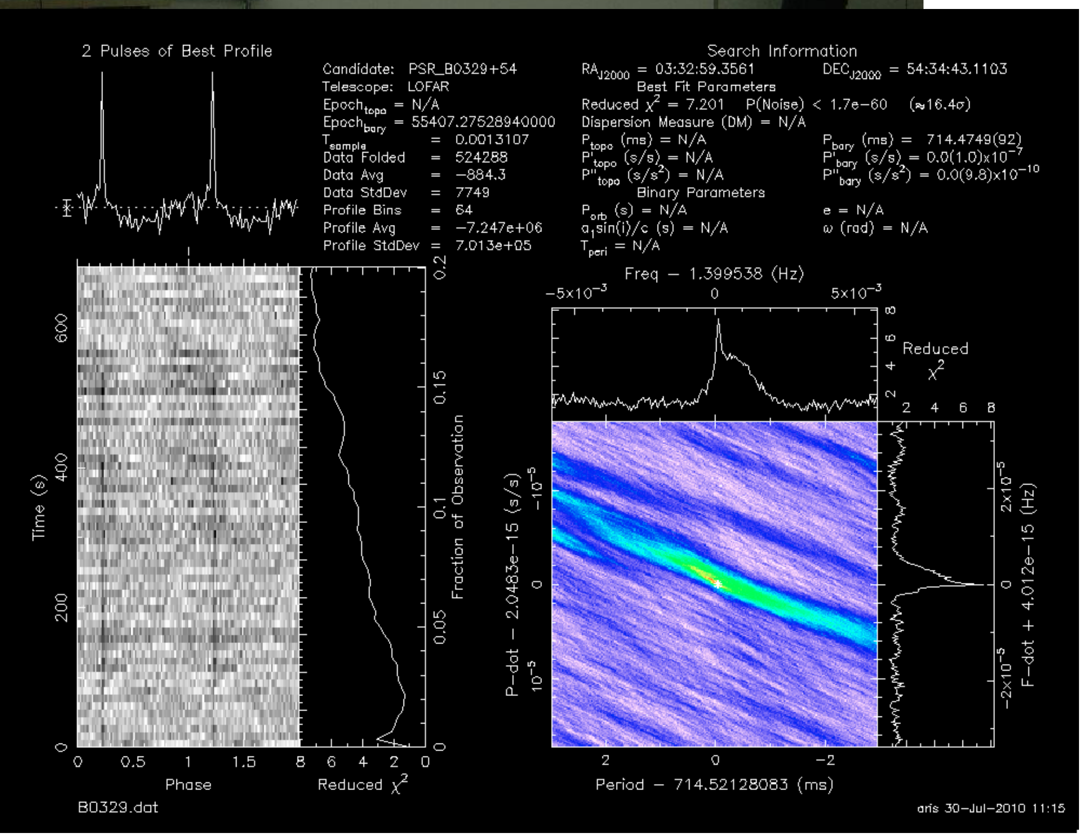
- Strong RFI is present at low frequencies, especially < 30 MHz
- RFI is especially problematic for single dish work

The spectral dynamic range of the LOFAR hardware helps to minimize the problem

- RFI does not spread in frequency unless the RFI is so strong that it overruns the linear range of the amplifier or A/D converter

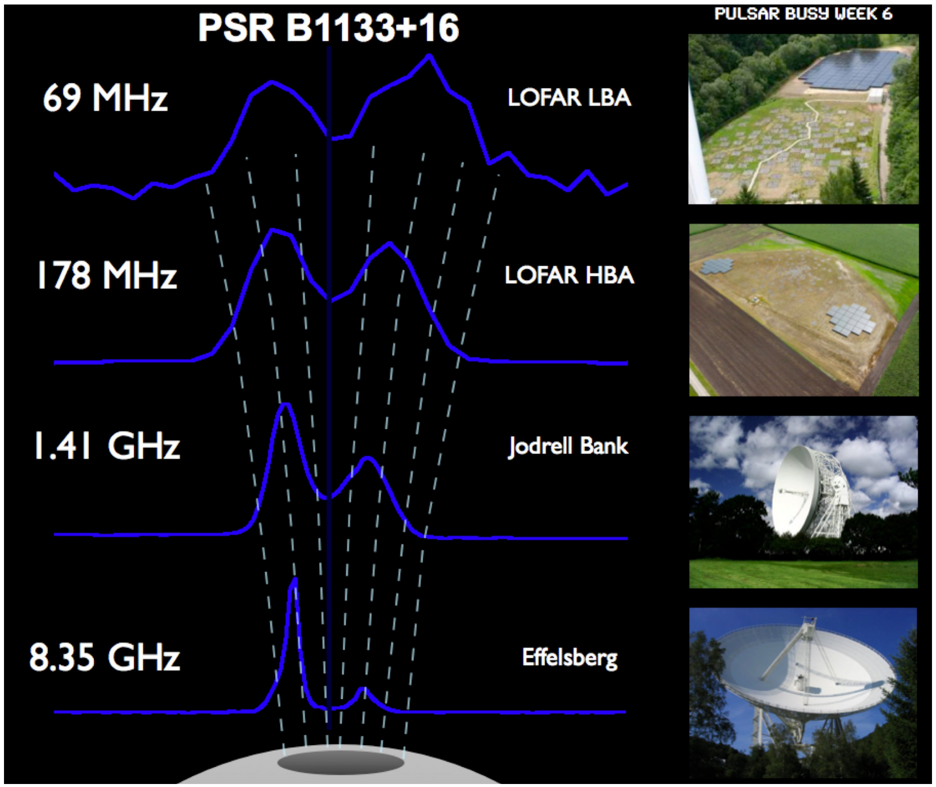
So What Can You Do With LOFAR?

Single Station Development



- LOFAR "single dish" operation and software still under development
- Picture from last meeting in Bochum
- Software development for reading/storing/processing data locally
  - Reader library written by Oxford
  - Writer application being developed by MPIfR (Kuniyoshi)
  - Pulsar detection using this system at left

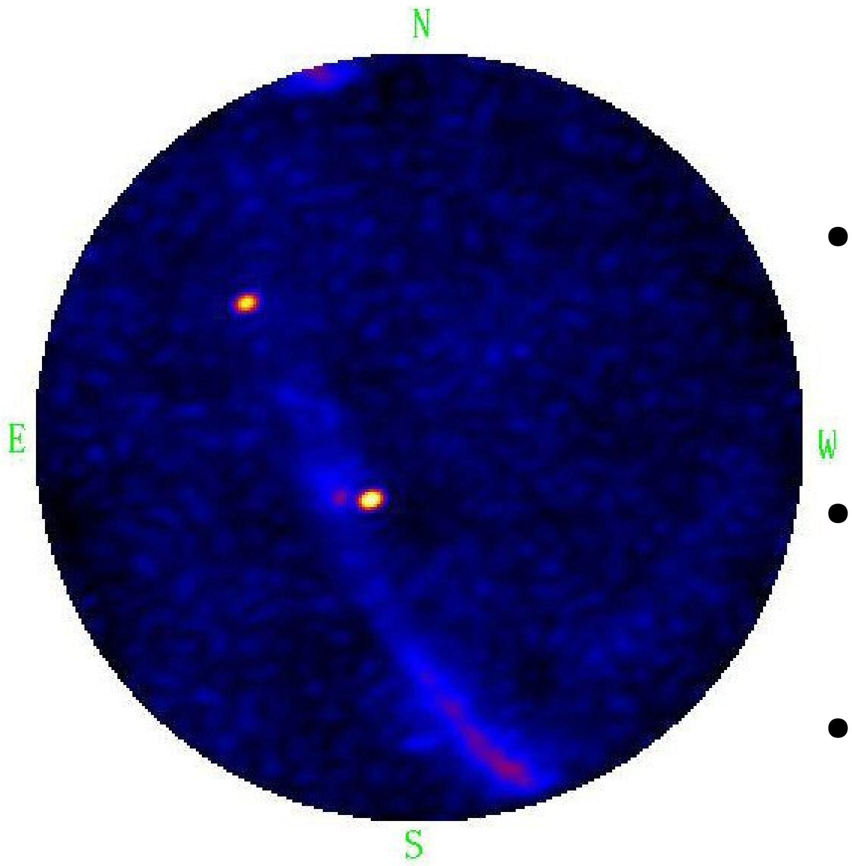
Pulsar Physics



Pulsar Science Working Group

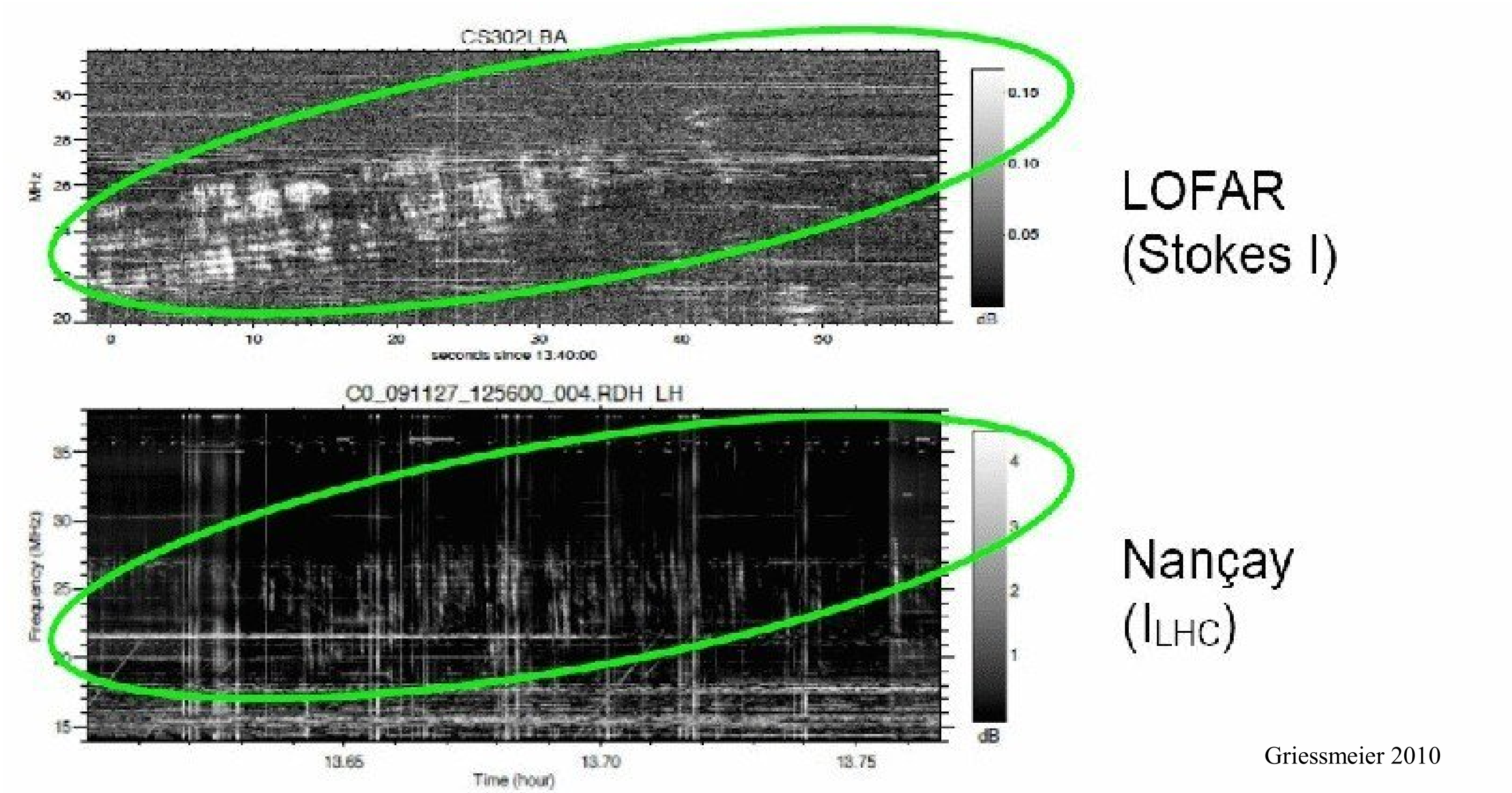
- Pulsars normally have very steep spectra, so low frequencies are ideal for some measurements
- LOFAR pulsar survey expects to find ~1000 new pulsars
- Many of these pulsars may only be visible at low frequencies
  - Regular timing observations can be carried out by individual LOFAR stations
- Extended frequency coverage helps to study emission region physics

All-Sky Imaging



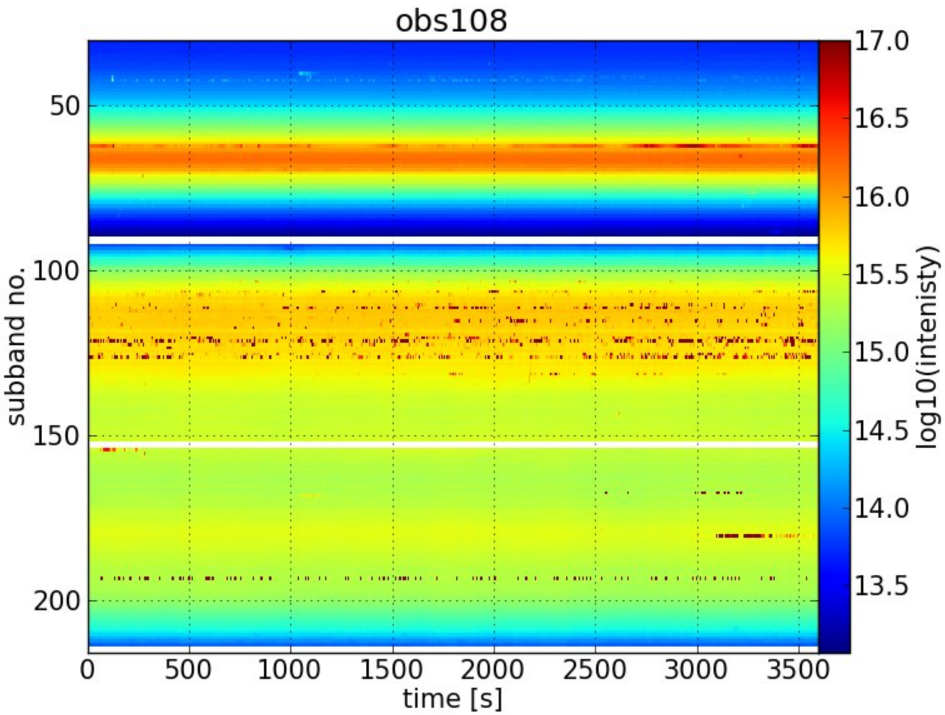
- Image shows the first LOFAR all-sky image using standard HBA station made with Effelsberg on 2009 November 10
- International stations important for imaging large spatial scales for Milky Way and large objects
- Useful for transient searches
  - 2π instantaneous field of view
- Technically not "single dish" work, as this is really interferometry

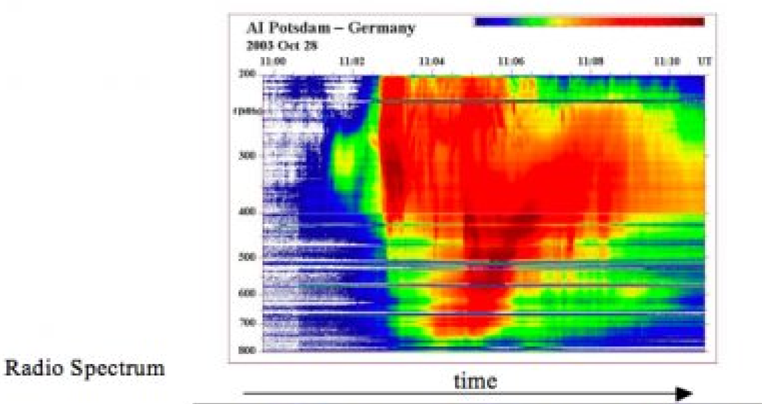
Planets



- Simultaneous observation of Jupiter bursts with Nancay and a LOFAR station

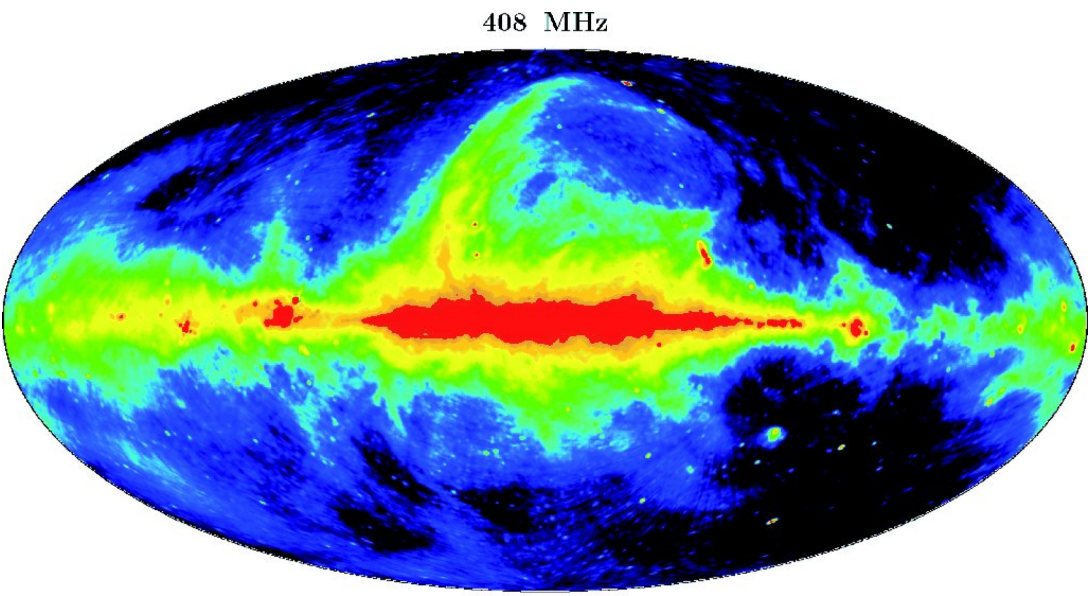
Solar Spectrum





- Solar radio bursts correspond to flares in the Solar corona
- Emission frequency related to the height in the corona by the plasma physics (geosynchrotron emission)
- Complete 10—260 MHz coverage at 0.01 s resolution sought by Solar KSP
- Of course, the Sun has been rather quiet lately, but it is expected to pick up in activity...

What We Want to Do in the Future



Haslam et al.

Jodrell-Bank 250-ft + Effelsberg 100-m + Parkes 64-m

- All-sky mapping
  - The Galactic emission is very large-scale, and zero-spacing information is critical
- Radio recombination lines
- ???

Using LOFAR For Single-Dish Work

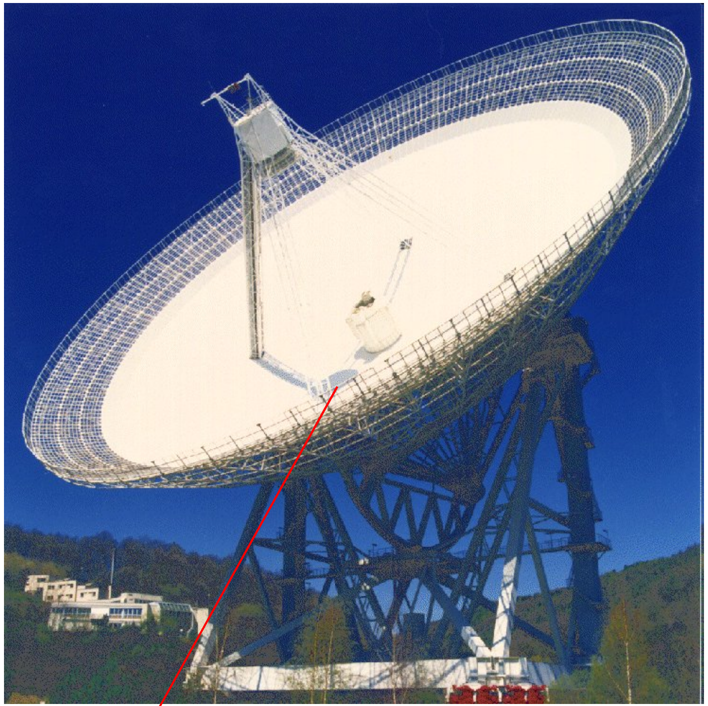
- Honestly, we have not worked everything out yet
  - Still under extensive development and”playing around” to see what we can do
- The ability to form multiple beams on the sky, 8 now and perhaps 24 or more in the future, opens up lots of possibilities which are impossible with other telescopes
  - Simultaneous observations of pulsars in different directions
  - Simultaneous calibration beams and multi-beam imaging with rapid changes to the beam arrangement
- Since there will be 10s of similar LOFAR stations available, simultaneous observations at different locations also open up new ideas
  - Expand frequency coverage
  - Different paths through ionosphere, Solar wind, ISM

Final Notes On LOFAR

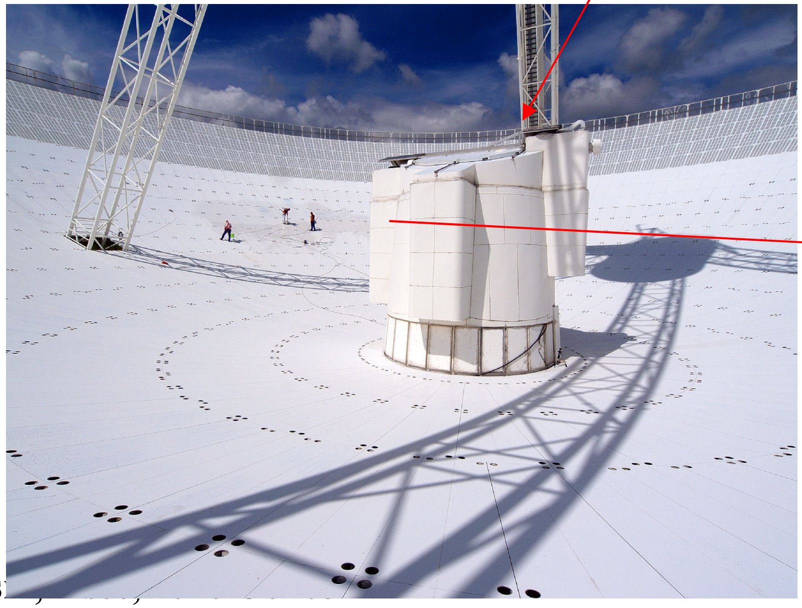
- LOFAR is still under extensive software development
  - Lots of software tools simply are not ready yet, or do not have full functionality
- Still a number of bugs in the LOFAR hardware/firmware system as well
- But progress is rapid, and LOFAR will soon be opened up for scientific use by astronomers

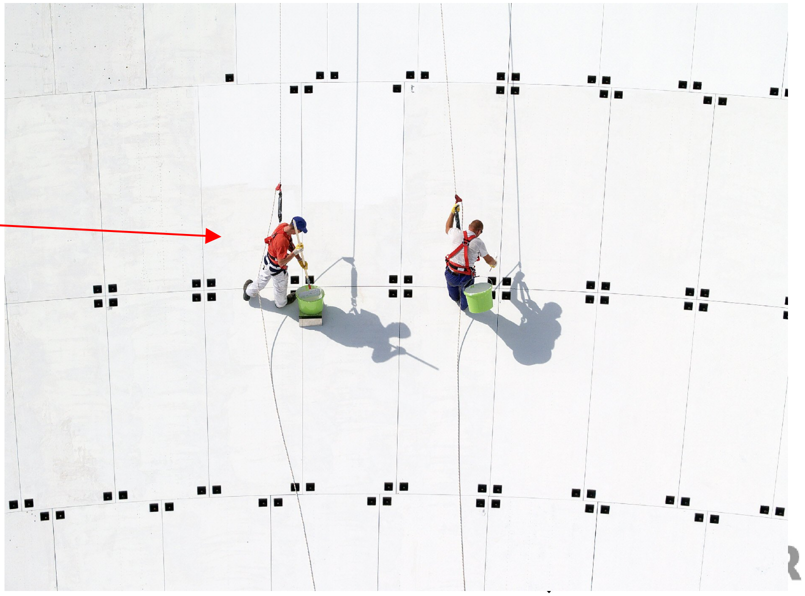

The End

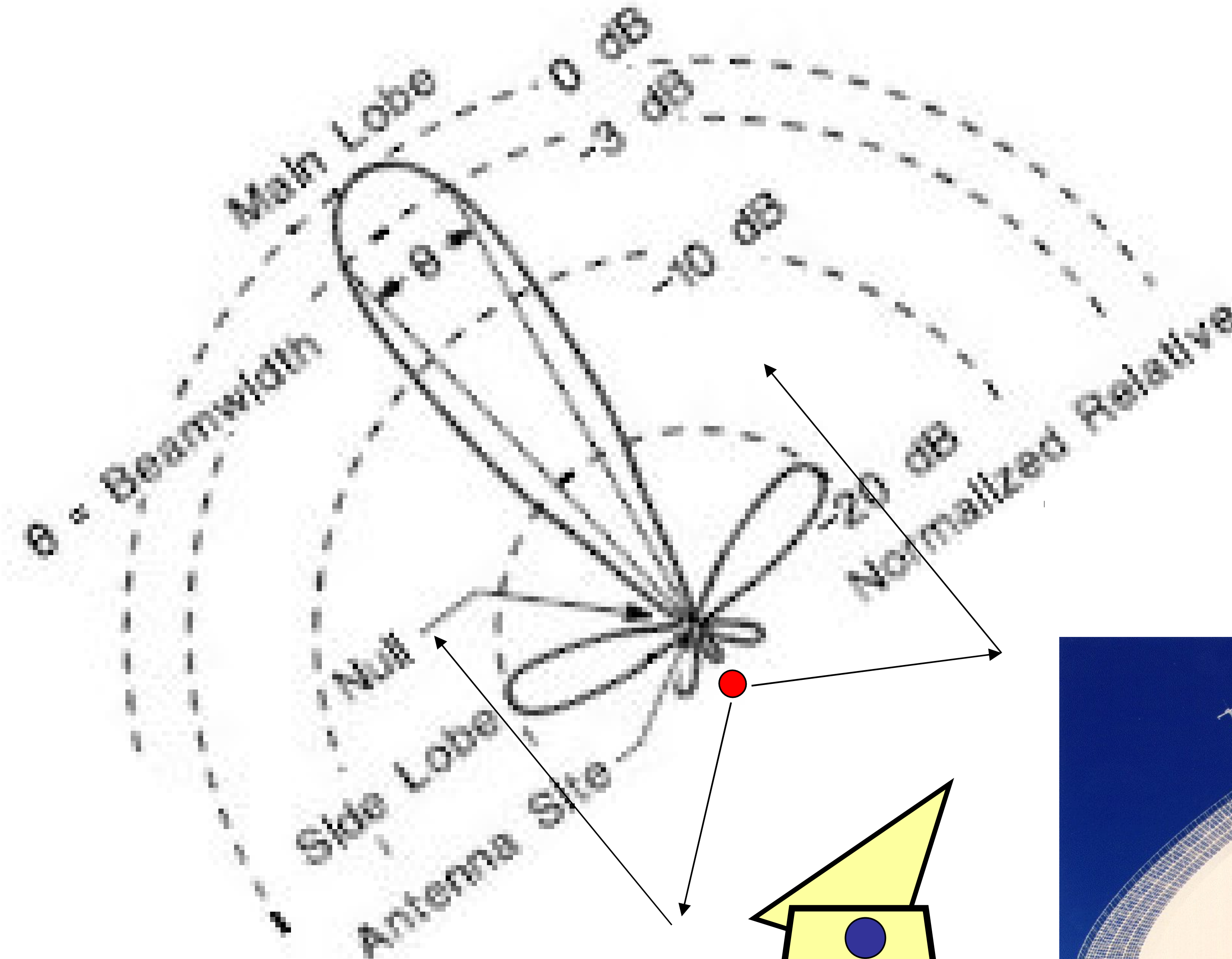
Effelsberg 100m



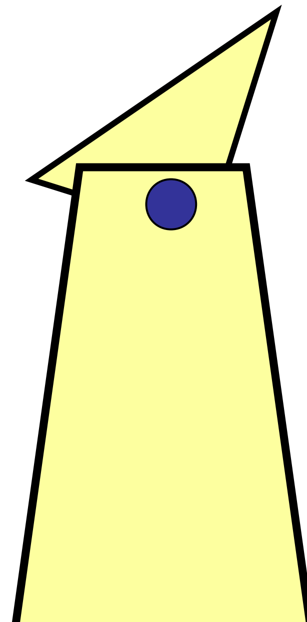
100m Effelsberg for
radio astronomy

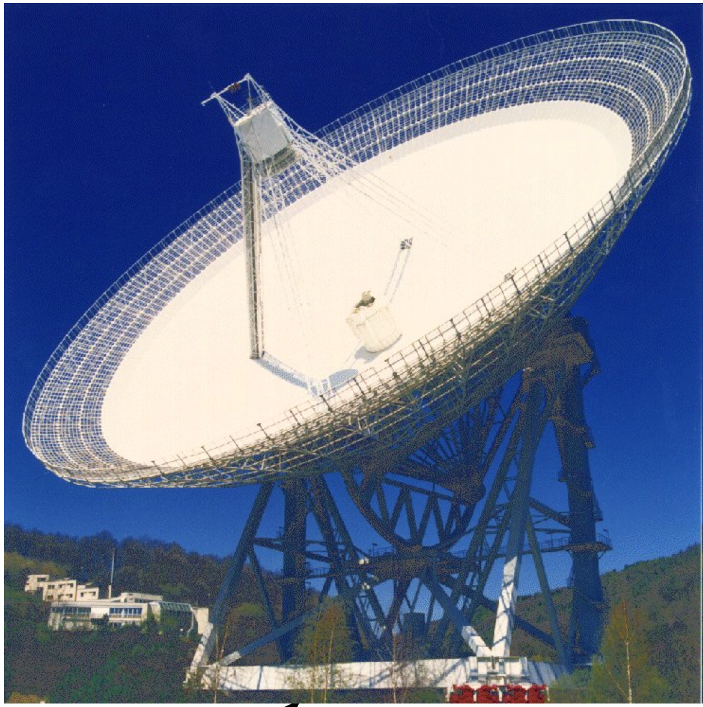




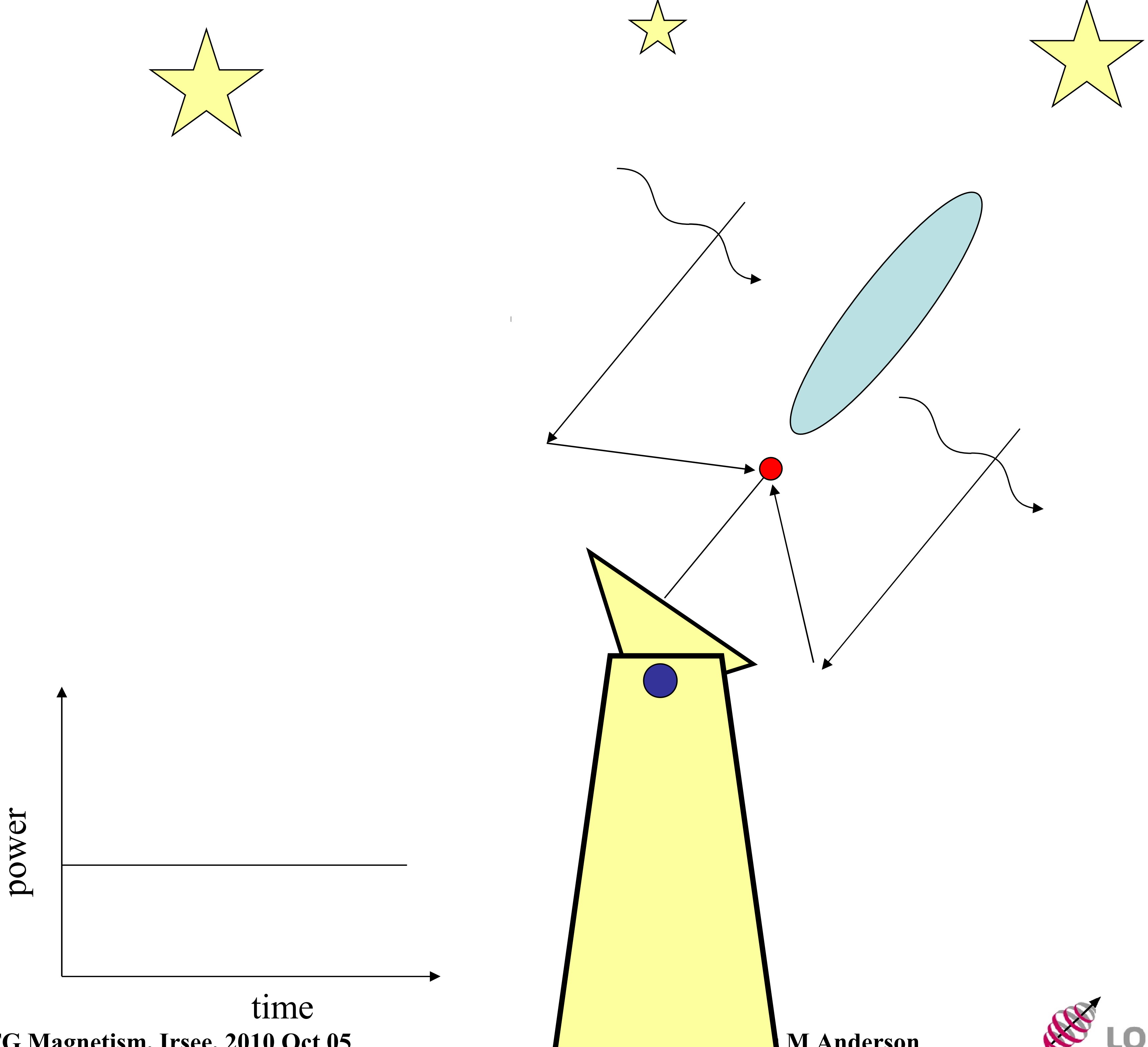


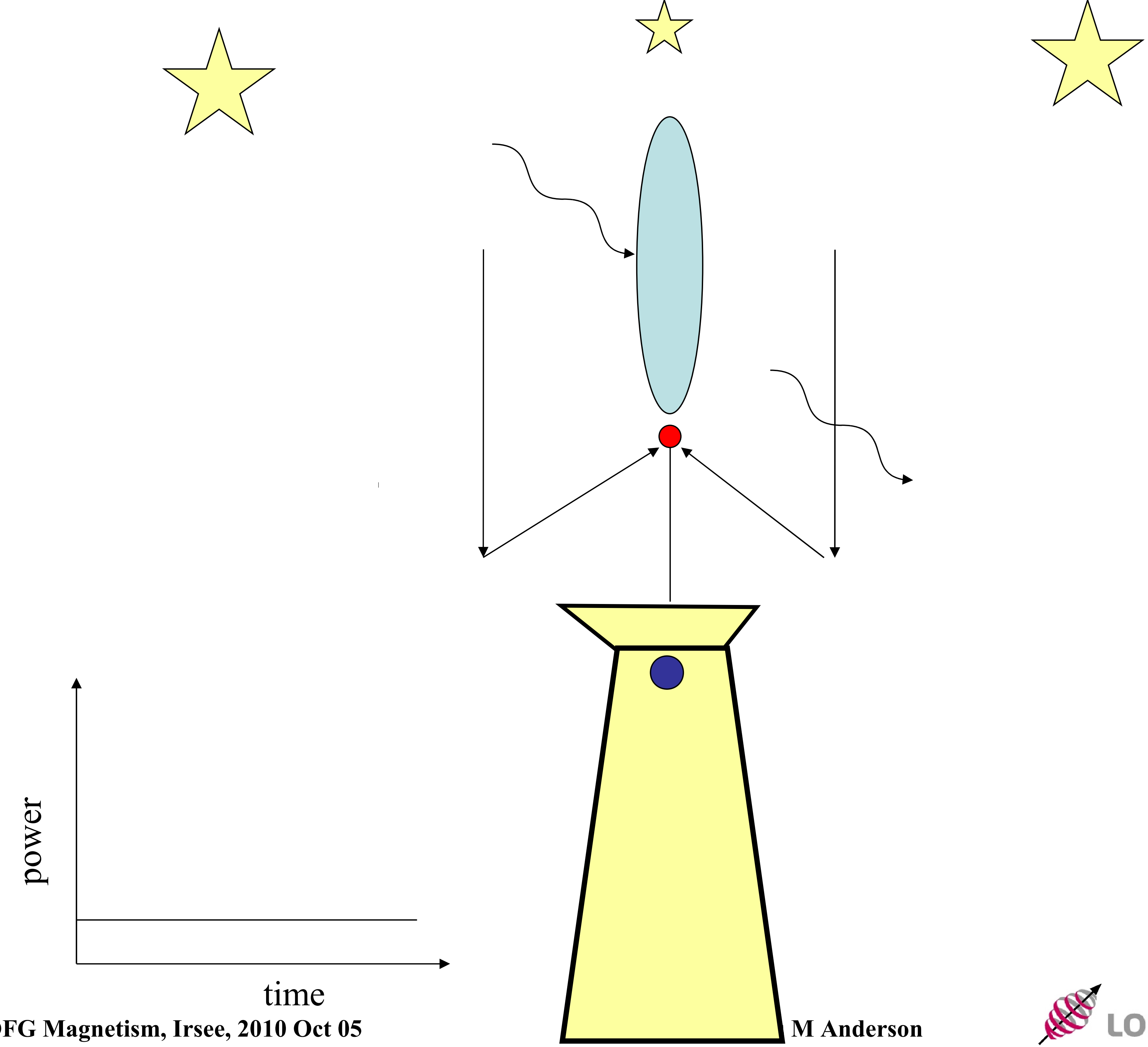
Beam pattern
(An antenna can be considered as
 a transmitting dish.)

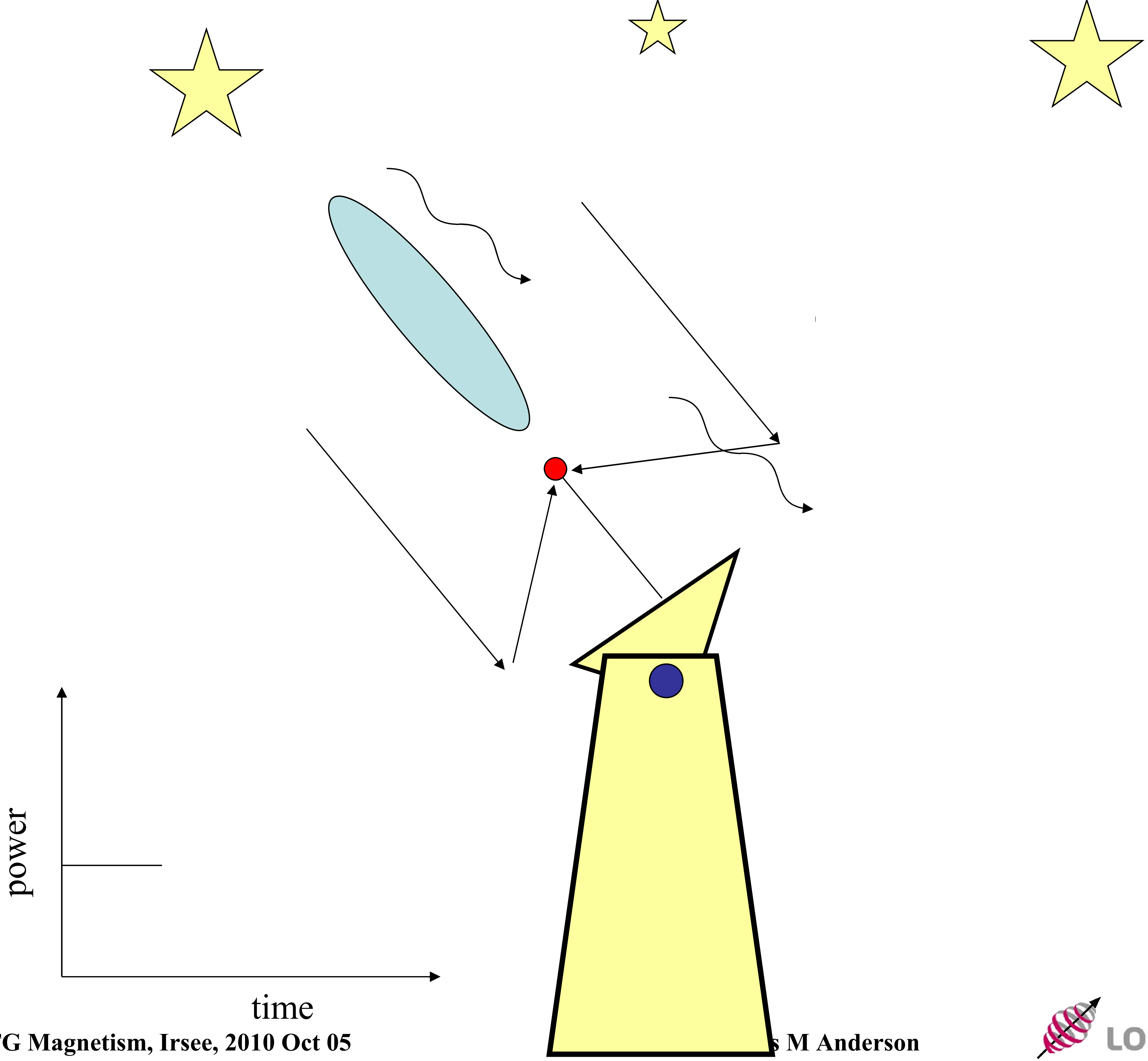


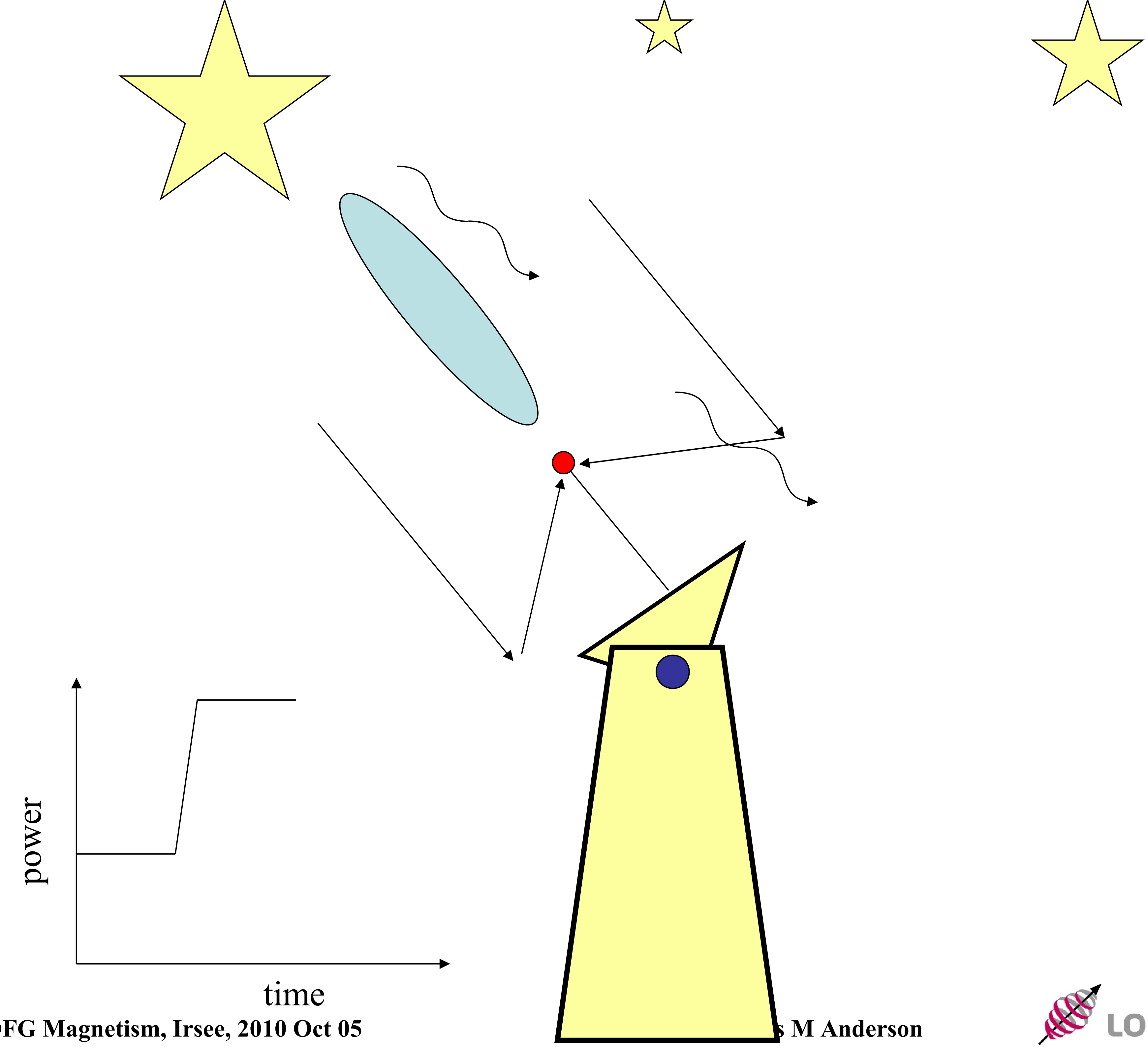


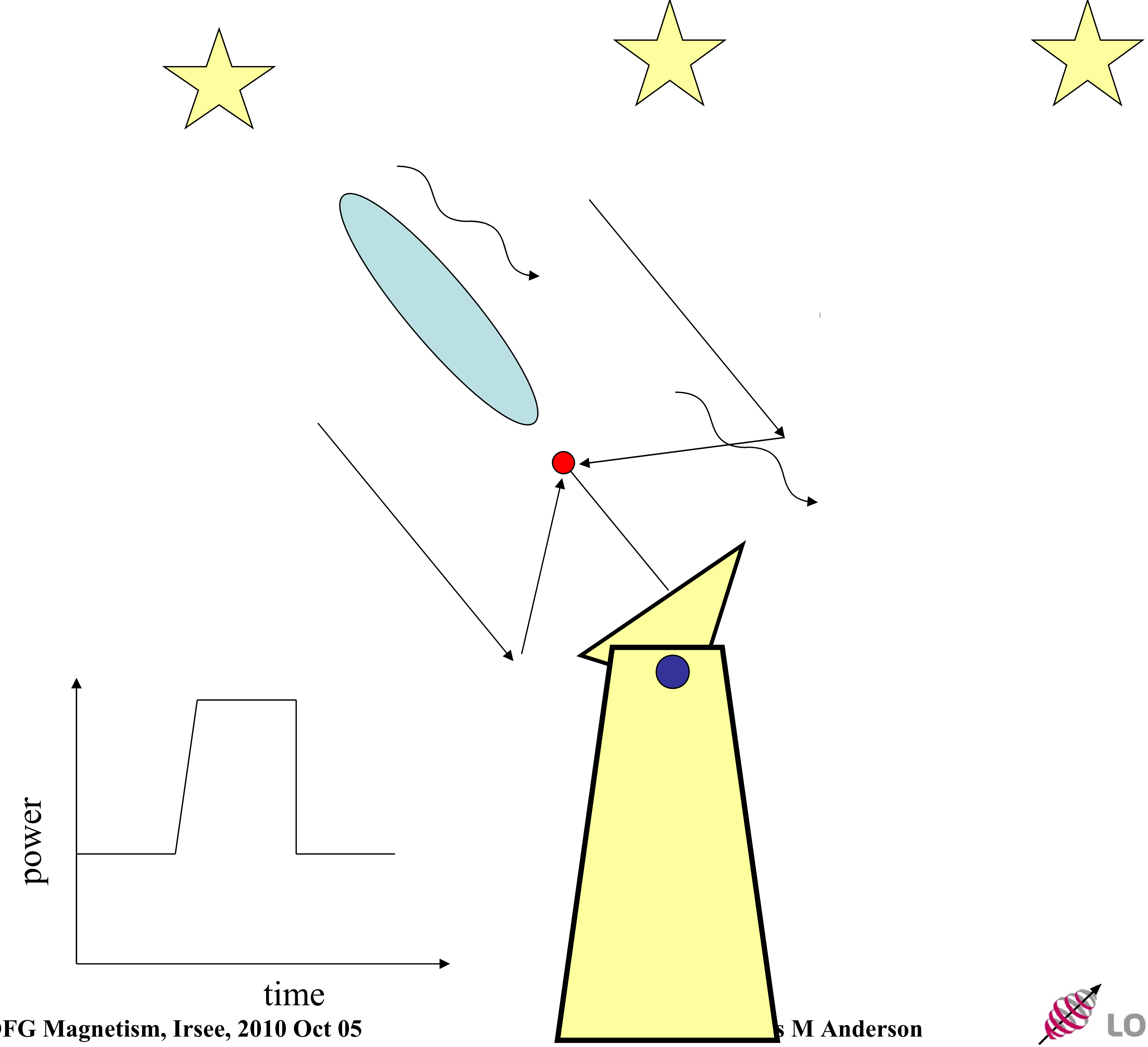
Fully steerable radio telescope

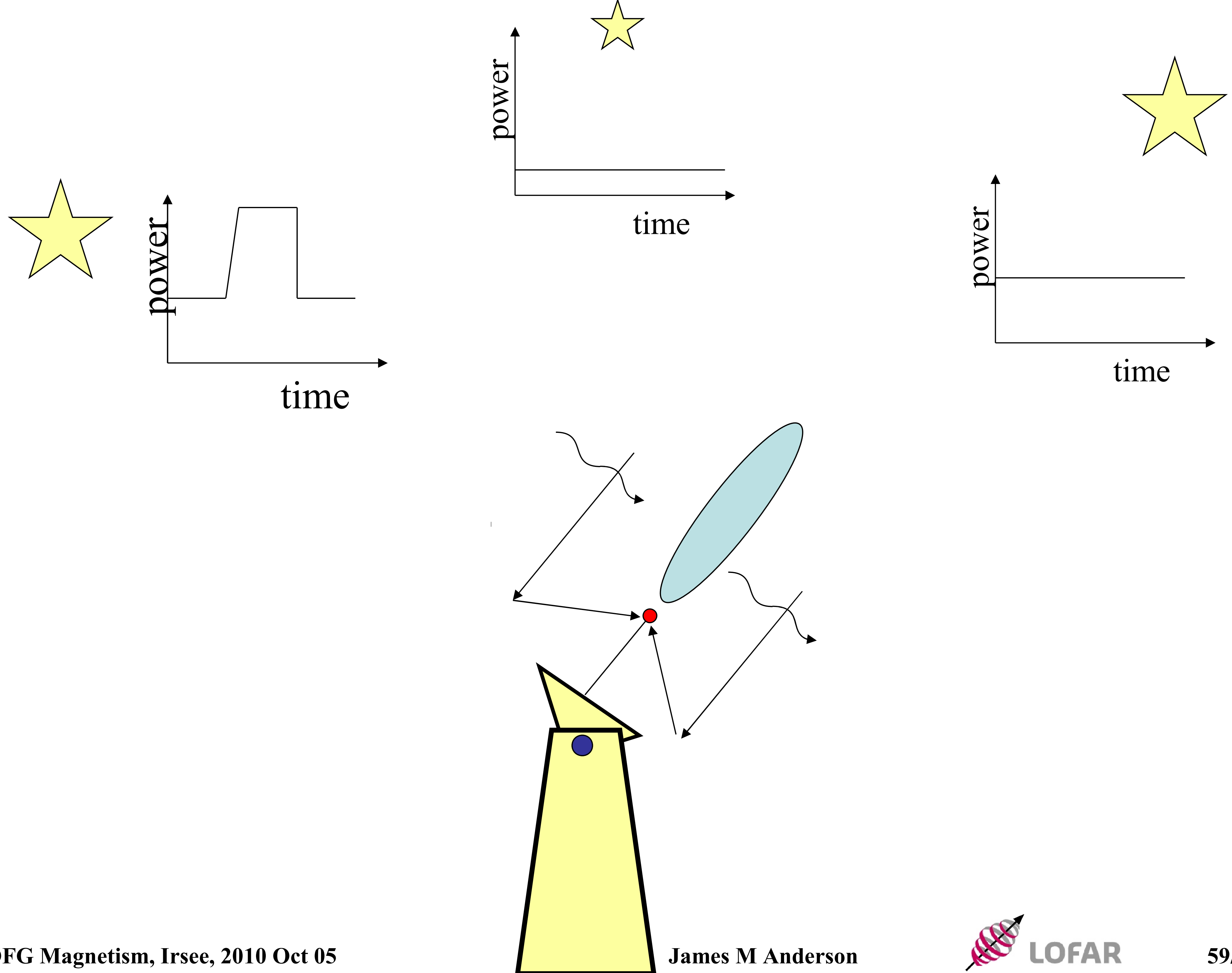

power
time


power
time


power
time


power
time


power
time

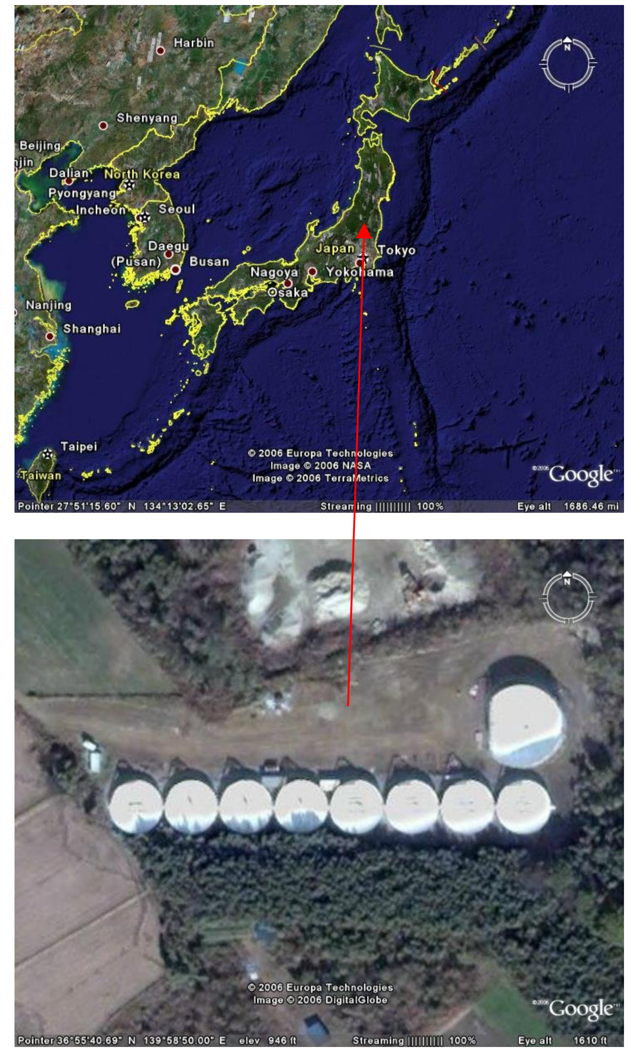

power
time
power
time
power
time

Multi-elements (dish or dipole)

Multi-elements (dish)

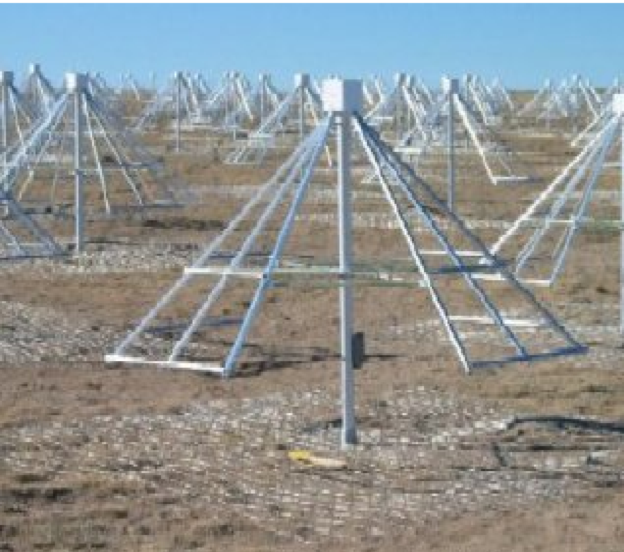
Waseda 64 elements

Multi-elements (dish)

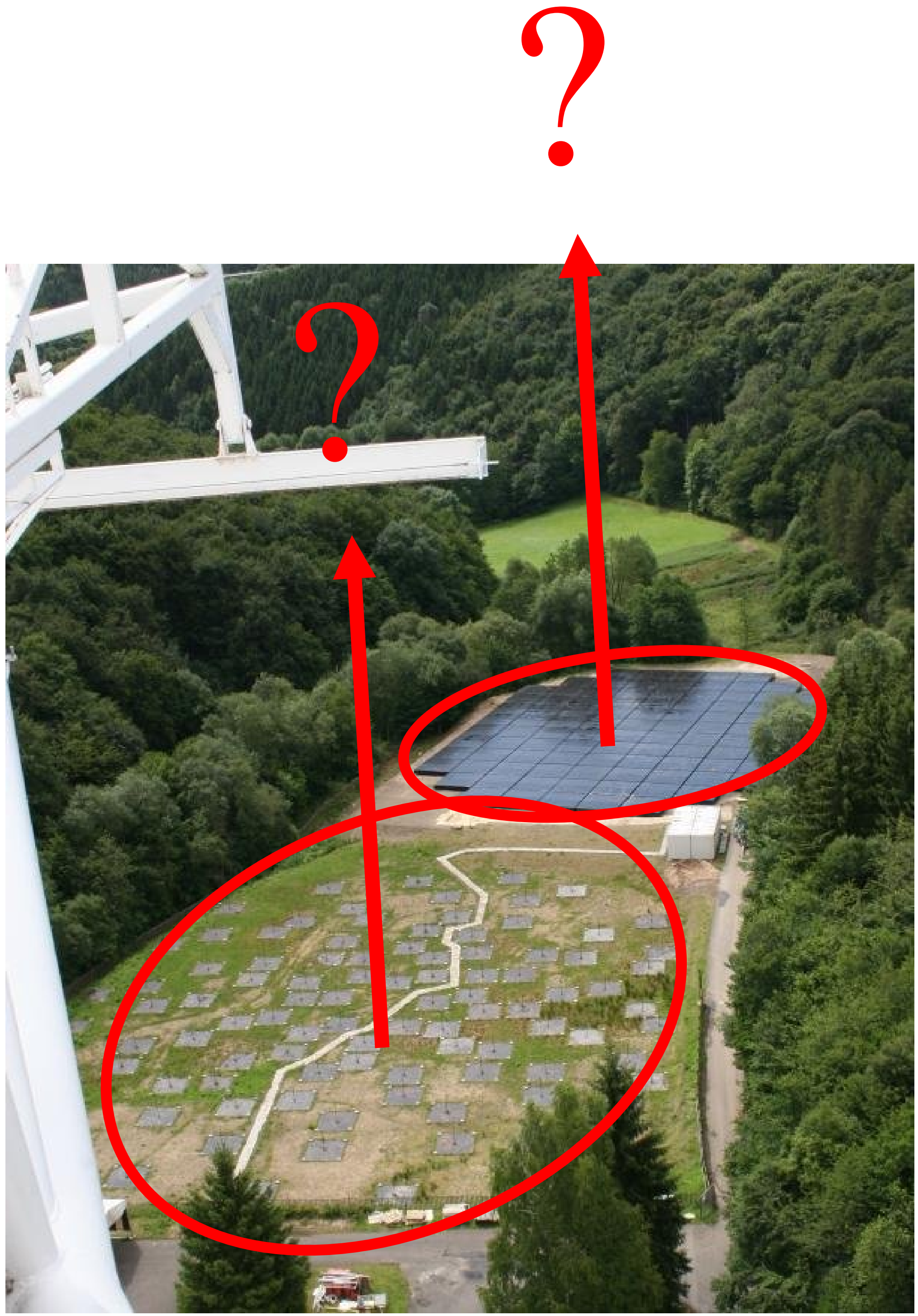


Nasu Observatory

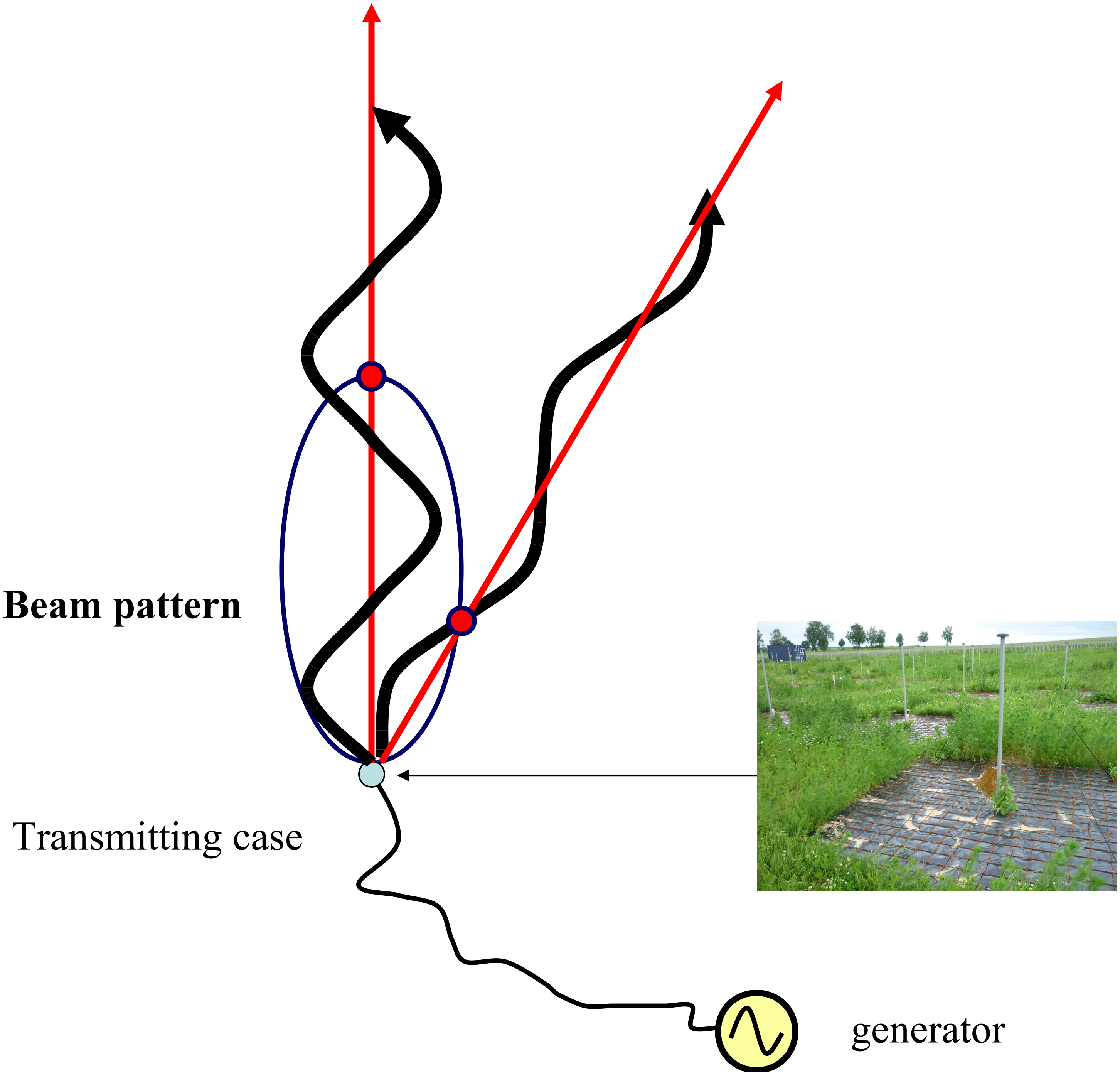
Multi-elements (dipole)



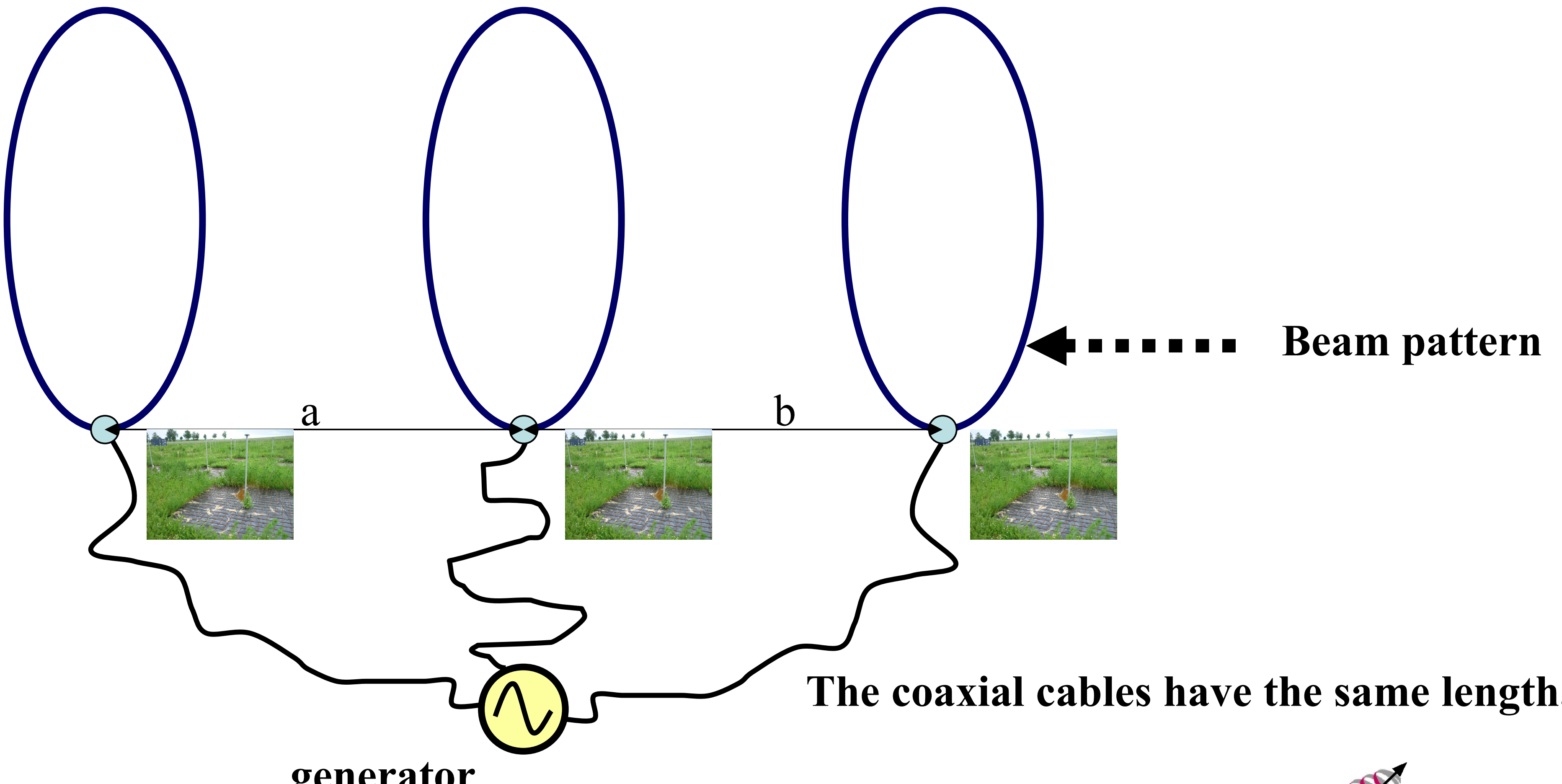




The principle of beamforming

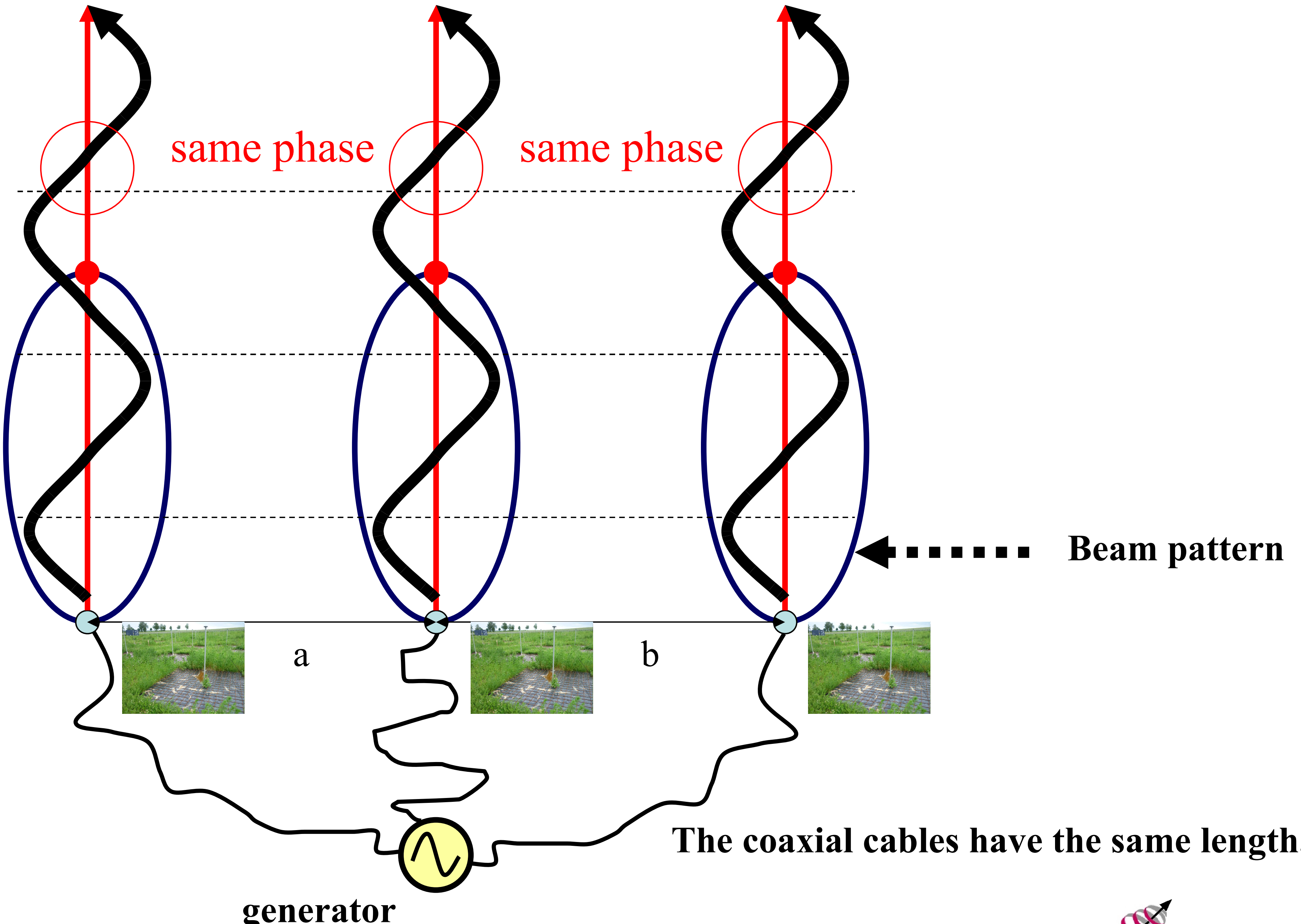


The principle of beamforming

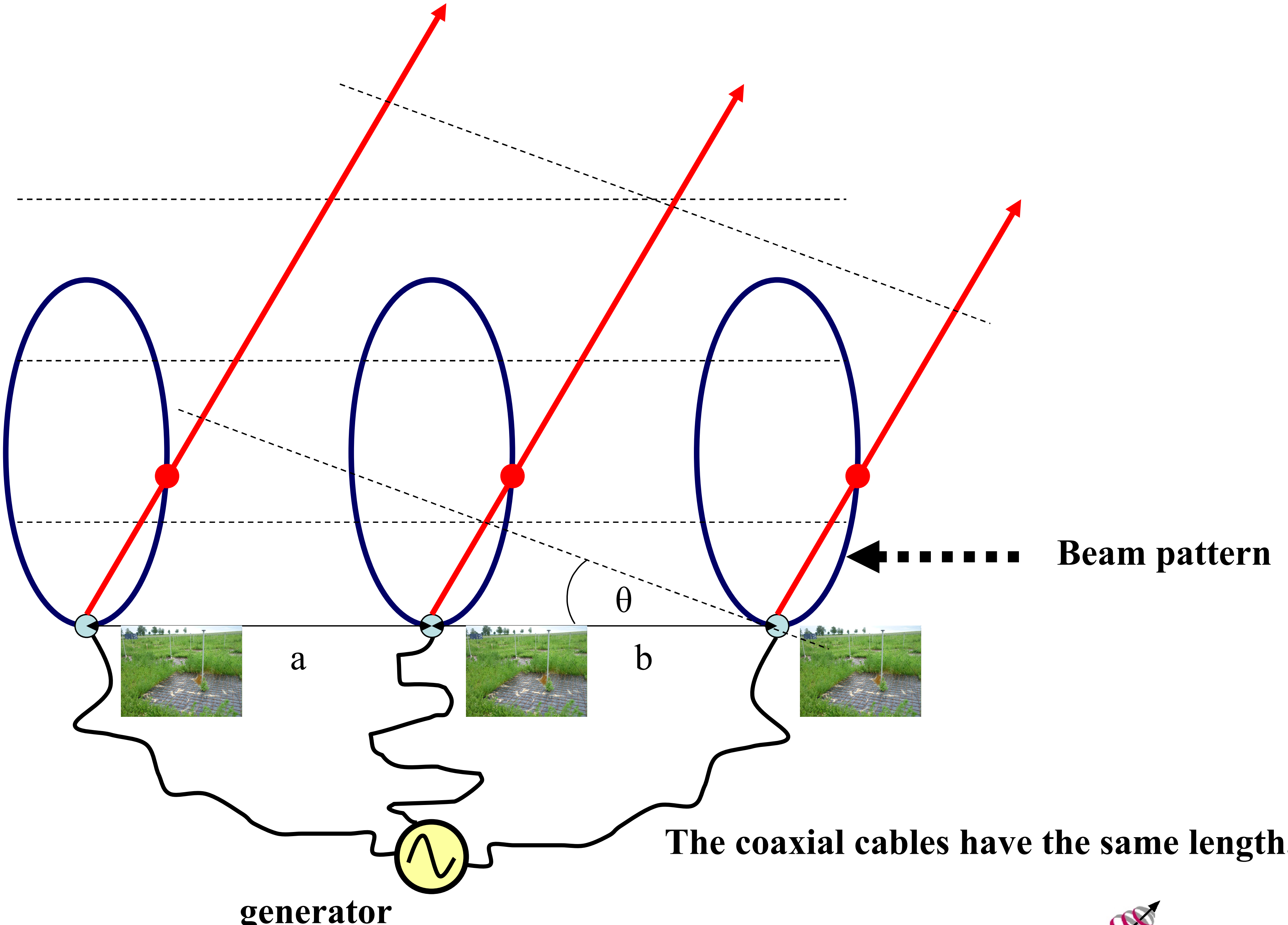


The coaxial cables have the same length.

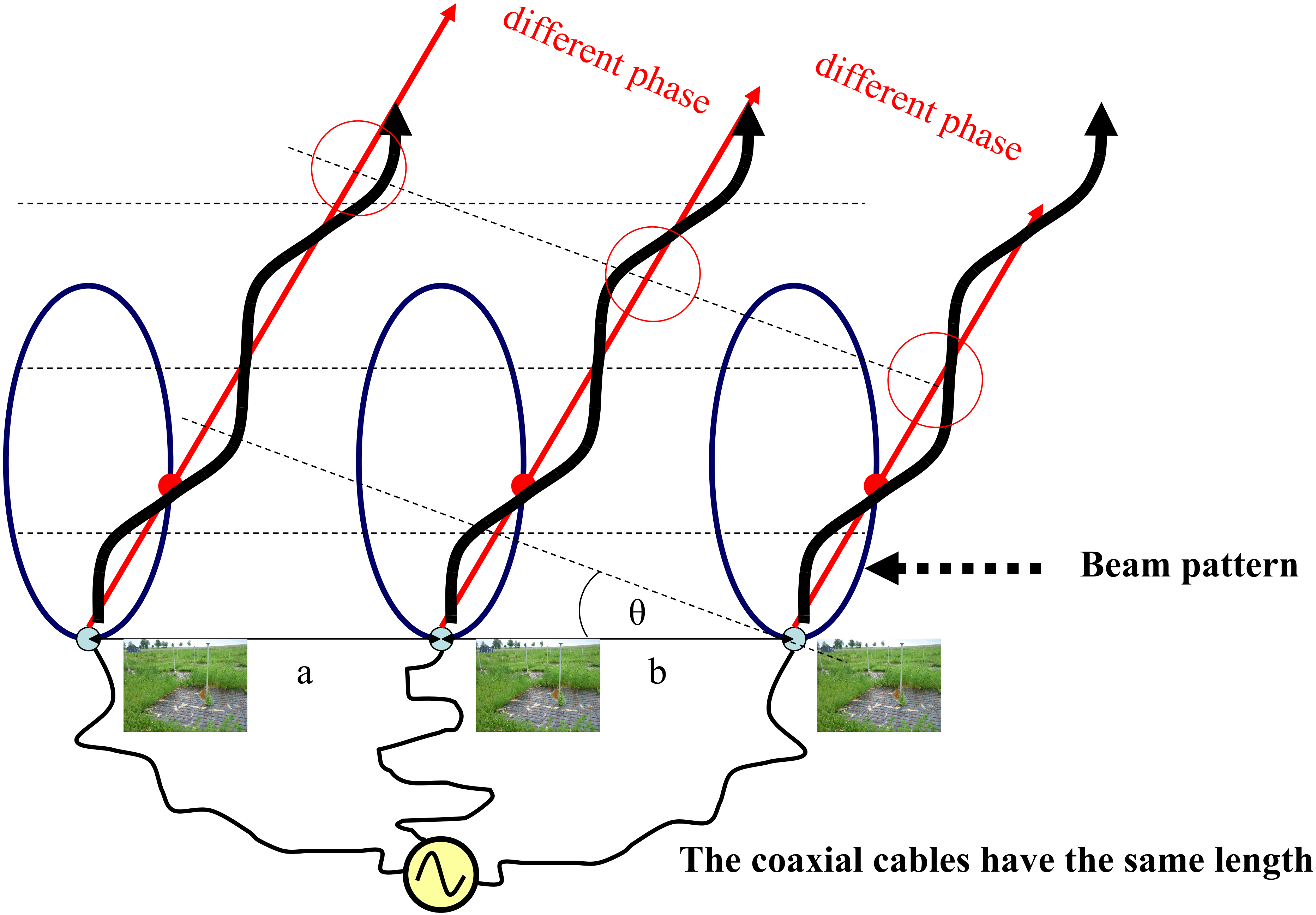
The principle of beamforming



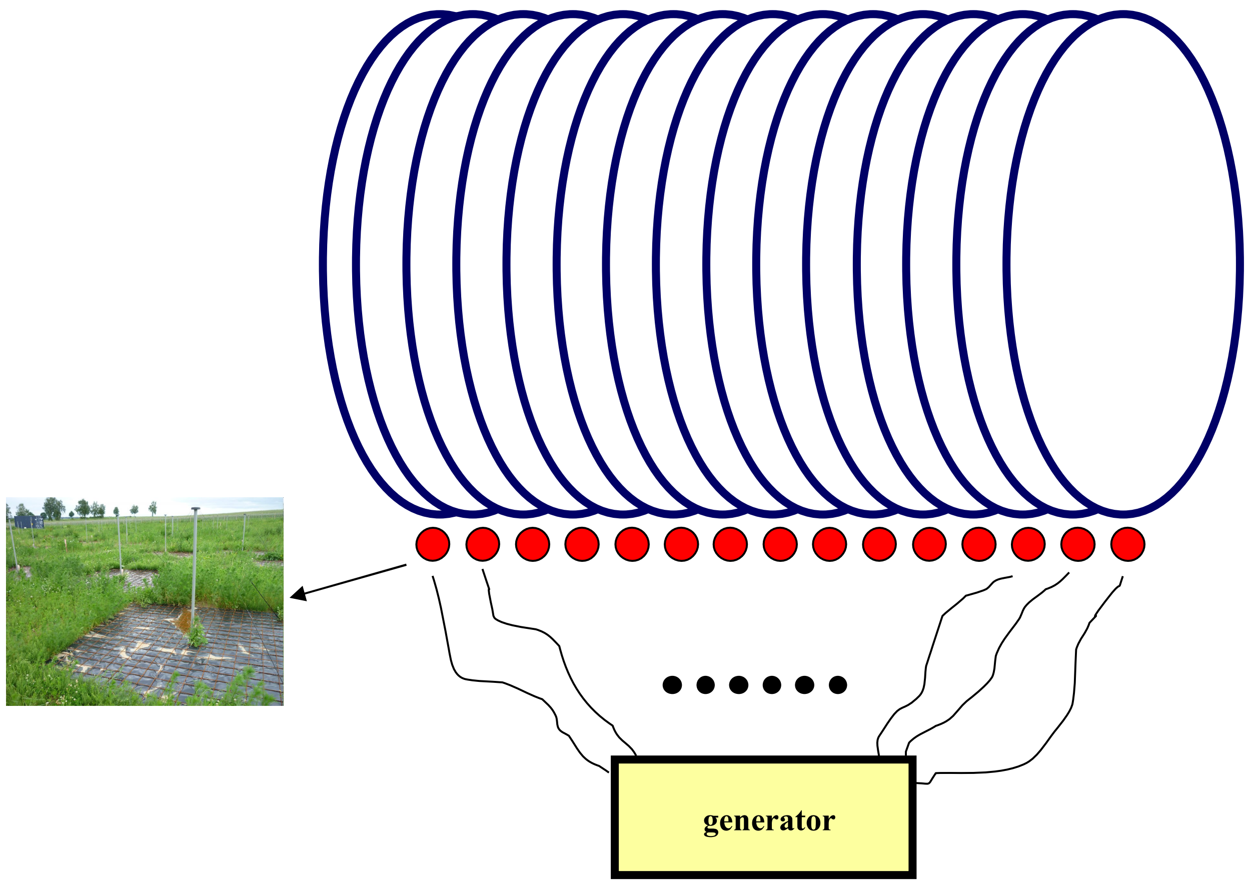
The principle of beamforming



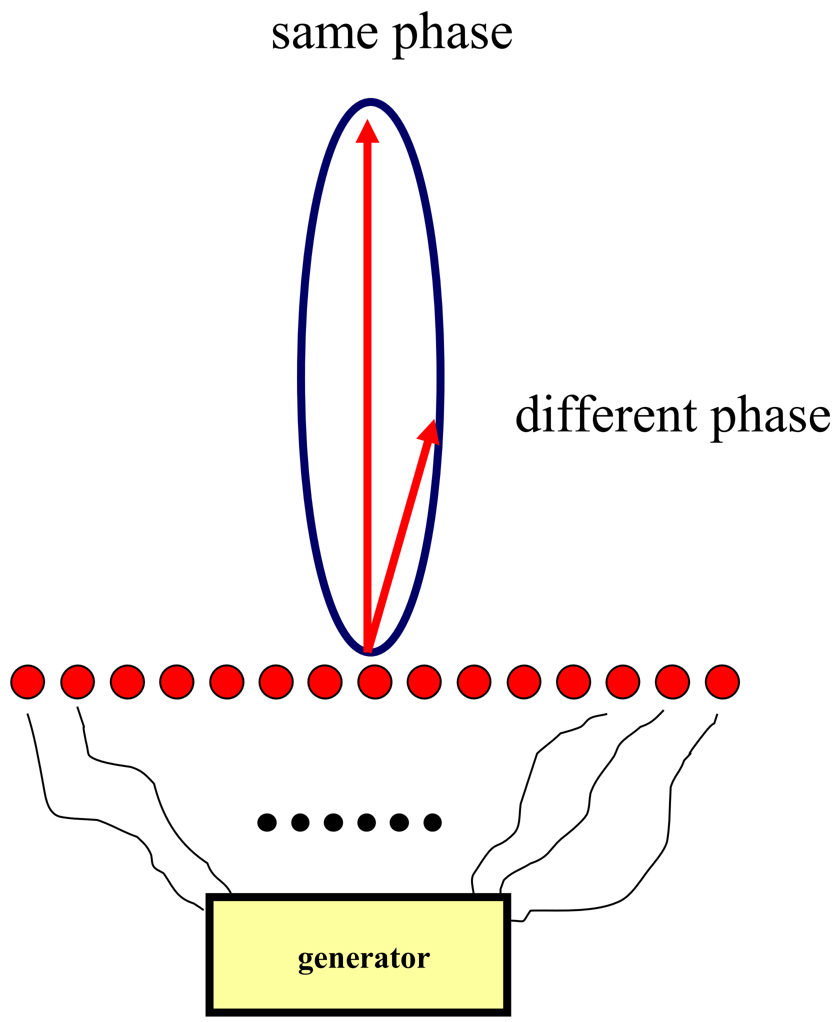
The principle of beamforming



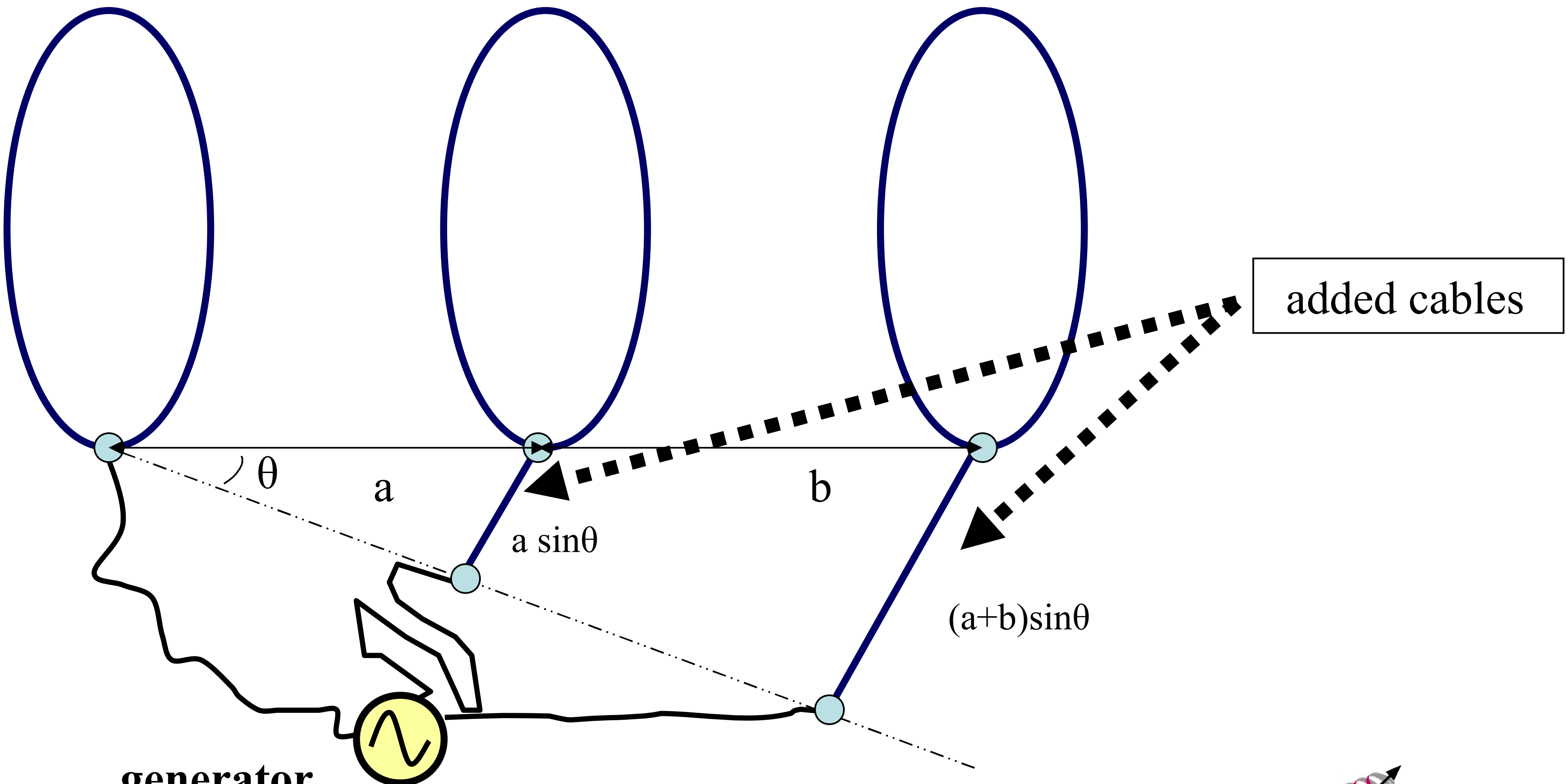
The principle of beamforming



Beam pattern after beamforming

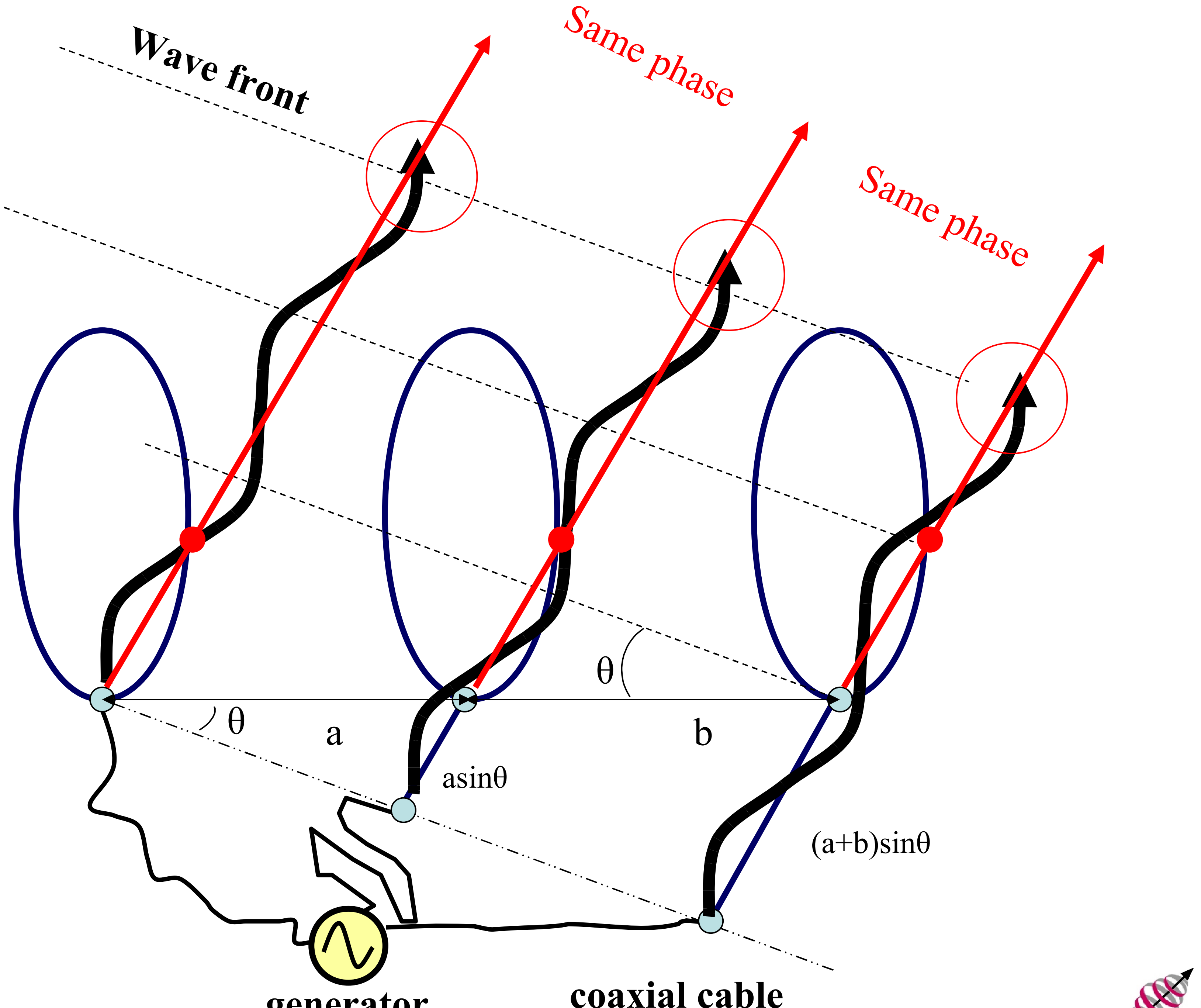


The principle of beamforming

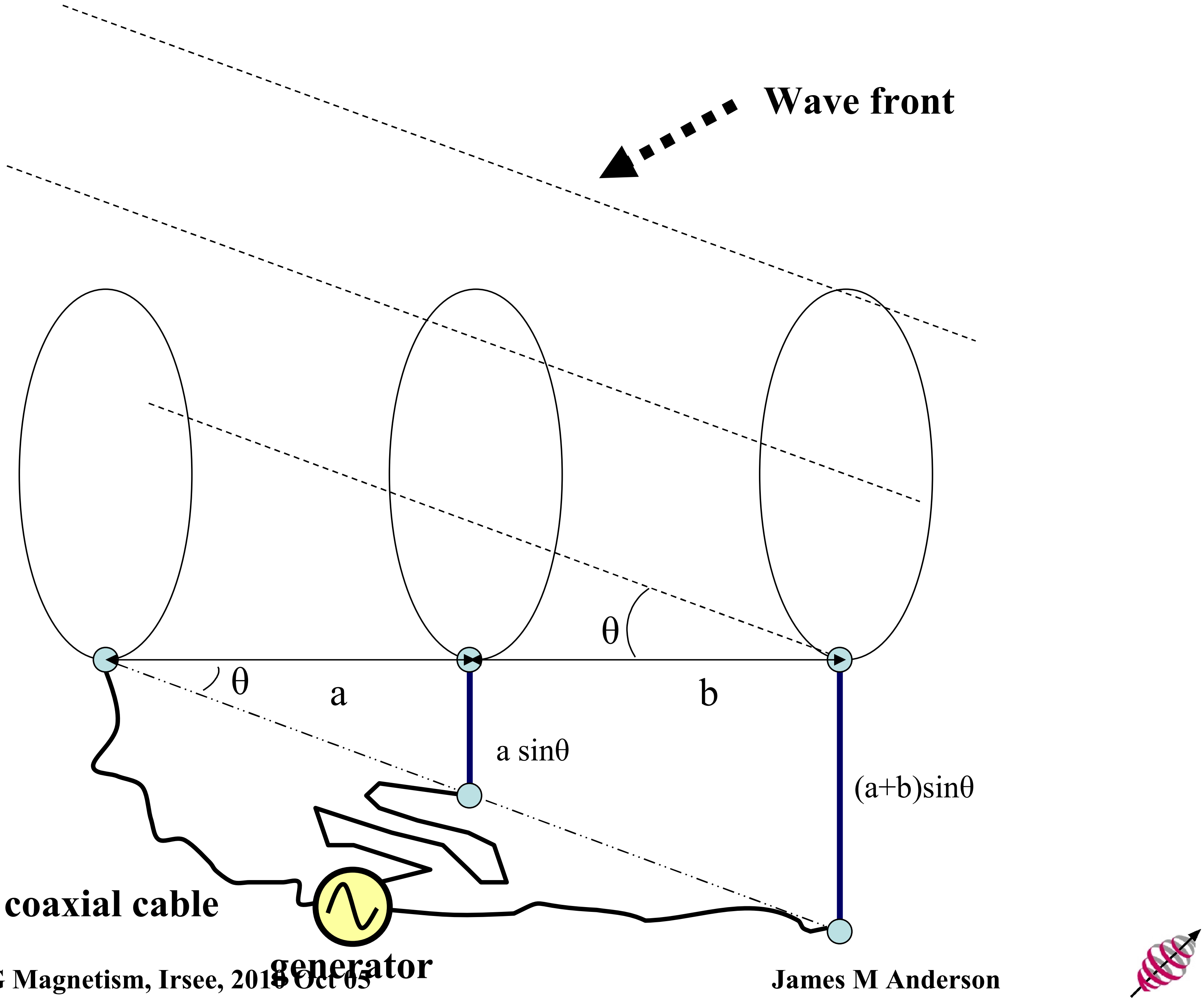


The coaxial cables have the same length.

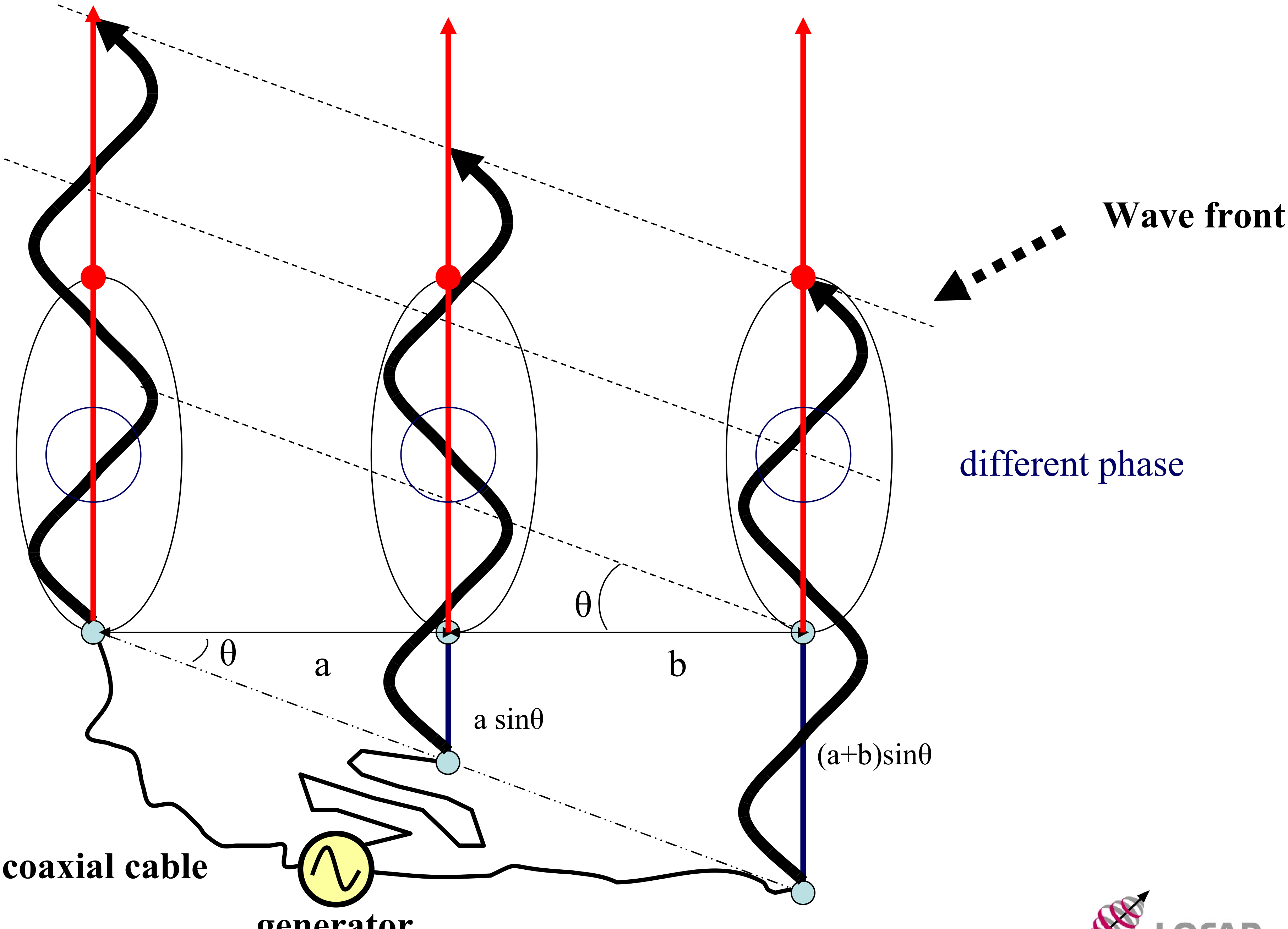
The principle of beamforming



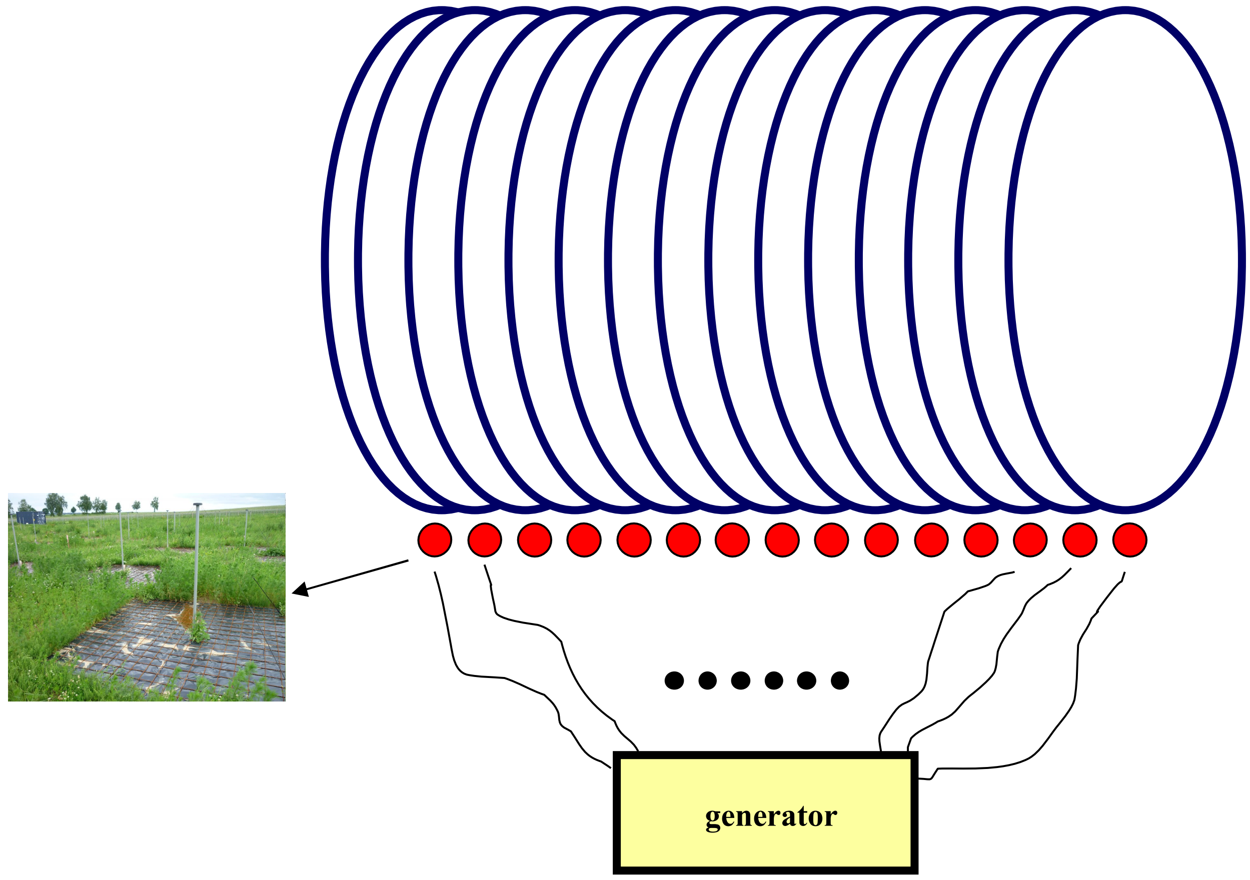
The principle of beamforming



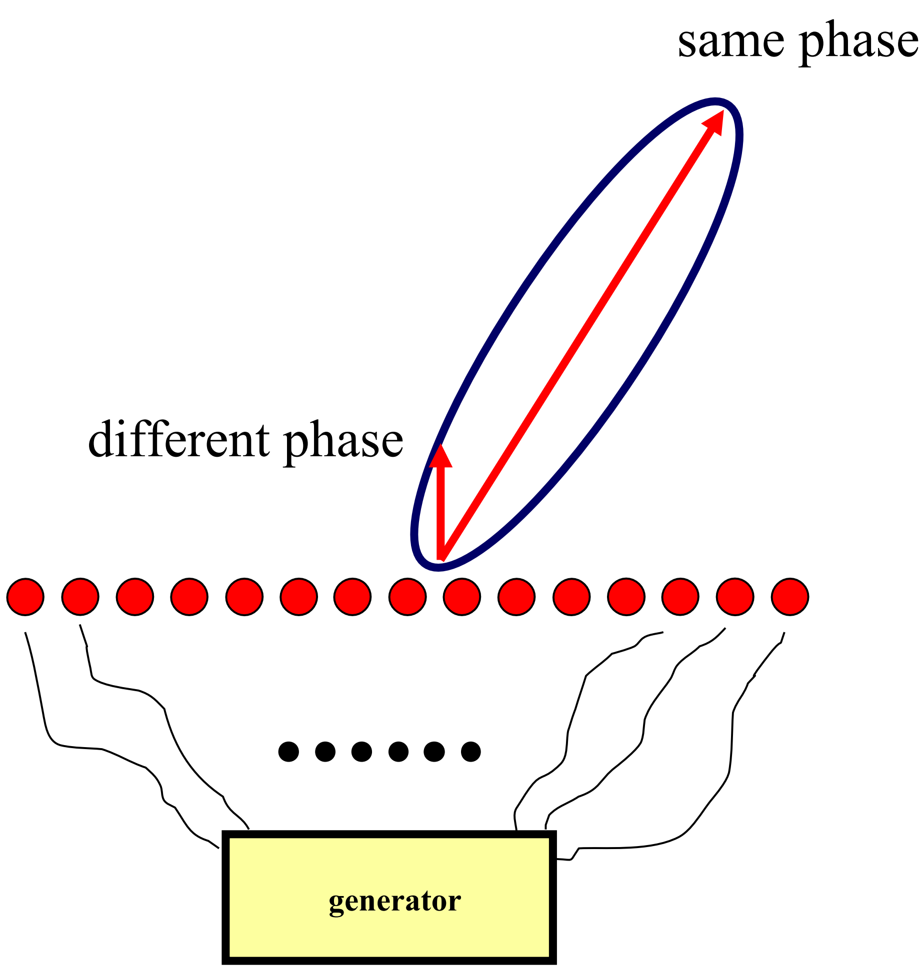
The principle of beamforming



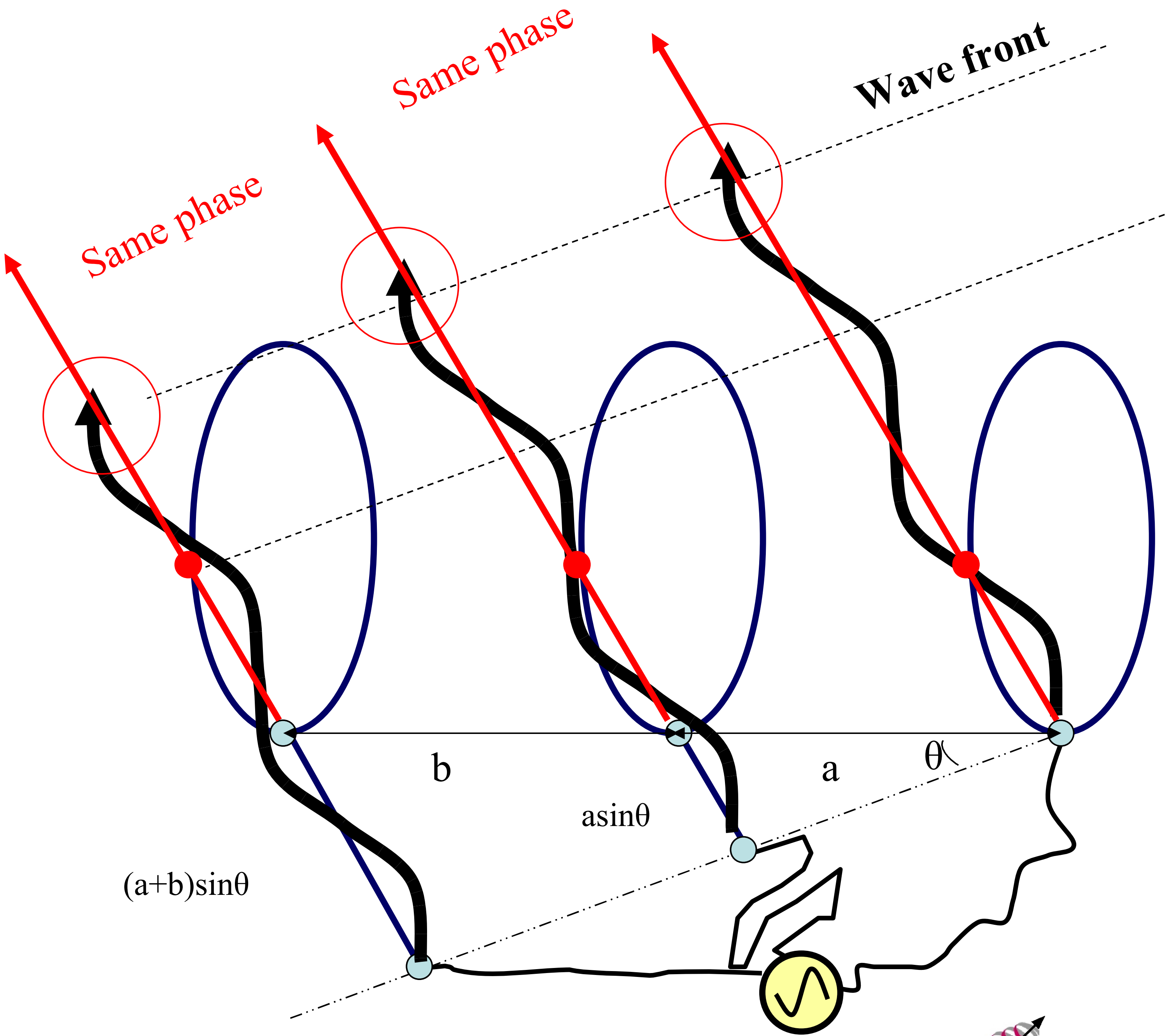
The principle of beamforming



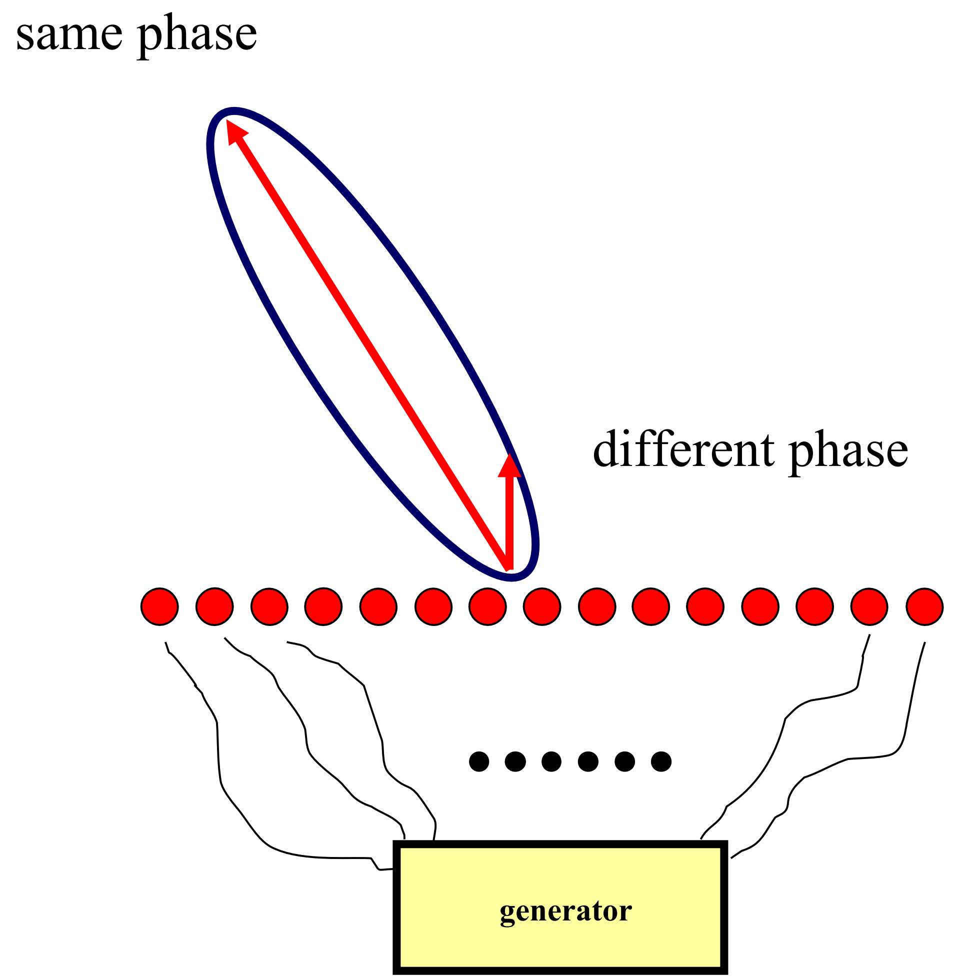
Beam pattern after beamforming



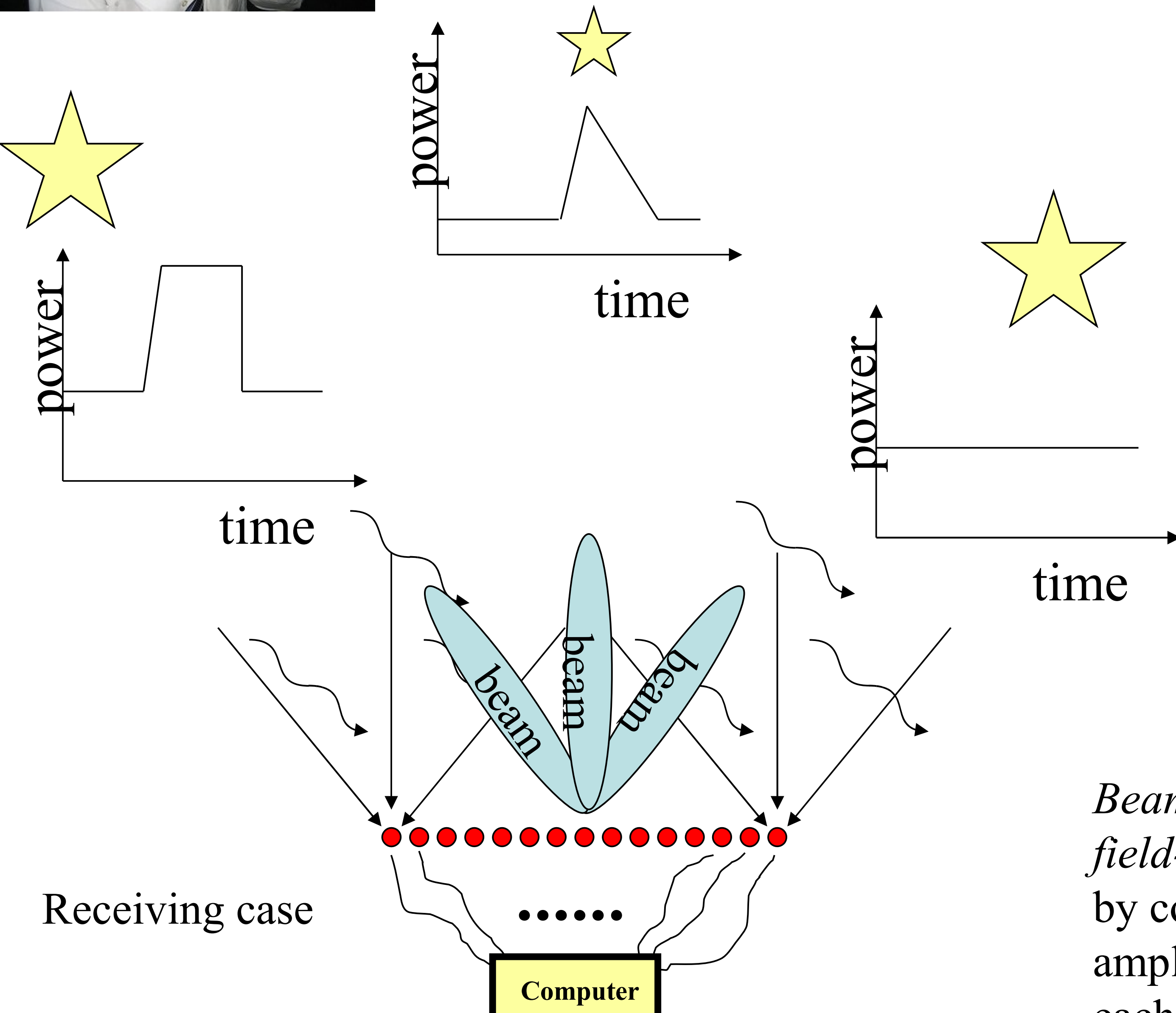
The principle of beamforming

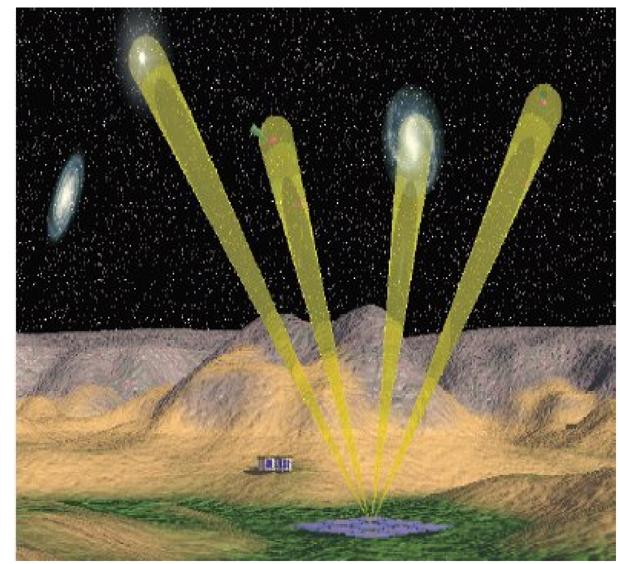


Beam pattern after beamforming



WOW





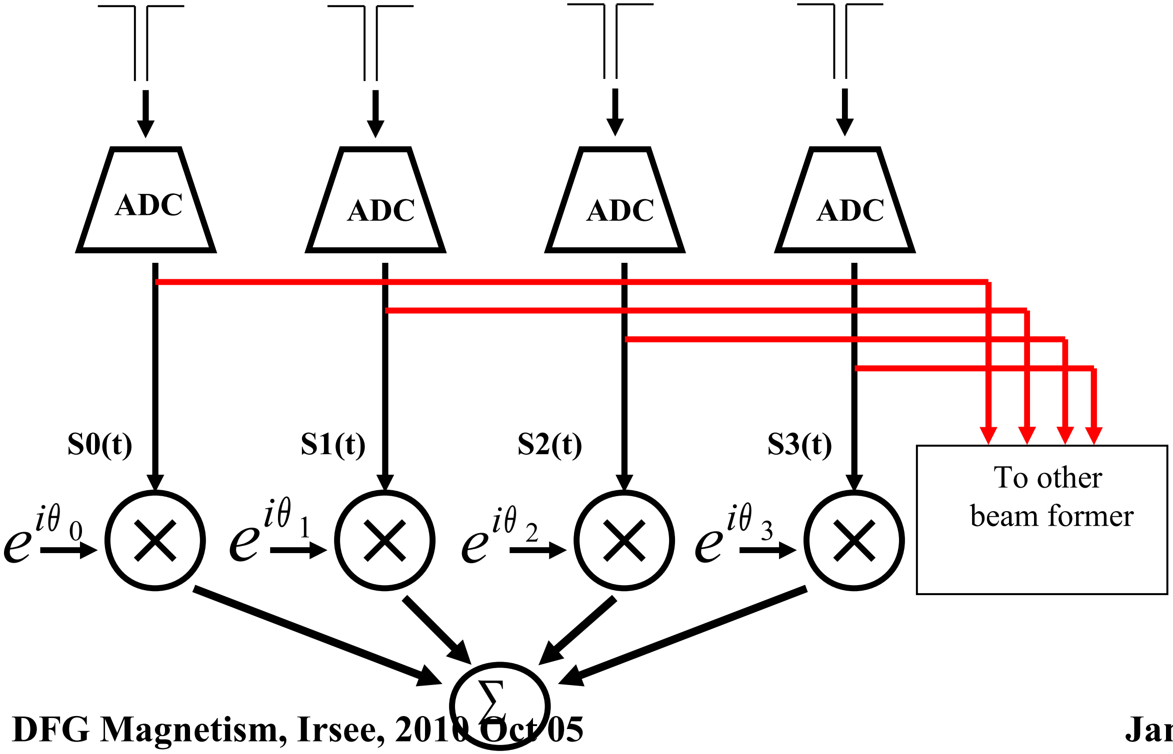
Beamforming provides multiple field-of-view at the same time by controling the phase and amplitude of the signal at each element.

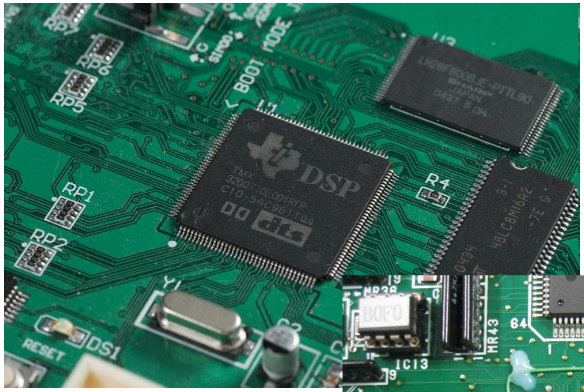
Analog Beamforming

Digital Beamforming

- DSP (Digital Signal Processor) - C,C++
- FPGA (Field Programmable Gate Array)
  - VHDL, Verilog, AHL

Remote Station Processing board





DSP

FPGA