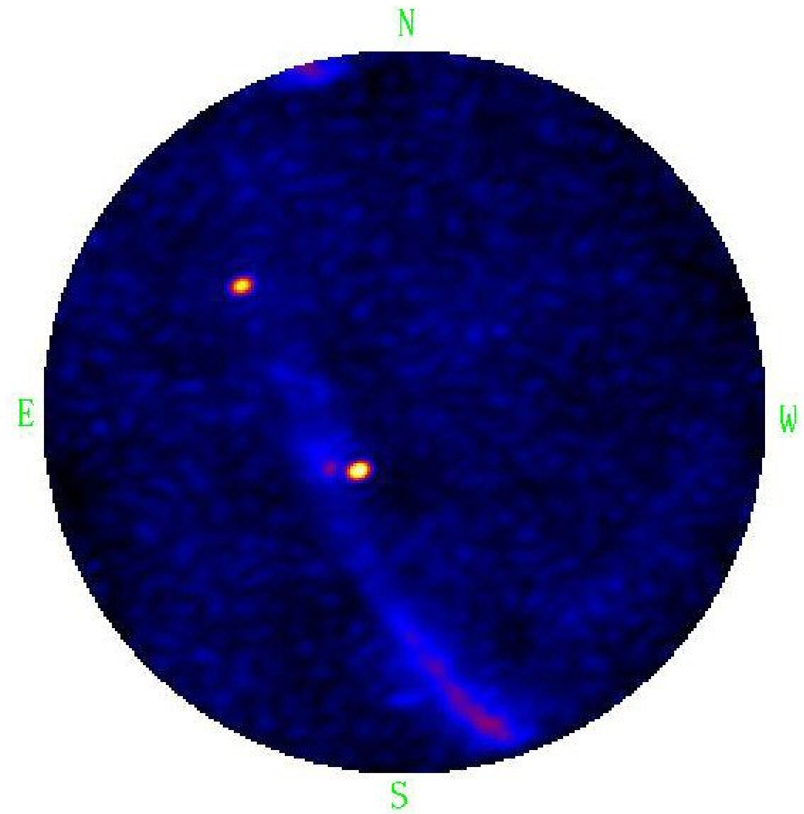
# LOFAR

James M Anderson
anderson@mpifr-bonn.mpg.de

**On behalf of the LOFAR collaboration**




Max-Planck-Institut
für Radioastronomie

LOFAR

MAX-PLANCK-GESELLSCHAFT

# Acknowledgements

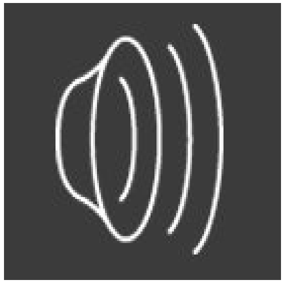
- LOFAR development is performed by a very large community
- Some of the slides in this presentation have been stolen from the antennas and receiver talks of Peter Napier (2006 school) and Mark McKinnon (2010 school)
    - See http://www.aoc.nrao.edu/events/synthesis/2010/
      http://www.aoc.nrao.edu/events/synthesis/2008/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

# What Is LOFAR?

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

# The Future of Radio Astronomy: The SKA

- Show SKA movie here



# Wait a Minute!

- The Square Kilometer **Array** and the Low Frequency **Array** are both arrays
  - Why talk about them at a single dish school?
  - Why is the school called ESSEA, the European Single dish School in the **Era of Arrays**?

# Effelsberg and LOFAR

Swinbourne/Junkes

Anderson/MPIfR

# 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?

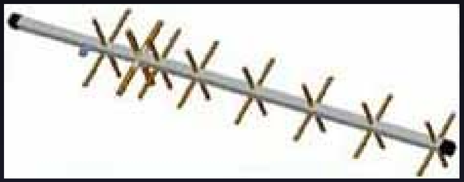
# General Antenna Types

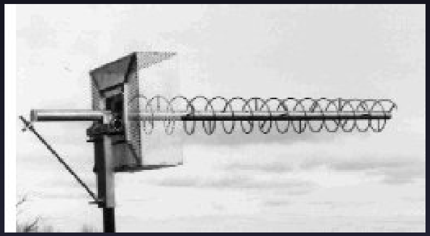
Wavelength > 1 m (approx)

Wire Antennas


Dipole

Yagi



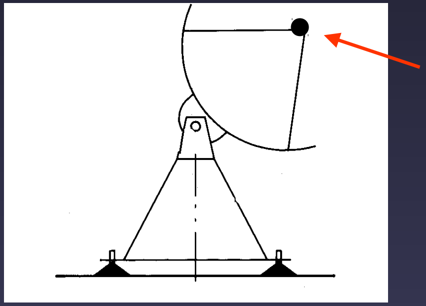


Helix

or arrays of these

Wavelength < 1 m (approx)

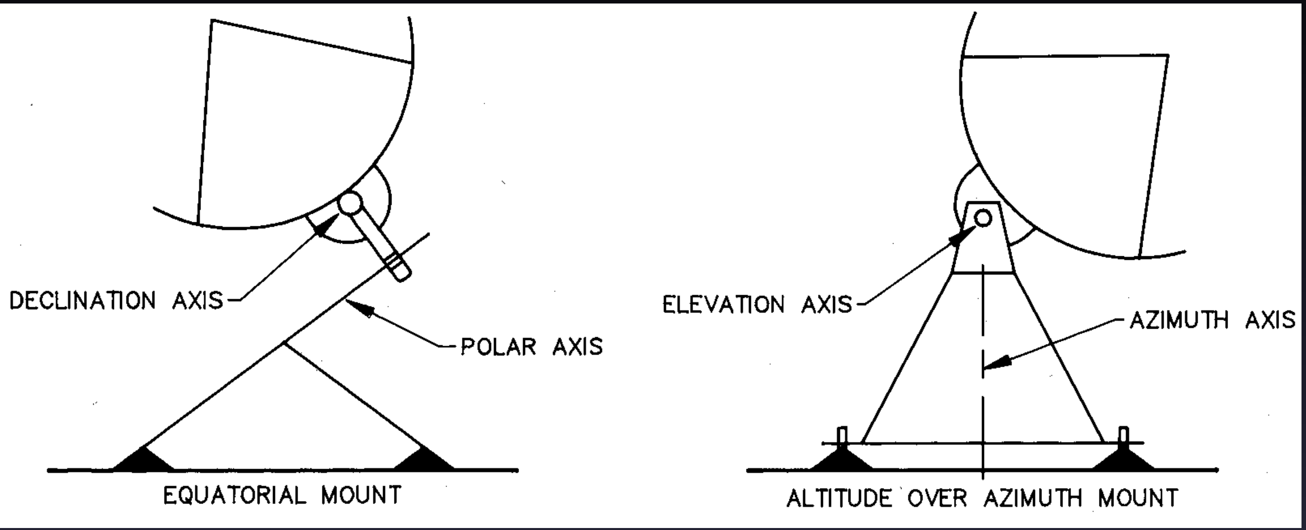
Reflector antennas



Feed

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

# Types of Antenna Mounts

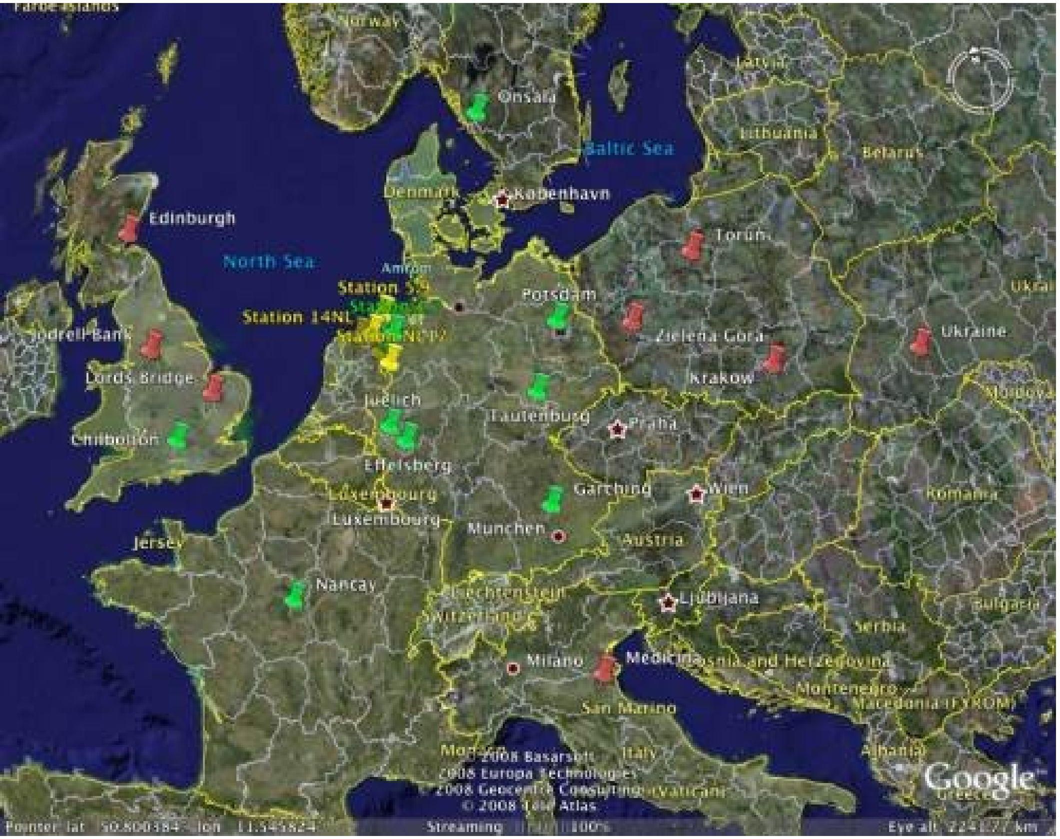



+ Beam does not rotate
+ Better tracking accuracy
– Higher cost
– Poorer gravity performance
– Non-intersecting axis

+ 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)

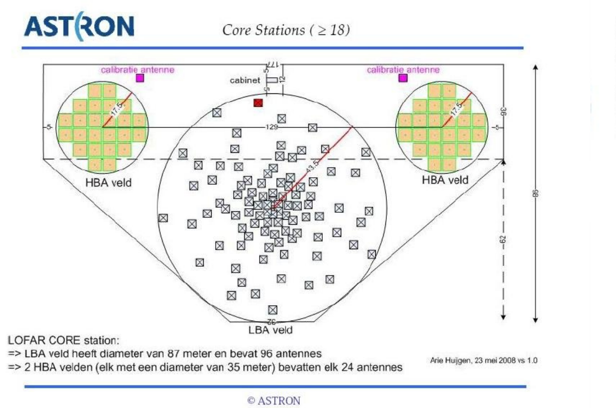
- Core (2 km diameter)
- Remote (inside NL)
- International (outside NL)

Core + Remote } Orginal LOFAR

Core + Remote + International } Current LOFAR

# Core

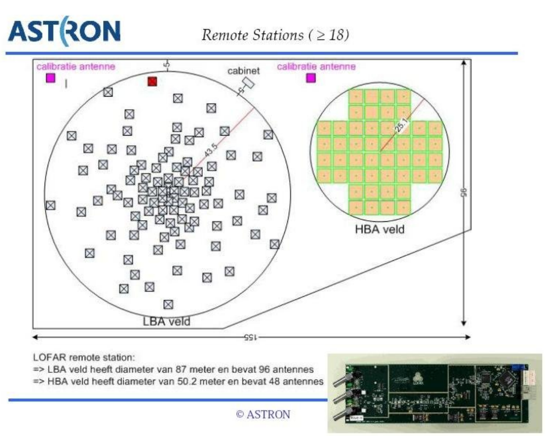

- Core area will be a nature reserve
- 96 LBA antennas (48 observing at a time) & 2 x 24 HBA tiles




- 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


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

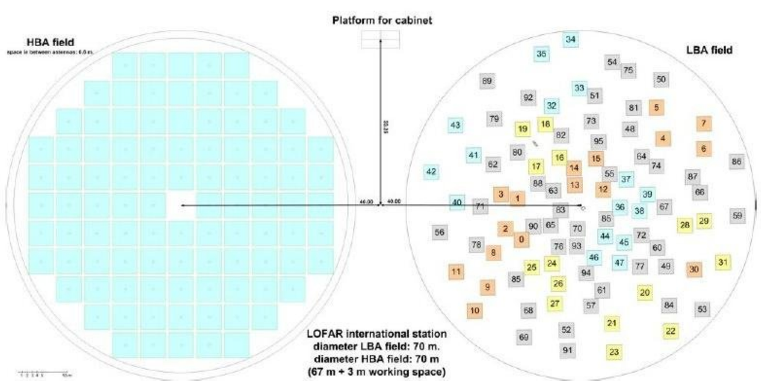



- Up to 130 km baselines
- Circular-pair half-design
- Station Beam FWHM
  - 8.7 6.6 3.7 1.9°
  - 30 75 120 240 MHz
- Synthesized beam
  - 20 8 5 3”
  - 30 75 120 240 MHz

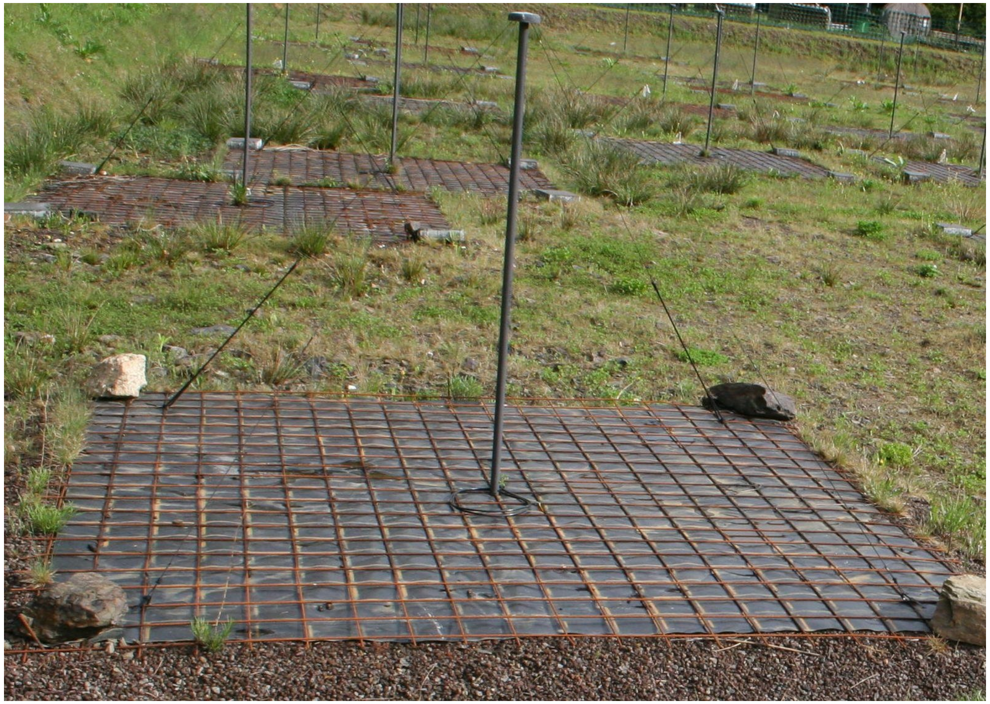

# International

- ~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

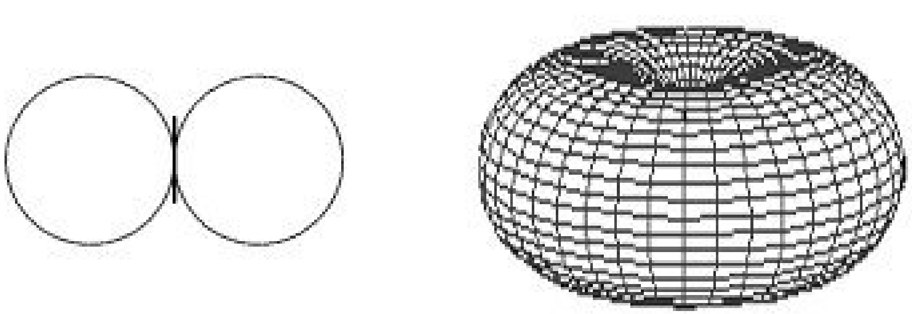
- 96 LBA and 96 HBA tiles
- Station rotation also applied



# LBA

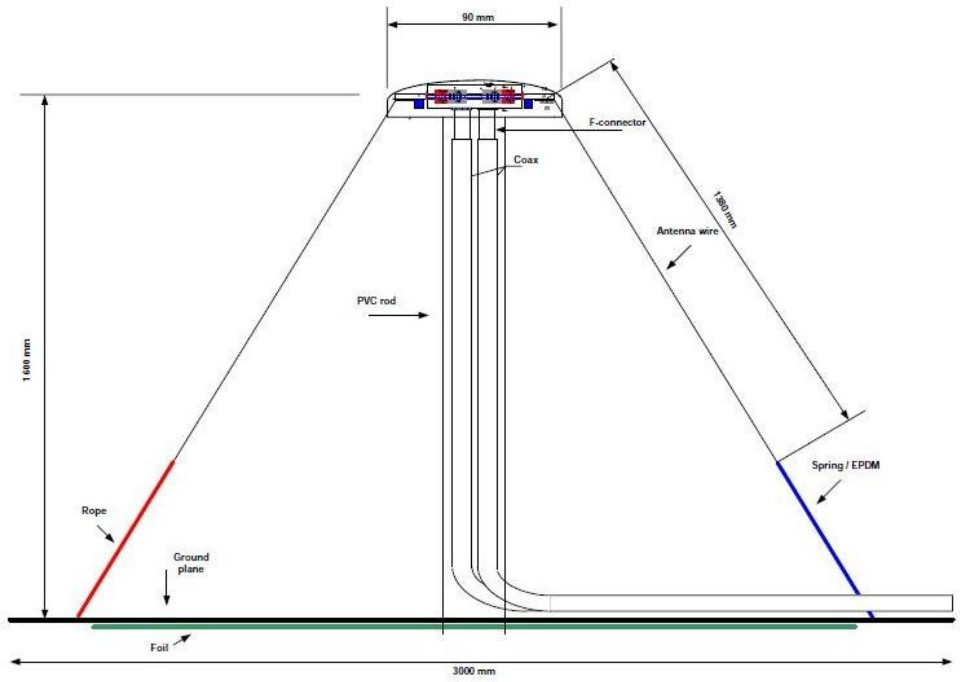


- Low Band Antenna
- 10 to 80 MHz
- Peak response ~56 MHz
- Normally filter out RFI below 30 MHz
- Bent dipole design



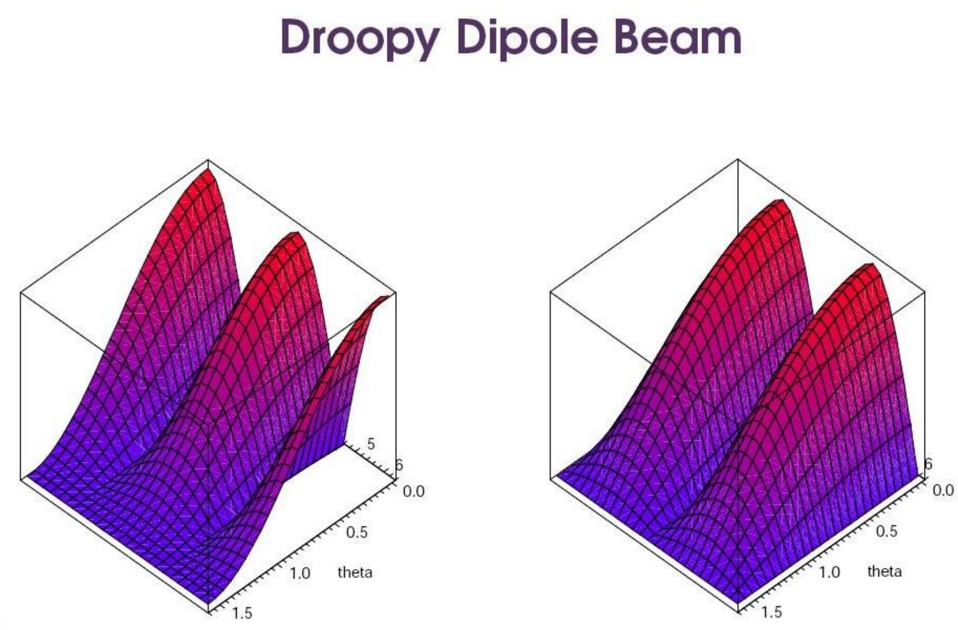
Dipole radiation patterns from Wikipedia

# LBA


- Head contains connectors for dipole wires
- Ambient temperature amplifiers

# LBA Antenna Beam

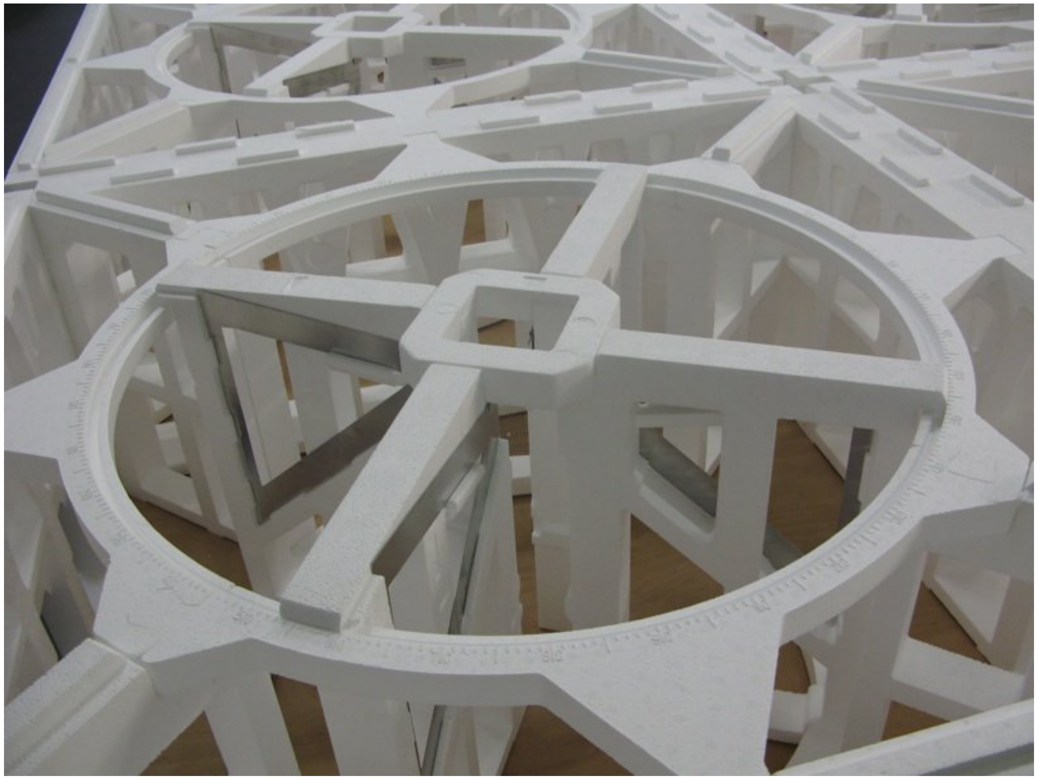


Analytic LBA dipole model by Yatawatta

- 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"

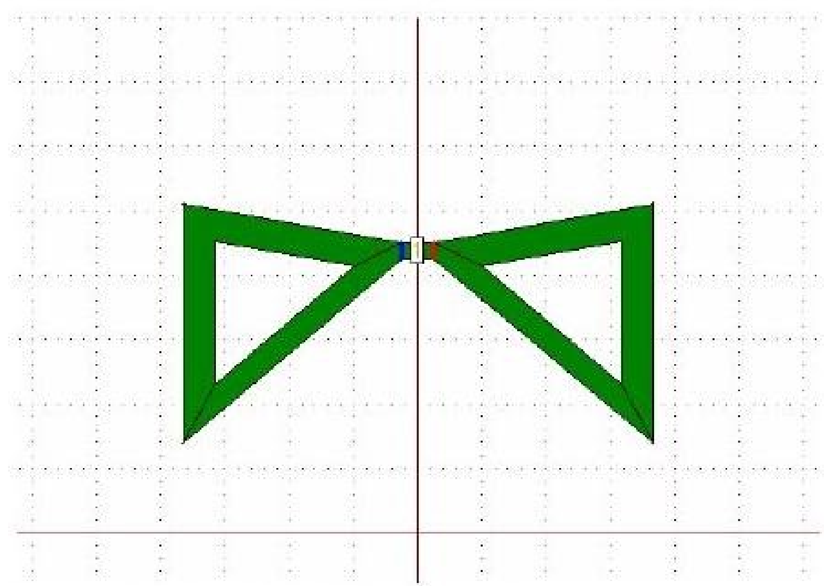
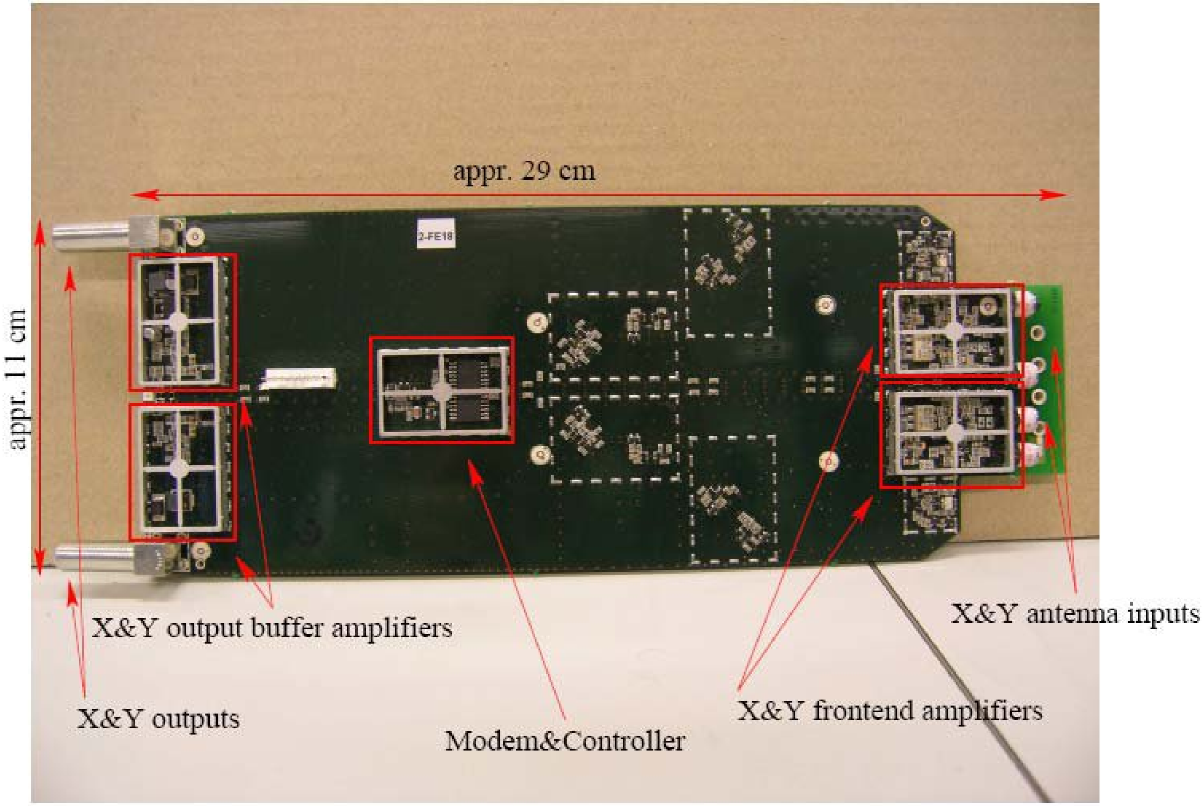
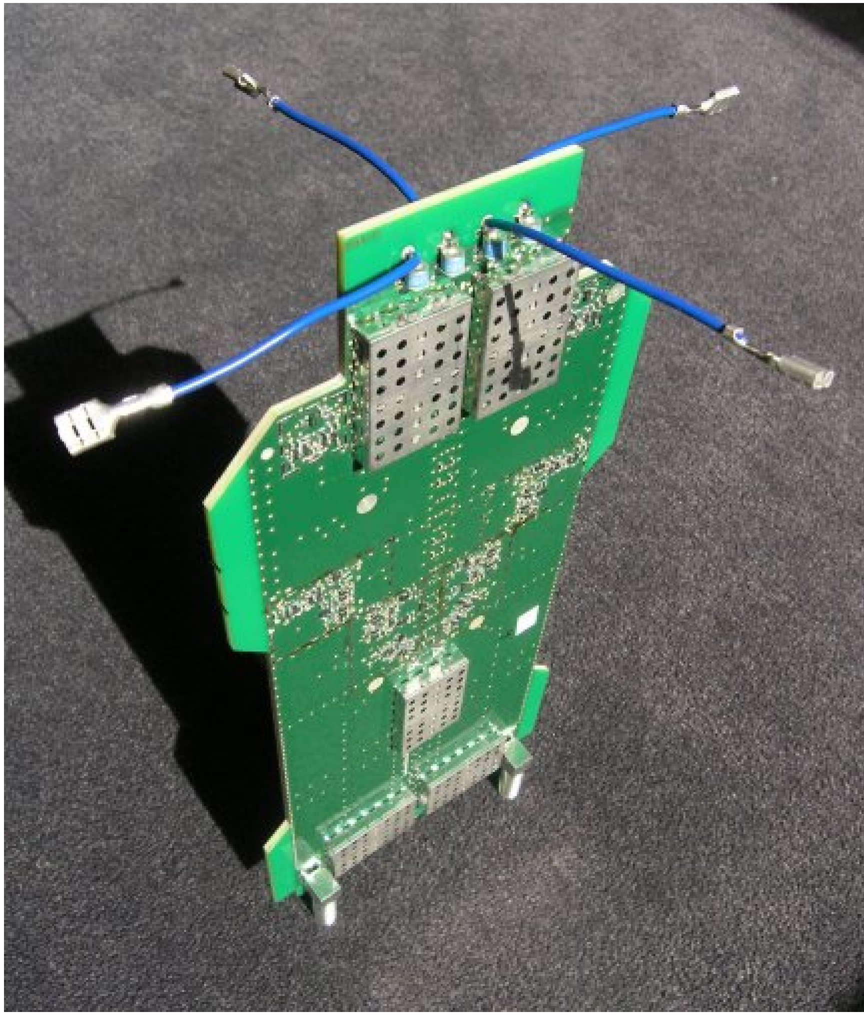


Figure 17 *A sketch of a HBA antenna element*

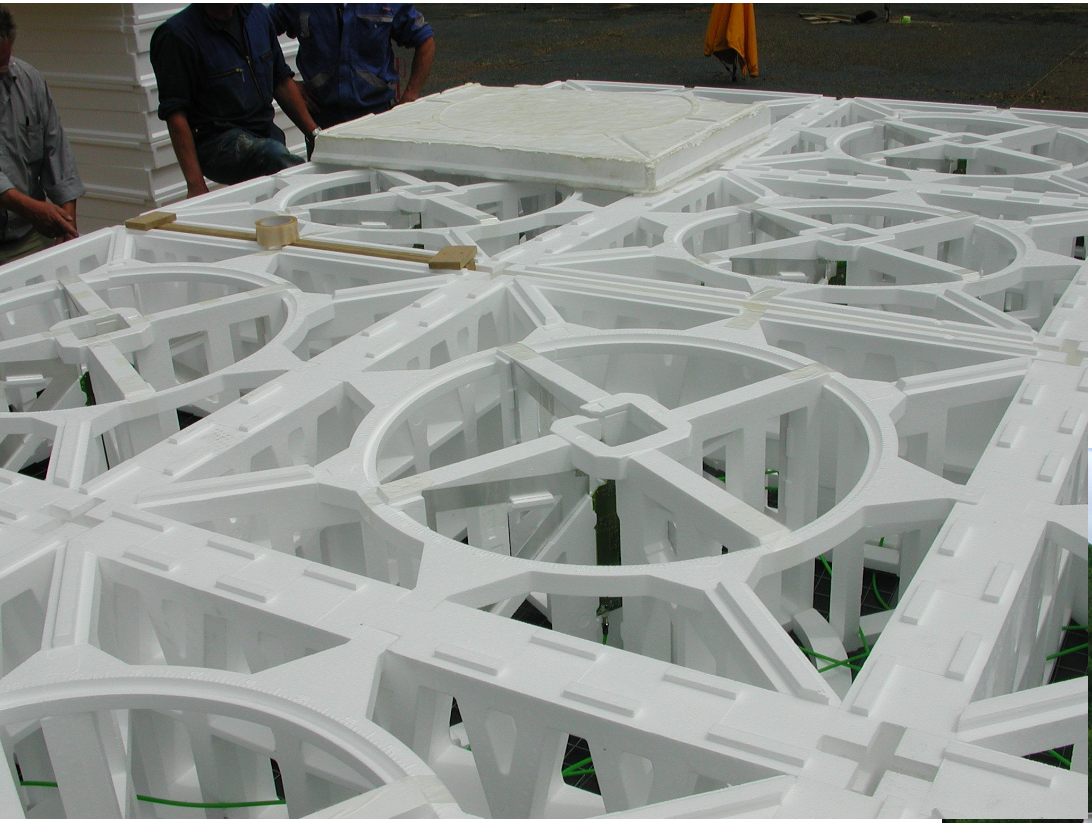
# HBA

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



# HBA Dipoles in 4x4 Tiles



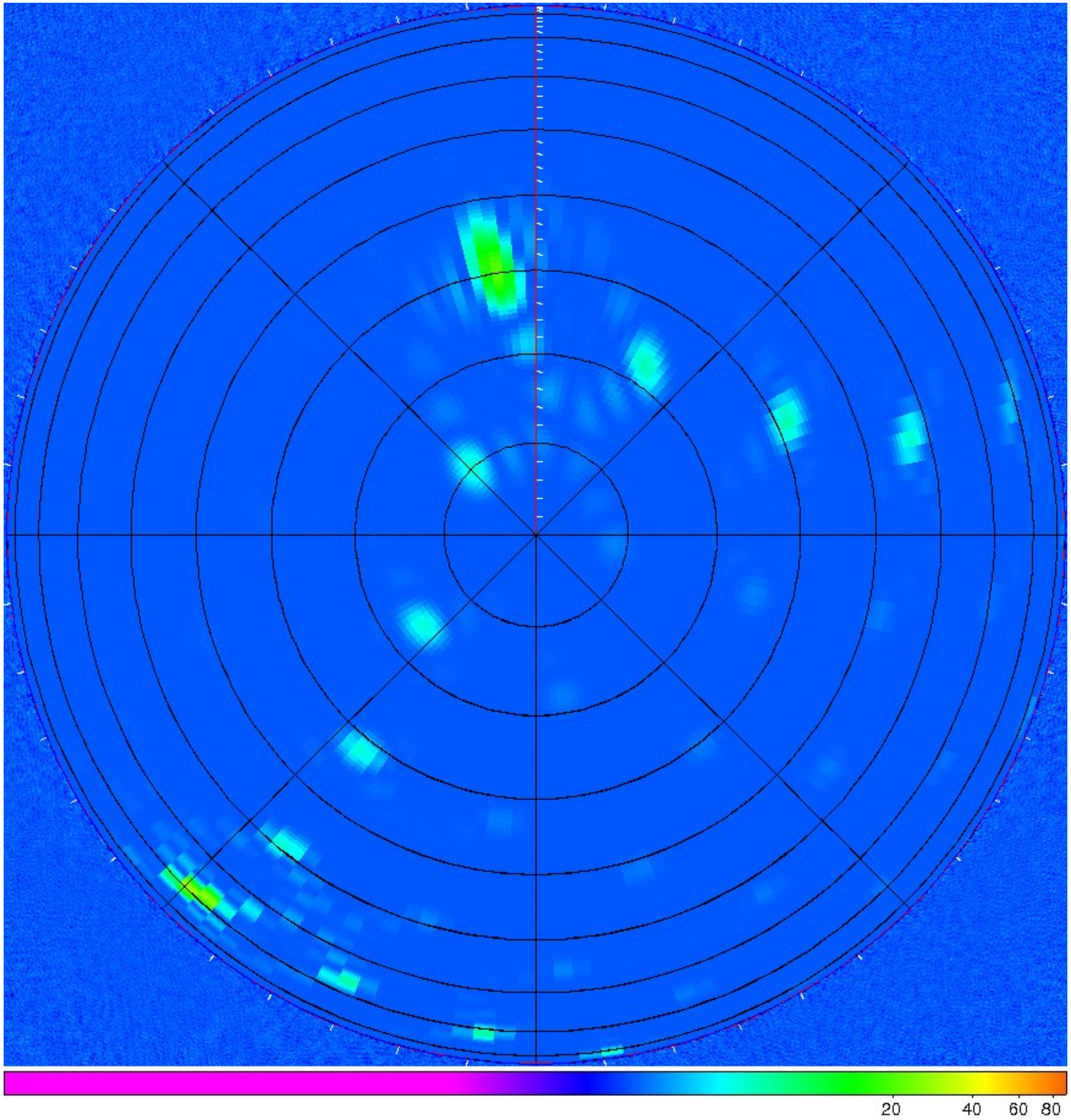
# Example LOFAR Stations


Thueringer Landessternwarte/Eisloeffel

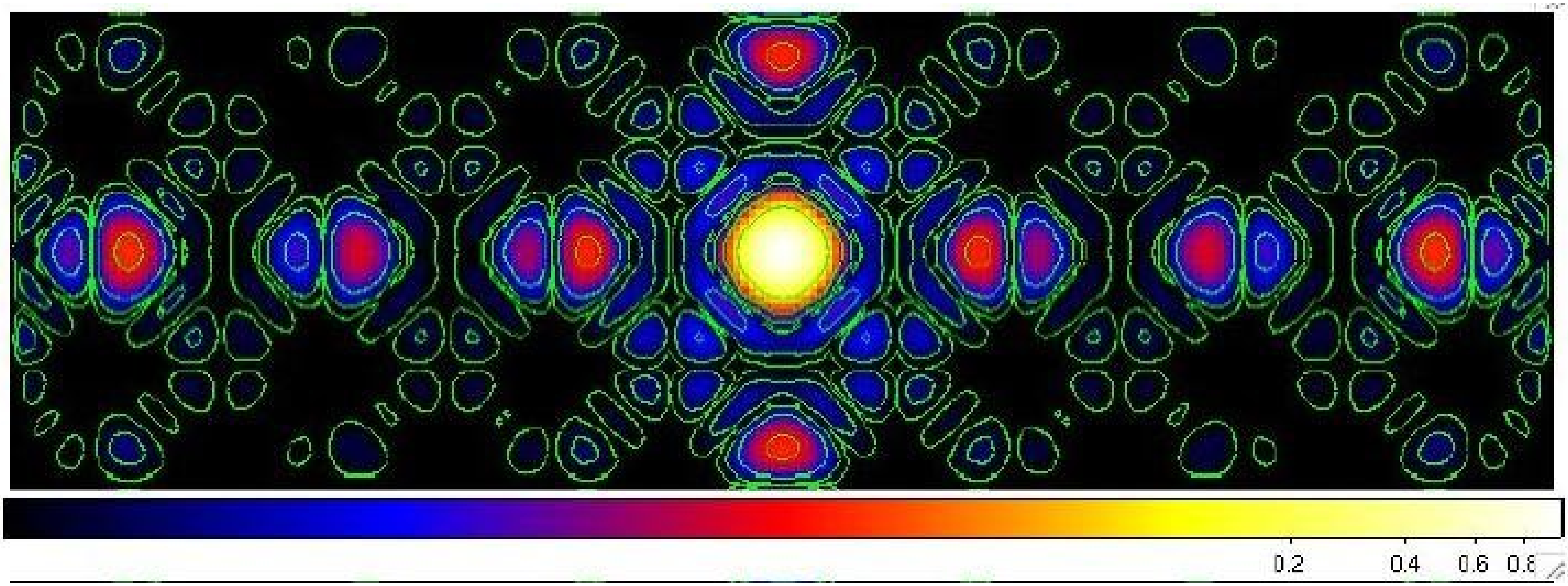
Thueringer Landessternwarte/M Pluto

# Your Destination Tomorrow

# Grating Lobes



# Station Beam Pattern

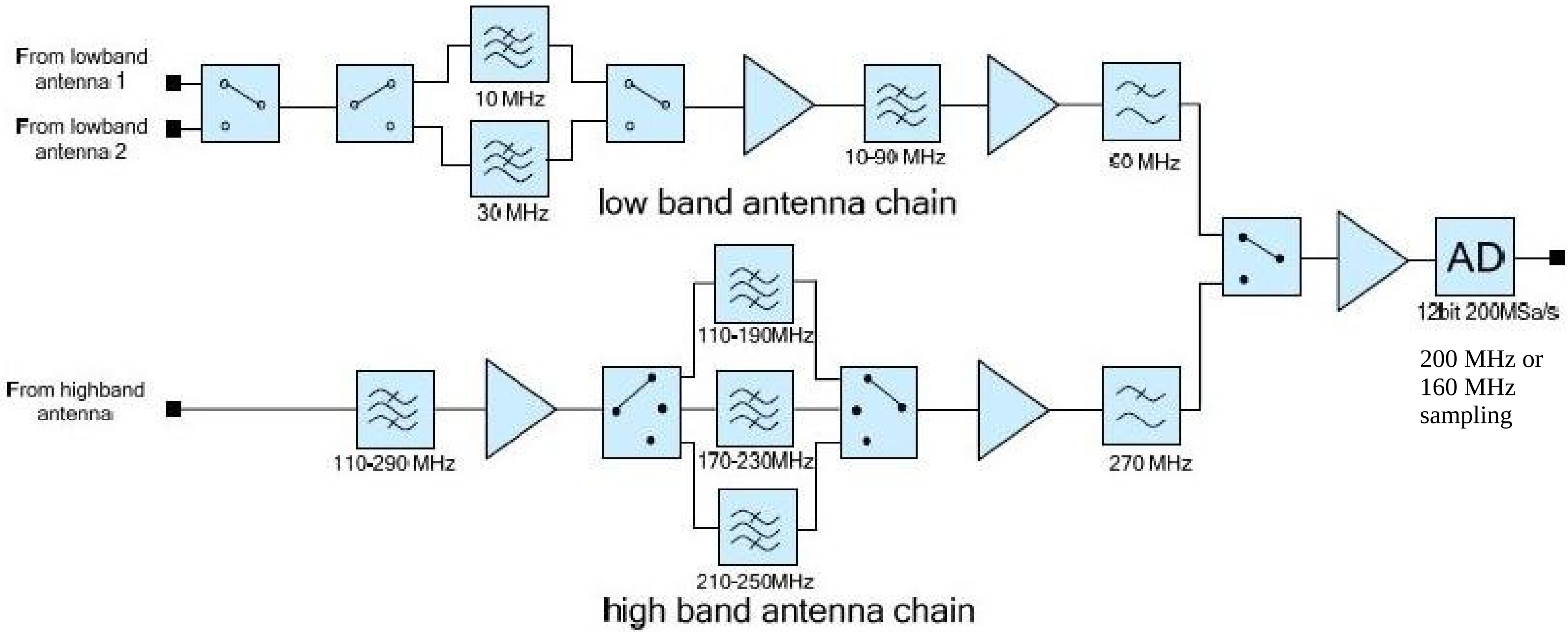



- Primary beam and sidelobe pattern not as clean as a circular filled aperture
  - HBA grid makes an especially bad grating response
- Have to pay attention more than other telescopes to beam pattern

# LOFAR Station Hardware

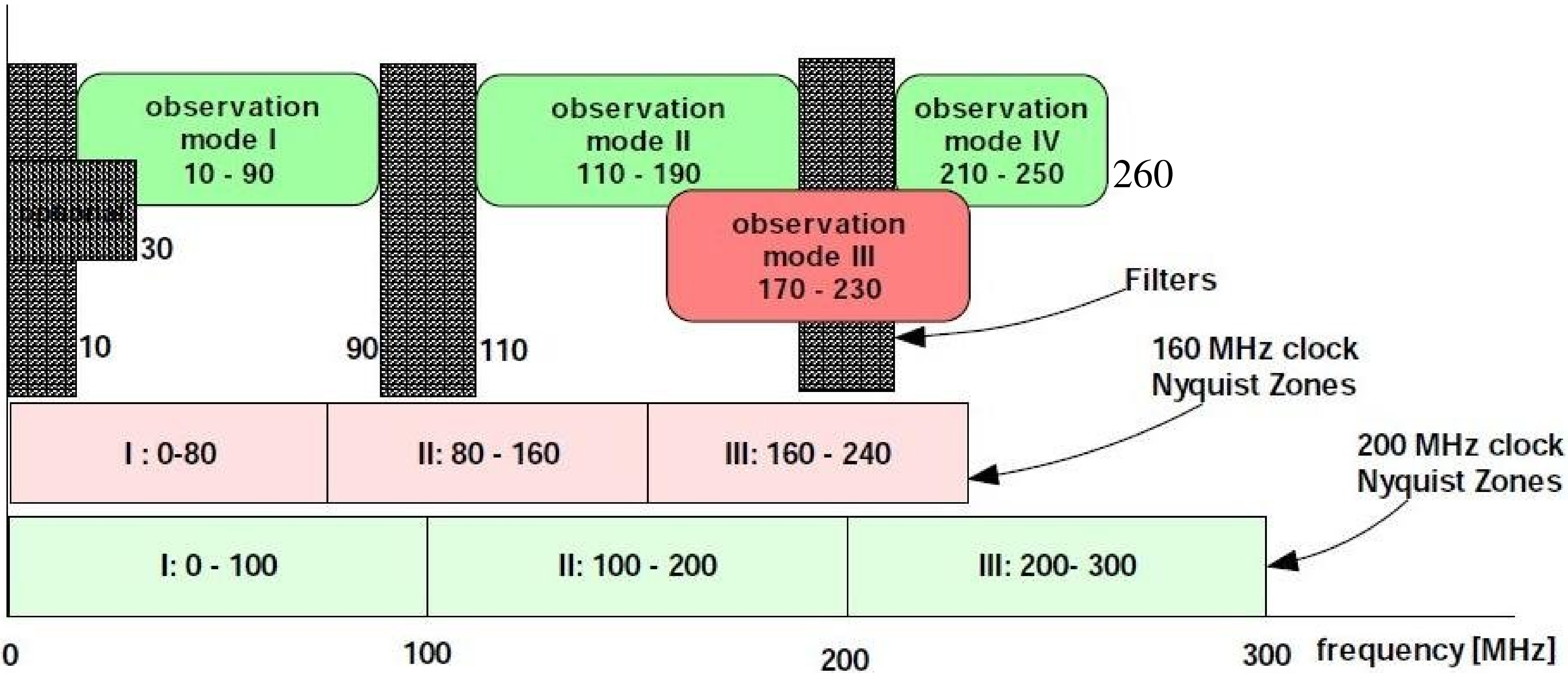
# RCU — Receiver Unit

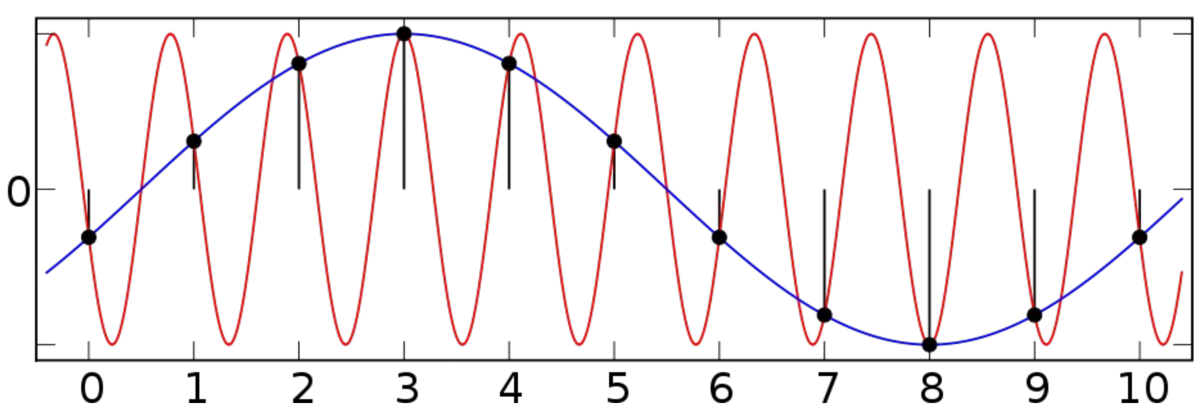
# LOFAR Frequency Selection




200 MHz or
160 MHz
sampling

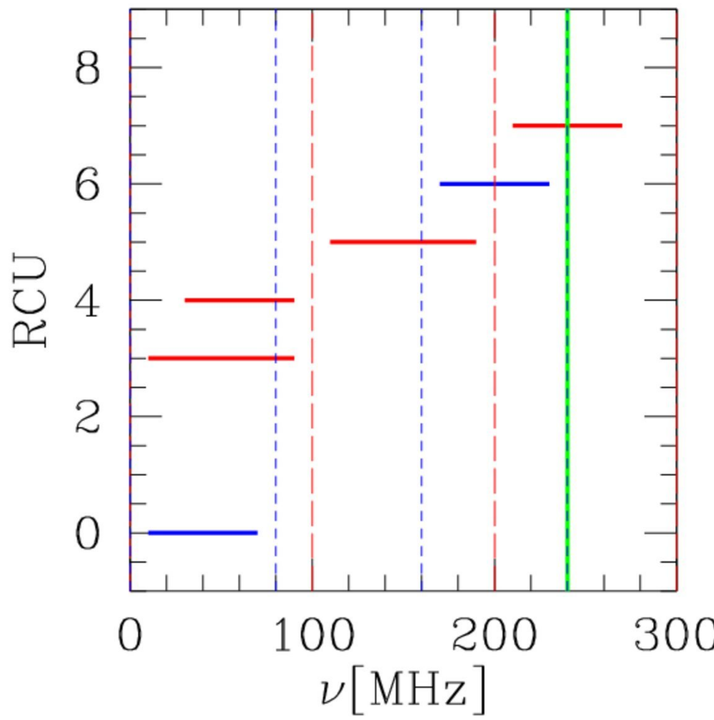
# LOFAR Band Selection



# 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

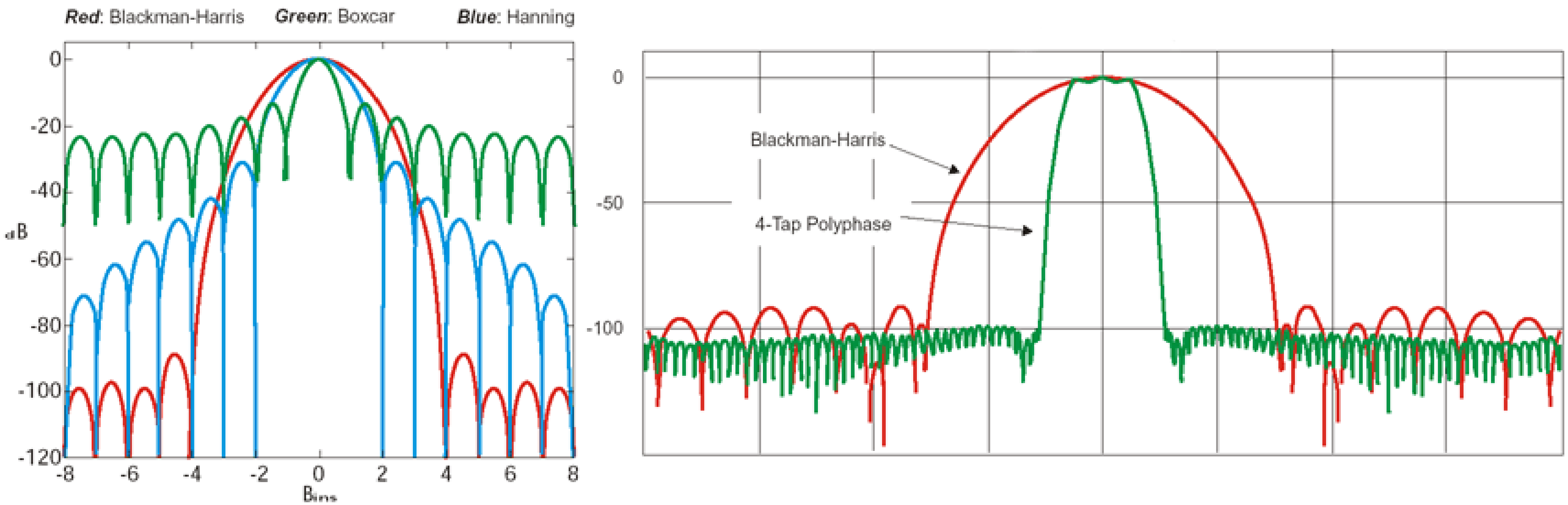
# Station Electronics: Gory Details 2

- 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

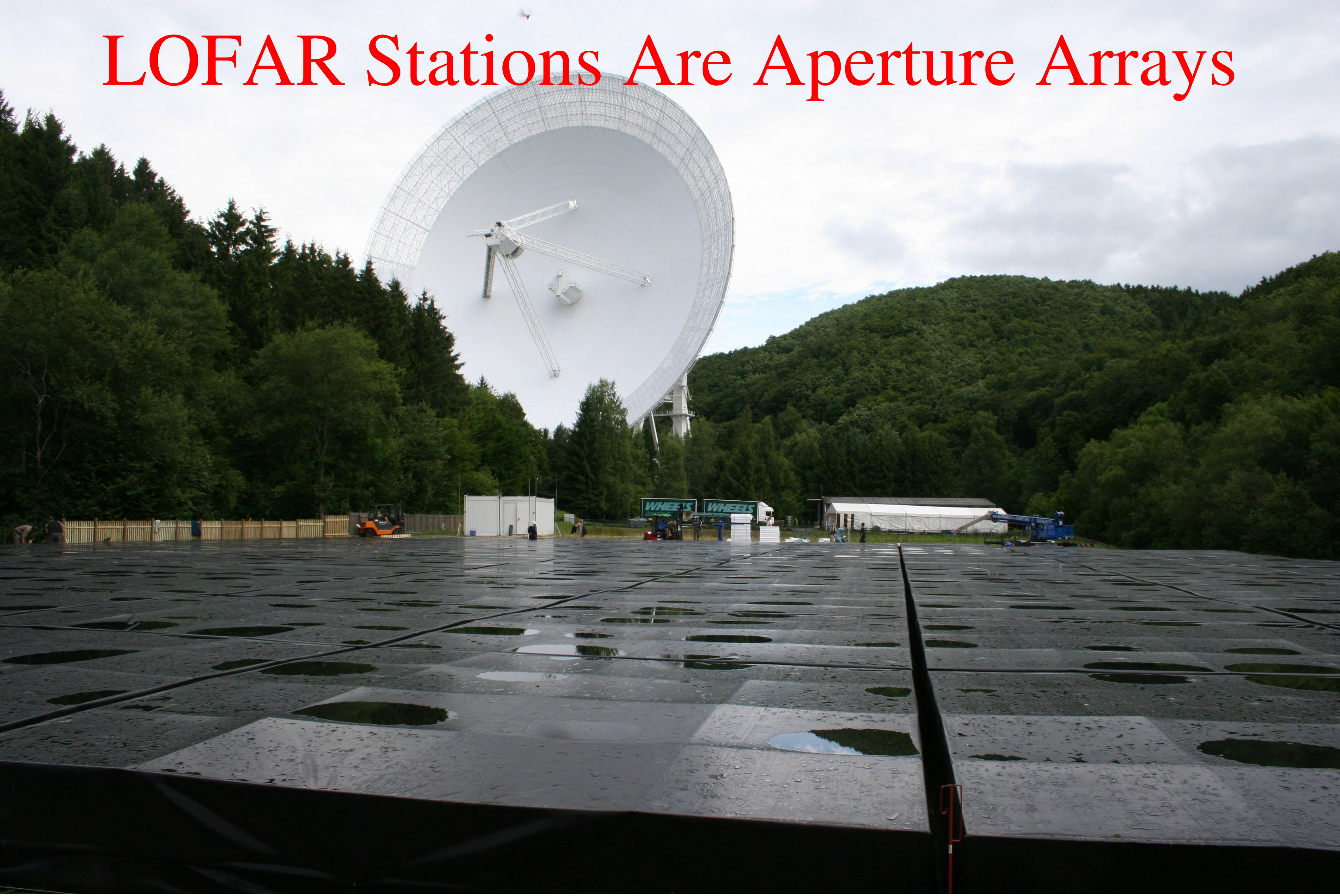
- 16 bit complex samples — total bandwidth 48.4375, 38.7500 MHz
  - 1 beam ≤ 248 subbands (48.4375, 38.7500 MHz for 200, 160 MHz clock)
  - 2 beams ≤ 124 subbands each (24.22, 19.38 MHz), may reuse subbands across beams
  - 4 beams ≤ 62 subbands each (12.11, 9.69 MHz), may reuse subbands across beams
  - 8 beams ≤ 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

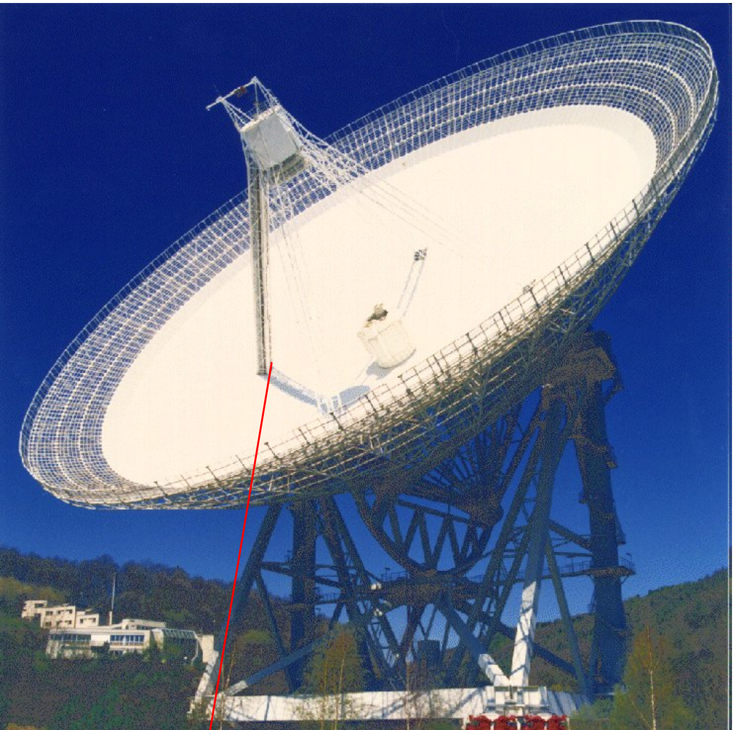



- Similar to a discrete Fourier transform (think of the FFT)
- But uses more datapoints in the transform, weighting the points differently
- Reduces sidelobe levels in frequency-space
  - Important for RFI mitigation
- Spectral dynamic range is normally greater than 80 dB for standard LOFAR data processing

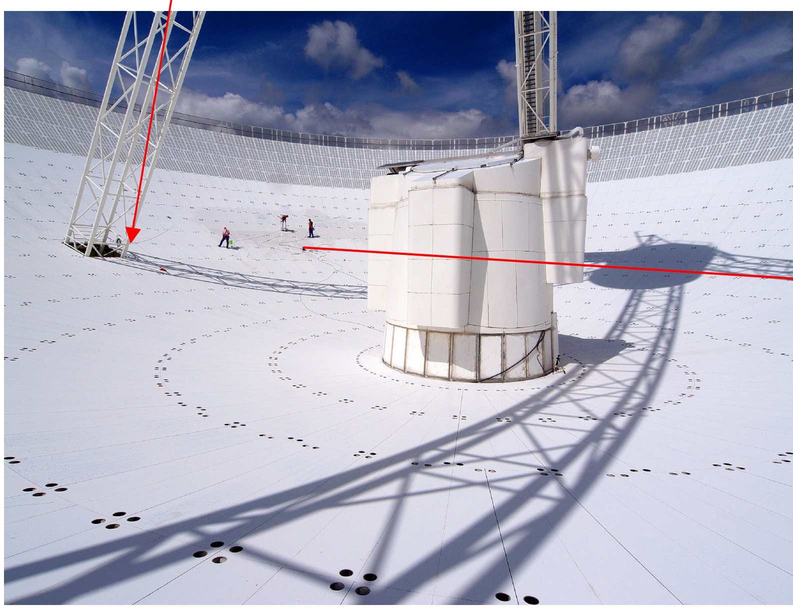
# LOFAR Stations Are Aperture Arrays

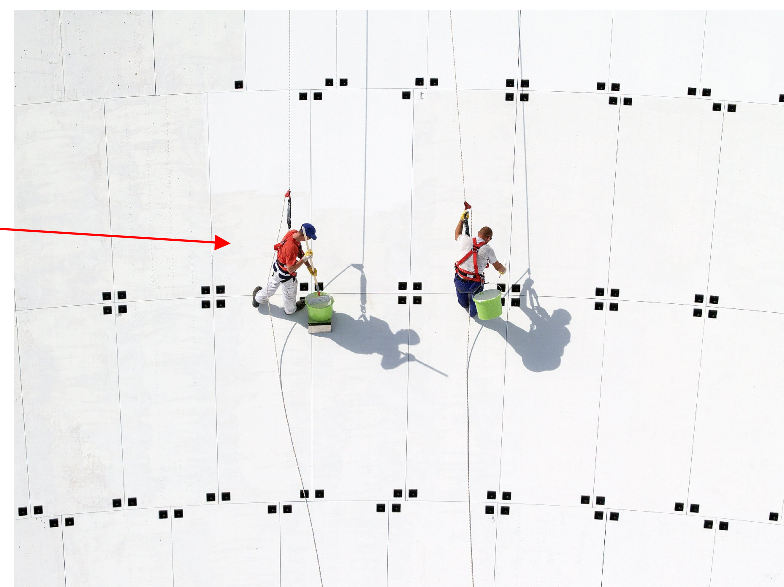


# Effelsberg 100 m



- 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)

# Phased Arrays


Adriaan Renting

CSIRO

# Optical Equivalents

ESO/Y. Beletsky

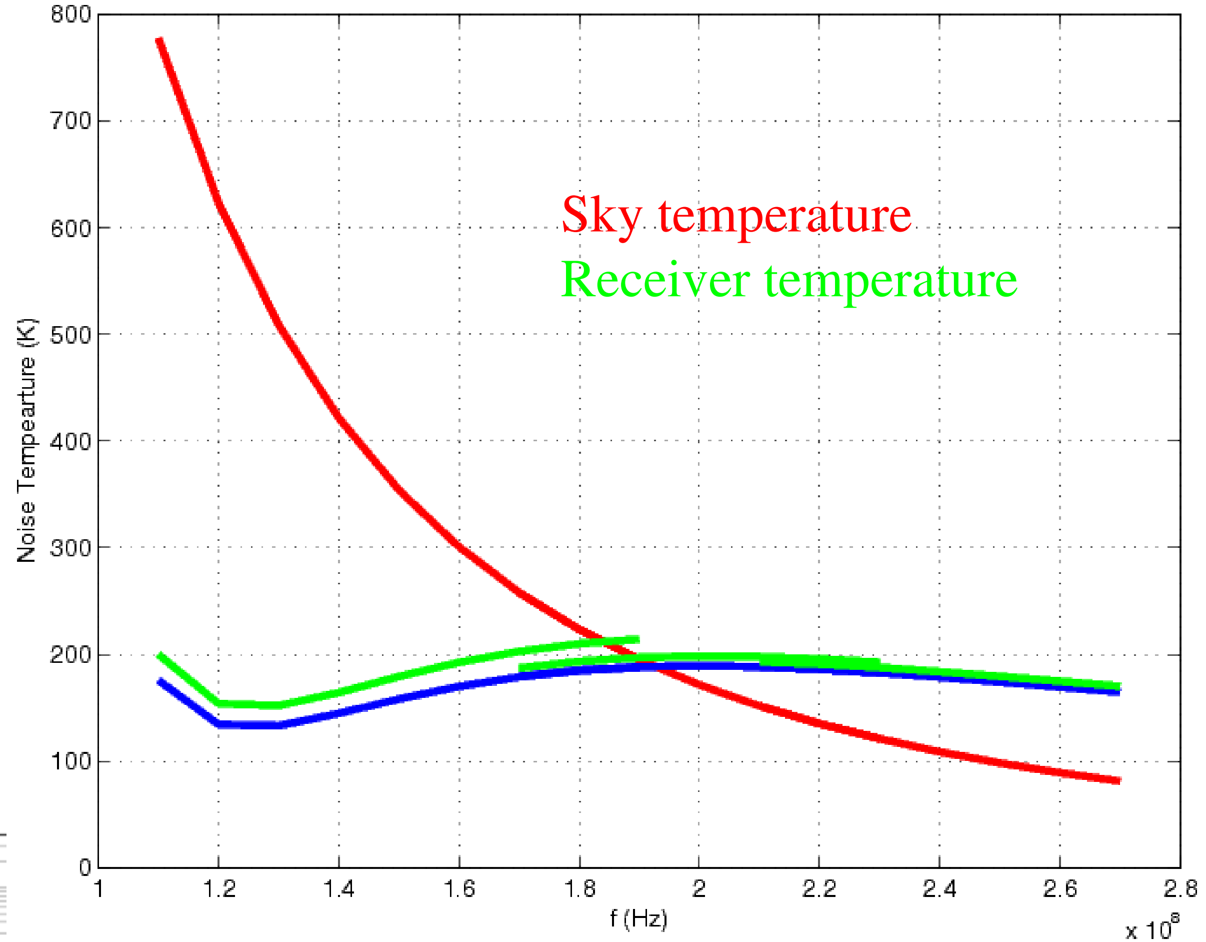
NASA

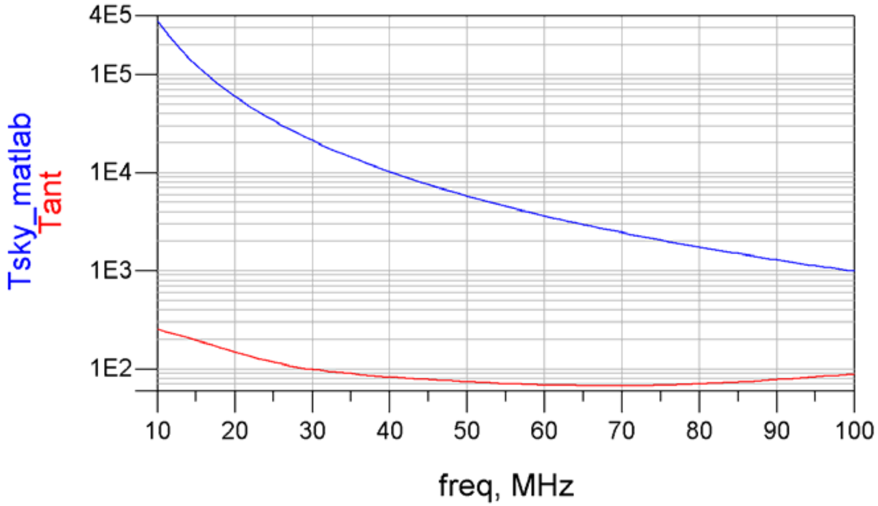
- Optical astronomy uses adjustable segmented mirrors, deformable mirrors, and adaptive optics to phase up the telescopes

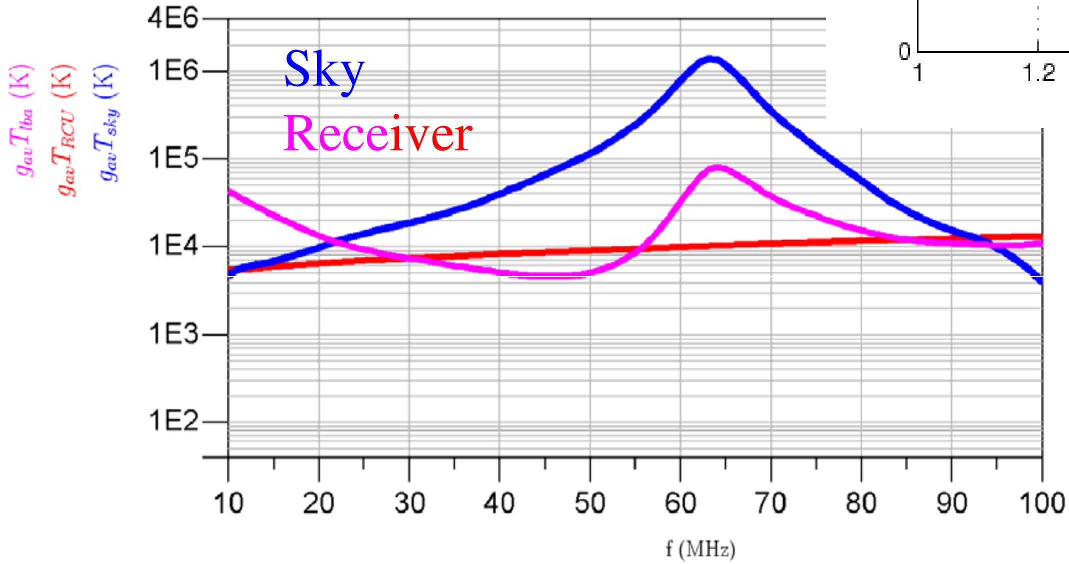
# LOFAR Approach

- 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 :(

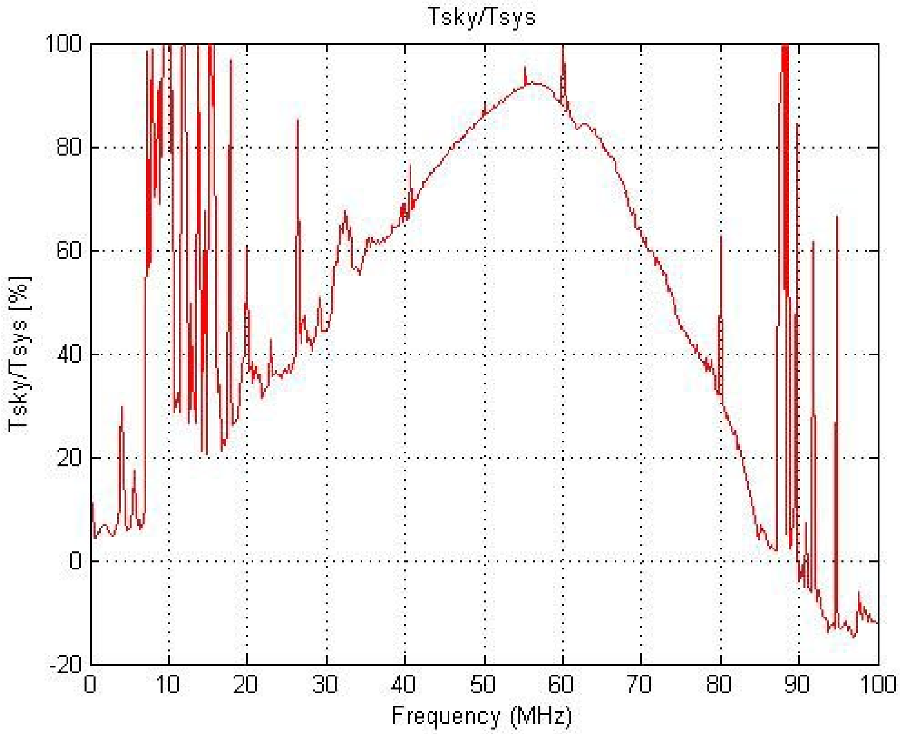
# LOFAR System Temperatures



# LOFAR and RFI



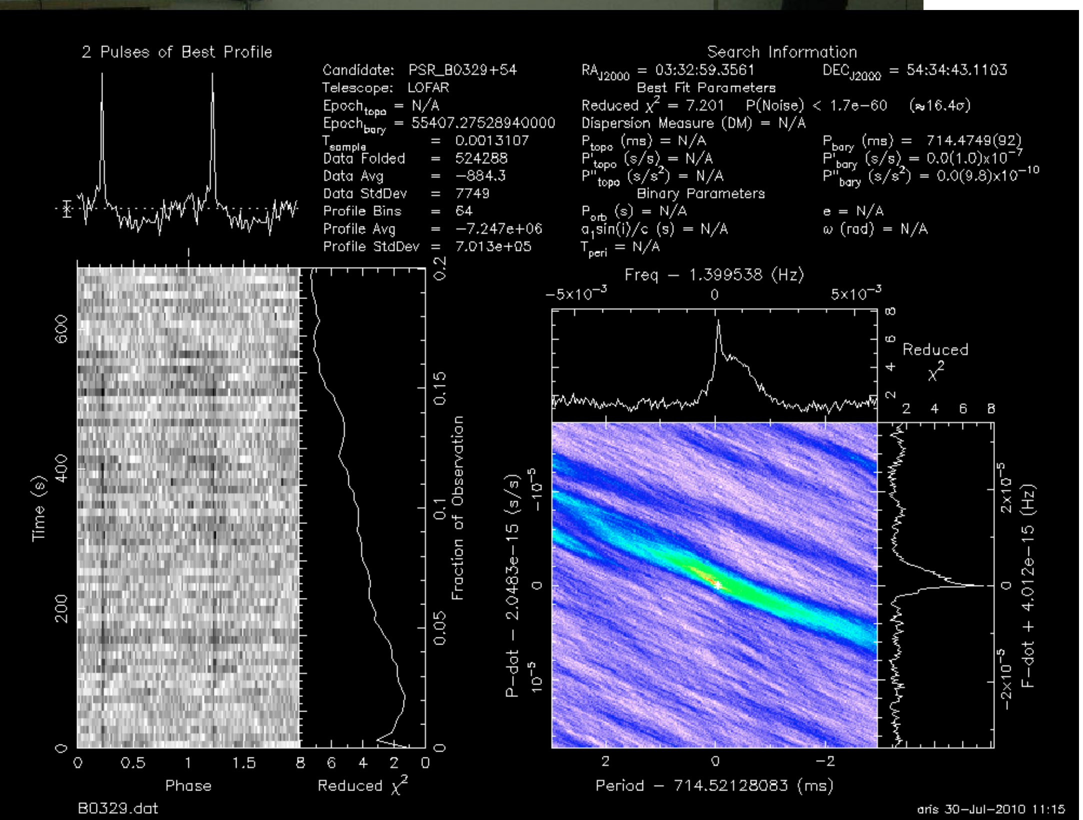

- Strong RFI is present at low frequencies, especially < 30 MHz
- RFI is especially problematic for single dish work

  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

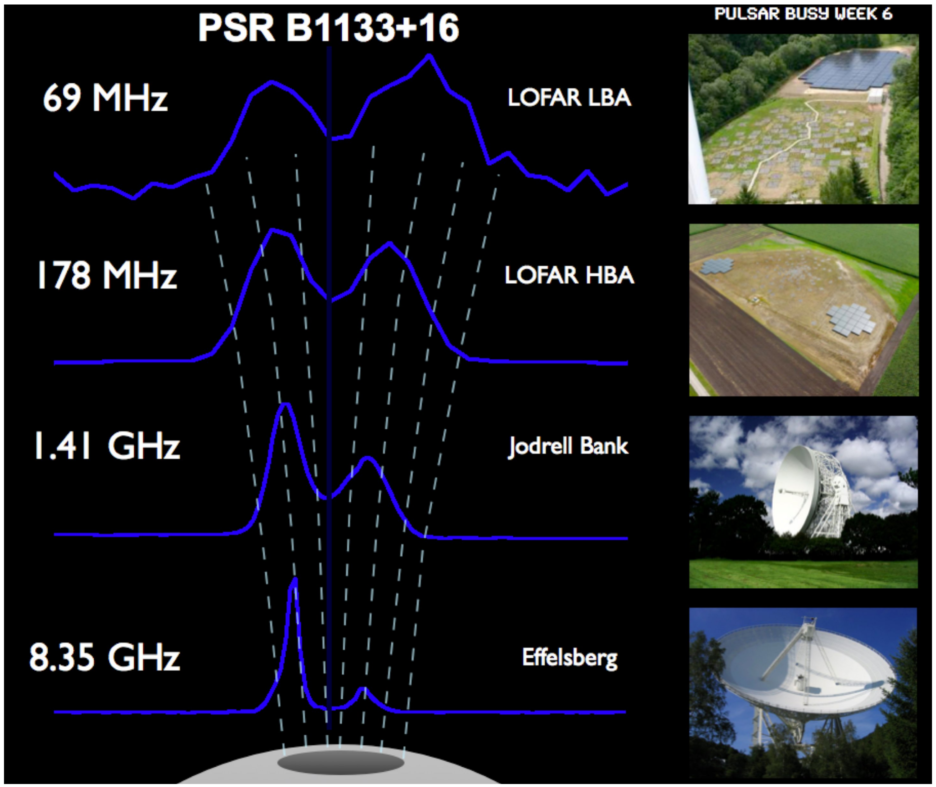
# So What Can You Do With LOFAR?

# 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

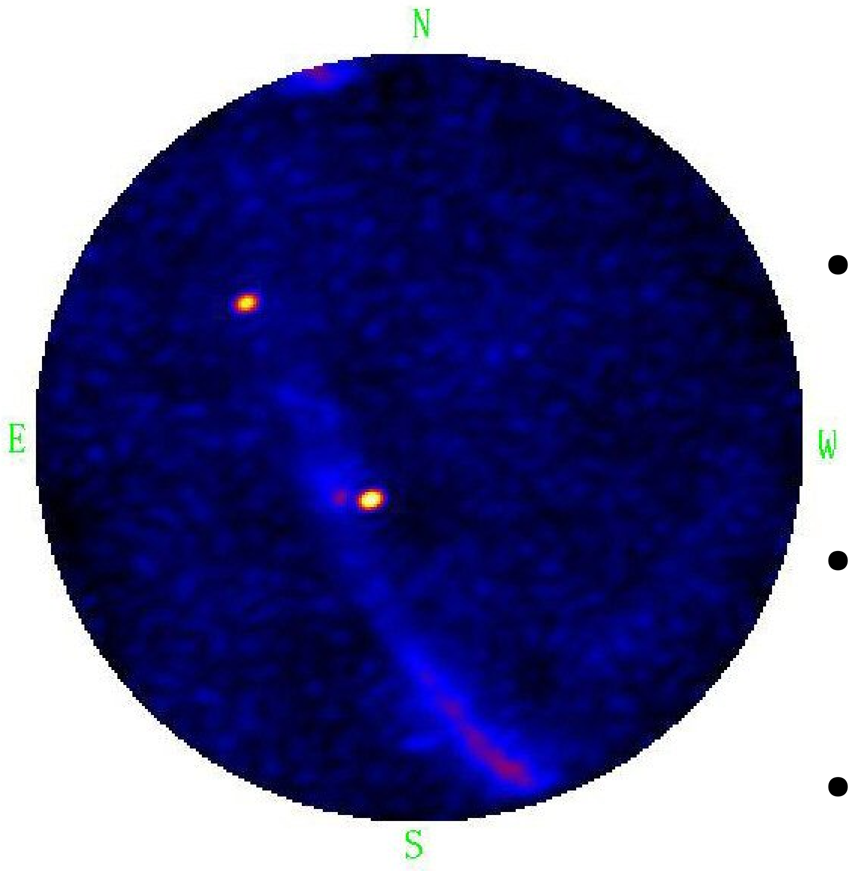
# Pulsar Physics




Pulsar Science Working Group

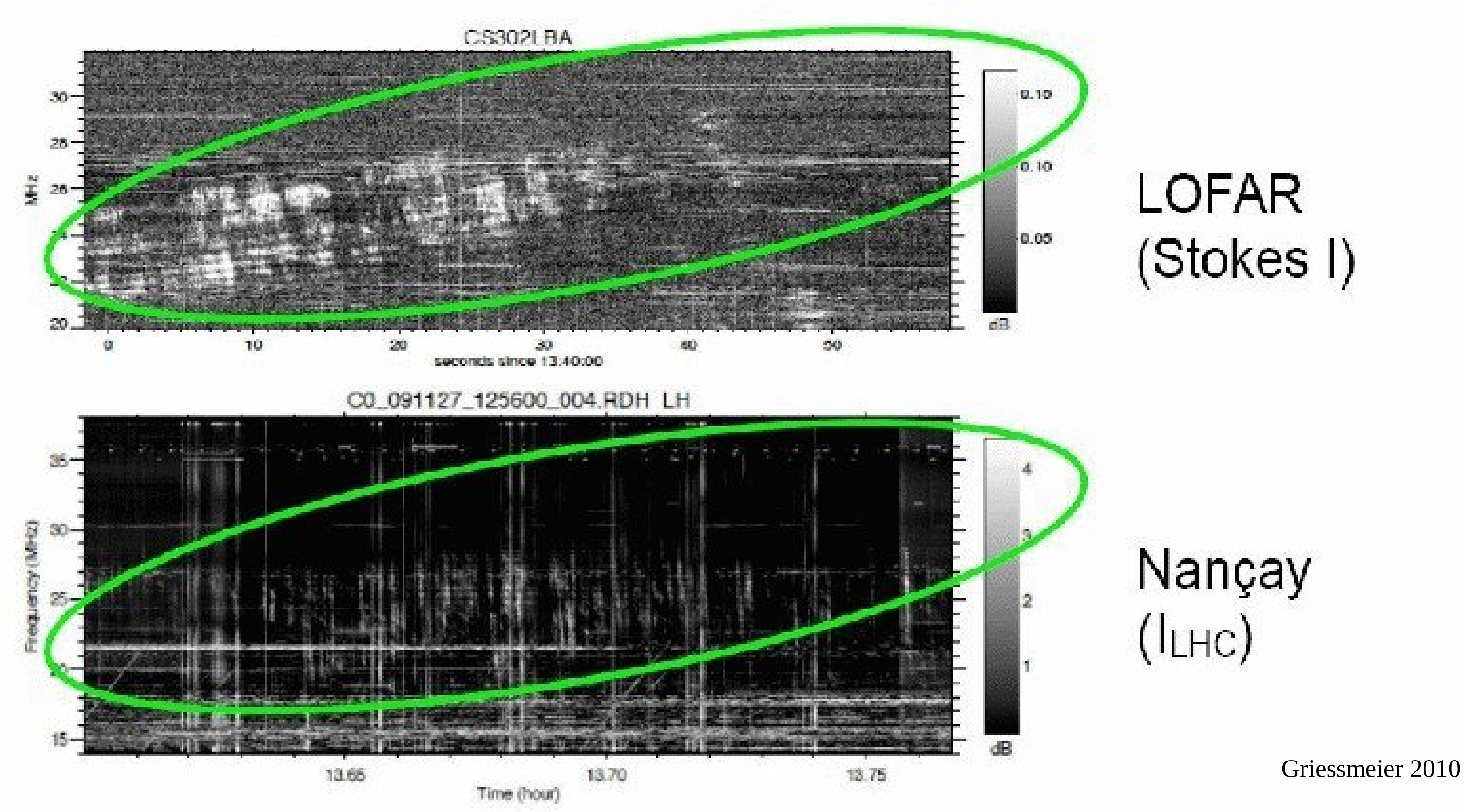
- Pulsars normally have very steep spectra, so low frequencies are ideal for some measurements
- LOFAR pulsar survey expects to find ~1000 new pulsars
- Many of these pulsars may only be visible at low frequencies
  - Regular timing observations can be carried out by individual LOFAR stations
- Extended 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
  - $2\pi$ instantaneous field of view
- Technically not "single dish" work, as this is really interferometry
  - So we won't cover this in the hands-on session

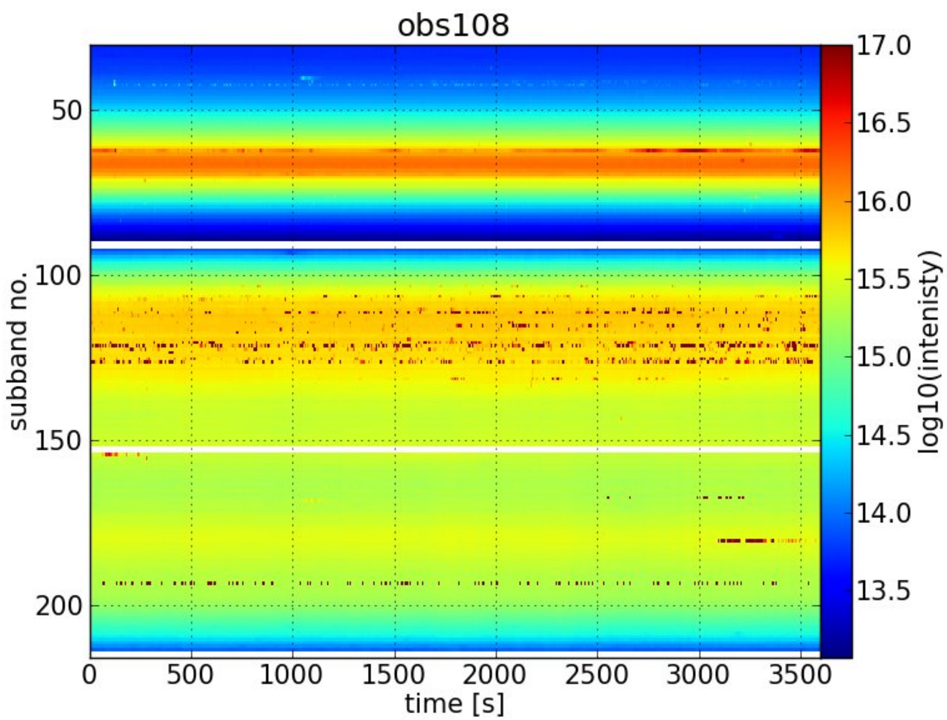
# Planets

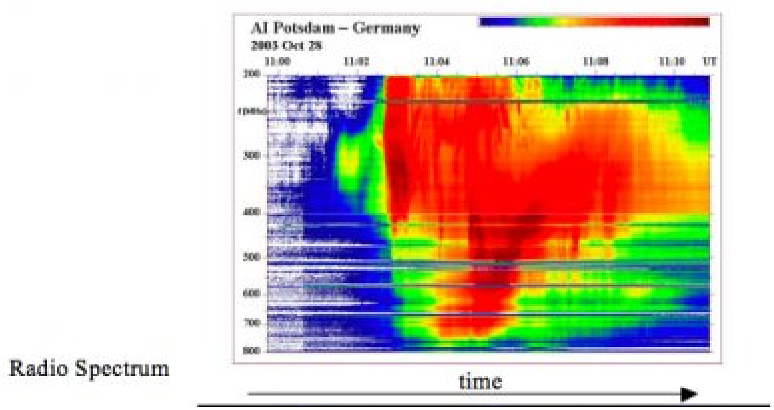



Griessmeier 2010

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

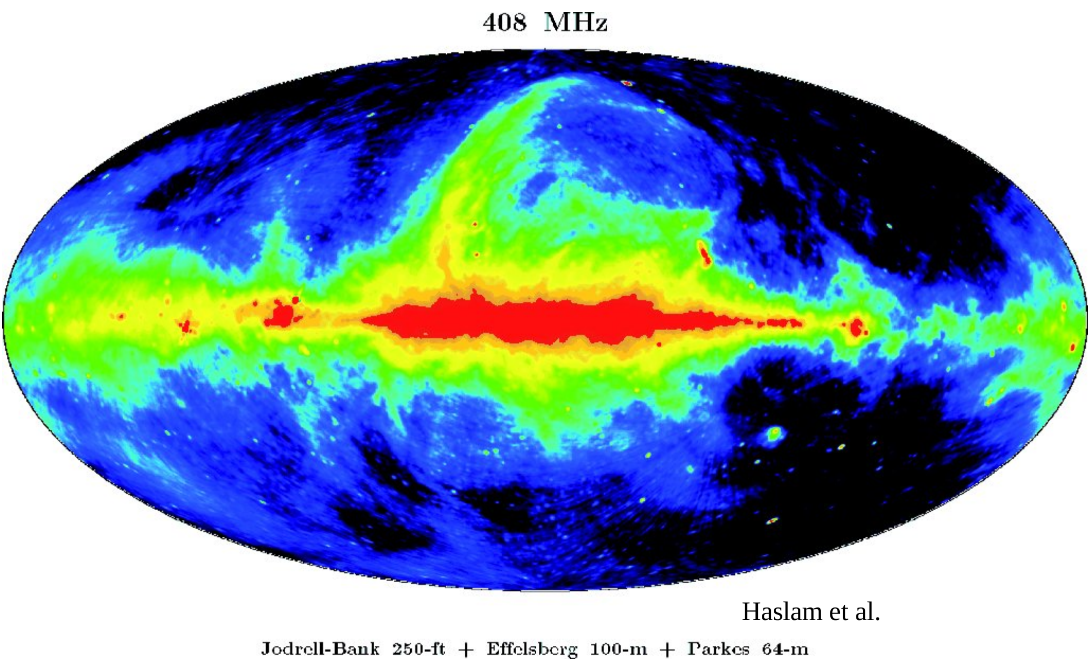
# Solar Spectrum




- 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.

- 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

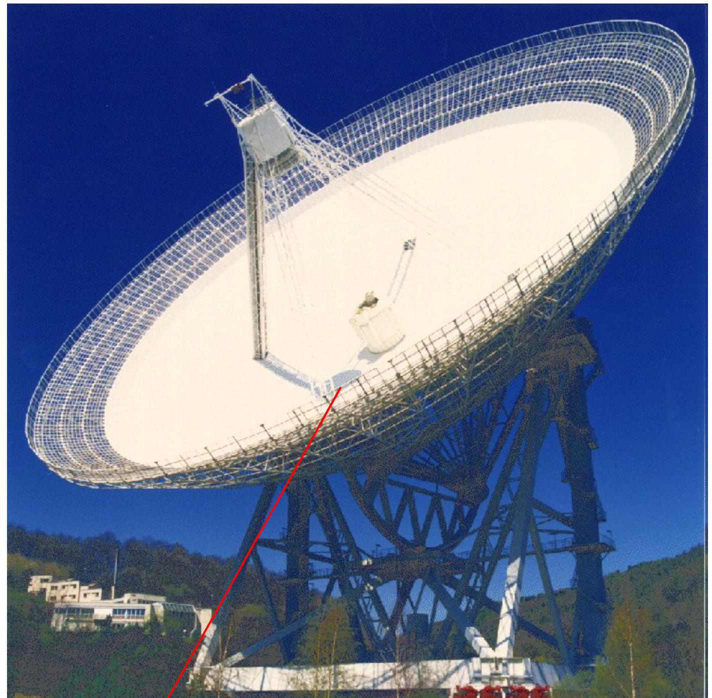
- Honestly, we have not worked everything out yet
  - Still under extensive development and"playing around" to see what we can do
- The ability to form multiple beams on the sky, 8 now and perhaps 24 or more in the future, opens up lots of possibilities which are impossible with other telescopes
  - 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

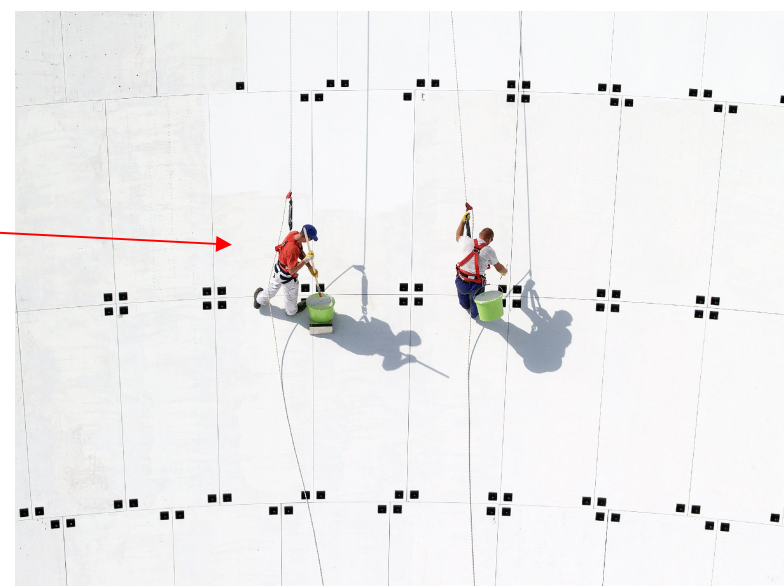
- LOFAR is still under extensive software development
  - Lots of software tools simply are not ready yet, or do not have full functionality
- Still a number of bugs in the LOFAR hardware/firmware system as well
- But progress is rapid, and LOFAR will soon be opened up for scientific use by astronomers

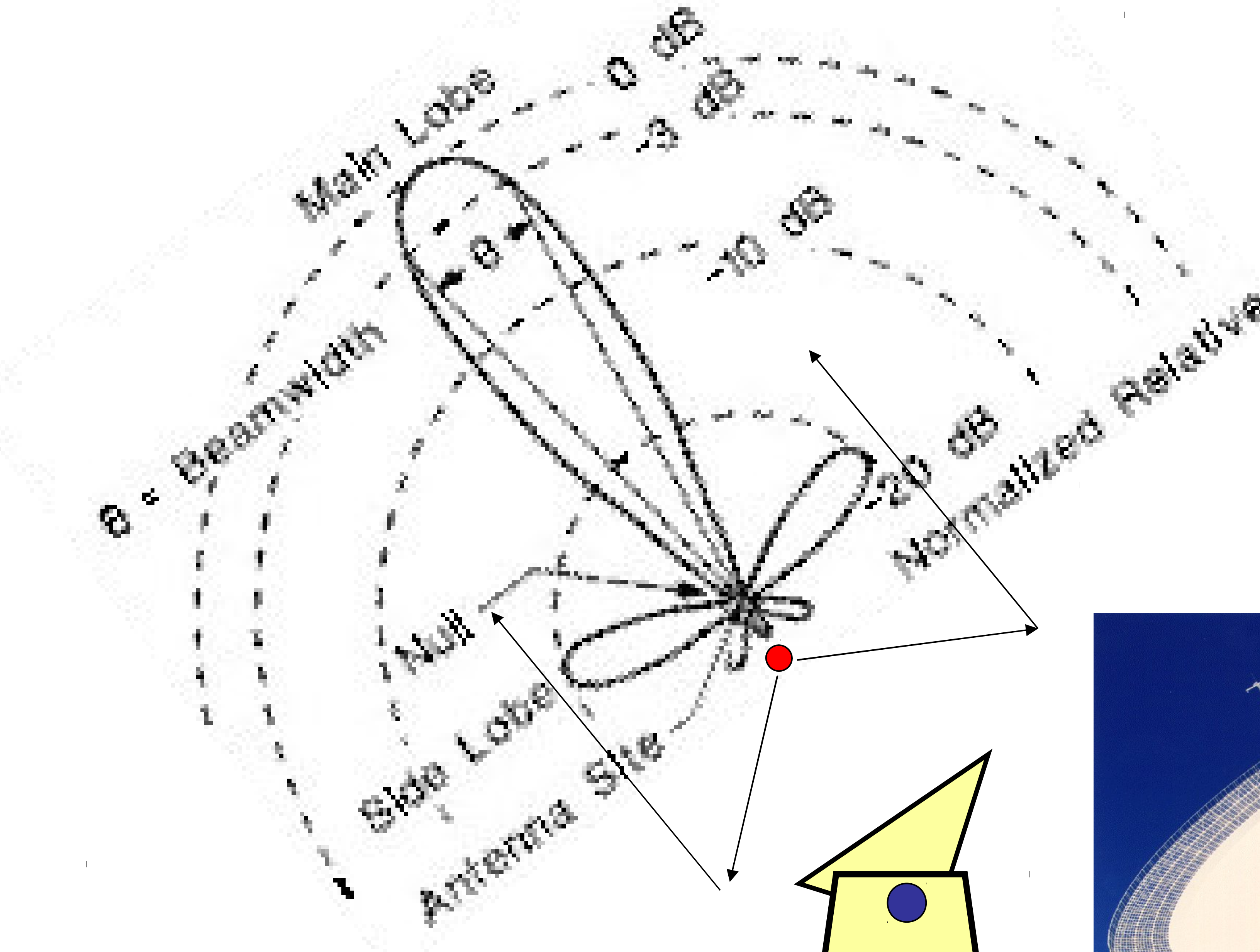

The End

# Effelsberg 100m

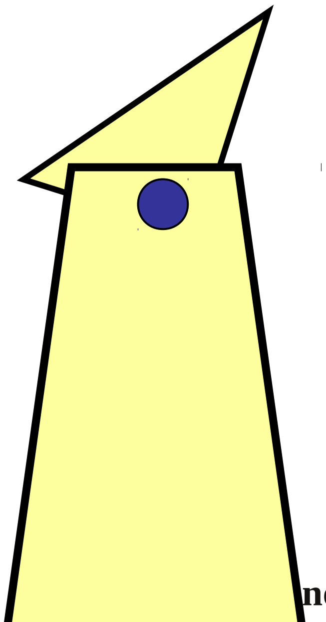


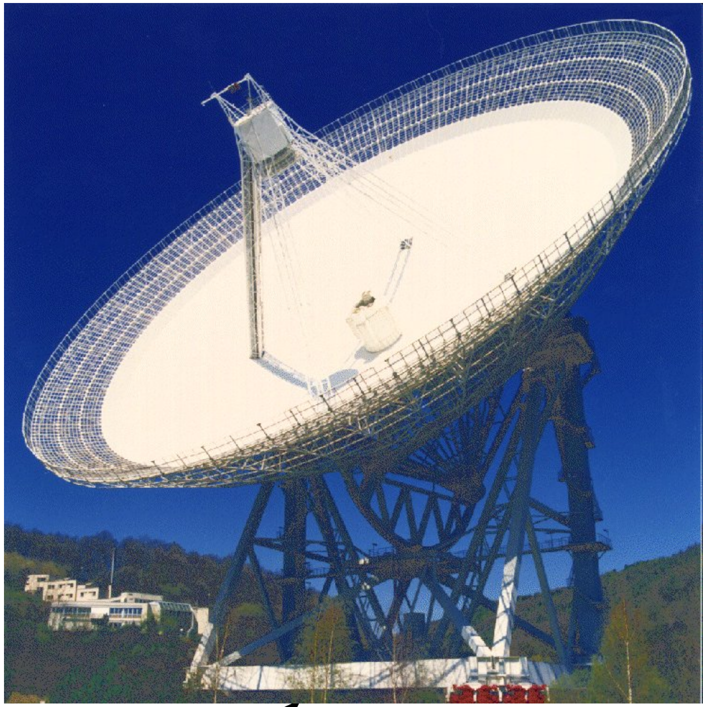
100m Effelsberg for
radio astronomy



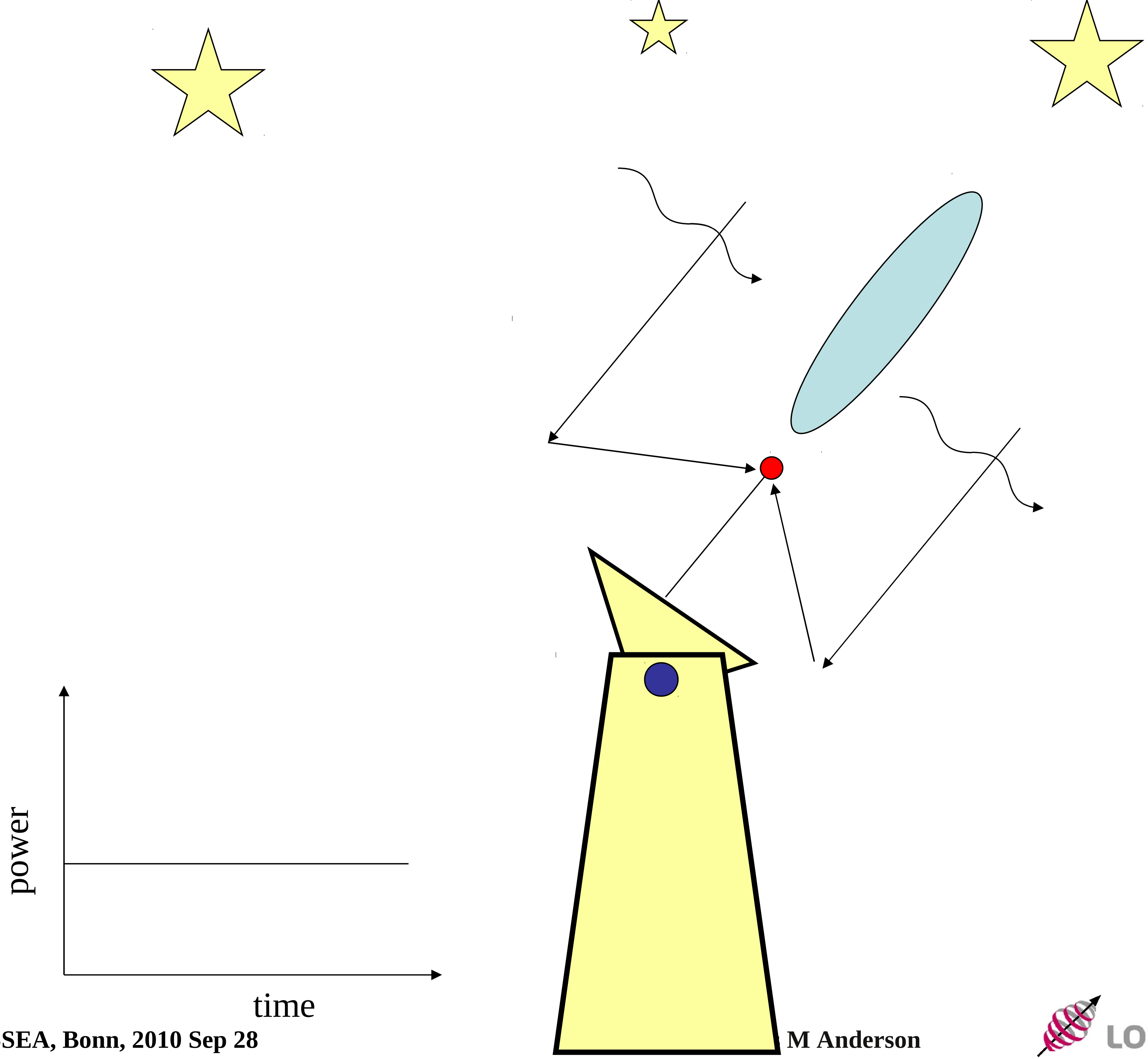


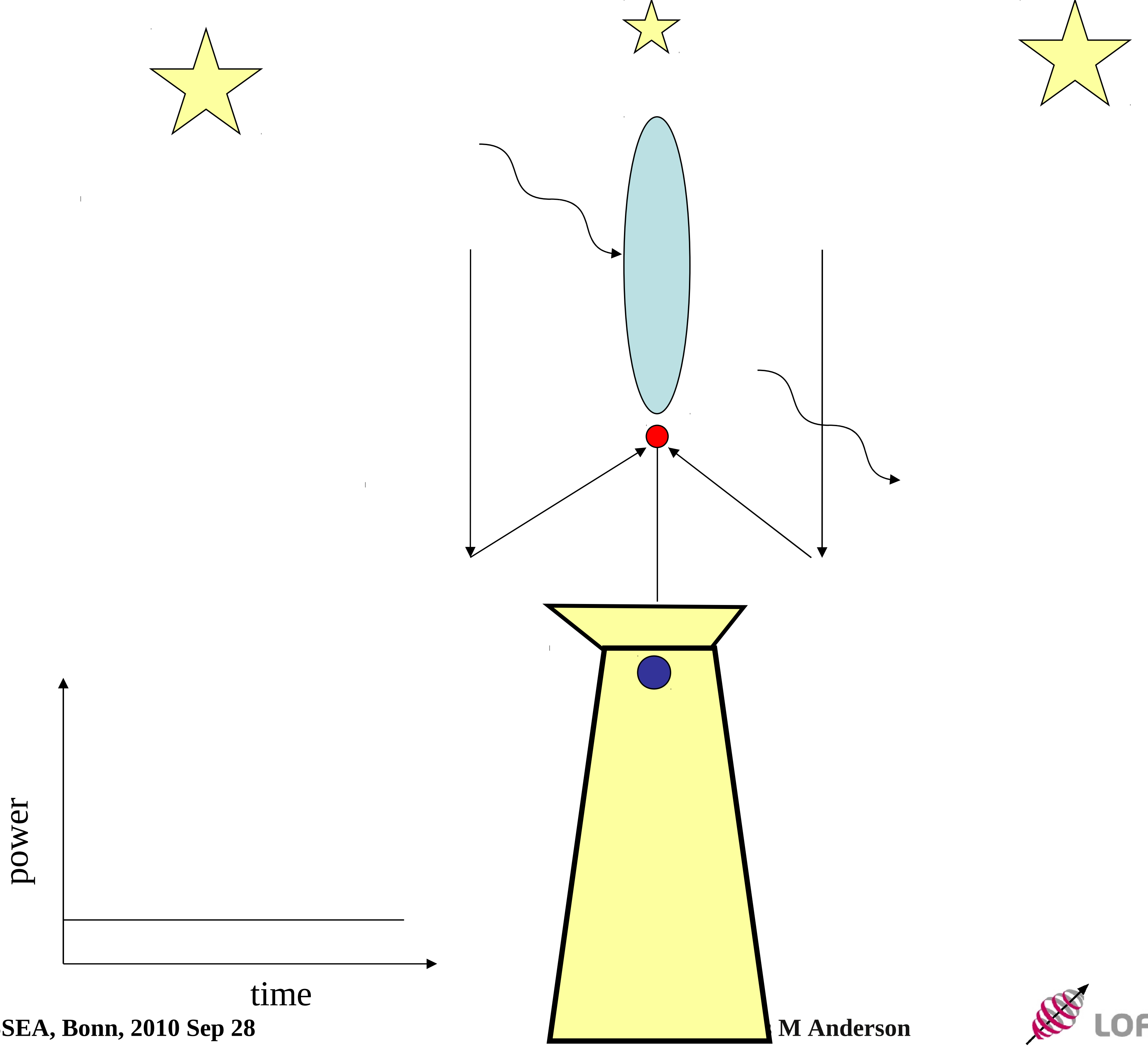

Beam pattern
(An antenna can be considered as
 a transmitting dish.)

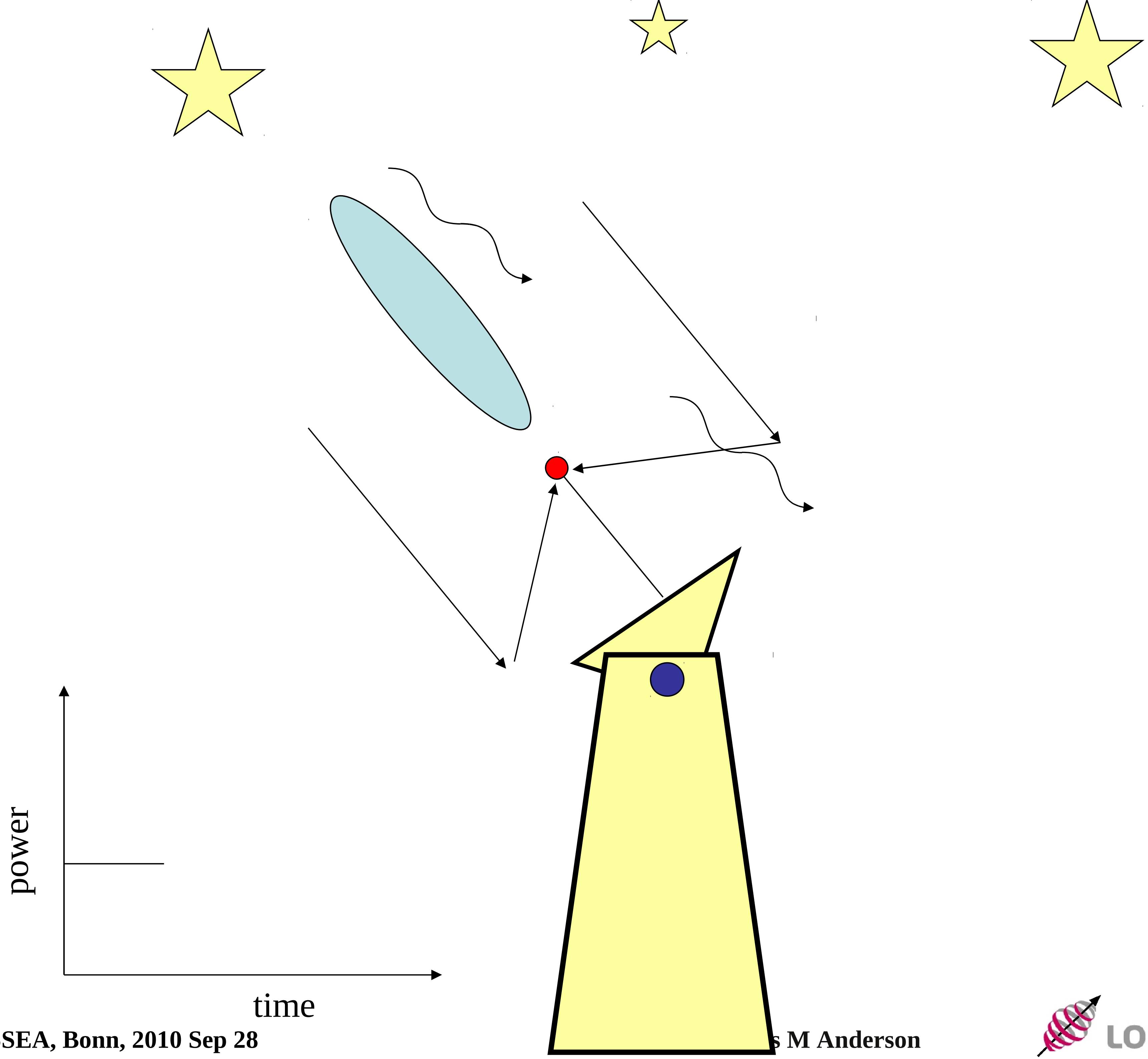


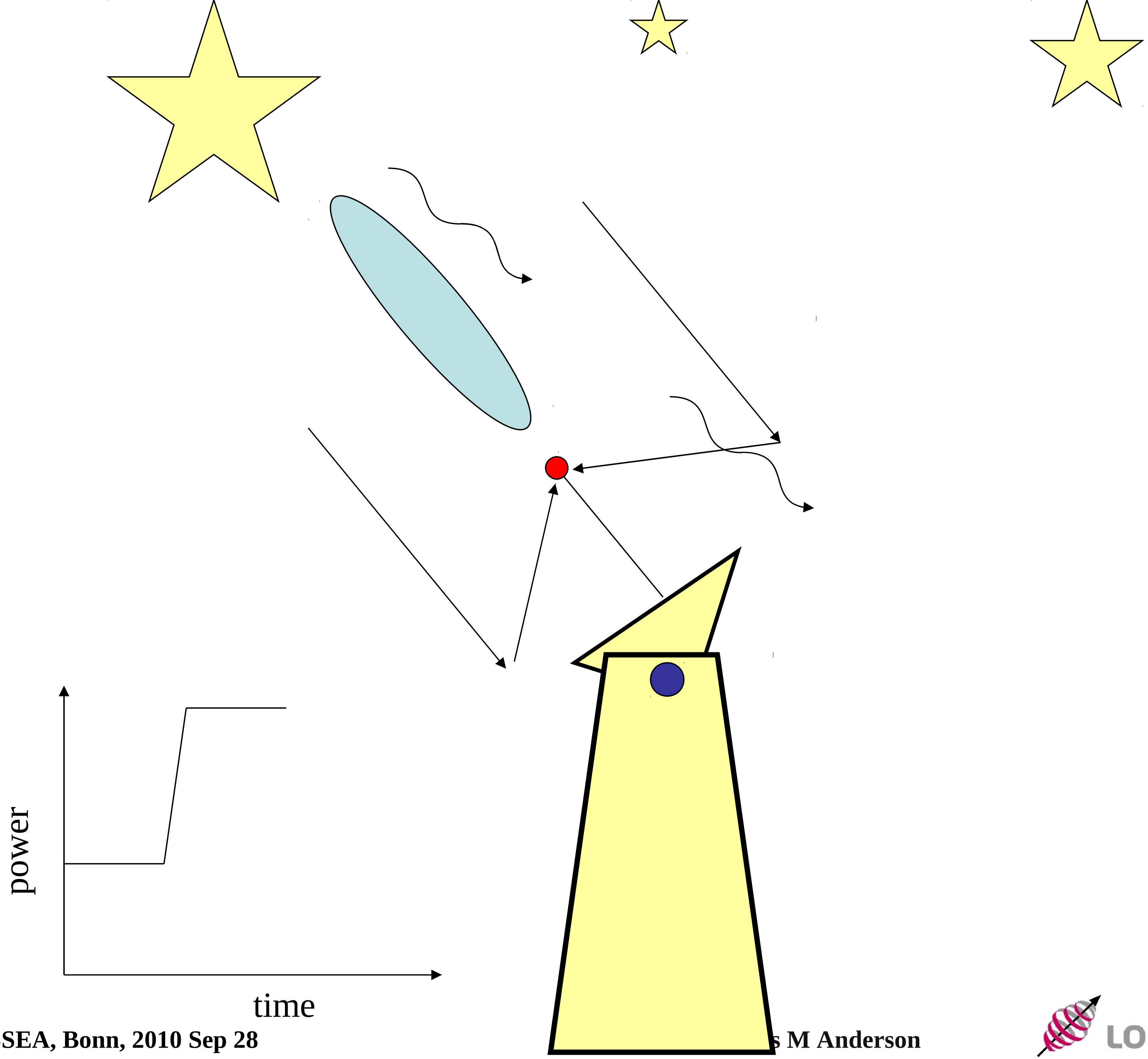


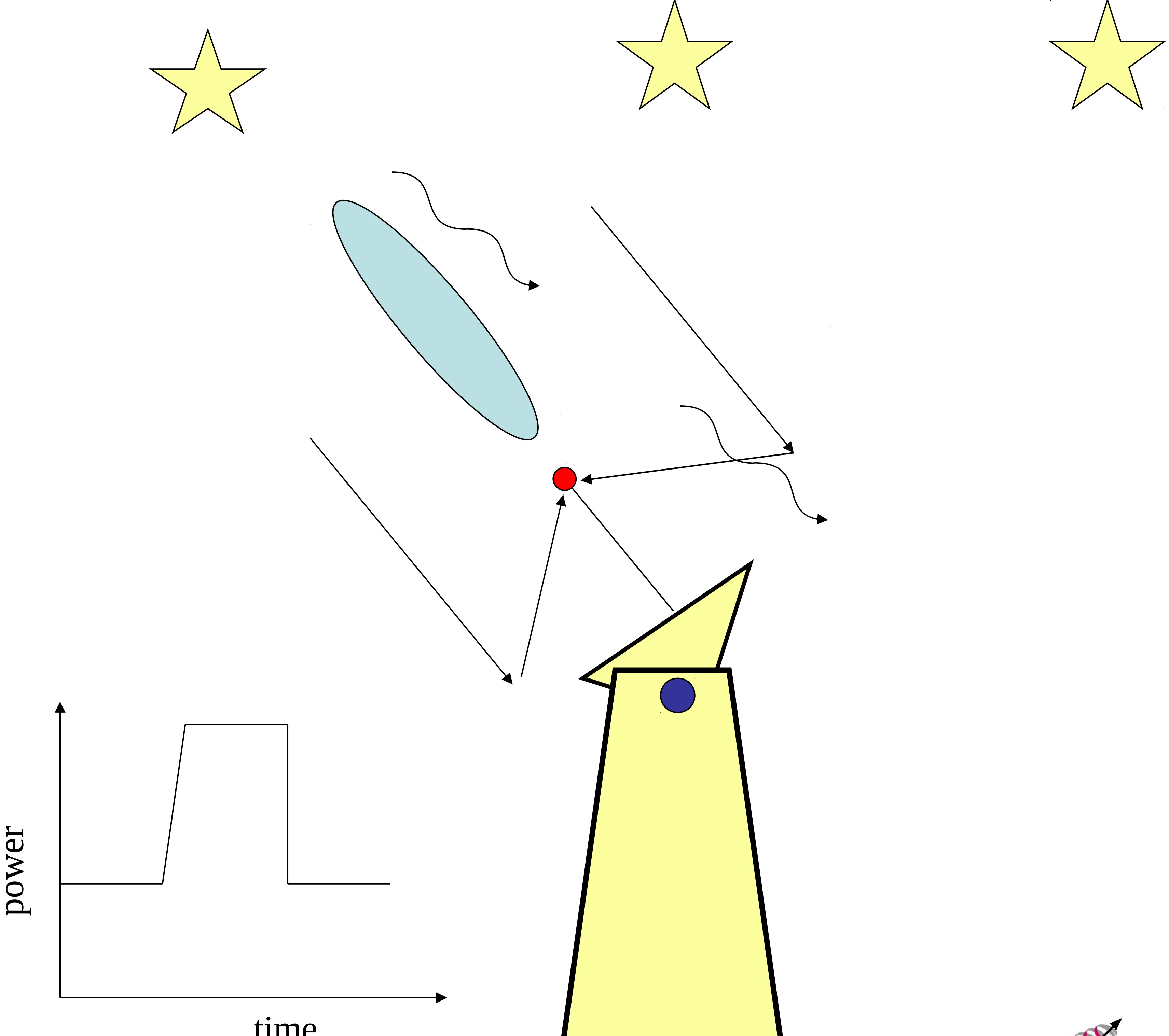
Fully steerable radio telescope

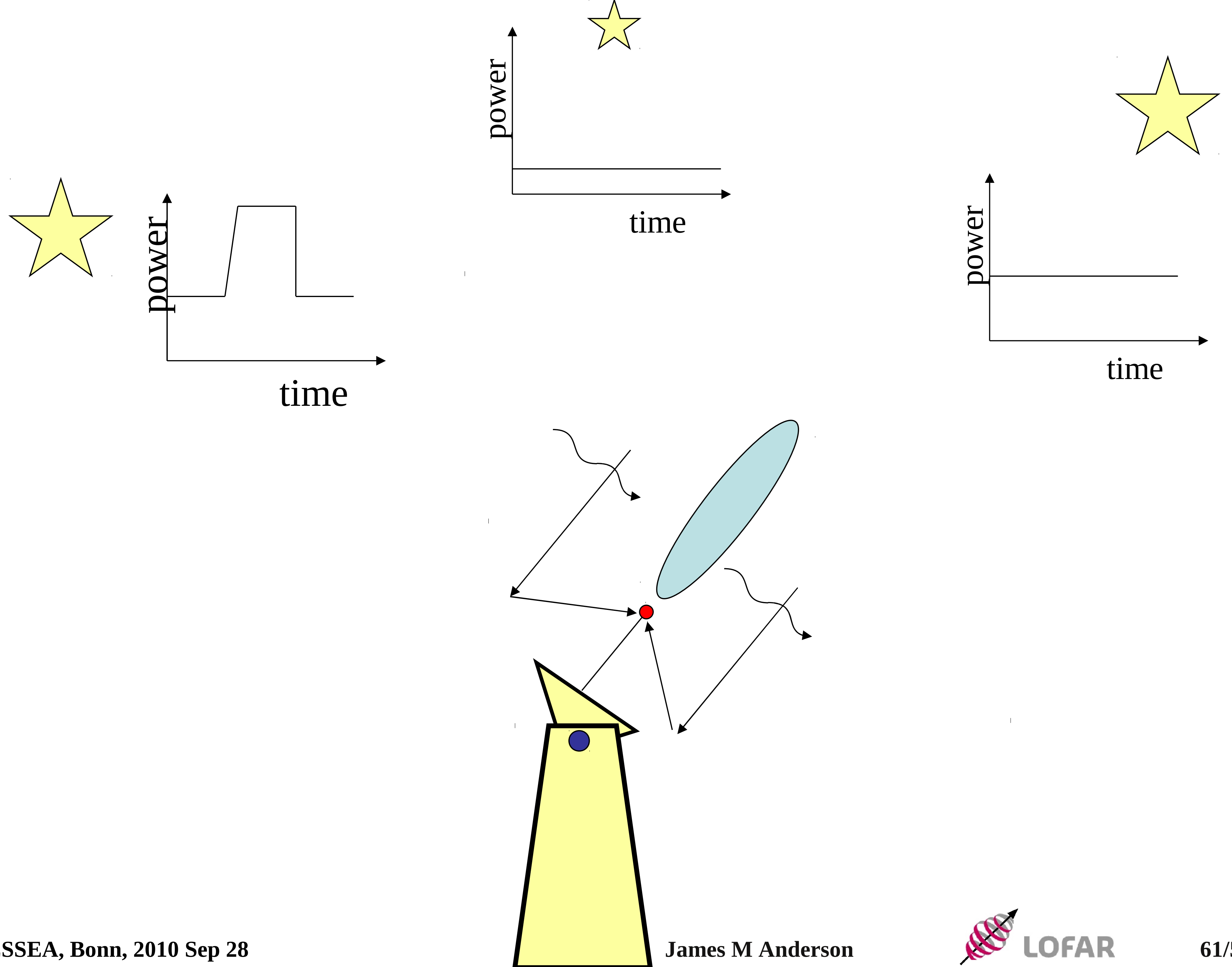

power
time


power
time


power
time


power
time


power
time

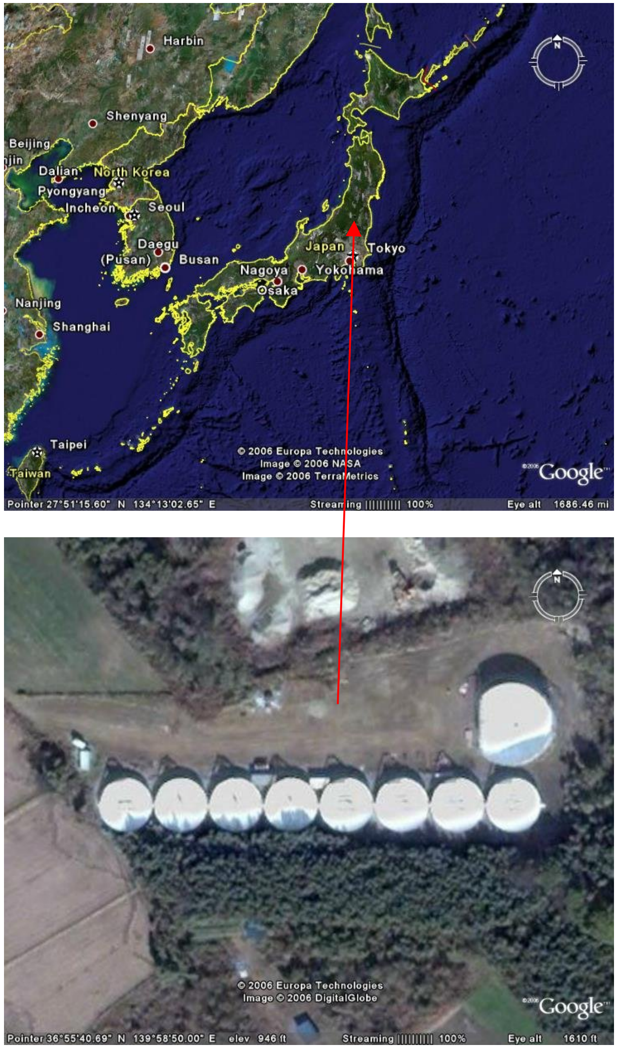

power
time
power
time
power
time

# Multi-elements (dish or dipole)

# Multi-elements (dish)

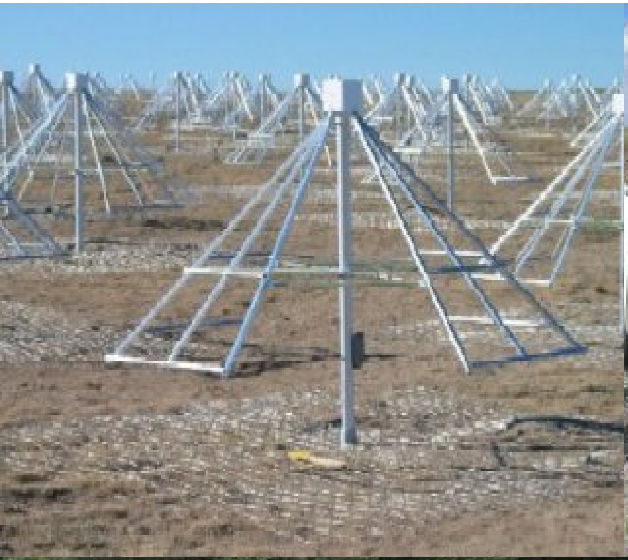
Waseda 64 elements

# Multi-elements (dish)

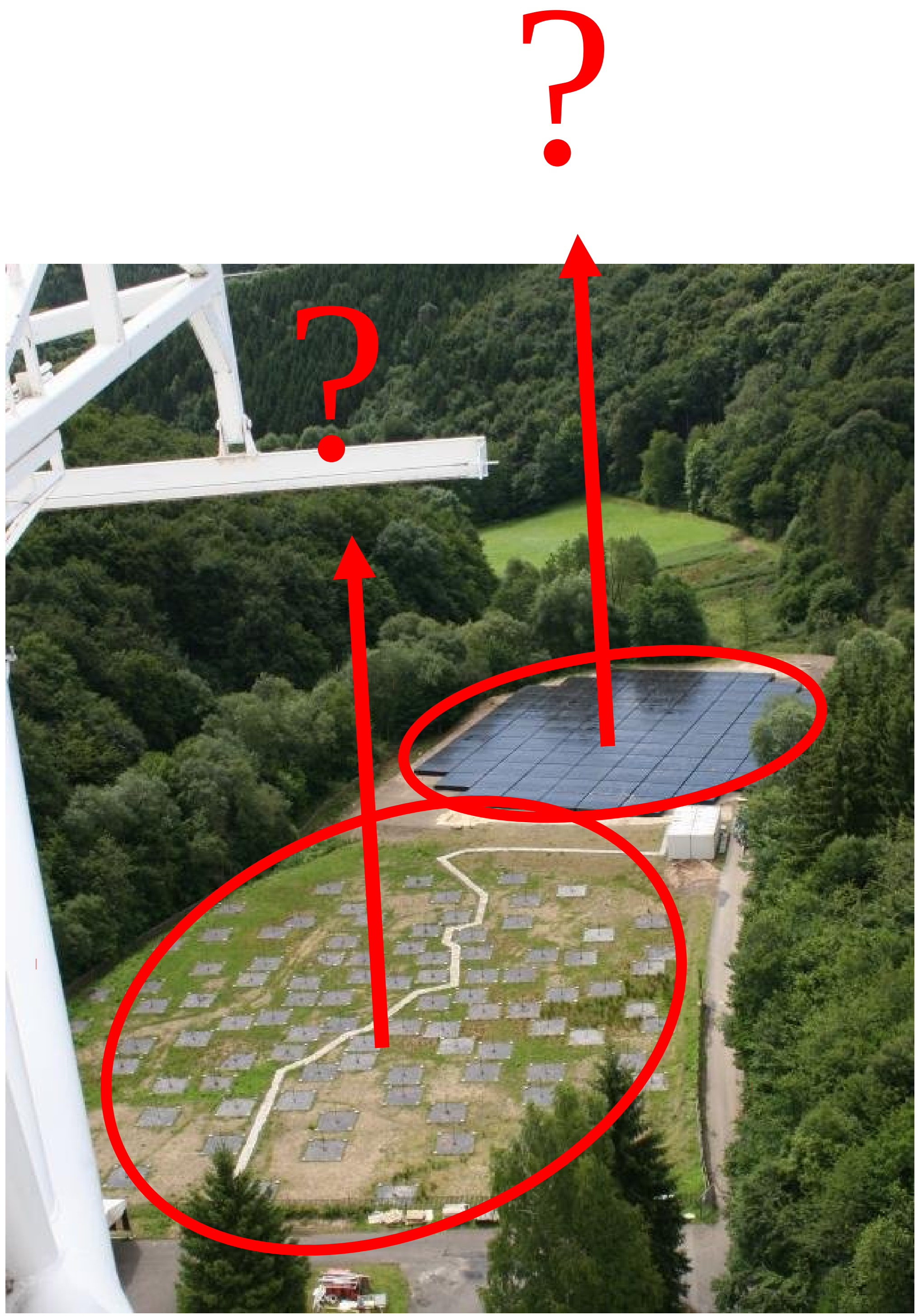



Nasu Observatory

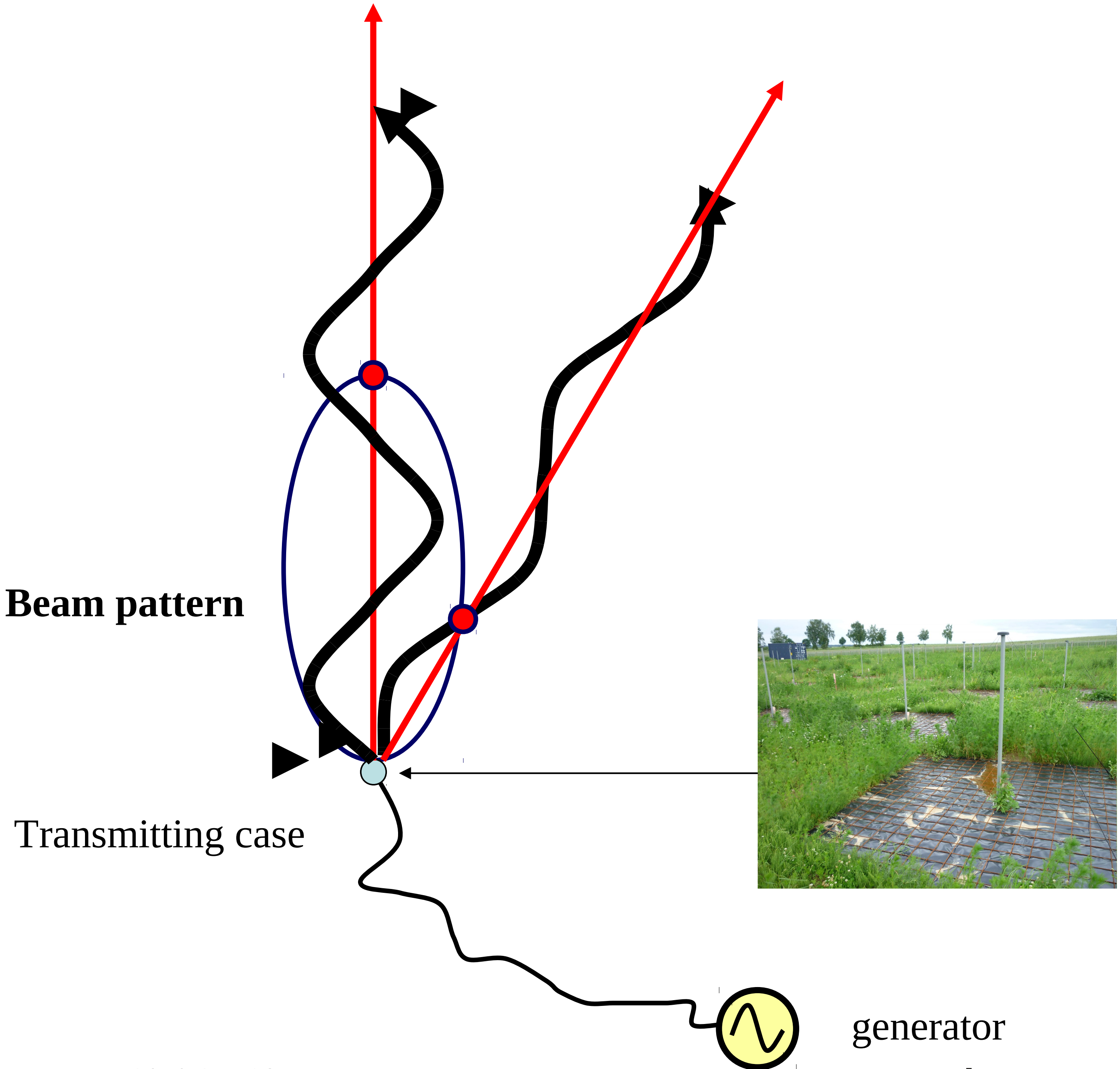
# Multi-elements (dipole)



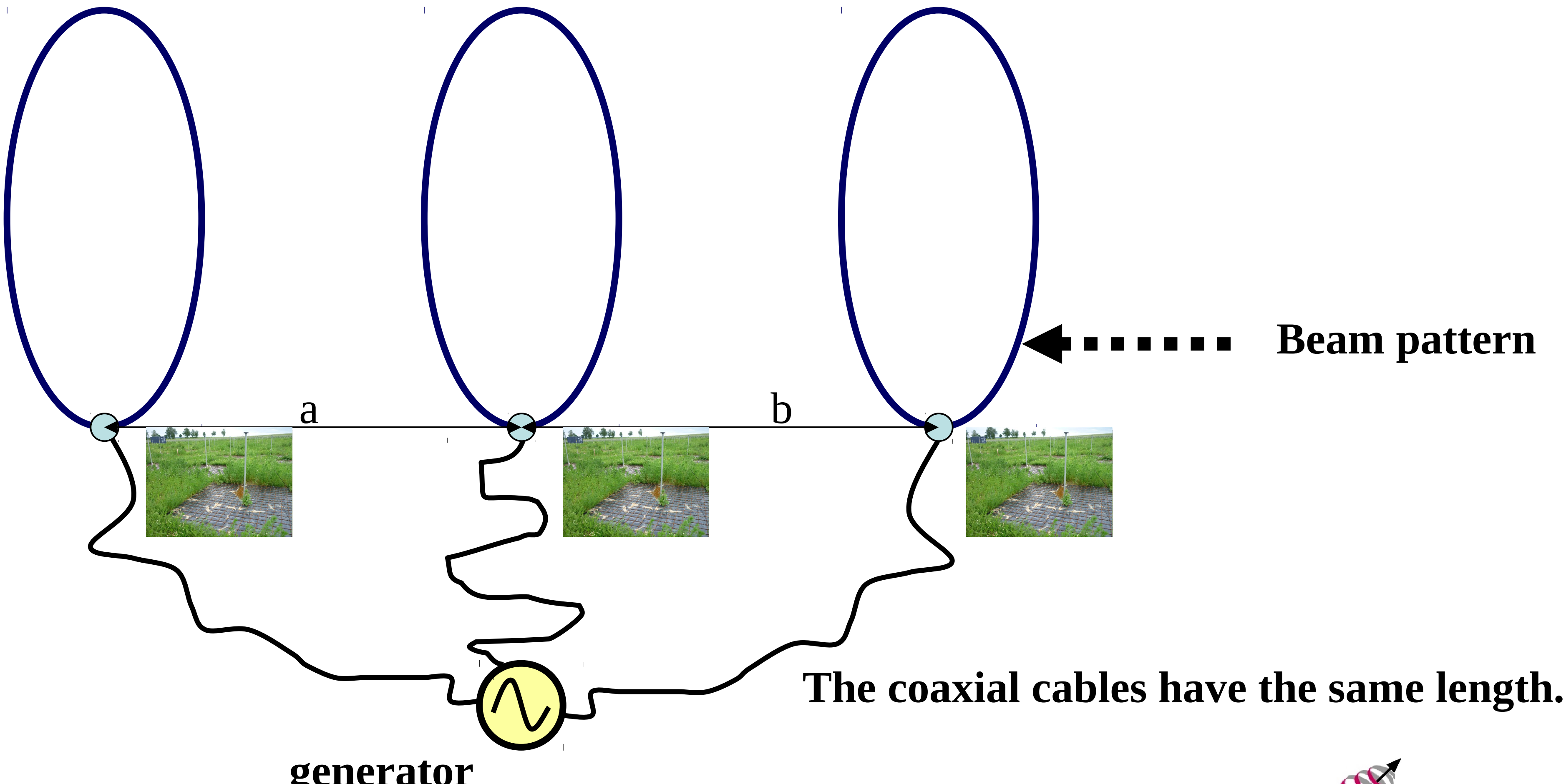




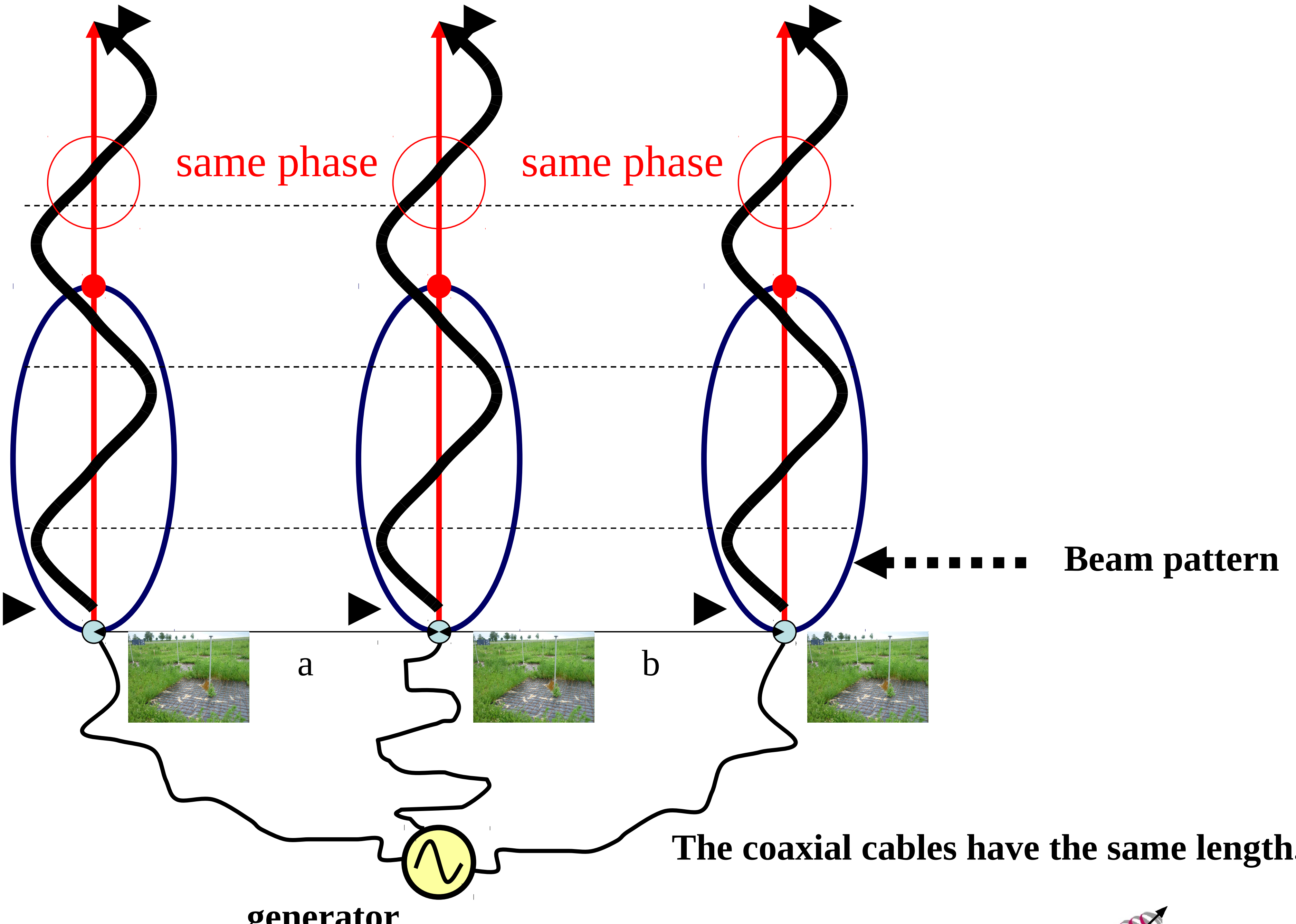
# The principle of beamforming



# The principle of beamforming

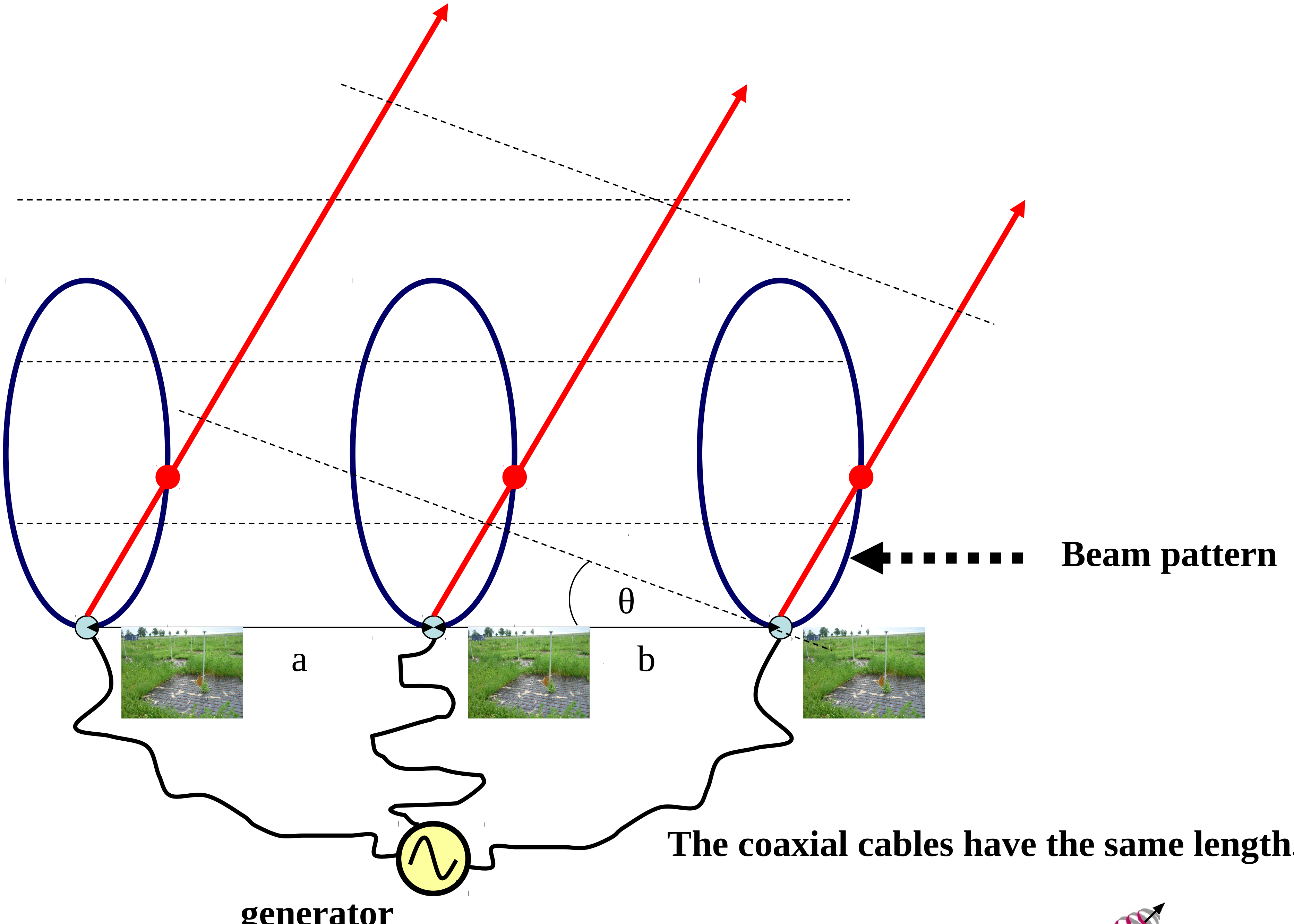


# The principle of beamforming

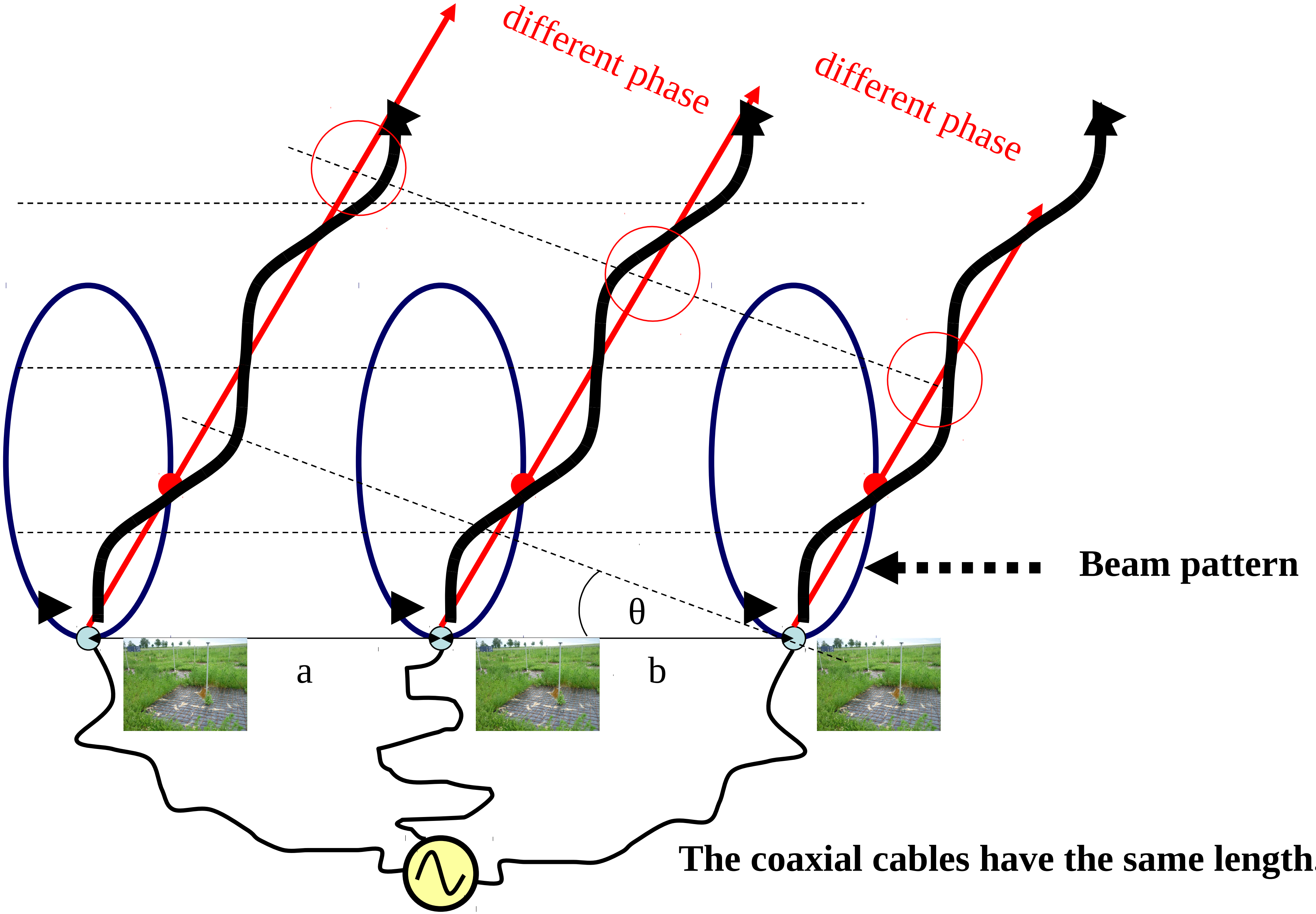



The coaxial cables have the same length.

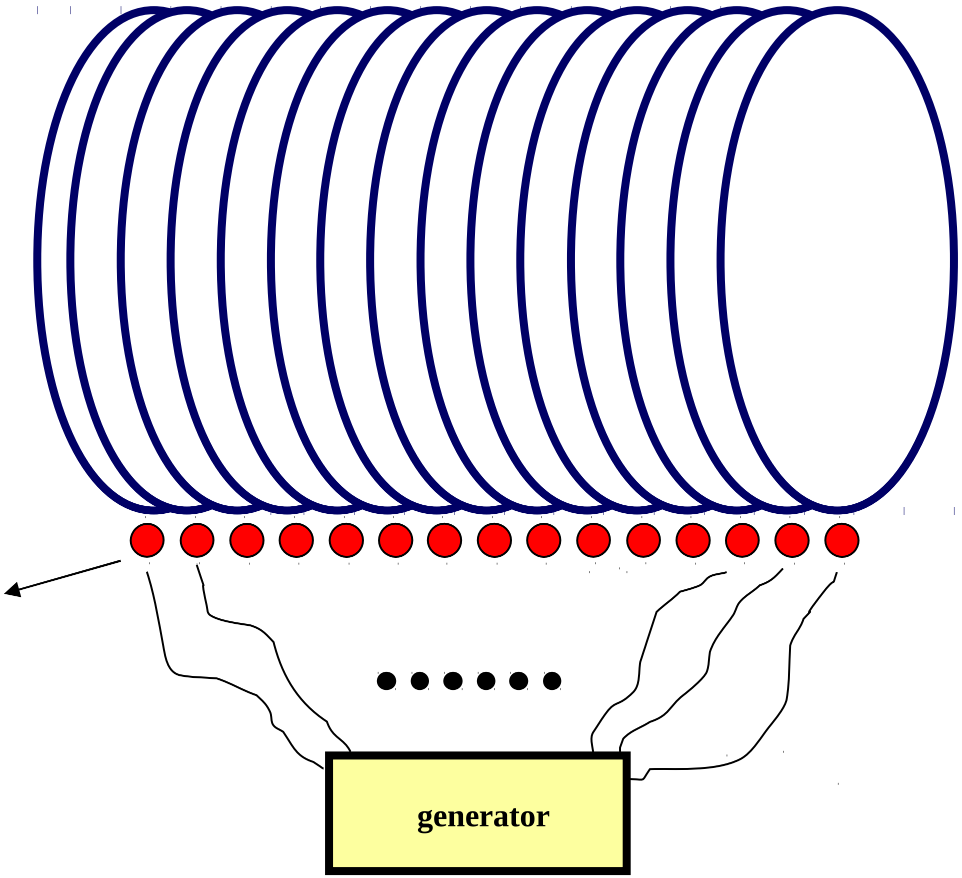
# The principle of beamforming



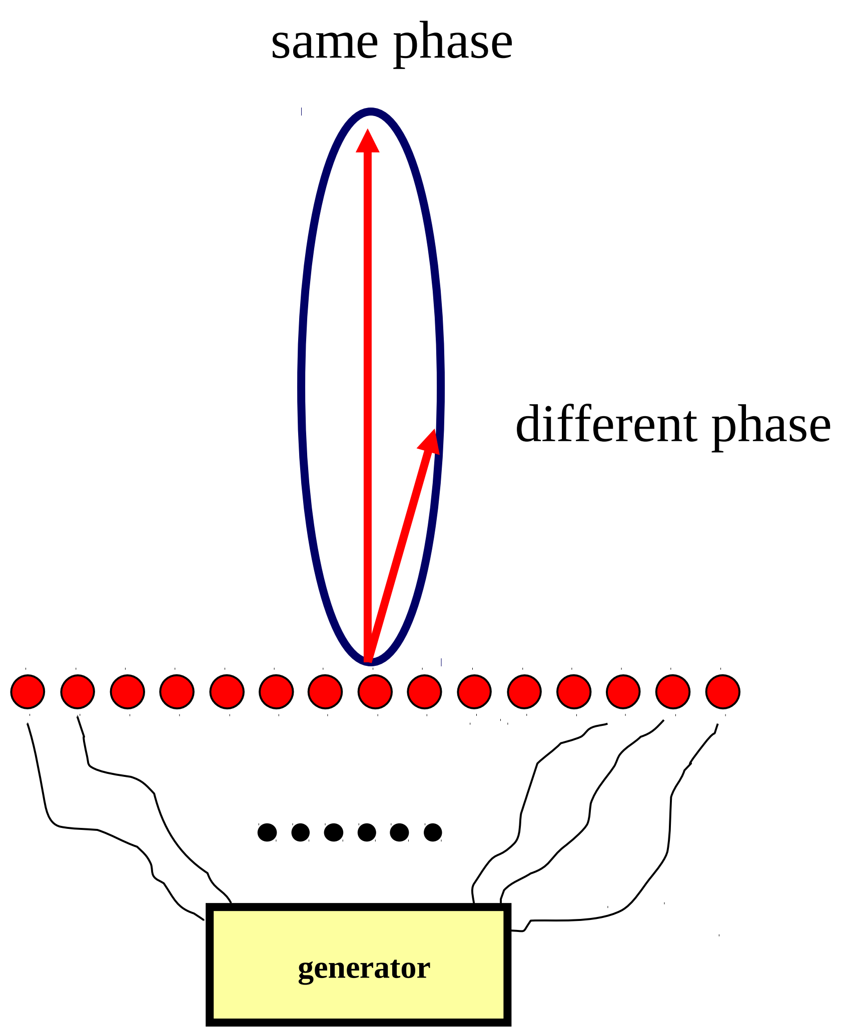
# The principle of beamforming



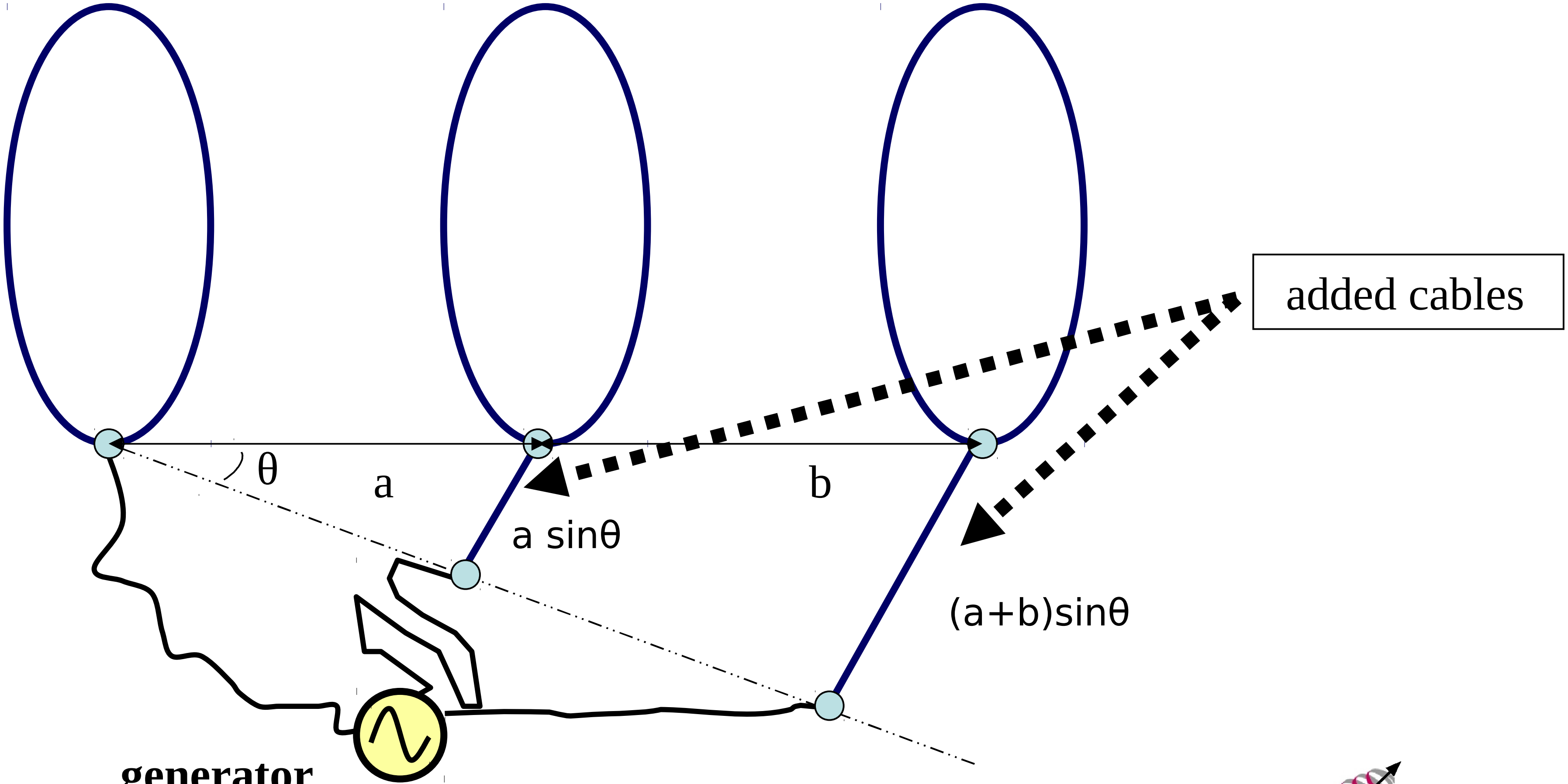
# The principle of beamforming



# Beam pattern after beamforming

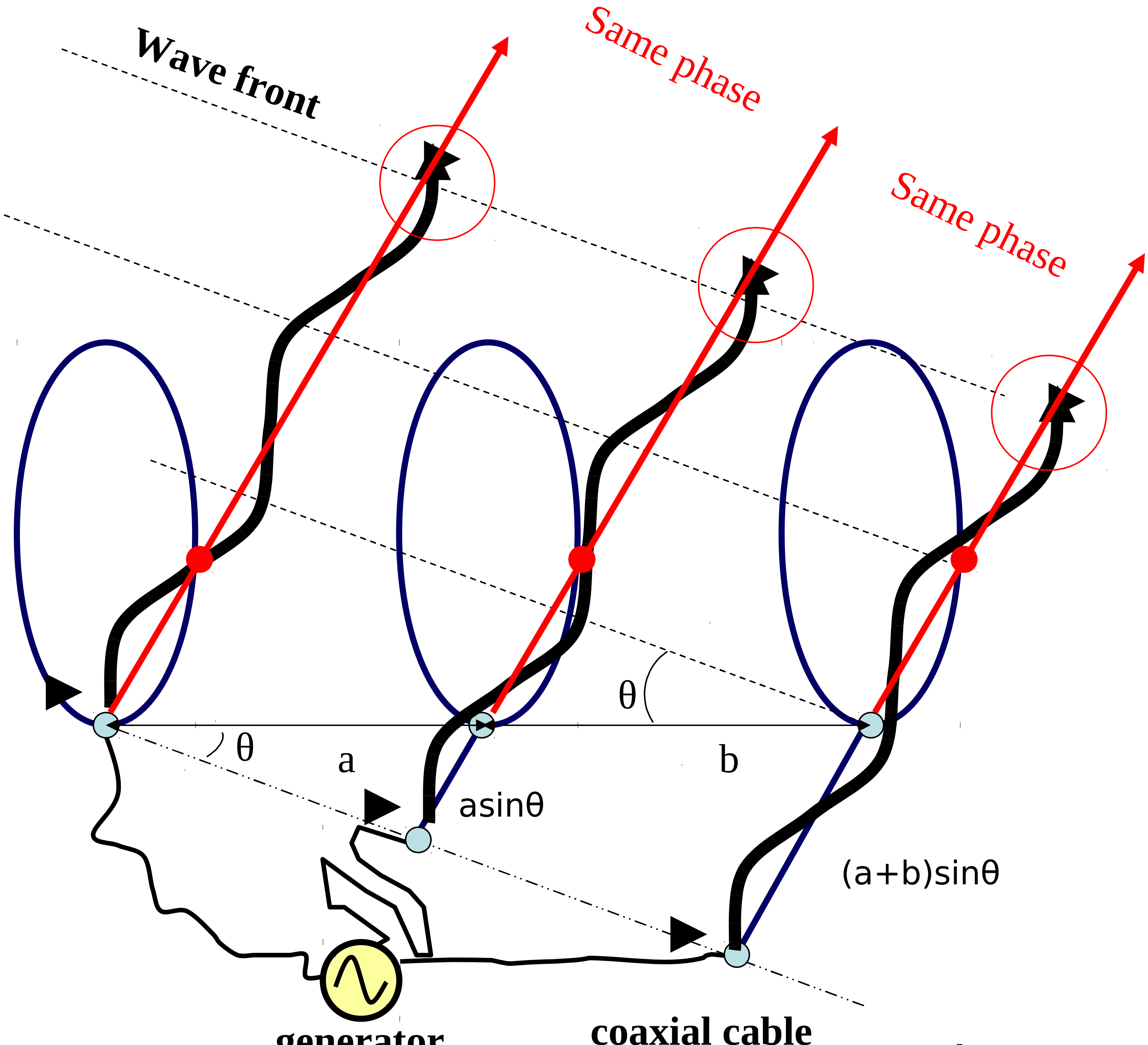


# The principle of beamforming




**The coaxial cables have the same length.**

# The principle of beamforming



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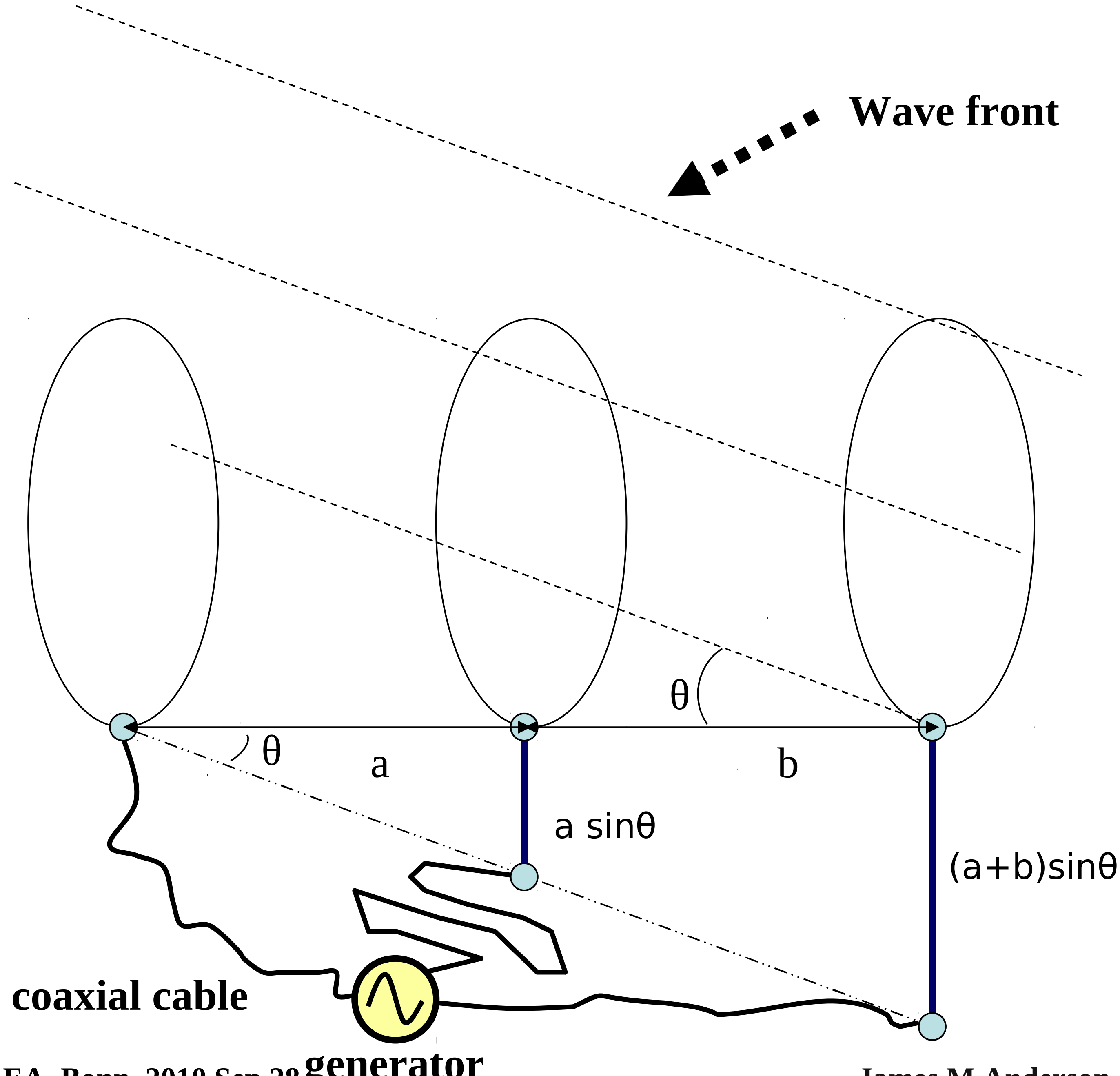
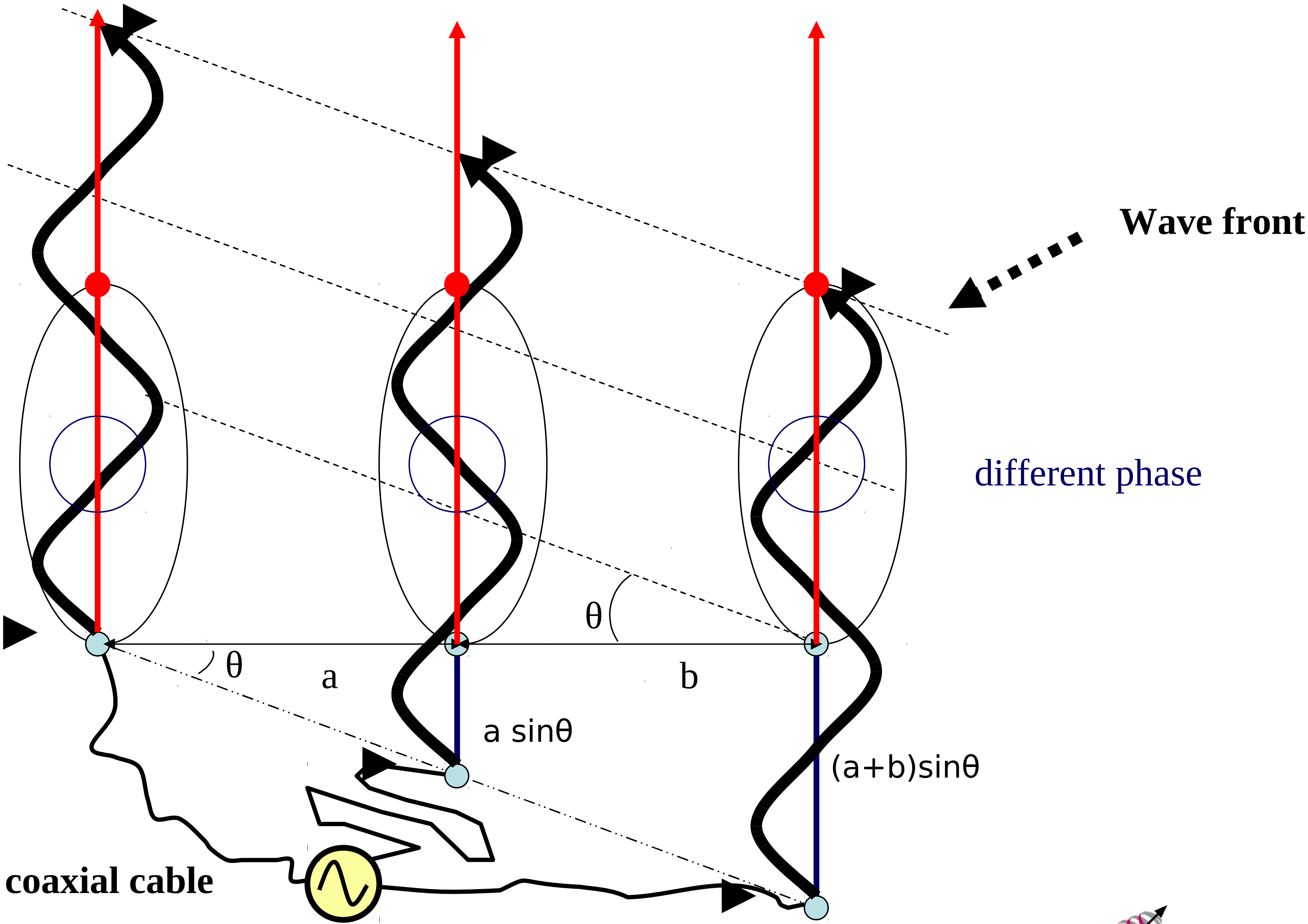
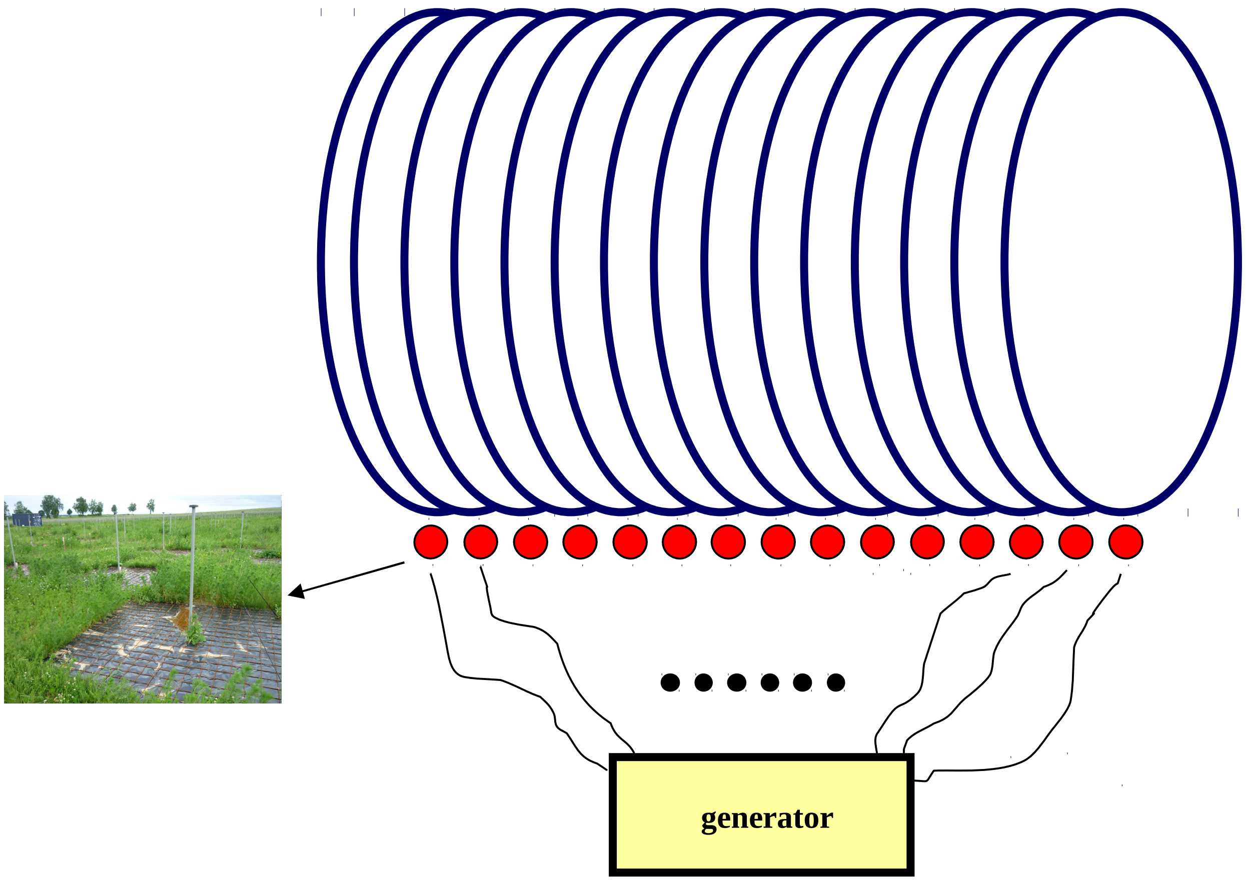


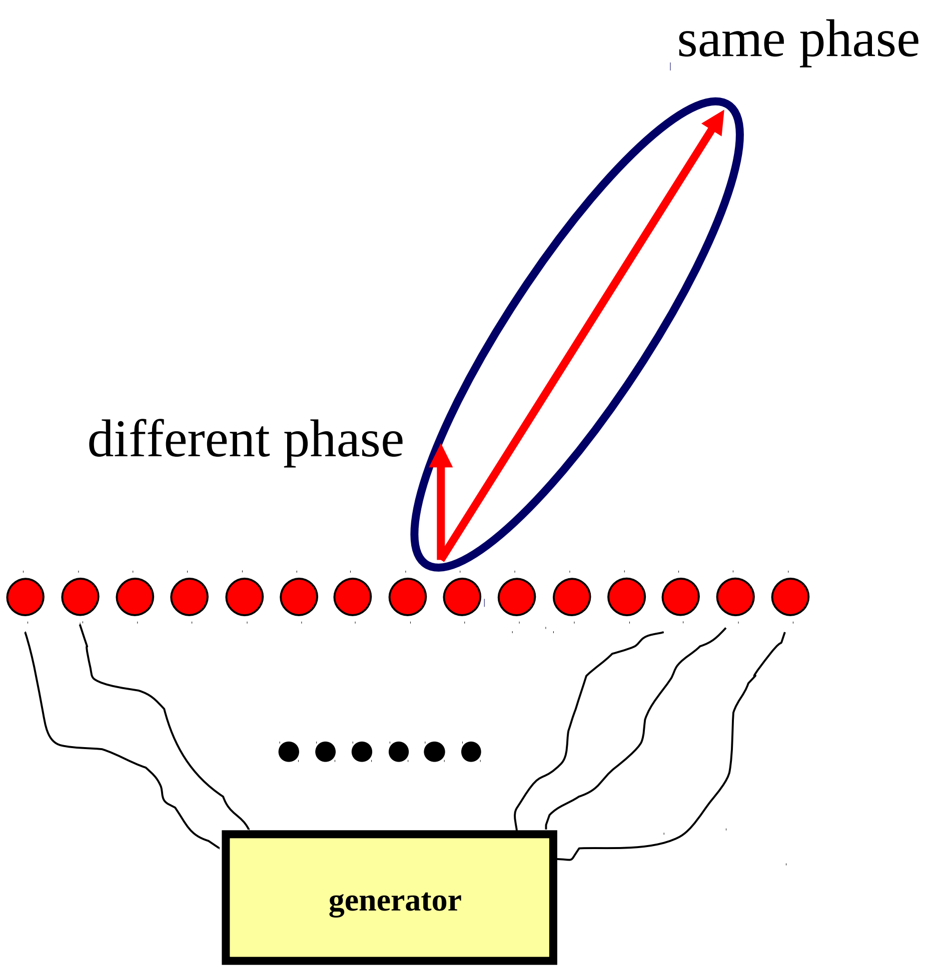
# The principle of beamforming



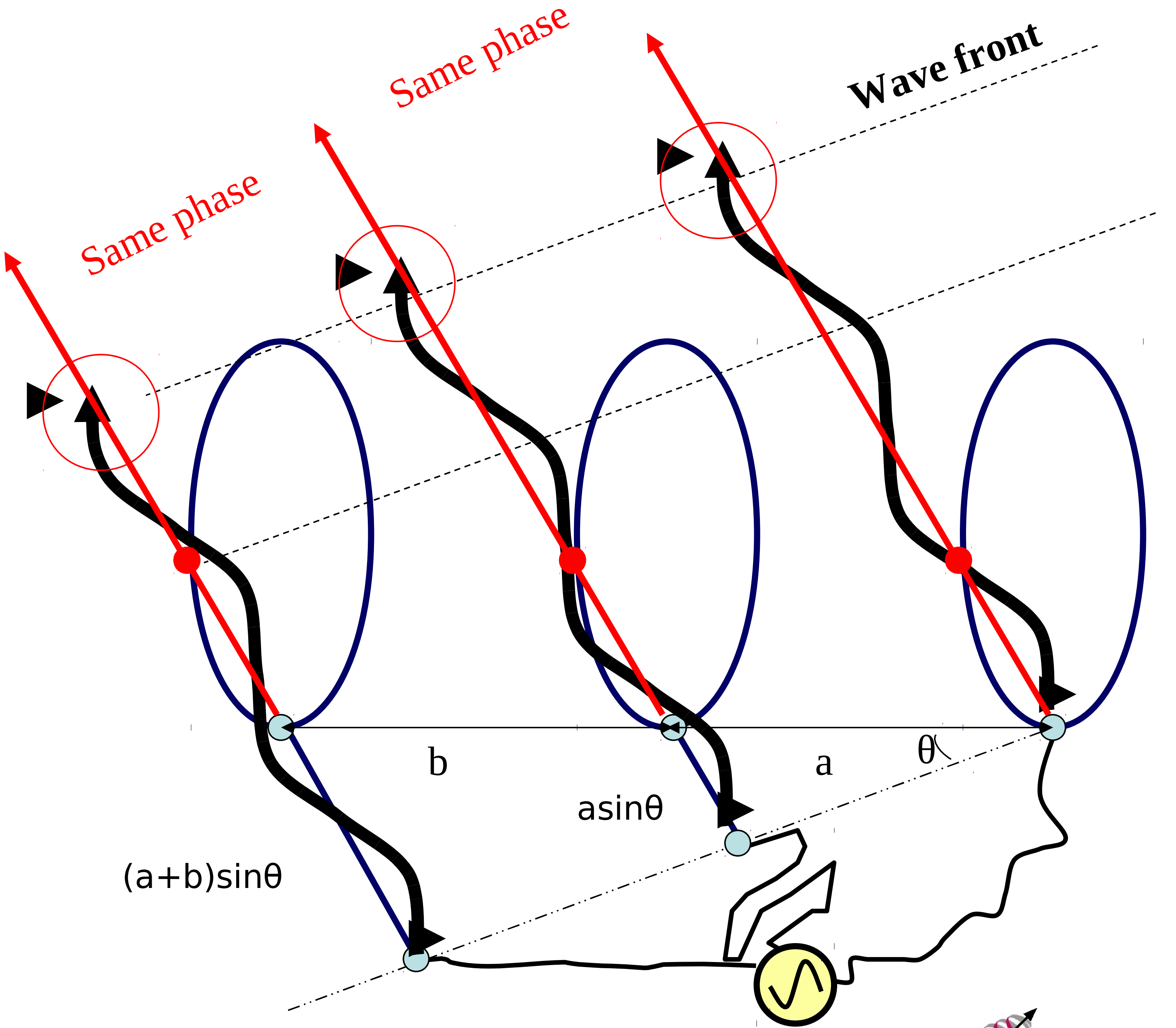
# The principle of beamforming



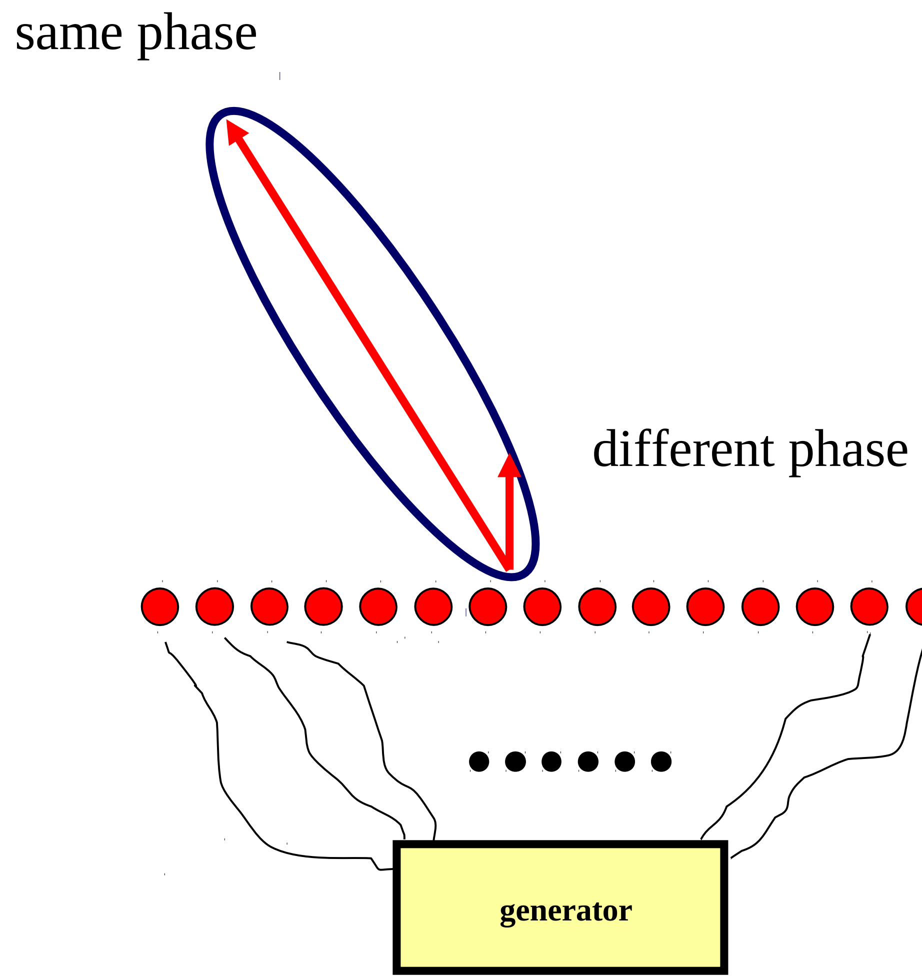
# Beam pattern after beamforming



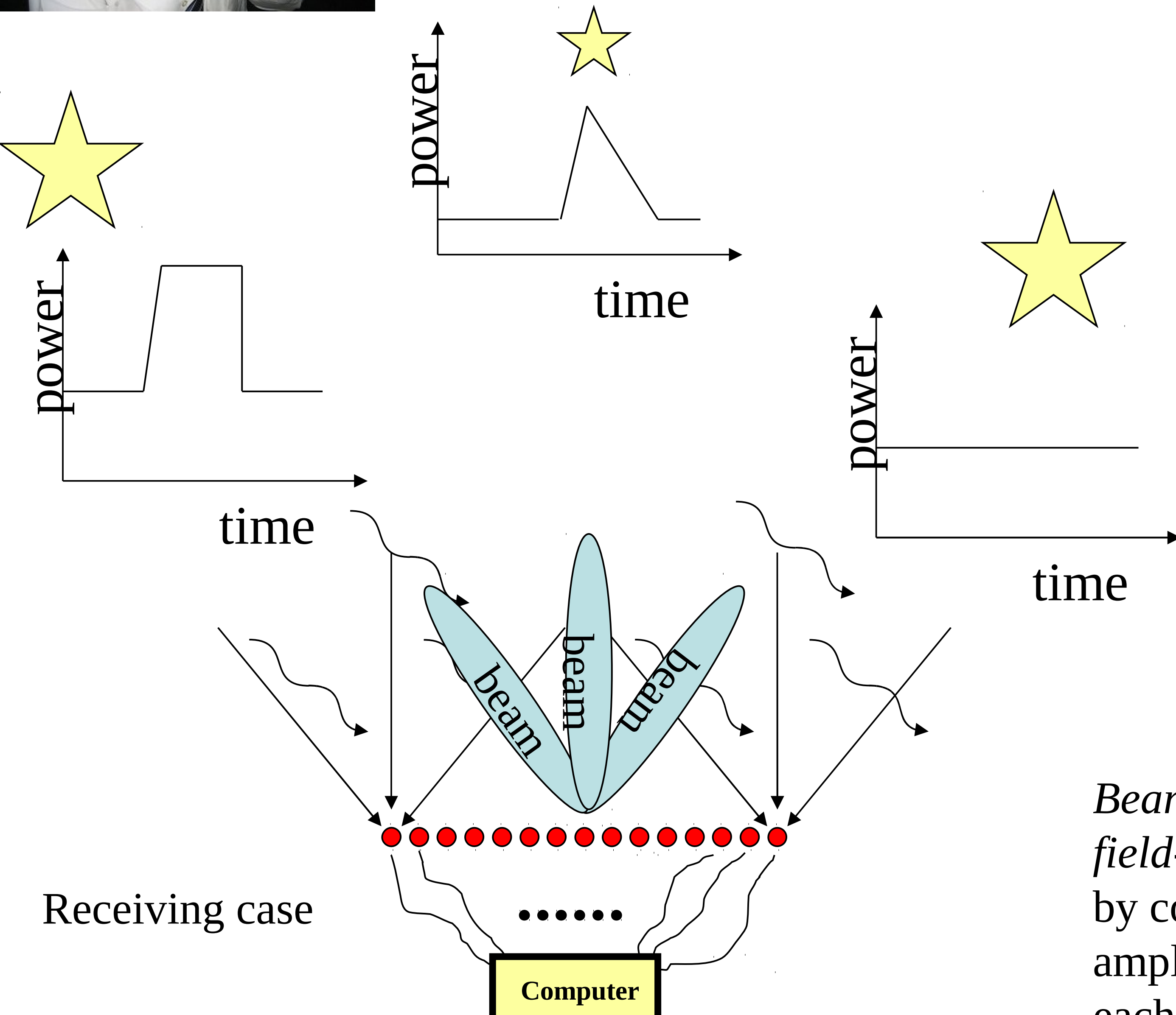
# The principle of beamforming



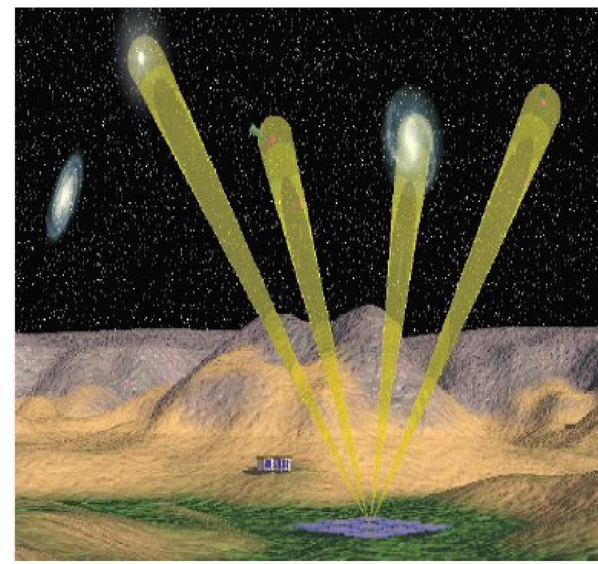
# Beam pattern after beamforming



# WOW




Receiving case



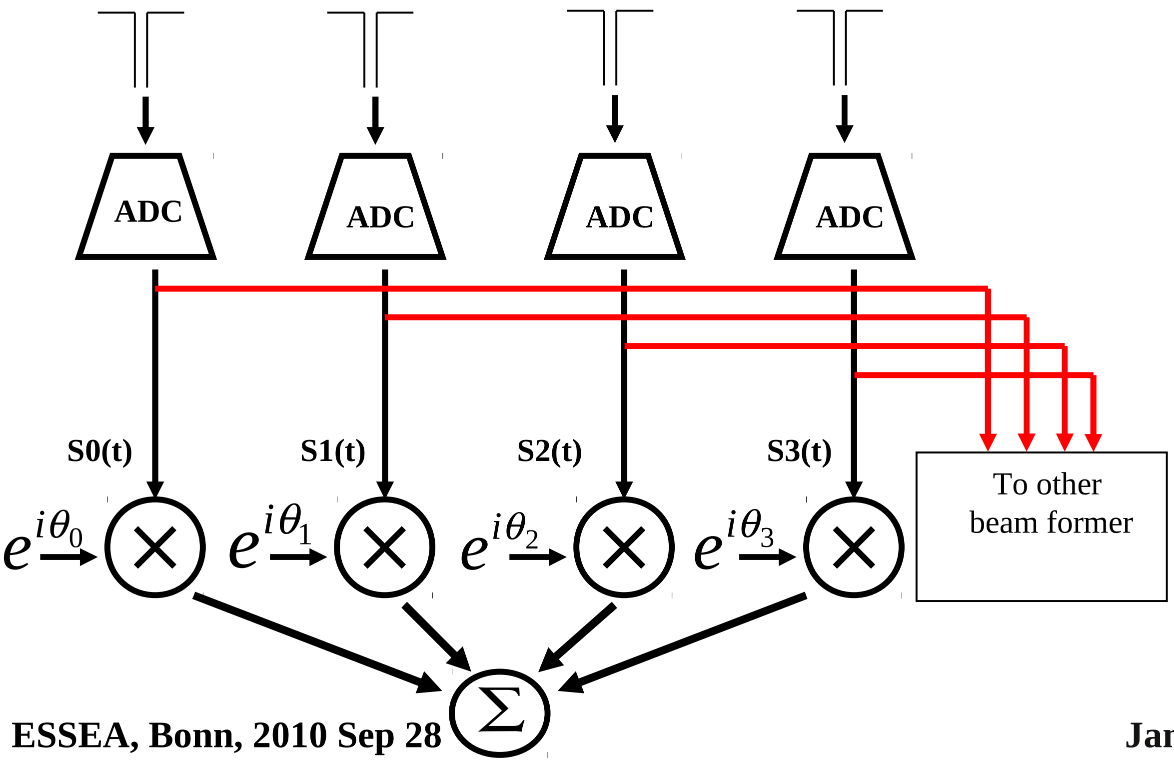
*Beamforming provides multiple field-of-view at the same time* by controling the phase and amplitude of the signal at each element.

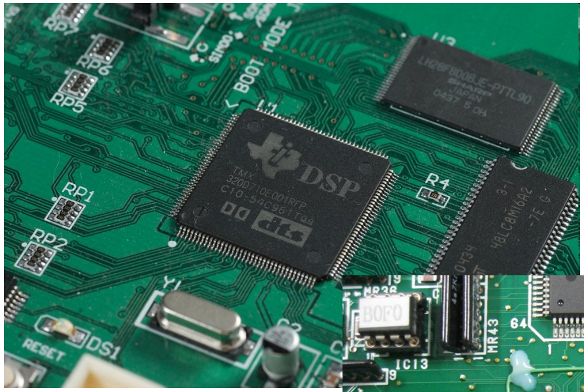
# Analog Beamforming

# Digital Beamforming

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

Remote Station Processing board




DSP


FPGA