Lectures on radio astronomy: 3

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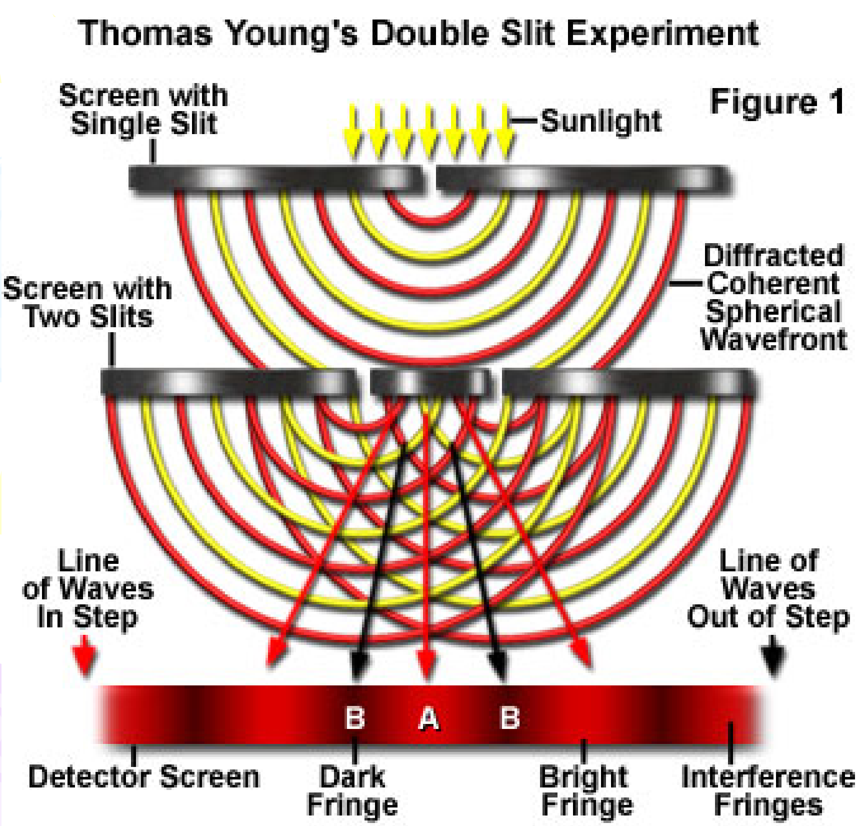
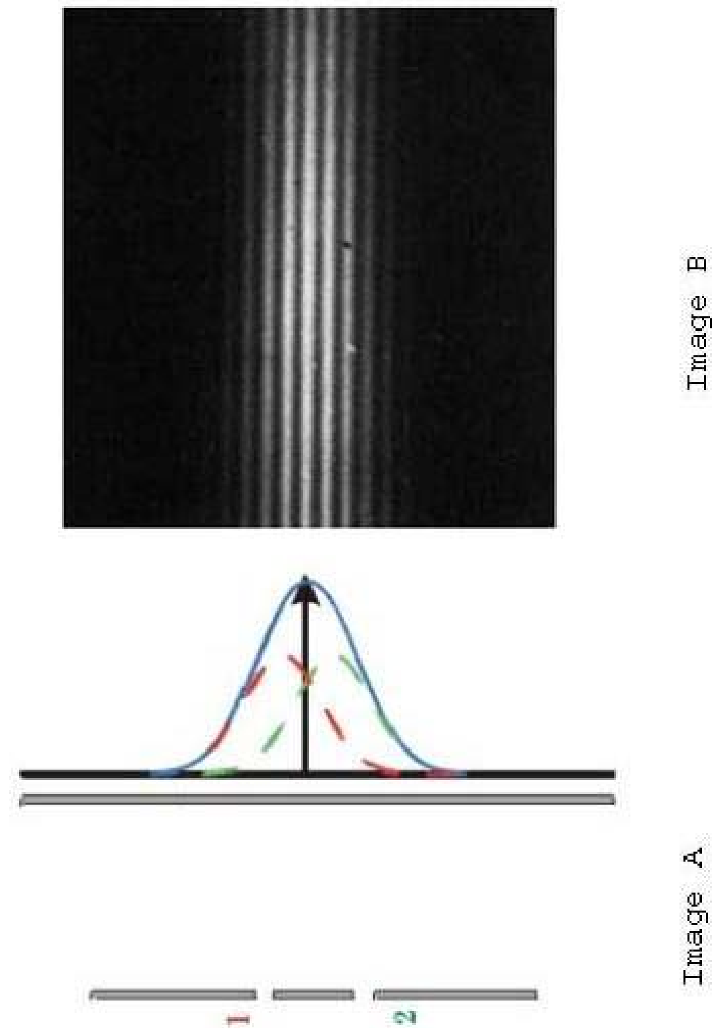
Interferometers

Early interferometry: Young's double slit experiment (1801)



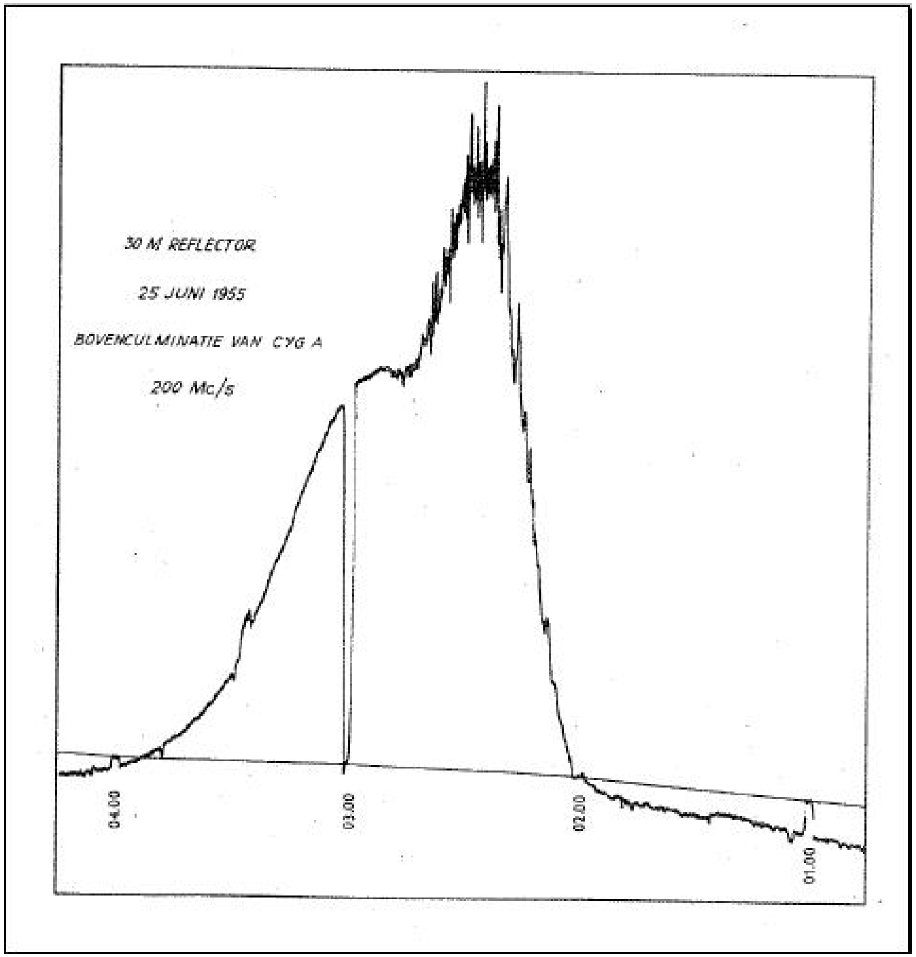


Radio engineers experimented in 1930s with interferometers

- A fixed array like the one shown here is a kind of interferometer
- Eight elements give a narrower beam
- It was originally used for radar in Australia

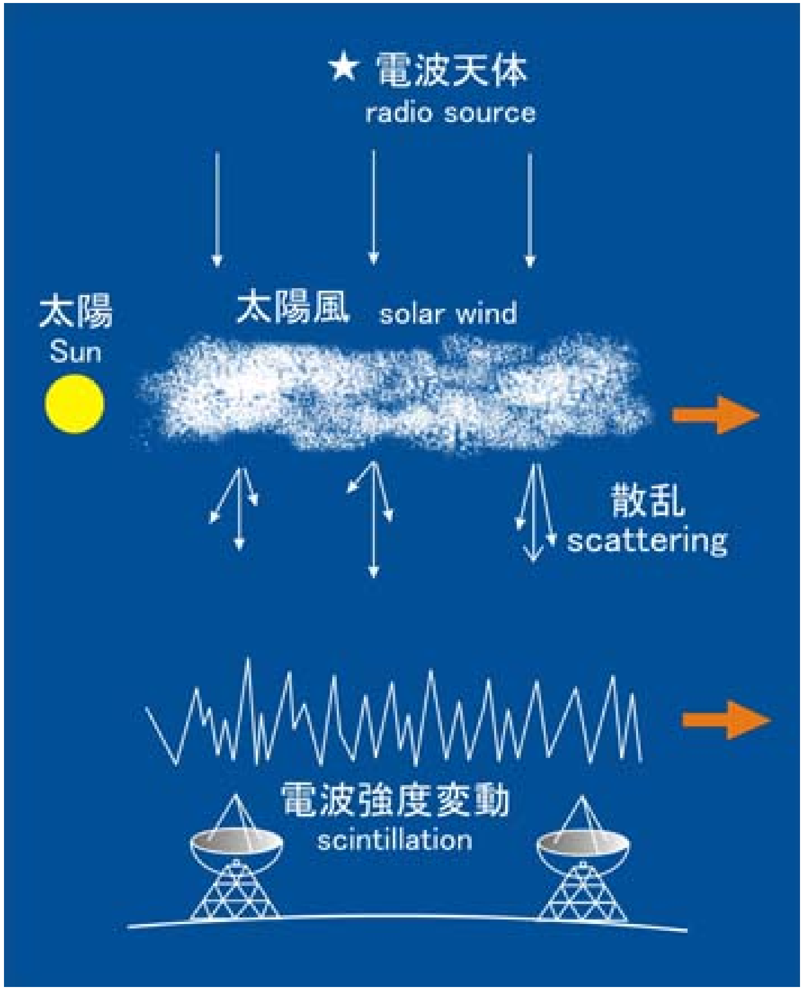
Radio telescopes in 1940s worked at long wavelengths

- Angular resolution quite limited
- Most sources were unresolved
- J.S. Hey noticed fluctuations in signal from Cygnus A
- Concluded must be scintillation in ionosphere & source must be compact



Scintillation – schematic description

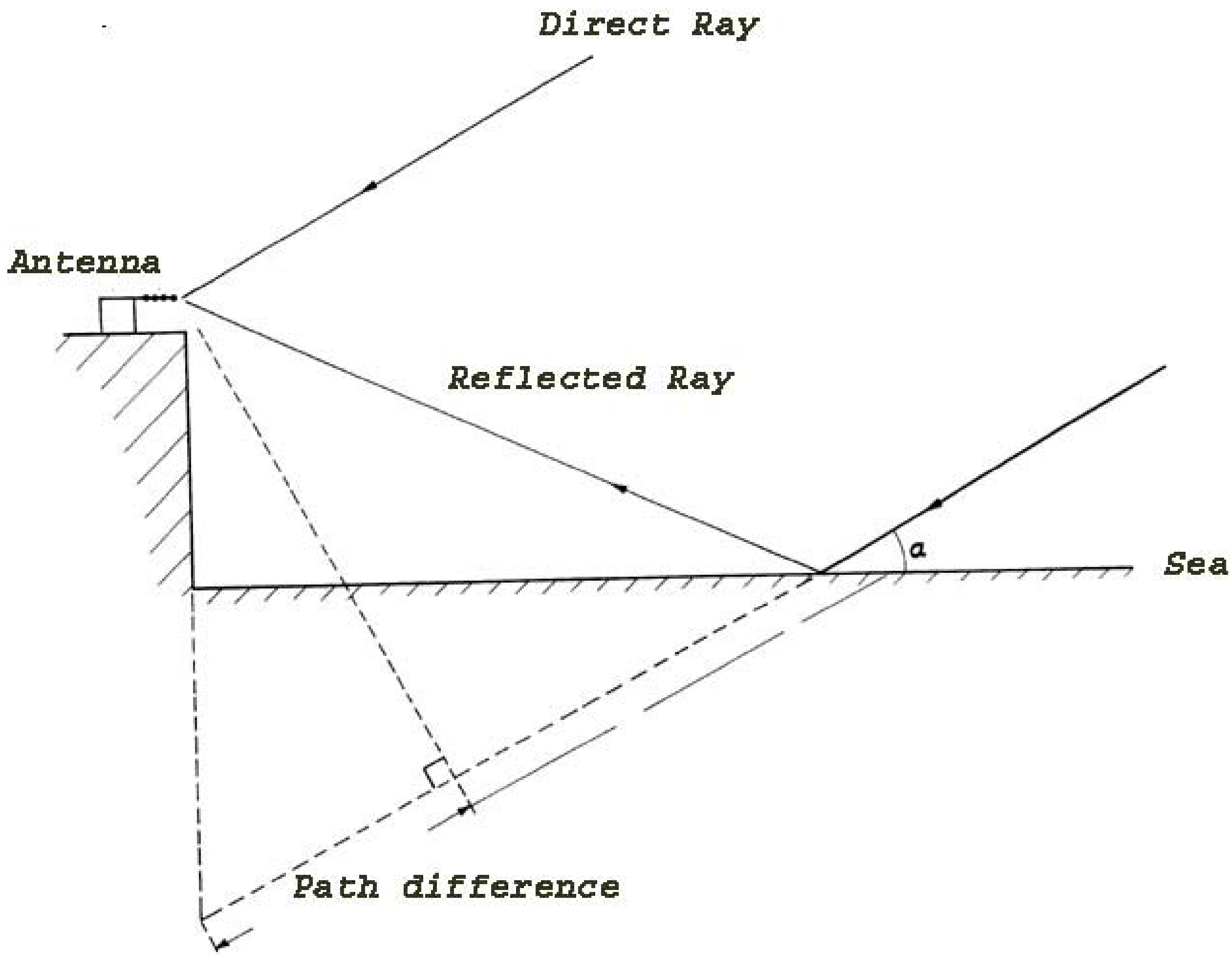
- Undistorted plane wave reaches ionized region
- Irregularities cause scattering by refraction
- Original wavefront now has brighter and fainter regions
- Scintillation can also be seen as a form of interferometry



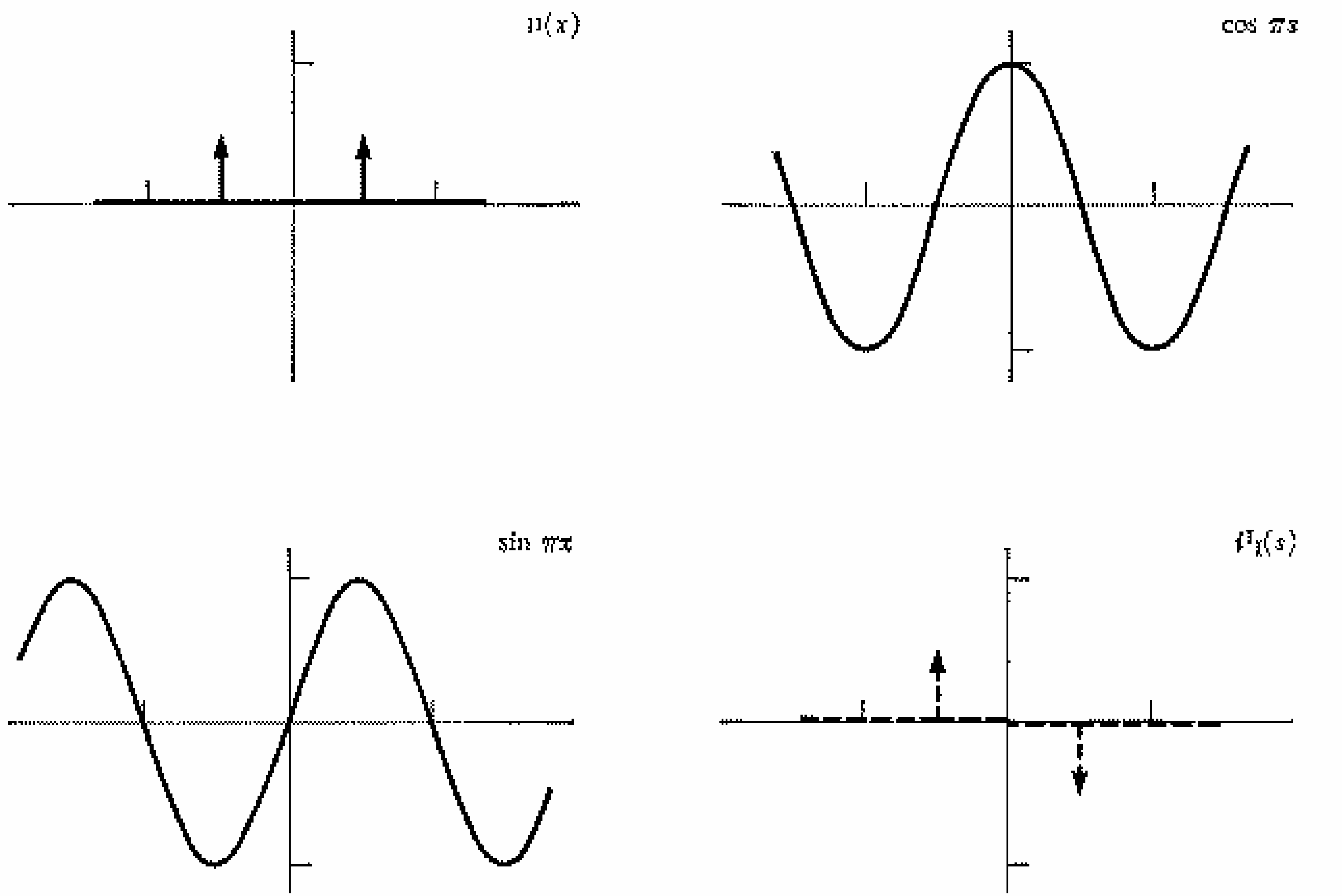
Early interferometry with one antenna

Geometry of Australian cliff-top antenna

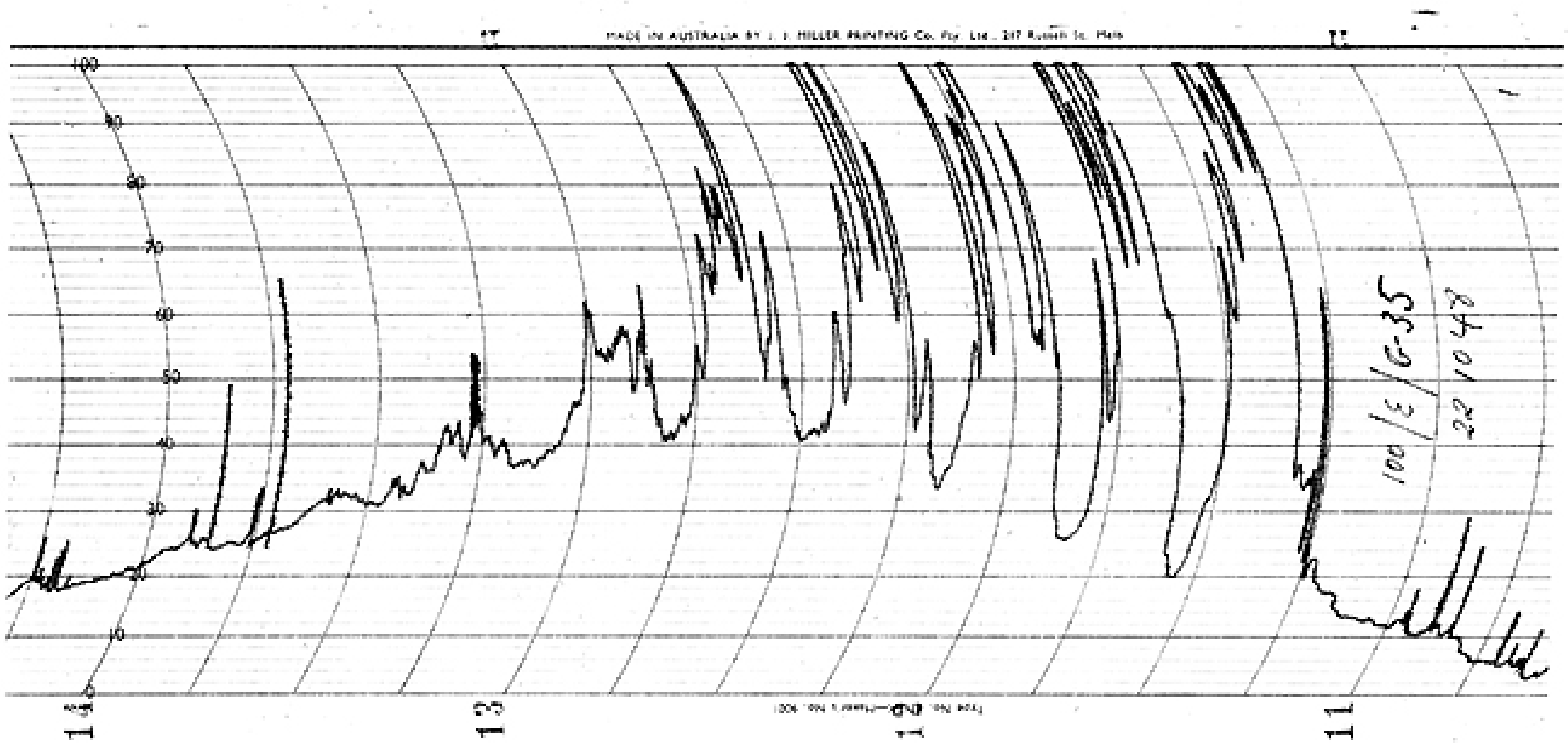
(in optics, called Lloyd's mirror)



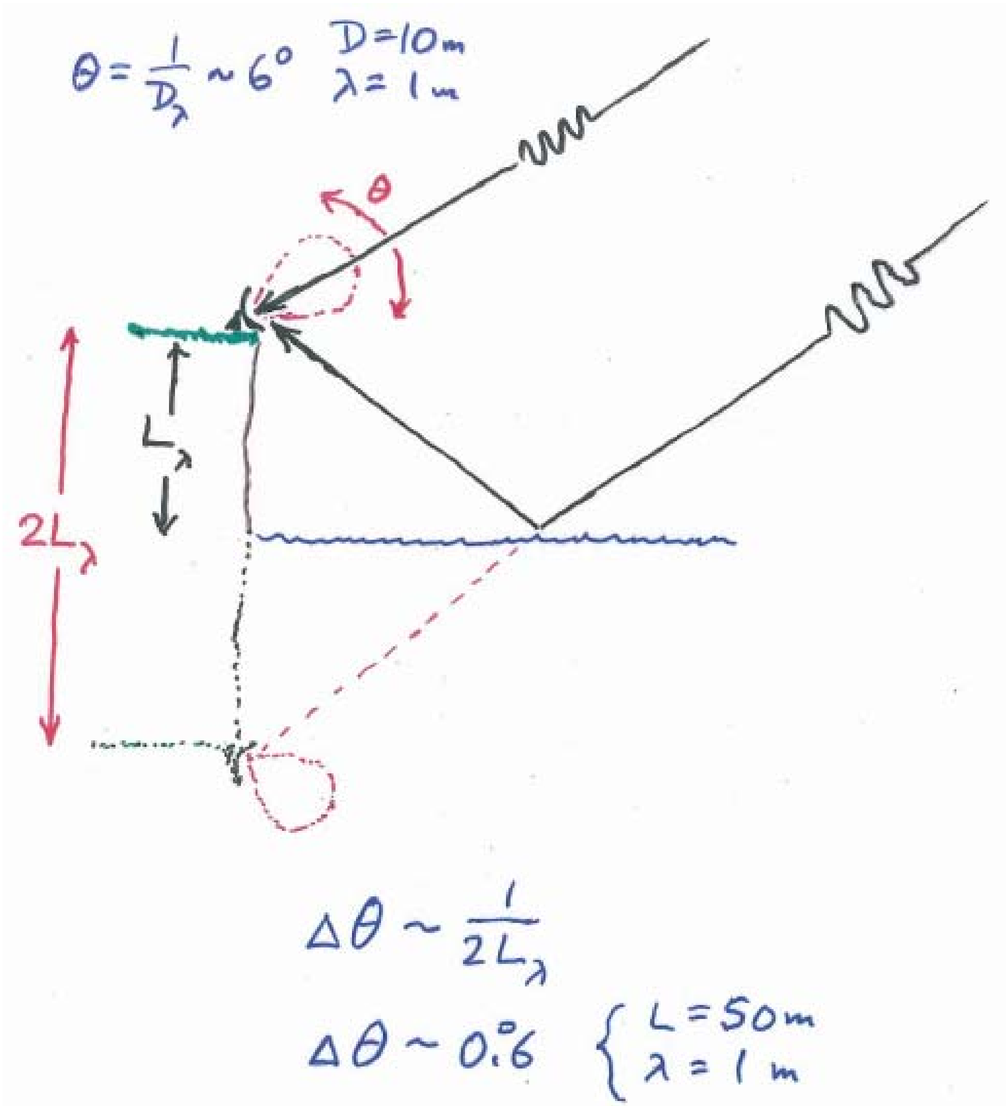
Response of two elements found by Fourier transform



Observation of Cygnus A – note cosine & scintillation



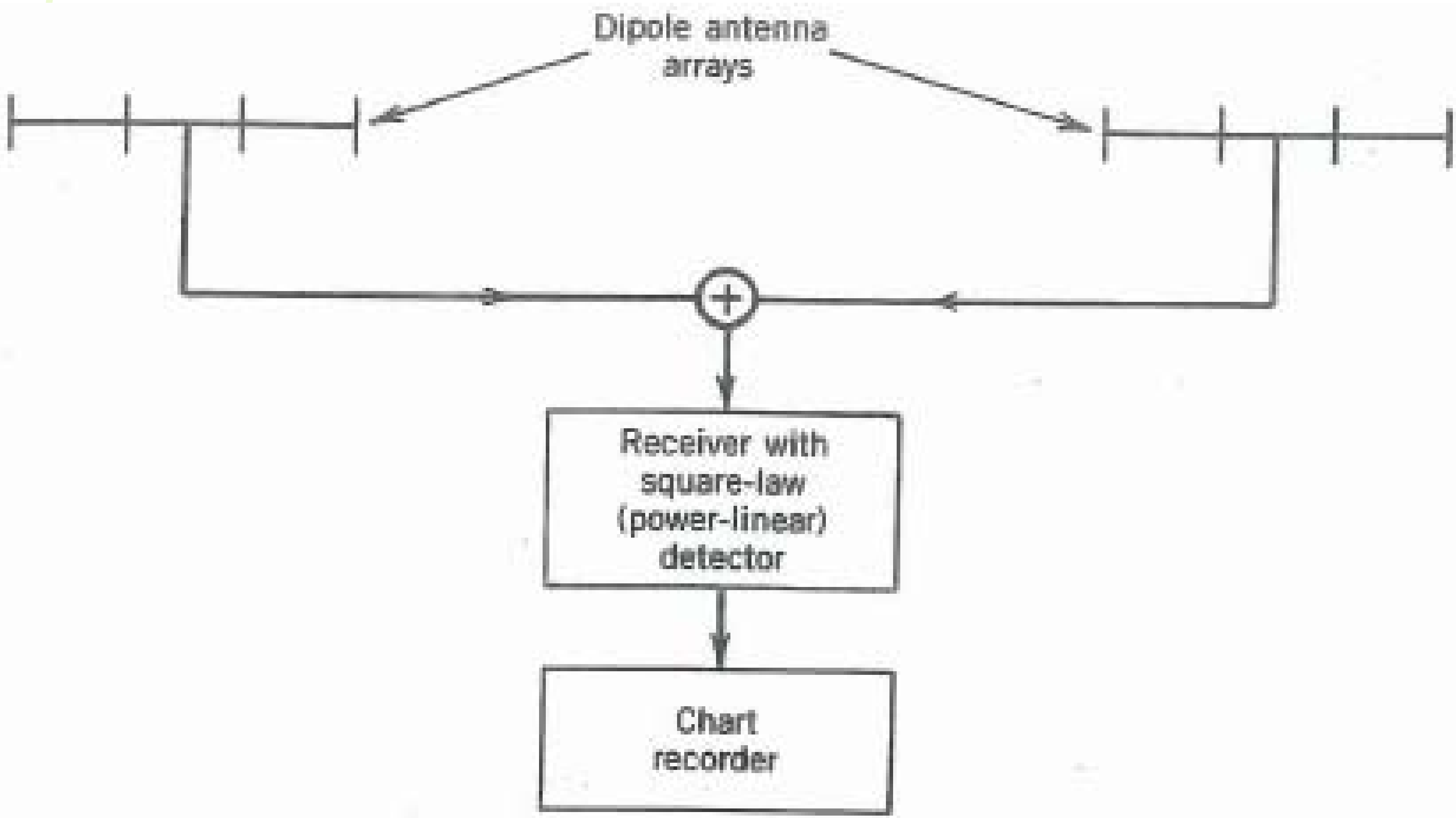
Angular resolution of the cliff-top interferometer



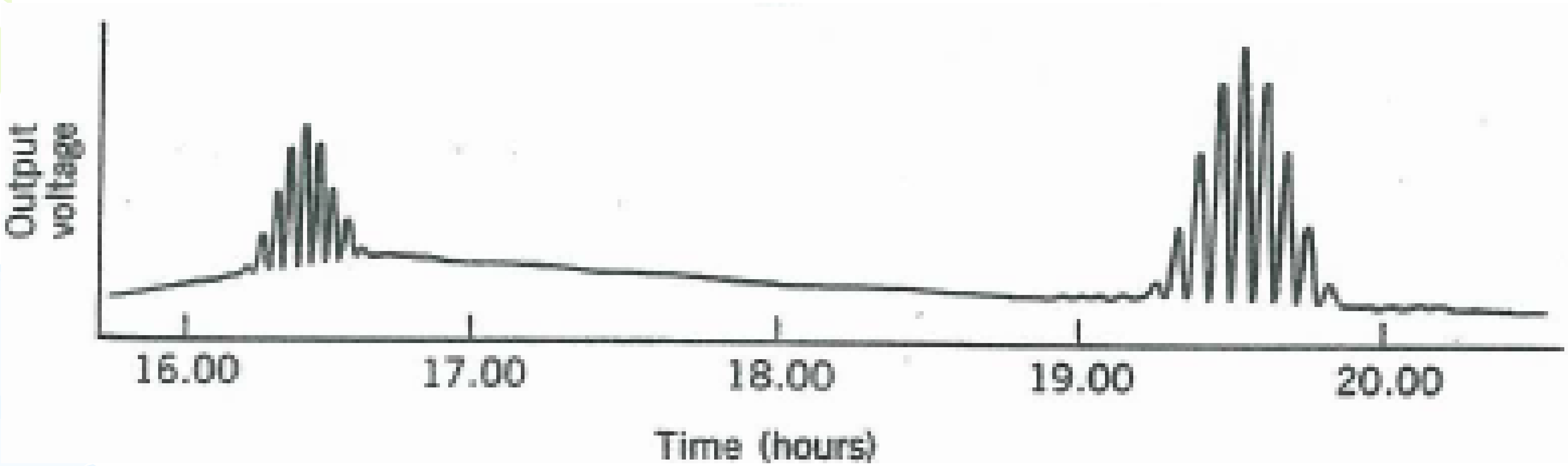
The cliff-top interferometer was a clever idea, but…

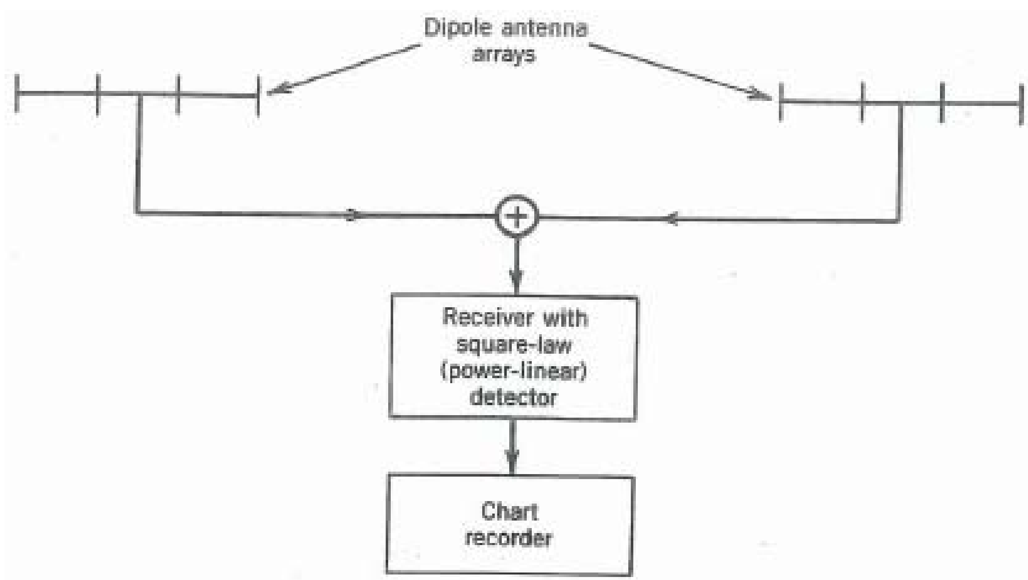
- Sources could only be observed at low elevation
- Ionosphere much thicker – sec z effect
- Refraction and scintillation made interpretation difficult

People also experimented with 2-element interferometers

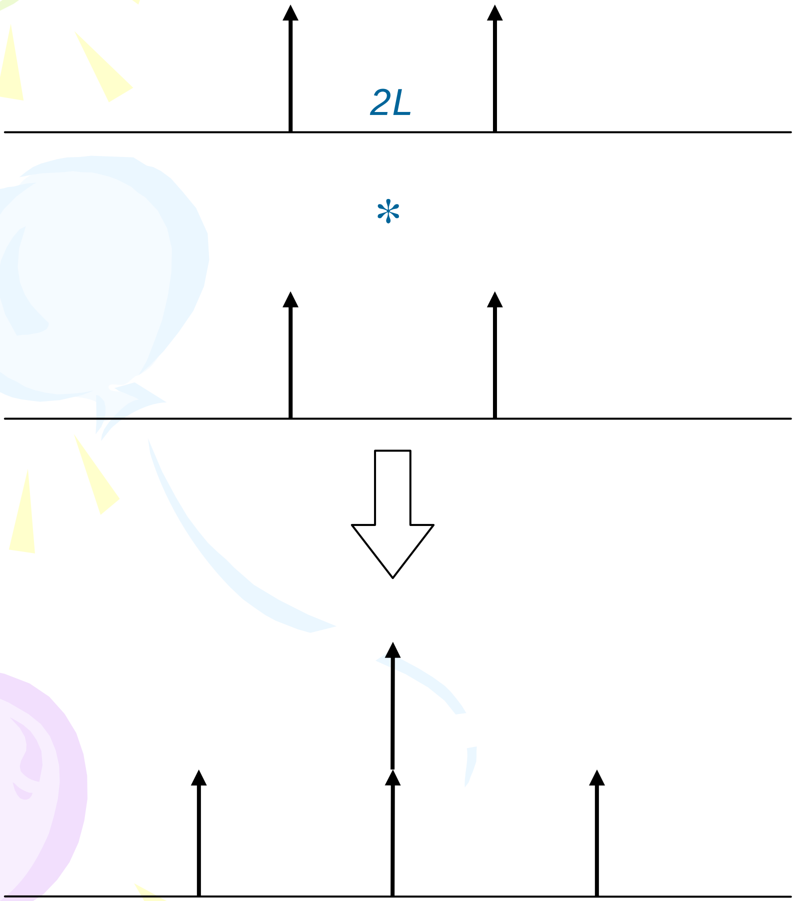


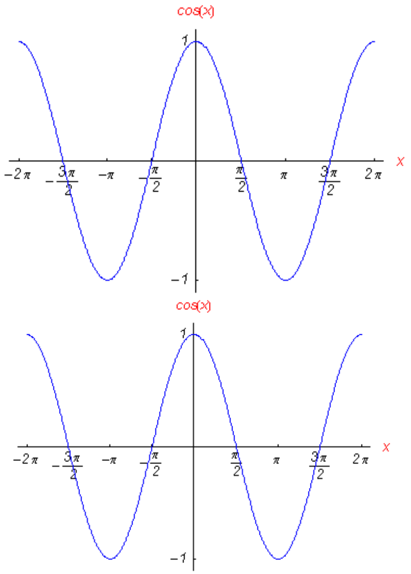
And this would be the result: beam $*$ source

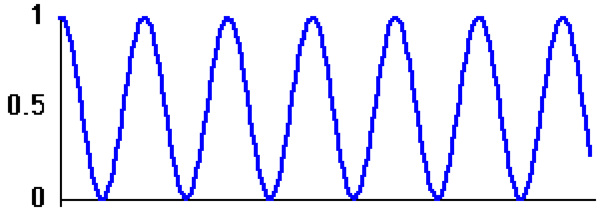




Fourier analysis of simple 2-element interferometer

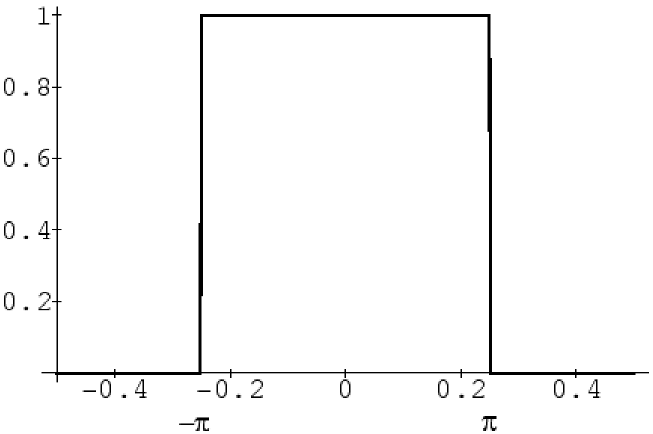


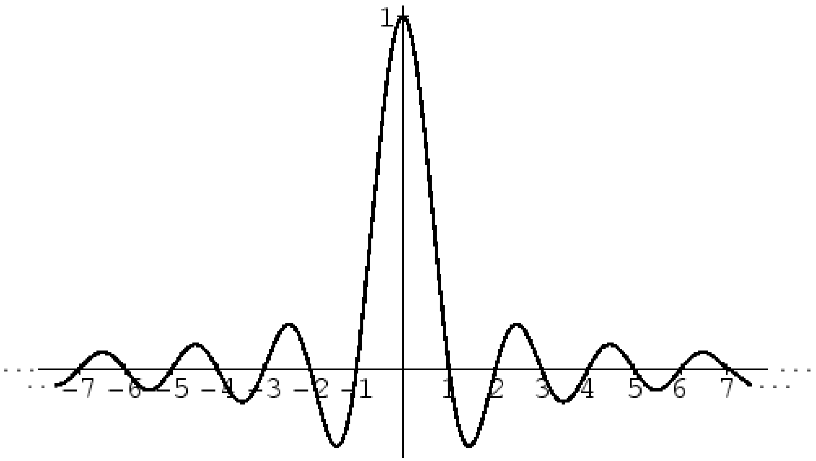




What happens if elements have their own beams?

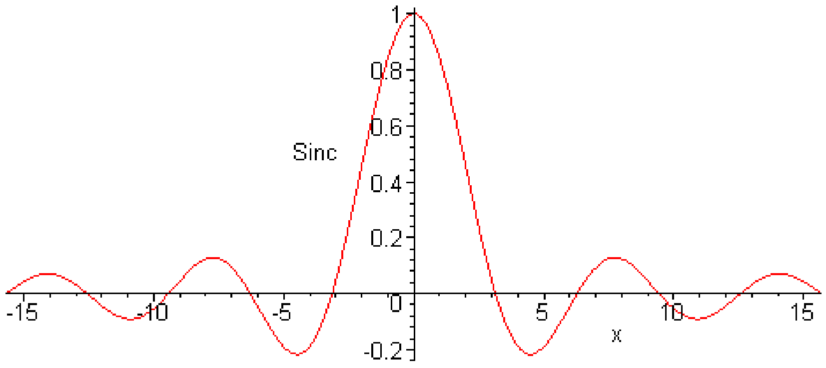
- As we know, for uniform illumination (square function)...
- ...the FT is a sinc ($\sin x/x$) function.
- This is the voltage beam pattern. As we know, the power beam can be found from (voltage)^2 ...

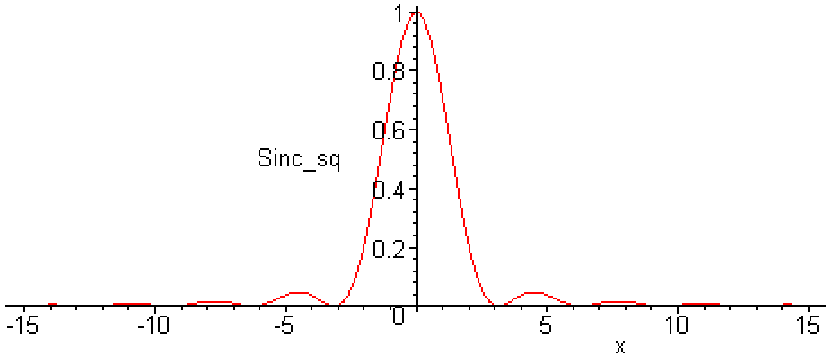




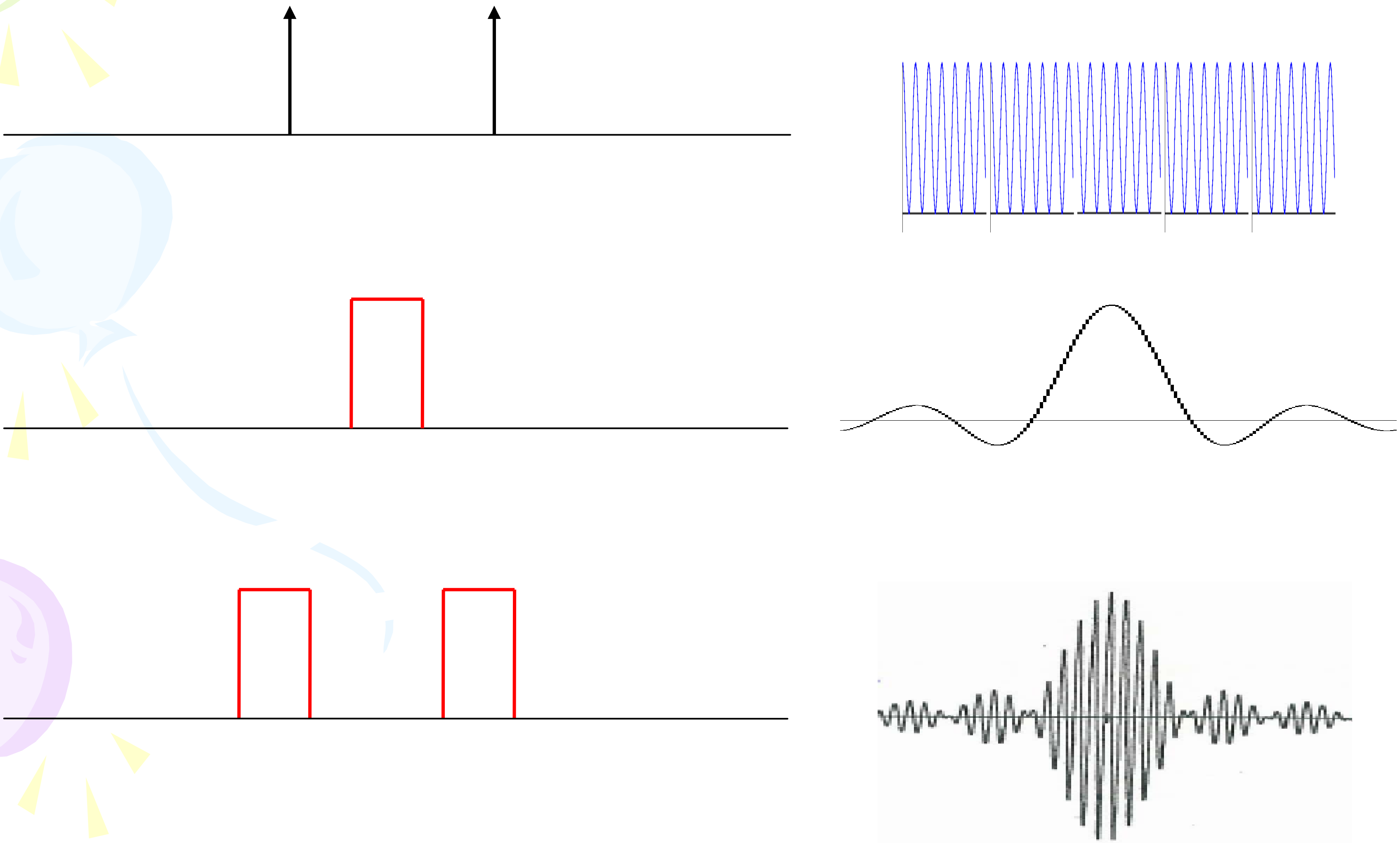
(...so by way of a review, here are voltage & power beams)

- Things to notice:
- Voltage (sinc) is wider than power ($sinc^2$) by 36%
- Zero points are the same
- Power sidelobes are all positive (of course) and lower
- Convolve beam with source

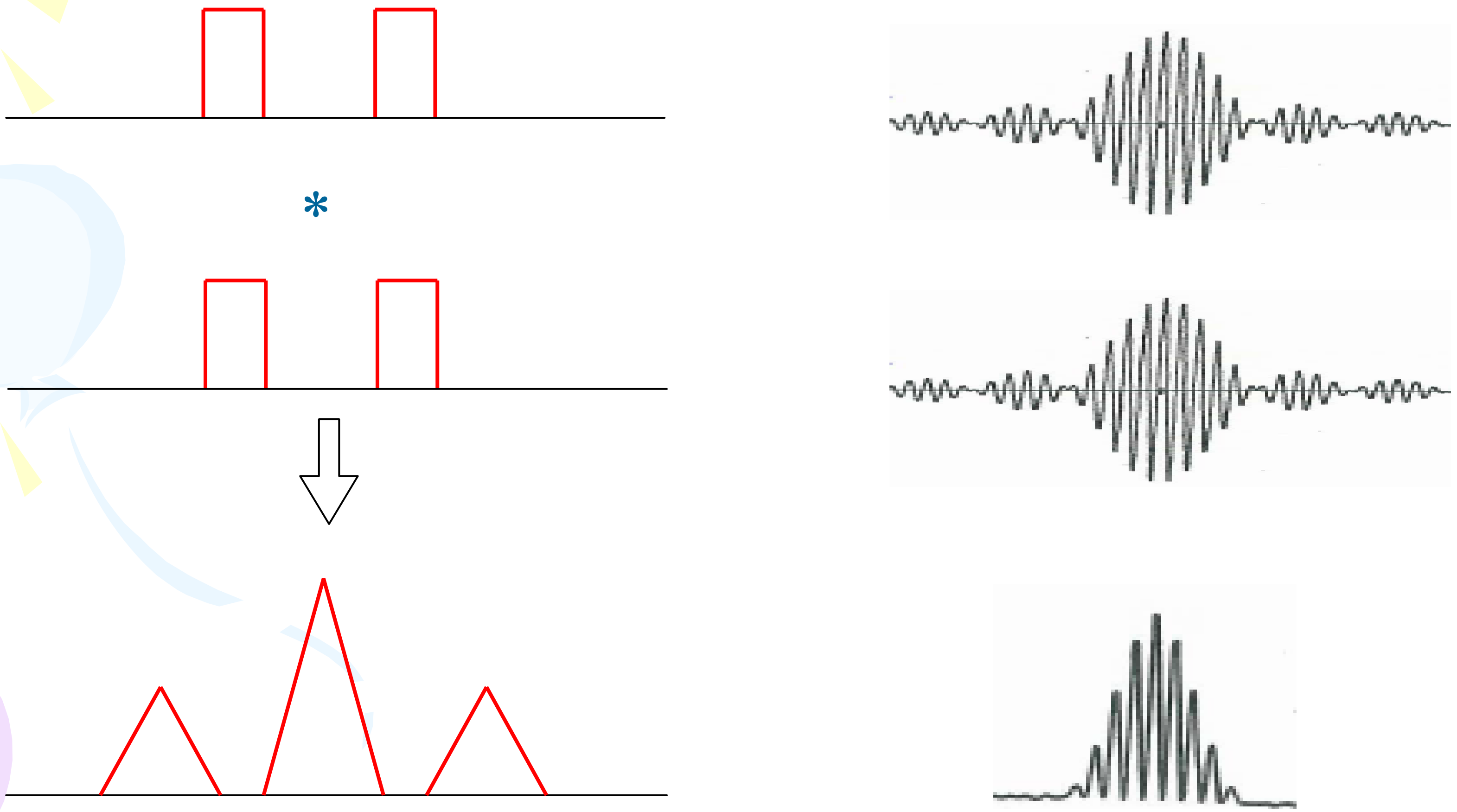




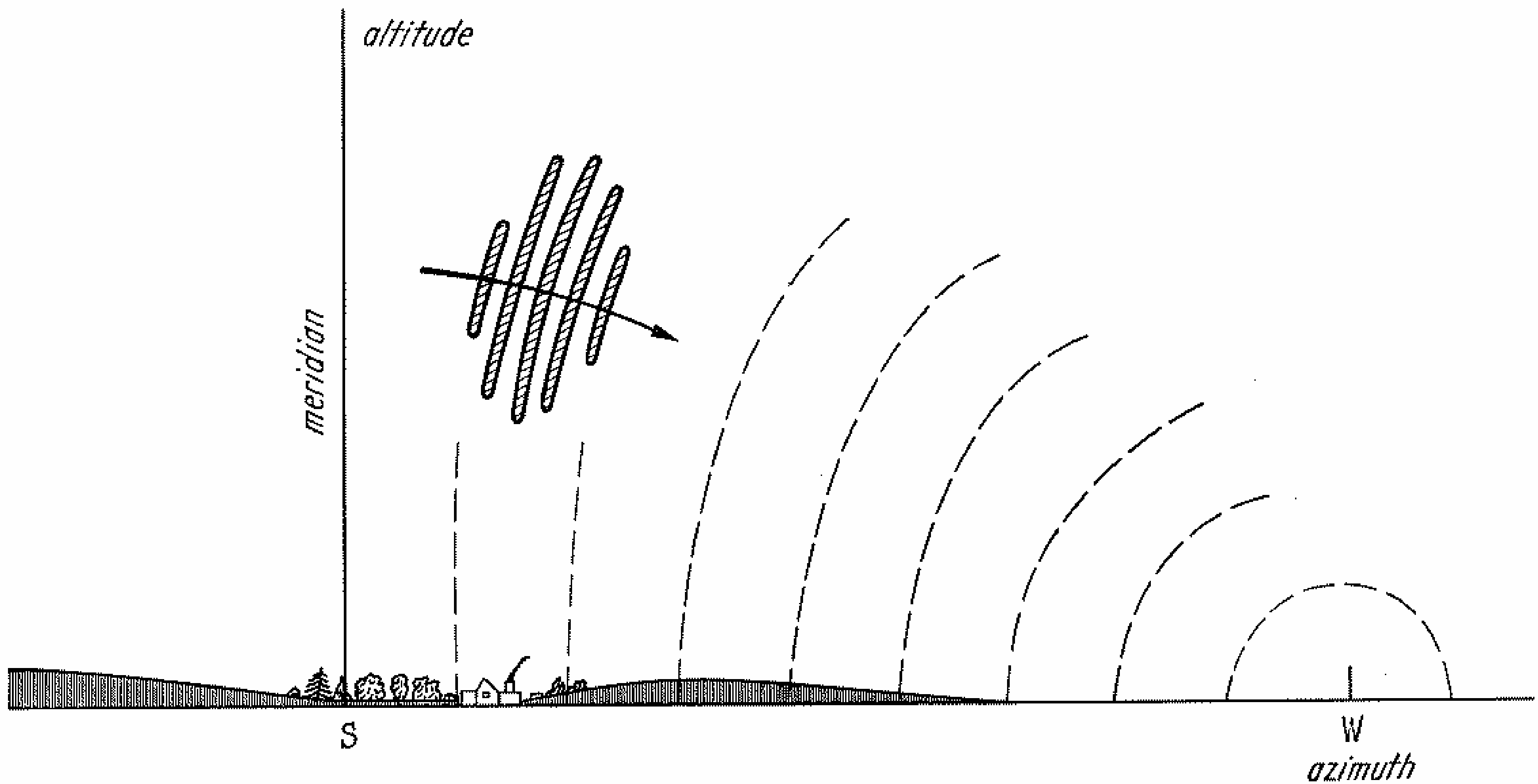
Back to interferometer: we use convolution here, too



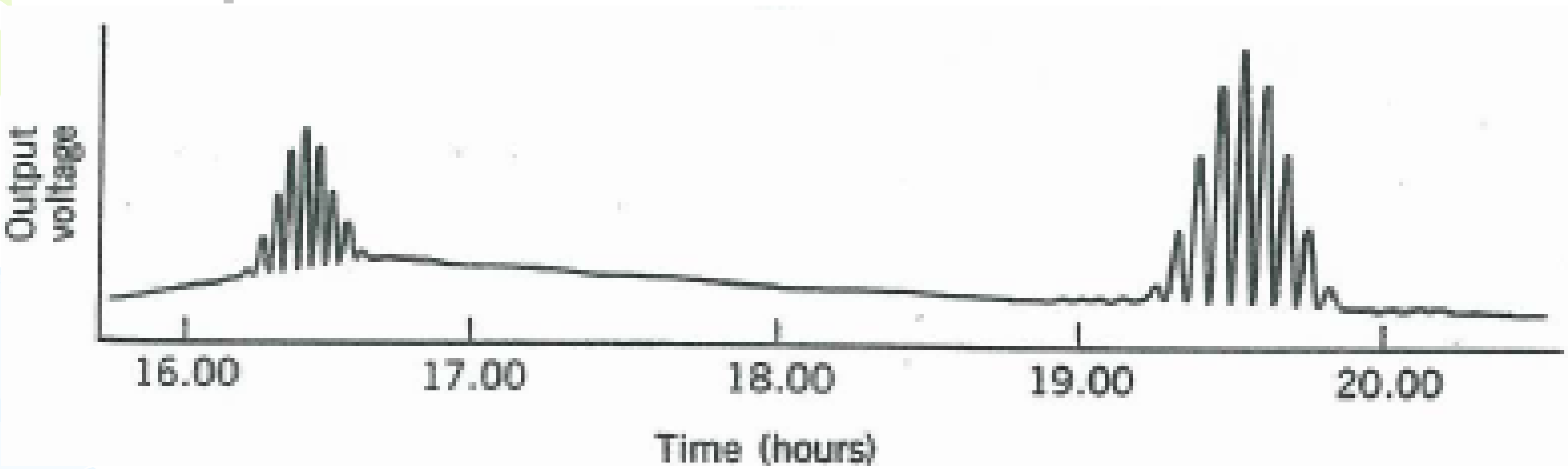
But we still need to derive the power beam pattern



Interferometer sets fringes on sky
Baseline determines fringe spacing
Element beam picks out region

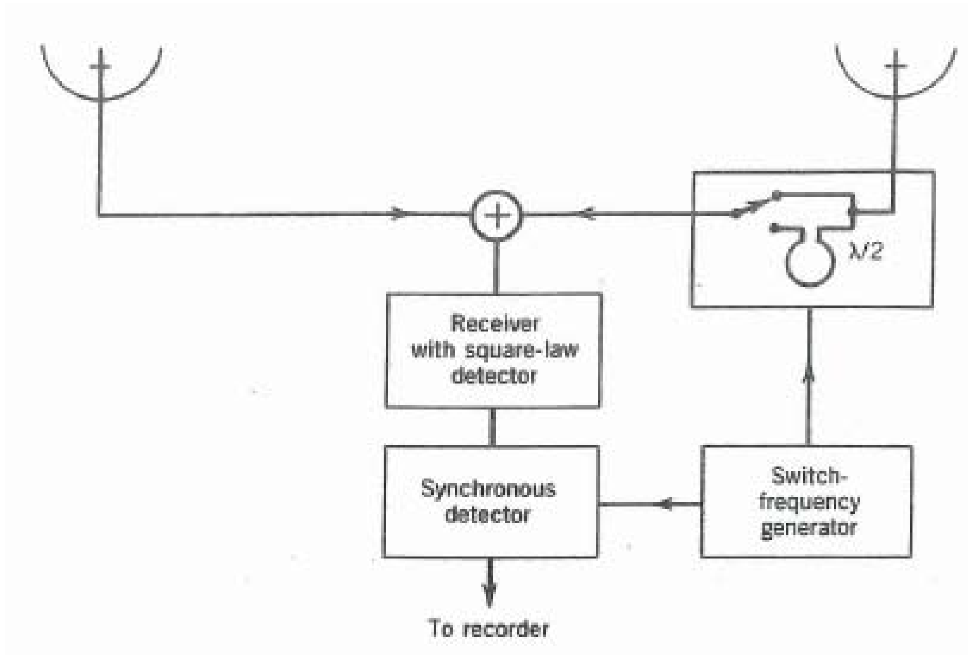


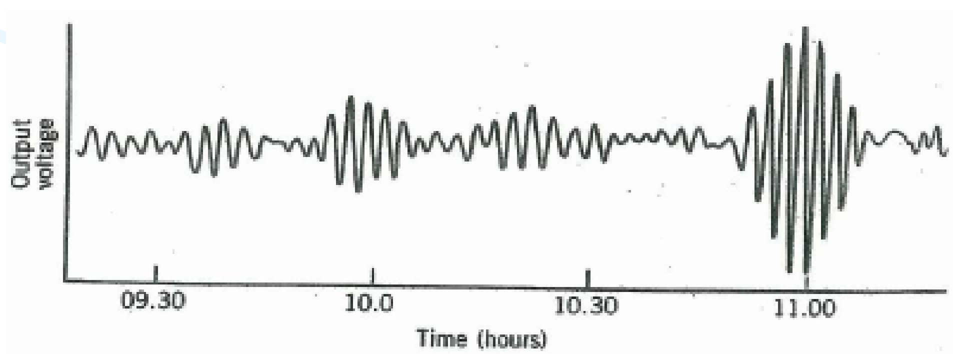
We are now able to explain simple interferometer result



- Observation is convolution of source by beam
- But notice the background level. This is because we have both the interferometer and single dish (central triangle) response
- This background, which may vary, is not always desirable, but it can be eliminated

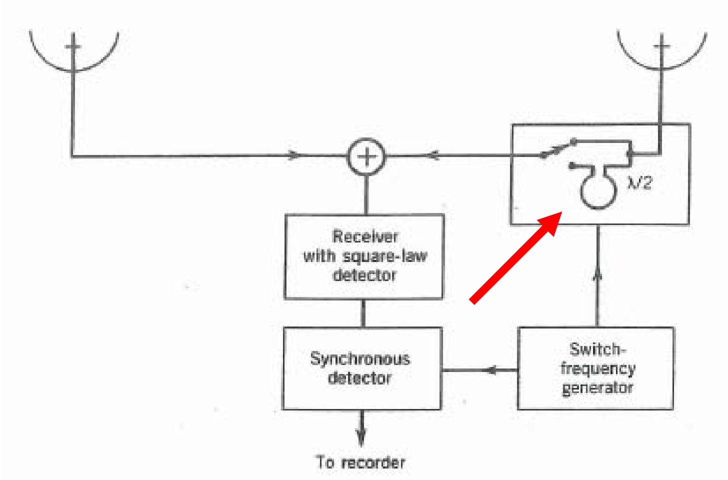
Martin Ryle's interferometer and its response



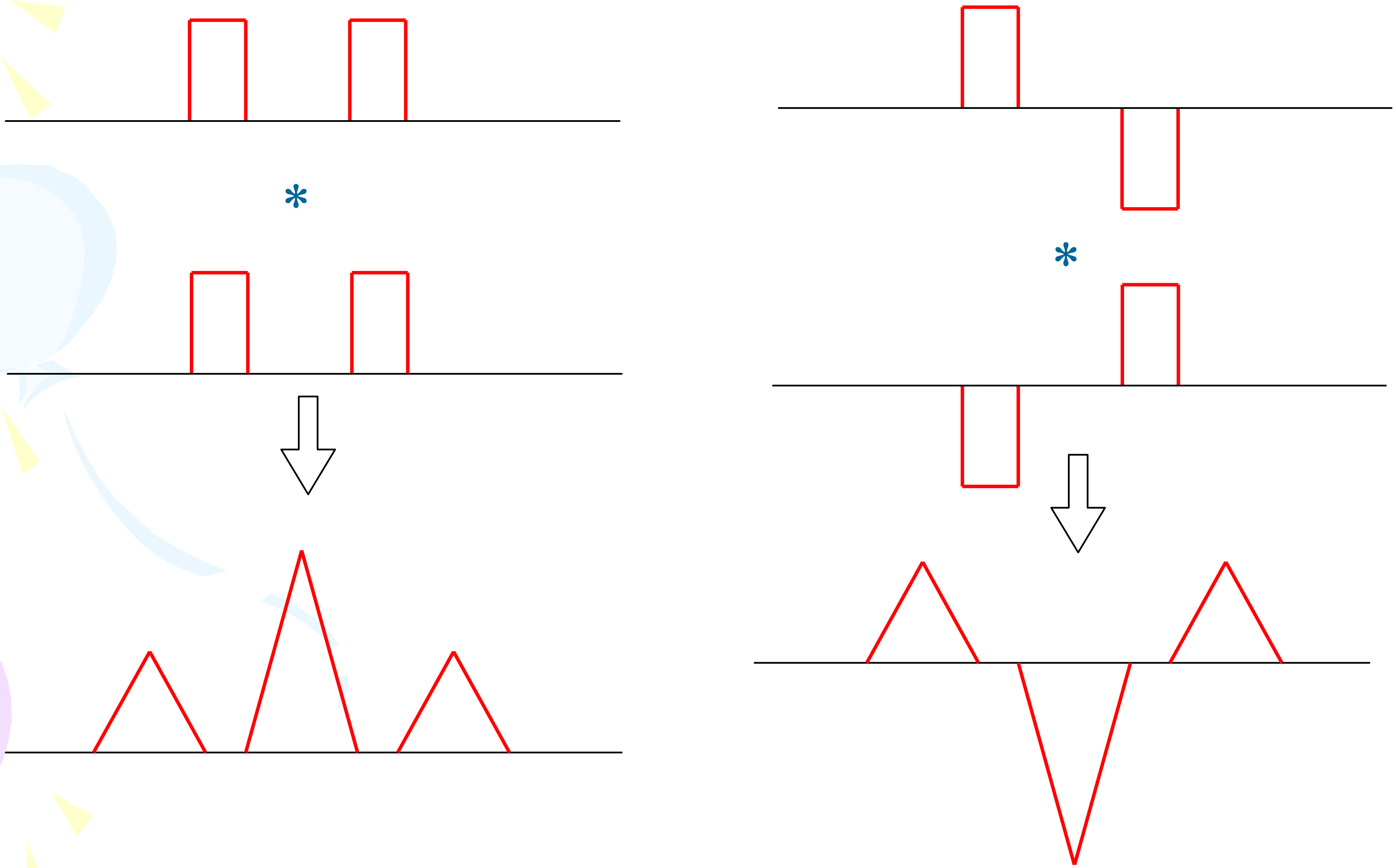


What is effect of introducing 180º (λ/2) phase switch?

- It is introduced into one arm of interferometer
- It has the effect of reversing the signal (multiply: $\times$ -1)
- Remember, to get the instrument's response, we have to convolve the aperture distributions
- Convolution means reversing one function

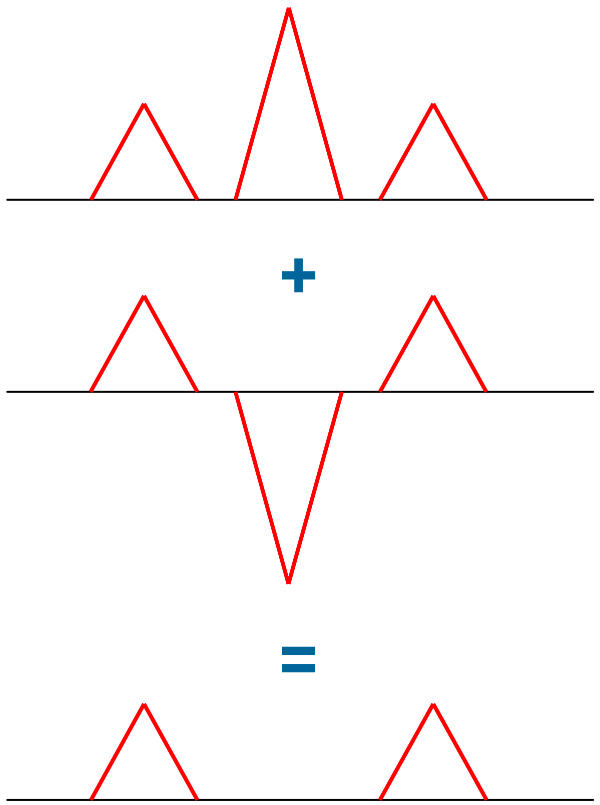


What Ryle did was clever – a bit like Dicke’s switch

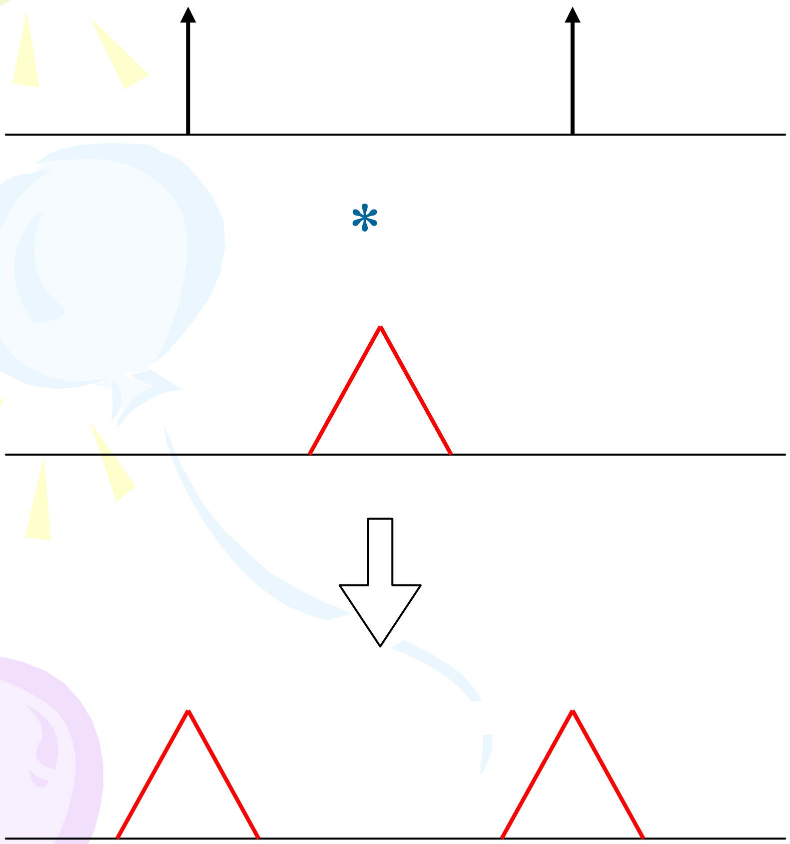


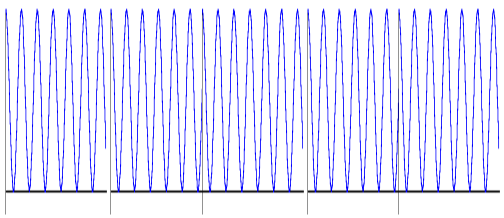
By combining the two, we can eliminate the center triangle

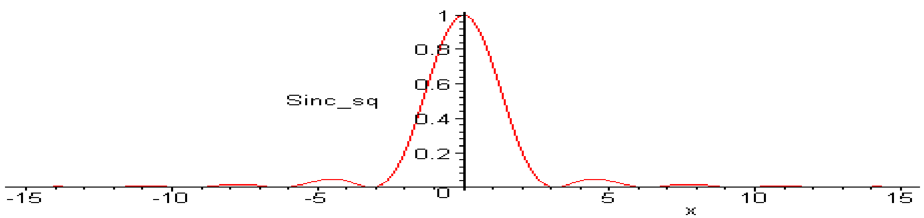
- The center triangle is just the single dish response
- The outer triangles give us the pure interferometer response
- We now need to know its beam

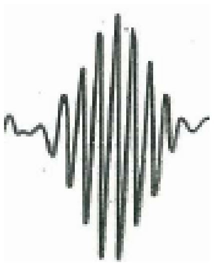


We can determine the beam in the usual way

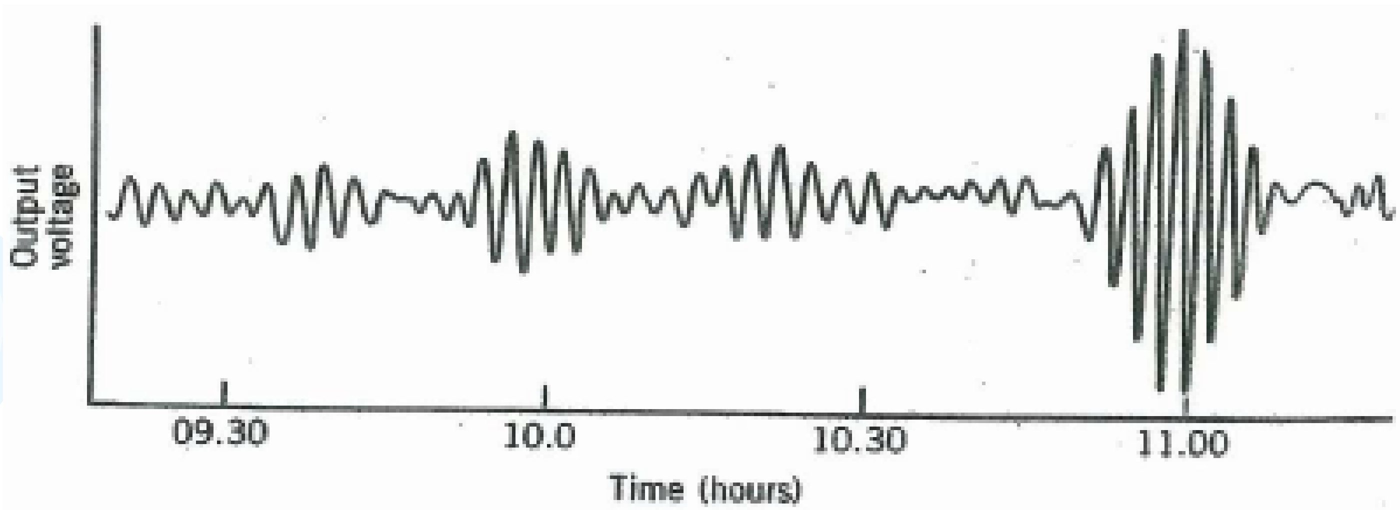








And this accounts for the response in an observation

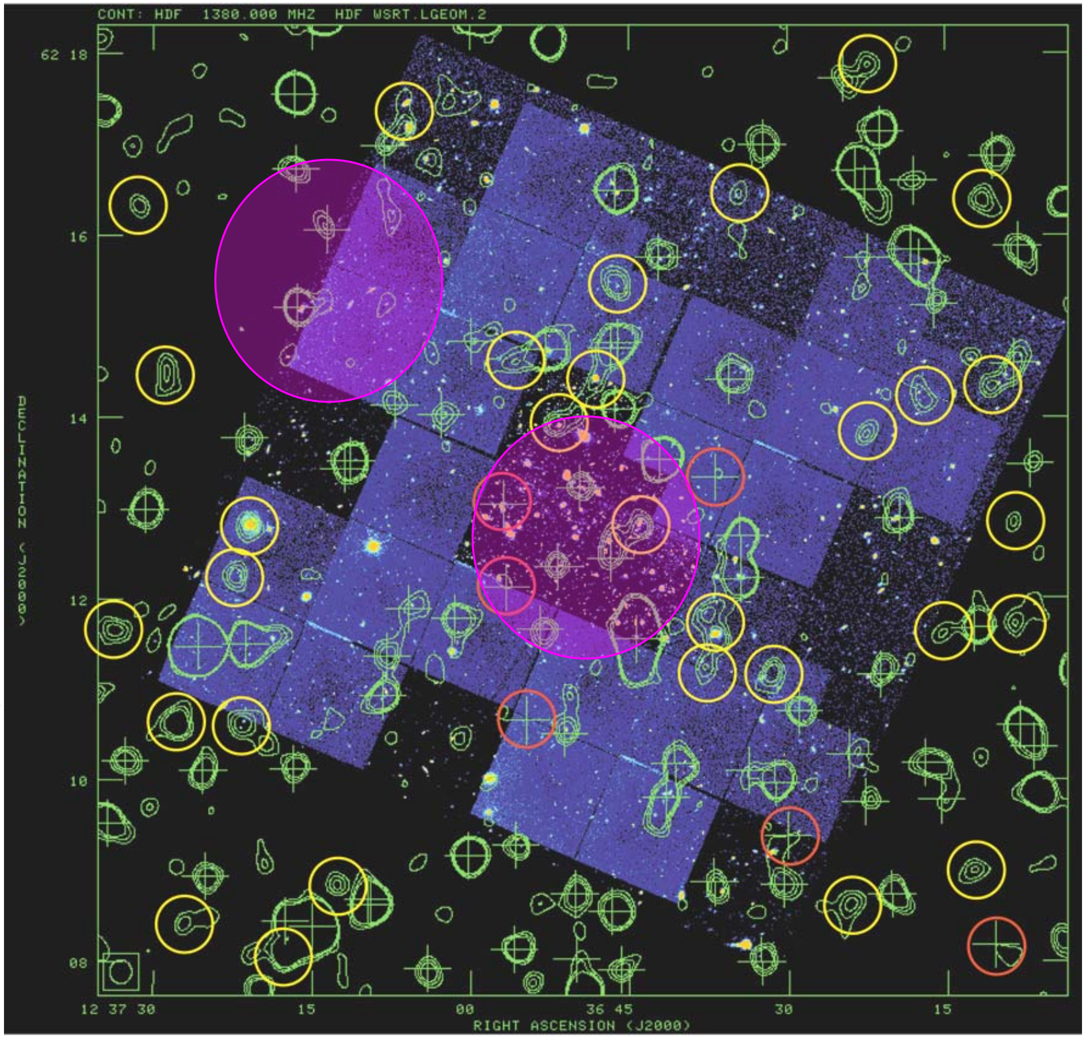


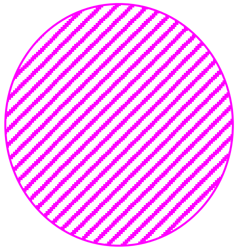
- Result is a flat zero level
- Each squiggly bit is a source convolved by the beam...

...or a sidelobe response (also part of the beam!)

- In fact, this looks near confusion level

Let’s for a moment consider confusion: Hubble Deep Field (HDF), observed by WSRT & VLA



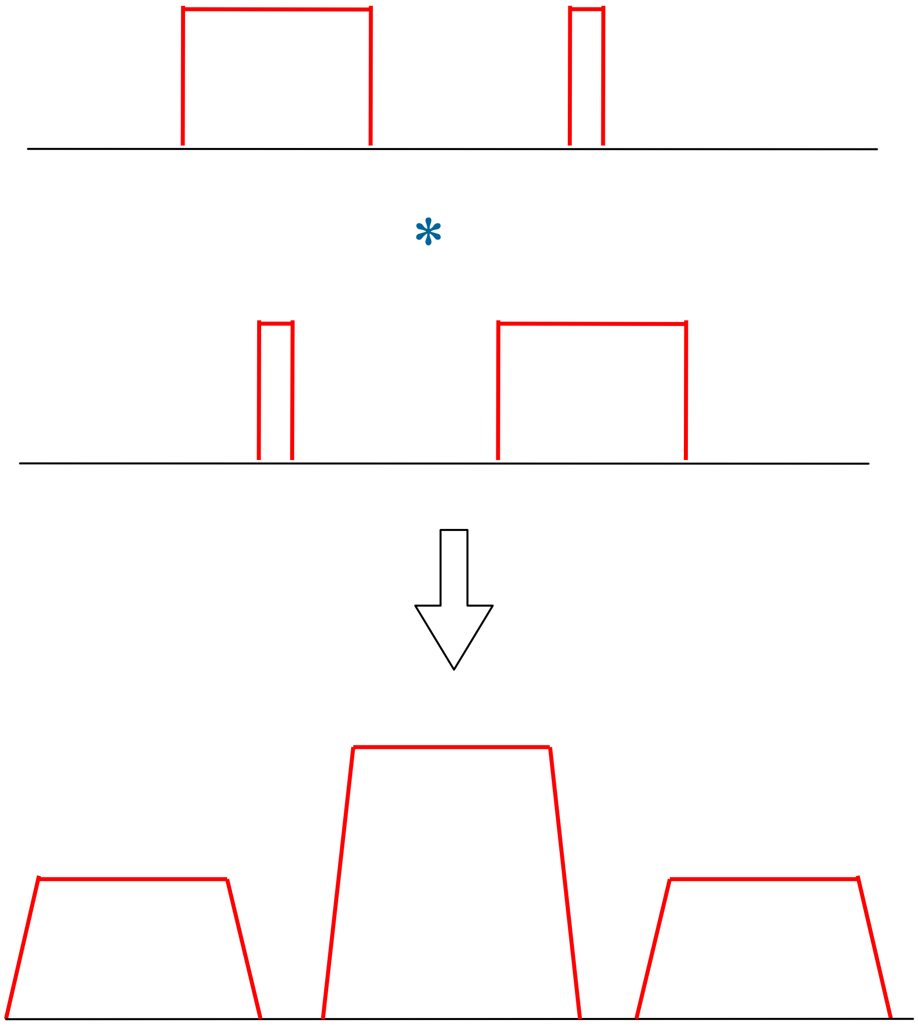


To overcome confusion requires a smaller beam

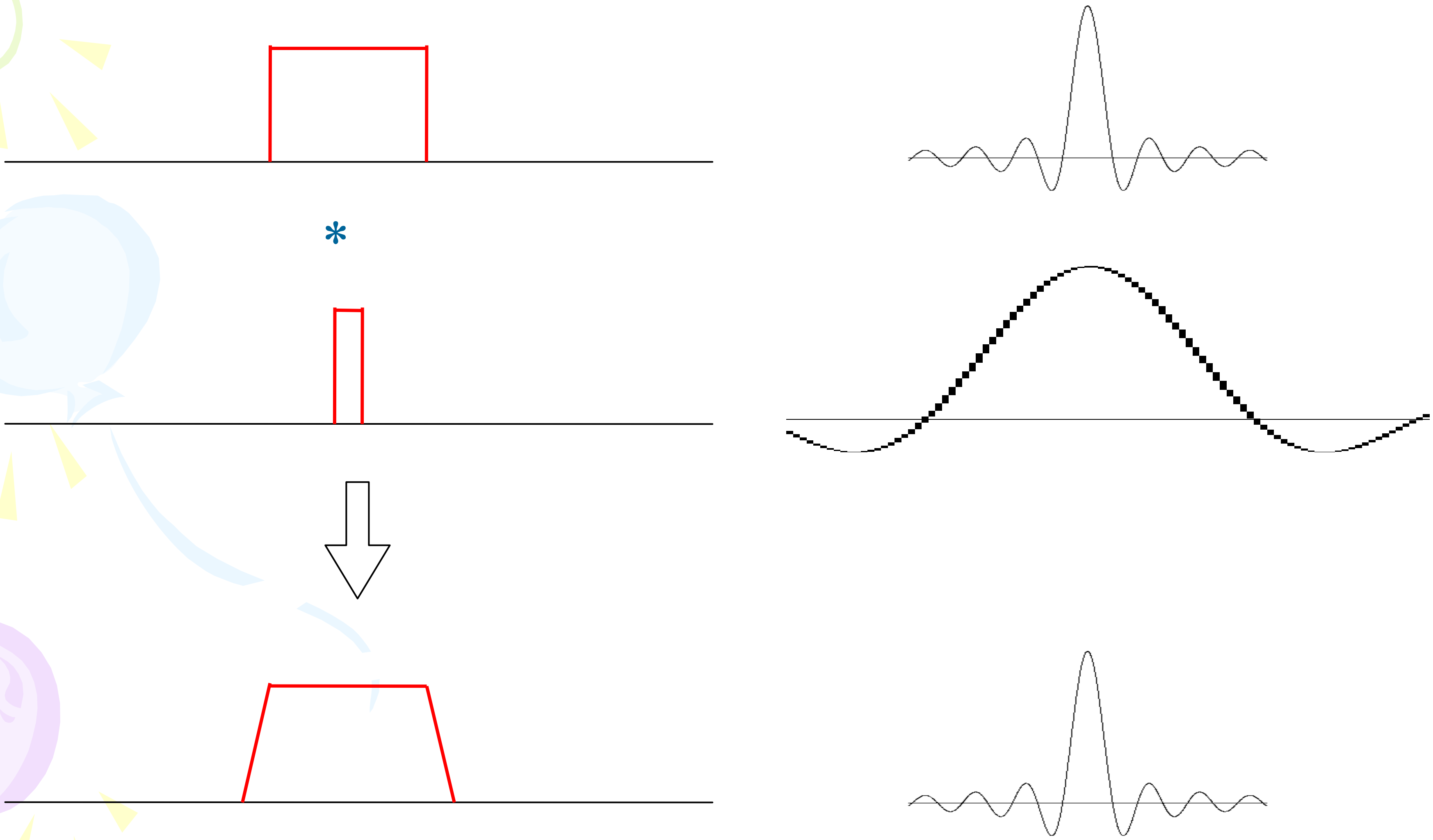
- Common definition of "confusion level" is 1 source/20 beams
- Source density increases as we go to weaker sources
- To estimate, need source number vs. strength curves (from observations)
- A more sensitive telescope requires greater angular resolution

What happens if the two elements are not the same?

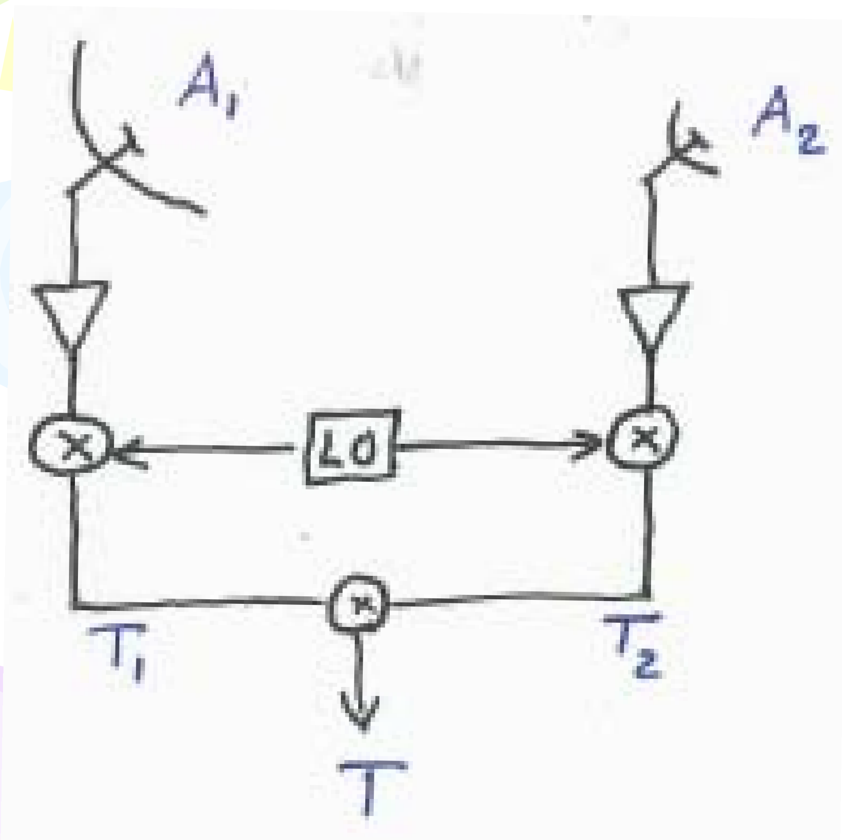
- We can generate, in the usual way, the aperture response
- For the interfero-meter, the trapezoids, right and left, determine the beam



For very unequal elements, get nearly voltage of large one



Interferometer – unequal elements & sensitivity

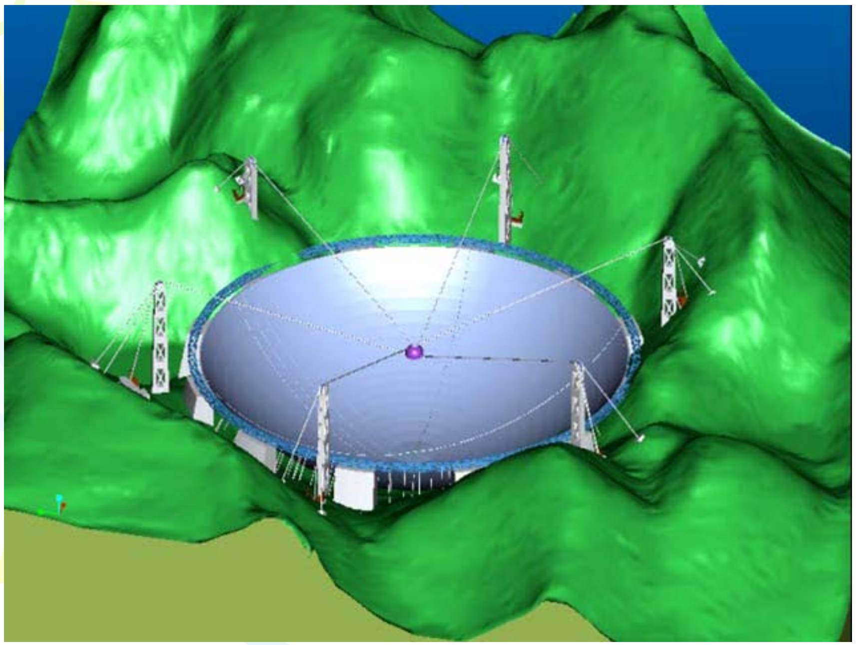


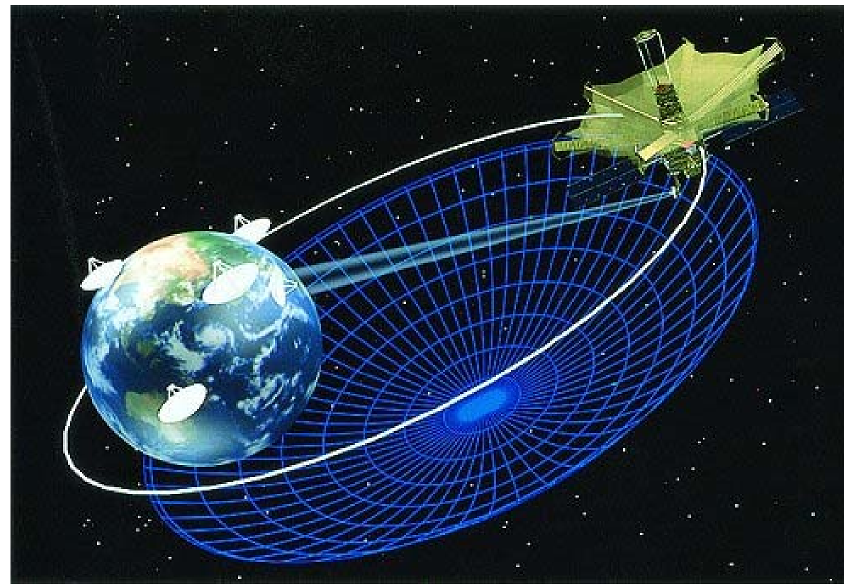
Where A_e and T_s of the elements are unequal, the interferometer values can be simply calculated:

$$A_{int} \approx (A_1 \times A_2)^{1/2}$$

$$T_{int} \approx (T_1 \times T_2)^{1/2}$$

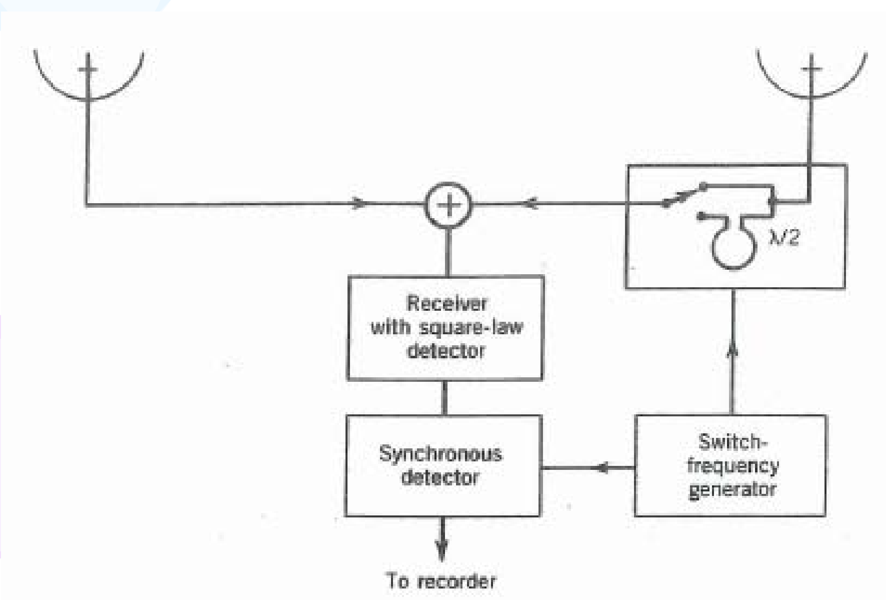
Can have particular advantage in, for example, space VLBI

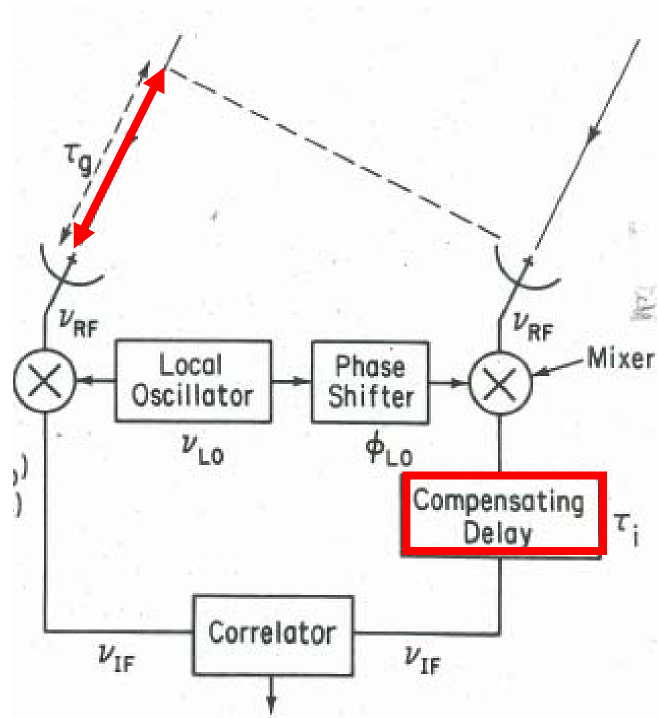




- Combining FAST (300 m) with VSOP (10 m) gives equivalent of: $(300\text{ m} \times 10\text{ m})^{1/2} = 55\text{ m}$ dish
- Probably cheaper than putting 55 m dish in space

Early interferometers like Ryle's only observed sources at transit. Observing all over the sky requires delay correction to avoid decorrelation.





Effect of delay on interferometer

$$S \cdot A^2 \xrightarrow{F.T.} r$$

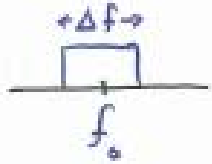
source, antenna, response

Delay (τ): [NB $\tau \sim \frac{1}{f}$]

$$r(\tau) = \iint S(l,f)\, A^2(l,f)\, F(f)\, e^{-2\pi i f \tau}\, dl\, df$$

filter

$F(f)$:



$$F = \begin{cases} 1, & f_0 \pm \frac{\Delta f}{2} \\ 0, & f < f_0 - \frac{\Delta f}{2},\ f > f_0 + \frac{\Delta f}{2} \end{cases}$$

$$b(\tau) = \int F e^{-2\pi i f \tau}\, df \;; \quad F \xrightarrow{F.T.} b$$

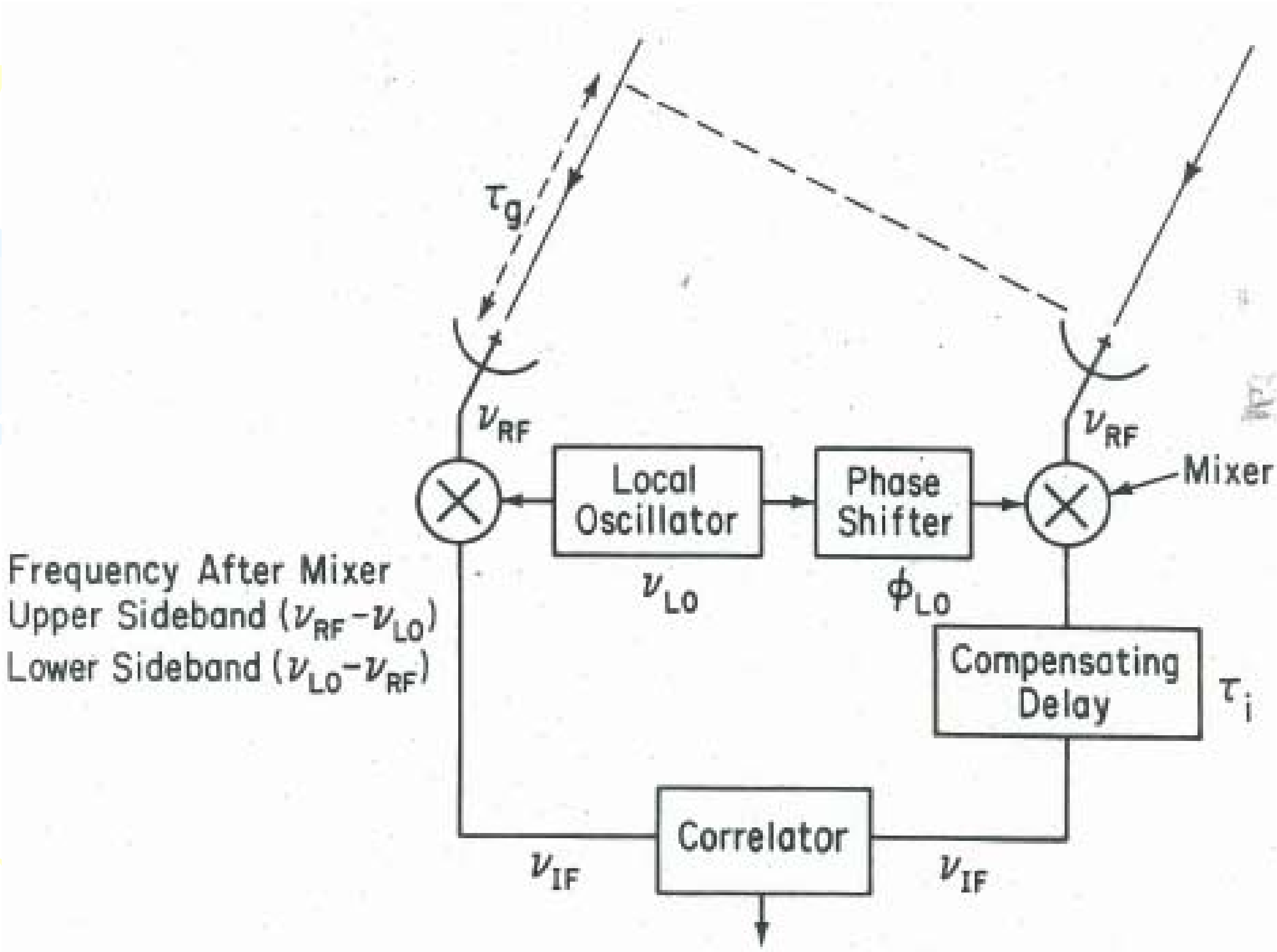
$$b(\Delta f \tau) = \frac{\sin(\pi \Delta f \tau)}{\pi \Delta f \tau} = \mathrm{sinc}(\pi \Delta f \tau)$$

NB: $\pi \Delta f \tau \ll 1$ (if not, decorrelation)

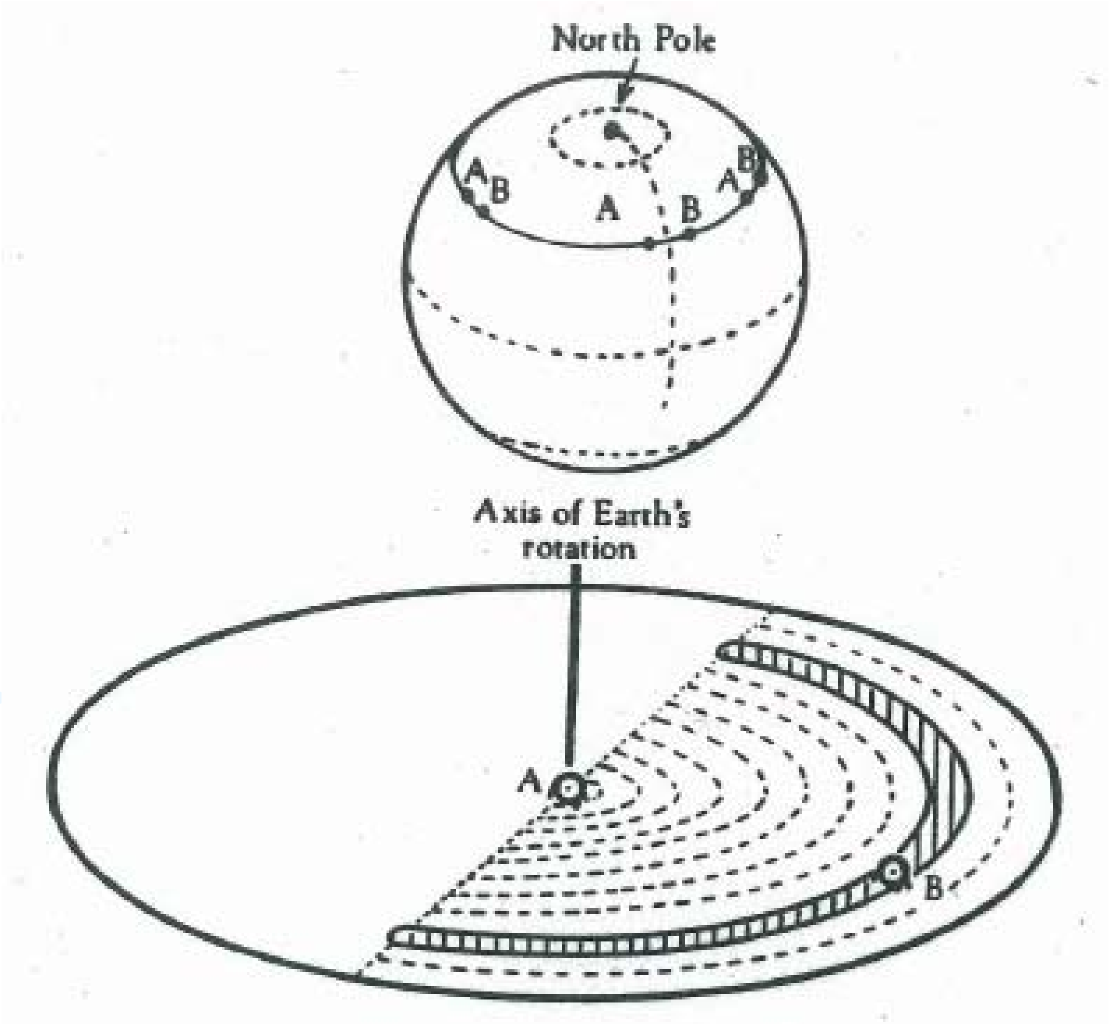
e.g. $\Delta f = 1$ MHz, $\tau \ll 0.3\,\mu$sec

($c\ 0.3\,\mu s \sim 90$ m)

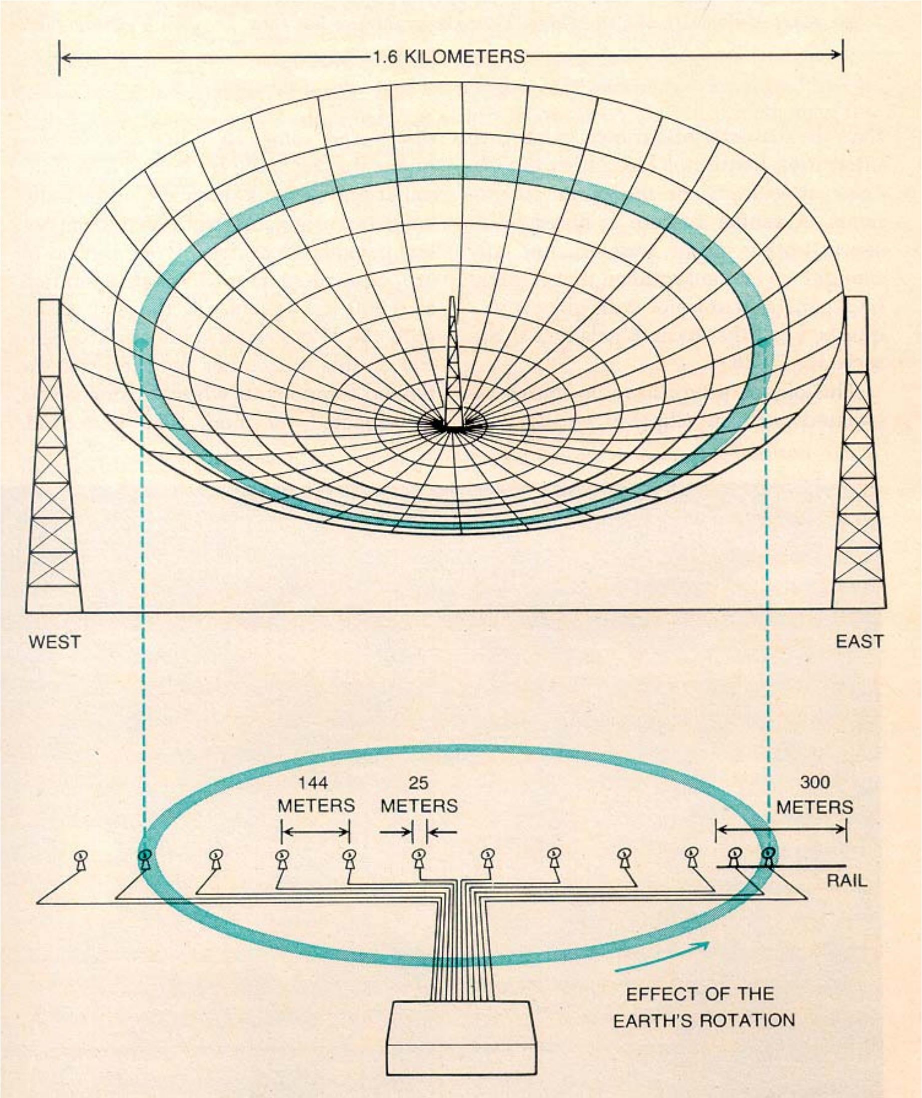
A modern interferometer with delay compensation



Ryle also introduced the idea of earth rotation synthesis



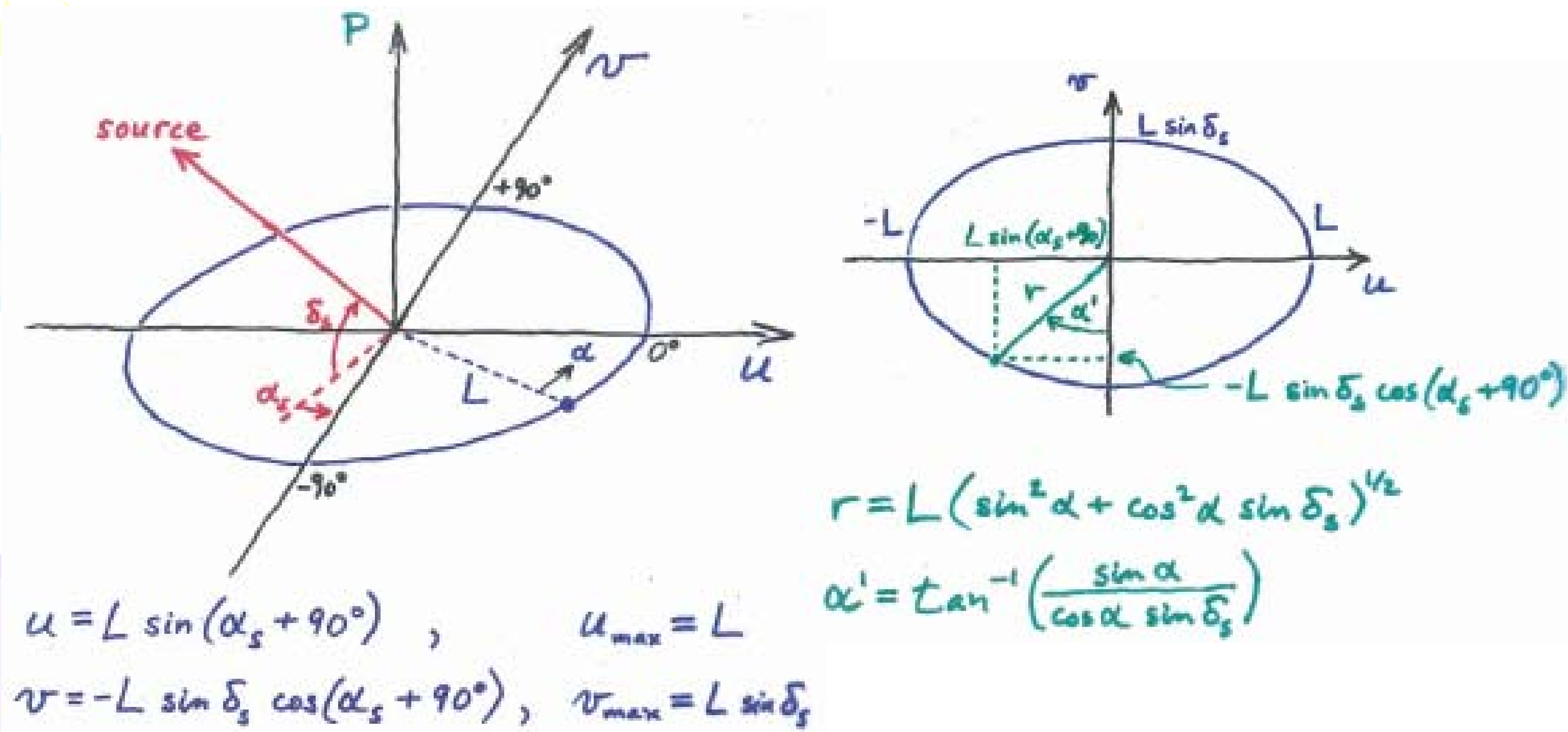
Also called super synthesis: synthesize large antenna



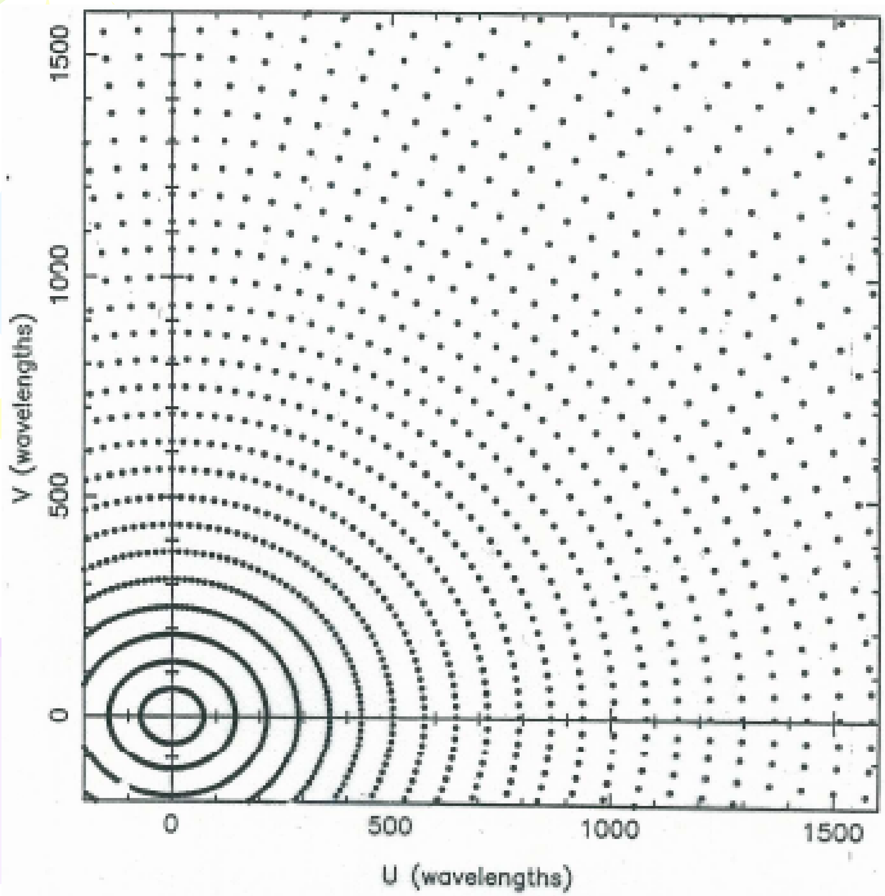
Use several small dishes. Move dishes and re-observe.

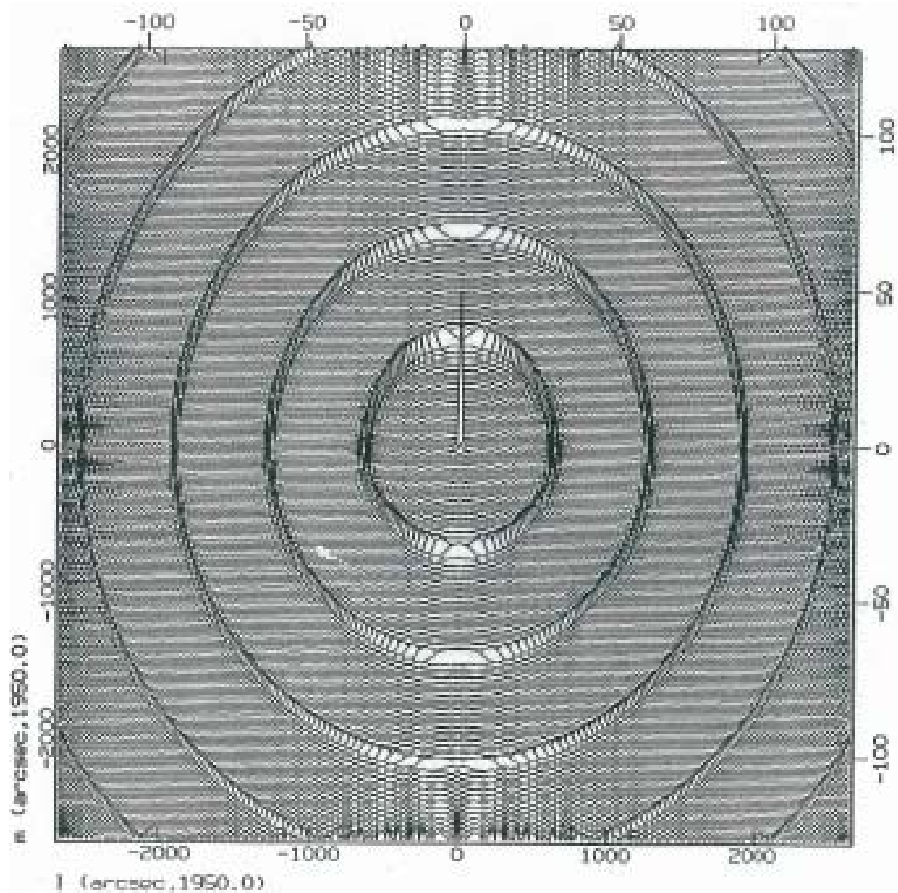
WSRT: more dishes, faster. Principle: sources not vary.

Geometry of east-west array and the u,v-plane

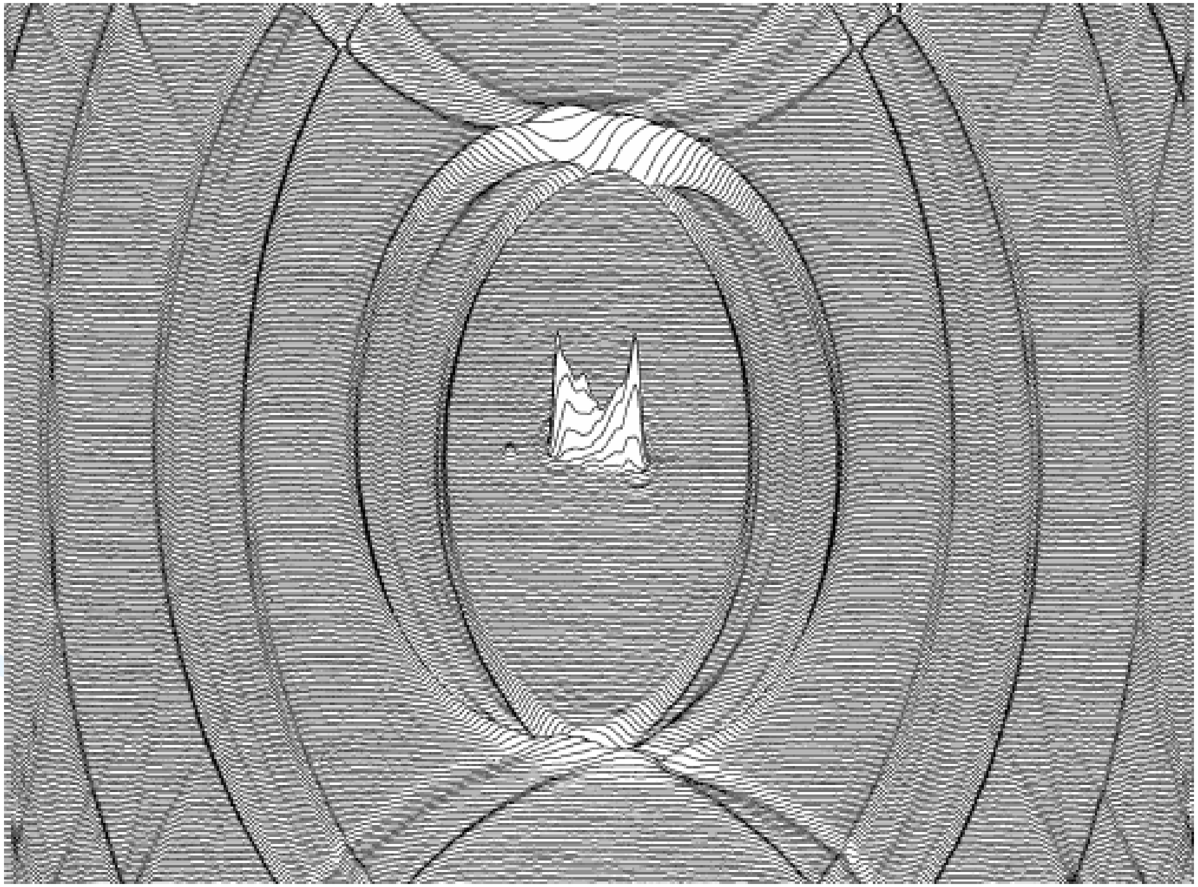


Example of WSRT u,v-ellipses, and the antenna pattern

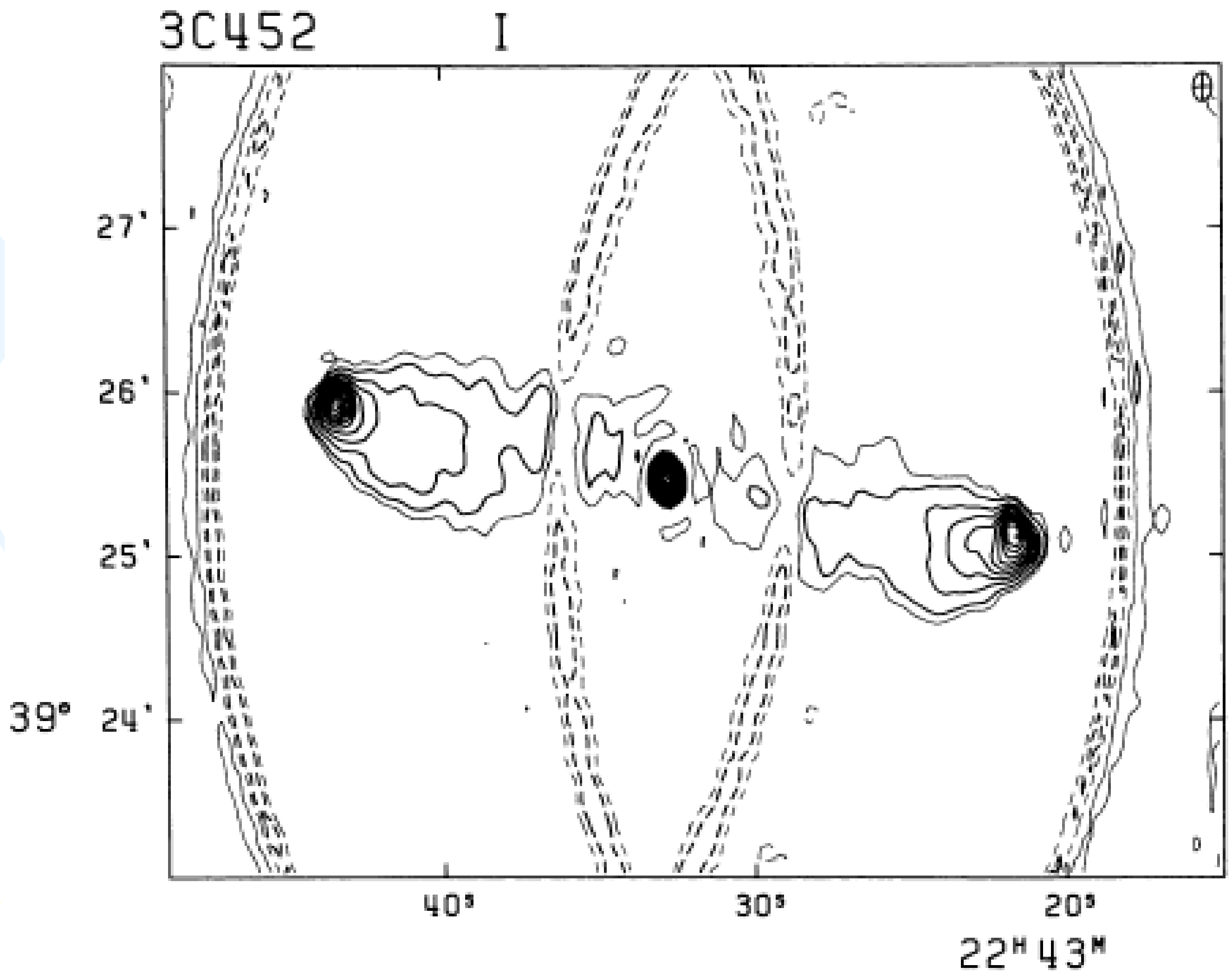




The source is convolved with the whole beam



Source size > grating lobe size - an example of self confusion



An important property: Hermitian symmetry

The sky brightness is real

Its Fourier Transform is ∴ Hermetian symmetric

$I(\theta) \xrightarrow{FT} i(x)$; $I(\theta) \sim$ real

$$i(x) = i_R(x) + i_I(x)$$

$$i(-x) = i_R(x) - i_I(x)$$

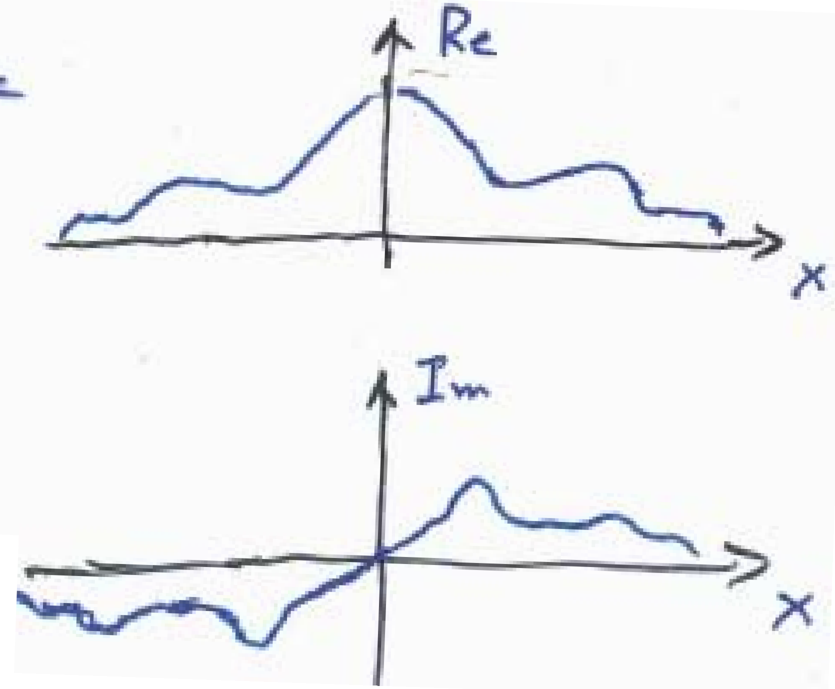
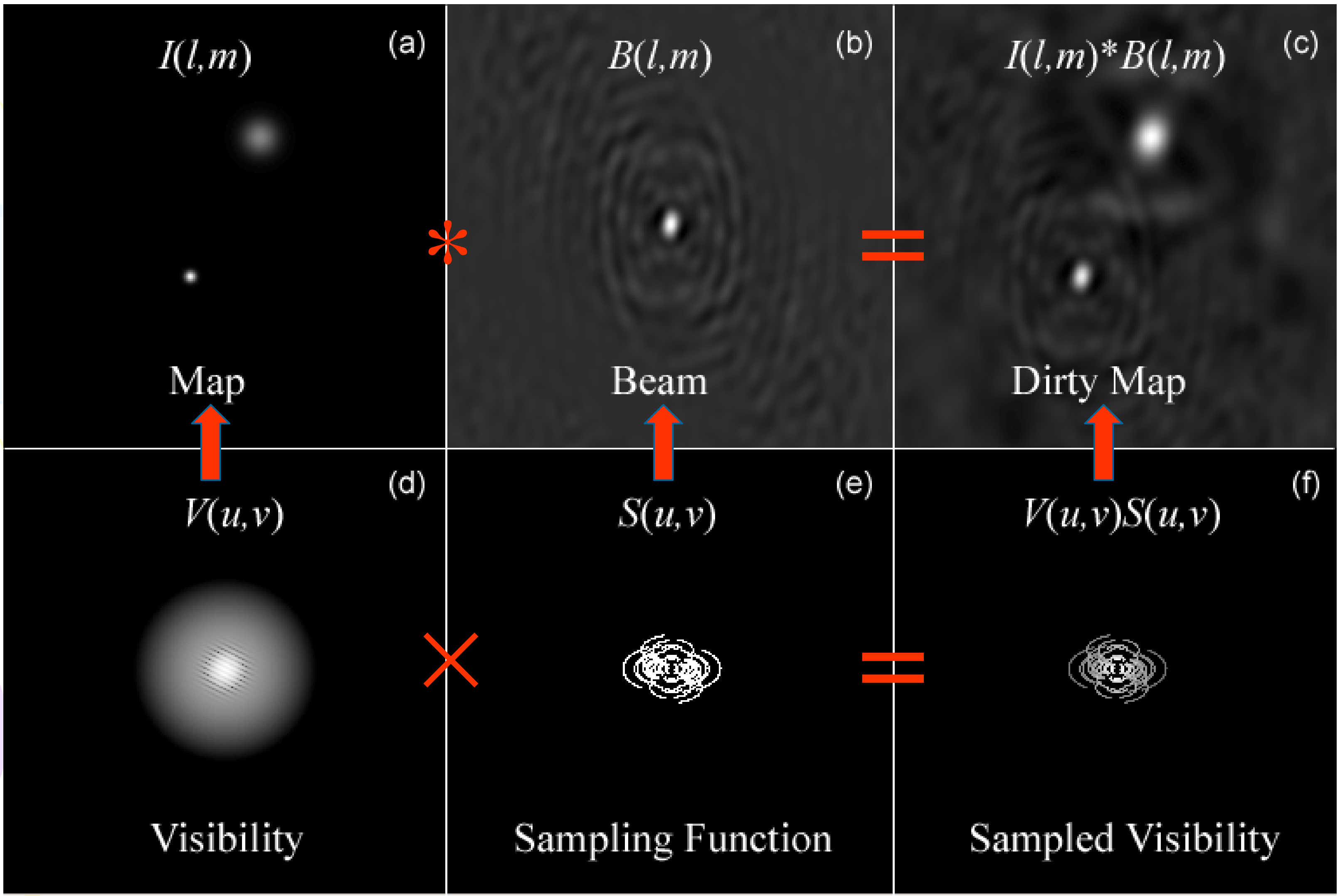
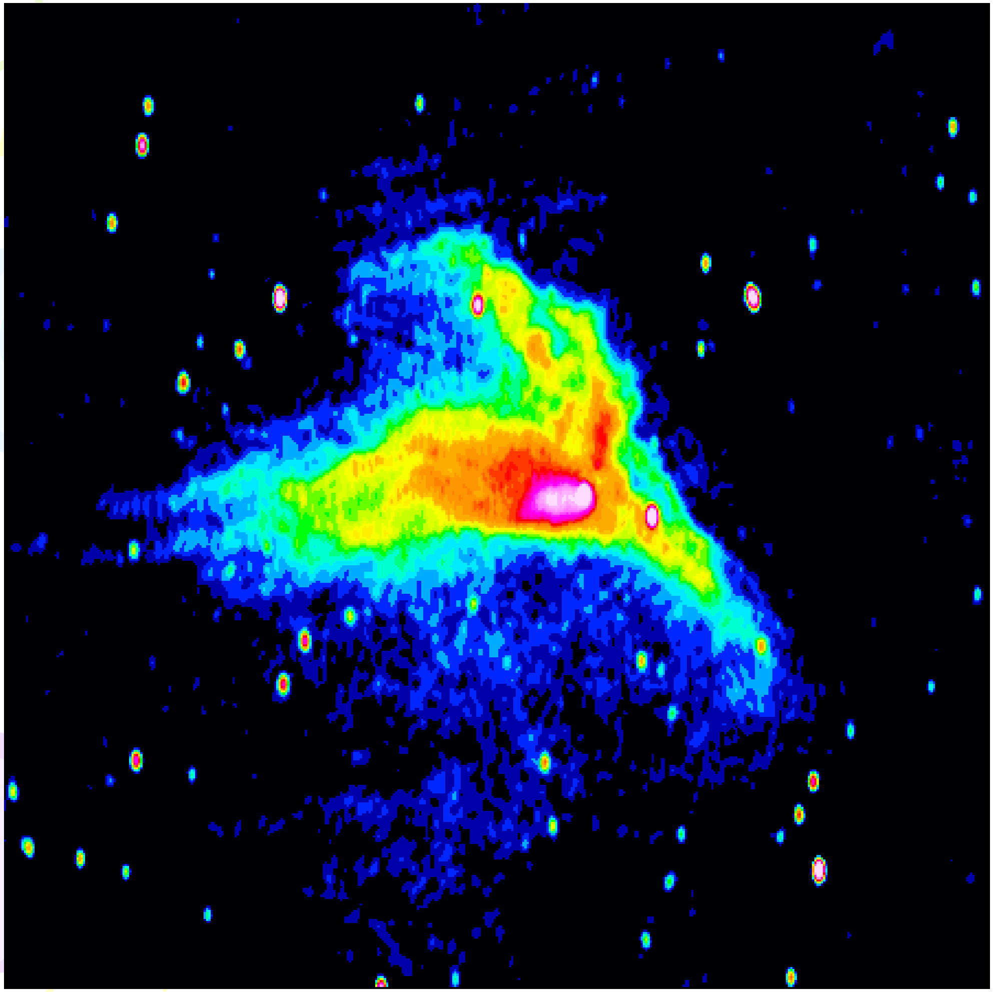
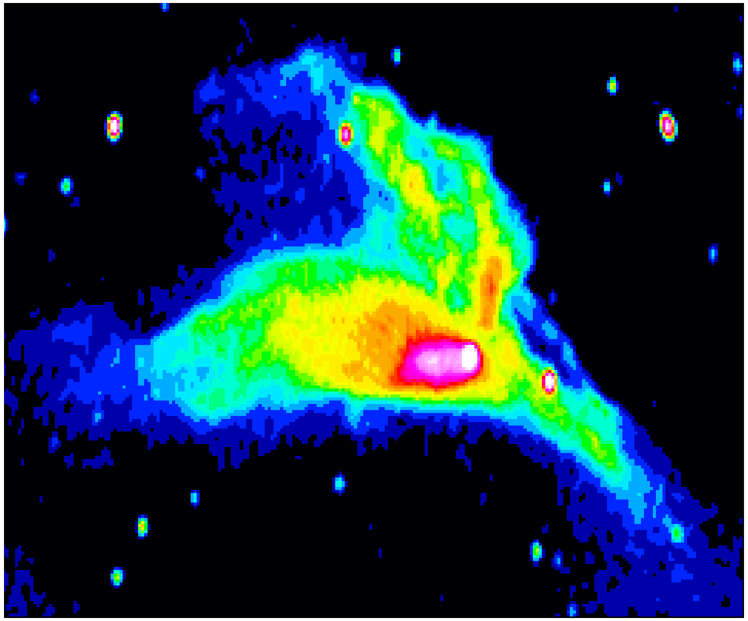


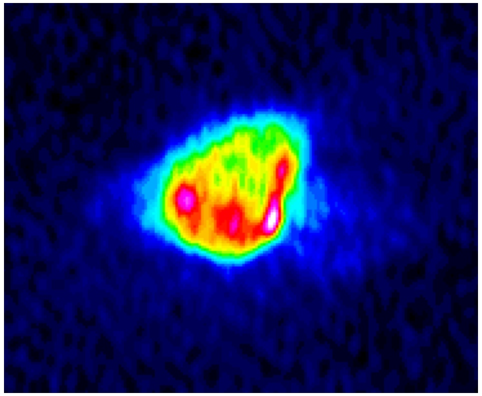
Illustration of the FT and image convolution relation



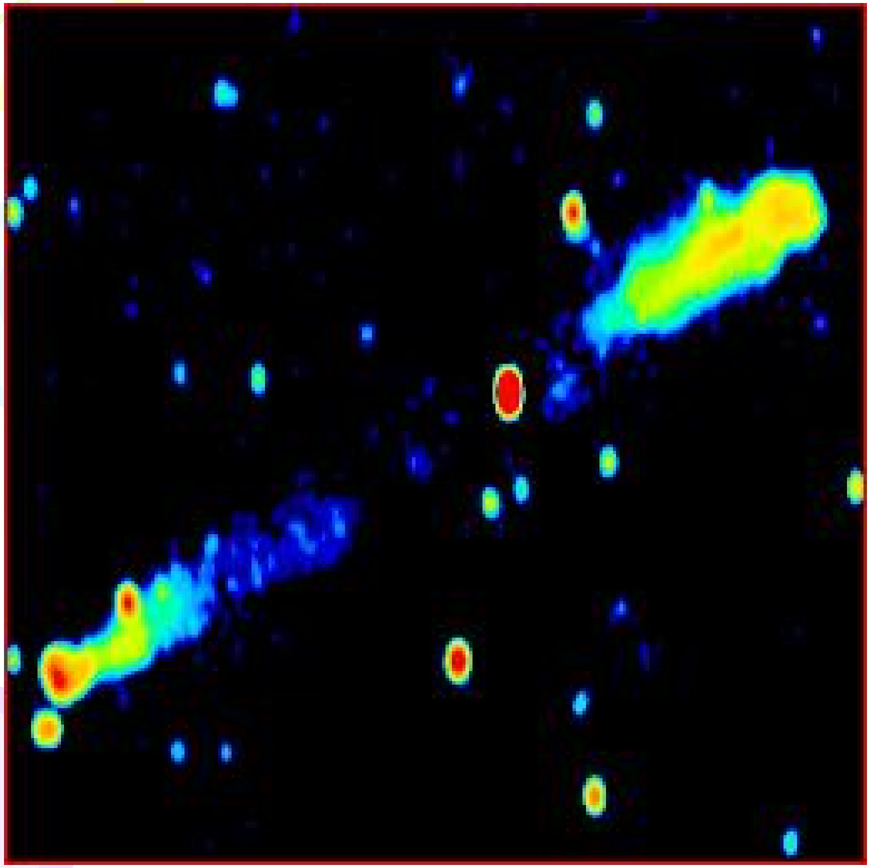
Aperture synthesis WSRT observations of CTB80 at 92 cm, 49 cm & 3.6 cm

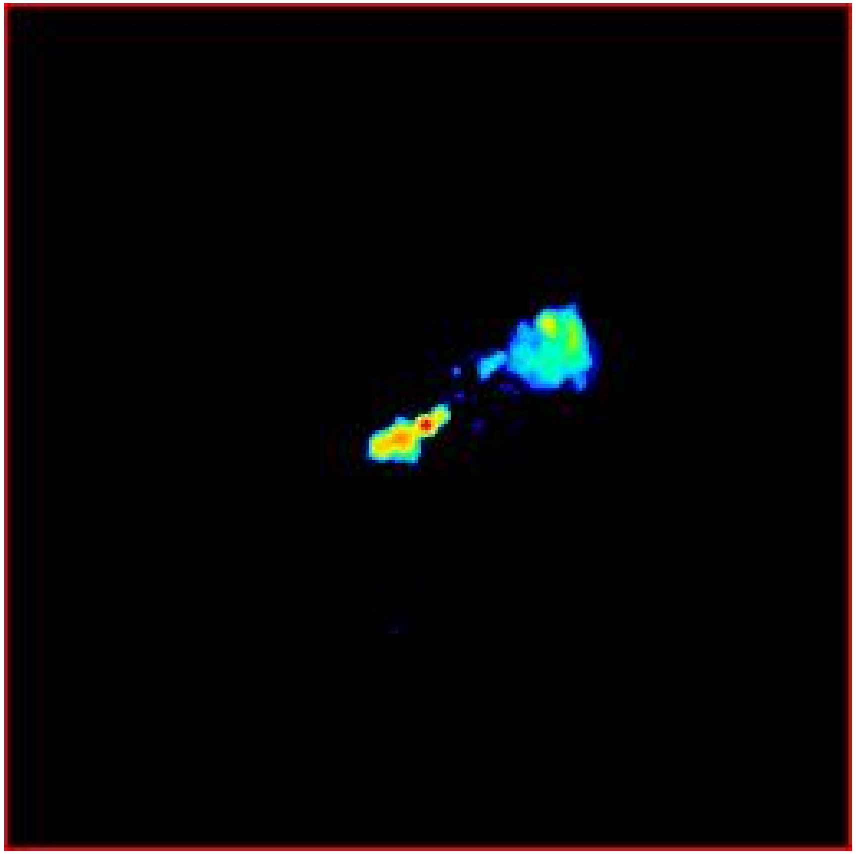






WSRT and VLBI observation of giant radio galaxy 3C236



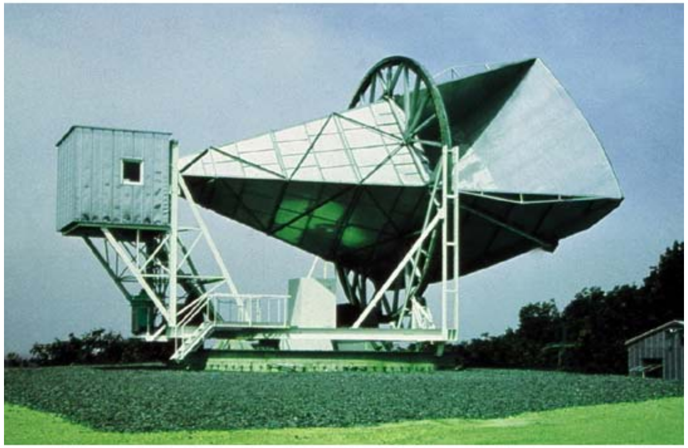


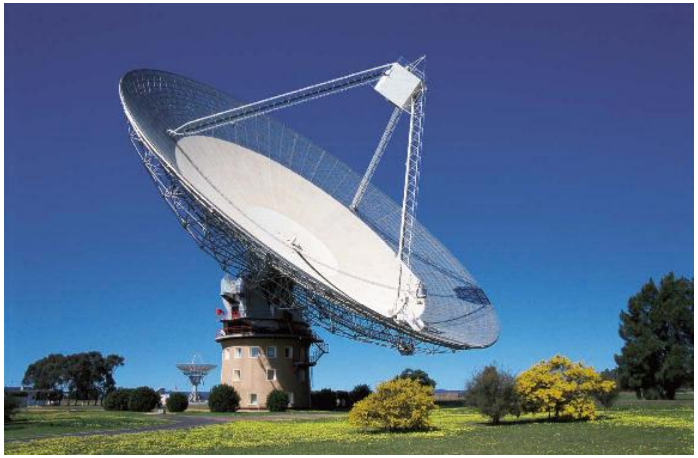
Data analysis: what do we need to calibrate an observation?

- Flux density: strength of sources
- Do we want absolute flux density determinations?
- Position: how to locate sources on sky
- Special calibration required for spectroscopy (frequency and line strength) and polarization

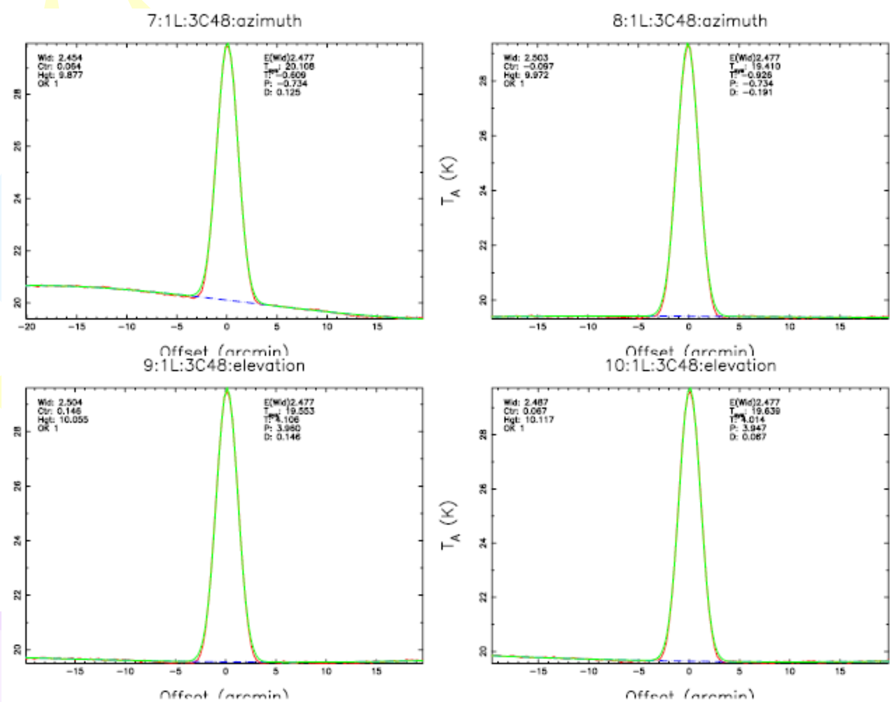
Position calibration largely related to antenna geometry

- Need to first determine direction of optical axis
- Survey of geometry may be required
- Observe sources of well-known location
- Need to correct for atmospheric refraction
- Right Ascension is determined by clock





Usually, we use standard calibrators to fix location, flux

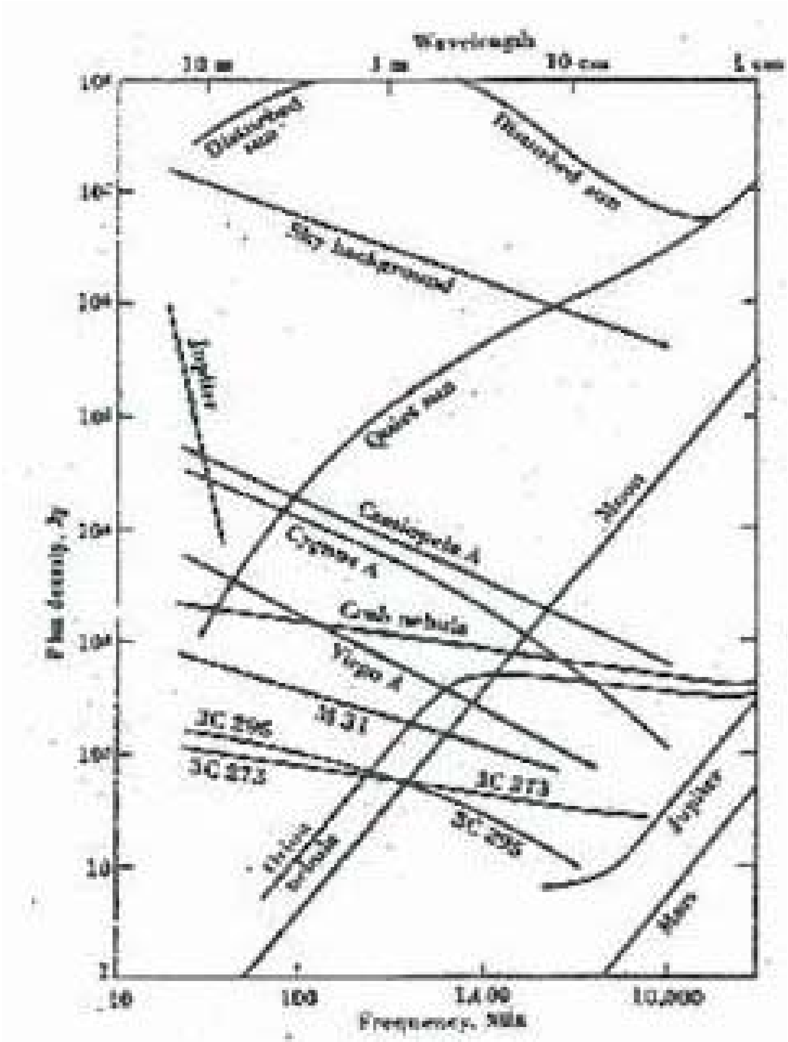


- Do scans in RA and Dec through source, get best fit
- Repeat for different values of RA & Dec
- List of typical calibrators for 6 cm:

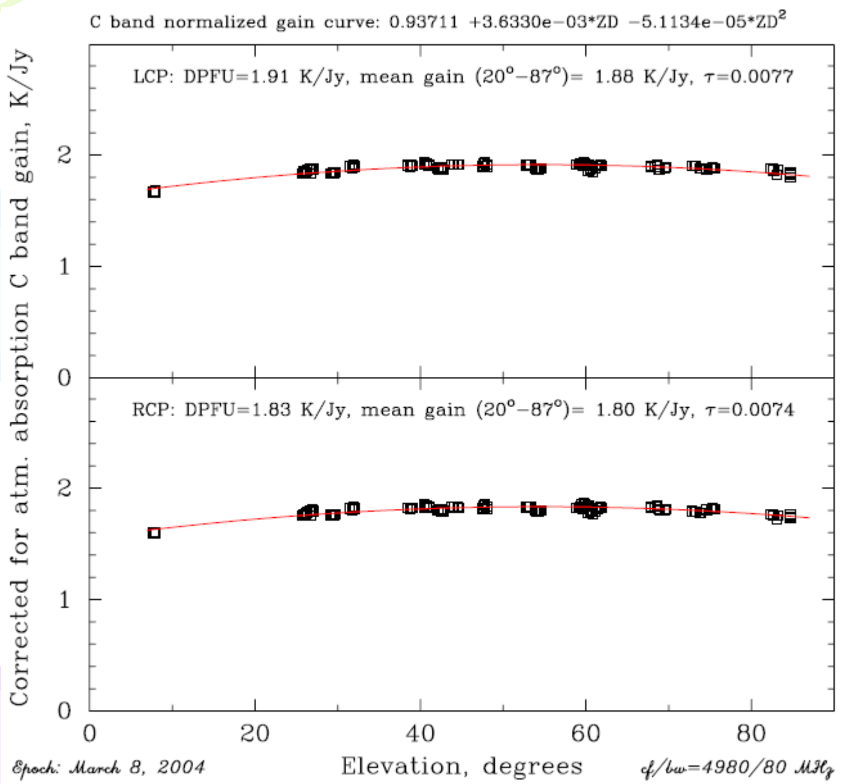
Calibrator	*Flux density (Jy)*
3C48	5.26
3C123	15.54
3C147	7.57
3C295	6.39
DR21	18.86
NGC7027	5.58

Most calibration depends heavily on standard sources

- Ideal standard source: strong, compact, steady
- Strong so it can be measured quickly
- Compact so antenna doesn't resolve it
- Distant (so motion is not a problem)
- Cas A & Cyg A often used for flux density

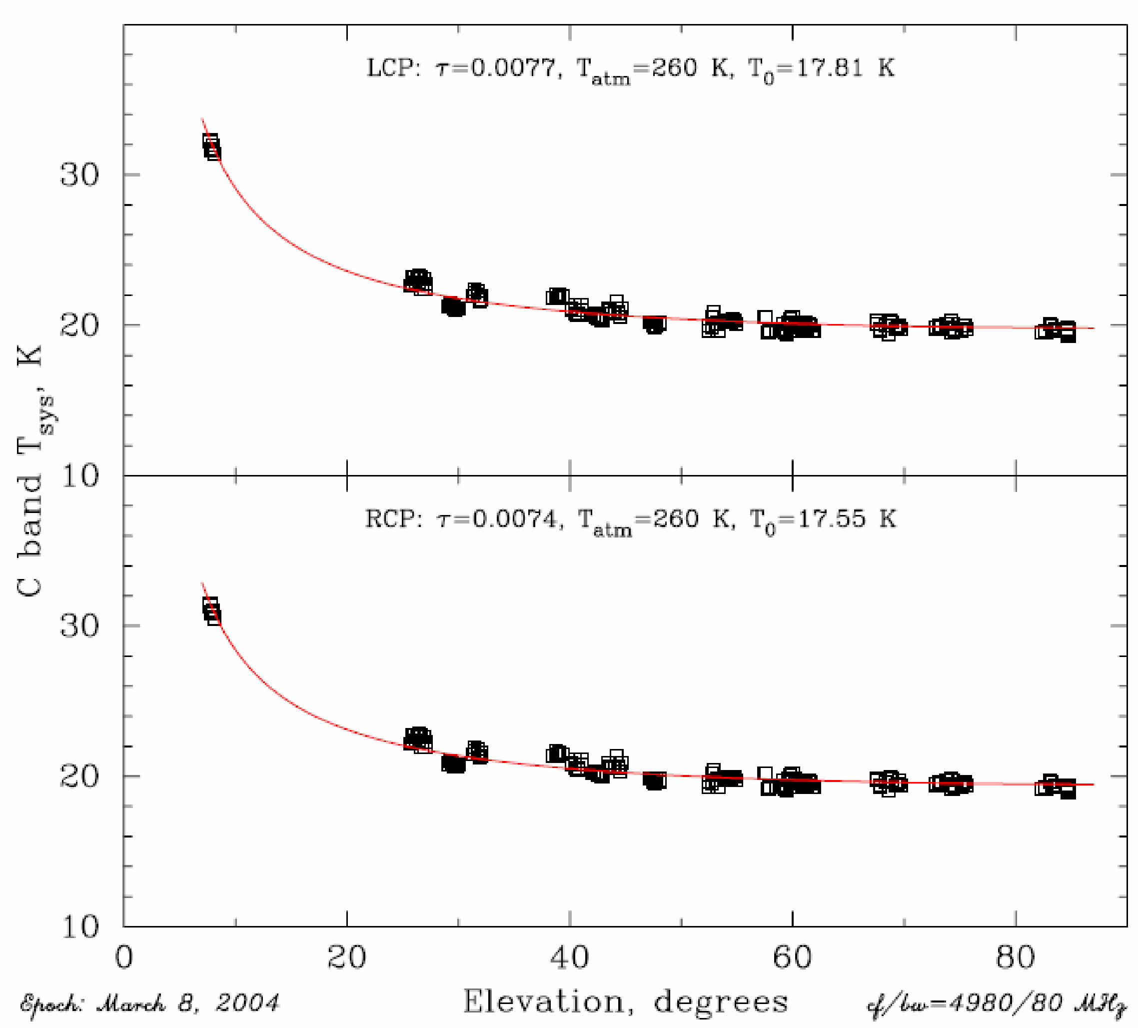


Antenna calibration: gain as function of elevation

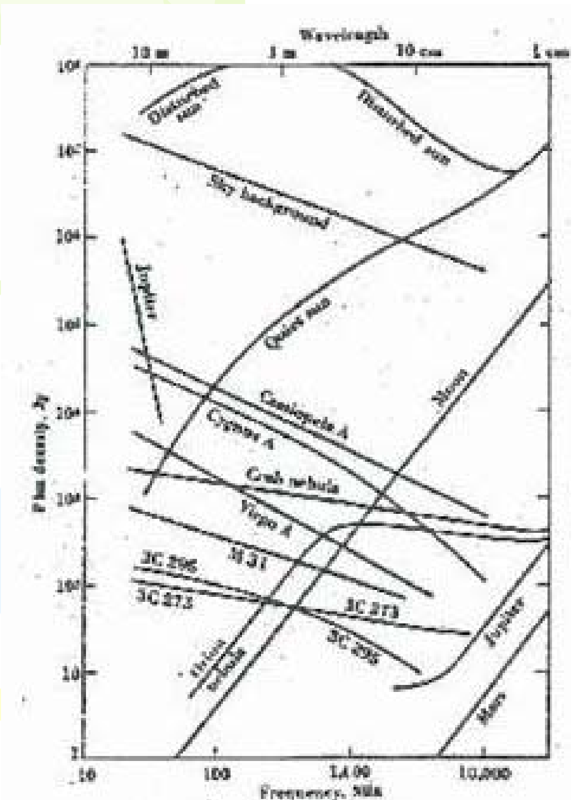


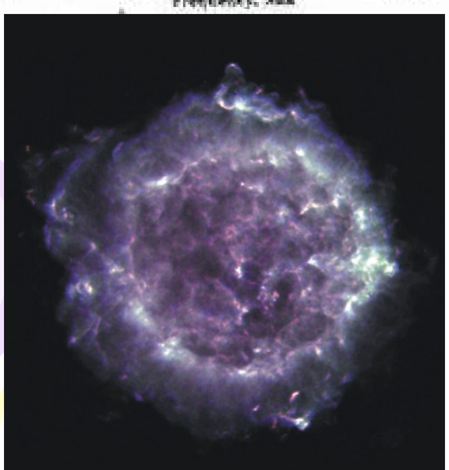
- Here we see "tipping" curves for the GBT 100 m telescope, 6 cm, K/Jy vs. elevation
- Curves almost flat: very good
- The small variation seen needs to be corrected for

This shows T_{sys} as function of elevation (atmosphere)



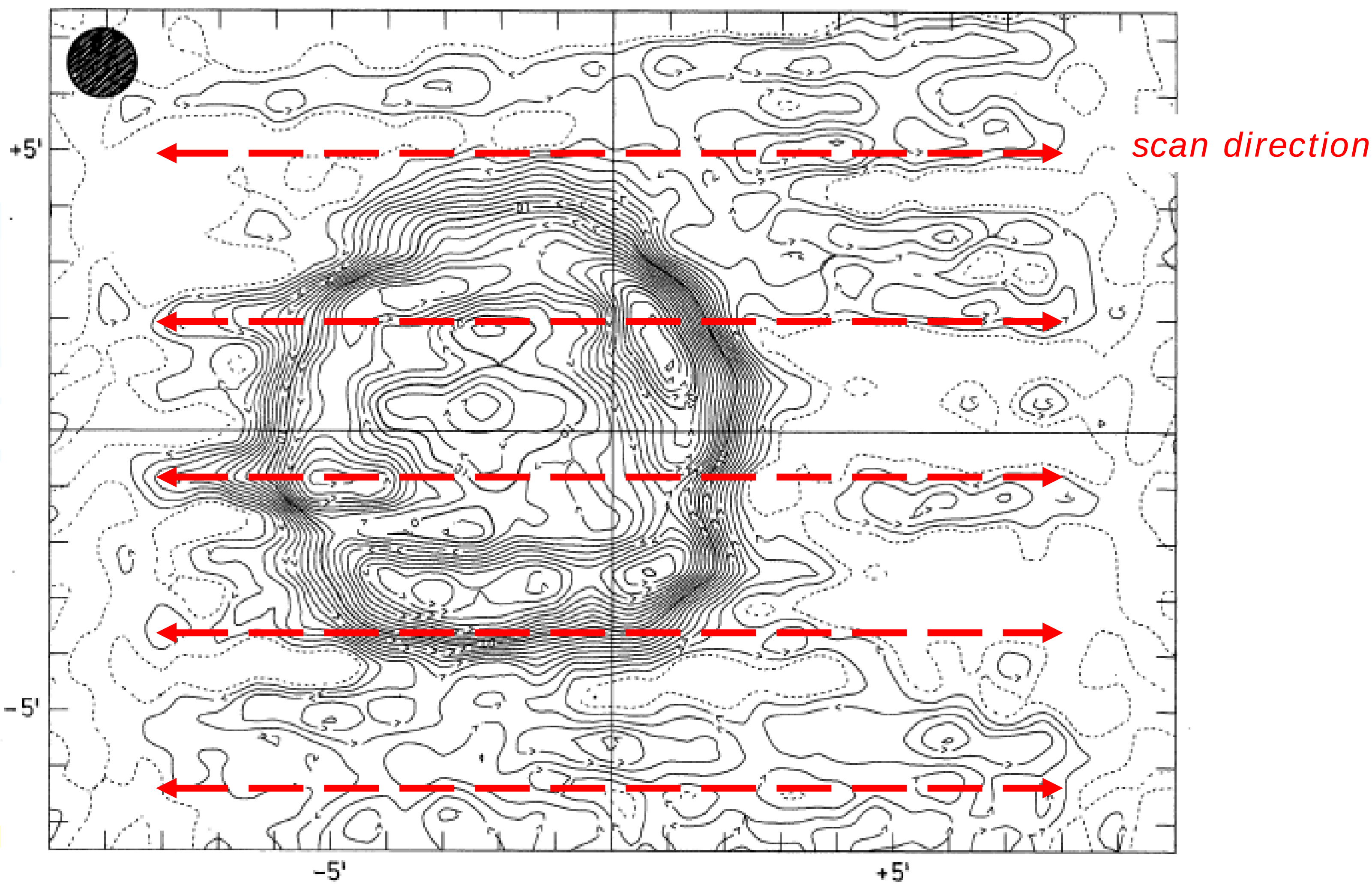
More on flux density calibration





- Cas A & Cyg A are strong, but in other ways not ideal
- Both are extended for most interferometers (OK for single dish)
- Cas A slowly getting weaker
- Many very compact sources are variable
- At short wavelengths, thermal sources can be used

To map with single dish, often scan source region



Calibration: other considerations

- If observing single source, or mapping small region, we often use nearby calibration source(s)
- By checking often on calibrator, may not need to correct for elevation effect
- Similarly, effect of atmosphere can be removed by frequent calibration at same elevation

Next lecture:

Some topics in radio astronomy and technology