Lectures on radio astronomy: 3

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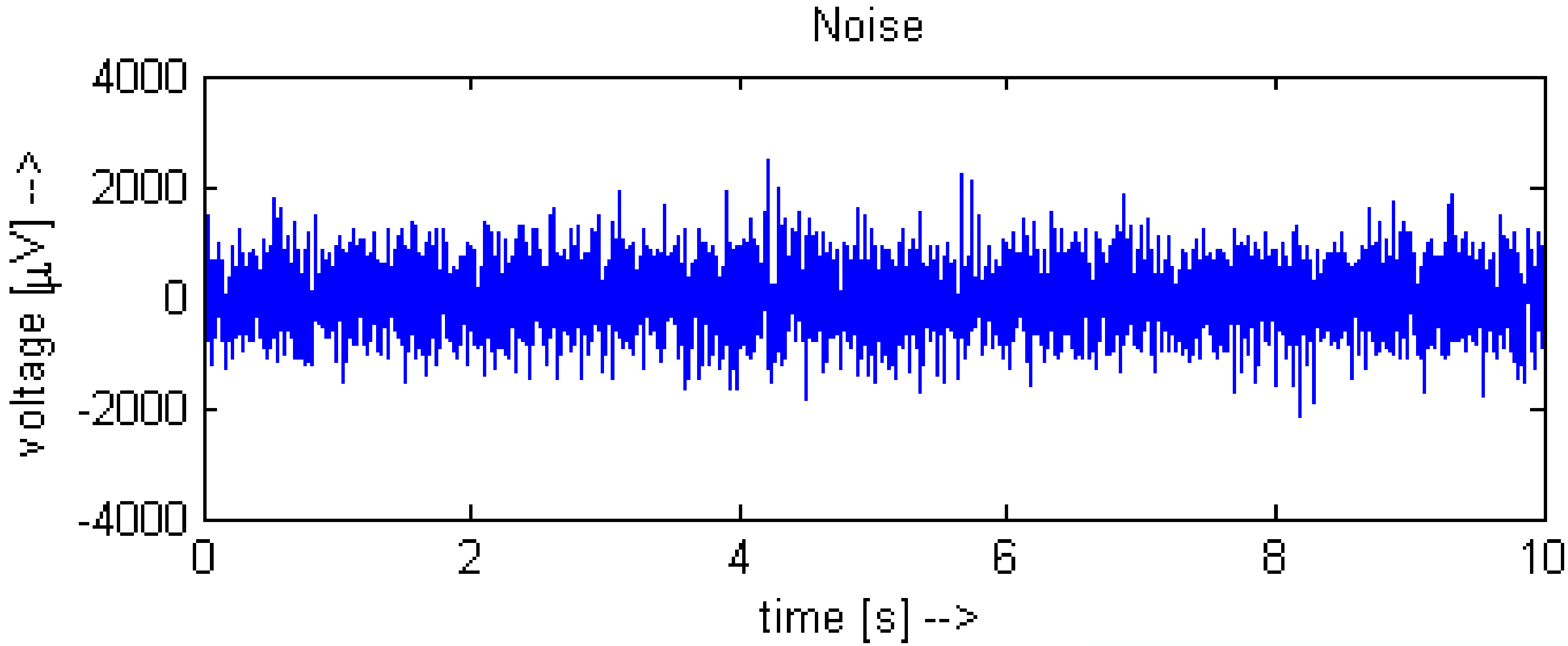
Receivers & noise

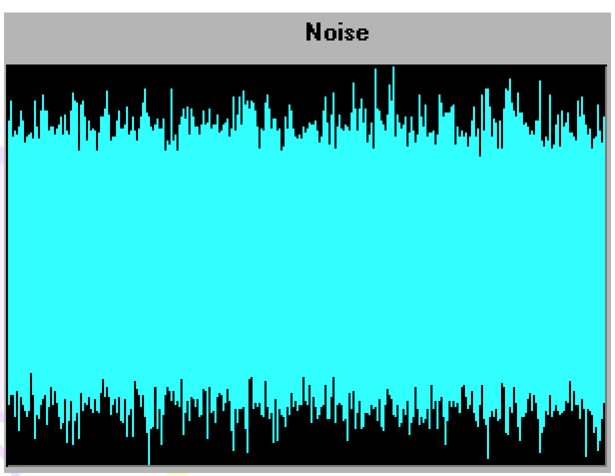
Signal we want (from sky) has unfortunate properties:

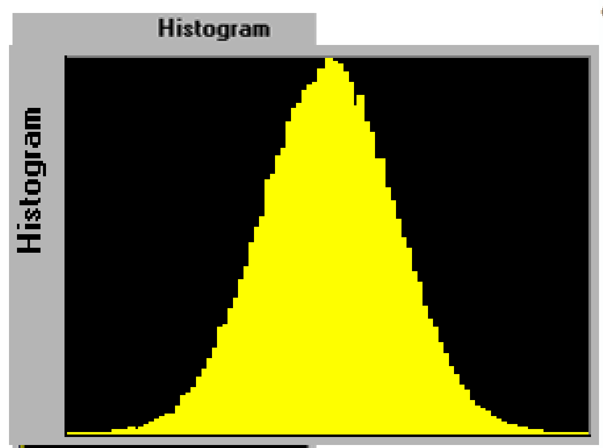
- Its statistical characteristics are just those of noise, indistinguishable from other background noise (from the ground, atmosphere, receiver, etc.)
- It is usually much weaker than other sources (ground, receiver, etc.)

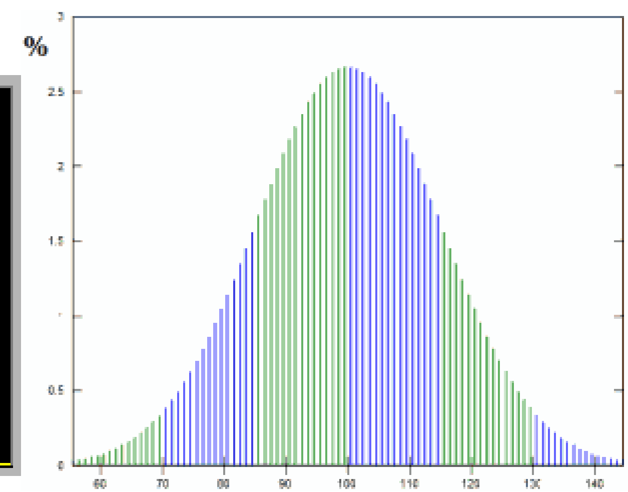
➔ Detecting it requires top technology, and a lot of clever tricks also

An example of noise

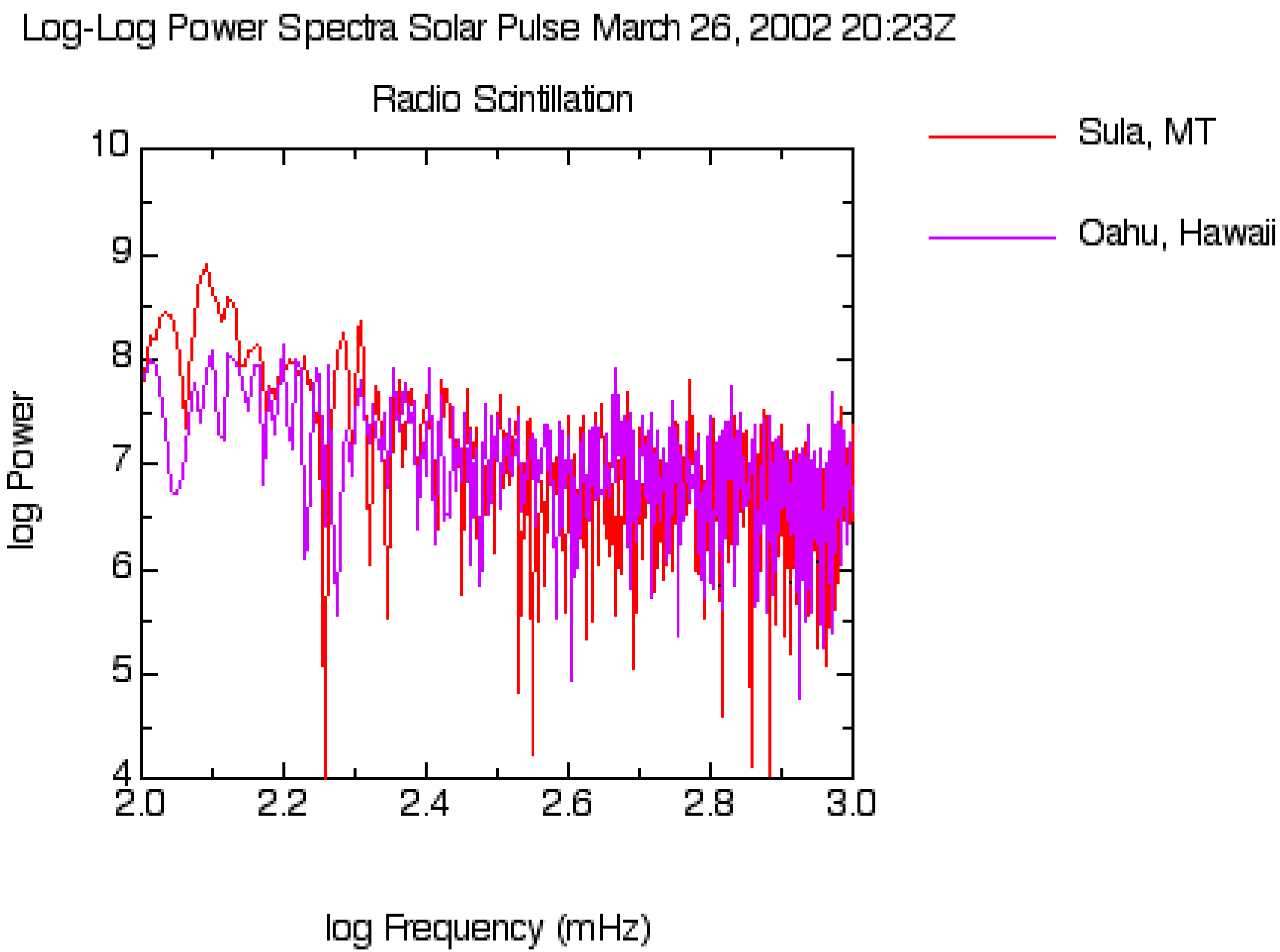








Noise from solar pulse (spectrum)



Telescope receiver system: essential elements –

- Sensitivity
- Tunable frequency
- Total (instantaneous) bandwidth
- Frequency channels/resolution
- Stability of output signal
- Dynamic range

Also useful are simplicity, ease of operation & maintenance, flexibility

Receiver sensitivity issues

- Choose low-noise components – nowadays often FET/HEMTs; can be cooled (even to <4 K) for less thermal noise
- Minimize effect of lossy components (cables, connectors, atmosphere, filters): loss of -0.1 dB (= 2.3%, or factor 0.977) will add 2.3% $\times$ 290 K = 7 K to system noise. So, short cables, cooled filters, etc. before amplifier

Troposphere significant for λ<10 cm; solutions?

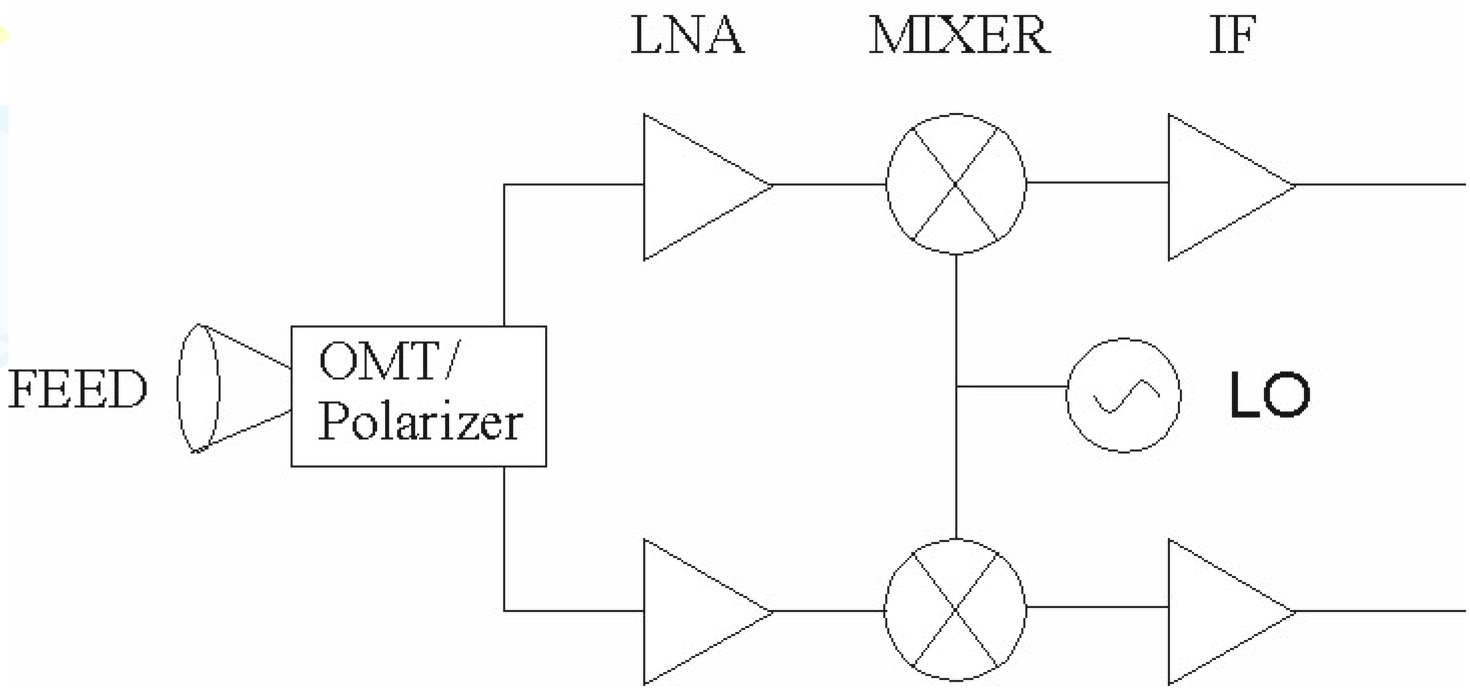
- Get above troposphere (mm telescopes are on mountains); go into space?
- Observe at high elevation. Atmospheric effect depends on thickness. Looking at zenith angle z ($z=0^\circ$ is straight up) increases thickness (and effect) by sec z
- Observe from dry site – effect is mainly due to water vapor in troposphere
- Observe short λ when weather's good

Telescopes like 15 m SEST: high (2500 m) and dry site

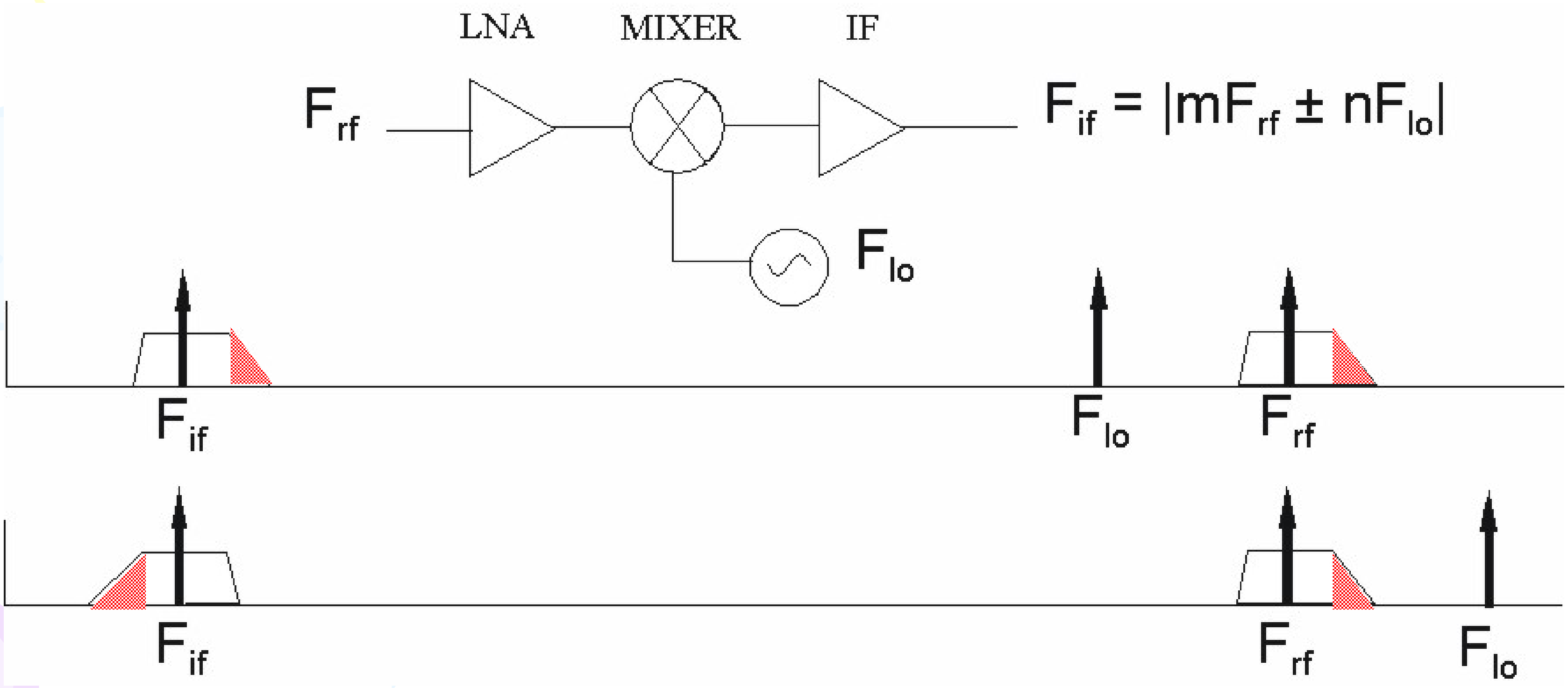
Frequency requirements of radio astronomy receivers

- Should be able to (quickly) tune to any frequency band
- Within that band, may want to have many channels over some range (line observations)
- For continuum, maximum possible bandwidth gives greatest sensitivity (includes more signal)

Structure of a typical superheterodyne receiver



Mixer used for frequency conversion of signal: $F_{rf} \Rightarrow F_{if}$



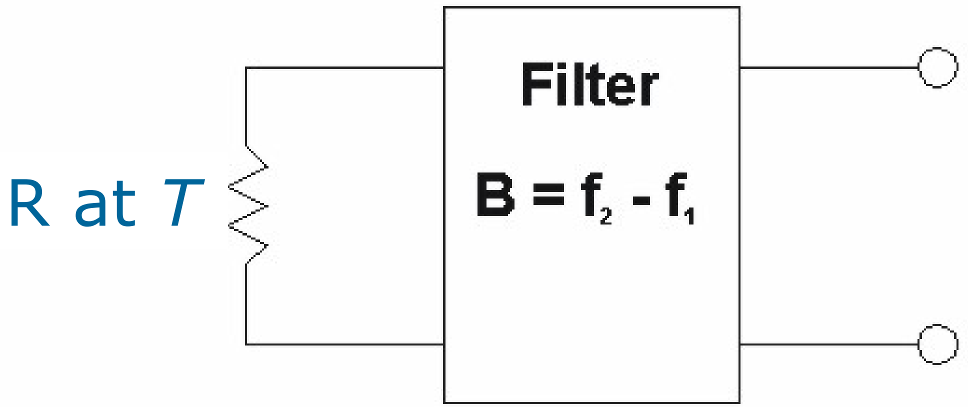
Mathematics of the super-heterodyne system

- Basic idea is to multiply together signals of two different frequencies
- From the trigonometric identity: $\sin f_1 \sin f_2 = ½\cos(f_1 - f_2) - ½\cos(f_1 + f_2)$
- The result of multiplying 2 sinusoidal signals together is signals at the sum and difference frequencies; the latter gives us an intermediate frequency: $f_{\mathrm{IF}} = |f_{\mathrm{sky}} - f_{\mathrm{LO}}|$

Features of the super-heterodyne system

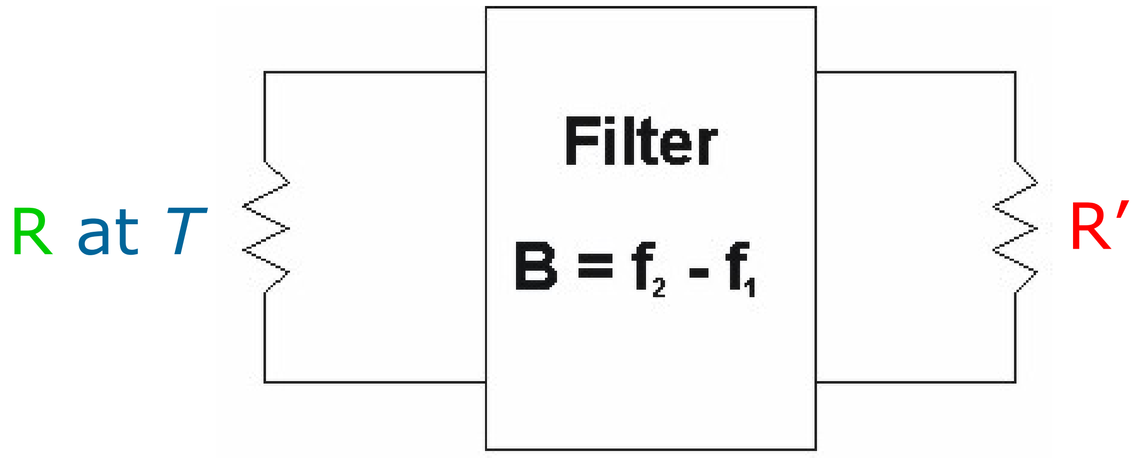
- A local oscillator (LO) signal is mixed with sky signal: converts sky to intermediate frequency (f_{IF})
- In general, 2 sky frequencies (upper and lower sidebands) are produced; may not be desirable, so filter one out if not wanted
- The same IF system can be used for different antenna signals

Power in noise signal: thermal voltage fluctuations



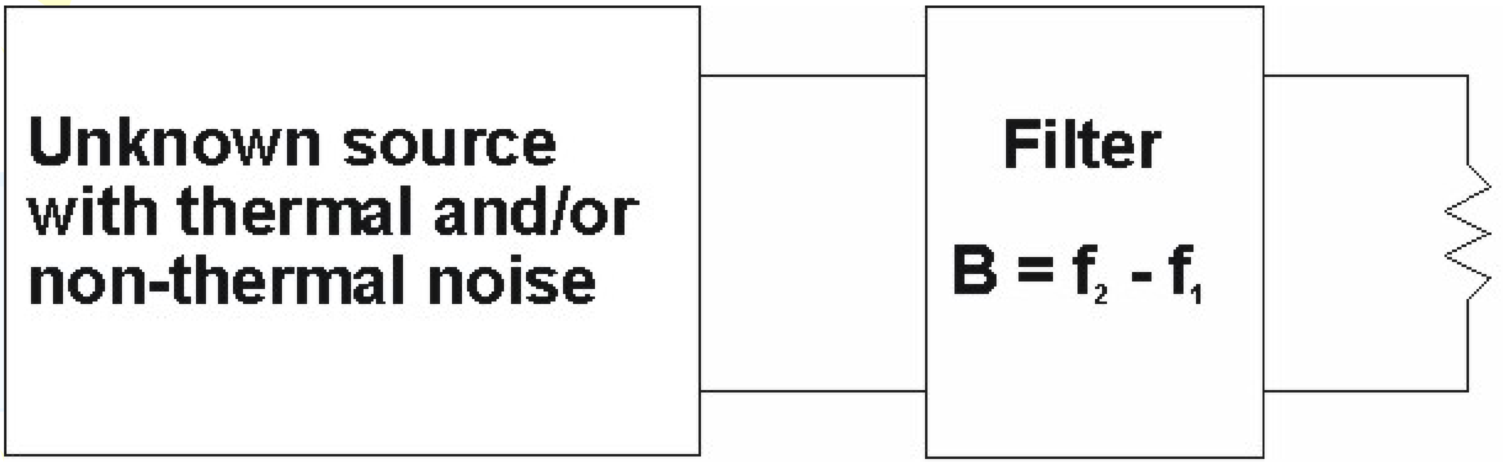
- After filtering, voltage at right-hand output can be written:
  $V^2_{rms} = 4kTR\int x/(e^x - 1)\, df$; $x = hf/kT$
- For $x \ll 1$, $V^2_{rms} = 4kTR\,(f_2 - f_1)$

Available noise power



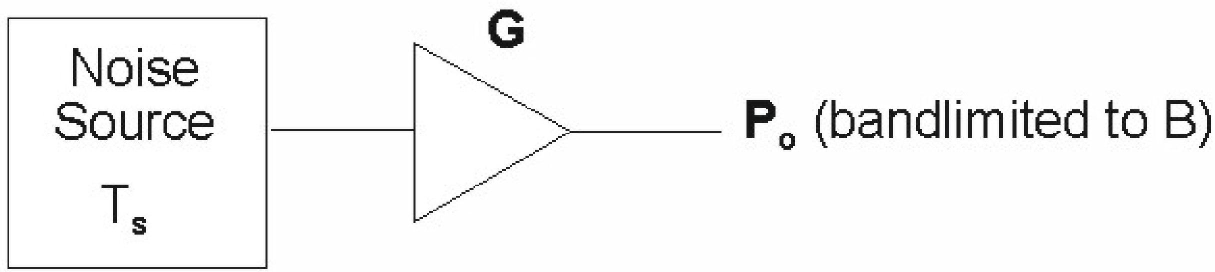
- The signal from resistor R, at temperature T, is filtered and limited to a bandwidth, B ($= f_2 - f_1$)
- The resulting signal in resistor R′ has a power, $P_n = BkT$

In a similar way, we can determine equivalent noise



- In a similar setup, we filter the signal from an unknown source
- From the power in resistor R′, we can calculate: $T_s = P_n/kB$

What is the equivalent noise of the amplifier?



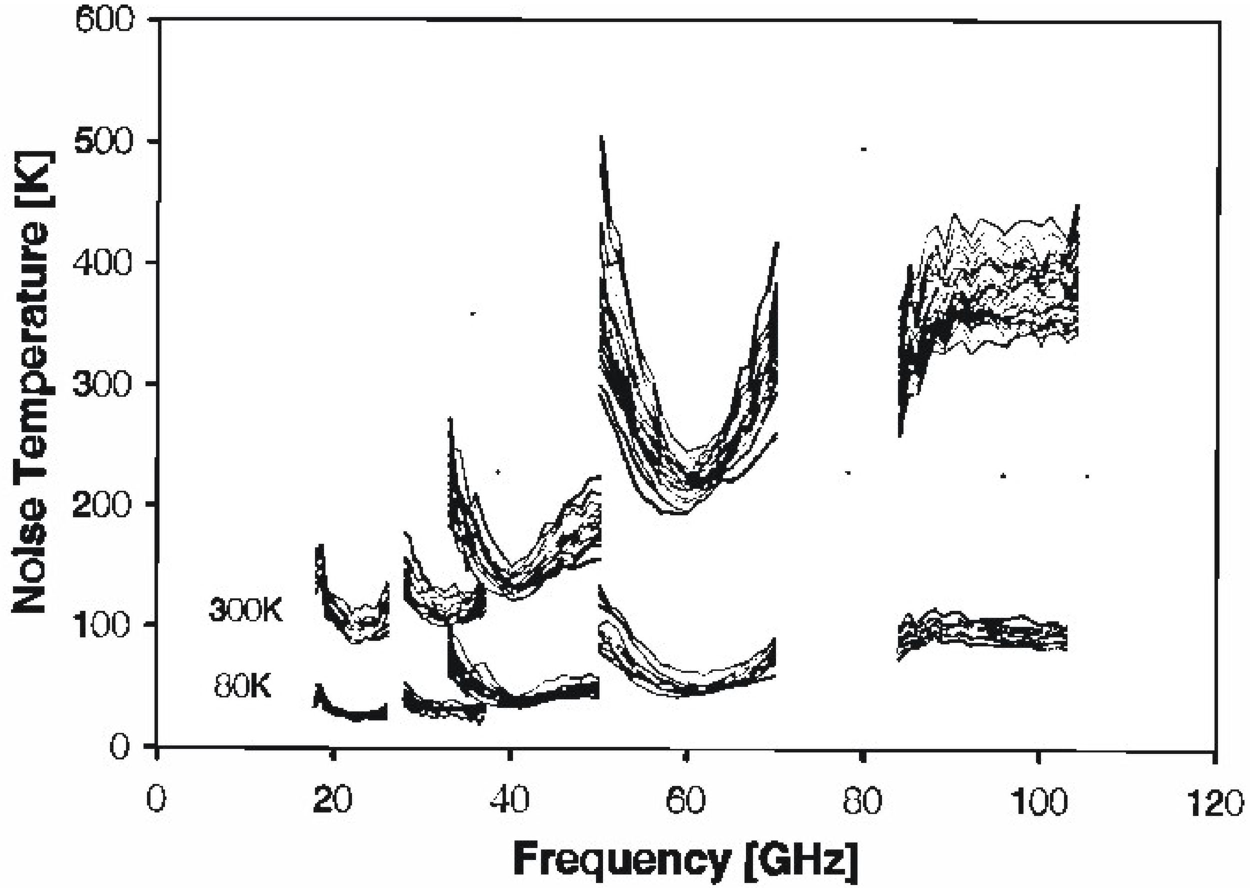
$P_o = GkBT_s + K$

Define $K = GkBT_e$

Then, $P_o = GkB(T_s + T_e)$

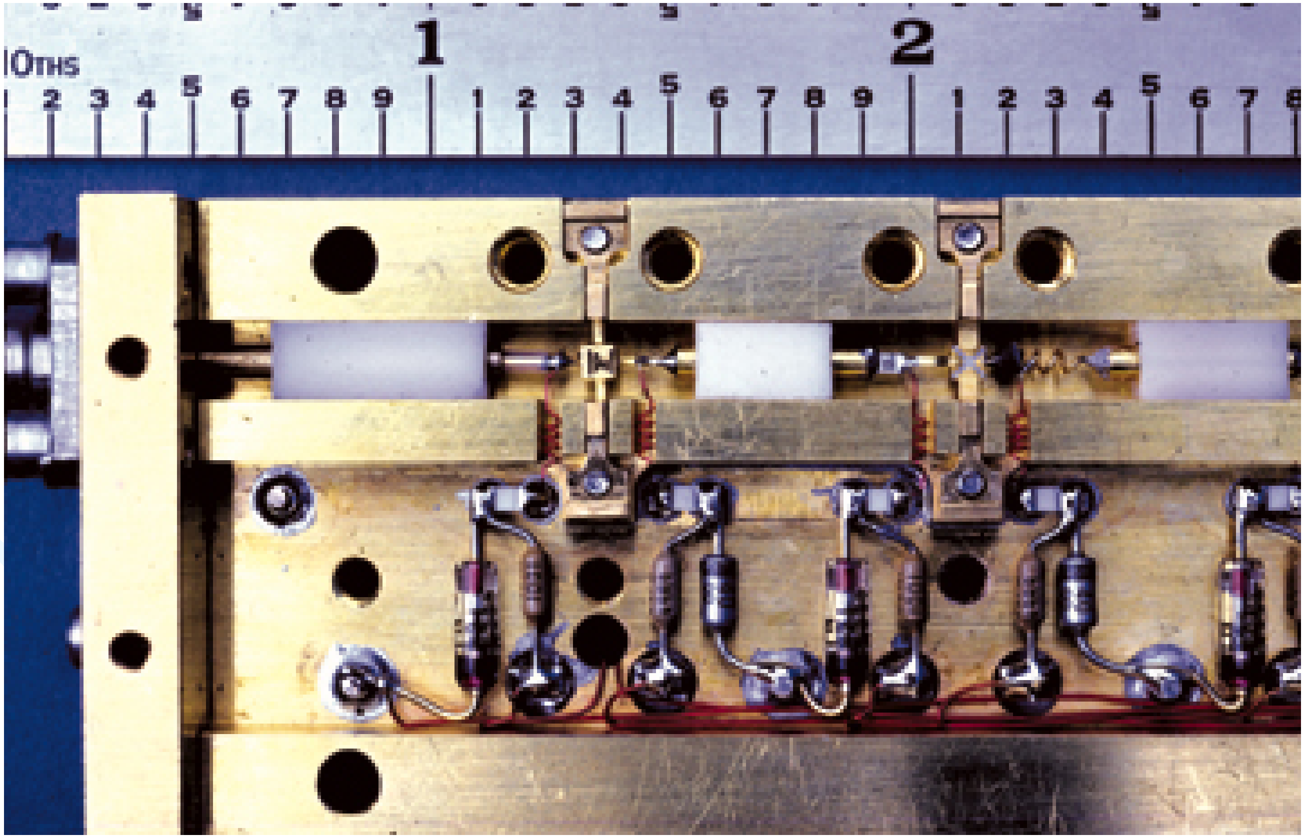
T_e is the amplifier *Equivalent Input Noise Temperature*

HFET noise temperature

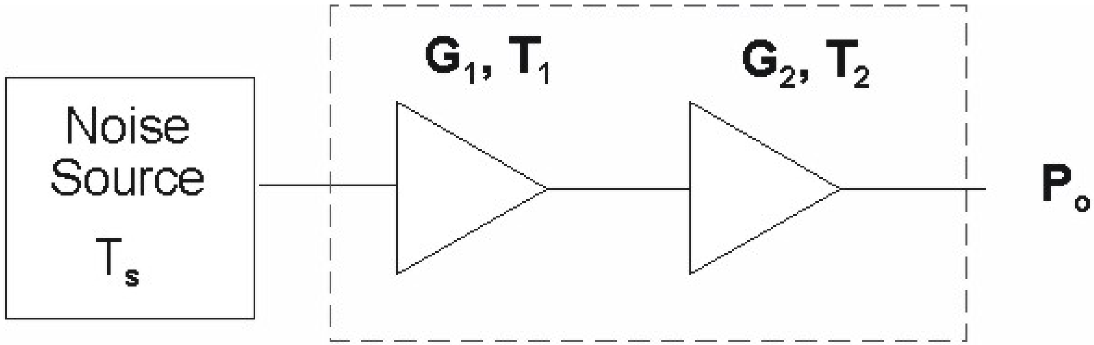


Data courtesy M. Pospieszalski of NRAO Central Development Laboratory

HFET (HEMT) Low Noise Amplifier (LNA)



What is the noise contribution of amplifiers in series?



$$P_o = G_1G_2kBT_s + G_1G_2kBT_1 + G_2kBT_2$$

or,

$$P_o = G_1G_2kB\,(T_s + (T_1 + T_2/G_1))$$

So, Amplifier Cascade has equivalent noise $T_1 + T_2/G_1$

Example of receiver temperature calculation

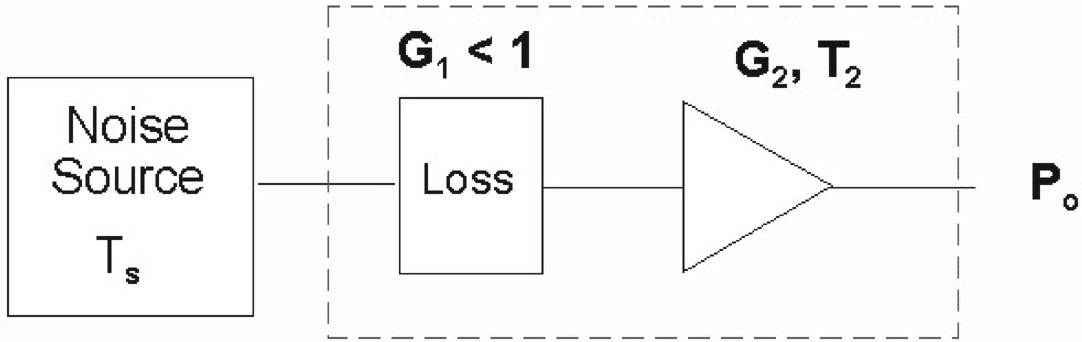
Receiver system, 3 amplifiers: 1, 2 & 3

- T_1=50 K, G_1=20 dB (=100×)
- T_2=300 K, G_2=10 dB (=10×)
- T_3=500 K

T_N=50 K +300 K/100 +500 K/(10×100)
=50 K + 3 K + 0.5 K = 53.5 K

So we see, 1st amplifier has greatest effect.

Noise contribution of input loss



Let $L = 1/G_1$, then for ohmic loss at physical temperature T_o,

the effective noise temperature of the loss is $(L-1)T_o$.

Effective noise temperature of the loss - amplifier cascade

is: $\boxed{(L-1)T_o + LT_2}$.

The lesson, when designing a receiver, is…

- Put a low noise amplifier (LNA) with high gain ($G \geq 20$ dB) at front
- Avoid any losses before the LNA (so, keep cables short, or use waveguide; avoid filters if possible, or cool them; keep atmospheric loss low – choose a good site)
- Noise from lossy element after LNA gets divided by LNA gain (G_1)

Final noise determined by T_N, bandwidth, duration

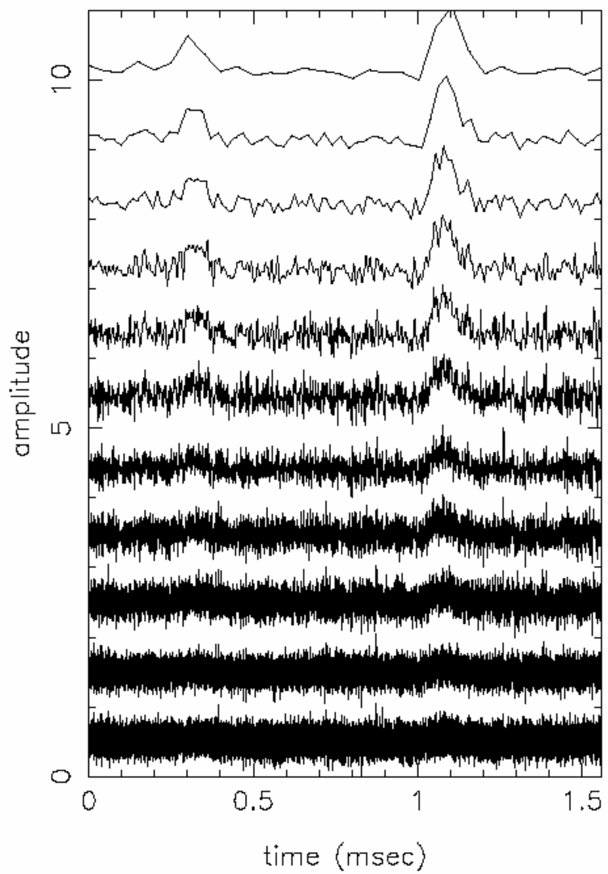
$$\sigma = \frac{T_N}{\sqrt{\Delta f \times \tau}}$$, where Δf is bandwidth,

and τ is integration time

σ is the final (rms) noise, to be compared with source signal strength

Here is an example of time integration in practice

- Observation of pulse from ms pulsar PSR1937+21
- Integration time increases by 2× each step from bottom
- See pulse better, lose some detail
- [frequency smoothing gives similar result]

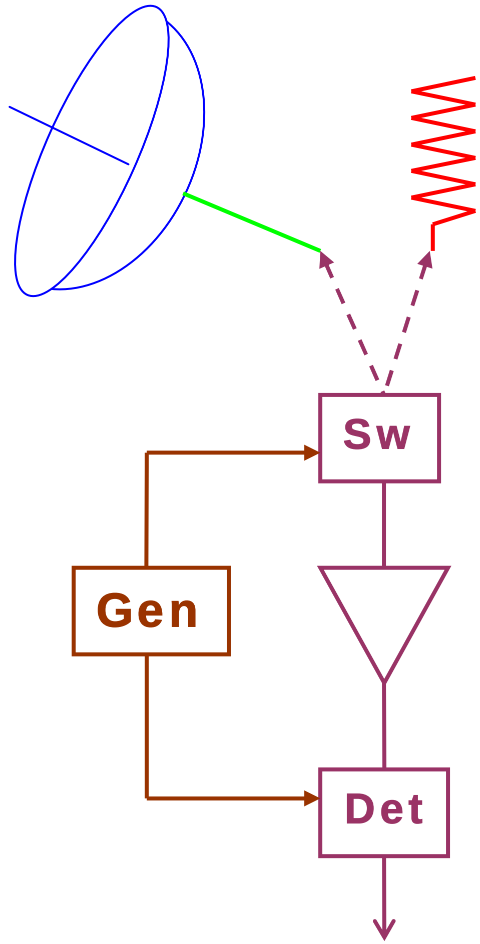


Having sensitivity is useless if stability is poor

- Amplifiers with high gain tend to be less stable
- To keep output stable, often add feedback loop: automatic gain control (AGC)
- Physicist Robert Dicke invented technique: switch to reference noise source, to monitor receiver.

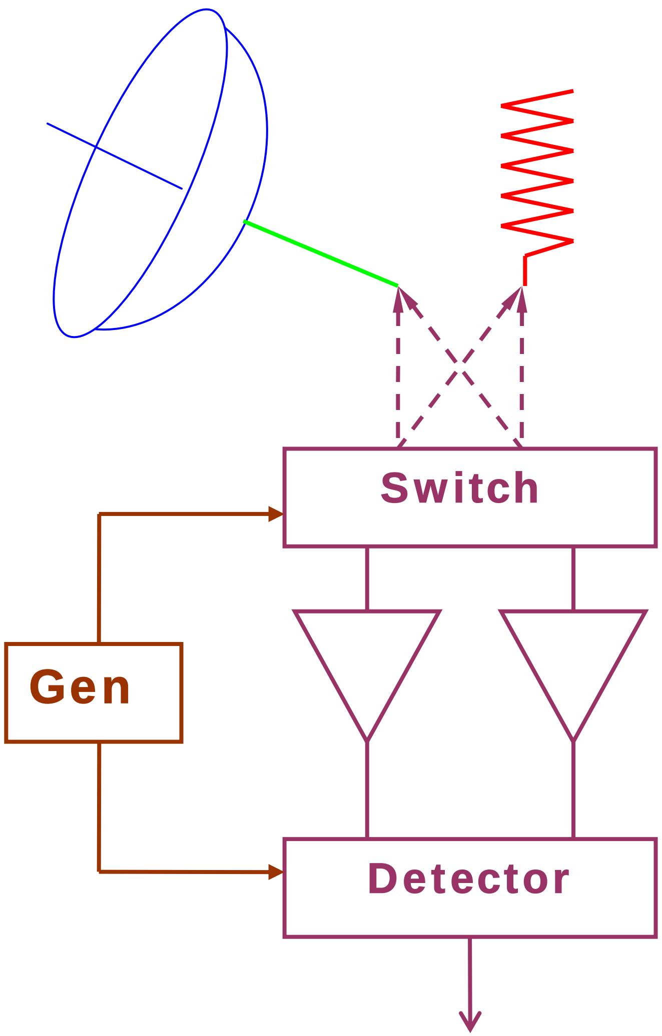
Example of a simple Dicke switch radio telescope

- Generate switching frequency, faster than system drift
- Demodulate at same frequency after detection
- Disadvantage is not all time spent on source: lose some observing time



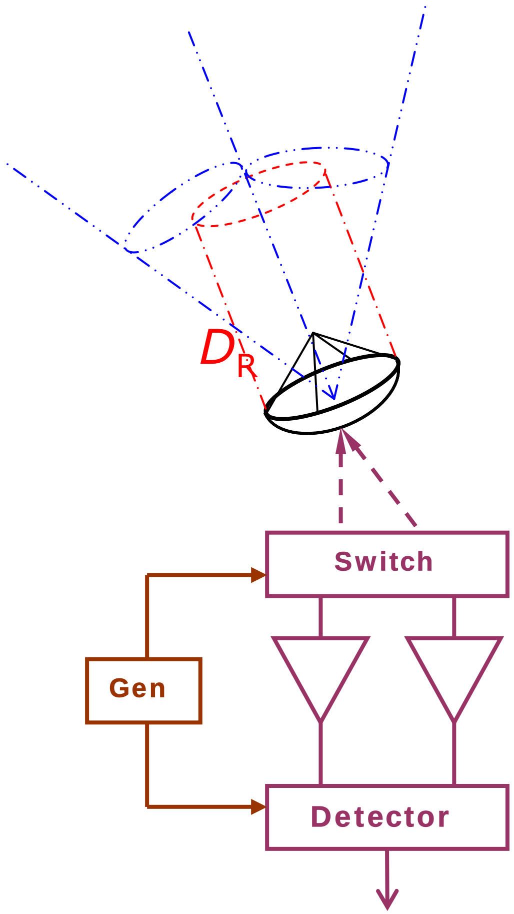
Avoid loss of observing time with two receivers

- Always observing sky and reference
- At end, average two difference signals
- Always need stable reference
- This system costs more (2 channels)

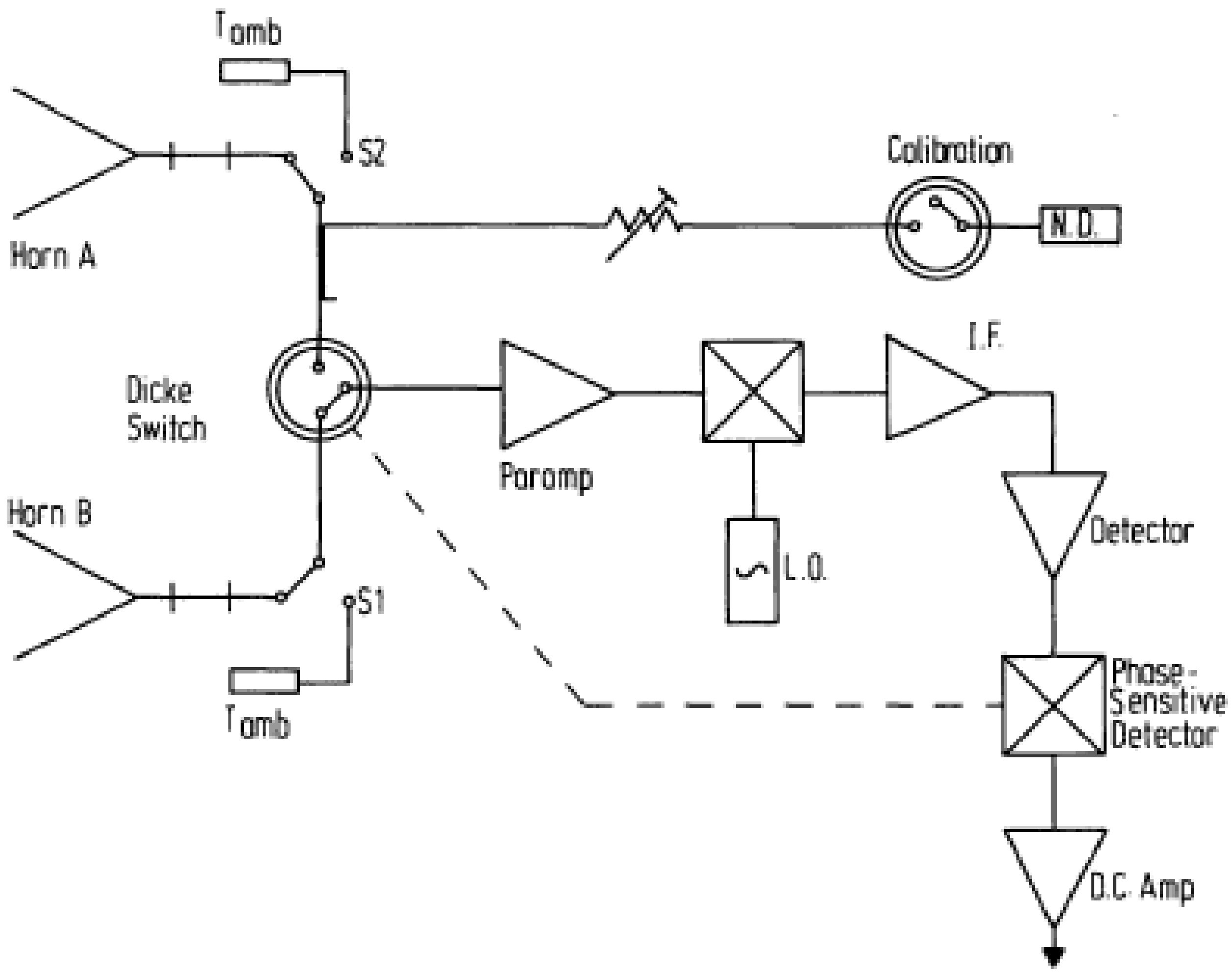


Dicke's technique widely used, in different ways

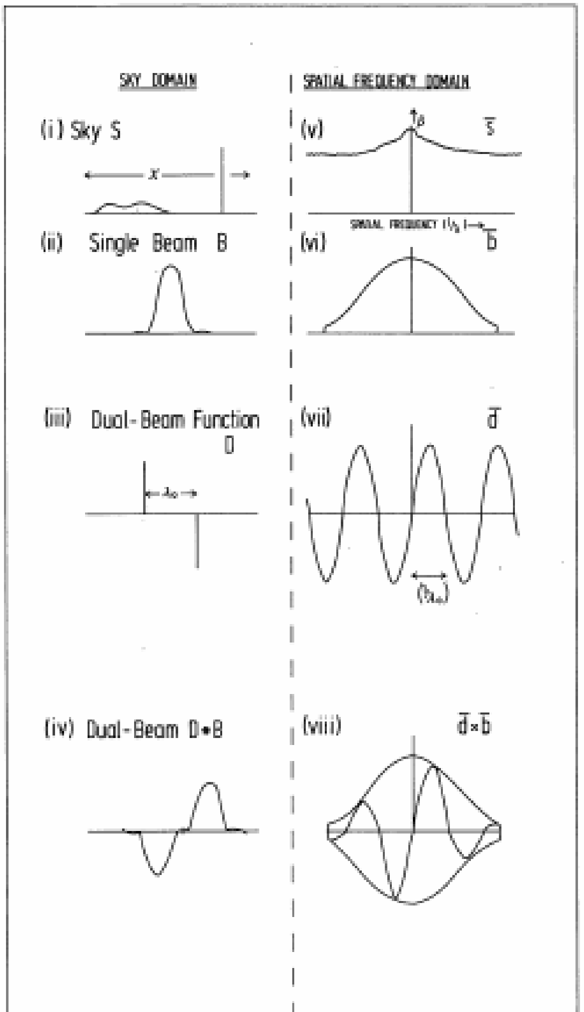
- For example, with two receivers, we can make two beams
- We can point one beam at source, other on empty sky.
- Using Dicke's switch, one beam becomes reference – can "switch out" effect of atmosphere.

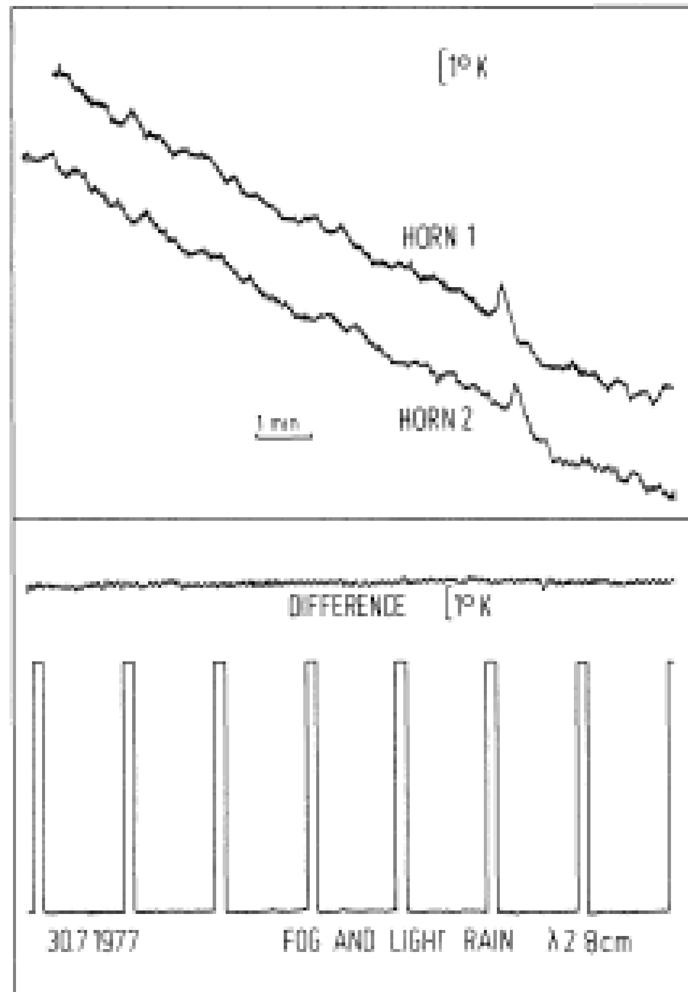


Effelsberg λ2.8 cm system (Emerson et al., 1979)

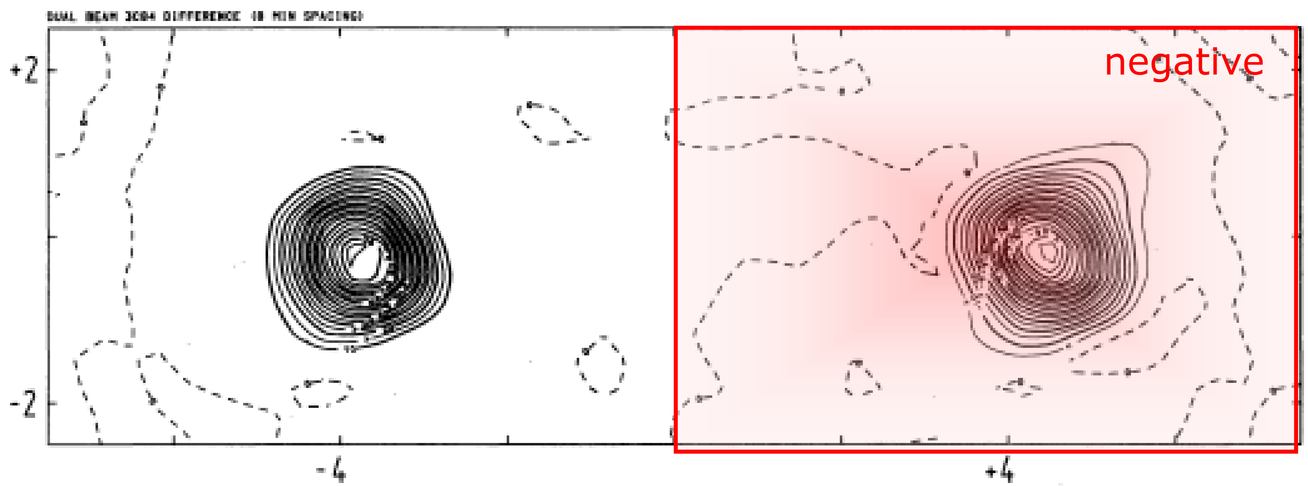


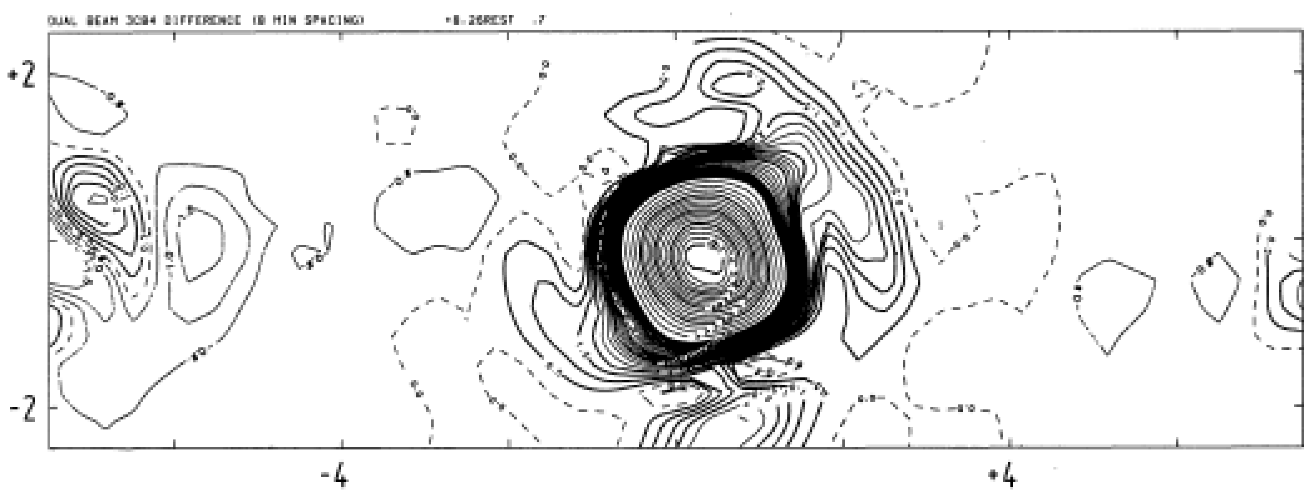
What dual-beam measures & example of data (in fog)





Observation of strong source 3C84: data & result

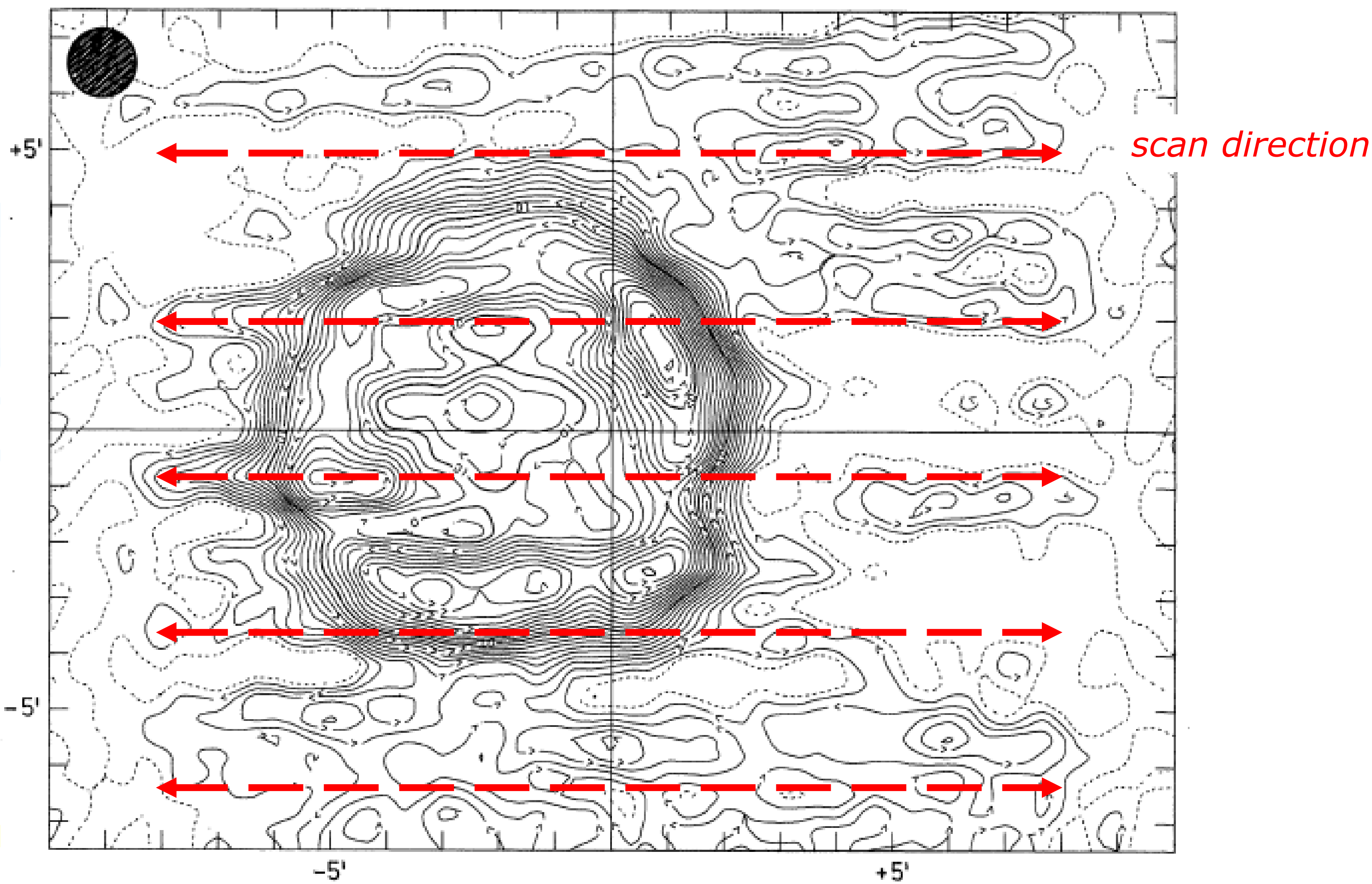




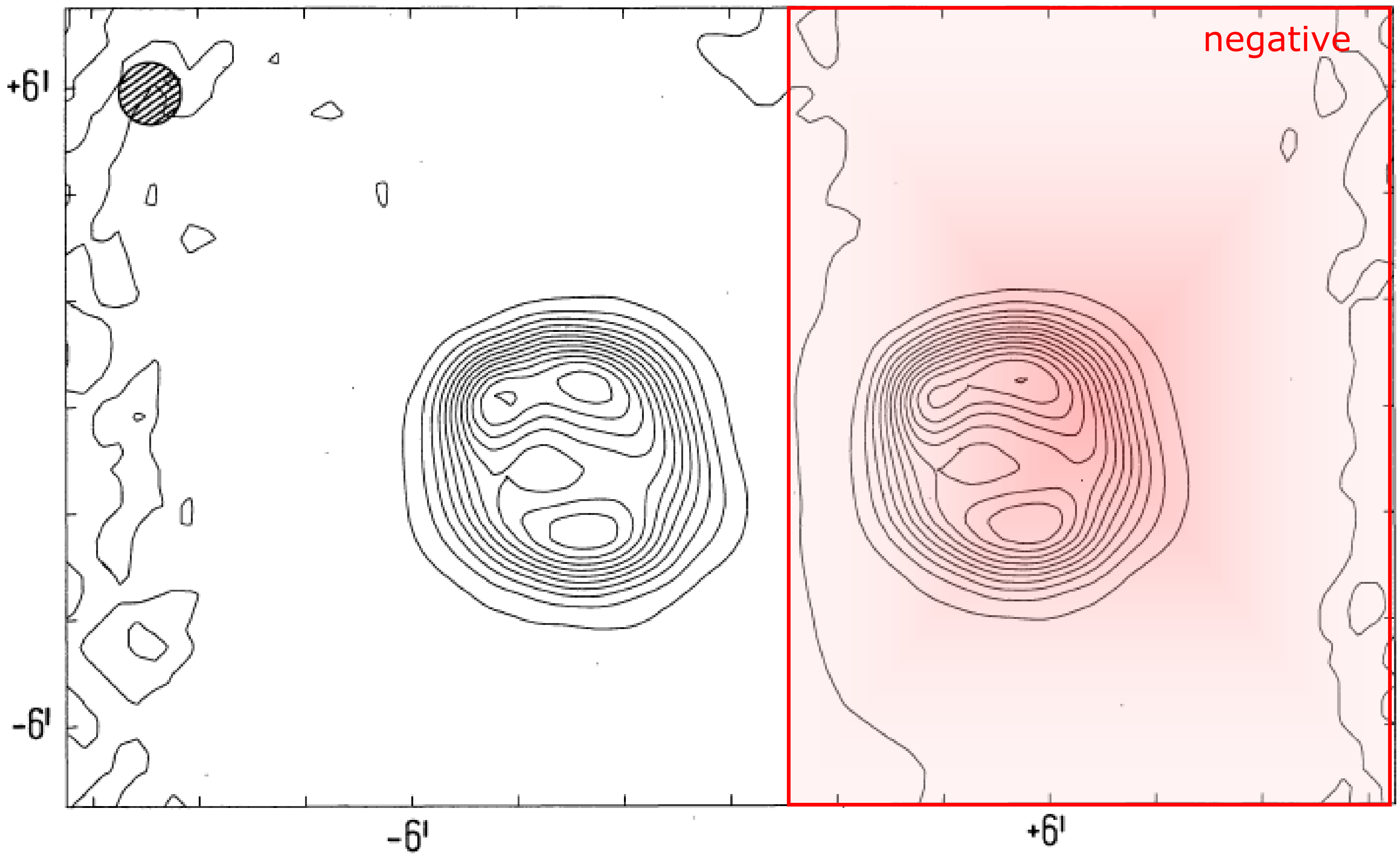
Technique can also be used for mapping extended sources

- For Effelsberg dish (100 m diameter) observing at λ=2.8 cm
- Rayleigh distance: $D_R \approx D^2/\lambda = 100^2/0.028 = 360$ km
- Troposphere (where water is) is at 2-3 km altitude, so should be same in both beams

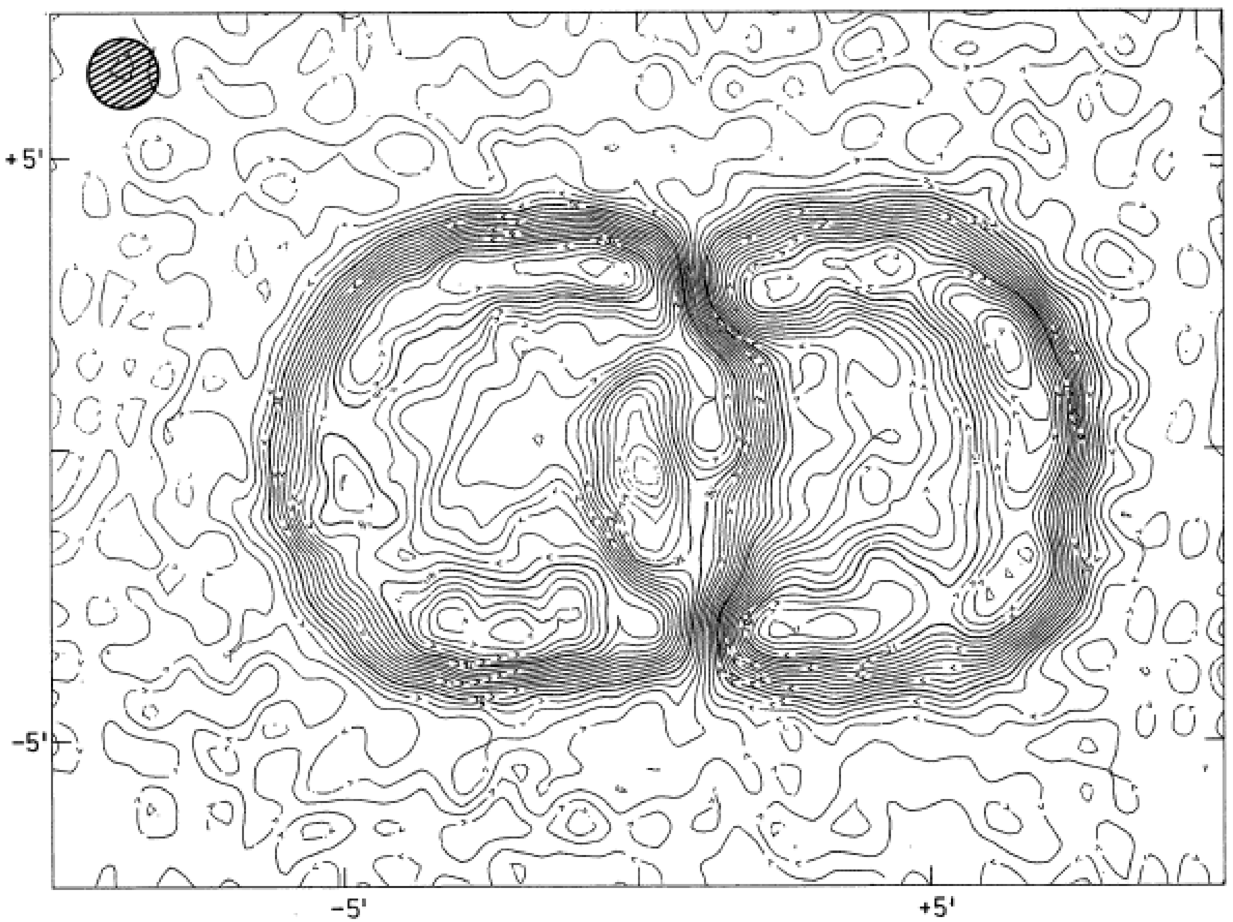
Single-beam map of 3C10, showing effects of atmosphere



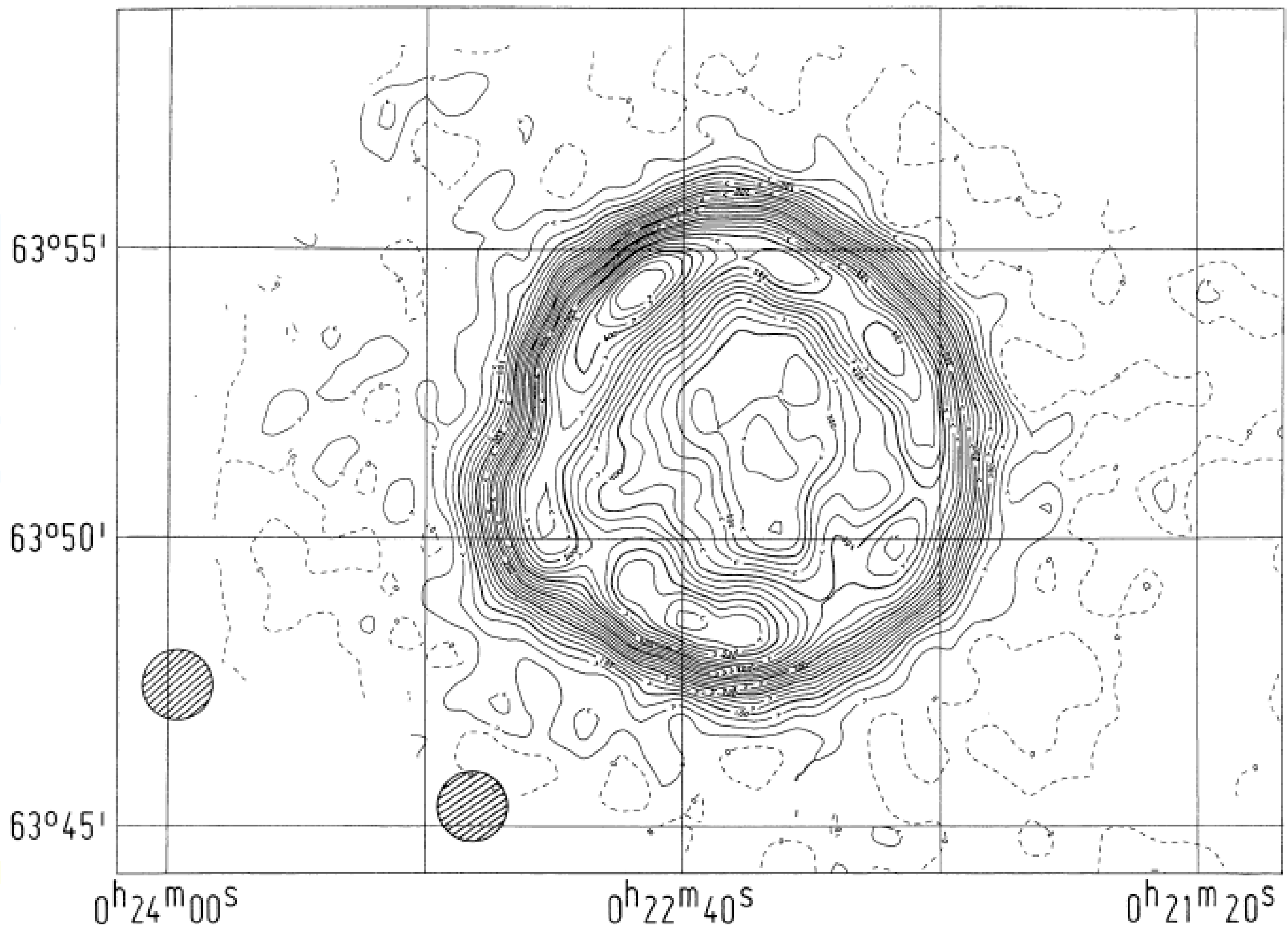
Cas A, beam separation = 8.2′ arc: 2 images well separated



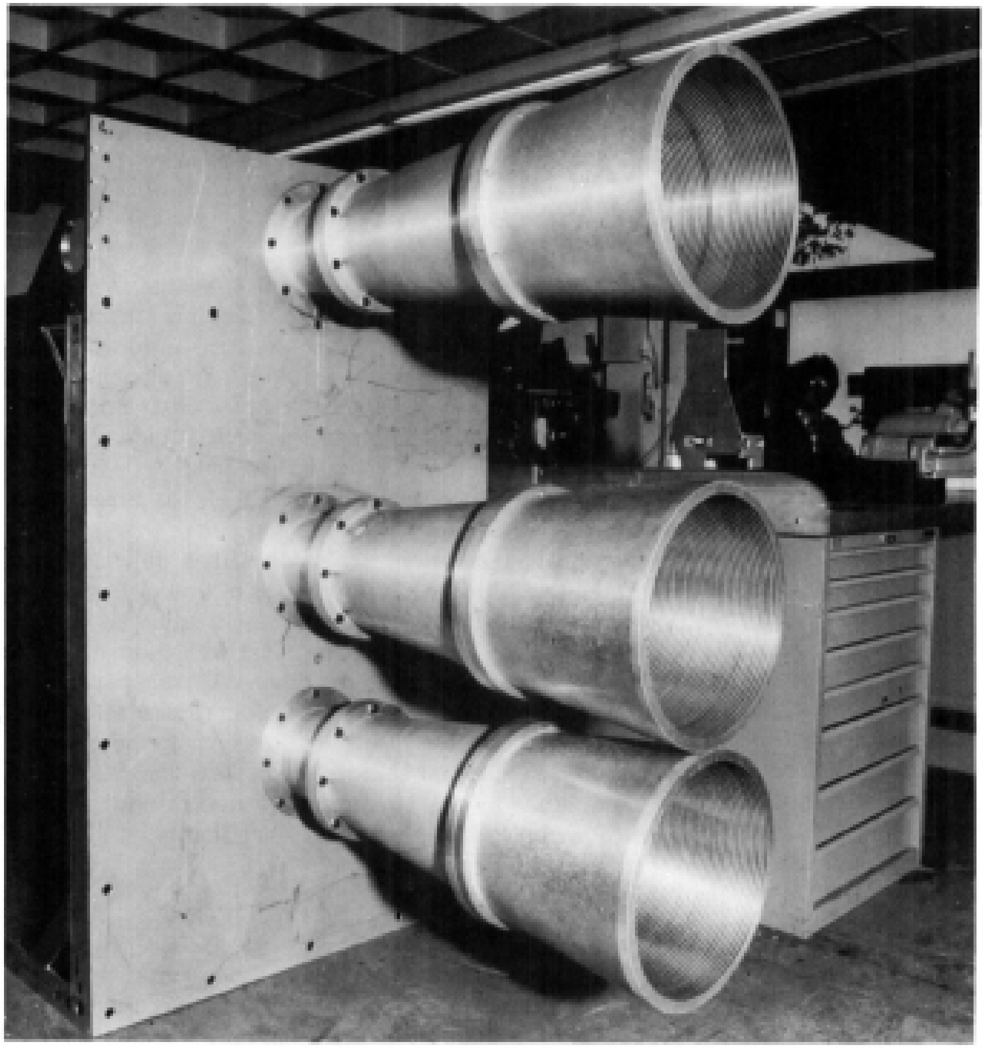
Images not always separated: 3C10, 5.5’ arc beam distance



3C10, final map separates and averages two images



Triple-horn system: 3 beams are even better



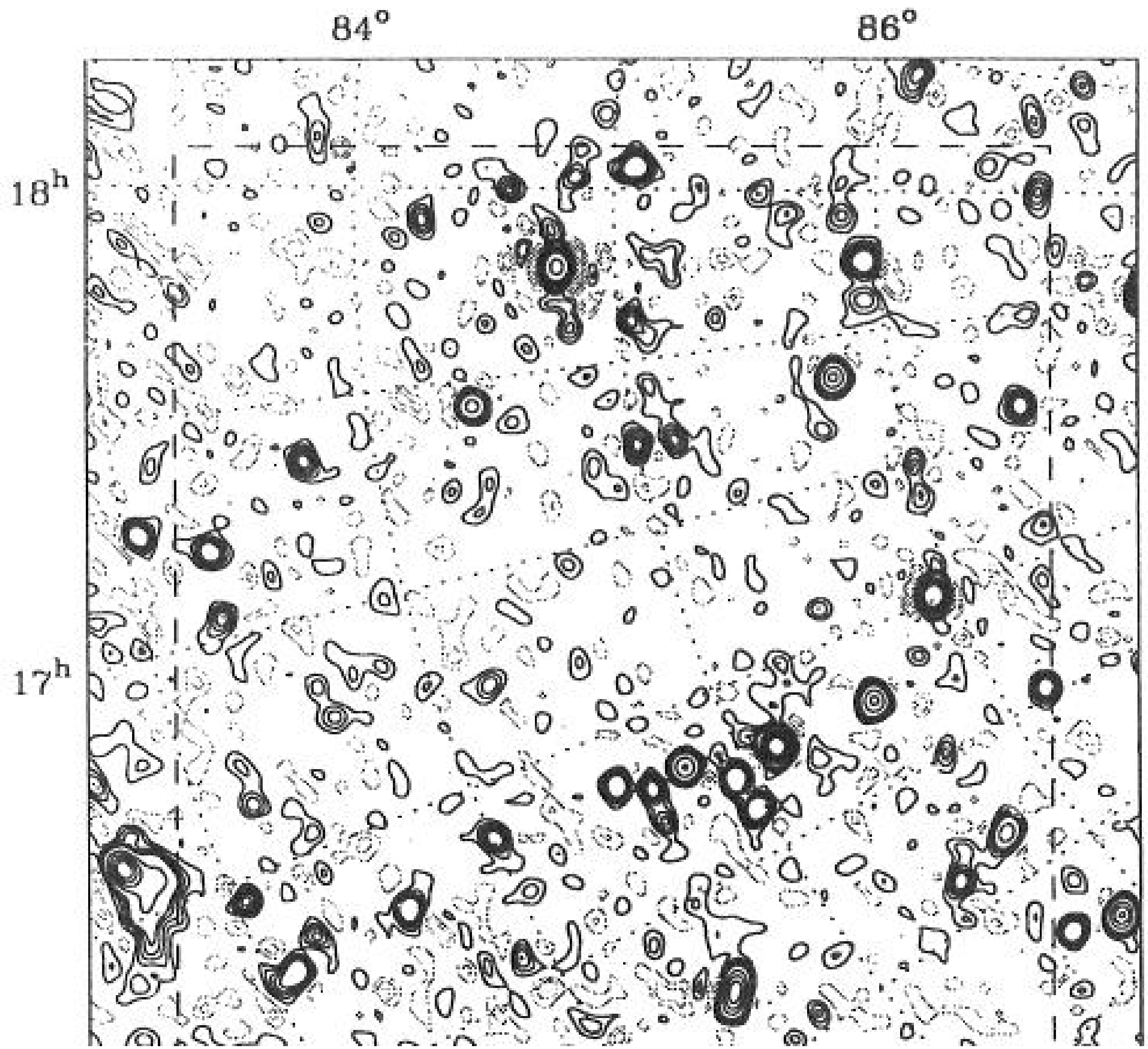
Two final sensitivity issues: polarization and confusion

- If we only observe with one antenna and receiver, we miss half the signal (for unpolarized sources).
- Must also have a second antenna with opposite sense of polarization
- Second antenna must have its own receiver system (so it costs more, but gives better sensitivity by $\sqrt{2}$)

⇨ *Why is sensitivity better by $\sqrt{2}$?*

Antenna with one polarization misses half the signal

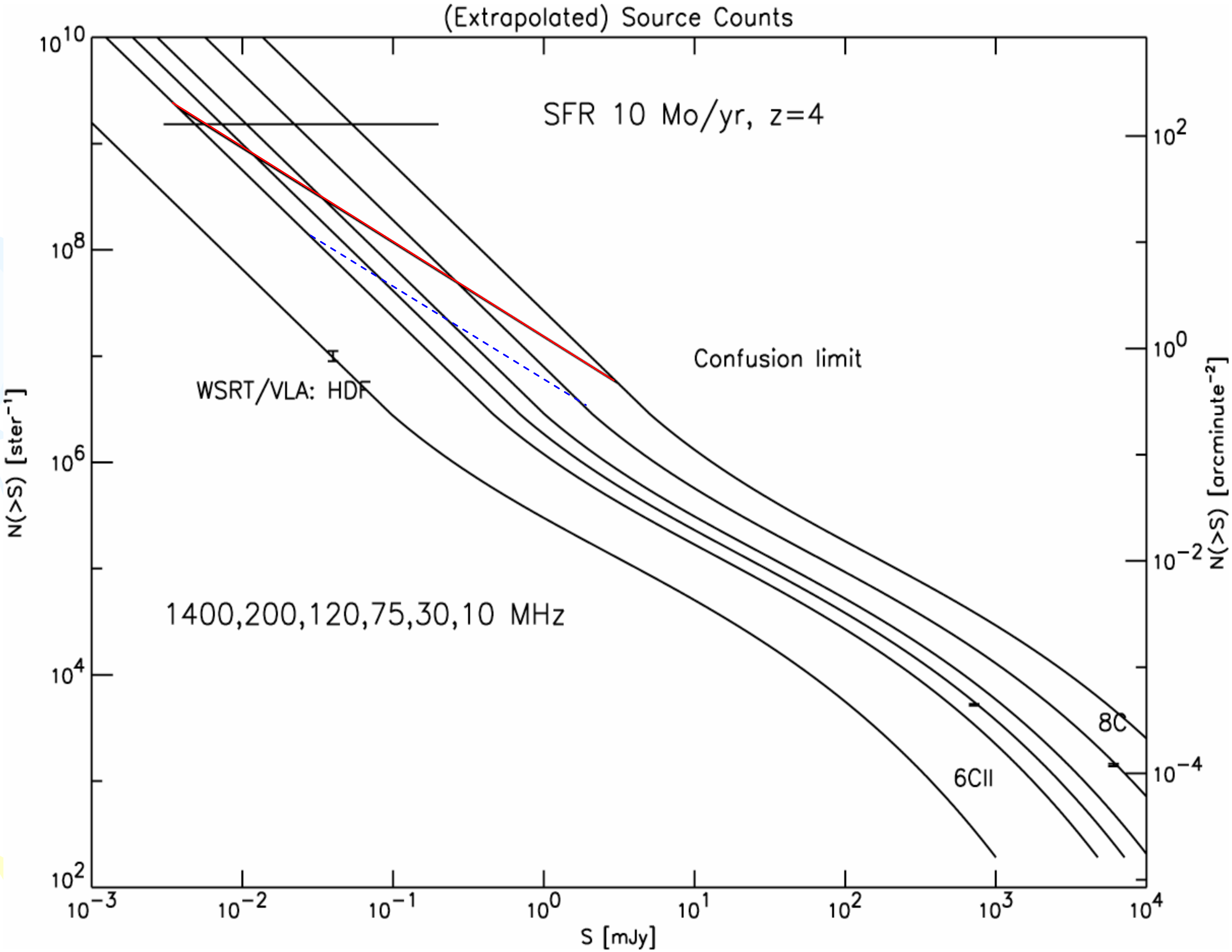
Confusion is where sources (almost) overlap each other



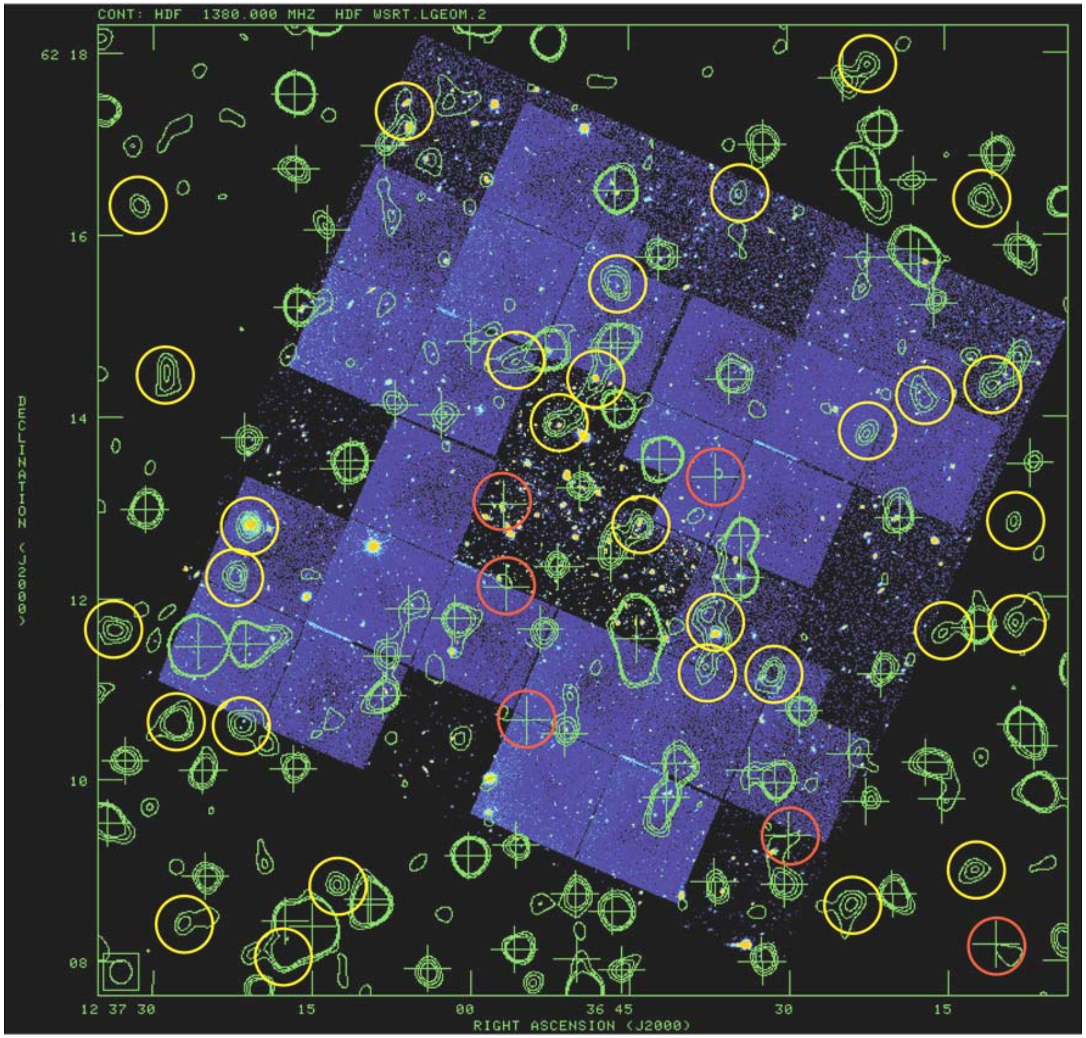
To overcome confusion requires a smaller beam

- 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); see next panel
- A more sensitive telescope needs greater angular resolution

Curves showing source density vs. *S* (flux density)



Hubble Deep Field (HDF), observed by WSRT & VLA



Next lecture we will look at interferometers