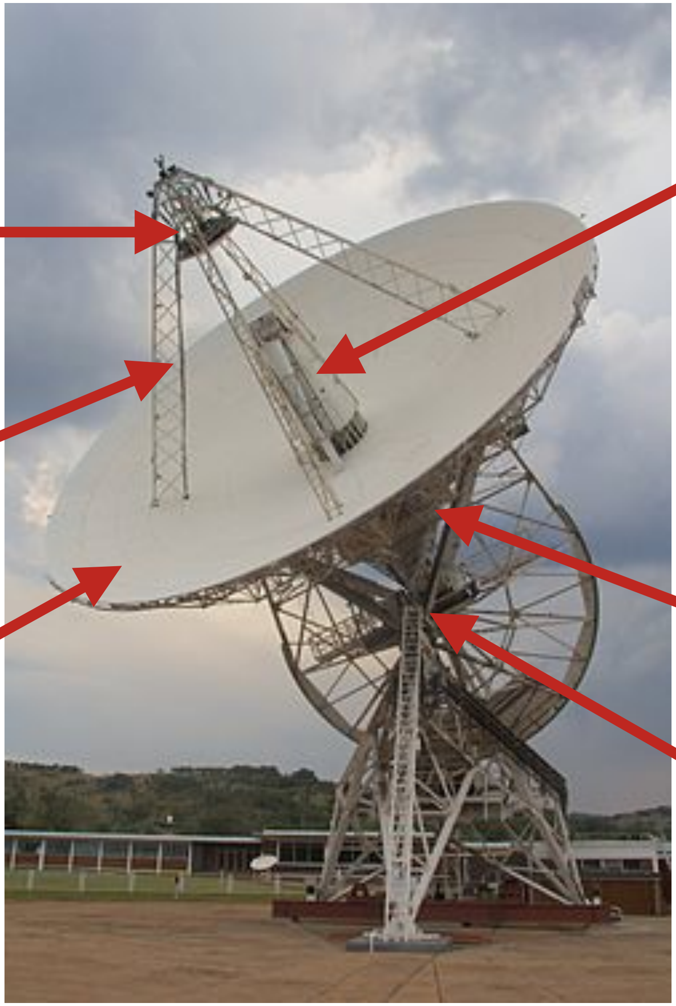
Radiometry and Calibration

Aletha de Witt
AVN/Newton-fund 2017
Observational & Technical Training HartRAO

National Research Foundation | Hartebeesthoek Radio Astronomy Observatory

Antenna Basics

The **HartRAO 26m telescope => equatorially mounted Cassegrain** radio telescope



The **antenna reflectors** concentrate incoming E-M radiation into the focal point of the antenna

Secondary reflector

Sub-reflector (small reflector of hyperbolic curvature in front of the focus of the main reflector).

Sub-reflector support legs

Primary reflector

Feed housing (feed horns receivers and support structure)

?

Converts E-M radiation in free space to electrical currents in a conductor.

26 m telescope receivers (7):

1.6, 2.3, 5, 6.7, 8.4, 12.2 GHz
5 & 8.4 GHz **dual beam**
new 22 GHz cooled receiver
15 GHz **dual beam** coming

Deck Room

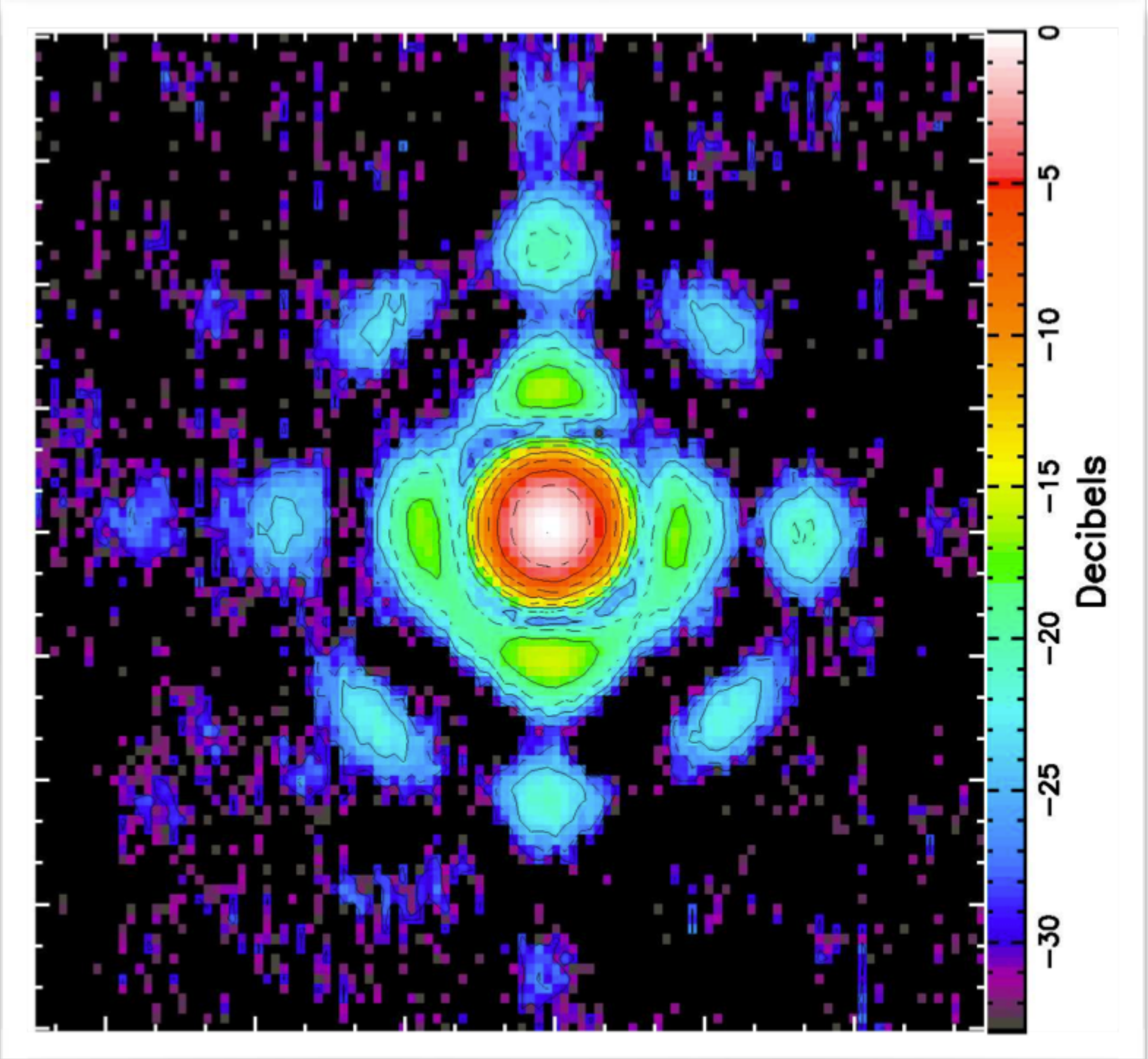
Local oscillator and **mixers**

Antenna positioner

The **antenna positioner** points the antenna at the desired location in the sky.

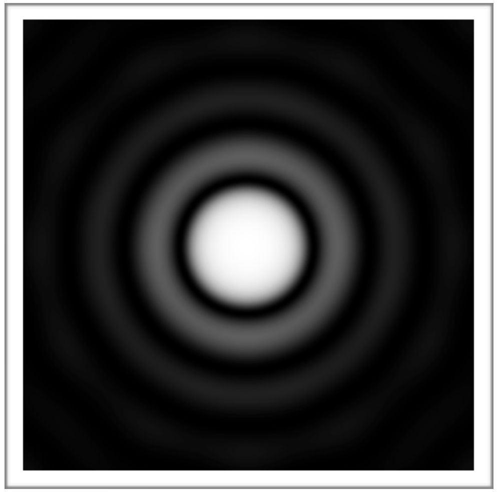
Antenna Basics

Actual **beam pattern at 2300 MHz** of the HartRAO 26m telescope

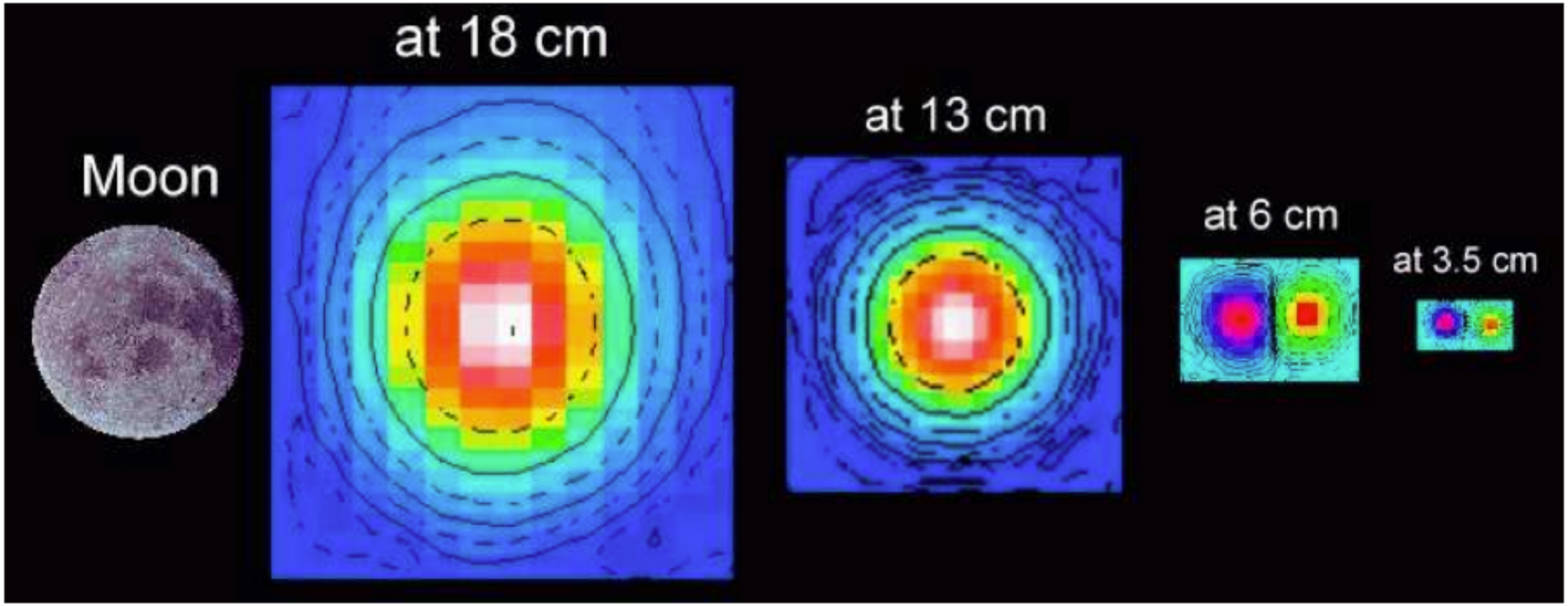


Diffraction pattern of a circular lens or reflector

?



Antenna Basics

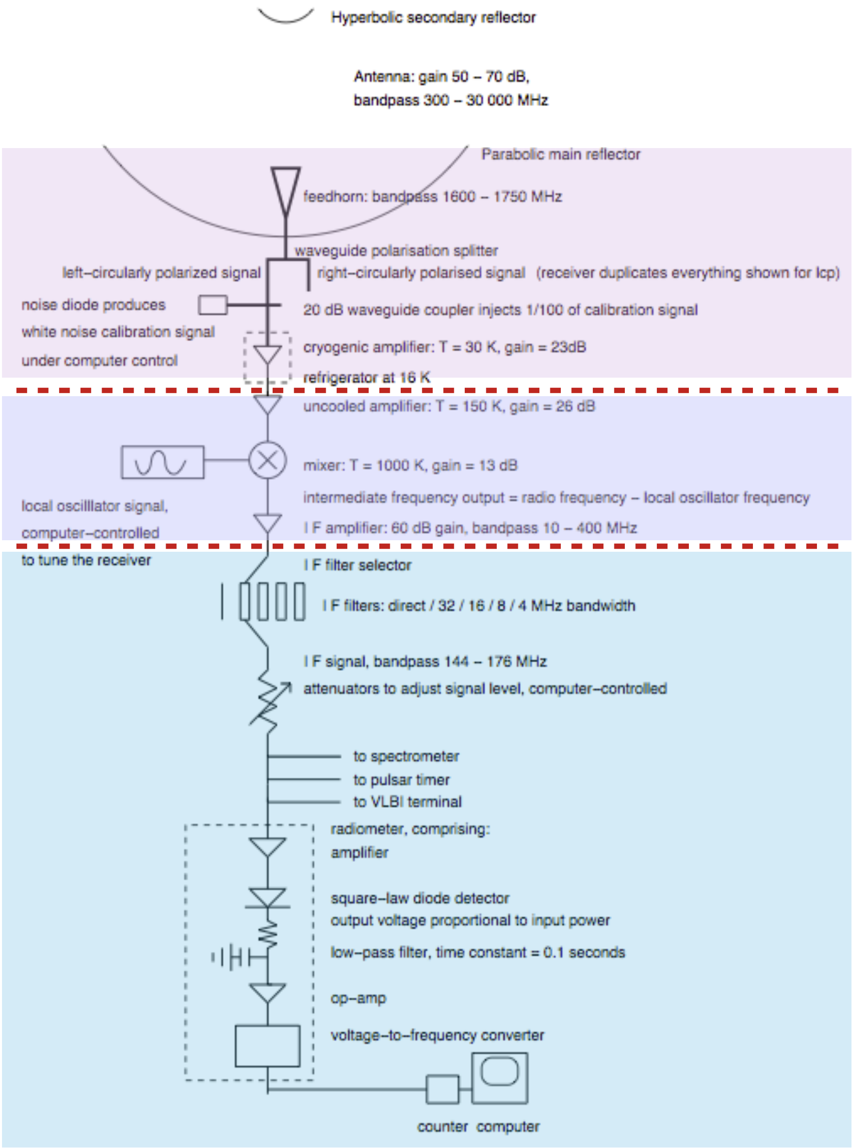


The **size of the main beam** of the 26-m telescope:

Depends on the **operating frequency/wavelength**. Here the actual observed main beam at four wavelengths are shown with the angular size of the Moon for comparison. Dual feeds on the 6 and 3.5 cm receivers produce two beams.

Antenna Basics

Signal chain: Main components of a typical **microwave receiver** and **radiometer**



Feed housing

Deck Room

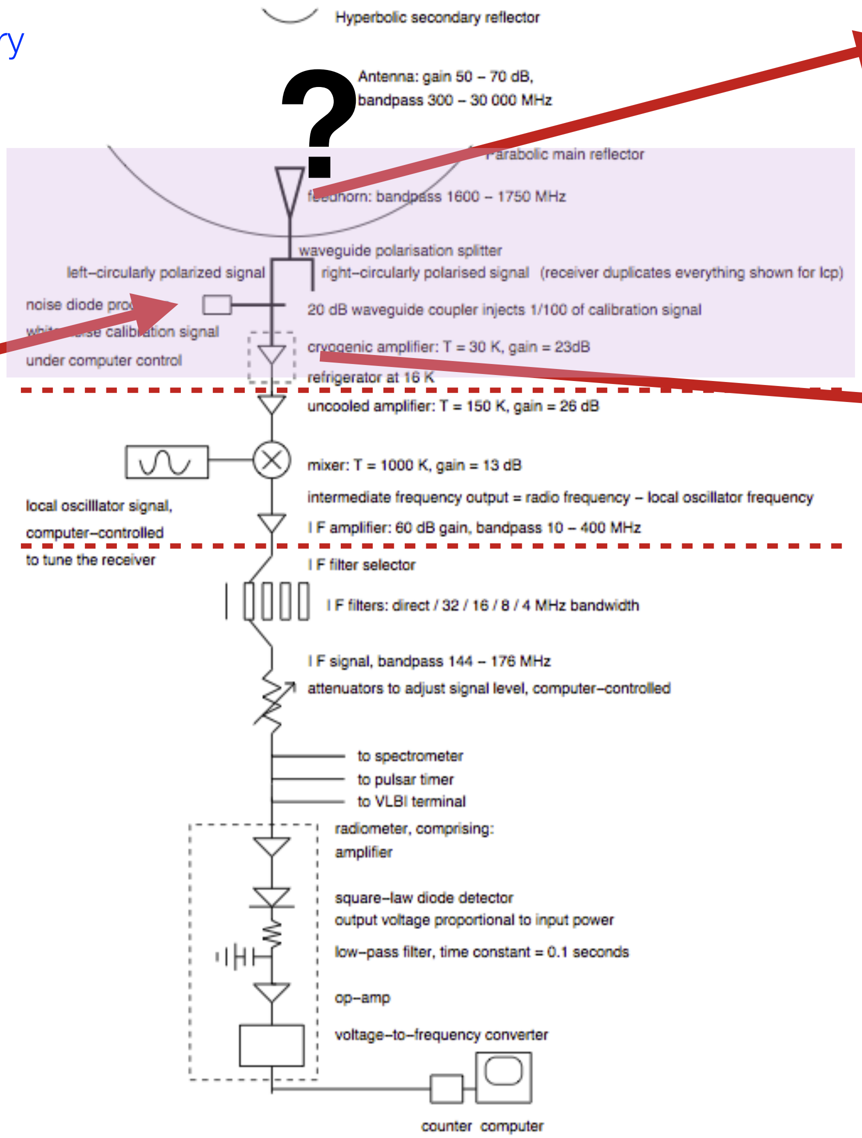
Control Room

Antenna Basics

Signal chain: Main components of a typical **microwave receiver** and **radiometer**

Incoming signal: are very faint and noise like.

To calibrate the system a high stability **noise diode** injects a known noise signal which is split equally by a power divider between the LCP and RCP receiver chains.



Feed horn and **waveguide** (to connect feed horn to first amplifier). All incoming signals are split into **LCP & RCP** by a hybrid waveguide polarisation splitter feeding LCP to one receiver chain and RCP to the other.

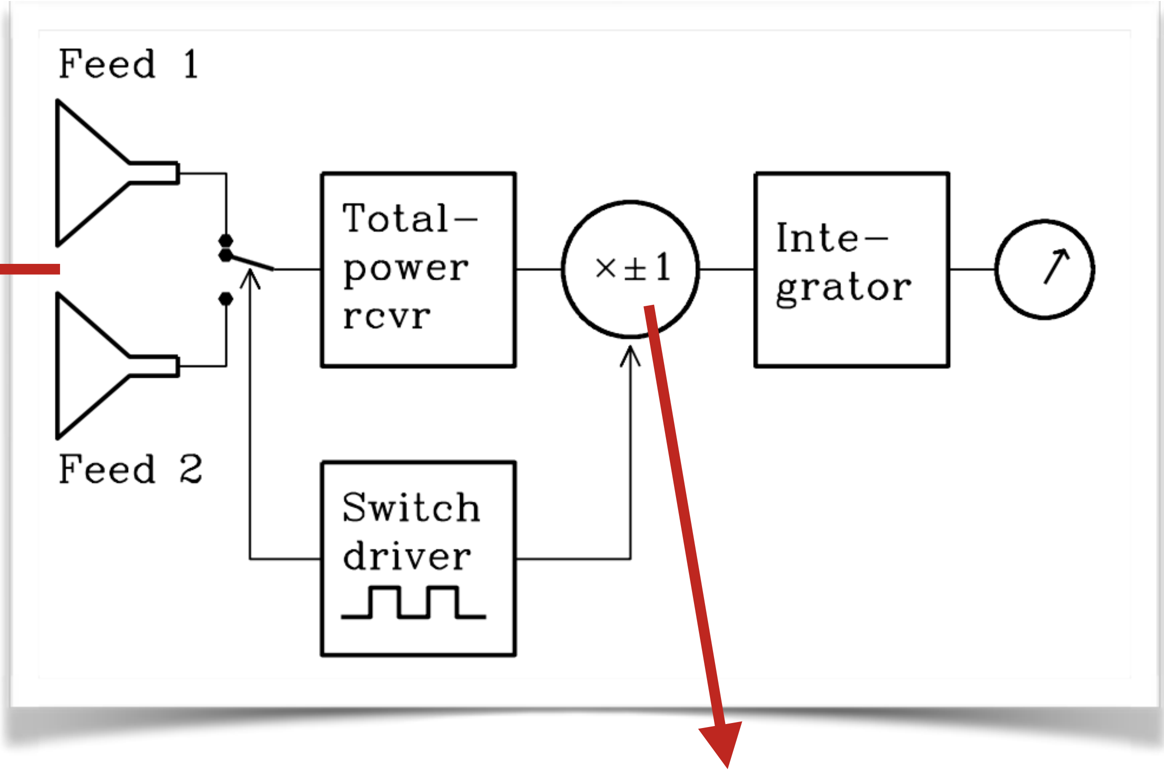
Amplification to a detectable level through a **low-noise amplifier.** Because the internal noise in the amplifiers is generally much larger than the signal, specially designed amplifiers that are **cryogenically cooled** are used to maximize sensitivity.

Detecting Radio Emission from Space

Signal chain: Main components of a typical **microwave receiver** and **radiometer**

If **feed 1** is pointing at the source (angular size of source smaller than separation of the beams from the two feeds) then **feed 2** will point off-source but measure nearly the same sample of atmosphere in the near field.

Dicke-switching: switching rapidly between two **identical feed horns** that are installed **East-West** next to each other on the telescope.

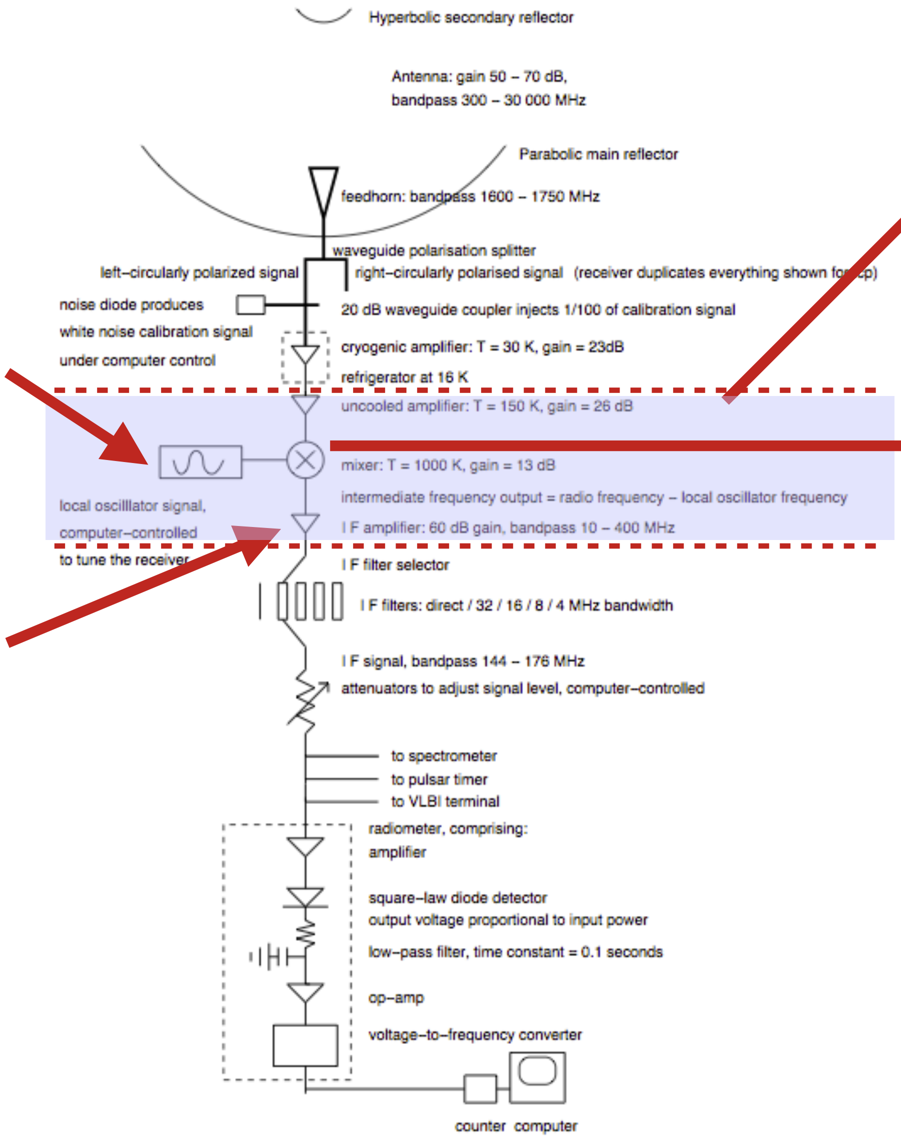


?

Output of receiver is **multiplied by +1** when receiver is connected to **feed 1 and by -1** when connected to **feed 2.** Fluctuations in atmospheric emission and drifts due to changes in receiver gain are canceled for frequencies below the switching rate.

Antenna Basics

Signal chain: Main components of a typical **microwave receiver** and **radiometer**



Local oscillator signal:
computer–controlled
to tune the receiver

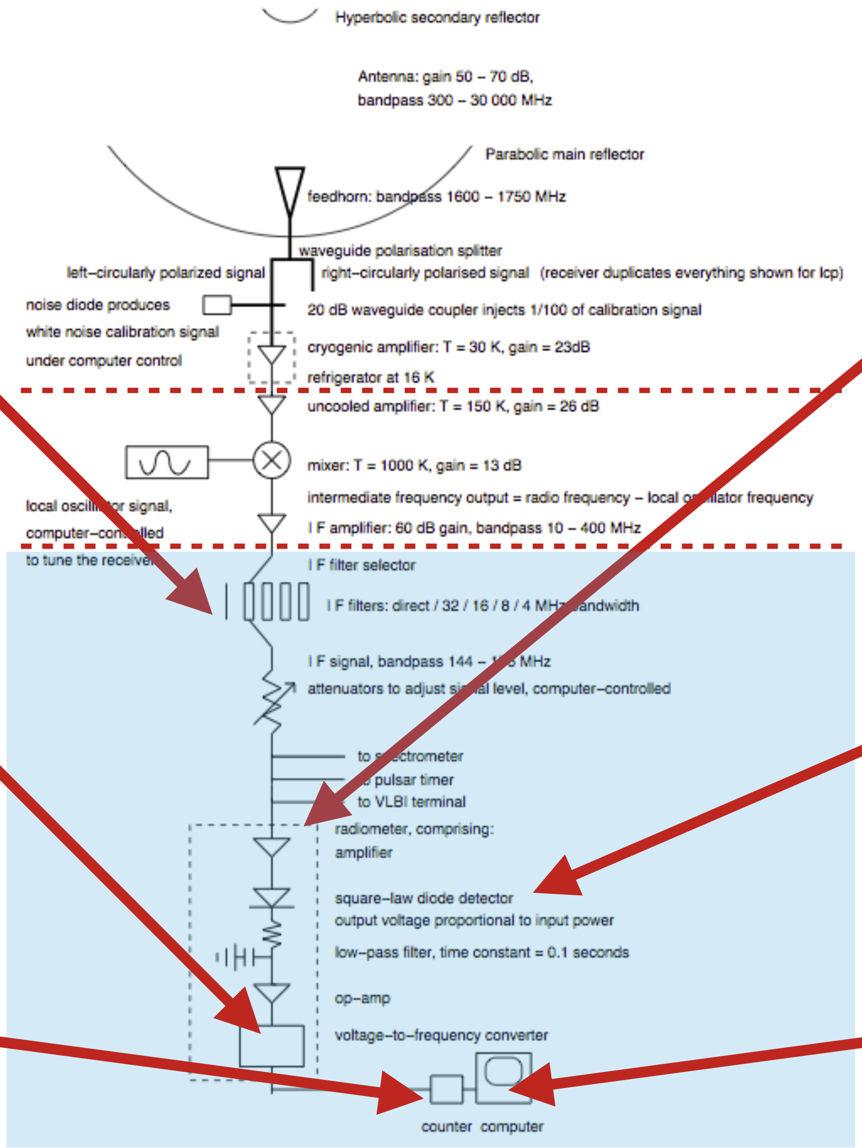
To get the final output the IF signal is amplified, this time using an **IF Amplifier**

RF signal is **down converted** to a lower frequency in order to minimise signal losses in co-axial cable).

The **mixer** multiplies the RF signal with the **local oscillator signal.** The output signal that is used is the difference frequency component (RF - LO) of the product and is called the **intermediate frequency (IF).**

Antenna Basics

Signal chain: Main components of a typical **microwave receiver** and **radiometer**



IF signal can be used unfiltered, or passed through **4, 8, 16 or 32-MHz bandwidth filters** to exclude interference from external signals at some observing frequencies.

Voltage to frequency converter converts the signal to a square wave train (amplitude remains constant but the frequency is proportional to the DC voltage input).

These oscillations are then measured with a **counter** such that the count rate (in units of Hertz) is proportional to the original IF signal's power.

The **radiometer** is the basic instrument for measuring the power of the incoming signal. The simplest form of radiometer is the **"total power"** type shown

The signal is then detected by a **Square law detector** which converts the IF signal into an output DC voltage proportional to the input power.

Signals are loaded onto the Hart26m server in **FITS (Flexible Image Transport System)** format

Detecting Radio Emission from Space

- The antenna needs to be **calibrated to convert the signal amplitude in units of Hertz to units of Antenna Temperature in Kelvins [K],** as it is the standard physically meaningful scale used with most radio analysis techniques.

- The output signal from the radiometer is proportional to the **T_{sys}**, from which we can extract the **T_A.**

$$T_{sys} = T_{Bcmb} + T_A + T_{at} + T_{wv} + T_g + T_R \ [\mathrm{K}]$$

- Prior to each drift scan, the **noise diode injects a noise signal with a known temperature** and this is used to **calibrate the antenna.**

- Comparing the noise diode's temperature to its count rate - can derive a conversion factor [K/Hz] to convert from counts (Hz) to antenna temp (K).

Radiation Basics

- The **aperture efficiency** can be obtained at each frequency;

$$\epsilon_{ap} = \frac{A_e}{A_p}$$

=> max achievable aperture efficiency ~ 0.64

- A_e is the **effective aperture (collecting area)** and A_p is the **physical collecting area,** obtainable from the known diameter of the telescope (25.9 m for the HartRAO 26m telescope).

- The source flux density S, is the product of the brightness and source solid angle

$$h\nu << kT, \quad B = \frac{2kT}{\lambda^2} \quad [\mathrm{W\ m^{-2}\ Hz^{-1}\ sr^{-1}}]$$

$$S = \frac{2kT\Omega_s}{\lambda^2} \ [\mathrm{W\ m^{-2}\ Hz^{-2}}]$$

$$\text{Remember !!! } 1\ \mathrm{Jy} = 10^{-26}\ [\mathrm{W\ m^{-2}\ Hz^{-2}}]$$

Radiometer Equation

- Radio Astronomers like to think of their telescopes as resistors …..

  .. and when you put power into a resistor
  … it heats up

$$h\nu << kT, \quad B = \frac{2kT}{\lambda^2} \quad [Wm^{-2}Hz^{-2}Sr^{-2}]$$

Rayleigh-Jeans Law holds all the way through the radio regime for any reasonable temperature.

- The question is: what flux density is received by your antenna **?**

$$\int Bd\Omega \; = S \; [Wm^{-2}Hz^{-2}]$$

Remember !!! $1 \text{ Jy} = 10^{-26} \text{ [W m}^{-2} \text{ Hz}^{-2}]$

Radiometer Equation

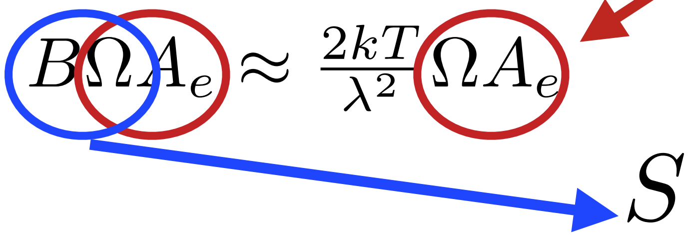
- Now lets look at the power that we actually received by the antenna at a given frequency …..

… we integrate the flux density over the area of the antenna

$$\int S dA = P \; [WHz^{-2}]$$

- Now the antenna theorem states: $A_e\Omega = \lambda^2$

- Lets go one step back from power (without using fancy integration) … what we effectively just did was …



$$B\Omega A_e \approx \frac{2kT}{\lambda^2}\Omega A_e$$

S

$$SA_e = 2kT$$

Radiation Basics

- We obtain the true flux density of the source by summing the antenna temperatures measured in RCP and LCP.

- **The total intensity is the sum of what is received in each polarisation.**

$$S = \frac{k(T_{Alcp}+T_{Arcp})K_s}{A_e} \times 10^{26} \ [\mathrm{Jy}]$$

- To obtain the true flux density S we introduce a size correction factor Ks. For sources that are very small compared to the beam size, *K*s = 1, but the correction must be taken into account if the source size is a significant fraction of the beam size.

- We can only calculate the source flux density if we know the effective aperture (collecting area) at the frequency being used, so we rewrite above equation and substitute the constants, to give;

$$A_e = \frac{1380(T_{Alcp}+T_{Arcp})K_s}{S_o} \ [\mathrm{m}^2]$$

Radiation Basics

- It is important to note that the **flux density** of a radio source is **intrinsic** to it, and the same flux density should be measured by any properly calibrated telescope. However the antenna temperatures measured for the same emitter by different telescopes will be proportional to their effective collecting areas.

- We can now calibrate the telescope at each frequency of interest. We can carry out scans of **standard calibrator sources** (Ott et al. 1994) and measure the peak antenna temperature in each polarisation.

Radiation Basics

- For convenience, we often refer to the **Point Source Sensitivity (*PSS*)**, which is the number of Kelvins of antenna temperature per polarisation, obtained per Jansky of source flux density. This is also known as the **'DPFU'** or **'Degrees per Flux Unit'**.

- For the HartRAO 26 m telescope the *PSS* is typically about 5 Jy/Kelvin per polarisation. The **PSS** in each polarisation is simple to determine experimentally from the measured T_A of calibrator sources of known flux density. **NB: unpolarised sources => half the total flux density is received in each polarisation.**

$$PSS_{lcp} = \frac{(S/2)}{K_s T_{Alcp}} \text{ and } PSS_{rcp} = \frac{(S/2)}{K_s T_{Arcp}} \;[\text{Jy K}^{-1} \text{ per polarisation}]$$

- Theoretically the values for the two polarisations should be the same; in practise there is always a small difference between them, and data from each polarisation should be corrected using the value appropriate for that polarisation.

Detecting Radio Emission from Space

- Simplest way to measure the intensity of a **compact source** in the sky, i.e. one that has an angular size much smaller than the beam, is to use an observing method called a **drift scan**.

- The output of the radiometer will be the **convolution of the antenna beam pattern** with the **brightness distribution of the source.**

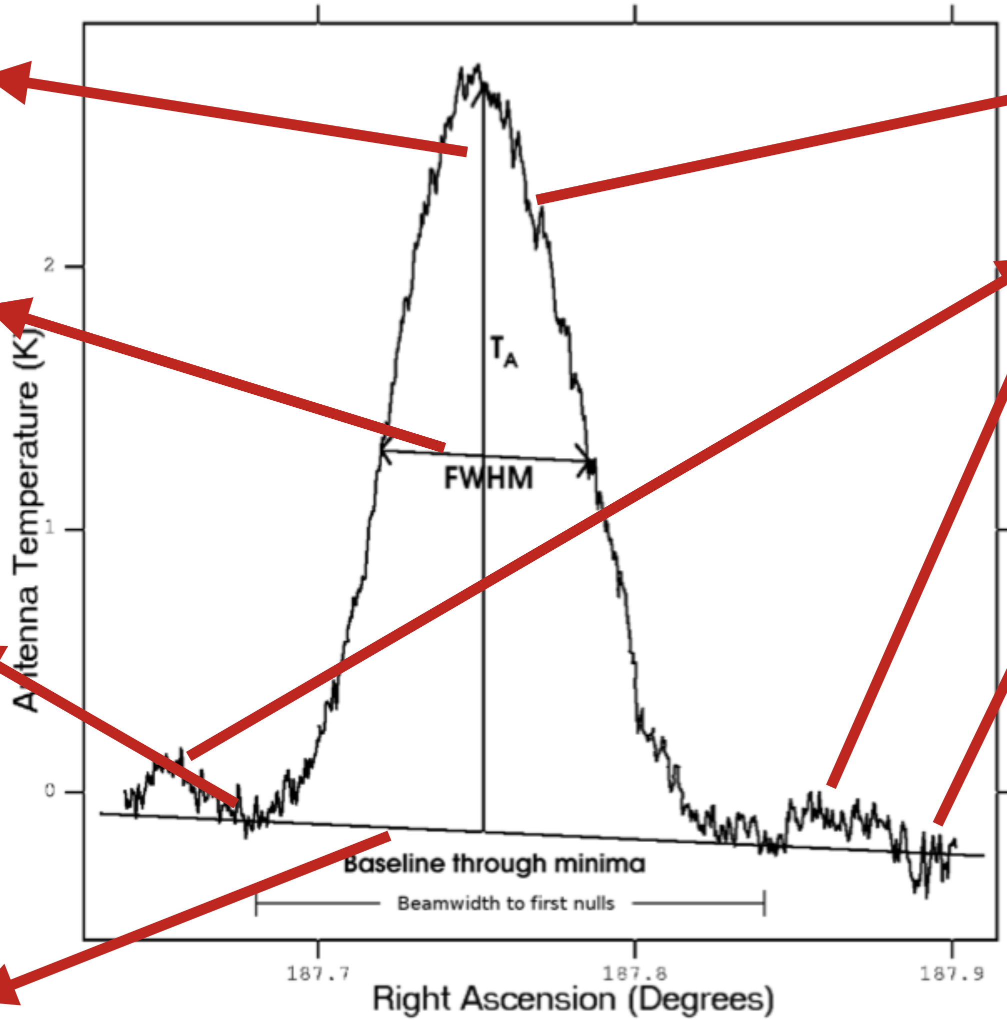
- If the source is compact, the output from the radiometer during the scan is effectively an **east-west cross-section of the beam** of the telescope.

Detecting Radio Emission from Space

NRF
National Research Foundation

HartRAO
Hartebeesthoek Radio Astronomy Observatory

An example of a **drift** scan



We measure the height above the baseline at the centre of the beam to get the **antenna temperature.**

We can also measure the **FWHM** if it is an unresolved source.

Looking at the **minima** across the scan we can see a **slow drift** in the signal level. This could be due to changing atmospheric conditions or a slow change in the gain of the receiver.

We need to establish the **slope between the first nulls** by drawing a line between them.

The passage of the **main beam** across the radio source is in the centre

The first **side lobes** are seen weakly on each side.

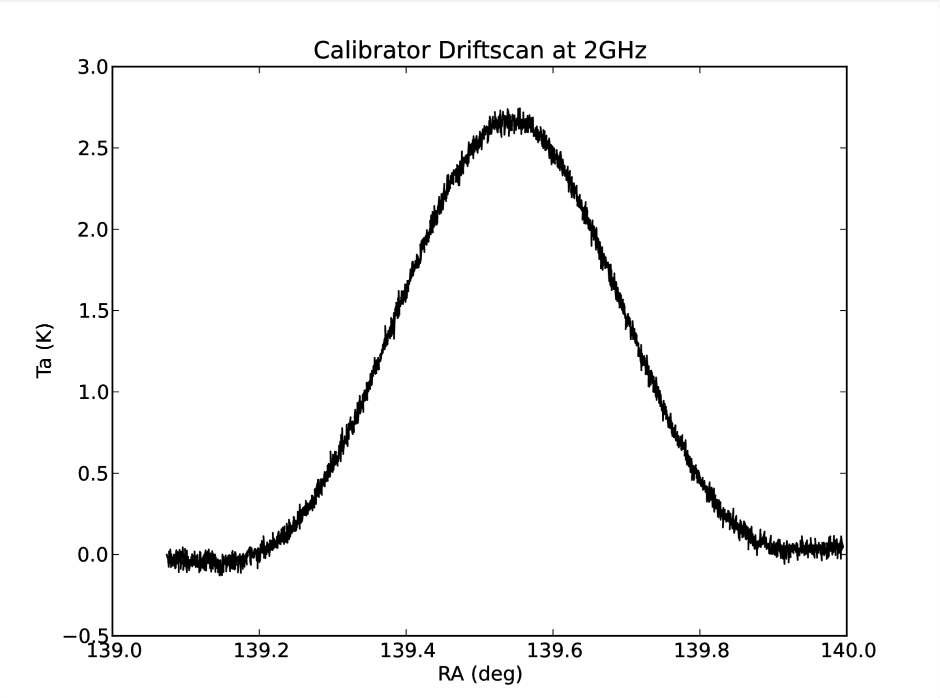
The **noise** is clearly visible.

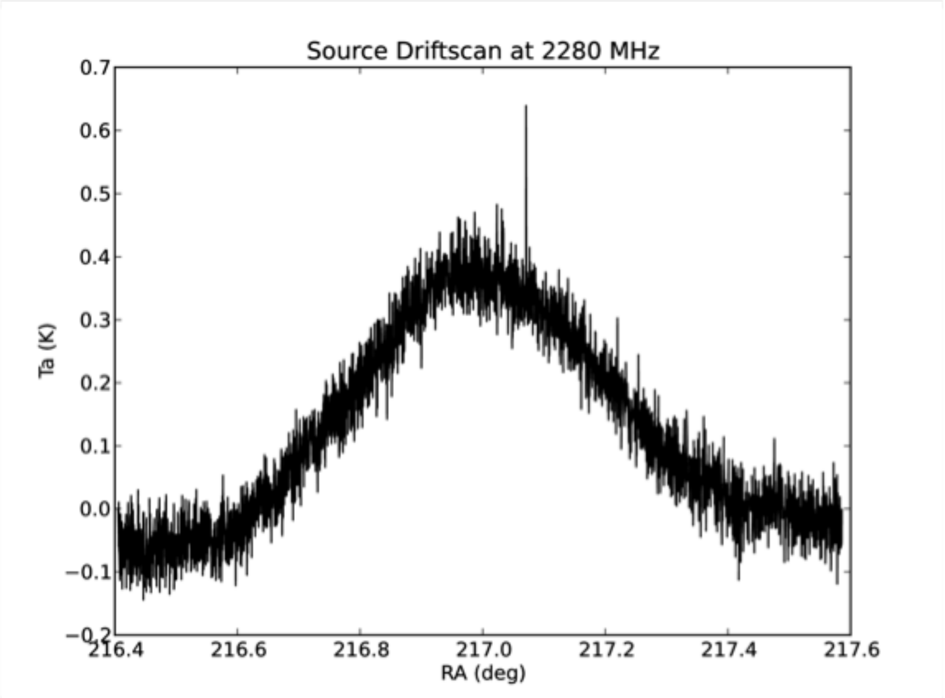
If the source is a calibrator, the *PSS* in this polarisation is obtained from the flux density S at the observing frequency (Ott et al. 1994).

Then we can find the flux density of unknown sources from their antenna temperature.

Monitoring of Active Galactic Nuclei

HartRAO 26 m telescope, drift scans => raw data





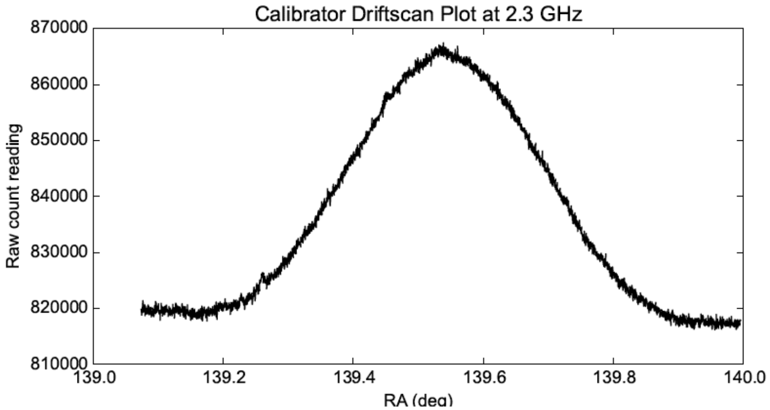
Calibrator: Hydra A
Image Credit: Pfesesani Nemanashi, Mike Gaylard

Source: J1427-4206 / PKS 1424-418Image Credit: Pfesesani Nemanashi, Mike Gaylard

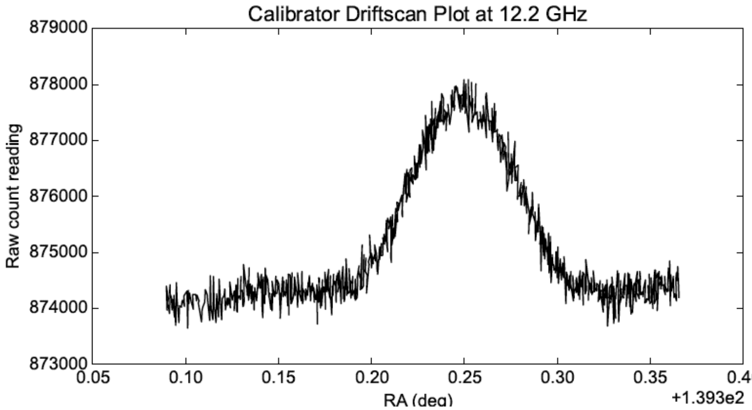
Monitoring of Active Galactic Nuclei

HartRAO 26 m telescope, drift scans => raw data

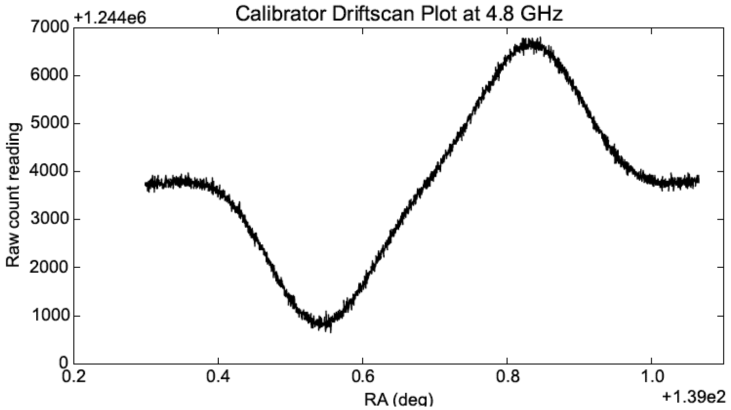
?



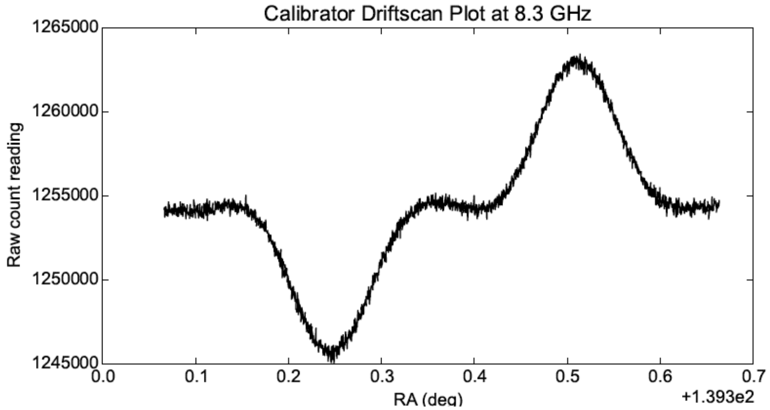
(a) Drift scan pattern output at 2.3 GHz.



(b) Drift scan pattern output at 12.2 GHz.



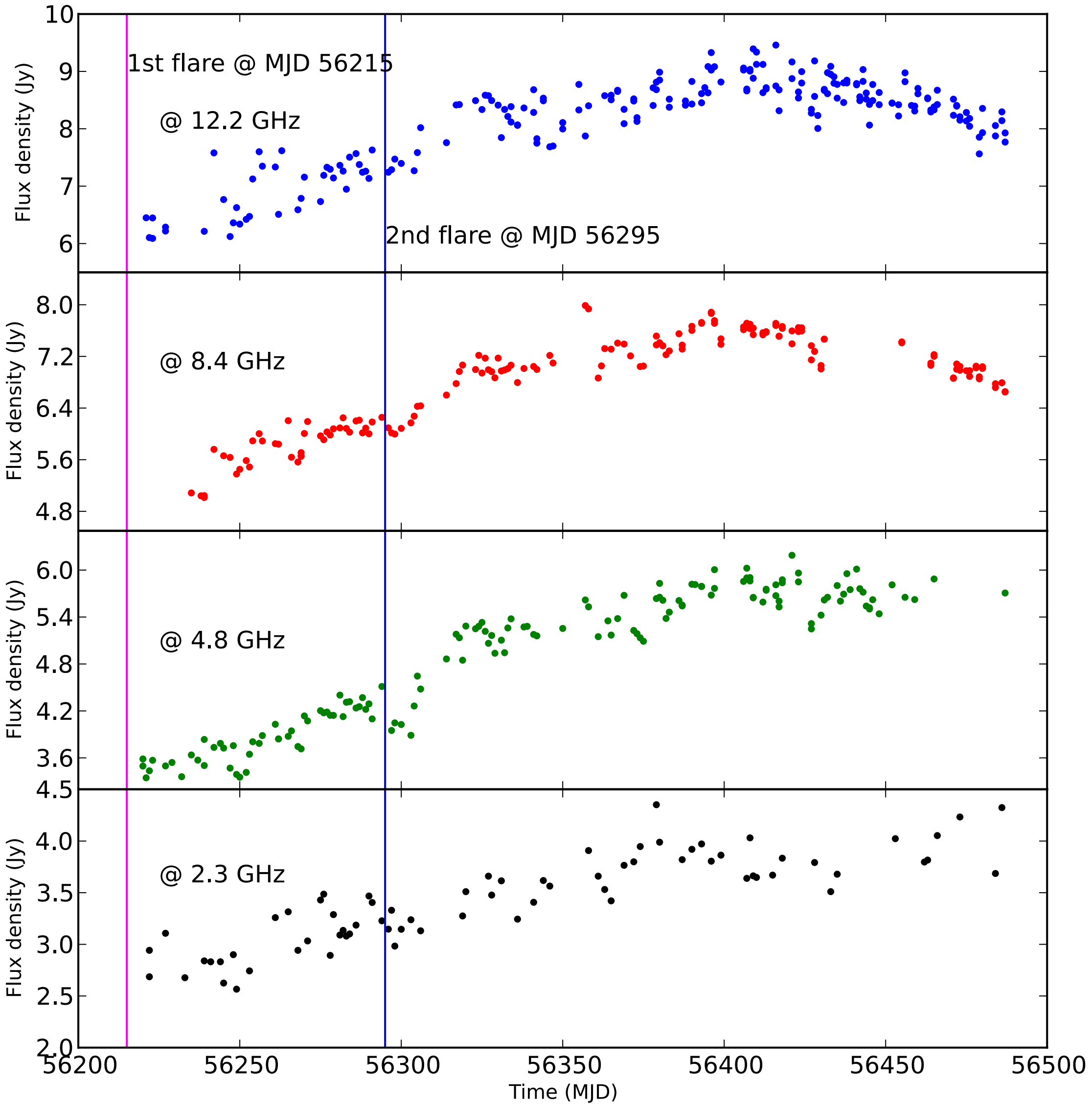
(c) Drift scan pattern output at 4.8 GHz.



(d) Drift scan pattern output at 8.3 GHz.

Monitoring of Active Galactic Nuclei

Monitoring of J1427-4206 - HartRAO 26 m



Data Reduction

3C218/Hydra A

J2000 coordinates RA:09h18m05.67s Dec: -12°05m44.0s

Equation 1

$$A_e = \frac{1380(T_{Alcp}+T_{Arcp})K_s}{S_o} \quad [\mathrm{m}^2]$$

Equation 2

$$\epsilon_{ap} = \frac{A_e}{A_p} \qquad A_p = \frac{\pi}{4}D^2 \quad D = 25.9\ \mathrm{m}$$

Equation 3

$$PSS_{lcp} = \frac{(S/2)}{K_s T_{Alcp}} \text{ and } PSS_{rcp} = \frac{(S/2)}{K_s T_{Arcp}} \ [\text{Jy K}^{-1} \text{ per polarisation}]$$