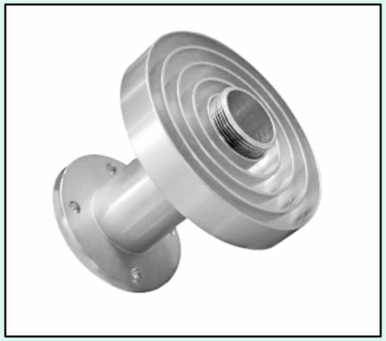

Radio Antennas, Feed Horns, and Front-End Receivers

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EGU and IVS Training School on
VLBI for Geodesy and Astrometry
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Radiation Basics – Power Flux Density

Spectral Power Flux Density, S_f *(Wm^{-2}H^{-1})*,
is the power per unit bandwidth at frequency, *f,* that passes through unit area. [Subscipt *f* indicates spectral density, i.e. that the parameter is a function of frequency and expessed per unit bandwidth (Hz^{-1})]

S_f can be used to express power in bandwidth, δf ,
passing through area, δA , i.e.:

$$P = S_f \cdot \delta A \cdot \delta f$$

S_f is the most commonly used parameter to characterize the strength of a source; it is often referred to simply as the ***Flux Density*** of the source.

Because the typical flux of a radio source is very small, a unit of flux, the ***Jansky,*** has been defined for radio astronomy:

$$1\ \mathrm{Jy} = 10^{-26}\,\mathrm{Wm^{-2}Hz^{-1}}$$

The power from a 1 Jy source collected in 1 GHz bandwidth by a 12 m antenna would take about 300 years to lift a 1 gm feather by 1 mm.

Radiation Basics – Surface Brightness

Surface Brightness, $I_f(\theta,\phi)$ ($\mathrm{Wm^{-2}Hz^{-1}sr^{-1}}$), is ***the Spectral Power Flux Density, S_f***, per unit solid angle (on the sky) radiating from direction, (θ,ϕ). (aka Intensity or Specific Intensity)

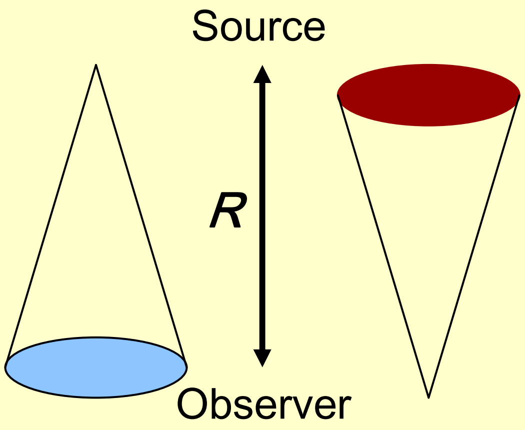
Because I_f ***varies continuously with position*** on the sky, it is the parameter used by astronomers ***for mapping*** sources.

I_f is related to S_f according to

$$S_f = \int_{\Delta\Omega} I_f \, d\Omega$$

Radiation Basics – Brightness Temperature

Flux decreases as 1/R^2 since power per unit area is diluted as the distance from the source increases.



Power generated per unit solid angle increases proportional to R^2 since the area of the source (in the solid angle) increases as the distance from the source increases.

These two opposing effects cancel so that I_f is independent of the distance from the source and hence a property of the source itself.

For a Black Body in thermal equilibrium and in the Rayleigh-Jeans limit (i.e. $\hbar\nu << kT$ which is good for all radio frequencies) of the Plank Equation,

$$I_f(\theta,\phi) = 2kT_B(\theta,\phi)\left(\frac{f}{c}\right)^2 = \frac{2kT_B(\theta,\phi)}{\lambda^2}$$

where k=1.38x10^{-23} (m^2 kg s^{-2} K^{-1}) is the Boltzmann Constant

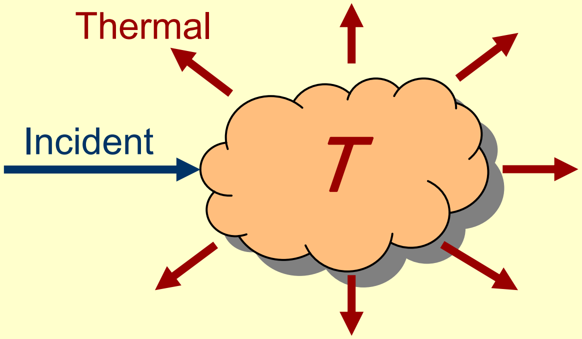
Brightness Temperature, $T_B(\theta,\phi)$, has become a proxy for $I_f(\theta,\phi)$ regardless of whether or not the radiation mechanism is that of a thermal Black Body.

Radiation Basics – Radiative Transfer

For a ***Black Body***, i.e. a perfect absorber,

$$I_f = 2kT_B\left(\frac{f}{c}\right)^2$$

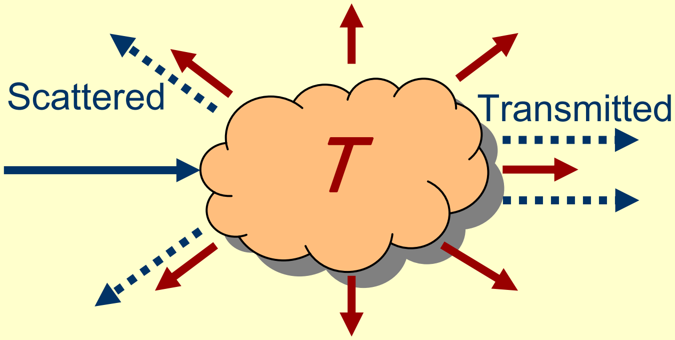
(see previous page)



For an ***imperfect absorber***

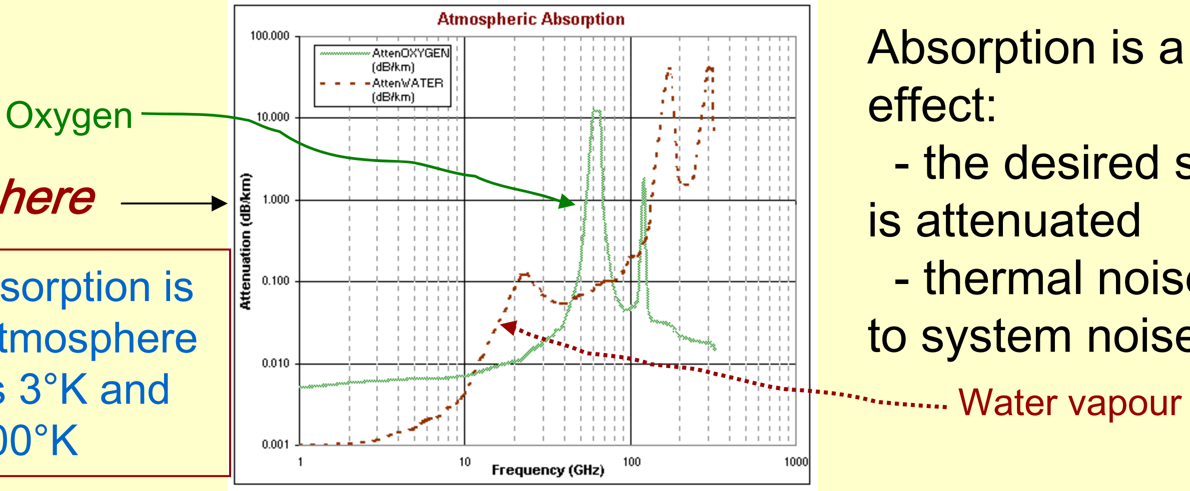
$$I_f < 2kT_B\left(\frac{f}{c}\right)^2$$

$I_f \propto$ absorption coefficient



For the ***atmosphere*** →

Imperfect absorption is why zenith atmosphere at x-band is 3°K and not 300°K



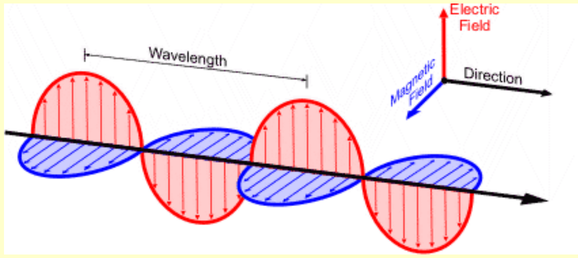
Absorption is a Lose-lose effect:

- the desired signal is attenuated
- thermal noise is added to system noise

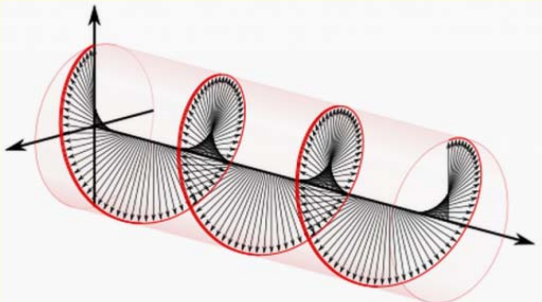
Radiation Basics - Polarization

The Polarization vector is in the instantaneous direction of the E-field vector

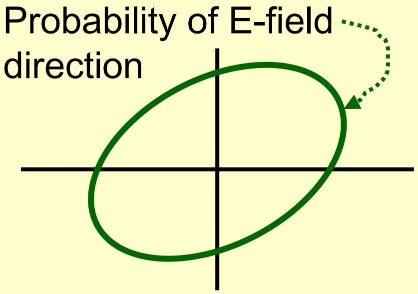
Linear Polarization



Circular Polarization



Random Polarization

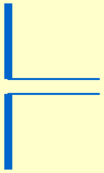


Most geodetic VLBI sources have nearly circular distributions, i.e. are nearly unpolarized.

The most efficient detection of linear and circular polarization signals is with a matched detector.

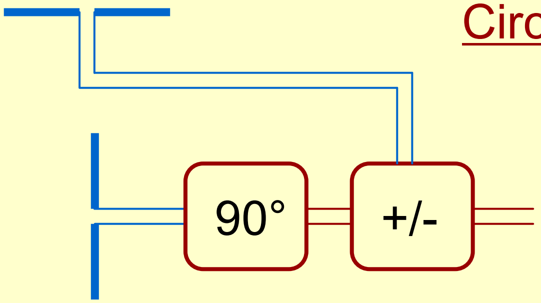
Regardless of the input signal, all of the radiated power can be detected with two orthogonal detectors, either Horizontal and Vertical linear polarization or Left and Right circular polarization. With random polarization this is the only option for detecting all the power.

Linear Detector



e.g. dipole

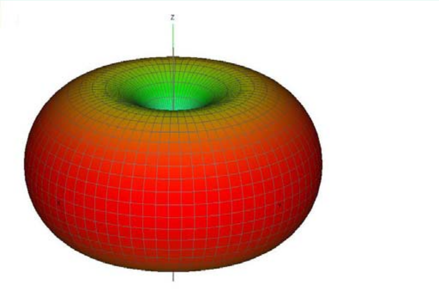
Circular Detector



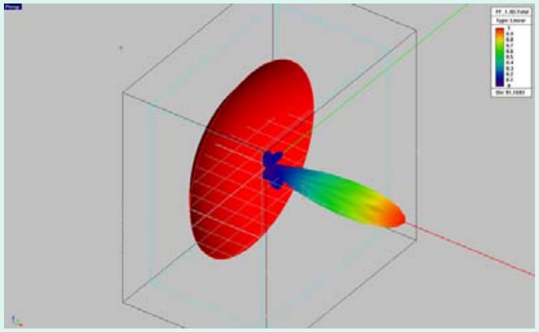
e.g. quadrature combination of dipole outputs

Antenna Basics

- A *Radio antenna* is a device for converting electromagnetic radiation in free space to electric current in conductors
- An *Antenna Pattern* is the variation of power gain (or receiving efficiency) with direction.



Antenna pattern: Dipole antenna



Antenna pattern: Parabolic antenna

- *Reciprocity* is the principle that an antenna pattern is the same whether the antenna is transmitting or receiving.
  - *Transmitting* antennas are generally characterized by *gain*
  - *Receiving* antennas are generally characterized by ***effective area***

Antenna Gain - Characterizes a *Transmitting* Antenna

Antenna gain is defined as, $G(\theta,\phi)=\dfrac{P(\theta,\phi)}{P_{iso}}$, where

$P(\theta,\phi)$ ~ power per unit solid angle transmitted in direction, (θ,ϕ)

P_{iso} ~ power per unit solid angle transmitted by an isotropic antenna, $P_{iso}=\dfrac{P_{in}}{4\pi}$

For a *lossless antenna*, $P_{out}=P_{in}$, hence $\langle G_{lossless}\rangle=1$ and $\int\limits_{Sphere} G d\Omega=4\pi$

An *isotropic antenna* is a ***hypothetical*** lossless antenna radiating uniformly in all directions, i.e. $G_{iso}(\theta,\phi)=1$.

[Note: An isotropic antenna is a useful analytic construct but cannot be built in practice.]

The *beam solid angle* of an antenna is defined as $\Omega_A=\int\limits_{Sphere}\dfrac{G(\theta,\phi)}{G_{\max}}d\Omega$ hence

$$\Omega_A=\frac{4\pi}{G_{\max}}$$

Effective Area – Characterizes a *Receiving* Antenna

The total power received into area, $A_e(\theta,\phi)$, and bandwidth, BW , is

$$P(\theta,\phi)=\left(\frac{S_f}{2}\right)A_e(\theta,\phi)BW$$

$$\therefore\ A_e(\theta,\phi)=\frac{2P(\theta,\phi)}{S_f\cdot BW}$$

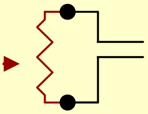
Note: *S* includes all radiated flux. For an unpolarized source, only one half the flux is received per polarized detector. Hence the use of $\left(\frac{S}{2}\right)$ in the equations.

At a particular frequency, $A_e(\theta,\phi)$ can be rewritten

$$A_e(\theta,\phi)=\frac{2P_f(\theta,\phi)}{S_f}$$

where P_f *(WHz*$^{-1}$*)* is the power received per unit frequency

The noise power (per Hz) generated by a resistor at temp, *T*, can be written $P_f=kT$.



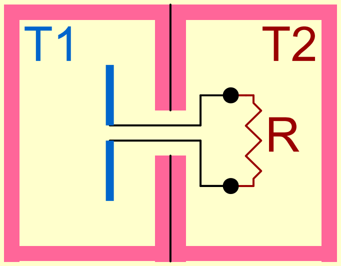
$$P_f=kT$$

Note: It is common to use *T* as a proxy for P_f, especially in low power/noise situations.

Average *effective area*

Antenna Side

Black Body cavities



Resistor Side

$$P_f = \int_{Sphere} A_e(\theta,\phi)\frac{I_f}{2}\,d\Omega$$

$$P_f = \frac{2kT}{2}\left(\frac{f}{c}\right)^2 \int_{Sphere} A_e\,d\Omega$$

Rayleigh-Jeans

$$P_f = kT$$

At thermodynamic equilibrium, T1=T2 and no current flows between antenna and resistor

Antenna Side must equal Resistor Side

$$\therefore \frac{2kT}{2}\left(\frac{f}{c}\right)^2 \int_{Sphere} A_e\,d\Omega = kT$$

$$\int_{Sphere} A_e\,d\Omega = \left(\frac{c}{f}\right)^2 = \lambda^2$$

$$\boxed{\langle A_e \rangle = \frac{\lambda^2}{4\pi}}$$

For an isotropic antenna

$$A_e(\theta,\phi) = \langle A_e \rangle = \frac{\lambda^2}{4\pi}$$

Effective Area ◄·····► Gain

From reciprocity

$$A_e(\theta,\phi) \propto G(\theta,\phi)$$

From earlier results

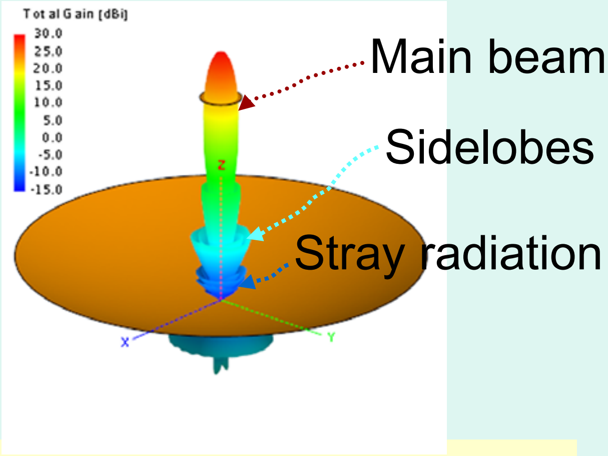
$$\langle A_e \rangle = \frac{\lambda^2}{4\pi} \qquad \text{and} \qquad \langle G \rangle = 1$$

Combining these

$$A_e(\theta,\phi) = G(\theta,\phi)\frac{\lambda^2}{4\pi} = G(\theta,\phi)\cdot A_{iso}$$

This allows us to calculate the receiving pattern from the transmitting pattern and vice versa.

High Gain Antenna (G_{max}>>1) e.g. Parabolic Reflector Antenna



It was already shown that, in a Black Body cavity, the received spectral density is

$$P_f = \int_{Sphere} A_e(\theta,\phi) \frac{I_f(\theta,\phi)}{2} d\Omega = kT$$

For a high gain antenna, $A_e(\theta,\phi)$ is concentrated in the main beam; hence

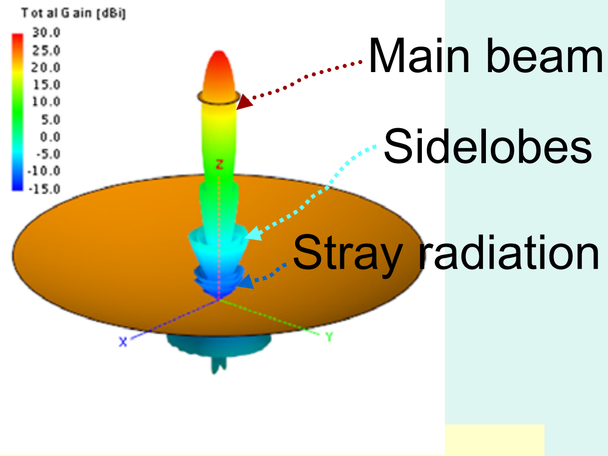
$$P_f = \int_{\Omega-Beam} A_e(\theta,\phi) \frac{I_f(\theta,\phi)}{2} d\Omega = kT$$

which implies that $I_f(\theta,\phi)$ need only cover the main beam for this result to be true.

If a source is smaller than the main beam,

$$P_f = \int_{\Omega-Beam} A_e \frac{I_f}{2} d\Omega = kT \frac{\Omega_{Source}}{\Omega_{Beam}}$$

High Gain Antenna (G_{max}>>1)
e.g. Parabolic Reflector Antenna



Spectral Power Flux Density, S_f, Relations

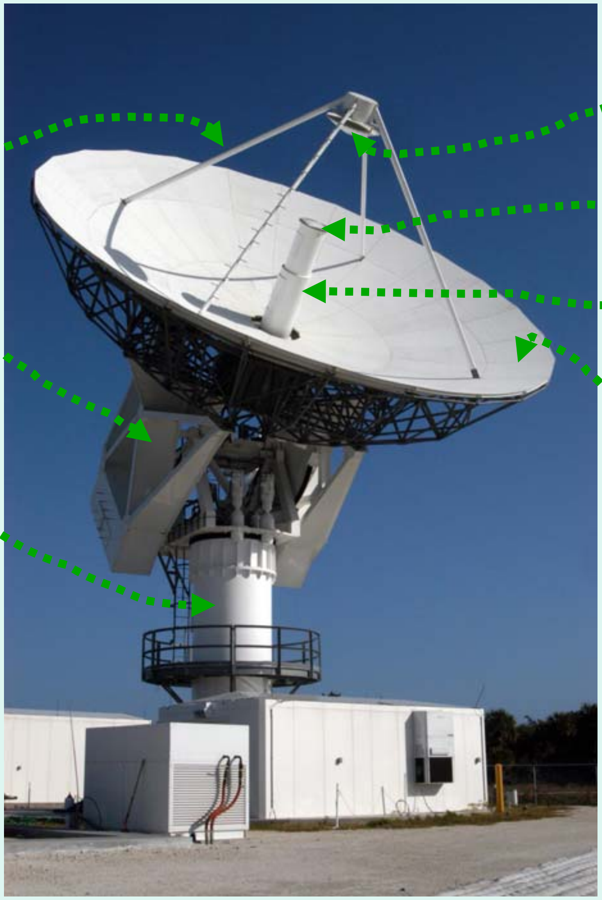
If the source is larger than the beam

$$P_f^{\mathrm{Received}} = \int_{\Omega-Beam} A_e \frac{I_f}{2}\, d\Omega = \frac{A_e S_f}{2} \frac{\Omega_{Beam}}{\Omega_{Source}}$$

If the source is smaller than the beam

$$P_f^{\mathrm{Received}} = \int_{\Omega-Source} A_e \frac{I_f}{2}\, d\Omega = \frac{A_e S_f}{2}$$

Parabolic Reflector Antenna



Sub-reflector support legs

Secondary reflector
(aka Sub-reflector)

Feed Horn

Feed Horn Support Structure

Antenna positioner

Primary reflector

Pedestal
(aka antenna tower)

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

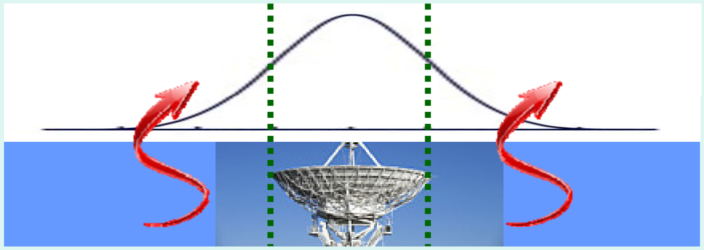
The *feed horn* converts E-M radiation in free space to electrical currents in a conductor.

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

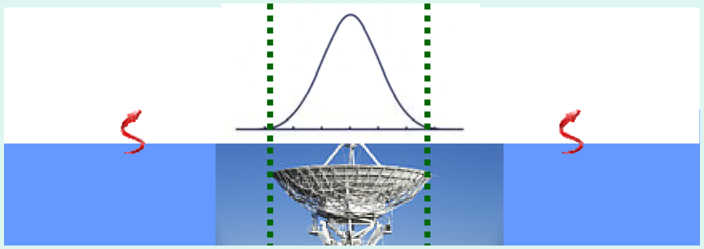
Aperture Illumination

The ‘***Feed Horn***’ is itself an antenna with a power pattern that ‘***illuminates***’ the reflector system. Although the terminology derives from signal transmission, the feed works equally well, in a radio telescope, as a receiving element.

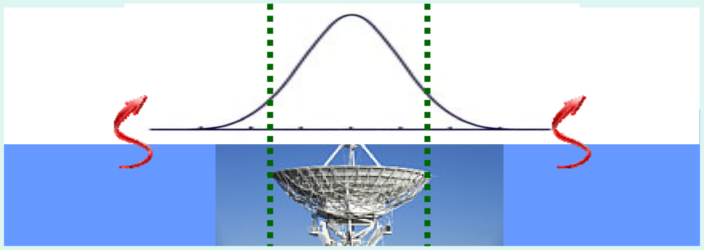
Over-illumination: The feed pattern extends well beyond the edge of the dish. Too much ground radiation is picked up from outside the reflector.



Under-illumination: The feed pattern is almost entirely within the dish. There is minimal ground pick-up but the dish appears smaller than it is.

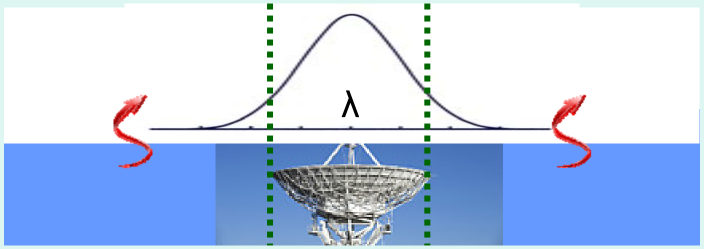


Optimal-illumination: This is the best balance between aperture illumination and ground pick-up. The power response is usually down about 10 dB (10%) at the edge of the dish.



Aperture Illumination ◀····▶ Beam Pattern

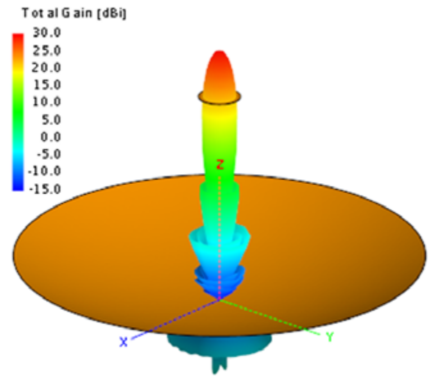
The beam pattern of the antenna is the Fourier Transform of the aperture illumination (assuming that the aperture is measured in units of λ).



Aperture illumination

FFT

◀·······▶



Beam pattern

Depending on the details of the aperture illumination, the Half Power Beam Width (HPBW) is approximately

$$HPBW \approx \frac{\lambda}{D}$$

where D is the diameter of the reflector.

The beam becomes narrower as dish becomes larger or λ becomes shorter. (λ becoming shorter is the same as the frequency becoming larger).

Aperture efficiency

The antenna effective area, A_e , can be compared to the antenna geometric area with the ratio, η_A , being the antenna efficiency, i.e.

$$A_e = \eta_A A_{geo}$$

where, for a circular antenna, $A_{geo} = \frac{\pi}{4} D^2$.

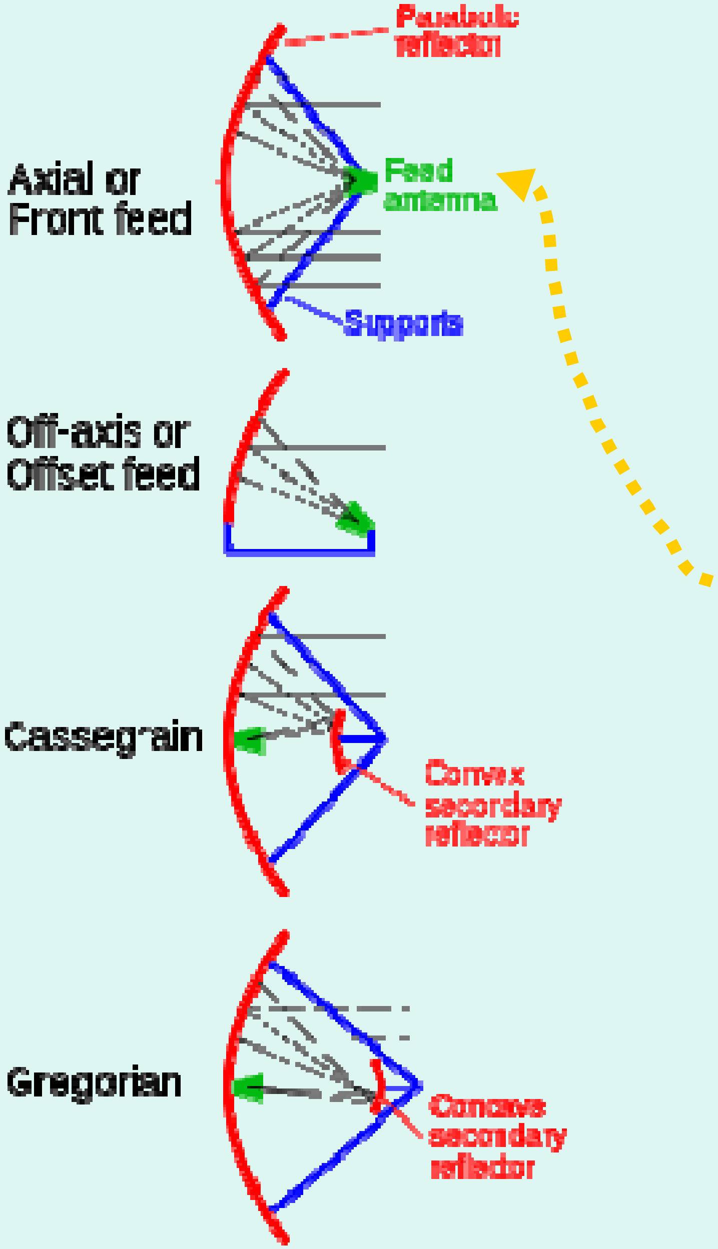
The antenna efficiency can be broken down into the product of a number of sub-efficiencies:

$$\eta_A = \eta_{sf} \times \eta_{bl} \times \eta_s \times \eta_t \times \eta_p \times \eta_{misc}$$

where

- η_{sf} Surface accuracy efficiency (both surface shape and roughness)
- η_{bl} Blockage efficiency
- η_s Spill-over efficiency
- η_t Illumination efficiency
- η_p Phase centre efficiency
- η_{misc} Miscellaneous efficiency, e.g. diffraction and other losses.

Antenna Optics – i.e. reflector configuration



The *purpose of the reflector system* is to concentrate the radiation intercepted by the full aperture (and from the boresite direction) into a single point.

Axial or Front Feed – aka Prime Focus

The front feed antenna uses a parabaloid primary reflector with the phase centre of the feed placed at the focal point of the primary reflector.

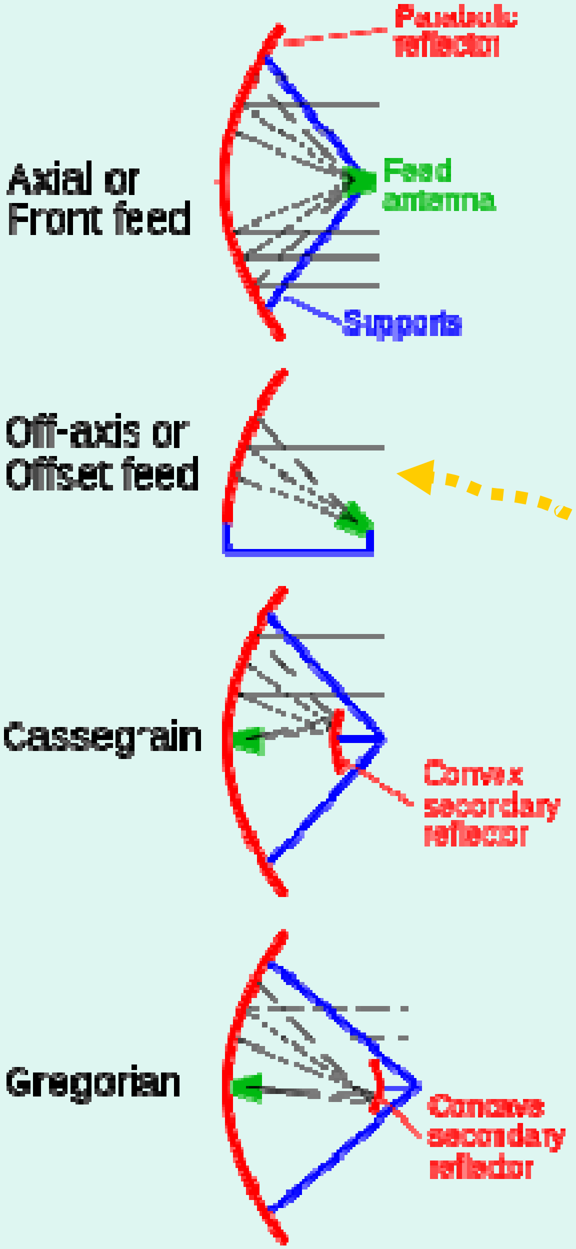
Advantages:

- Simple
- No diffraction loss at the sub-reflector (more important at lower frequencies)
- Only one reflection required leading to less loss and less noise radiated (minimal benefit if the reflector material is a good conductor).

Disadvantages:

- Spill-over looks directly at the warm ground.
- Added structural strength required to support feed plus front end receiver at the prime focus

Antenna Optics – i.e. reflector configuration



Off-axis or Offset Feed

The primary reflector is a section of parabaloid completely to one side of the axis, with the feed supported from one side of the reflector.

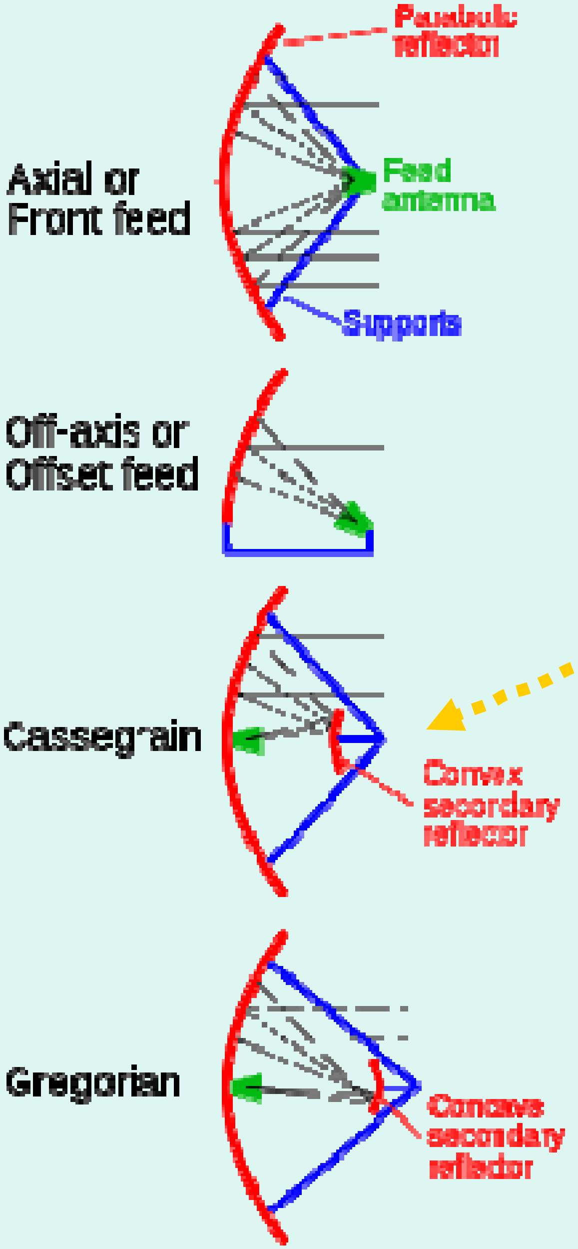
Advantages:

- No aperture blockage (leading to higher antenna efficiency)

Disadvantages:

- Spill-over looks preferentially toward the warm ground (especially for high-side feed support).
- Lack of symmetry.
- Added structural strength required to support feed plus front end receiver to one side of the reflector.
- Complications with all-sky positioner for low-side feed support
- Complications with feed/receiver access for high-side feed support

Antenna Optics – i.e. reflector configuration



Cassegrain

This is a two reflector system having a hyperboloid secondary reflector (sub-reflector) between the prime focus and the primary reflector. The sub-reflector focuses the signal to a point between the two reflectors.

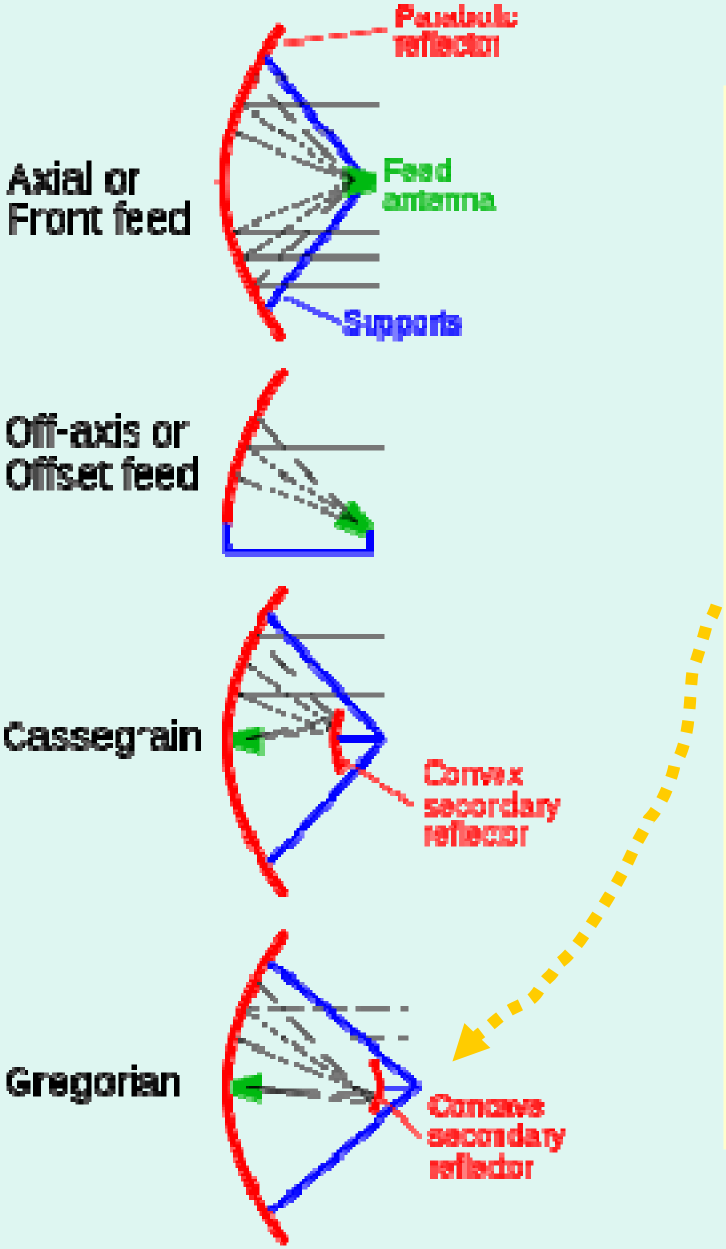
Advantages:

- Spill-over past the sub-reflector is preferentially toward cold sky.
- Minimal structural strength is required since the sub-reflector is located nearer the primary.

Disadvantages:

- The sub-reflector obscures the prime focus so it is difficult to achieve simultaneous operation with a prime focus feed.

Antenna Optics – i.e. reflector configuration



Gregorian

This is a two reflector system having a parabaloid secondary reflector (sub-reflector) located on the far side of the prime focus. The sub-reflector focuses the signal to a point between the prime focus and the primary reflector.

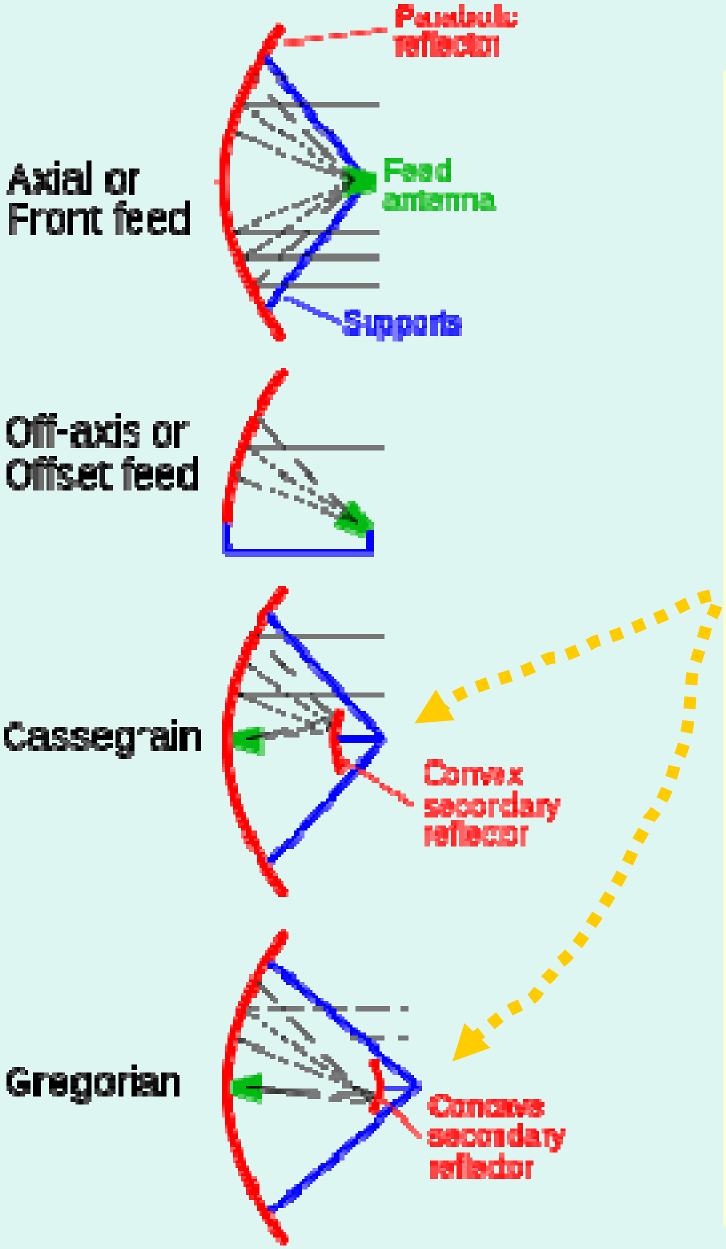
Advantages:

- Spill-over past the sub-reflector is preferentially toward cold sky.
- The sub-reflector does not obscure the prime focus so it is easier to achieve simultaneous operation with a prime focus feed.

Disadvantages:

- Greater structural strength is required since the sub-reflector must be supported further away from the primary.

Antenna Optics – i.e. reflector configuration



Shaped Reflector System

A shaped reflector system requires optics that involve more than one reflector, e.g. the Cassegrain or Gregorian systems. With a shaped reflector system, the shape of the secondary reflector is altered to improve illumination of the primary. To compensate for the distortion of the secondary, the shape of the primary must also be changed away from a pure parabaloid.

Advantages:

- Improved efficiency

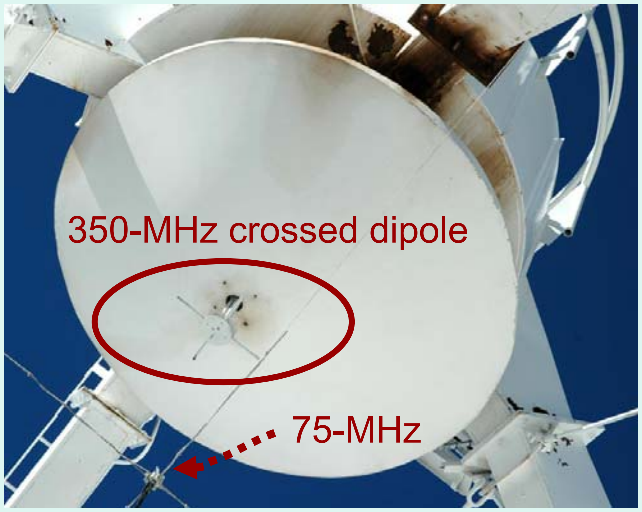
Disadvantages:

- The reflectors are no longer simple parabaloids or hyperbaloids but more complex mathematical shapes. [With the advent of readily available computer aided design and manufacture this is no longer a significant complication.]

Antenna Feed – crossed dipole

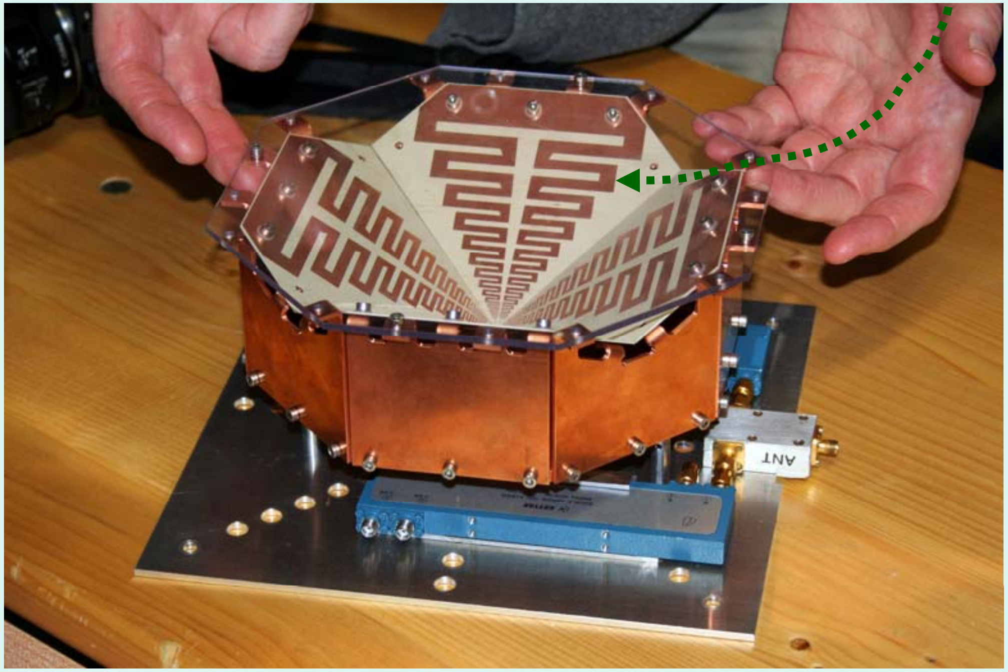
An antenna feed is itself an antenna. Whereas the reflector system concentrates radiation from a wide area into a single point, the feed converts the E-M radiation at the 'single point' into a signal in a conductor.

One of the simplest feeds is a crossed dipole, i.e. a pair of orthogonal ½-λ dipoles usually located ¼-λ above a ground plane, e.g. the VLA crossed dipoles.



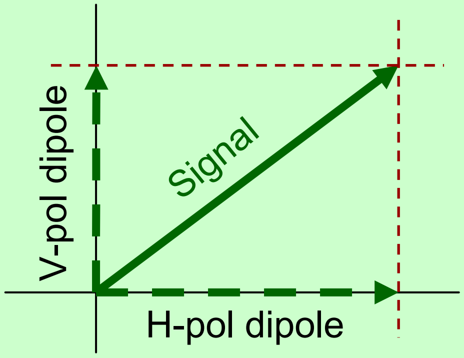
Antenna Feed - Broadband

A broadband feed can be designed using a series of log periodic dipoles. Log periodic means that the length and separation of the dipoles increases in a geometric ratio chosen so that all frequencies are covered. Here we see a version of the Eleven Feed developed at Chalmers University for VLBI2010. This version covers 2-12 GHz with a newer version covering 1-14 GHz.



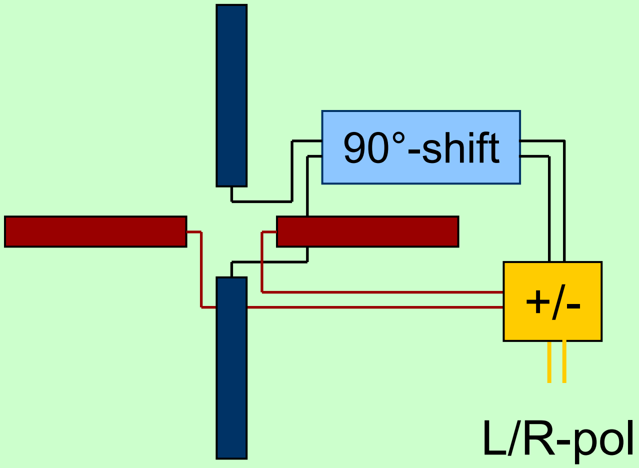
Folded dipoles of the Eleven Feed

Crossed dipole - polarization



An arbitrary polarization vector decomposed into orthogonal components

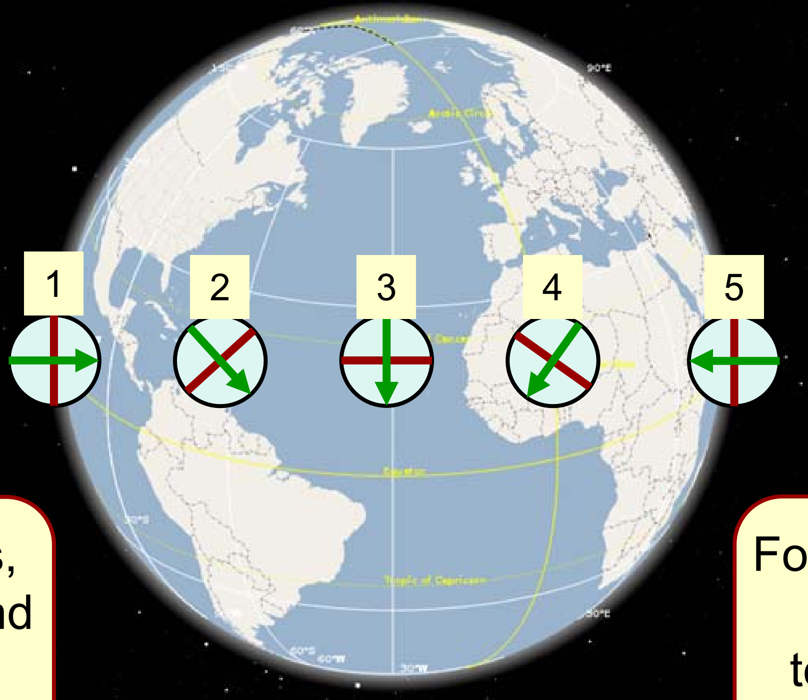
Each dipole of a crossed dipole is sensitive to signals with polarization vectors parallel to the dipole. Two orthogonal dipoles can receive all the power from an arbitrary signal.

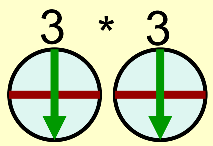


Circular polarization is formed by combining linear signals in quadradure (i.e. by adding and subtracting linear polarizations after one of them has been shifted by 90°). This works easily for narrow band signals – but the existence of broadband 90°-shifters (hybrids) also makes it applicable to broadband signals (like VLBI2010). For this to work well, the electronics must represent the mathematics accurately.

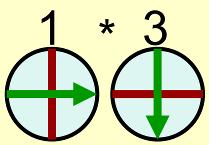
VLBI works best with circular polarization

As seen from above, the linear polarization orientation for alt/az antennas varies with geographic location





For parallel orientations, correlated signal is found in the co-pol products, e.g. v1*v2 and h1*h2

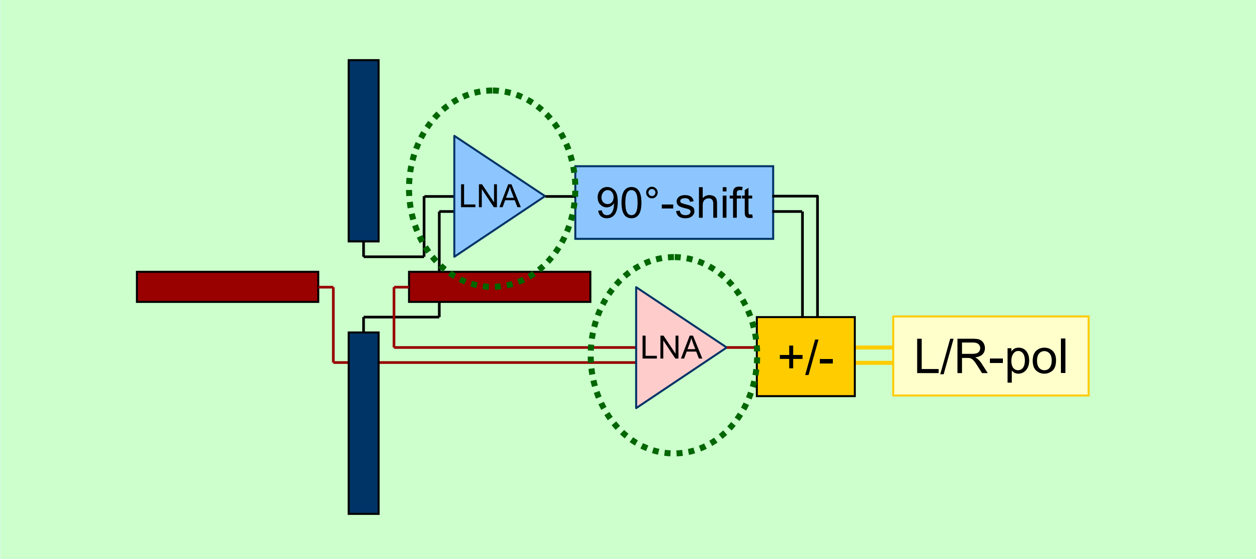


For orthogonal orientations, correlated signal shifts to the cross-pol products e.g. v1*h2 and h1*v2

To avoid the shifting of correlated amplitude between cross- and co-pol products , VLBI traditionally uses circular polarization, where correlated amplitude is independent of relative polarization orientation.

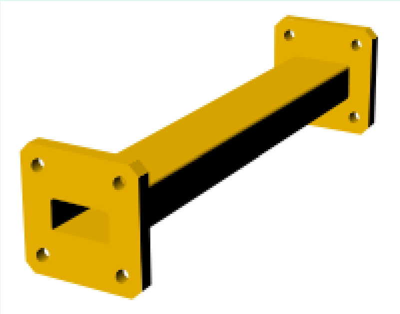
Circular Polarization

To avoid noise degradation in the combining network, LNA's are required immediately on the outputs of the dipole antennas. Any amplitude or phase imbalances in the amplifiers or inaccuracies in the 90° phase shifter or combiners will degrade the generation of circular polarization.



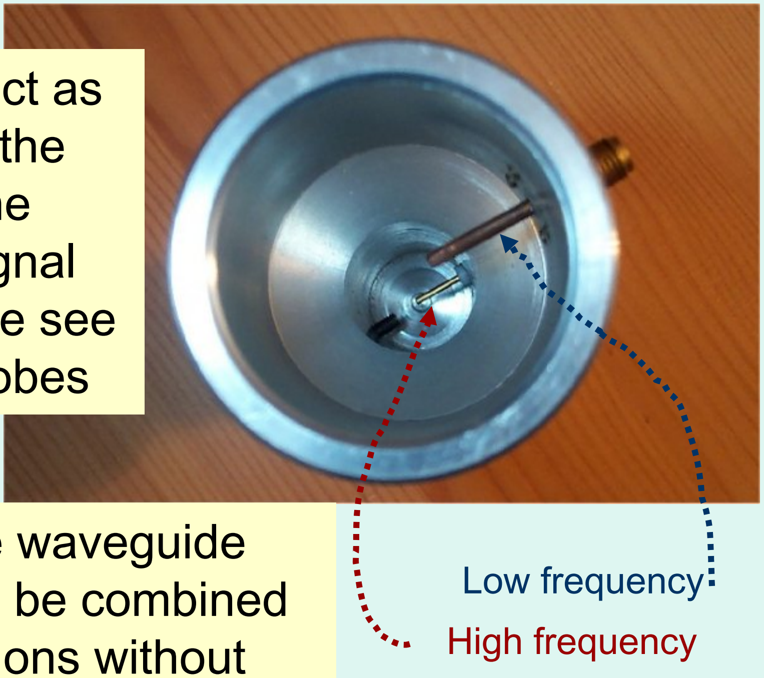
Feed Horns (as used in S/X-band feeds)

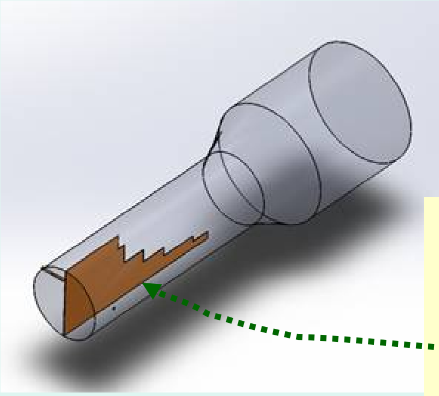
A piece of waveguide can be used directly as a feed. However, because there is a significant mismatch between the impedence of the waveguide and that of free space, much of the input radiation is reflected or scattered.



To improve the match the waveguide is often flared and corrugated.

Dipole antennas act as probes to convert the E-M radiation in the waveguide to a signal in a cable. Here we see dual frequency probes





If a septum is inserted in the waveguide both linear polarizations can be combined to get both circular polarizations without the need for external circuitry.

Antenna Positioners – Alt-az

The antenna positioner is system that points the beam of the antenna toward the area of sky of interest. There are three main positioner systems: alt-az, equatorial, and X-Y.

Alt-az

This is the workhorse antenna mount for large radio telescopes. It has a fixed vertical axis, the azimuth axis, and a moving horizontal axis, the altitude (or elevation) axis that is attached to the platform that rotates about the azimuth axis. The azimuth motion is typically ±270° relative to either north or south and the elevation motion is typically 5° to 85°.

Advantages:

- Easy to balance the structure and hence optimum for supporting a heavy structure.

Disadvantages:

- Difficult to track through the zenith due to the coordinate singularity (key hole).
- Complications with cable management due to 540° of azimuth motion (cable wrap problem).

Antenna Positioners - Equatorial

Equatorial

This type of positioner is no longer used for large antenna's although it was in widespread use prior to the advent of high speed real-time computers for calculating coordinate transformations. It has a fixed axis in the direction of the celestial pole, the equatorial axis, and a moving axis at right angles to the equatorial axis, the declination axis. The declination axis is attached to the part of the antenna that rotates around the equatorial axis. The axis motion is somewhat dependent on latitude but is < ±180° in hour angle (equatorial) and < ±90° in declination.

Advantages:

- Can be used without computer control – just get on source and track at the sidereal rate.
- No cable wrap ambiguity

Disadvantages:

- Difficult to balance the structure and hence sub-optimal for large structures.
- Key hole problem at the celestial pole.

Antenna Positioners – X-Y Mount

X-Y Mount

This type of positioner is mainly used for high speed satellite tracking where key holes cannot be tolerated. The fixed axis points to the horizon and hence the only keyhole is at the horizon, which is too low for tracking. Full sky coverage can be achieved with ±90° motion in both axes.

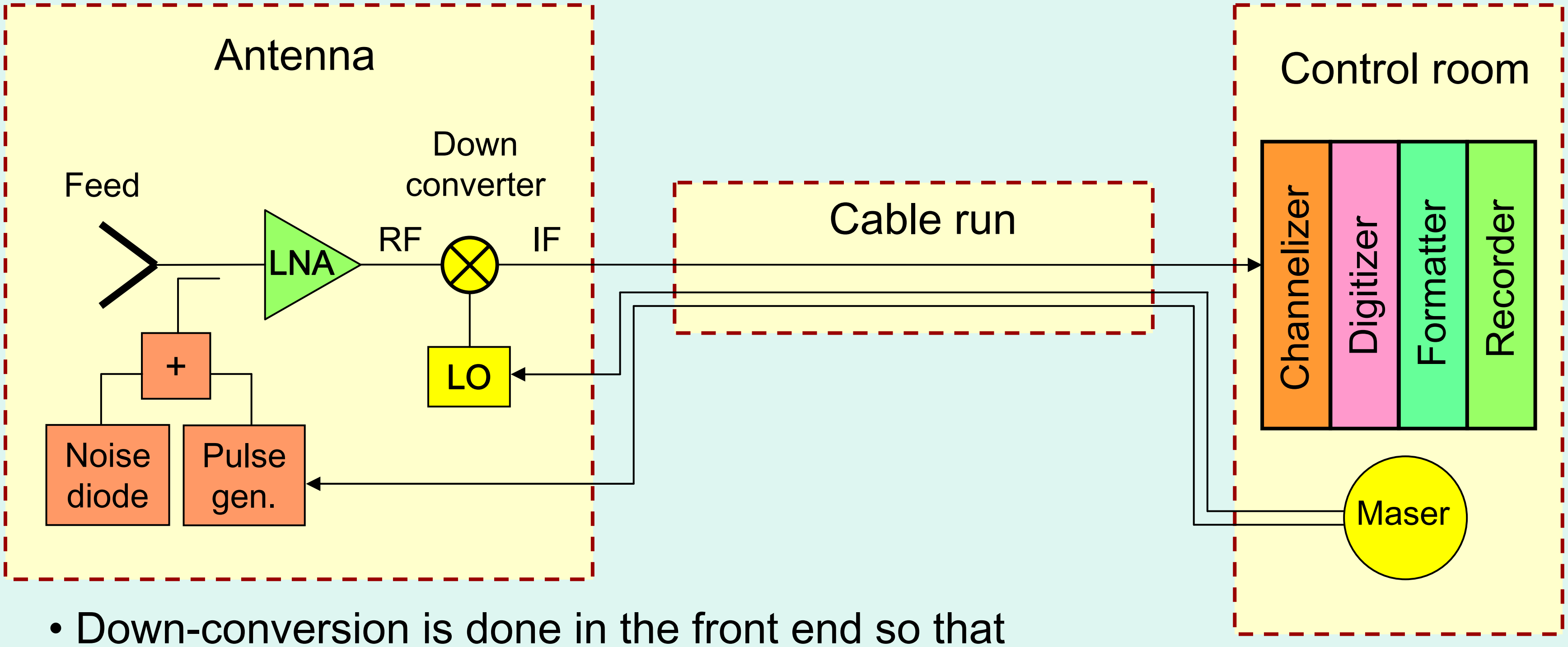
Advantages:

- No place where an object cannot be tracked (i.e. no key holes).
- No cable wrap ambiguity

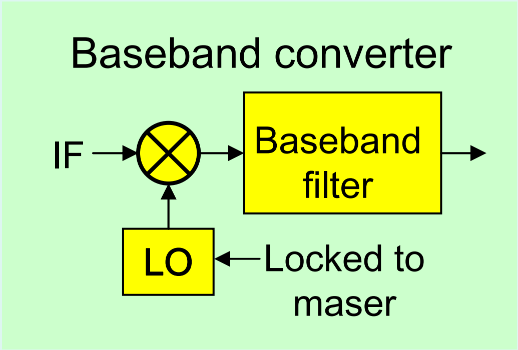
Disadvantages:

- Structurally difficult to construct (compared with alt-az).

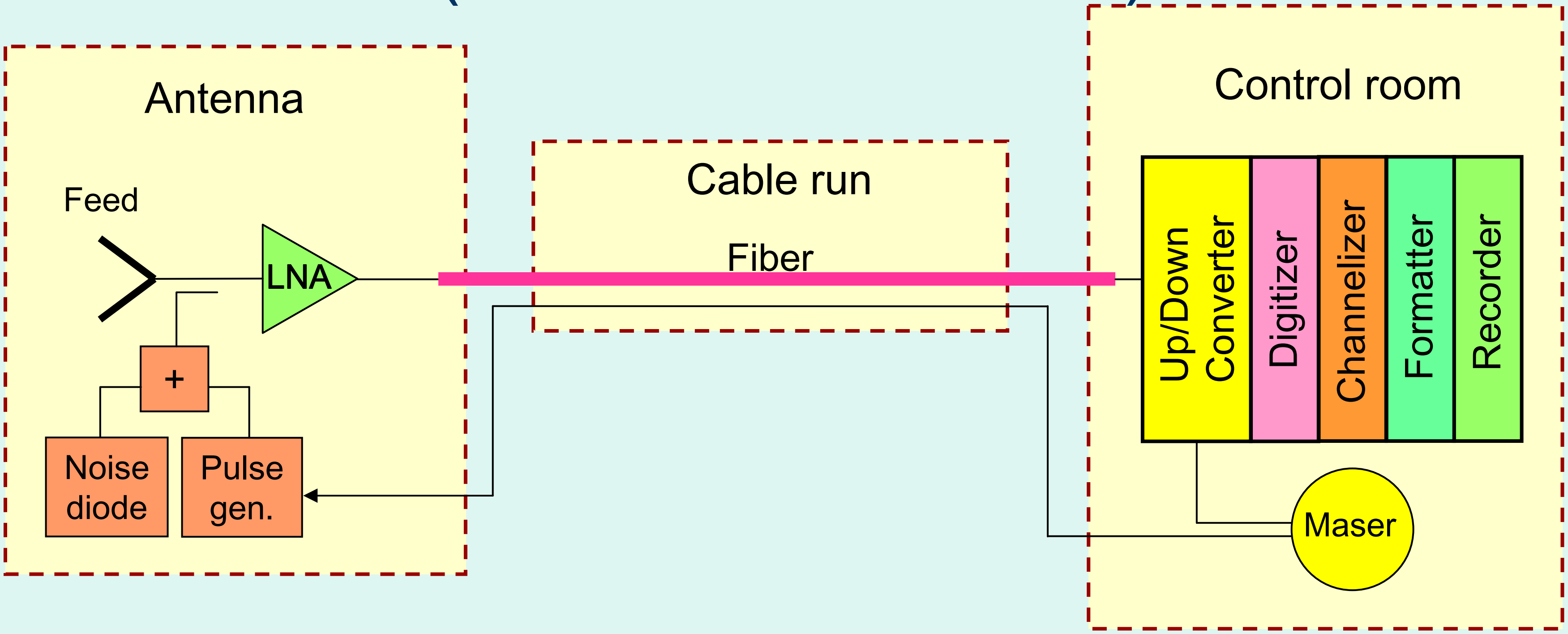
Typical Traditional VLBI Receiver (S- or X-band)



- Down-conversion is done in the front end so that Intermediate Frequency (IF) signals can be transmitted to the control room on cables.
- The channelizer is an analog function hence it appears ahead of the digitizer in the diagram. Channelization is achieved using a set of baseband converters (each including an LO, single sideband mixer and programmable filter).

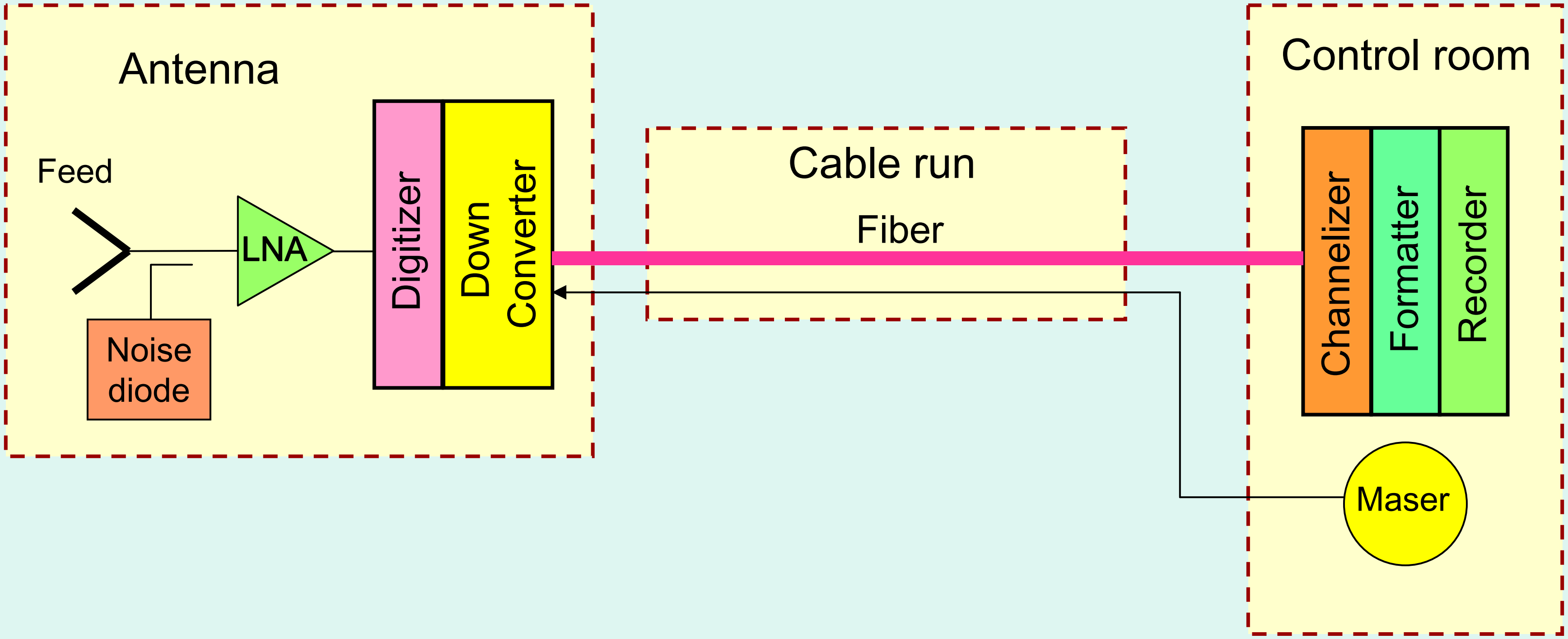


More Modern VLBI Receiver (similar to VLBI2010)



- The full analog Radio Frequency (RF) signal is transmitted to the control using analog over fibre, involving conversions from electrical to optical and back to electrical.
- Flexible (any frequency) down-conversion is achieved using an Up-Down converter
- The digitizer is ahead of the channelizer, which is implemented digitally in a Digital Back End (DBE) as a Polyphase Filter Bank (PFB).

Most Modern VLBI Receiver (DBBC3)



- Digitization is done immediately after the LNA so that both down-conversion and channelization are done digitally
- The signal is transmitted to the control room digitally over fibre.

Amplification - Low Noise Design

The signal received from a radio source is very weak, e.g. using

$$P_f = A_e S_f = 2kT_a$$

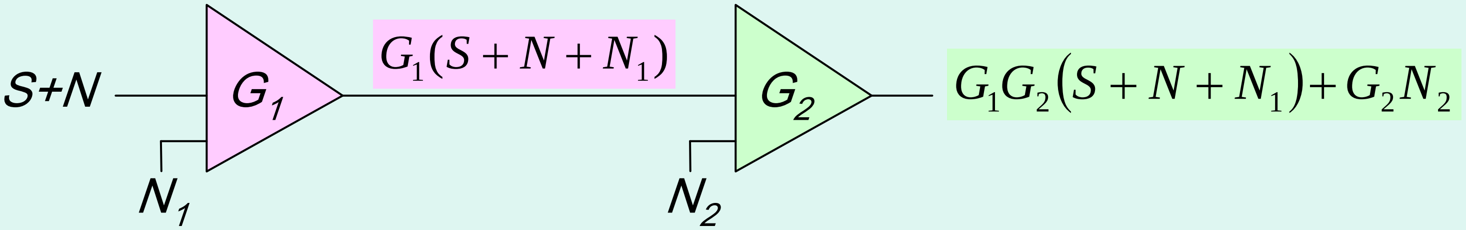
a 1 Jy source observed by a 12 m antenna with 50% efficiency will produce an antenna temperature, T_A=0.02° K about 1000 times smaller than typcial system noise. [See the table below for a breakdown of system noise components.]

Source of noise	*Typical antenna temperature (°K)*	*Major dependencies*
Cosmic microwave background	3	
Milky Way Galaxy	0-1	frequency, direction
Ionosphere	0-1	time, frequency, elevation
Troposphere	3-30	elevation, weather
Antenna radome	0-10	
Antenna	0-5	
Ground spillover	0-30	elevation
Feed	5-30	
Cryogenic LNA	5-20	
Total	16-130	

Amplification - Low Noise Design

Hence it is important that good low noise design strategies be used, i.e. that the first amplifier in the signal chain (the one immediately after the feed) has:

- very low input noise, i.e. that it is a cryogenically cooled Low Noise Amplifier (LNA).
- high gain to dilute the noise contribution of later stages.



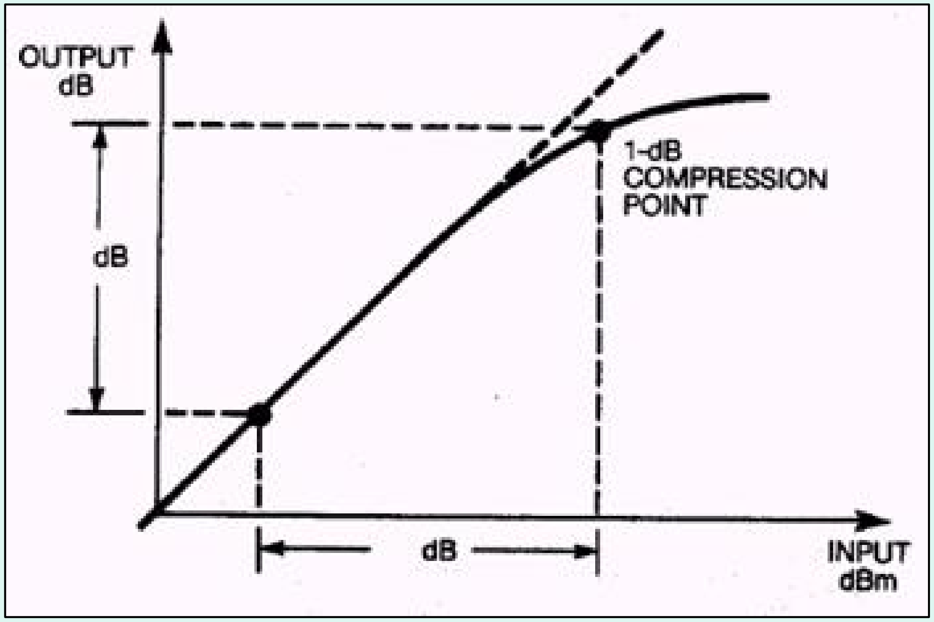
Hence, $SNR = \dfrac{G_1G_2S}{G_1G_2\left(N+N_1\right)+G_2N_2} = \dfrac{S}{N+N_1+\dfrac{N_2}{G_1}}$

The second noise contribution has been reduced by the first gain.

For example, if G_1=3000 (35-dB) and N_2=200°K, N_2/G_1=0.07°K.

Amplification - Gain Compression

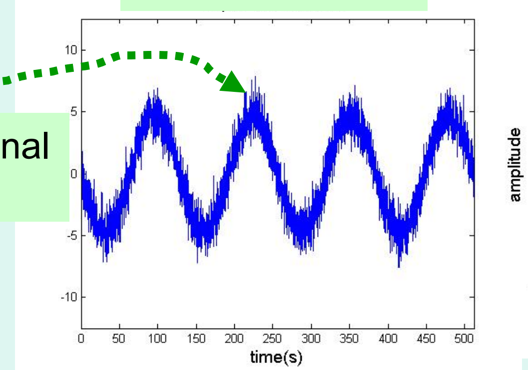
It is important that amplifiers operate in the linear range, i.e. output is simply a multiple of the input (e.g. if input doubles the output must also double).

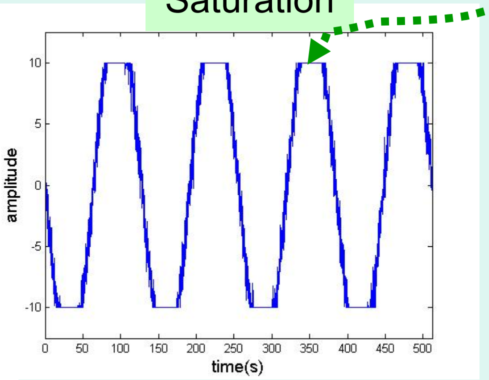


The *1 dB compression point* is an important amplifier specification. It is a measure of how large a signal can be input to an amplifier before significant non-linear behaviour begins. It occurs at the input signal level where output increases 1 dB less than the input. To guarantee linear operation, systems are usually designed to operate at least 10 dB below the 1 dB compression point.

Consequenses of non-linear behaviour

VLBI noise signal plus cw RFI

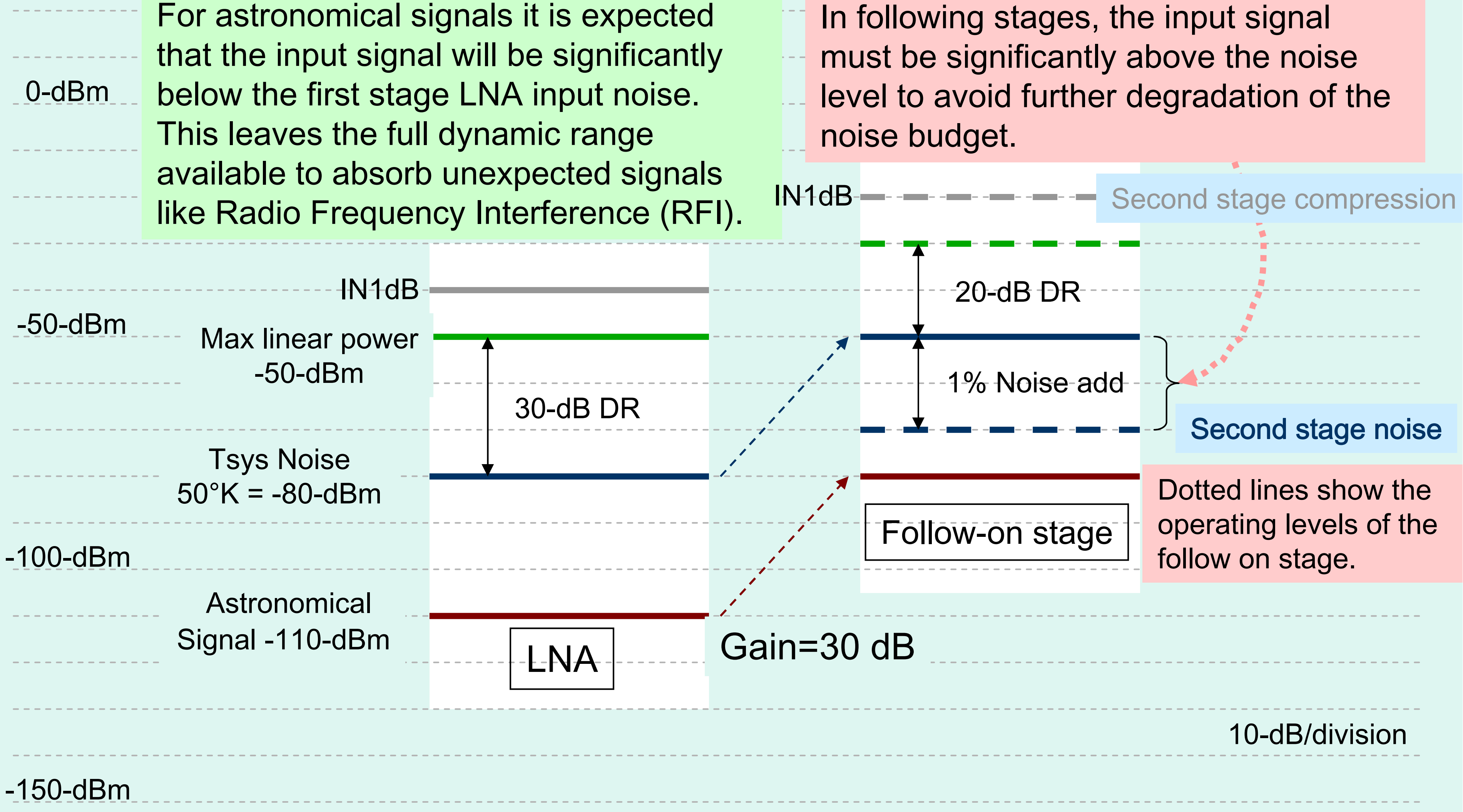

Linear operation


Saturation

- VLBI signal disappears at saturation.
- Amplitude modulation shifts frequencies

Dynamic Range Example

Dynamics Range is the range of amplitudes in which an amplifier can operate. The lower end is limited by noise performance of the amplifier and the upper end is limited by gain compression.



For astronomical signals it is expected that the input signal will be significantly below the first stage LNA input noise. This leaves the full dynamic range available to absorb unexpected signals like Radio Frequency Interference (RFI).

In following stages, the input signal must be significantly above the noise level to avoid further degradation of the noise budget.

Dotted lines show the operating levels of the follow on stage.

System Equivalent Flux Density (SEFD)

SEFD is the flux density that produces, in any particular system, an antenna temperature equal to the system temperature. It is a figure of merit for the sensitivity of the antenna/feed/receiver system ($SNR=S_f/SEFD$). Using

$P_f = \frac{A_e S_f}{2} = kT_a$ and $A_e = \frac{\eta_A \pi D^2}{4}$, T_a can be expressed as,

$$T_a = \frac{\eta_A \pi D^2 S_f}{8k}$$

Under the condition $T_a = T_S$ it is true by definition that $S_f = SEFD$ so that

$$SEFD = \frac{8kT_s}{\eta_A \pi D^2}$$

Note: SEFD decrease as sensitivity increases.

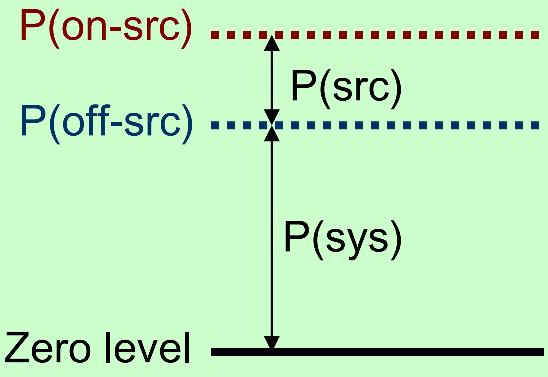
SEFD is very useful in VLBI for predicting the correlated amplitude and SNR, i.e.

$$Amp = \frac{\eta_c S_f}{\sqrt{SEFD_1 \times SEFD_2}} \qquad SNR = Amp\sqrt{2 \times BW \times T}$$

where η_c is the correlator digital processing efficiency and *2xBWxT* is the number of independent samples. *Amp* is typically 10^{-4} so *2xBWxT* must be very large to get a good SNR. [Note: The SEFD spec for VLBI2010 is 2500.]

Measurement of SEFD

Operationally, the SEFD is determined by measuring the power on and off a source with a calibrated flux density.



P(on-src) = P(sys)+P(src)

P(off-src) = P(sys)

Using P(on-src), P(off-src) and the flux of the calibration source, SEFD can be determined according to:

$$SEFD = \frac{S_f(cal - src)}{\left(\frac{P_{on-src}}{P_{off-src}} - 1\right)}$$

Note: The units of P(on-src) and P(off-src) are irrelevant (provided they are both the same) since only their ratio is used in the equation.

Noise Calibration

- Noise calibration measures changes in the power sensitivity.
- A signal of known strength is injected ahead of, in, or just after the feed, and the fractional change in system power is measured.
- The system temperature is then calculated from the known cal signal strength as

$$T_{sys} = \frac{T_{cal}}{\left(\frac{P_{on}}{P_{off}} - 1\right)}$$

- Even if the true value of the T_{cal} is unknown, the calculated T_{sys} values are useful as measures of the relative changes in sensitivity.
- If T_{cal} is small (≤5% of T_{sys}), continuous measurements can be made by firing the cal signal periodically (VLBA uses an 80 Hz rep rate) and synchronously detecting the level changes in the backend.
- For reliable T_{sys} *measurements*
  - T_{cal} must be stable (may require physical temperature control) and
  - the system gain ahead of the injection point must be stable.

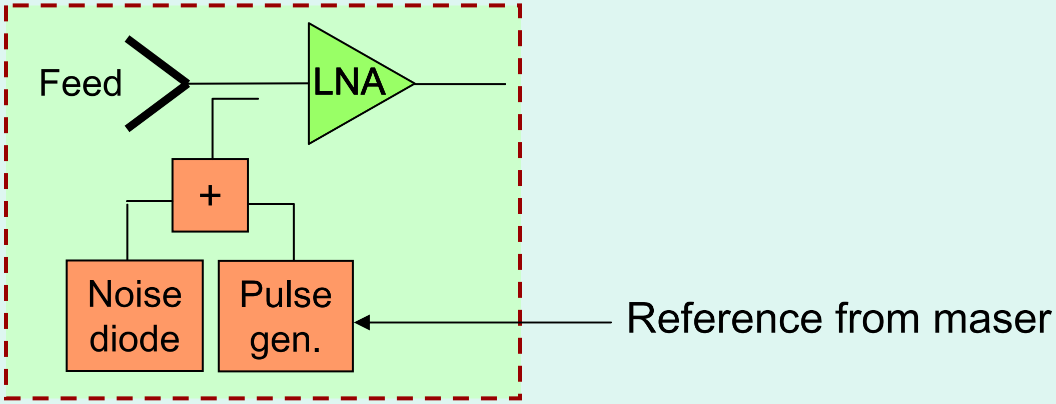
Phase Calibration

The *phase calibration* system measures changes in system phase/delay.

- This is particularly important for cable delays that can vary with antenna pointing direction and hence correlate with station position.

A train of narrow pulses is injected ahead of, in, or just after the feed - typically at the same location as the noise cal signal.

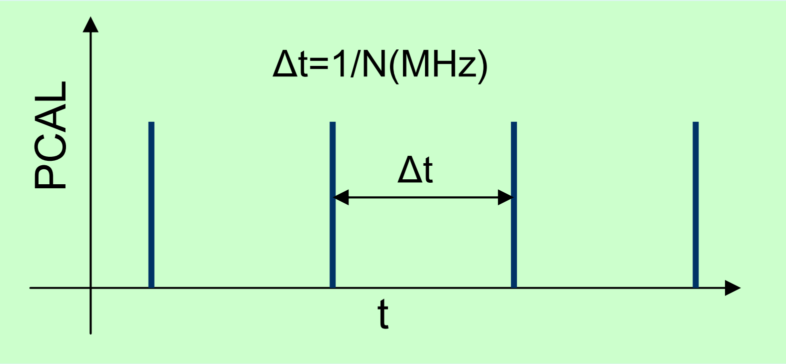
- Since the PCAL signal follows exactly the same path (from the point of injection onward) as the astronomical signal, any changes experienced by the calibration signal are also experienced by the astronomical signal.



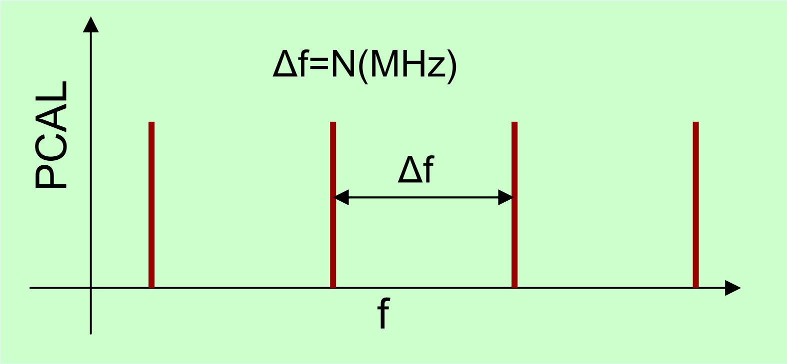
Phase Calibration (cont'd)

Pulses of width t_{pulse} with a repetition rate of N MHz correspond to a series of frequency tones spaced N MHz apart from DC up to a frequency of $\sim 1/t_{pulse}$

- E.g., pulses of width ~50 ps yield tones up to ~20 GHz
- Typical pulse rate is 1 MHz, but it will be 5 or 10 MHz in VLBI2010 (to reduce the possibility of pulse clipping).



Time domain representation



Frequency domain representation

The PCAL signal is detected in the digital output of the receiver (usually at the correlator where it is used). The detection can be either in the time domain or the frequency domain:

- In the frequency domain, a quadrature function at the frequency of the tone stops the tone so that it can be accumulated thus implementing the *tone extractor*.
- In the time domain, averaging of the repetitive pulse periods implements the *pulse extractor* with an FFT transforming the result to the frequency domain.

Phase Calibration (cont'd)

- Older pulse generators used *tunnel or step recovery diodes*.
- Newer pulse generators use *high-speed digital logic devices.*

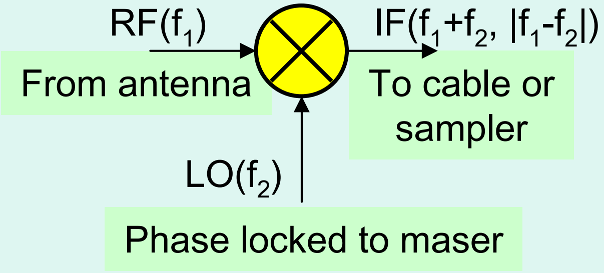
Precision of the instrumental phase/delay measurements can be no better than the stability of the phase cal electronics

  - Temperature sensitivity of the new phase cal is <1 ps/°C
  - If temperature or mechanical stability of cable carrying the reference signal up to the antenna is inadequate, need to measure cable length.

Down converter: mixer operation

A down converter translates a signal downward in frequency. [Lower frequencies are required for example for signal transmission on cables or for digitization.]

An important element of a down converter is a mixer. Conceptually, a mixer can be considered a multiplier producing outputs at the sum and difference frequencies of the two inputs:



$RF(f_1)$

From antenna

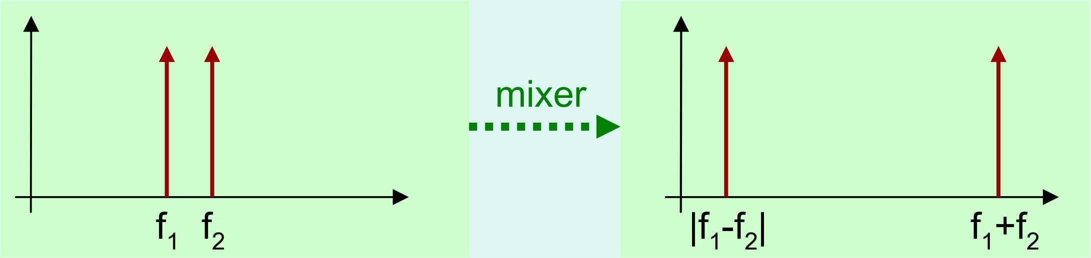
$IF(f_1+f_2, |f_1-f_2|)$

To cable or sampler

$LO(f_2)$

Phase locked to maser

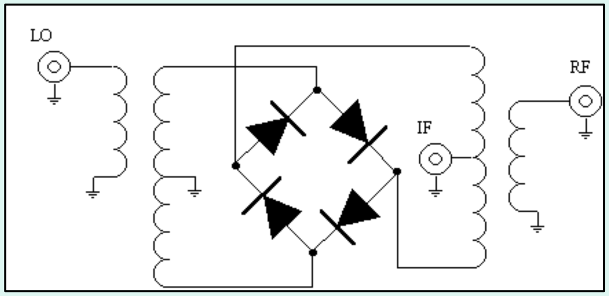
$$\cos(f_1 t)\times\cos(f_2 t)=\frac{\cos(f_1+f_2)t+\cos(f_1-f_2)t}{2}$$



If the frequency *sum* is isolated using a filter this is referred to as an *up converter.*

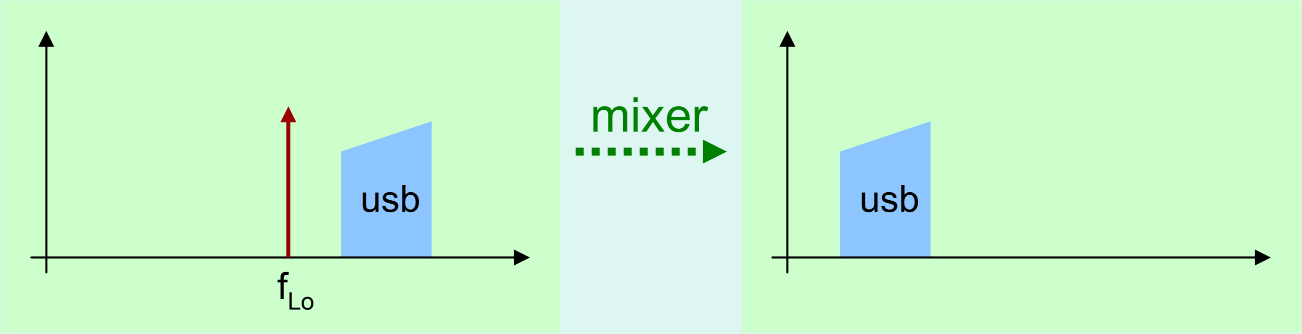
If the *difference* is isolated using a filter this is referred to as a *down converter.*

Mixers used at RF frequencies are typically double or triple balanced ring diodes and not pure multipliers. As a result, other (usually unwanted) mixer products can be found in the output, e.g. at frequencies f_1, $2f_1$, $3f_1$, f_2, $2f_2$, $3f_2$, $2f_1-f_2$, $2f_1+f_2$, $(nf_1 \pm mf_2)$, …..

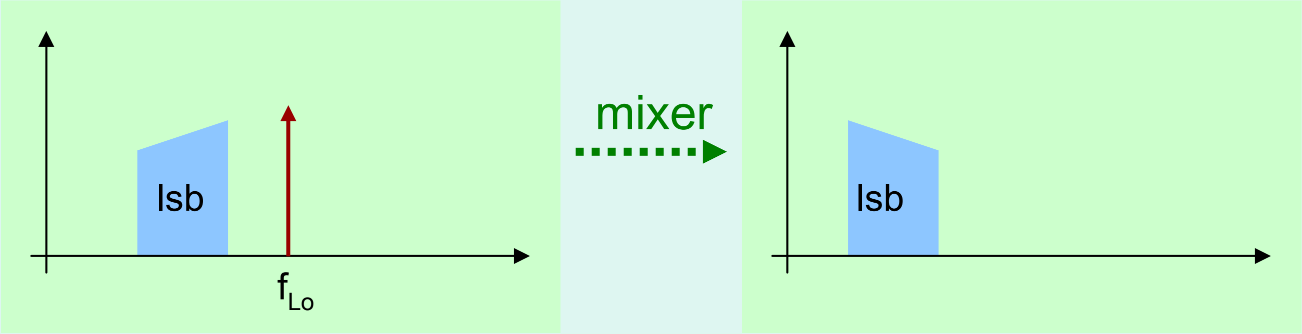


Down converter: sidebands

Signals, at the input to a down converter, with frequencies higher than the Local Oscillator (LO) frequency are referred to as *upper sideband (usb)* signals.



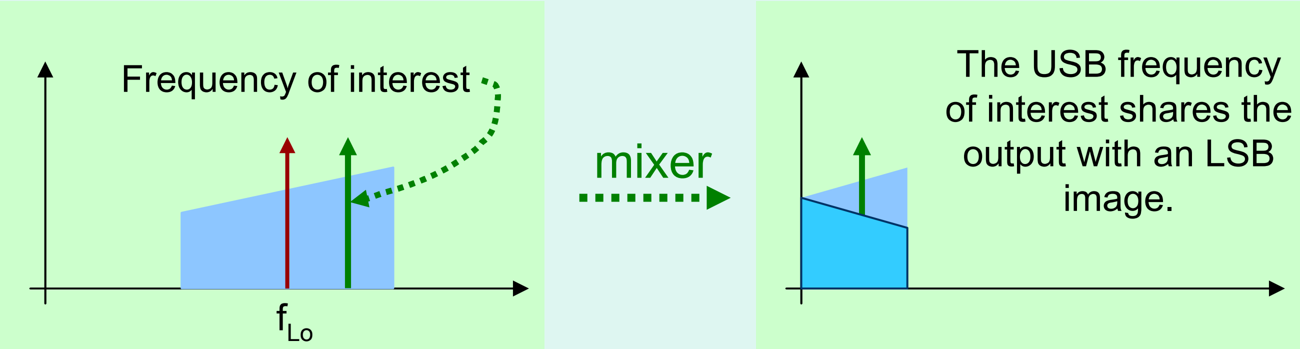
Signals with frequencies lower than the Local Oscillator (LO) frequency are referred to as *lower sideband (lsb)* signals.



Note that in the lower sideband (lsb) output, the ordering of the frequencies is reversed.

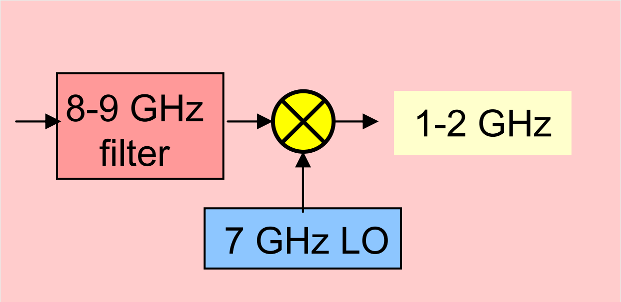
Down converter: Image rejection

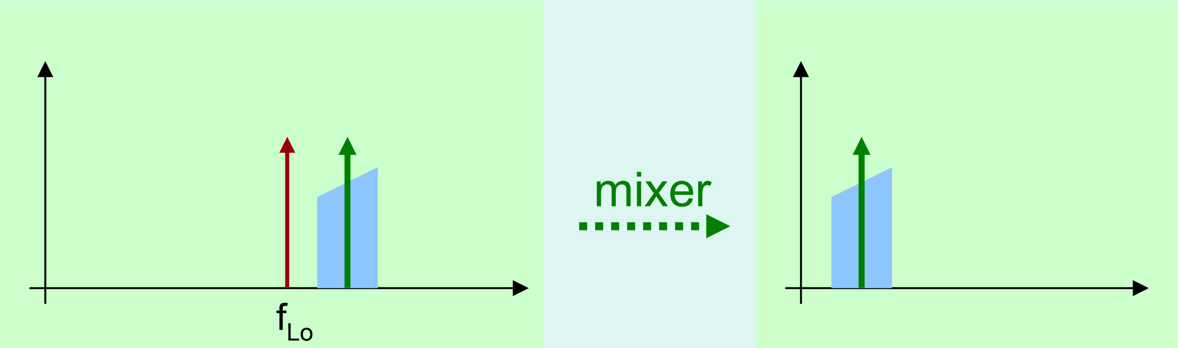
The *image* is the RF signal from the undesired sideband that has the same IF frequency as the desired signal.



The USB frequency of interest shares the output with an LSB image.

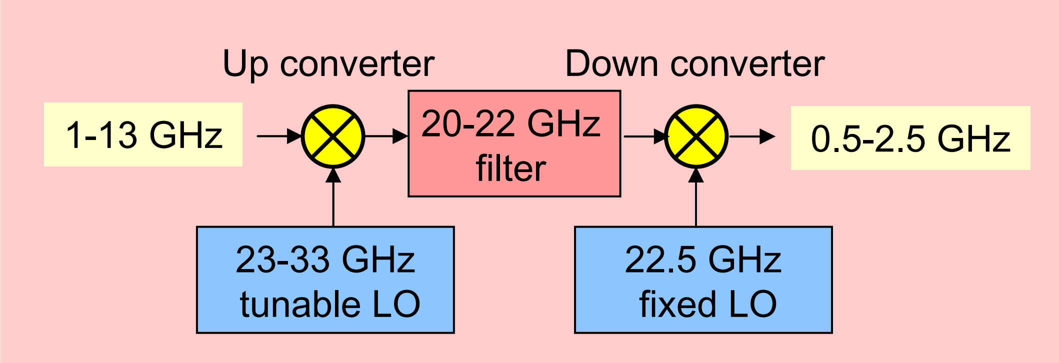
The easiest solution is to use a *pre-LO filter* to eliminate the unwanted image.





Pre-LO filters work well in many circumstances, but an up/down converter works better for flexible down conversion in a system with a very broad input frequency range (like VLBI2010).

Flexible down converter: Up/down converter



Up converter

Down converter

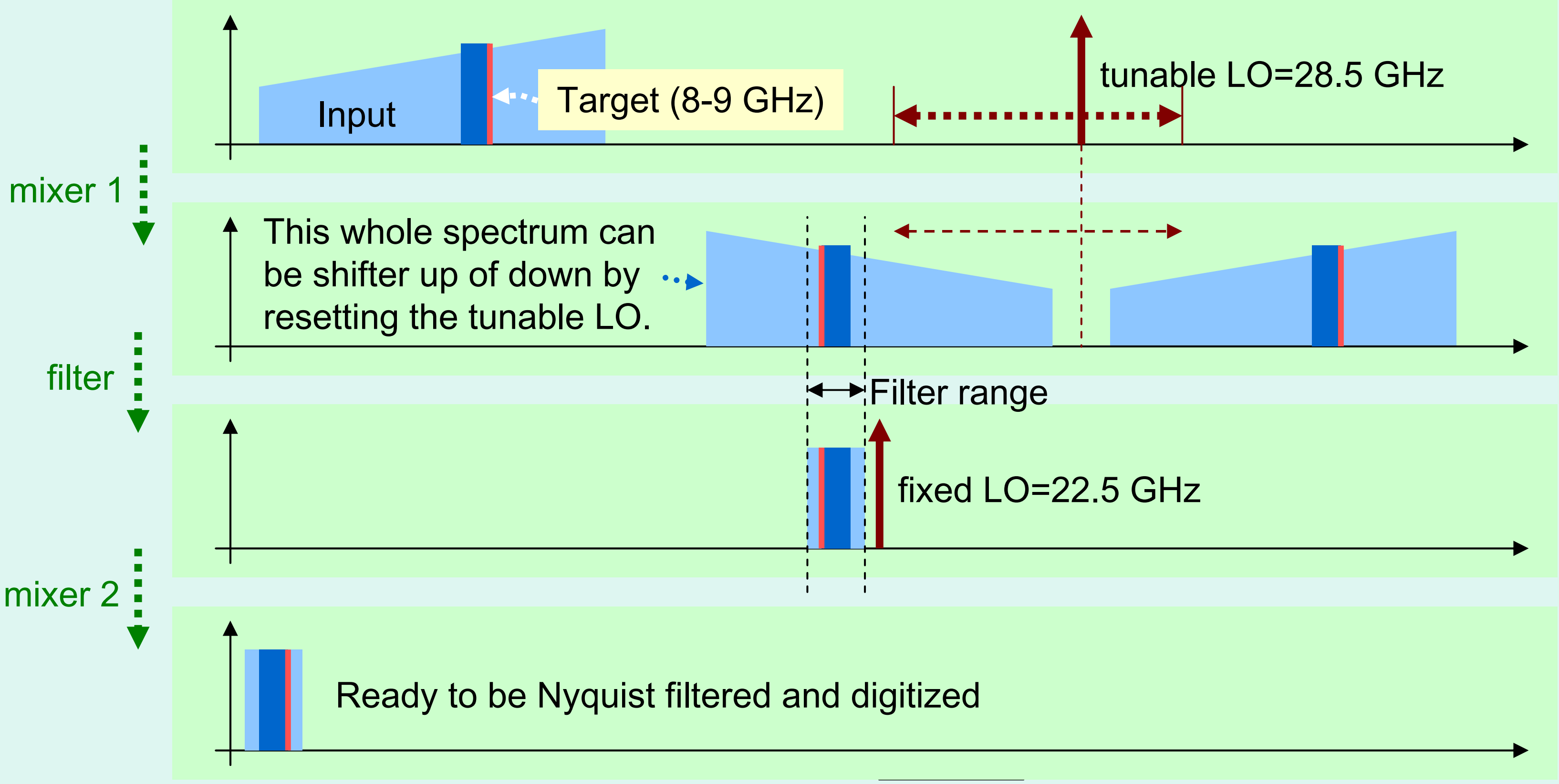
1-13 GHz

20-22 GHz filter

0.5-2.5 GHz

23-33 GHz tunable LO

22.5 GHz fixed LO



Input

Target (8-9 GHz)

tunable LO=28.5 GHz

mixer 1

This whole spectrum can be shifter up of down by resetting the tunable LO.

filter

Filter range

fixed LO=22.5 GHz

mixer 2

Ready to be Nyquist filtered and digitized

Can down convert any 1 GHz target band in the 1-13 GHz input range.

Sources of RFI (2-14 GHz)

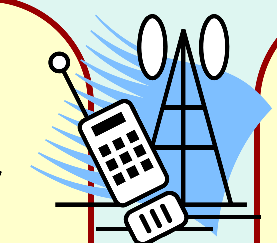
Entire frequency range is already fully allocated by international agreement

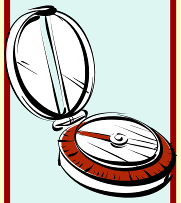
Sources internal to VLBI and co-located space geodetic techniques (e.g. SLR, DORIS, GNSS)

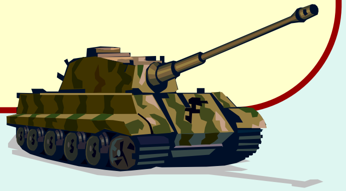
- Local oscillators, clocks, PCAL pulses, circuits
- DORIS beacon at ~2 GHz
- SLR aircraft avoidance radar at ~9.4 GHz

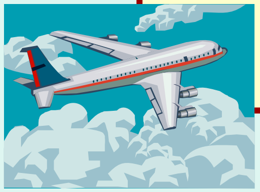
Terrestrial Sources

- General communications, fixed and mobile – land, sea, air
- Personal communications cell phones, wifi
- Broadcast
- Military
- Navigation
- Weather
- Emergency



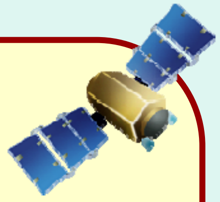






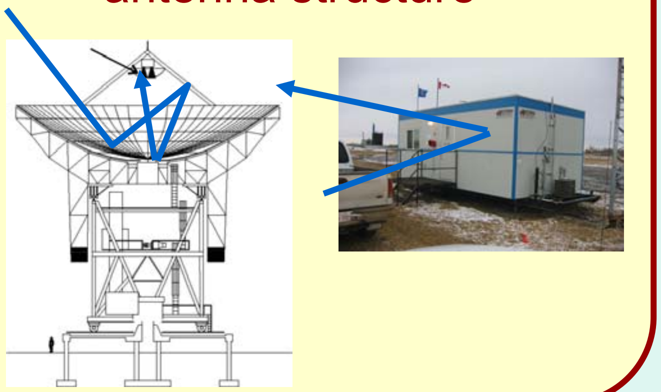
Space Sources

- Communications
- Broadcast (C-, Ka-band; in Clarke belt at ±8° dec)
- Military
- Exploration
- Navigation
- Weather
- Emergency

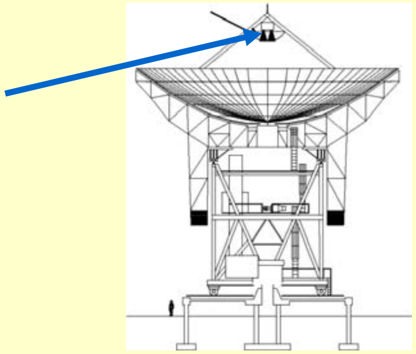


How does RFI enter the receiver chain?

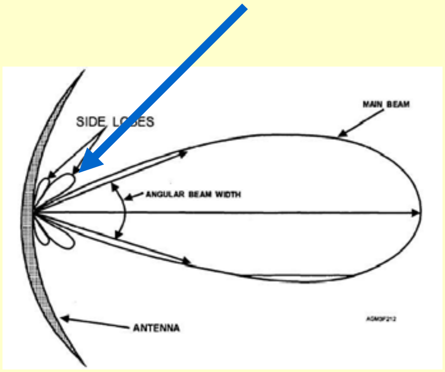
Multipath off objects and antenna structure



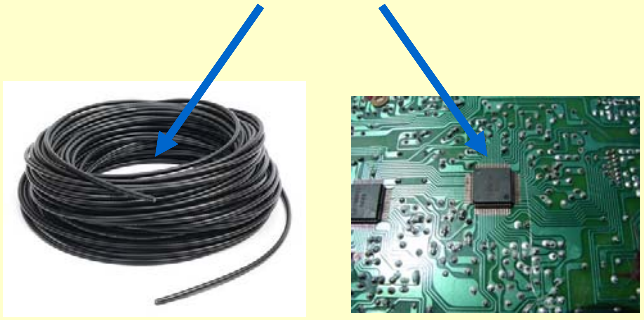
Spillover direct into the feed



Antenna sidelobes



Direct coupling into cables and circuits



Negative Impacts of RFI

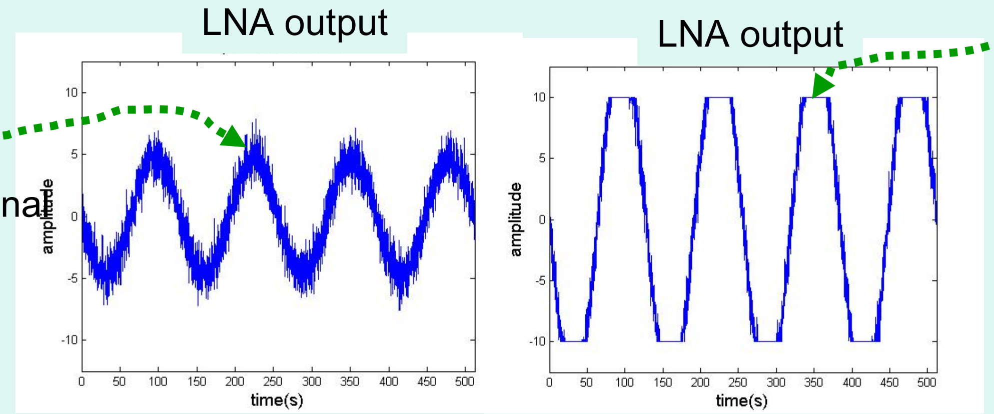
Increasing severity

Small RFI appears as added noise

- Reduces performance of the system
- Only impacts frequencies where RFI occurs
- Undesirable but can be tolerated within limits

Larger RFI can saturate the signal chain

- Impacts entire band, not just frequencies where RFI occurs
- Must be avoided (observation is lost)



VLBI noise signal
plus cw RFI

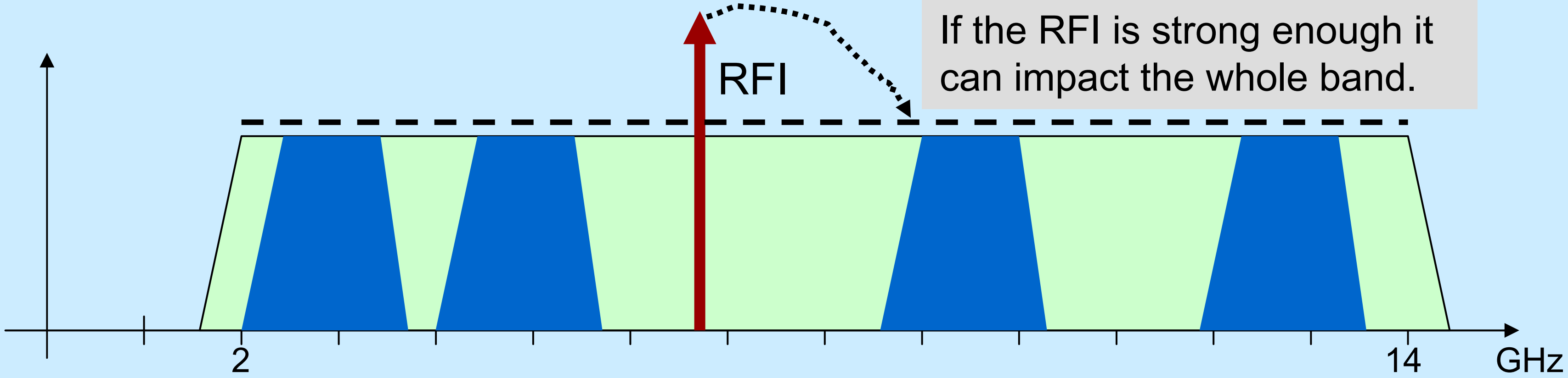
- VLBI signal
disappears at
saturation.
- Amp modulation
shifts frequencies

Even larger RFI can damage the VLBI receiver

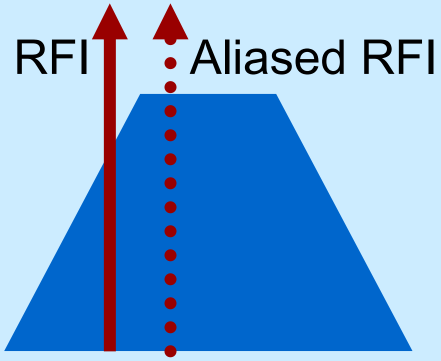
- Typically LNA is most vulnerable
- Must be protected against (leads to expense and down time)

Impacts of out-of-band RFI

Strong out-of-band RFI (even if in a very narrow band) that saturates the signal chain prior to the point where bands are separated will destroy the whole input range and hence destroy all bands.



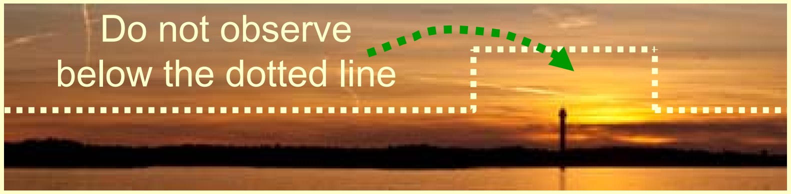
If the RFI is strong enough it can impact the whole band.



If the band select filters do not cut off sharply enough, strong RFI can penetrate the wings of the filter and be aliased into the band during Nyquist sampling.

RFI Mitigation Strategies

Avoidance mask

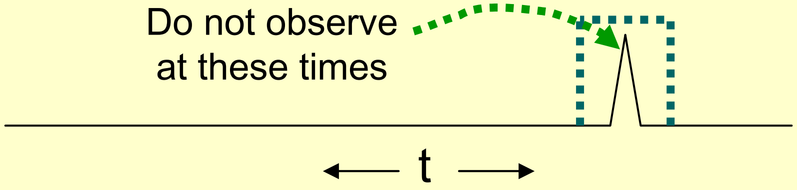

Do not observe
below the dotted line

Physical barrier as attenuator

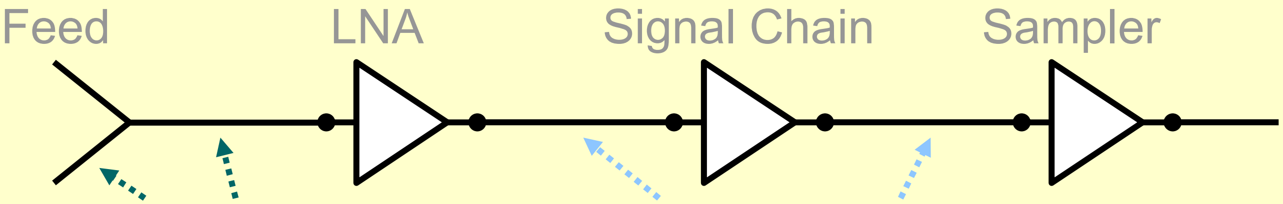
Design improvements

-Diode protection for LNA`s
- Higher dynamic range components
- Lower antenna sidelobes

Time windowing for pulsed signals


Do not observe
at these times

Frequency reject filters



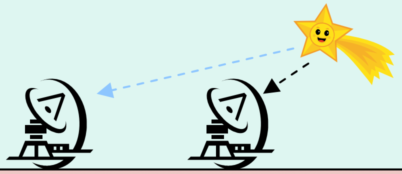
Frequency selective feeds or
cryogenic IF filters are technically
challenging and expensive

Less flexible

IF filters are
technically easier and
less expensive

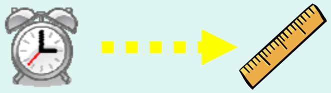
More flexible

Geodetic VLBI: How does it work?



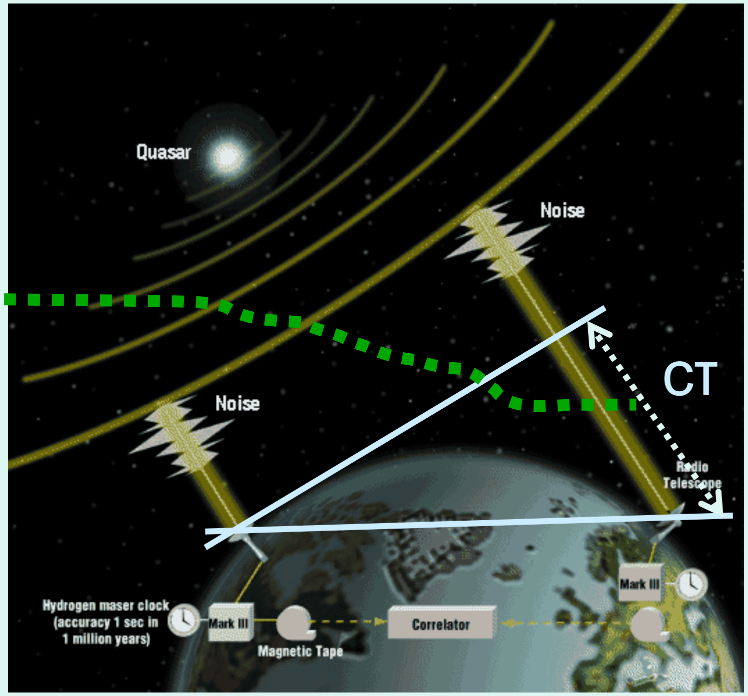
A network of antennas observes a Quasar

The delay between times of arrival of a signal is measured



Using the speed of light, the delay is interpreted as a distance

The distance is the component of the baseline toward the source

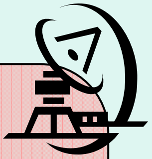


By observing many sources, all components of the baseline can be determined.

VLBI2010: Why do we need a next generation geodetic VLBI system?

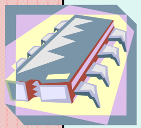
Aging systems (now >30 years old):

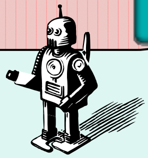
- Old antennas
- Obsolete electronics
- Costly operations
- RFI



New Technology:

- Fast cheap antennas
- Digital electronics
- Hi-speed networks
- Automation





New system

New requirements:

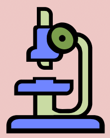
- Sea level rise
- Earthquake processes
- 1-mm accuracy
- GGOS

Goals of the next generation system

VLBI2010 Goals

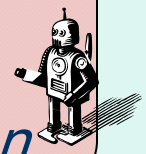
1-mm position accuracy *(based on a 24-hour observation)*

- *Unprecedented, needs research*



Continuous measurements of station position and EOP

- *Update processes and increase automation*



Turnaround time to initial products < 24-hrs

- *Use eVLBI*

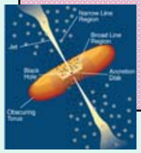
Strategy for VLBI2010 Goal #1:
1-mm accuracy

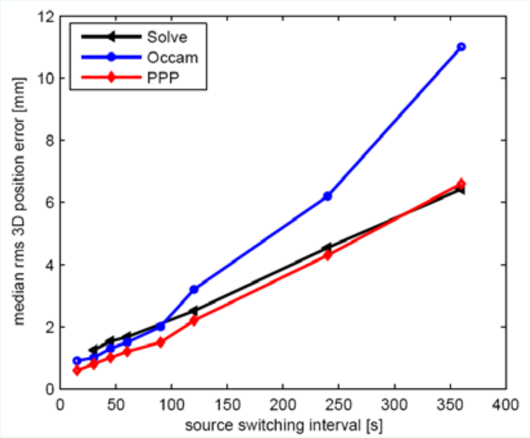
Reduce Random Errors:

Atmosphere
Clocks
Delay Measurement

Reduce Systematic Errors:

Antenna Deformations
Source Structure
Electronics





Remedy:
Careful design
Calibration

Remedy:
Reduce Source Switching Interval
Faster slewing antennas
Shorter “on-source” time

Monte Carlo Simulations

For VLBI2010 need faster slewing antennas

Smaller diameter: ~12-m; >50% efficient

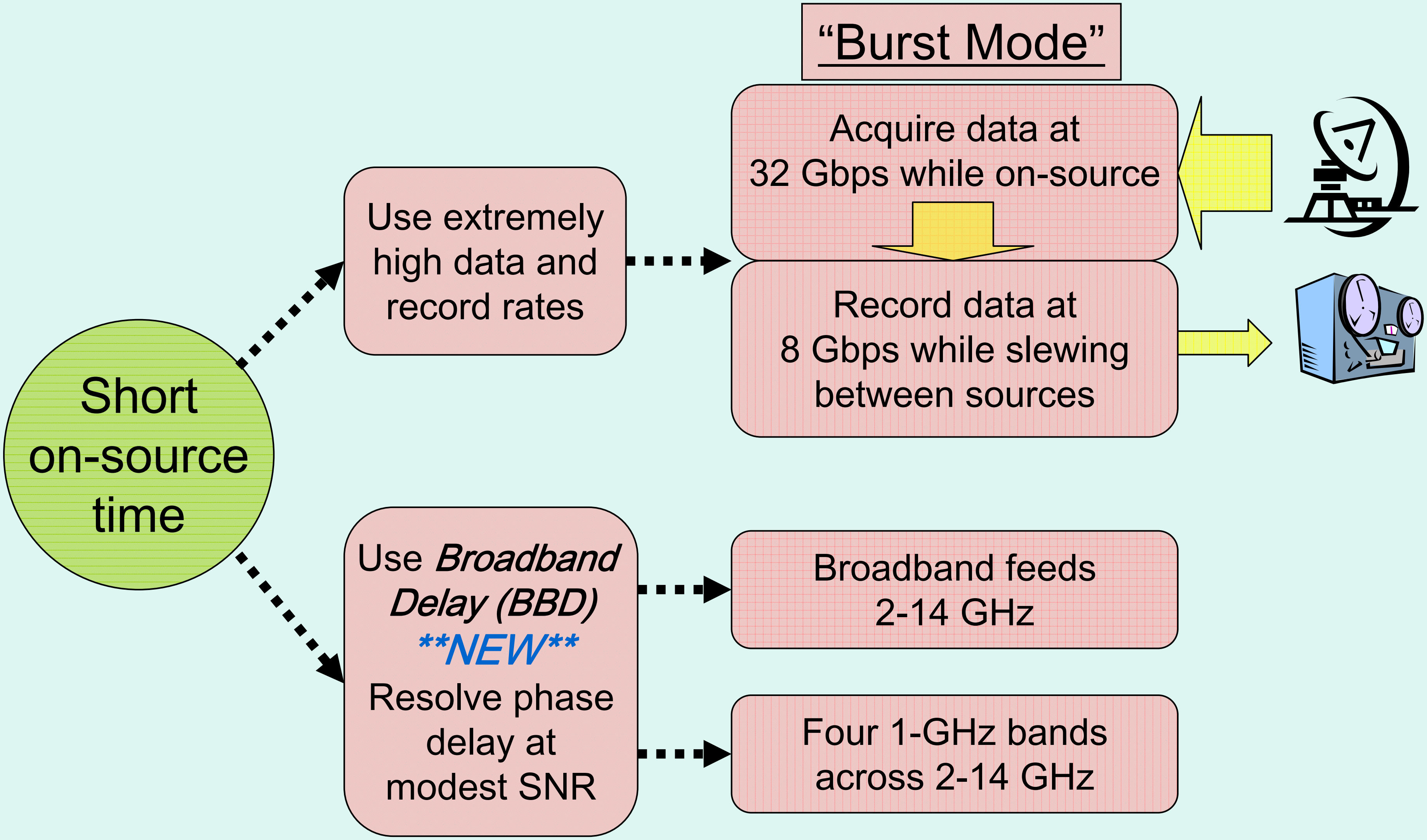
12°/s azimuth rate; 6°/s elevation rate

Pictured here:
Twin Telescopes Wettzell (Vertex)

Other antennas meeting spec include:

- MT Mechatronics - RAEGE project (Spain & Portugal)
- Intertronics

Need short on-source times



Short on-source time

Use extremely high data and record rates

"Burst Mode"

Acquire data at 32 Gbps while on-source

Record data at 8 Gbps while slewing between sources

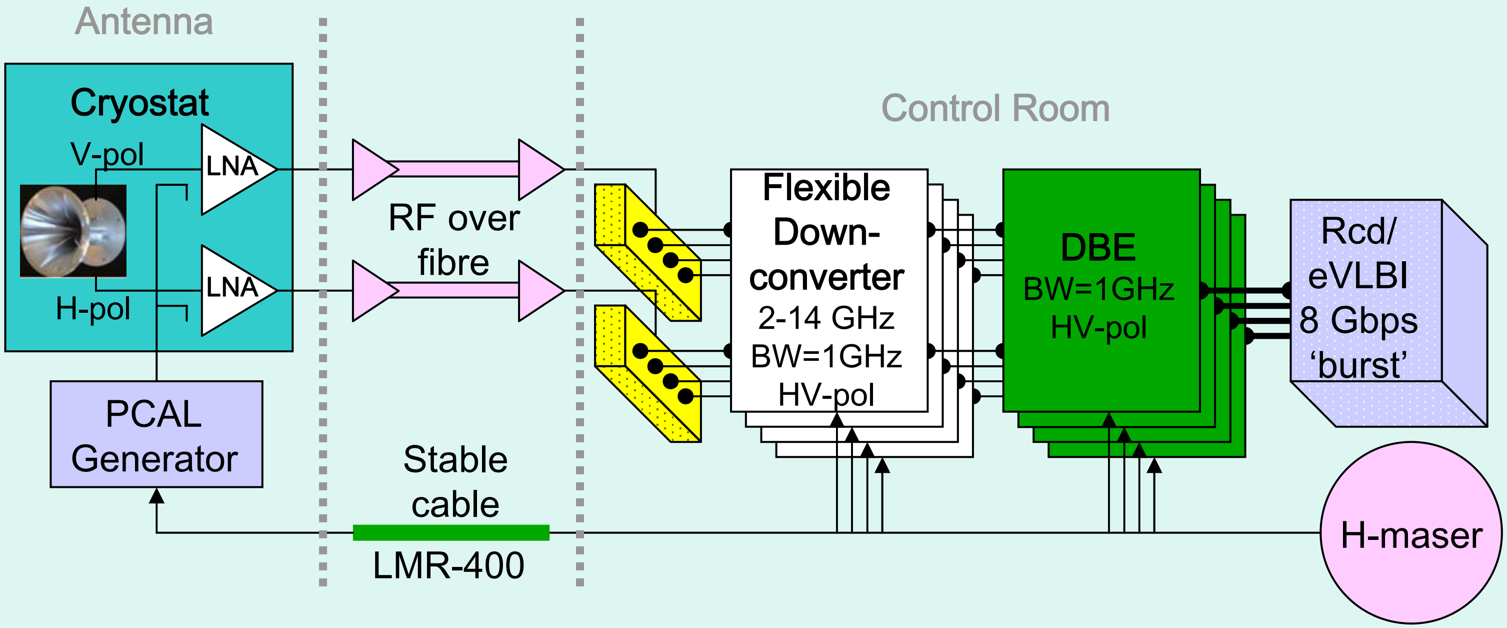
Use *Broadband Delay (BBD)* *****NEW***** Resolve phase delay at modest SNR

Broadband feeds 2-14 GHz

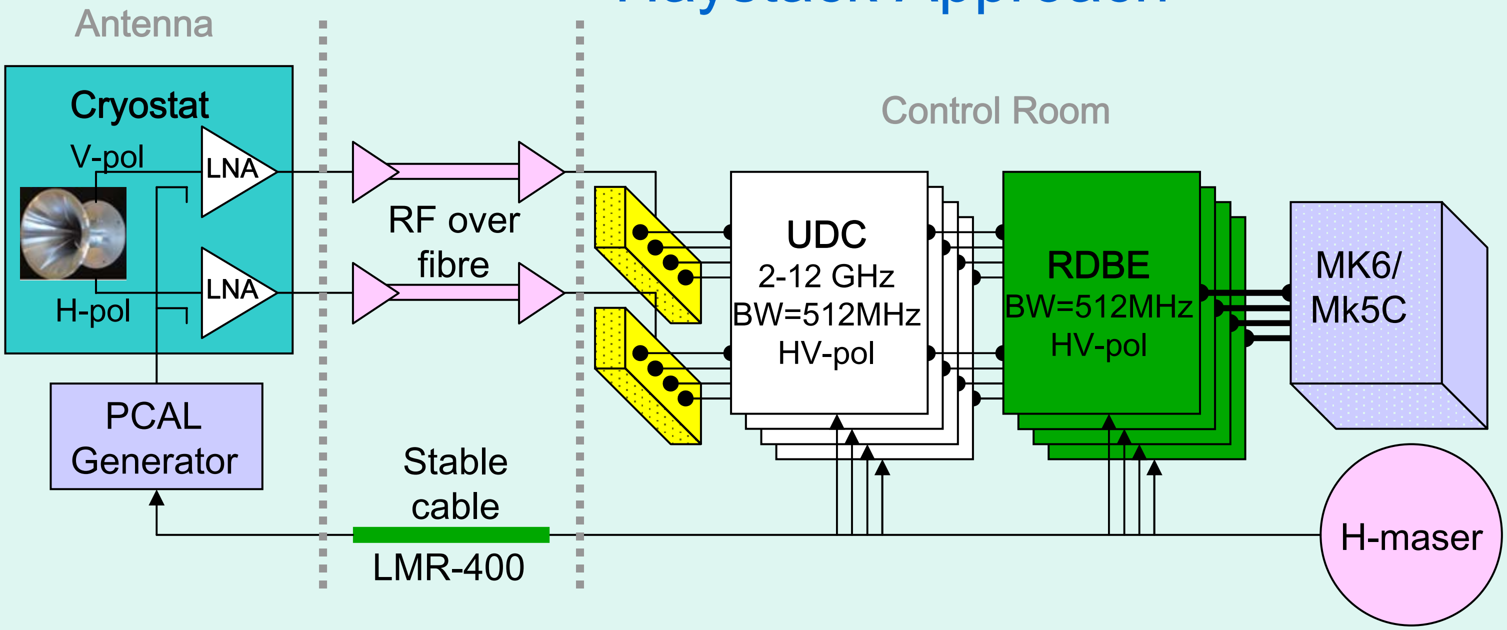
Four 1-GHz bands across 2-14 GHz

VLBI2010 System Block Diagram

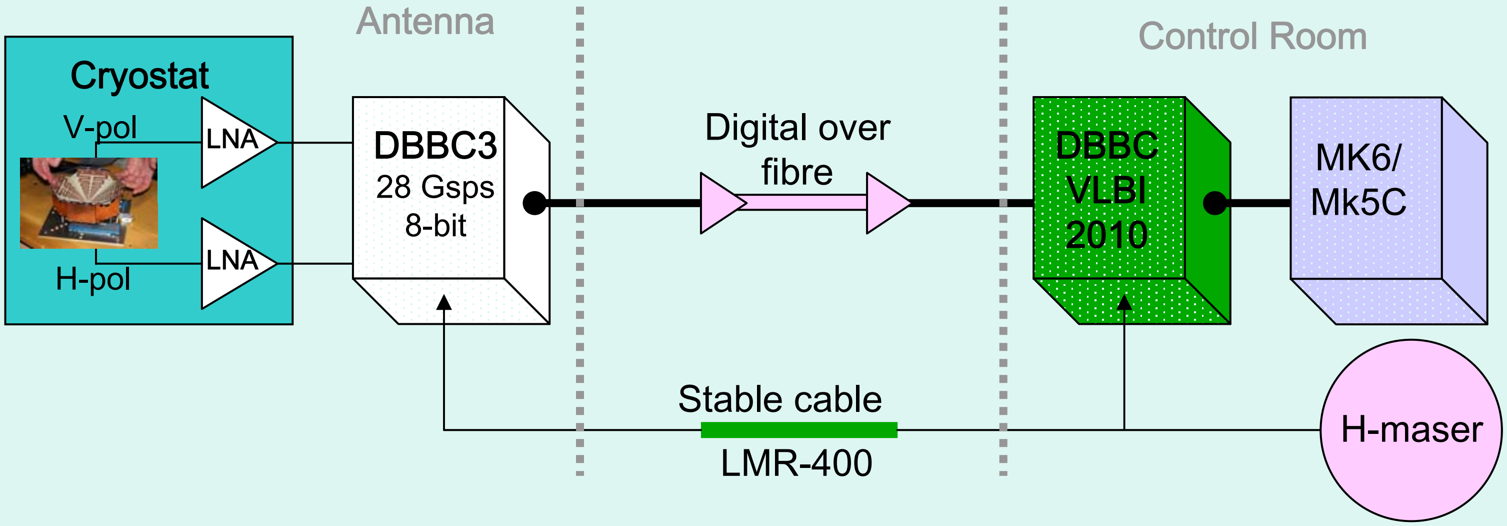
Complete redesign relative to legacy S/X system



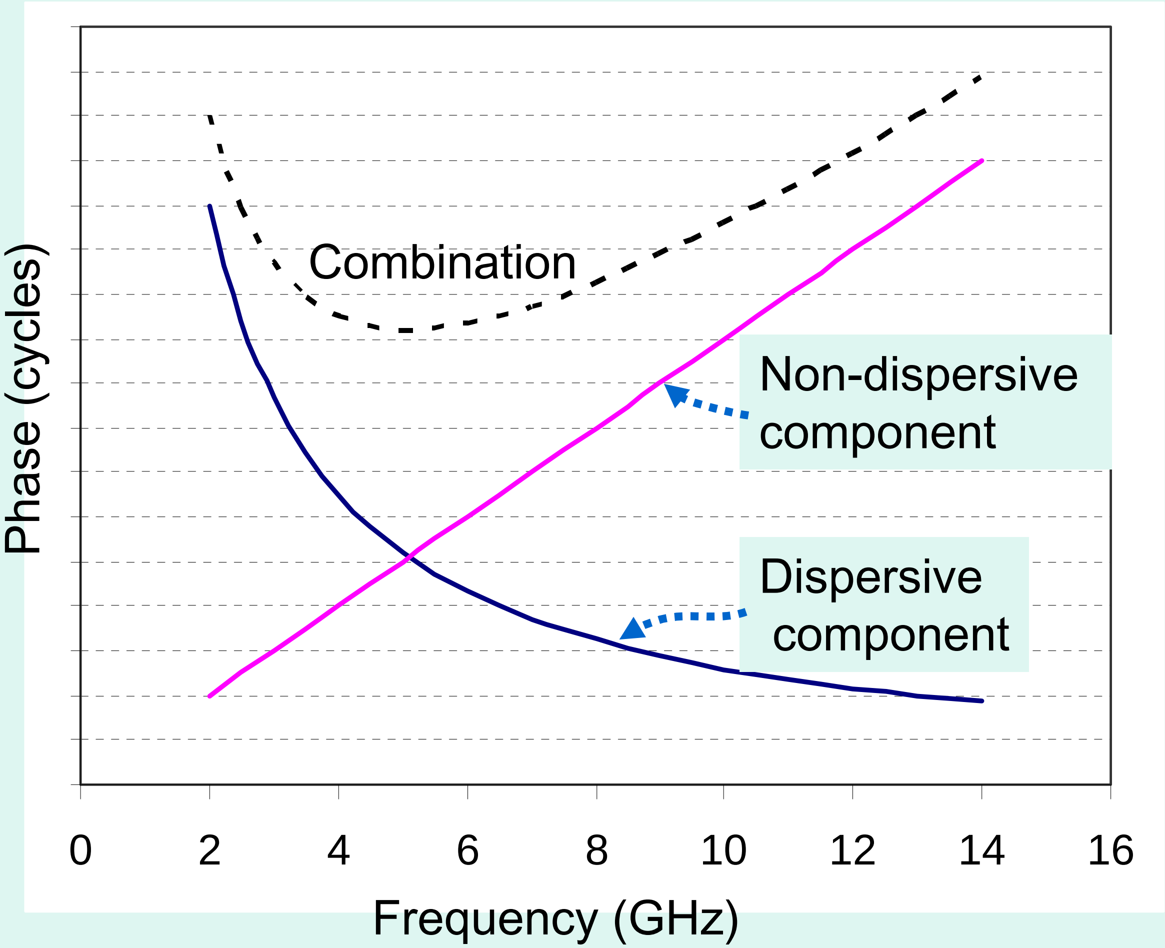
Haystack Approach



DBBC Approach



Broadband Delay requires separation of dispersive and non-dispersive delay *during* (not after) fringe detection



Non-dispersive delay.
Delay is independent of frequency (phase is linear wrt frequency)

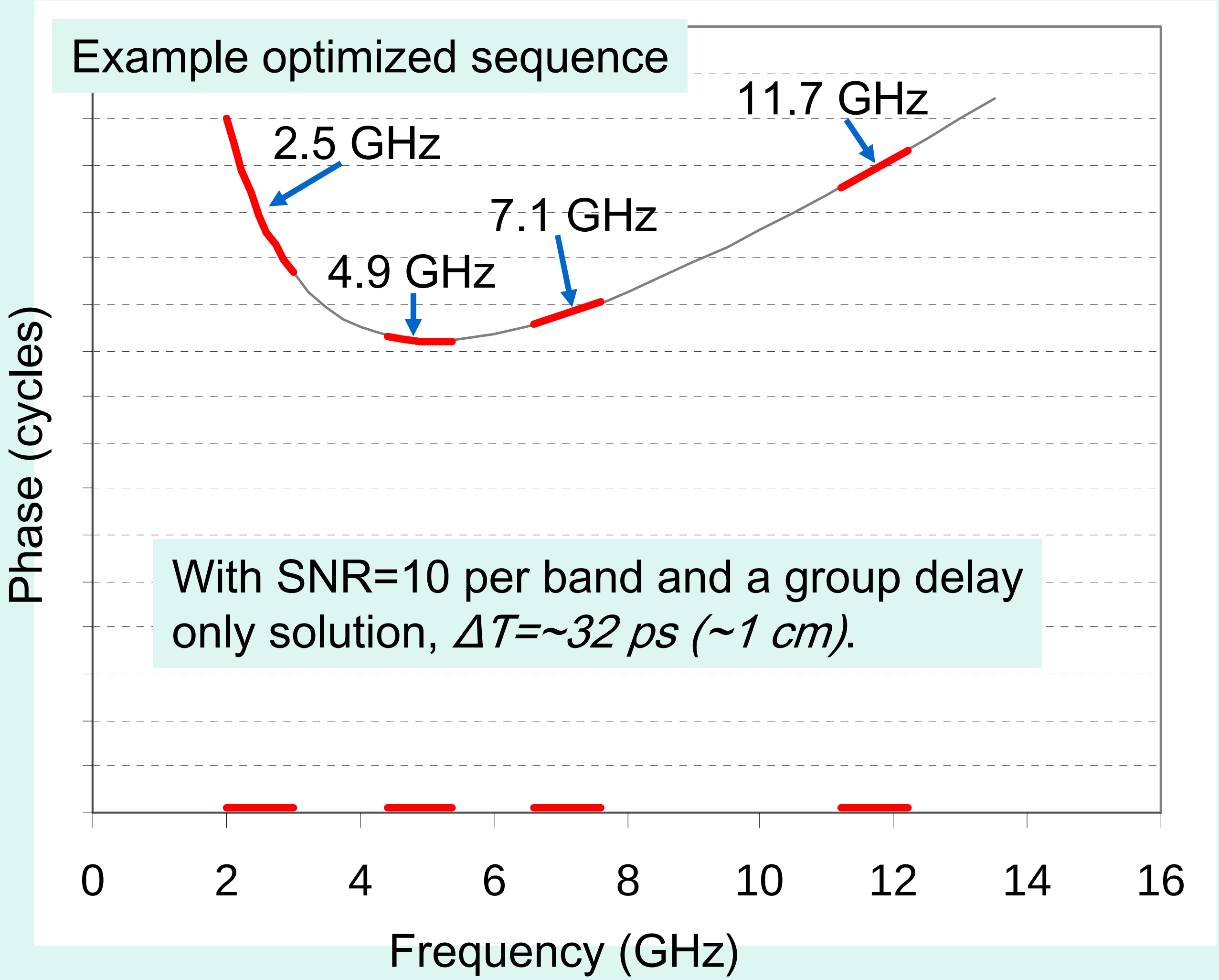
$$\phi = f \cdot \tau$$

$$\phi = f \cdot \left(\tau_g + \tau_{clk} + \tau_{atm} + \ldots\right)$$

Dispersive delay.
Delay varies with frequency. Variation is due to the Ionosphere.

$$\phi_{Ion} = \frac{K}{f} \qquad \tau_{Ion} = -\frac{K}{f^2}$$

Level 1 Solution: Group Delay only

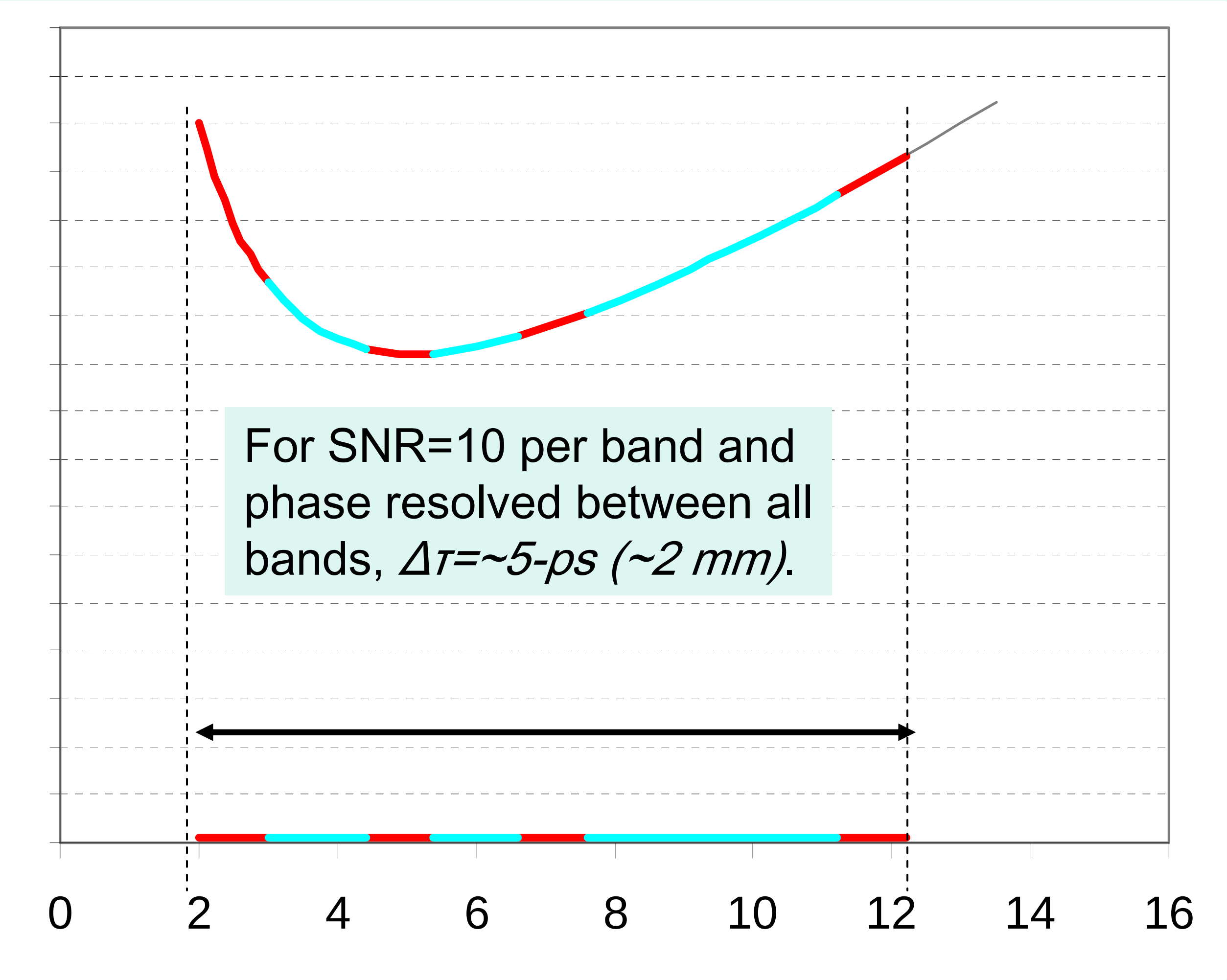


Example optimized sequence

With SNR=10 per band and a group delay only solution, *ΔT=~32 ps (~1 cm)*.

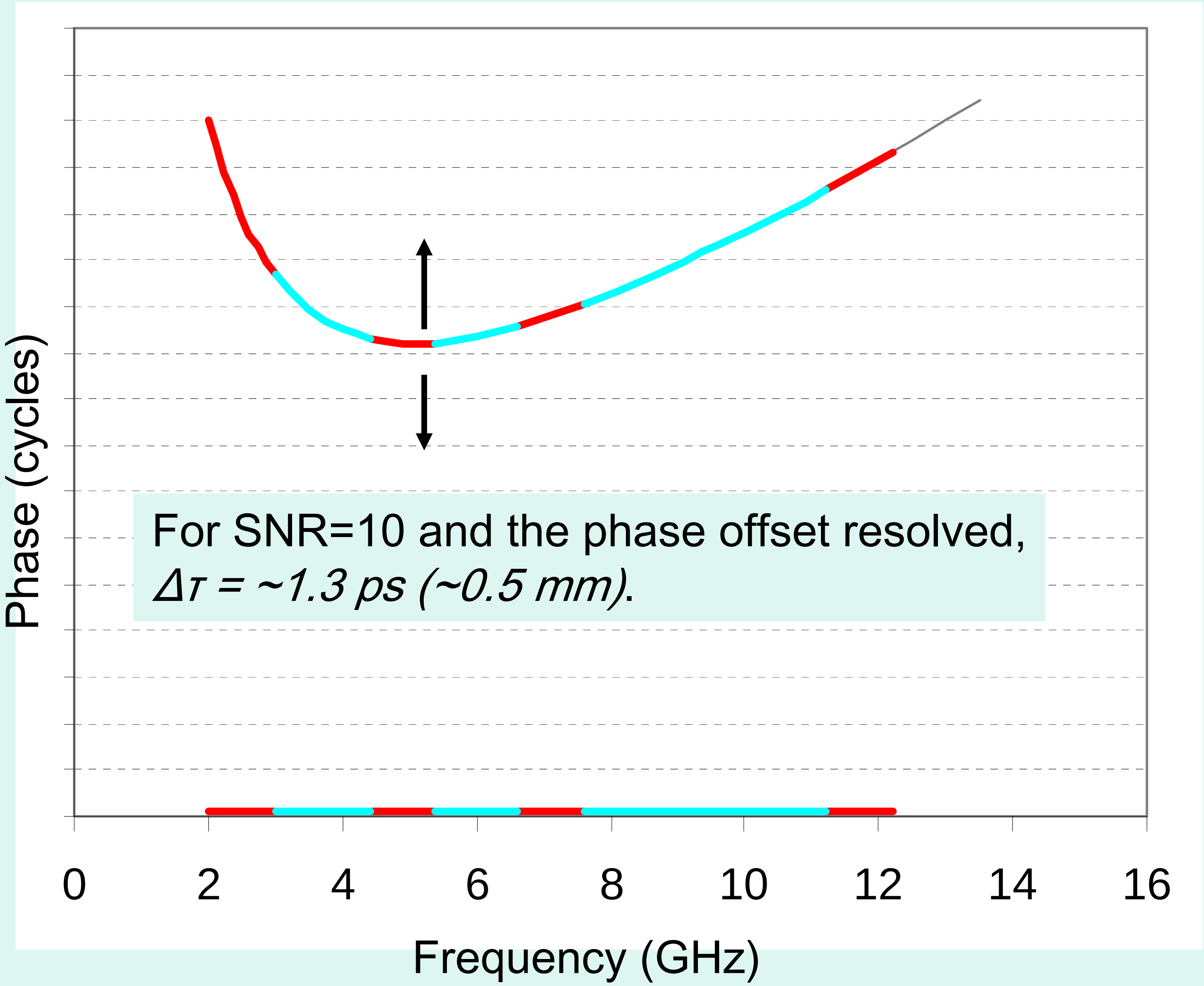
Level 2 solution: Using the group delay solution, connect the phase between bands

Need to resolve integer cycles of phase between bands



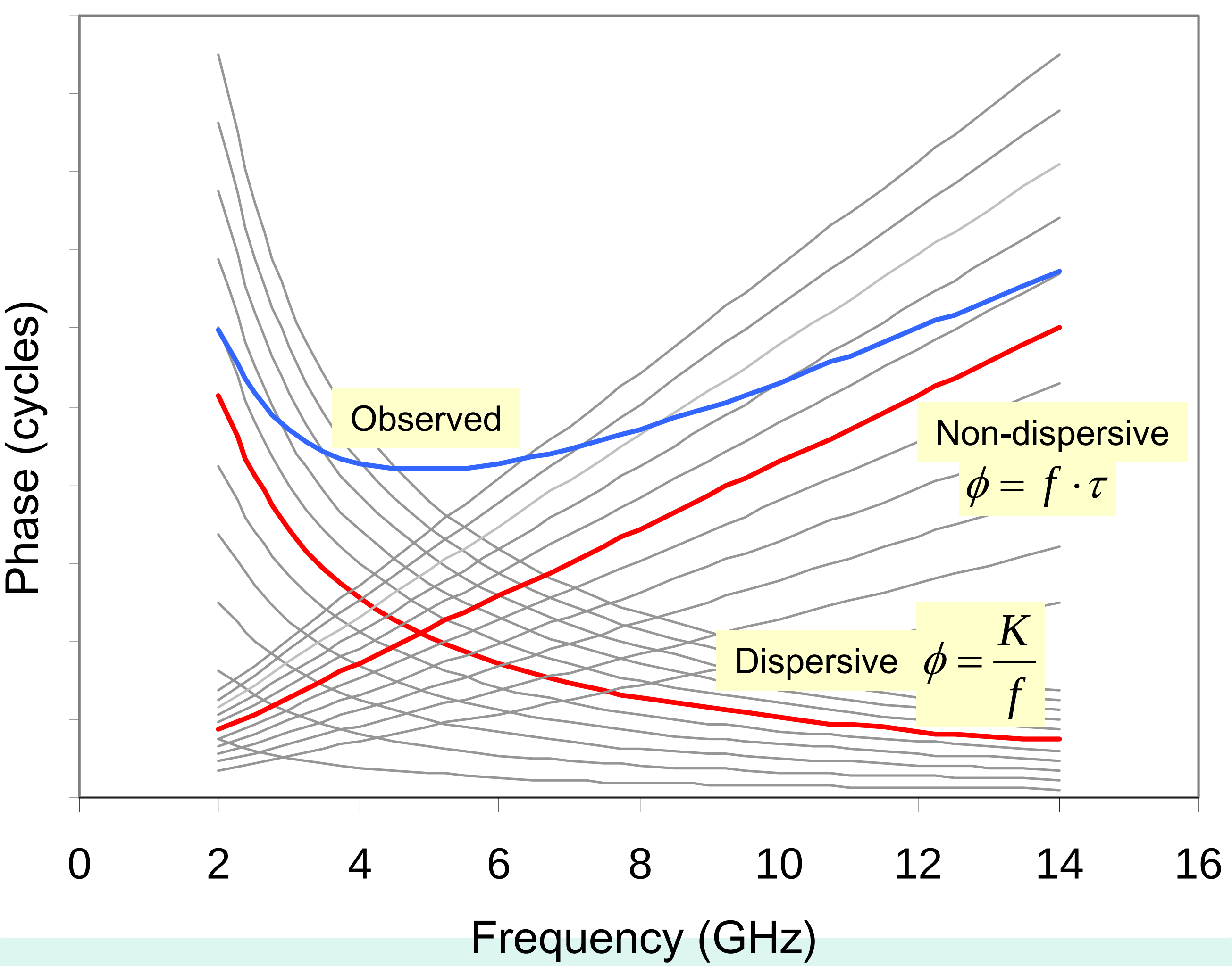
For SNR=10 per band and phase resolved between all bands, *Δτ=~5-ps (~2 mm)*.

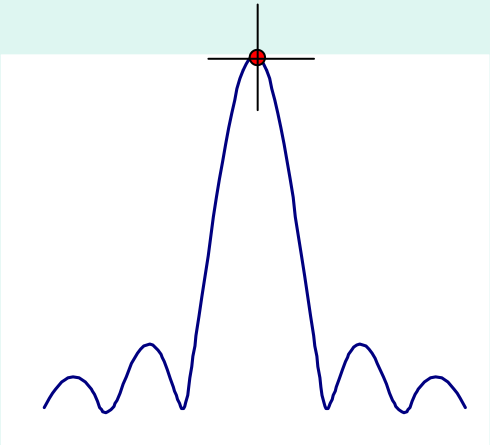
Level 3 solution: Using the connected phase solution, resolve the phase offset



For SNR=10 and the phase offset resolved, *Δτ = ~1.3 ps (~0.5 mm)*.

In practice, a search algorithm is used to determine T and K

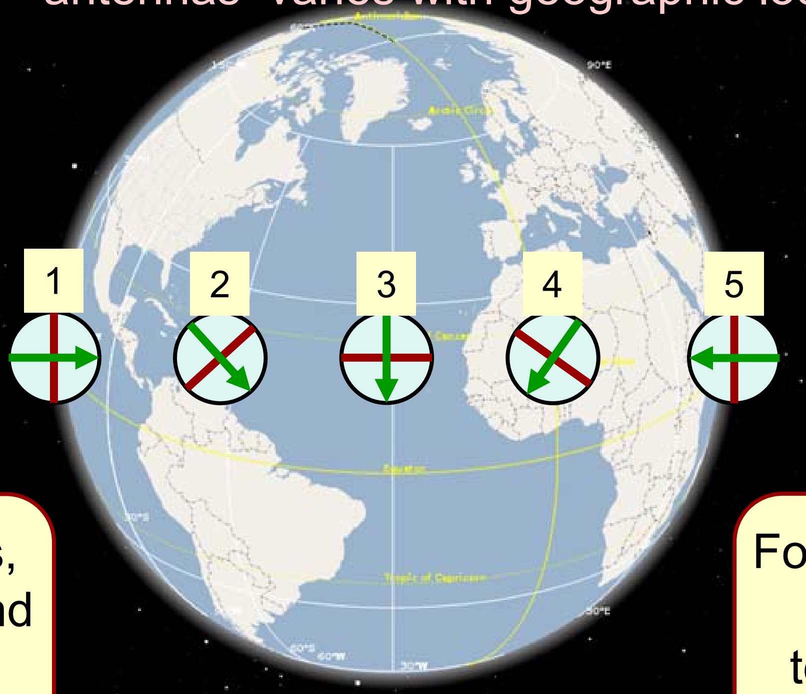


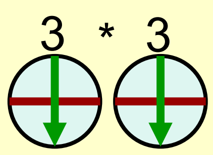


Search to find values of T *and* K that flatten the observed delay (when subtracted) and hence maximize the coherent sum

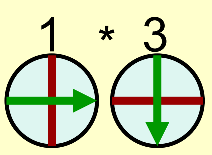
VLBI works best with circular polarization

As seen from above, the linear polarization orientation for alt/az antennas varies with geographic location





For parallel orientations, correlated signal is found in the co-pol products, e.g. v1*v2 and h1*h2



For orthogonal orientations, correlated signal shifts to the cross-pol products e.g. v1*h2 and h1*v2

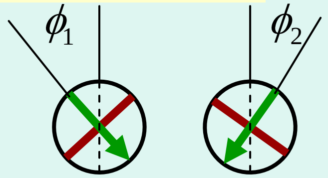
To avoid the shifting of correlated amplitude between cross- and co-pol products , VLBI traditionally uses circular polarization, where correlated amplitude is independent of relative polarization orientation.

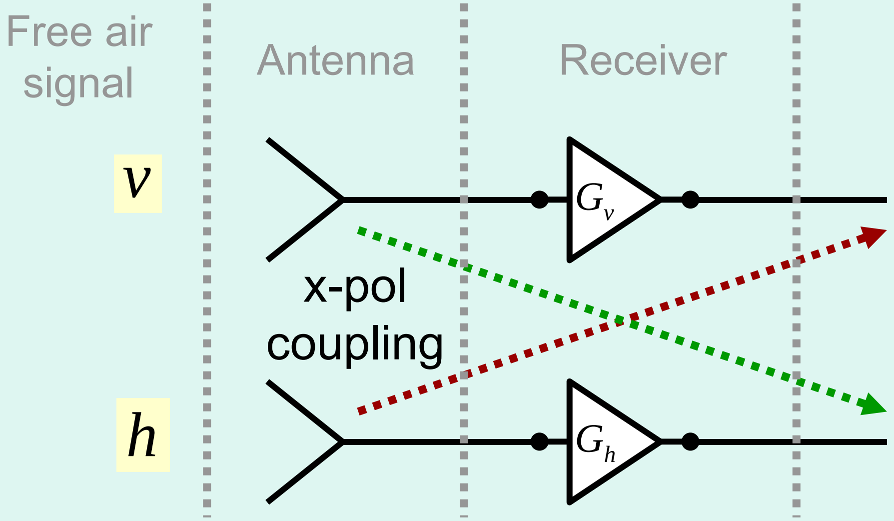
Although unprecedented, VLBI2010 uses linear polarizations directly. All four polarization products are correlated and combined to generate a total intensity (I) observable post-correlation. [Circular polarization could be generated electronically at each antenna using 90°-hybrids but LNA imbalances are a problem.]

Post-correlation determination of Total Intensity

$$I = \left(\langle v_1 \cdot v_2^* \rangle + \langle h_1 \cdot h_2^* \rangle \right) \cdot \cos\Delta + \left(\langle v_1 \cdot h_2^* \rangle - \langle h_1 \cdot v_2^* \rangle \right) \cdot \sin\Delta$$

Δ ~ differential antenna polarization angle, i.e. $\Delta = \phi_2 - \phi_1$





$$V = G_v \cdot (v + D_h \cdot h)$$

$$H = G_h \cdot (h + D_v \cdot v)$$

Need to know *G* and *D* terms

- can be determined by observing a strong unpolarized point source
- *G terms* can be tracked using noise and phase cal signals

VLBI2010 Antenna/Feed/Receiver Summary

- Antenna Azimuth slew rate: 12°/s
- Antenna Elevation slew rate: 6°/s
- SEFD: < 2500 Jy
- Frequency range: 2-14 GHz
- Polarizations: V-pol, H-pol (linear)
- # of bands: 4
- Bandwidth per band: 1 GHz
- Data rate (burst): 16 Gbps (eventually 32 Gbps)
- Sustained record rate: 8 Gbps (eventually 16 Gbps)

Resources, e.g.:

- “Radio Astronomy Tutorial”, http://www.haystack.mit.edu/edu/undergrad/materials/RA_tutorial.html
- “Essential Radio Astronomy”, http://www.cv.nrao.edu/course/astr534/ERA.shtm

Many thanks to Brian Corey for assistance with course material preparation!

Questions?