UFYS2010: Radio astronomy instrumentation and interferometry

Kaj Wiik

Tuorla Observatory

Spring 2013

Some of the figures are from Wilson, Rohlfs, Hüttemeister: 'Tools of Radio astronomy'

Outline

Recap from lecture 2

Antennas and aperture efficiency

Antenna temperature

Antenna types

Aperture-beam Fourier transform relationship

Antenna mounts

Antenna Performance Parameters

Radiometer sensitivity

Receiver internals

Recap: opacity

If medium is isothermal, the observed brightness temperature $T_b(s)$ with medium thickness s is

$$T_b(s) = T_b(0)e^{-\tau_\nu(s)} + T(1 - e^{-\tau_\nu(s)}). \tag{1}$$

If opacity is very small, the absorbation and radiation of the medium has no effet. However, if it is very large, the observed brightness temperature is the *physical temperature of the medium*.

Recap: flux density

$$S = \int \frac{2kT_b}{\lambda^2}\,\mathrm{d}\Omega = \frac{2k}{\lambda^2}\int T_b\,\mathrm{d}\Omega \tag{2}$$

For point source (fills the beam):

$$S = \frac{2kT_b}{\lambda^2} \tag{3}$$

Flux density is fundamental quantity in radio astronomy. Two 'shorthands':

1 Jy (Jansky) $= 10^{-26}\left[\frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{Hz}}\right]$

1 sfu (solar flux unit) $= 10^{-22}\left[\frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{Hz}}\right]$

Relation to optical magnitudes (V-band):

$$\mathrm{m_V} = 0 \Leftrightarrow S = 3.83610^{-23}\left[\frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{Hz}}\right] = 3836\ \mathrm{Jy} \tag{4}$$

Antennas and aperture efficiency

The task of the antenna is to scoop radio photons that land on its aperture. Therefore the most important paramter of an antenna is the ideal *effective aperture* A_e in square meters.

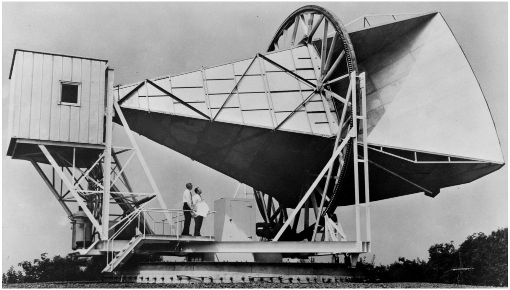
Image: Meerkat, South Africa

Real antennas are less effective and this is described by *aperture efficiency* η_e which is usually $0.5 \ldots 0.9$. All losses from structure, deformations and surface material are included in η_e

Aperture antennas

For aperture antennas (e.g. paraboloid- and horn antennas) the effective aperture can be calculated from the physical aperture and aperture efficiency:

$$A_e = \eta_e A \quad [\mathrm{m}^2] \tag{5}$$



Paraboloid-horn antenna that was used by Arno Penzias and Robert Wilson when they discovered the 3 K CMB (Bell Labs).

Antenna temperature

Power generated by an antenna looking at a brightness B_ν:

$$P = \frac{1}{2} A_e \int_{\nu}^{\nu+\Delta\nu} \int_{\Omega} B_\nu \, \mathrm{d}\Omega \, \mathrm{d}\nu, \tag{6}$$

where A_e is the effective aperture of the antenna and $\frac{1}{2}$ comes from a fact that an antenna is sensitive only to one polarization component.
Noise power generated by a resistor at a temperature of T (Nyqvist):

$$P = kT\Delta\nu \tag{7}$$

and

$$S = \int B(\nu) \, \mathrm{d}\Omega \left[\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{Hz}} \right] \tag{8}$$

Antenna temperature due to a flux density

Finally we get,

$$S = \frac{2kT_a}{A_e} \left[\frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{Hz}}\right] \tag{9}$$

where T_a is the *antenna temperature*, i.e. the increase of the temperature of a 'resistor' due to the source flux density.

A convenient measure of antenna performance is the DPFU (Degrees Per Flux Unit) figure:

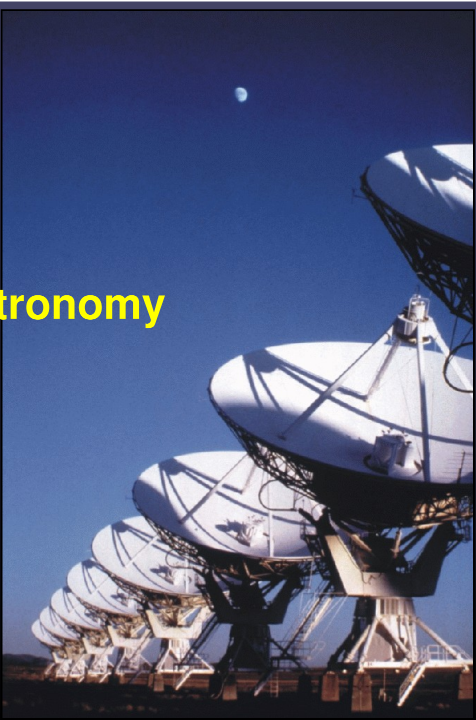
$$DPFU = \frac{A_e}{2k} 10^{-26} \left[\frac{\mathrm{K}}{\mathrm{Jy}}\right] \tag{10}$$

e.g.

Telescope	diameter [m]	DPFU [mK/Jy]
Tuorla solar telescope	2	0.6
Metsähovi	13.7	26.7
Effelsberg	100	1580

Antennas in Radio Astronomy

Peter Napier



Ninth Synthesis Imaging Summer School

Socorro, June 15-22, 2004

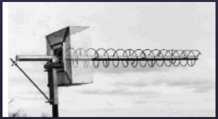
General Antenna Types

Wavelength > 1 m (approx)

Wire Antennas

Dipole

Yagi

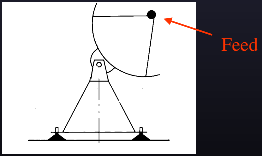


Helix

or arrays of these

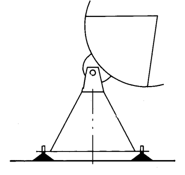
Wavelength < 1 m (approx)

Reflector antennas



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

Importance of the Antenna Elements



- Antenna amplitude pattern causes amplitude to vary across the source.
- Antenna phase pattern causes phase to vary across the source.
- Polarization properties of the antenna modify the apparent polarization of the source.
- Antenna pointing errors can cause time varying amplitude and phase errors.
- Variation in noise pickup from the ground can cause time variable amplitude errors.
- Deformations of the antenna surface can cause amplitude and phase errors, especially at short wavelengths.

Basic Antenna Formulas

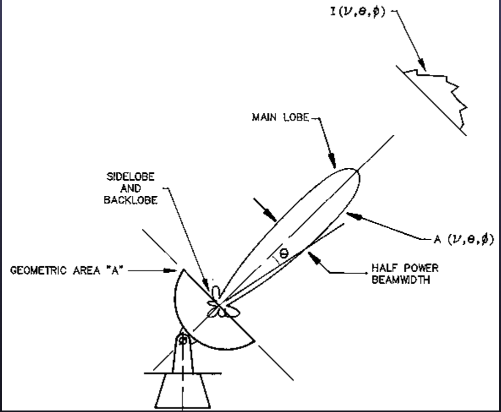
Effective collecting area $A(\nu,\theta,\phi)$ m^2

On-axis response $A_0 = \eta A$

η = aperture efficiency

Normalized pattern (primary beam)

$\boldsymbol{A}(\nu,\theta,\phi) = A(\nu,\theta,\phi)/A_0$



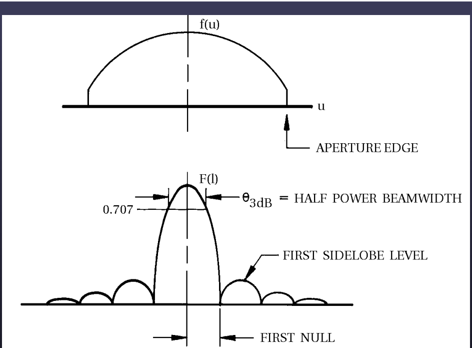
Beam solid angle $\Omega_A = \iint_{\text{all sky}} \boldsymbol{A}(\nu,\theta,\phi)\, d\Omega$

ν = frequency

λ = wavelength

$A_0 \Omega_A = \lambda^2$

Aperture-Beam Fourier Transform Relationship



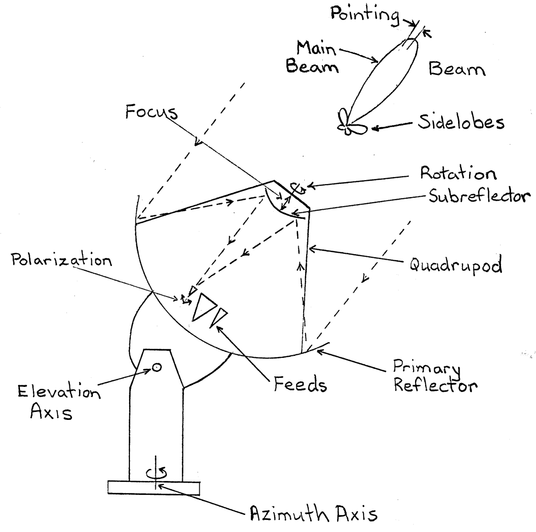
f(u,v) = complex aperture field distribution
u,v = aperture coordinates (wavelengths)

F(l,m) = complex far-field voltage pattern
$l = \sin\theta\cos\phi$, $m = \sin\theta\sin\phi$

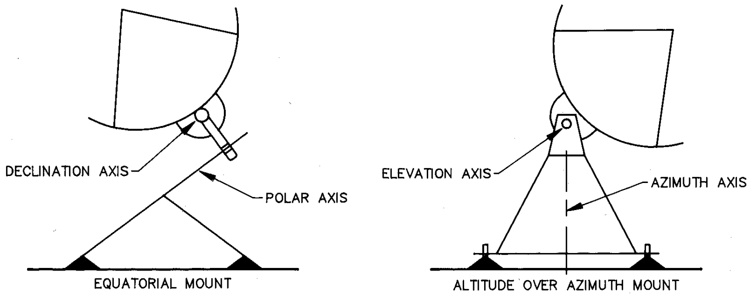
$F(l,m) = \iint_{\text{aperture}} f(u,v)\exp(2\pi i(ul+vm))\,du\,dv$
$f(u,v) = \iint_{\text{hemisphere}} F(l,m)\exp(-2\pi i(ul+vm))\,dl\,dm$

For VLA: $\theta_{3dB} = 1.02/D$, First null = 1.22/D,
D = reflector diameter in wavelengths

Primary Antenna Key Features



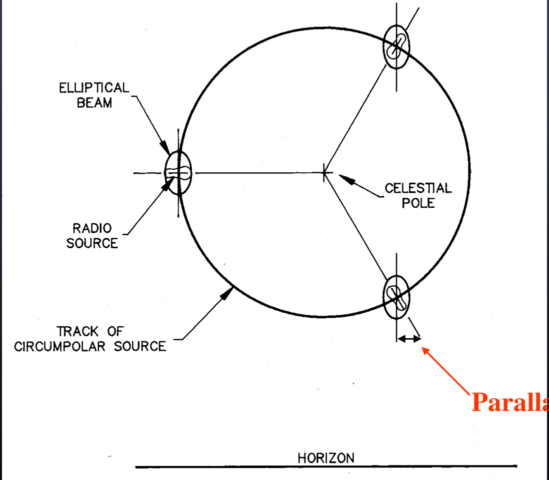
Types of Antenna Mount



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

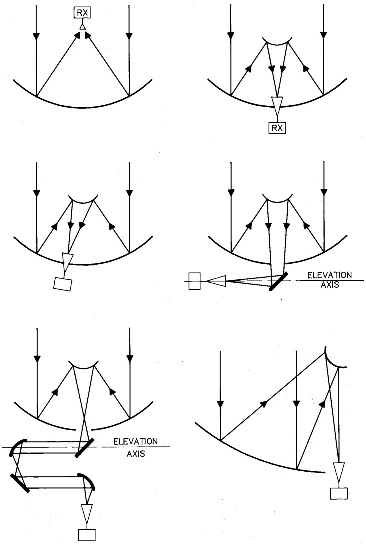
+ Lower cost
+ Better gravity performance
– Beam rotates on the sky

Beam Rotation on the Sky



Parallactic angle

Reflector Types



Prime focus
(GMRT)

Cassegrain focus
(AT)

Offset Cassegrain
(VLA)

smith
(OVRO)

Beam Waveguide
(NRO)

Dual Offset
(ATA)

Reflector Types

Prime focus
(GMRT)

Cassegrain focus
(AT)

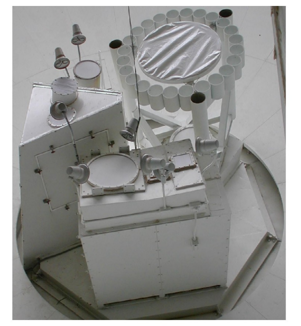
Offset Cassegrain
(VLA)

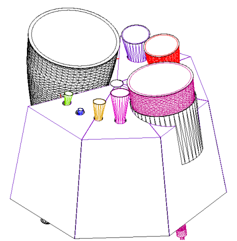
ith
(OVRO)

Beam Waveguide
(NRO)

Dual Offset
(ATA)

VLA and EVLA Feed System Design





Antenna Performance Parameters

Aperture Efficiency

$A_0 = \eta A,\ \eta = \eta_{sf} \times \eta_{bl} \times \eta_s \times \eta_t \times \eta_{misc}$

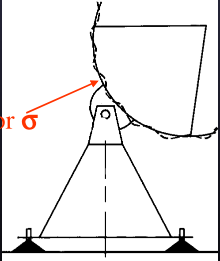
η_{sf} = reflector surface efficiency

η_{bl} = blockage efficiency

η_s = feed spillover efficiency

η_t = feed illumination efficiency

η_{misc}= diffraction, phase, match, loss

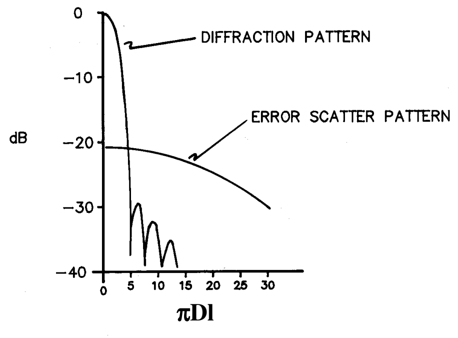


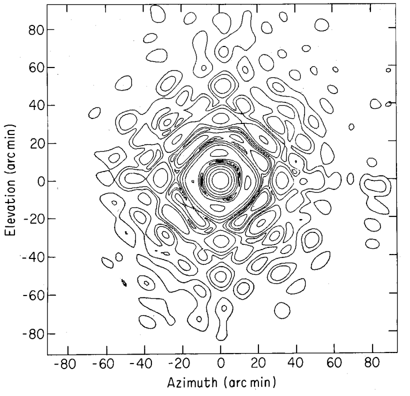
$\eta_{sf} = \exp(-(4\pi\sigma/\lambda)^2)$

e.g., $\sigma = \lambda/16$, $\eta_{sf} = 0.5$

Antenna Performance Parameters

Primary Beam





l=sin(θ), D = antenna diameter in wavelengths

dB = 10log(power ratio) = 20log(voltage ratio)

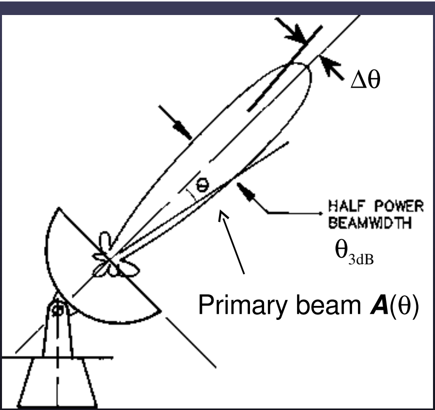
For VLA: θ_{3dB} = 1.02/D, First null = 1.22/D

contours:–3,–6,–10,–15,–20,–25, –30,–35,–40 dB

Antenna Performance Parameters

Pointing Accuracy

$\Delta\theta$ = rms pointing error



Often $\Delta\theta < \theta_{3dB}/10$ acceptable

Because $\boldsymbol{A}(\theta_{3dB}/10) \sim 0.97$

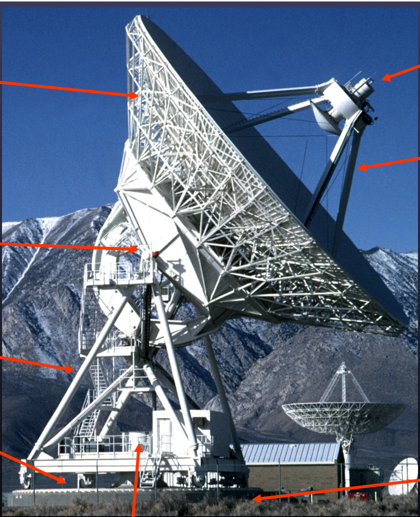
BUT, at half power point in beam

$\boldsymbol{A}(\theta_{3dB}/2 \pm \theta_{3dB}/10)/\boldsymbol{A}(\theta_{3dB}/2) = \pm 0.3$

For best VLA pointing use Reference Pointing.

$\Delta\theta = 3$ arcsec $= \theta_{3dB}/17$ @ 50 GHz

Antenna Pointing Design



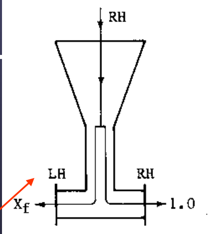
ALMA 12m Antenna Design

Surface: $\sigma = 25\ \mu m$
Pointing: $\Delta\theta = 0.6$ arcsec

Carbon fiber and invar reflector structure

Pointing metrology structure inside alidade

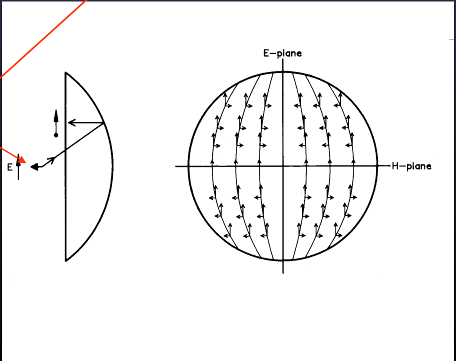
Antenna Performance Parameters



Polarization

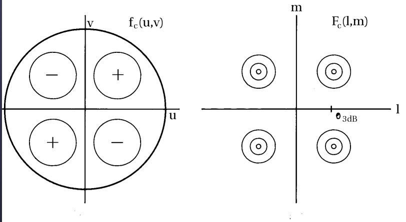
Antenna can modify the apparent polarization properties of the source:

- Symmetry of the optics
- Quality of feed polarization splitter
- Circularity of feed radiation patterns
- Reflections in the optics
- Curvature of the reflectors

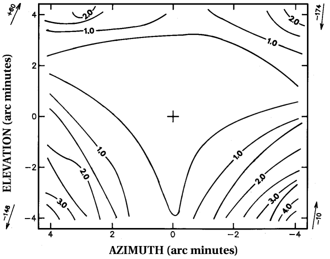


Off-Axis Cross Polarization

Cross polarized aperture distribution



Cross polarized primary beam



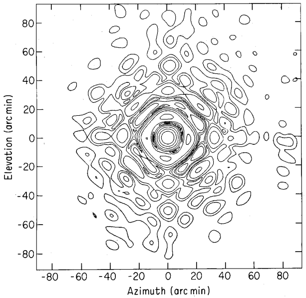
VLA 4.8 GHz cross polarized primary beam

Antenna Holography

VLA 4.8 GHz

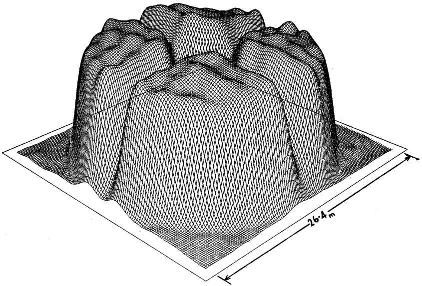
Far field pattern amplitude

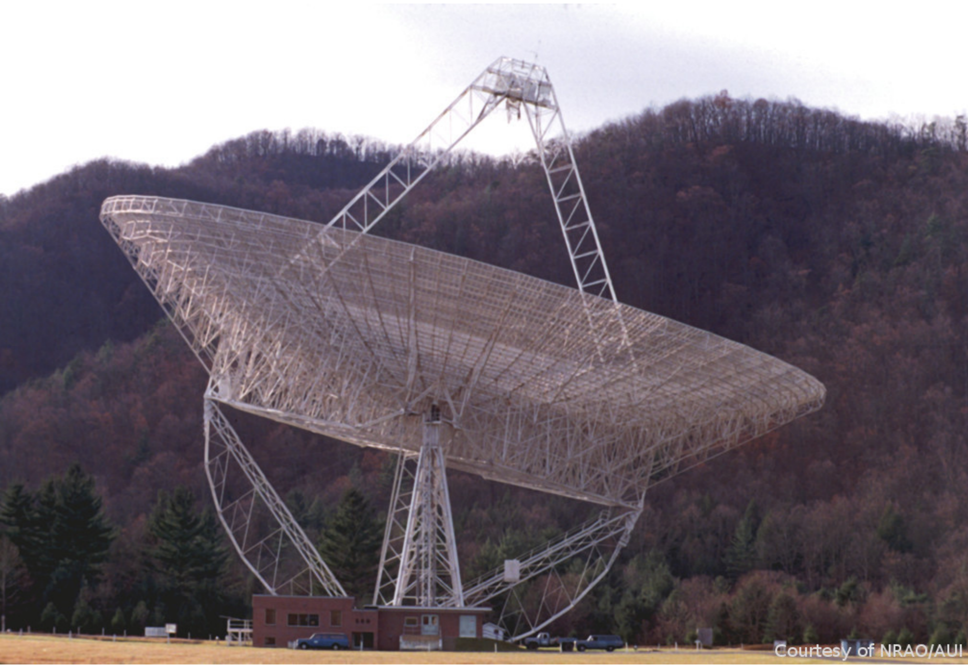
Phase not shown



Aperture field distribution amplitude.

Phase not shown





Courtesy of NRAO/AUI

Courtesy of NRAO/AUI

America's most powerful radio telescope IS . . .

ZAPPED!

. . . by hostile space aliens!

THE Green Bank radio telescope in West Virginia after the alien attack. At left is how it looked after construction.

BEFORE ▲ **AFTER ▶**

Space aliens zapped the enormous radio telescope at Green Bank, W. Va., with a powerful laser to keep scientists from monitoring their activities in the northern hemisphere!

By RAGAN DUNN

That's the claim of Swiss astronomer Peter Voisard, who says the destruction of the 300-foot instrument on November 15 qualifies as the boldest act of extraterrestrial aggression in the history of the world.

"We know that extraterrestrials have shot down planes and abducted people but this is the first time they have been brazen enough to destroy a government research facility," the expert told newsmen in Geneva. "The Americans must have been learning too much about them," he continued. "There is no other rational explanation for such a strike as this. In some circles, it might be considered an act of war."

Dr. Voisard's report sent shockwaves throughout the world's scientific community. But the handful of men who can talk about the Green Bank disaster with authority refused to describe the incident as anything more than "a mystery."

There is no doubt that the instrument — which could detect objects almost two-thirds of the way to the edge of the visible universe — was essential to monitoring extraterrestrial activity in the northern skies.

And its devastation by a destructive beam stands as compelling proof that it was zapped by extraterrestrials who wanted to mask their activity from mankind, Dr. Voisard said.

"Any other explanation defies logic," he continued. "The telescope had been in operation since 1962 and was solid as a rock.

"Suddenly it collapses in the dead of night. What are we supposed to think? That the telescope just fell apart?"

French radio astronomer Marc Kraemer was inclined to agree with Dr. Voisard but warned against jumping to conclusions.

"I firmly believe that we can prove extraterrestrials toppled the telescope at Green Bank," he said. "But let's wait until all the evidence is in.

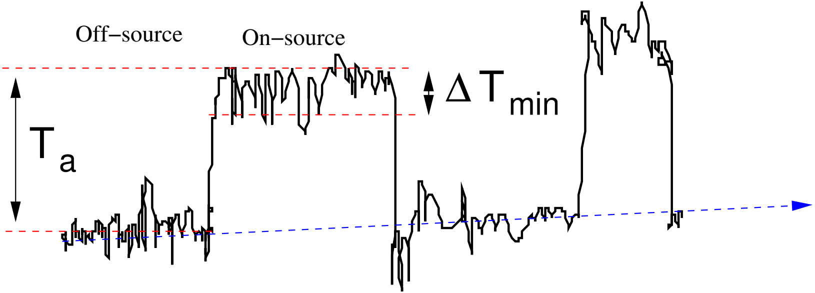
"Then we can take whatever steps are necessary to prevent things like this from happening in the future."

Radiometer sensitivity

We know now that the noise temperature at our receiver input is

$$T_a = \frac{SA_e}{2k} \tag{11}$$

How much does the receiver generate noise by itself (T_r) and what is the minimum detectable T_a?



Here the antenna has switched between the source and a blank sky, note the increase in noise level (T_a).

$T_{sys} = T_a + T_r + T_{sky}$

When determining the sensitivity of a radiometer, total noise contribution $T_{sys} = T_a + T_r + T_{sky}$ to the radiometer must be taken into account, i.e the noise from source, receiver and atmosphere.

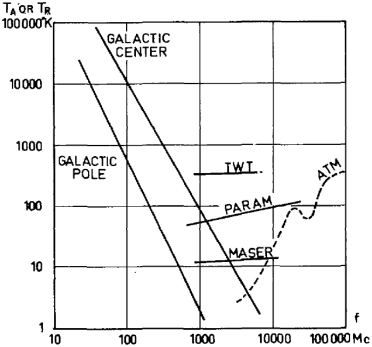


Fig. 2—Antenna sky noise temperature T_A with beam pointing at the galactic pole and galactic center and due to the atmosphere (dashed) as a function of the frequency. Noise temperatures T_R of some typical receivers are also shown.

Total system noise temperature

It should be noted that the quantity radiometer is measuring (in radio astronomy) is noise itself and adds to the total noise temperature and to the standard deviation of the result. Because of this, *all* noise sources including the source that is been measured (antenna temperature), atmosphere, CMB and the telescope itself must be taken into account:

$$T_{\mathrm{sys}} = T_{\mathrm{a}} + T_{\mathrm{atm}} + T_{\mathrm{cmb}} + T_{\mathrm{tel}} + \ldots \tag{12}$$

The total noise of a receiver is called the *total system noise temperature* T_{sys}.

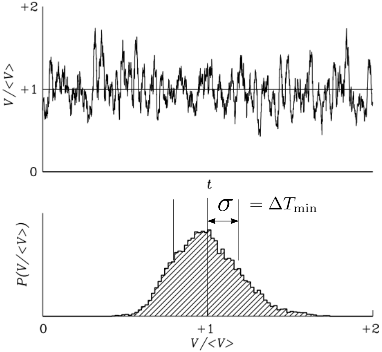
Sensitivity is also a function of *bandwidth* $\Delta\nu$ or B from where the noise power is collected and amount of averaging, i.e. the *integration time* τ.

Minimum detectable noise difference ΔT_{min}

Then the minimum detectable noise difference *for ideal radiometer* is

$$\Delta T_{\min} = \frac{T_{\rm sys}}{\sqrt{\Delta\nu\tau}}. \qquad (13)$$

There are effectively $\Delta\nu$ independent noise contributions per second, $\Delta\nu\tau$ in total. Therefore RMS deviation is $1/\sqrt{\Delta\nu\tau}$ times the average output.



Receiver types

Bolometer: polarizer, frequency band filter and thermometer

- Power is tramsformed into temperature which is measured.
- Very wideband and therefore sensitive, no spectral information
- Has to be cooled to less than 4K (superconductors)

Direct detecting receiver: polarizer, amplifier and power detector

- Simple and low-cost
- Microwave amplifiers can be operated (even) at room temperature
- Wideband and sensitive but no spectral information

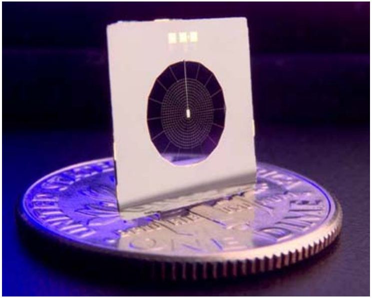
Heterodyne receiver

- Signal from antenna is translated down to a more convenient frequency
- Local oscillator and mixer increase complexity
- Full spectral information available
- DSB: double (folded) sideband, SSB: single sideband

Bolometer

A *bolometer* measures the power of incident electromagnetic radiation via the heating of a material.

To improve sensitivity, thermometers in bolometers are usually superconductors that are cooled down to below 4 K. They are very wideband instruments, that is one reason for their sensitivity.

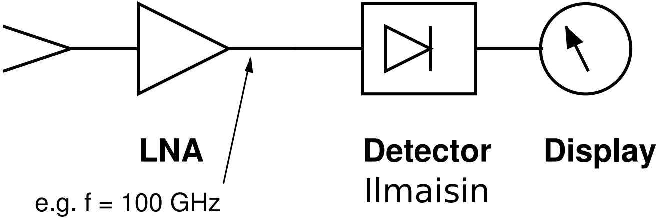


Credit: NASA/JPL-Caltech

If any frequency selectivity is needed, it must be implemented using (rather wide) filters. Because bolometers cannot measure phase of the incident radiation, they cannot be used in interferometers.

Direct detecting receiver (or radiometer)

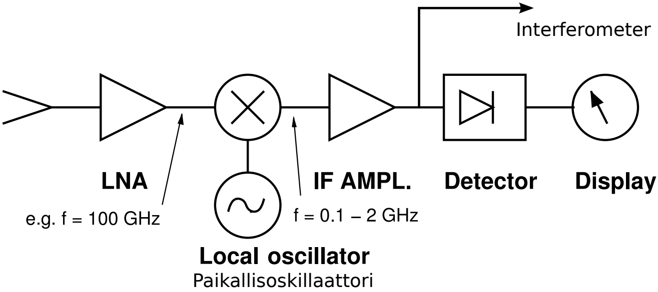
Direct detecting receiver consists of only amplifier and a detector. The advancement of amplifier technology in 1990's made this type of receiver more popular. Before it was necessary to downconvert the frequency before amplification.



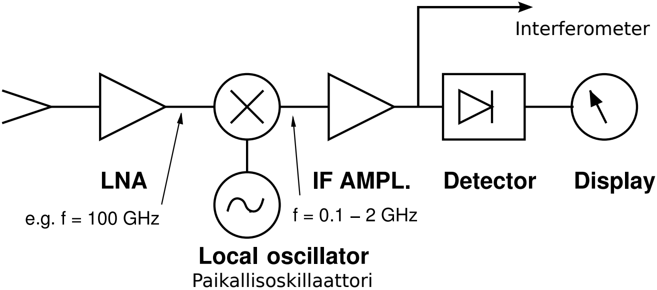
The advantages are *simplicity* and, due to the wide bandwidth, *sensitivity*. Because phase information is lost, this receiver type cannot be used for interferometry either.

(Super)heterodyne receiver I

In heterodyne receivers, the received frequency band is translated with a mixer to a lower, *intermediate frequency (IF)*. Especially some tens of years back, manufacturing high frequency ($\nu > 10$ GHz) amplifiers was expensive and difficult but mixers were much easier and cheaper. Therefore downconverting in frequency and amplifying with cheaper and more manageable components (size scales with wavelength!) was considerably easier.



(Super)heterodyne receiver II



After IF amplifier, signal can be either detected (total power), i.e averaged amplitude squared is preserved (radiometer) or the processing can be continued further (digitization, spectrometer, polarization correlator, interferometry, storage. . .)