Radio astronomy and interferometry

Silja Pohjolainen

First solar lecture 2015

Radio telescopes

Tuorla 2-meter solar radio telescope

Radio telescopes

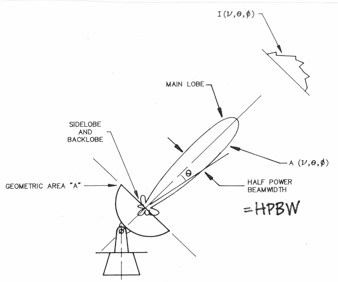


Figure 3–2. The reception pattern of an antenna.

HPBW 'half power beam width'
FWHM 'full width half maximum'

True (efficient) antenna area =
aperture efficiency × geometric area; efficiency varies ≈ 0.3 − 0.7
Surface accuracy of the dish has to be better than the λ used

Antenna pattern

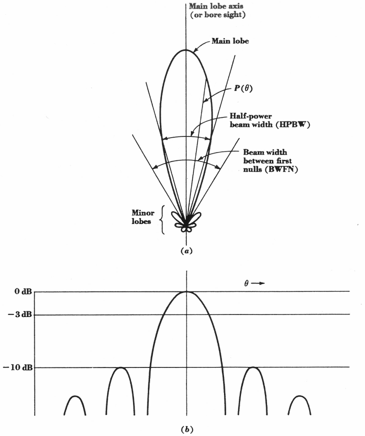


Fig. 6-1. (a) Antenna pattern in polar coordinates and linear power scale; (b) antenna pattern in rectangular coordinates and decibel power scale.

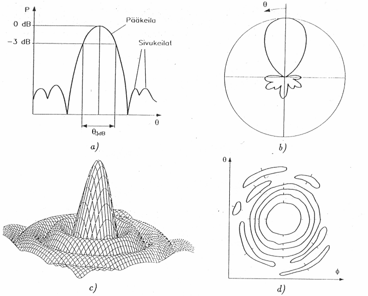
HPBW $\sim$ BWFN/2 (beam width between first nulls)

Note the size of the sidelobes and effects in solar obs!

Spatial resolution and sidelobes

Taulukko 9.1. Viivalähteiden suuntakuvioiden ominaisuuksia.

Kentänjakauma apertuurissa	Keilanleveys (−3 dB)	1. sivukeila	1. nollakohta
Tasainen	$0{,}89\lambda/a$	−13,3 dB	λ/a
$\cos(\pi x/a)$	$1{,}19\lambda/a$	−23,1 dB	$1{,}5\lambda/a$
$\cos^2(\pi x/a)$	$1{,}44\lambda/a$	−31,5 dB	$2{,}0\lambda/a$
$1-0,5(2x/a)^2$	$0{,}97\lambda/a$	−17,1 dB	$1{,}14\lambda/a$
Taylor, $n=3$, reuna −9 dB	$1{,}07\lambda/a$	−25,0 dB	

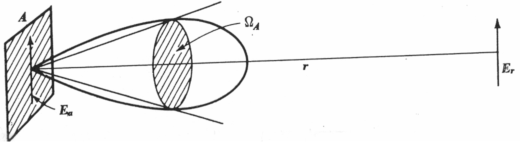


Kuva 9.3. *Suuntakuvion esitysmuotoja: a) suorakulmainen, b) polaarinen, c) kolmiulotteinen, d) vakioarvokäyrästö*

Antenna beamwidth – which basically means the spatial resolution – can be approximated with $\theta = 1.2\ \frac{\lambda}{D}$ or $1.0\ \frac{\lambda}{D}$

Antenna solid beam

where Ω_A = beam solid angle of antenna, rad²



The beam width (angle θ) is in **radians** (rad)

A squared radian (solid angle Ω) is in **steradians** (sr).
This can be calculated using the sphere or approximated with θ^2

Antenna pattern

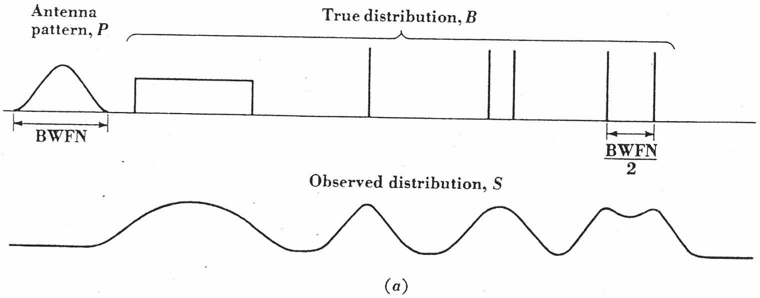
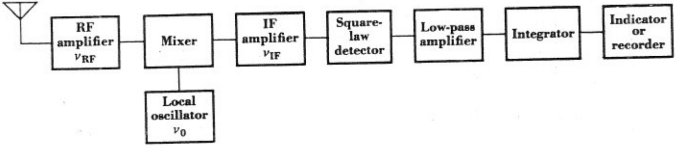


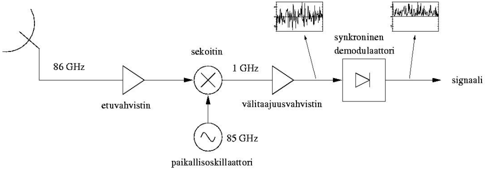
Fig. 6-11a. Smoothed distribution S observed with antenna pattern P.

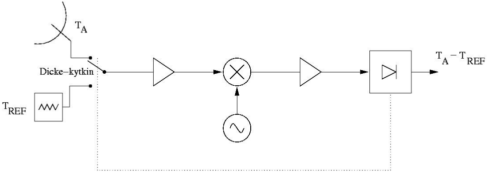
Tuorla-Bern polarimeters

Several antennas and/or receivers can be mounted in the same tracking system

Receivers







Solar observations usually require an attenuator if the receiver is used for other observations. Absolute calibration is only done once or twice a day (not to break up observations)

Flux density

$$\begin{aligned} \text{Solar flux unit, sfu} &= 10^{-22}\ \text{W m}^{-2}\ \text{Hz}^{-1} \\ &= 10^{-19}\ \text{erg cm}^{-2}\ \text{s}^{-1}\ \text{Hz}^{-1} \end{aligned}$$

1 sfu = 10 000 jansky

Observed flux

Flux density S of a source (for the two polarizations) is related to the source brightness temperature T_b

$$S = \frac{2k\nu^2}{c^2} \int T_b \, d\Omega \qquad (\mathrm{W\ m^{-2}\ Hz^{-1}})$$

where $d\Omega$ is a differential solid angle and the integral is over the projected area of the source.

The observed flux density can then be written as

$$S_0 = \frac{2kT_A}{A_{ef}} \qquad (\mathrm{W\ m^{-2}\ Hz^{-1}})$$

Simplified Example: How much flux?

Antenna diameter D$= 14$ m

Antenna area A$= \pi r^2 = 154$ m^2

Antenna efficient area A$_{ef} = 0.5 \times 154 = 77$ m^2

Observing frequency $\nu = 37$ GHz ($\lambda = \frac{c}{\nu} = 8$ mm)

Beam size HPBW $\approx 1.2\frac{\lambda}{D} = 0.000695$ rad $= 0.04^\circ = 2.4$ arc min

Antenna temperature $T_A \approx$ brightness temperature T$_b$
(source $>$ beam, absorbing atmosphere ignored)

T$_b \approx 7200$ K at 37 GHz (from litterature)

Simplified Example

$$S_0 = \frac{2kT_A}{A_{ef}} = 2 \times 1.3805 \times 10^{-23} \times 7200/77$$
$$= 2.58 \times 10^{-21} \text{ W m}^{-2} \text{ Hz}^{-1} = 26 \text{ sfu}$$

For a 2-m antenna with similar efficiency $S_0 = 1266$ sfu
(note that HPBW ≈ 0.5 degrees which is the full solar disk!)

Observed flux

If the source size (Ω_s) is smaller than the antenna beam size (Ω_A), the observed antenna temperature from the source reduces to:

$$T_A = \frac{\Omega_s}{\Omega_A} T_b$$

This means part of the beam sees e.g., the background sky, and only part of the beam sees the source

Example

Example. Mayer, McCullough, and Sloanaker (1958*a*, *b*) at the Naval Research Laboratory measured an antenna temperature of 0.24 K at a wavelength of 3.15 cm, when their radio-telescope antenna was directed at Mars. At the time of the measurements the disk of Mars subtended an angle of 18 sec of arc. Assuming that the antenna has a pencil beam of 0.116° between half-power points, find the equivalent temperature of the source (Mars).

Solution. The radius of the disk of Mars is 9 sec of arc or 9/3,600 = 0.0025°. Hence, the solid angle of the disk is given by

$$\Omega_s = \pi r^2 = \pi\,(0.0025^\circ)^2 = 2 \times 10^{-5}\ \text{deg}^2$$

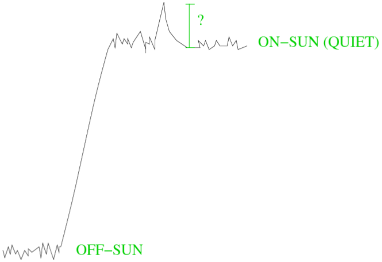
The beam area Ω_A of the antenna is given approximately by (see Chap. 6)

$$\Omega_A = \tfrac{4}{3}(0.116)^2 = 0.018\ \text{deg}^2$$

Hence, assuming a constant temperature over the disk, the average equivalent temperature of Mars by this measurement is, from (3-118),

$$T = T_A \frac{\Omega_A}{\Omega_s} = 0.24\,\frac{0.018}{2 \times 10^{-5}} = 216^\circ$$

Relative radio flare brightness



$T_{b,\nu}$ = X Kelvin (quiet Sun brightness temperature at frequency ν from literature or absolute calibrations)

On-Sun − Off-Sun = Y mV
$\Rightarrow$ Y mV $\equiv$ X Kelvin

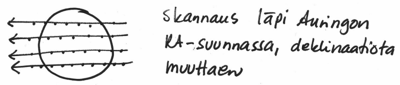
Calibration

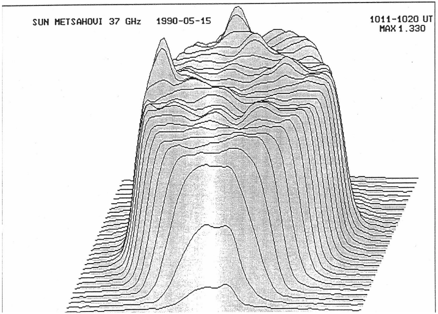
- Absolute calibration using radio sources and hot+cold loads
- No calibration, using units relative to 'quiet Sun' level

The method of using relative solar flux units provides the advantage of removing atmospheric and radome effects (variable attenuation) and instrumental effects, but it is more sensitive to errors in quiet Sun level determination.

Furthermore, the true source size of the radio emitting region in solar flares is not always known and it can vary from a few arc seconds to several arc minutes.

Metsähovi 14-m antenna is covered by a radome which attenuates the flux

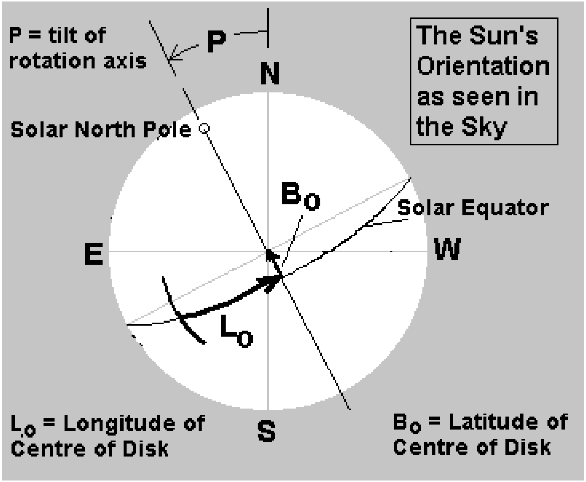




Scanning method: antenna is moved along Right Ascension (RA) and changing Declination (Dec) between scans

Sampling rate should exceed beam size

Scanned area should be larger than source size (allow antenna to catch up in movement!)



P = tilt of rotation axis
P
N
The Sun's Orientation as seen in the Sky
Solar North Pole
B_o
Solar Equator
E
W
L_o
S
L_o = Longitude of Centre of Disk
B_o = Latitude of Centre of Disk

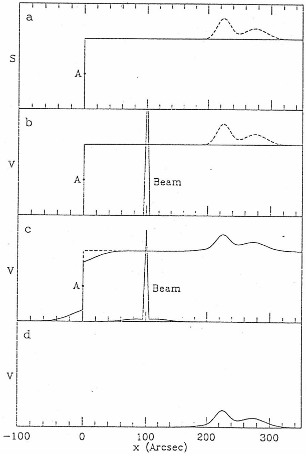
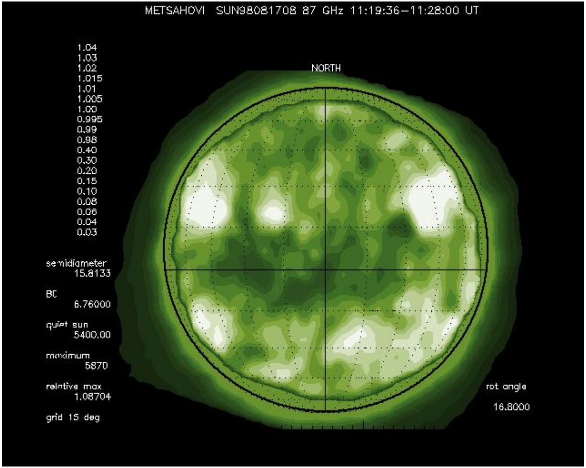


FIG. 3.—Diagrams illustrating the result of convolving sources with beams that have a sharp core and symmetric far wings. (*a*) Shows a source consisting of a simple step-function discontinuity (*solid curve*) at x (i.e., a Heaviside function). The dashed curve shows continuous variations introduced well inside the discontinuity. (*b*) Shows the result, V, of convolving the source in (*a*) with a simple Dirac delta function with no wings, which duplicates the source exactly. (*c*) Illustrates artificial limb darkening with an equal measure of artificial sky brightening, which results when the source profile is convolved with a beam that has symmetric wings. (*d*) Shows only continuous variation far to the right without the limb discontinuity. If we are given that the far wings of the beam are symmetric, we can conclude that the signal profiles in (*b*) and (*c*) can only have come from the source plotted in (*a*). The source that gave rise to the smooth signal profile shown in (*d*) remains ambiguous without further knowledge of the beam profile.



Effect of sidelobes: artificial limb darkening inside the disk and non-true brightening outside the disk

Note: there is also true limb darkening at certain wavelength ranges

Brightness temperature

Ideal (blackbody) radiator at temperature T radiates with intensity

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1} \qquad (\mathrm{W\ m^{-2}\ Hz^{-1}\ sr^{-1}})$$

At radio frequencies we can use the Rayleigh-Jeans approximation ($e^{h\nu/kT} \sim 1 + h\nu/kT + ...$)

$$B_\nu = \frac{2kT\nu^2}{c^2} \qquad (\mathrm{W\ m^{-2}\ Hz^{-1}\ sr^{-1}})$$

for the observed brightness (regardless of the emission mechanism).

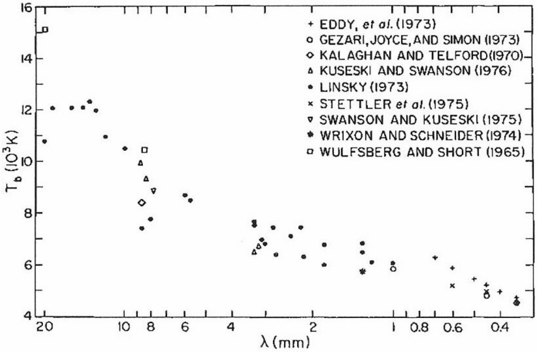


FIG. 5.—Selected brightness temperature observations of the Sun at millimeter wavelengths

T_b from Sun–Moon Calibrations

Solar brightness temperatures (Vernazza, Avrett & Loeser, 1981)

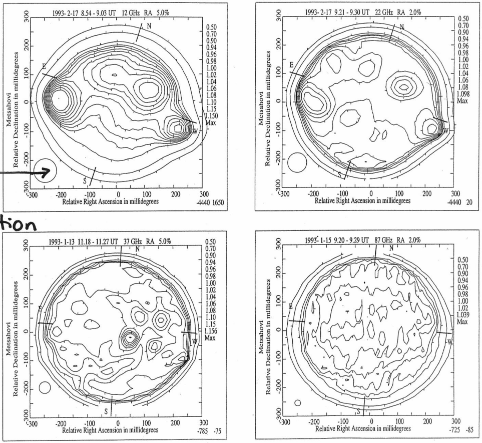
Solar maps measured at different wavelengths

12 GHz $T_b \approx 12000$ K

22 GHz $T_b \approx 9000$ K

antenna beam size = resolution $\sim 1.2 \frac{\lambda}{D}$

antenna ⌀ 14 m

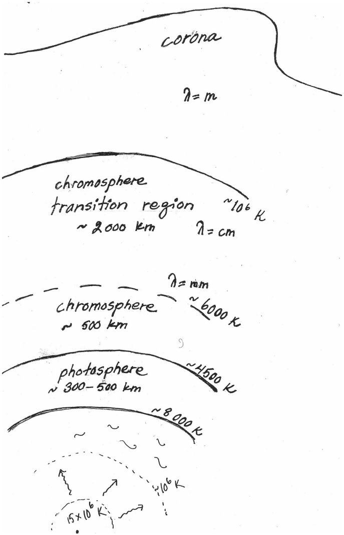


$T_b \approx 7800$ K

37 GHz

$T_b \approx 7200$ K

87 GHz



Different wavelengths probe different heights - plasma limit!

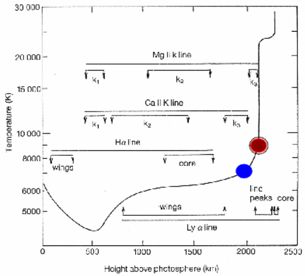
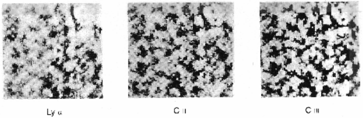


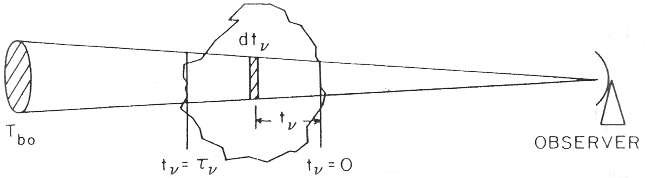
Fig. 4.12 The variation of temperature with height in the solar atmosphere up to the transition region for an average quiet-sun region. Also indicated are the height ranges over which the Hα and Ly-α, Ca II H and K, and Mg II h and k lines are formed. (After Vernazza, Avrett and Loeser (1981))

13 mm radio emission (quiet Sun, plasma limit)

3 mm radio emission (quiet Sun, plasma limit)



Radiative transfer equations



Geometry of a source with effective temperature T_{eff} and optical depth τ, located in front of a background with brightness temperature T_{bo}.

$$T_b = \int_0^{\tau_\nu} T_{eff} e^{-t_\nu} dt_\nu + T_{bo} e^{-\tau_\nu} = T_{eff}(1 - e^{-t_\nu}) + T_{bo} e^{-\tau_\nu}$$

Radiative transfer equations

Just the source, with no background:

$$T_b = \int_0^{\tau_\nu} T_{eff} e^{-t_\nu} dt_\nu$$

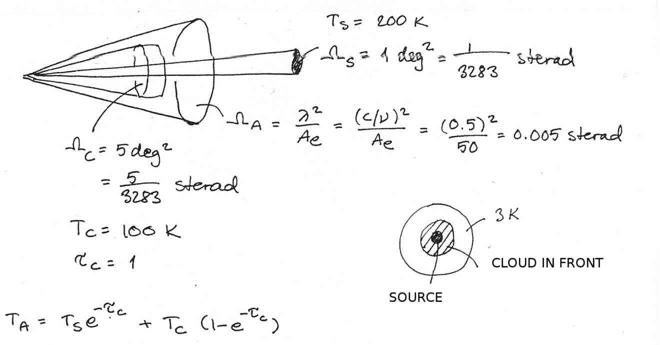
$$T_b = T_{eff}(1 - e^{-t_\nu})$$

if $\tau_\nu \gg 1$, $e^{-t_\nu} \to 0$: $\mathrm{T}_b = \mathrm{T}_{eff}$ (optically thick)

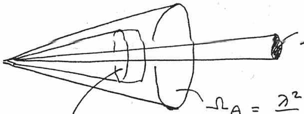
if $\tau_\nu \ll 1$, $(1 - e^{-t_\nu}) \to \tau_\nu$: $\mathrm{T}_b = \mathrm{T}_{eff}\,\tau_\nu$ (optically thin)

Example

An emission source, with brightness temperature of 200 K and source solid angle of 1 deg^2 is observed through a cloud. The brightness temperature of the cloud is 100 K and its solid angle is 5 deg^2. The effective area of the radio telescope is 50 m^2. Observations are done at 600 MHz and the optical depth of the cloud is 1. Calculate the antenna temperature when the telescope is pointing to the source (you can ignore the 3 K cosmic background radiation).



Example



$T_S = 200\ K$

$\Omega_S = 1\ deg^2 = \frac{1}{3283}$ sterad

$\Omega_A = \frac{\lambda^2}{A_e} = \frac{(c/\nu)^2}{A_e} = \frac{(0.5)^2}{50} = 0.005$ sterad

$\Omega_C = 5\ deg^2$

$= \frac{5}{3283}$ sterad

$T_C = 100\ K$

$\tau_C = 1$

$$T_A = T_S e^{-\tau_C} + T_C (1 - e^{-\tau_C})$$

$$T_{SA} = \frac{\Omega_S}{\Omega_A} T_S = \frac{1/3283}{0.005} \cdot 200\ K = 12.18\ K$$

$$T_{CA} = \frac{\Omega_C}{\Omega_A} T_C = \frac{5/3283}{0.005} \cdot 100\ K = 30.46\ K$$

$$T_A = T_{SA} \cdot e^{-1} + T_{CA} (1 - e^{-1}) = 23.73\ K$$

Example

Solar radio radiation at 37 GHz originates from an atmospheric layer that is approximately at height 2100 km from the bottom of the photosphere (i.e., from the solar "surface"). The effective temperature there is about 8 000 K and the electron density is about 2×10^8 cm^{-3}. Filaments are dense clouds with an effective temperature of 6100 K and electron density of about 5×10^{10} cm^{-3}. Their optical thickness can be assumed to be $\tau = 2.1$.

Calculate the solar brightness temperature at 37 GHz with and without a filament present. So, are filaments observed as radio depressions or bright structures on the solar disk? Can you estimate how they would look at other radio frequency ranges?