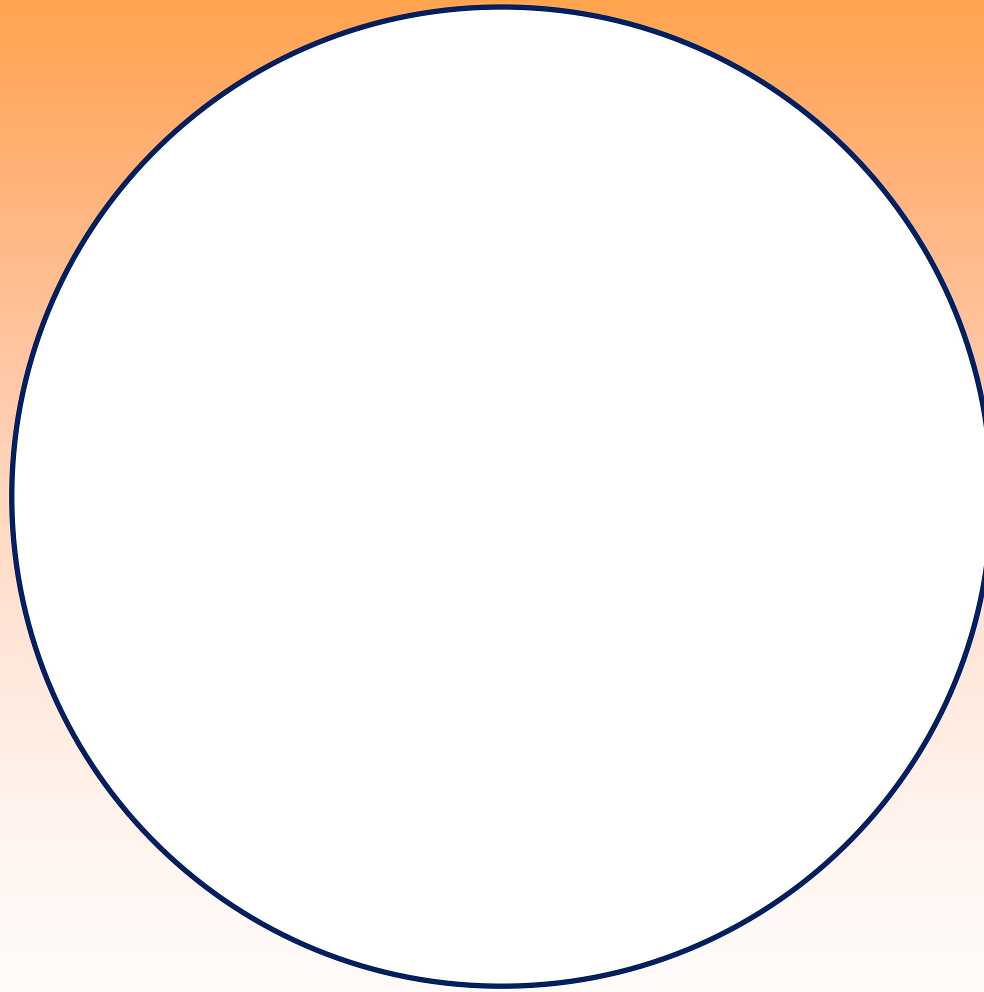
Millimeter Antenna Calibration

9th IRAM Millimeter Interferometry School
10-14 October 2016

Michael Bremer, IRAM Grenoble

- The beam (or: where does an antenna look?)
- How and where to build a mm telescope
- Calibration

The Aperture



Aperture, Optics, Image Plane

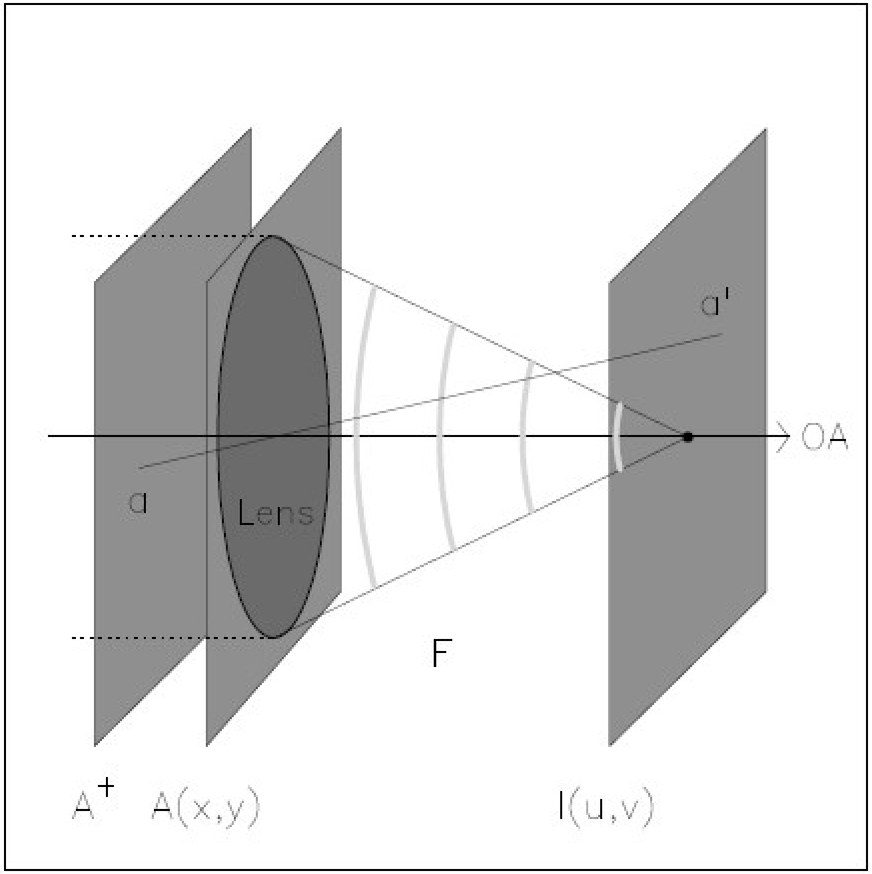
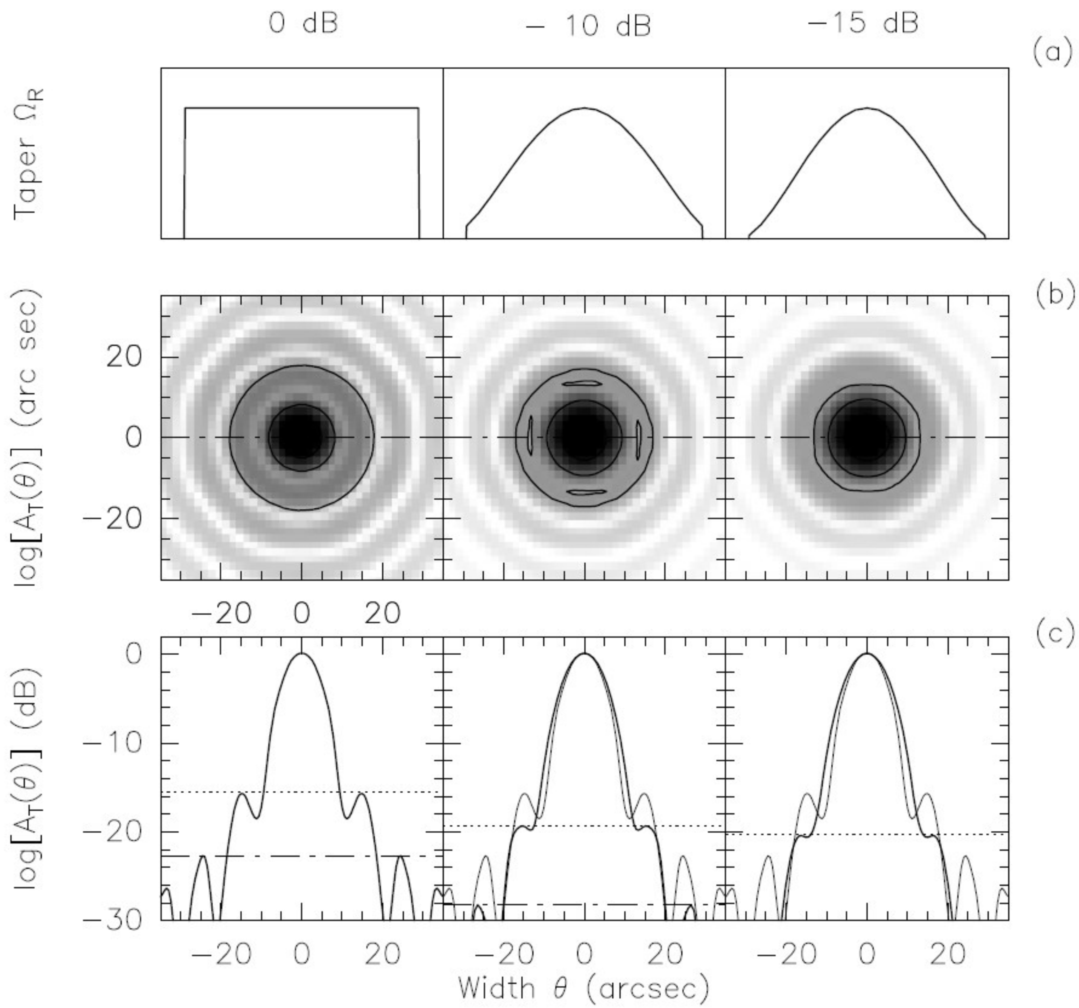


Illustration of imaging through a lens, which operates in an equivalent way as a complex radio telescope. OA is the optical axis; F the focal length, in this case of the lens. **A** is the aperture plane of the lens, **I** the image plane = focal plane.

Why modify the illumination with a taper?



(a) Taper across the aperture of the main reflector Eq.(12.12), the value of the edge taper is indicated. (b) Focal plane beam pattern $A_T(\theta,\phi)$ (in log–scale). (c) Cut through the beam pattern $A_T(\theta,\phi)$. The dashed line shows the level of the 1st side lobe, the dashed–dotted line the level of the 2nd side lobe.

Taper function:
Gaussian or parabolic

Beam pattern = FFT(illumination)

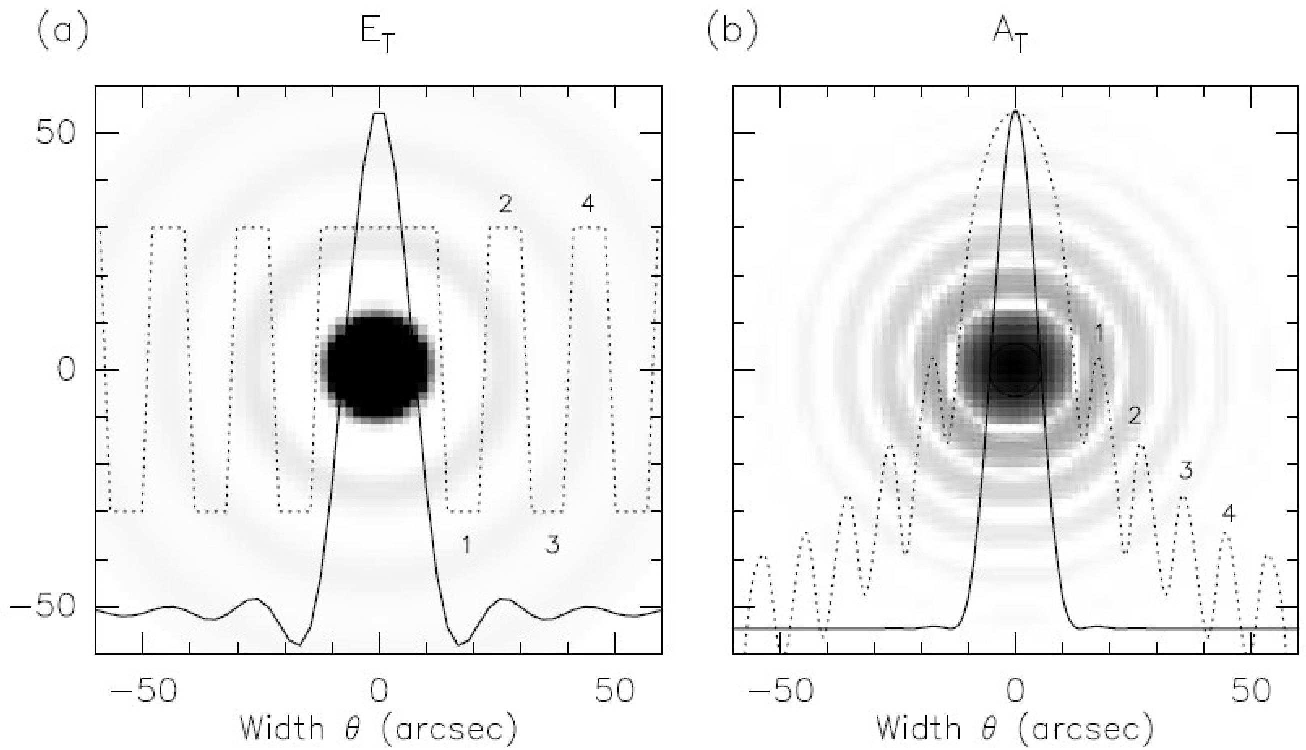
Beam size (FWHM):
$\theta_{mb}=\alpha\ \lambda/D$ [rad]

with α = 1.0 … 1.3, depending on taper

Full width (diameter to 1st minimum):
$\theta_{fb} \approx 2.2\ \theta_{mb}$

A "typical" single dish antenna observes one point.

Sidelobes and their phases, in linear & $\log_{10}$



(a) Field distribution E_T and (b) power distribution A_T of a perfect telescope with – 15 dB edge taper. Inserted are the on–axis cuts through E_T (amplitude: solid line and periodic phase change of 180° between the main beam and the side lobes: dashed line) and A_T (in linear scale: solid line and dB scale: dashed line). The central part of the beam pattern is the main beam, the 1st, 2nd, 3rd and 4th side lobe is indicated.

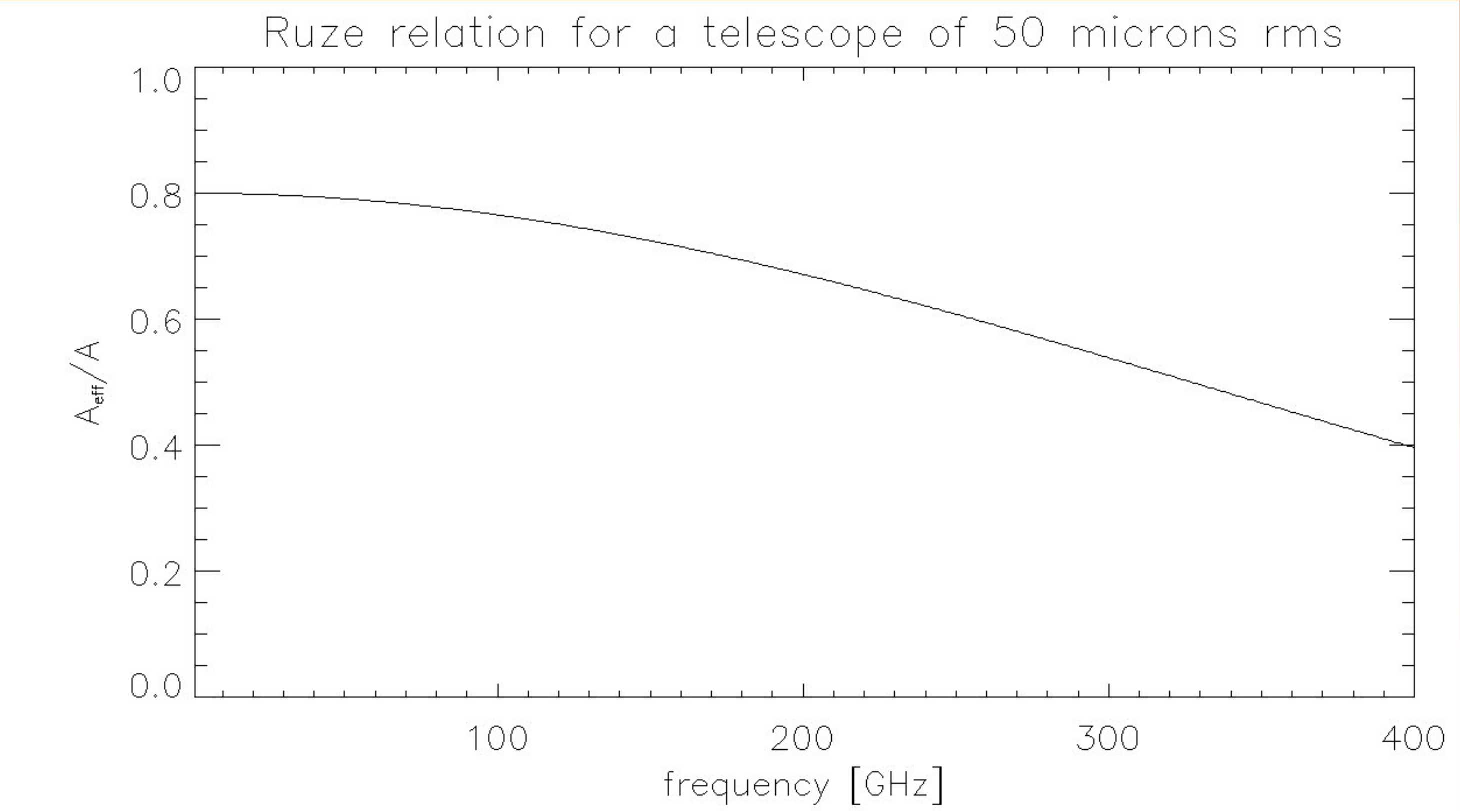
Aperture efficiency: the surface is not ideal

Ruze formula for the aperture efficiency ε_a:

$$\frac{A_{eff}}{A} = \varepsilon_a(\lambda) = \varepsilon_0 \cdot \exp\left(-(4\pi \boldsymbol{R}\frac{\sigma}{\lambda})^2\right)$$

With R ≈ 0.8 depending on the telescope geometry and ε_0 the asymptotic efficiency for $\lambda \rightarrow \infty$ (≈ 0.6 … 0.8)

ε_a can be measured on a known calibration source.



Beam efficiency

The beam efficiency can be calculated from the beam pattern

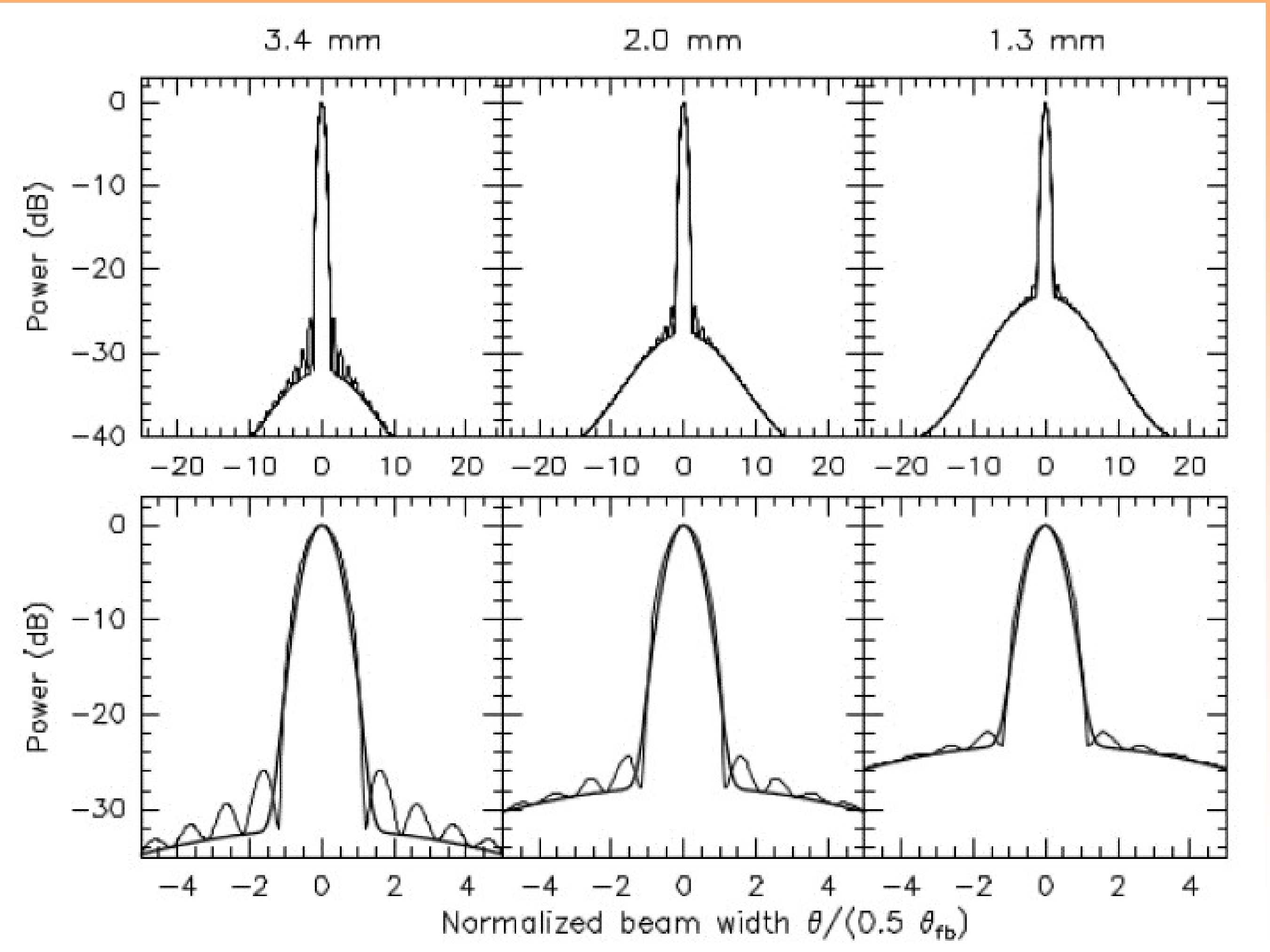
$$\mathrm{B}_{\mathrm{eff}} \equiv T_a'/\mathrm{T}_{\mathrm{mb}} = \varepsilon_a \cdot \frac{A\,\Omega_b}{\lambda^2}$$

with the main beam solid angle $\Omega_b \cong 1.133\,{\theta_{mb}}^2$

This is the link between antenna temperature and main beam temperature.

And finally, the error beam

The error beam is due to surface deformations with a given correlation length. The FFT of this results in a broad Gaussian. This becomes important for very extended sources at the IRAM 30-m telescope.
Experimentally derived from Moon scans.



The temperature scales

Antenna temperature (telescope specific) and brightness temperature (source specific) are both proportional to power and purely fictitious equivalent temperatures. **They relate to the flux density S as follows:**

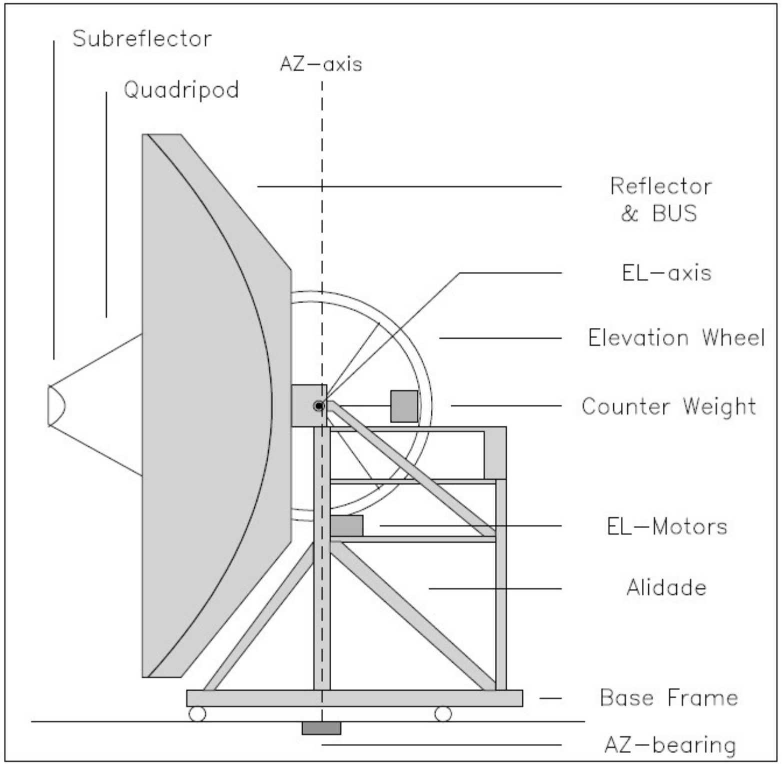
Table 3. Equations for antenna temperature and brightness temperature.

	Antenna temperature, T_a' (temperature of equivalent resistor)	Brightness temperature, T_b (temperature of equivalent black body)
in general:	$S = \frac{2k}{A_e} \frac{\int T_a' \, d\Omega_r}{\int P \, d\Omega_b}$	$S = \frac{2k}{\lambda^2} \int T_{mb} \, d\Omega_r = \frac{2k}{\lambda^2} \int T_b \, d\Omega_s$
point source:	$S = \frac{2k}{A_e} T_a'$	$S = \frac{2k}{\lambda^2} T_{mb} \, \Omega_b$
gaussians:	$S = \frac{2k}{A_e} T_a' \frac{\theta_r^2}{\theta_b^2}$	$S = \frac{2k}{\lambda^2} T_{mb} \, 1.133 \, \theta_r{}^2$
formulae:	$\frac{S}{\mathrm{Jy}} = \frac{3516}{\epsilon_{ap}} \frac{D^{-2}}{\mathrm{m}^{-2}} \frac{T_a'}{\mathrm{K}}$	$\frac{S}{\mathrm{Jy}} = 2.64 \frac{\lambda^{-2}}{\mathrm{cm}^{-2}} \frac{T_{mb}}{\mathrm{K}} \frac{\theta_r^2}{\mathrm{arcmin}^2}$ (for gaussians)

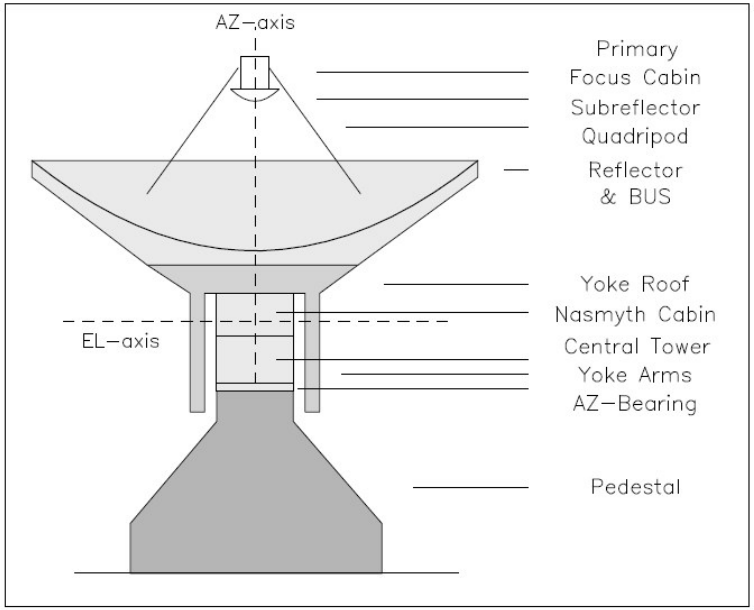
k = Boltzmann constant = $1.38 \, 10^{-23}$ J K^{-1}, λ = wavelength, A_e = effective collecting area,
D = dish diameter, ϵ_{ap} = aperture efficiency (eq.(11)), P = beam pattern (eq.(4)),
T_b = brightness temperature, T_{mb} = main-beam brightness temperature,
T_a' = antenna temperature outside the atmosphere, $T_a' = T_a \exp(\tau_o \sec z)$,
θ_b = beamwidth (FWHP), θ_r = response width (beam convolved with source),
Ω_b = main-beam solid angle; $d\Omega_r$, $d\Omega_b$, $d\Omega_s \Rightarrow$ integrate over response, beam or source, respectively.

From: D. Downes (1989), Radio Astronomy Techniques, LNP 333, 351

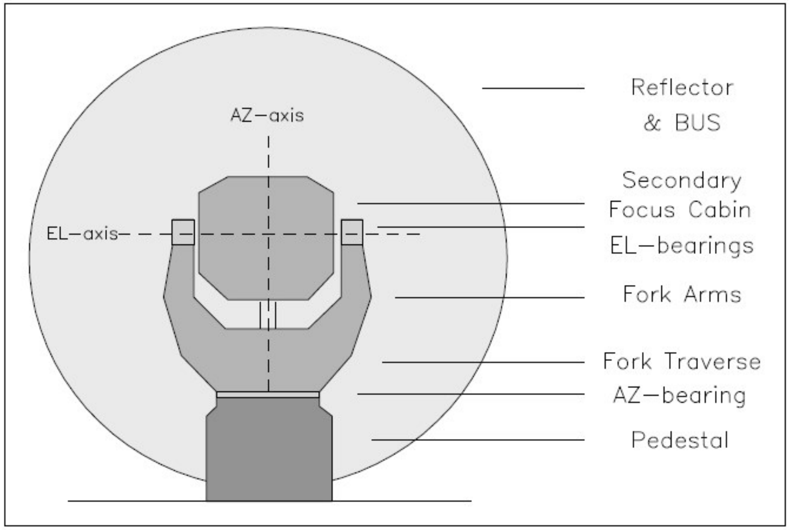
Some fully steerable telescope schematics



ig. 1.1.a Alidade supported radio telescope.



Pedestal–Yoke supported radio telescope.



Pedestal–Fork supported radio telescope.

Building your own radio telescope

Fig. 1-5. Grote Reber's meridian-transit radio telescope. Many modern radio telescopes bear a striking resemblance to this early instrument.

Mr. Grote Reber built a 31.4 ft. radio telescope in his backyard in 1937 (Wheaton, Illinois).

Its observing wavelength was 1.9 m.

He did astronomy in his free time while working for a radio company in Chicago.

Required mechanical precision is proportional to wavelength – a mm antenna must be 1000× more precise!

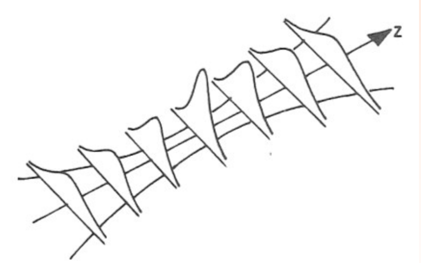
Radio telescopes vs. optical telescopes

Table 1.2 Electromagnetic Reflector Diameter and Surface Precision.

Telescope (Country) [a]	Reflector Diameter [m]	Wavelength (λ)/ Frequency (ν) [b] [mm]/[GHz]	Electromagnetic Diameter $\mathscr{D} = D/\lambda$ [$\mathscr{D}$/1000]	Reflector Quality $Q = D/\sigma$ [b] [Q/1000]
Radio Telescope				
Arecibo (USA)	300	60 / 5	5	200
Effelsberg (Germany)	100	10 / 30	10	150
Nobeyama (Japan)	45	3 / 100	15	400
IRAM (Spain)	30	1.3 / 230	23	460
IRAM (France)	15	1.3 / 230	11	300
JCMT (Hawaii)	15	0.65 / 460	23	750
CSO (Hawaii)	10	0.37 / 800	27	500
Optical Telescope				
Palomar (USA)	5	$5\times10^{-4}/5\times10^{15}$	10 000	100 000
KECK (USA)	10	$5\times10^{-4}/5\times10^{15}$	20 000	200 000
ELT [c]	~ 50	$5\times10^{-4}/5\times10^{15}$	100 000	1 000 000

[a] see list of Acronyms of observatory sites;
[b] approximately shortest wavelength of observation, estimated precision σ;
[c] next generation extremely large optical telescope (see http://www.eso.org).

Radio telescopes and their optics: **Gaussian optics formalism required**.



If you are familiar with cm Radio Astronomy: What changes for mm waves?

With increasing frequency:

- No external human interference in the data
- Non-thermal sources become weaker but thermal sources are not strong yet. *Important: molecular lines!*
- atm. water vapor and clouds become more absorbent, therefore:
  - stronger weather dependency of observations
  - Tsys of low elevation observations becomes a lot worse (choose your sources carefully, don't skim the horizon!)
- polarization in astronomical objects becomes weaker
- the time variability of quasars increases (flux and polarisation)

Why observe in the millimeter range?

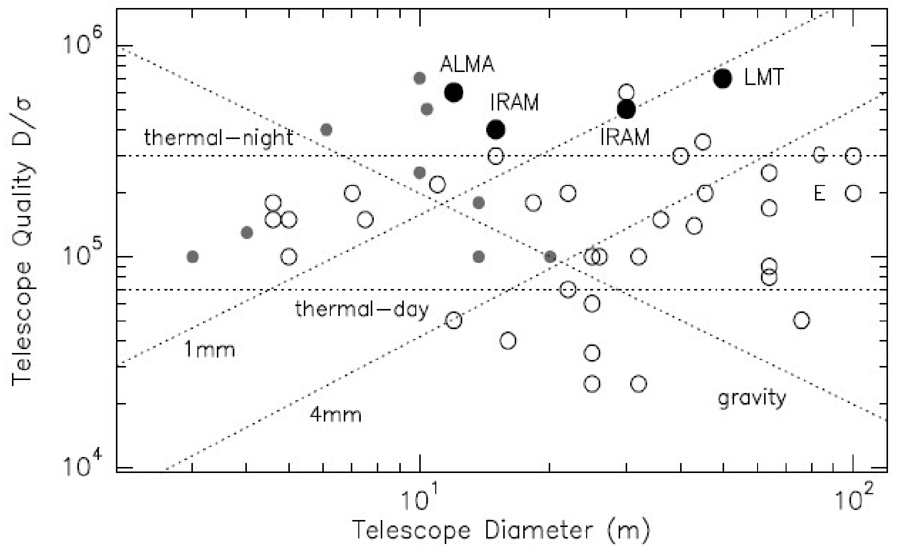
molecule	abundance[a]	transition	type	λ	$T^b_\circ$ (K)	A_{ul} (s^{-1})	n^c_{crit} (cm^{-3})	comments
H_2	1	$1\rightarrow0$ S(1)	vibrational	2.1 μm	6600	8.5×10^{-7}	7.8×10^{7}	shock tracer
CO	8×10^{-5}	J= $1\rightarrow0$	rotational	2.6 mm	5.5	7.5×10^{-8}	3.0×10^{3}	low density probe
OH	3×10^{-7}	$^2\Pi_{3/2}$;J=3/2	Λ-doubling	18 cm	0.08	7.2×10^{-11}	1.4×10^{0}	magnetic field probe
NH_3	2×10^{-8}	(J,K)=(1,1)	inversion	1.3 cm	1.1	1.7×10^{-7}	1.9×10^{4}	temperature probe
H_2CO	2×10^{-8}	$2_{12}\rightarrow1_{11}$	rotational	2.1 mm	6.9	5.3×10^{-5}	1.3×10^{6}	high density probe
CS	1×10^{-8}	J= $2\rightarrow1$	rotational	3.1 mm	4.6	1.7×10^{-5}	4.2×10^{5}	high density probe
HCO^+	8×10^{-9}	J= $1\rightarrow0$	rotational	3.4 mm	4.3	5.5×10^{-5}	1.5×10^{5}	tracer of ionization
H_2O		$6_{16}\rightarrow5_{23}$	rotational	1.3 cm	1.1	1.9×10^{-9}	1.4×10^{3}	maser
//	$<7\times10^{-8}$	$1_{10}\rightarrow1_{11}$	rotational	527 μm	27.3	3.5×10^{-3}	1.7×10^{7}	warm gas probe

[a] number density of main isotope relative to hydrogen, as measured in the dense core TMC–1
[b] equivalent temperature of the transition energy; $T_\circ \equiv \Delta E_{ul}/k_B$
[c] evaluated at T=10 K, except for H_2 (T=2000 K) and H_2O at 527 μm (T=20 K)

From: Stahler & Palla, "The Formation of Stars"

The importance of CO was the main driver to
build instruments for frequencies beyond 100 GHz.

Engineering of a millimeter antenna



Von Hoerner–diagram. Telescope quality D/σ (D = reflector diameter, σ = surface precision, rms value) and natural limits of gravity and thermal effects, for mm – wavelength (•) and cm–wavelength telescopes (○). The lines labelled 1 mm and 4 mm show the relation $\lambda_{min} = 16\,\sigma$. For the limiting relations see von Hoerner [1967 a, 1977 a] and Baars [2007]. G = GBT telescope, E = Effelsberg telescope.

Problem:

- must be precise enough for your highest frequency,
- with a large collecting area,
- in a place where you have encouraging weather statistics,
- and stay within budget.

Homological Design:

Manage grav. deformations: Tilted main reflector changes its focus but stays a paraboloid.

Millimetre Telescopes vs. the Real World

Forces acting on a Telescope (and Enclosure).

Influence/ Force	Time Variability	Components	Loss of Observing Time
Gravity	quasi–static	gravity	negligible
Temperature	slow 1/4 – 3 h	air, wind, sun, sky, ground & internal heat source	some
Wind & Gusts	fast, 1/10 – 10 s	ambient air	important
Atmosphere	fast	temperature, H_2O vapour, clouds, precipitation	(dominant)

Engineering of a millimeter antenna

Surface precision and stability: $\sigma \lesssim \lambda/16$

Focus stability: $\Delta f \lesssim \lambda/10$

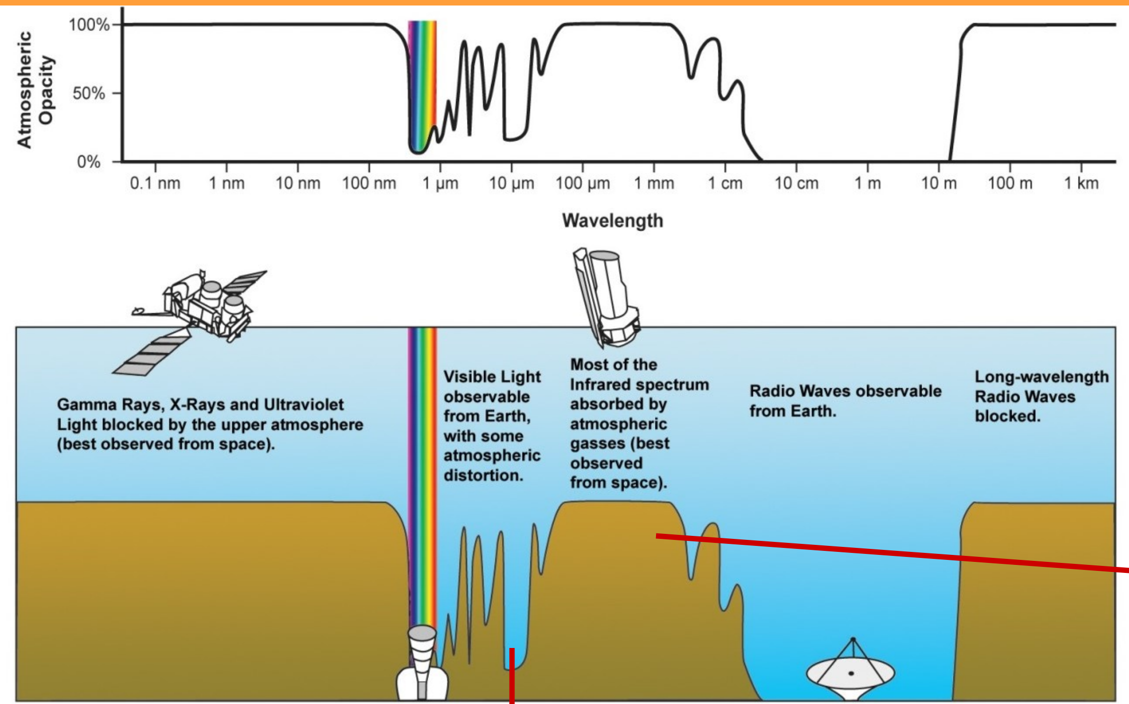
Pointing stability (θ_{mb}=HPBW): $\Delta\Theta_{mb} \lesssim \Theta_{mb}/10 \propto (\frac{\lambda}{10})/D$

For interferometers,
Path length stability: $\Delta H \lesssim \lambda/10$

What kind of signal do we want to detect? 1 Jansky = 10^{-26} W m^{-2} Hz^{-1}

i.e. observe with an ideal 100m antenna with 1 Ghz bandwidth
for 400000 years to get 1 Joule.

Where to build a mm telescope



Main absorbers between the optical and radio transmission windows:

- H_2O
- CO_2

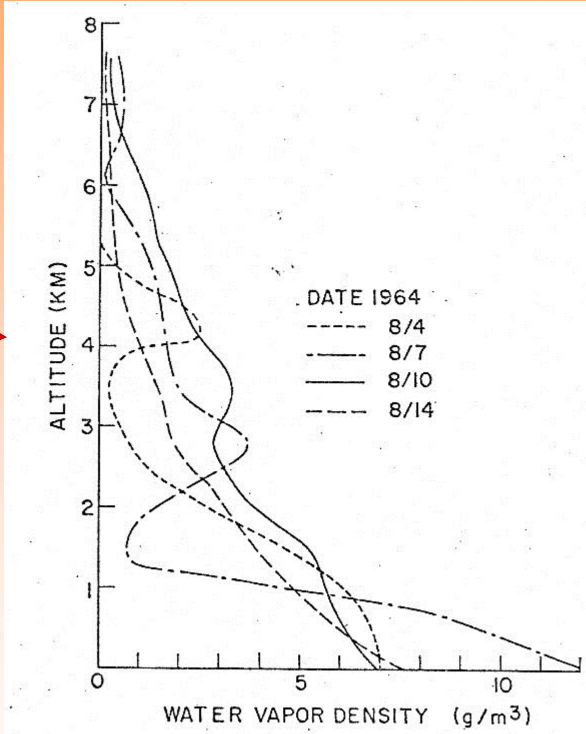
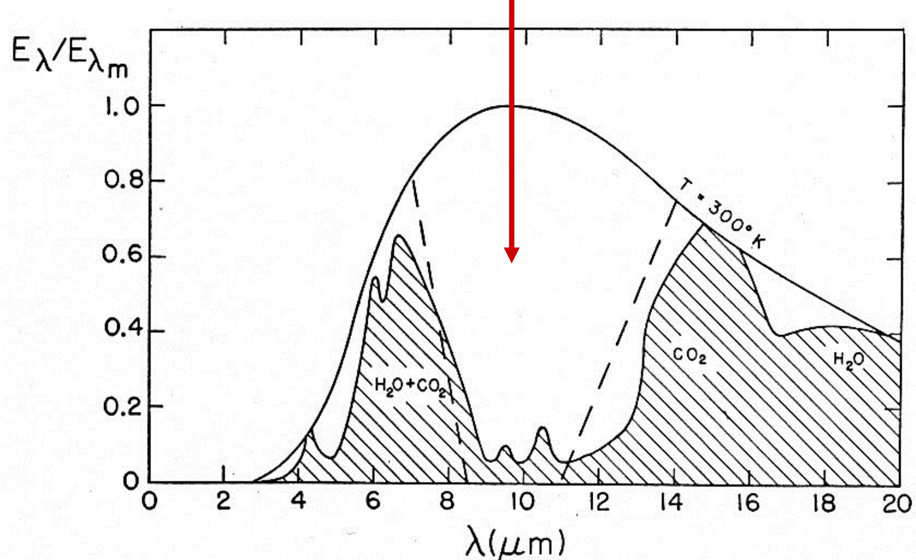


Fig. 3. Atmospheric water vapor profiles measured by radiosondes.



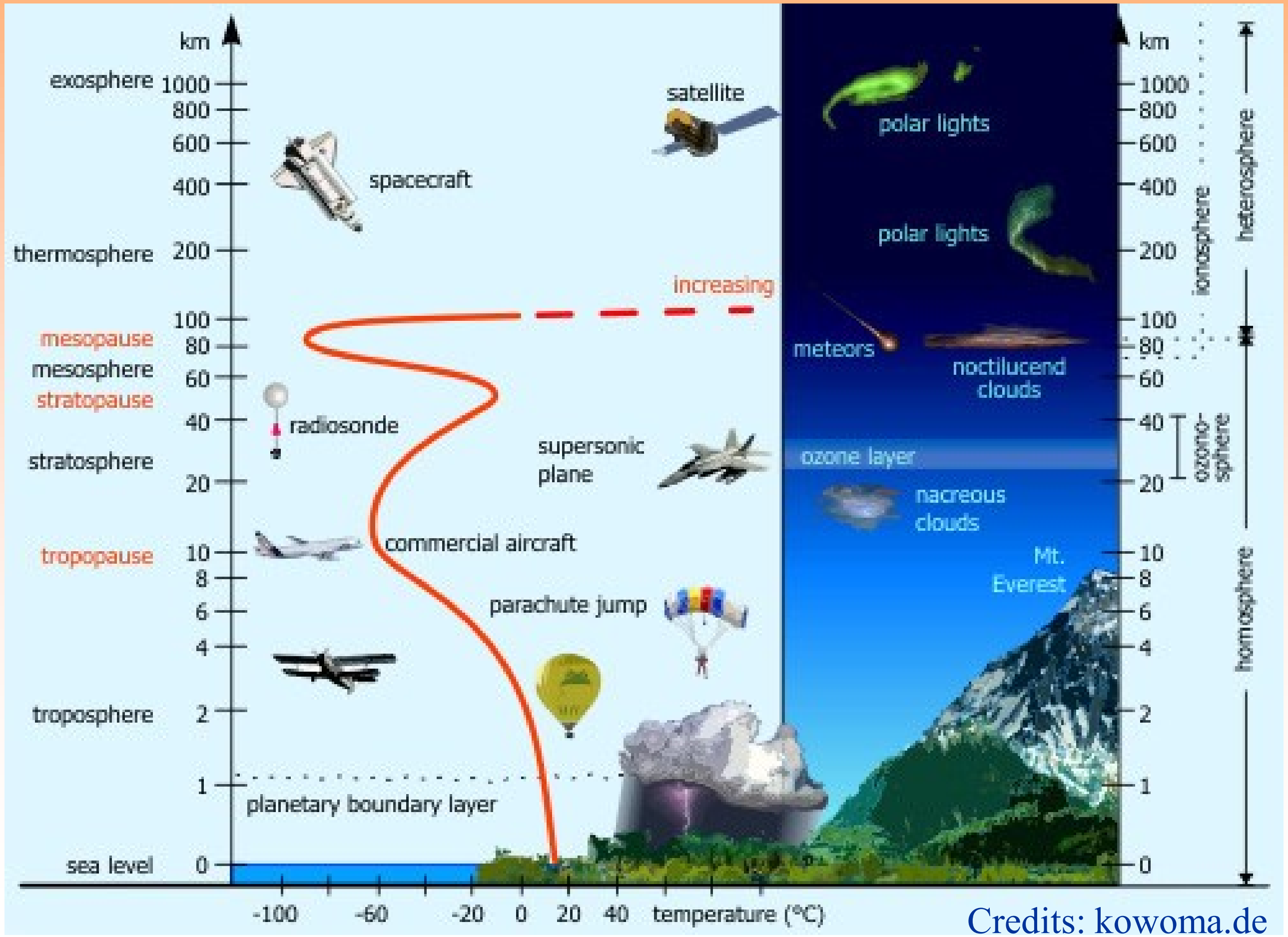
From: Irbarne & Cho, Atmospheric Physics

From: Staelin, 1966 (method: radiosondes, profiles from different balloon launches)

Do we need to go to Space?

Dry air: scale height 8.4 km
Water vapor: scale height 2.0 km

You can (nearly) walk into Space for mm radio astronomy!
A desert can do for the 3mm band. **Favourite:** High altitude desert.



Credits: kowoma.de

Getting rid of water vapor by going high and/or dry

ALMA: 5000m

SMA: 4100m

NOEMA: 2550m

ATCA: 208m

Temperature variations and telescope geometry

Two approaches to get the desired millimetre telescope performance:

- choose a material with compatible constant of thermal expansion
- control the reflector temperature (insulation, climatisation, radome, astrodome)

$$6\,[\mathrm{mm}](D/100[\mathrm{m}])(\Delta T/^{\circ}\mathrm{C}) \lesssim \lambda_{\mathrm{min}}$$

$$\Delta T \lesssim \lambda_{\mathrm{min}}[\mathrm{mm}]/(6D/100[\mathrm{m}]) \quad (\mathrm{steel})$$

Von Hoerner (1967, 1975)

Reflector Diameter D	100 m	30 m	20 m	15 m	12 m	12 m
Material	steel	steel	aluminium	CFRP–steel	steel	CFRP
CTE [μm/m/K]	12	12	22	5 [a]	12	3
Example	Effelsberg	IRAM	Onsala	IRAM		ALMA
λ_{min} [mm]/ν_{min} [GHz]	30/10	1/300	3/100	1/300	0.375/800	0.375/800
ΔT [$^{\circ}$C] $\lesssim$	5	0.5	1.25	2.5	0.5	2

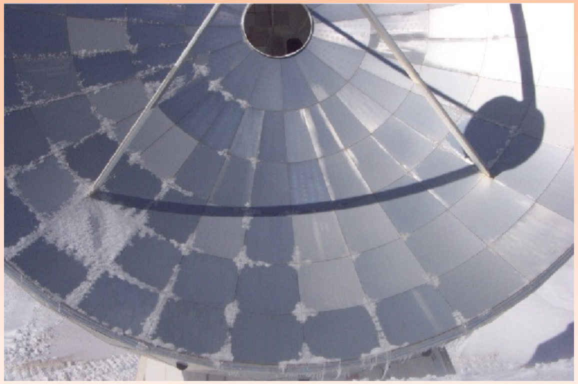
[a] estimated value for a combination of CFRP and steel.

Wind and Ice

At high altitude, one has to expect wind and large temperature fluctuations, and often snow and ice.

- mm Telescopes are mostly of Cassegrain or Gregorian design, with filled reflector surfaces (no wire mesh). Wind force: $F_w = ½ \rho V^2 A c_w$

  Free-standing telescopes are more sensitive to high wind speeds but protective radomes absorb strongly at mm and sub-mm wavelengths



- Reflectors may need de-icing (heated surfaces). Pre-emptive heating to avoid ice attachment, getting rid of ice after formation is not easy.

Table 4.4 Thermal Properties of Water, Frost, Snow and Ice.

Precipitation	Density ρ [kg/m^3]	Heat Capacity $\mathscr{C}$ [J/kg/K]	Volume Heat Capacity $\rho\mathscr{C}$ [MJ/m^3/K]	Heat Conductivity k [W/m/K]
Water	1 000	4 200	4.20	0.6
Ice	920	2 000	1.84	2.25
Snow	400	2 000	0.80	0.5
Frost	∼ 100 – 200	∼ 600	∼ 0.1	∼ 0.05 – 0.2

Calibration

To calibrate = to measure precisely with an absolute scale

The **real** antenna is corrected to become an **ideal** antenna;
in a sense it disappears to allow a clear view on the
astronomical source.

Calibration

There are different kinds:

Observatory maintenance, Real-time, and Post-observation

1. **Measure and adjust slowly variable parameters**
   (commissioning, maintenance, surface holographies, baseline estimates, pointing models, receiver tuning tables…)

2. **Measure and correct parameters in the real-time system.**
   This is the "calibration overhead" of the observations:
   load calibration, pointing, focus, level adjustment for optimum sensitivity etc., and the necessary observations for the next point:

3. **Establish a post-observation calibration.**
   This is the reduction you do later. It produces the data that you interpret for your publication.

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   You will encounter this part when you observe yourself at a telescope. Follow closely the recommended calibration cycles to get data that you can use later – time overhead is no luxury!

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3. **Establish a post-observation calibration.**
   This is where it all comes together, and calibration data taken at the end of the observing run can be applied everywhere.

All kinds of temperatures

Receiver Temperature T_R:
Temperature of an equivalent resistor of the same noise power as the receiver, according to the Nyquist formula $P=kT\Delta\nu$

We need two calibrator loads of known different physical temperature T_{hot} and T_{cold} to measure it:

$Counts_{hot} = G\cdot(T_{hot}+T_R)$ $\quad$ $Counts_{cold} = G\cdot(T_{cold}+T_R)$

$T_R=(T_{hot}-Y\cdot T_{cold})/(Y-1)$ $\quad$ where $\quad$ $Y= Counts_{hot} / Counts_{cold}$

System Temperature T_{sys}:
Temperature of an equivalent resistor of the same noise power as the whole instrument, including the atmosphere above it.

The sensitivity of the system is $\Delta T_a = \kappa\, T_{sys}/\sqrt{\Delta\nu\, t}$

with κ depending on observing mode. Interferometry: $\kappa=1$

All kinds of temperatures

Chopper wheel calibration method (Penzias and Burrus, 1973):

$$\mathrm{Counts}_{load} = K\cdot(T_{load}+T_R)$$

$$\mathrm{Counts}_{sky} = K\cdot(T_{emission}+T_R)$$

$$\mathrm{Counts}_{source} = K\cdot(B_s\cdot T_B\cdot e^{-\tau(elevation)}+T_{emission}+T_R)$$

with B_S the antenna to source coupling factor. We want to know T_B .
With some algebra:

$$T_B = T_{cal}\cdot\frac{\mathrm{Counts}_{source}-\mathrm{Counts}_{sky}}{\mathrm{Counts}_{load}-\mathrm{Counts}_{sky}}$$ where

$$T_{cal} = (T_{load} - T_{emission})\cdot\frac{e^{\tau(elevation)}}{B_s}$$ and we get:

$$T_{sys} = T_{cal}\cdot\frac{\mathrm{Counts}_{sky}}{\mathrm{Counts}_{load}-\mathrm{Counts}_{sky}}$$

All kinds of temperatures

We still don't know: $T_{emission}$ and τ(elevation)

But we know T_{load} , T_R

$$T_{emission} = (T_{load} + T_R) \cdot \frac{Counts_{sky}}{Counts_{load}} - T_R$$

However, not all detected emission really comes from the sky:

$$T_{sky} = \frac{T_{emission} - (1-Feff) \cdot T_{cabin}}{F_{eff}}$$

with the forward efficiency F_{eff} in the range [0 … 1]

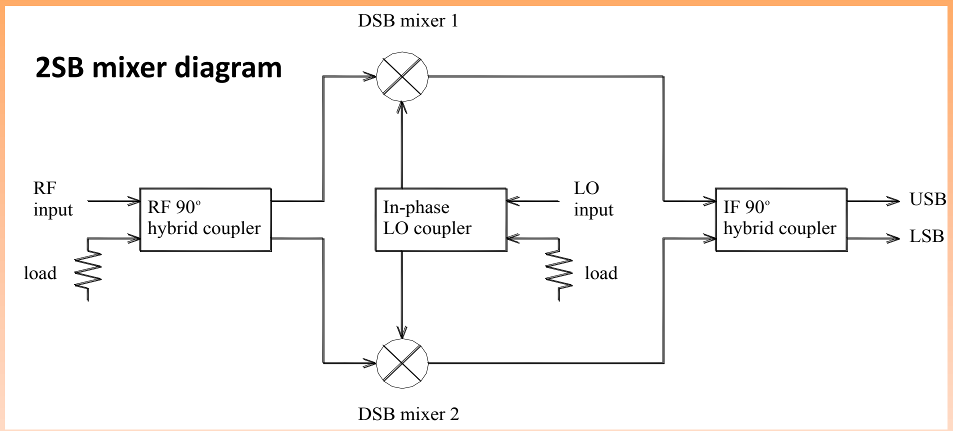
We can now use a simple atmospheric model based on a standard atmosphere and meteo station data to determine τ(elevation).

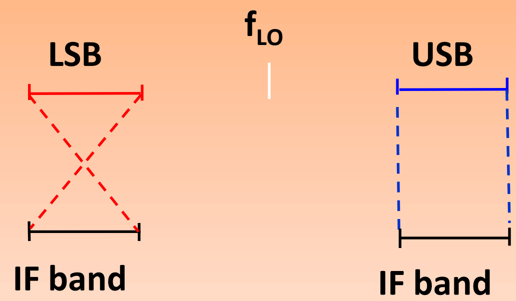
F_{eff} is determined over a skydip, i.e. observing $T_{emission}$ at different elevations during stable clear-sky weather conditions.

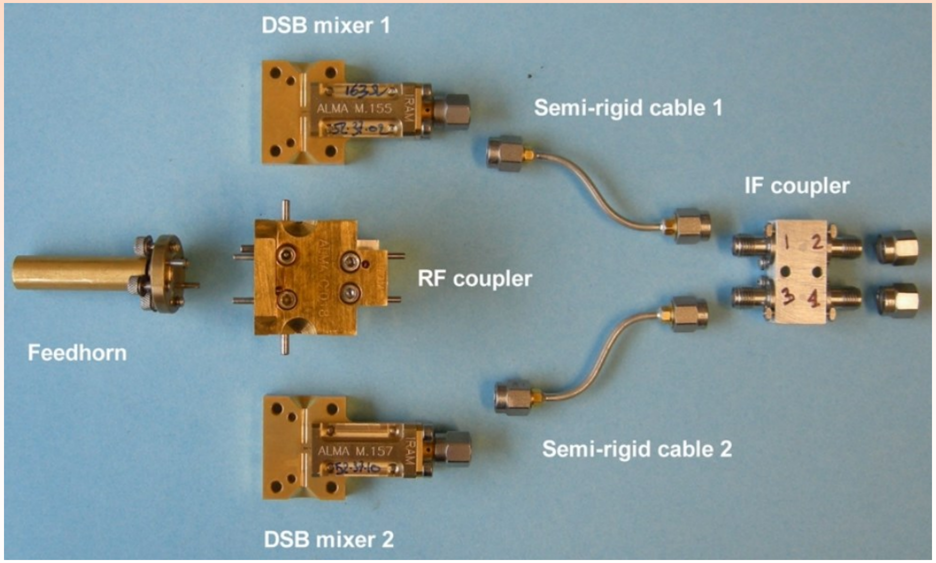
Some more details that play a role in calibration

You can have different receiver technologies: DSB, SSB and 2SB

The most recent is the Sideband Separating mixer (2SB): Both sidebands (USB and LSB) are downconverted and separated to independent outputs







We are currently changing our SIS mixers to 2SB technology.

It is necessary to measure the rejection of the two bands relative to each other.

Photos: Courtesy A. Navarrini

Some more details that play a role in calibration

We measure a weighted mixture of two atmospheric bands, one in the signal band (where our signal is), and one in the image band (where we typically do NOT want to observe).
The Gain is the ratio between the two.

$$T_{sky} = \frac{T_{sky\ S} + Gain_I \cdot T_{sky\ I}}{1 + Gain_I}$$

i.e. $Gain_I \ll 1$: good sideband rejection,
$Gain_I = 1$: DSB receiver

$$T_{cal} = \frac{T_{load} \cdot (1+Gain_I) - T_{emission\ S} - Gain_I \cdot T_{emission\ I}}{B_s \cdot e^{-\tau_S(elevation)}}$$

We get those values from the atmospheric model, except the beam efficiency B_S. In single dish mode, B_S must be determined carefully but in interferometry $B_S = F_{eff} \cdot$ (Amplitude calibration)

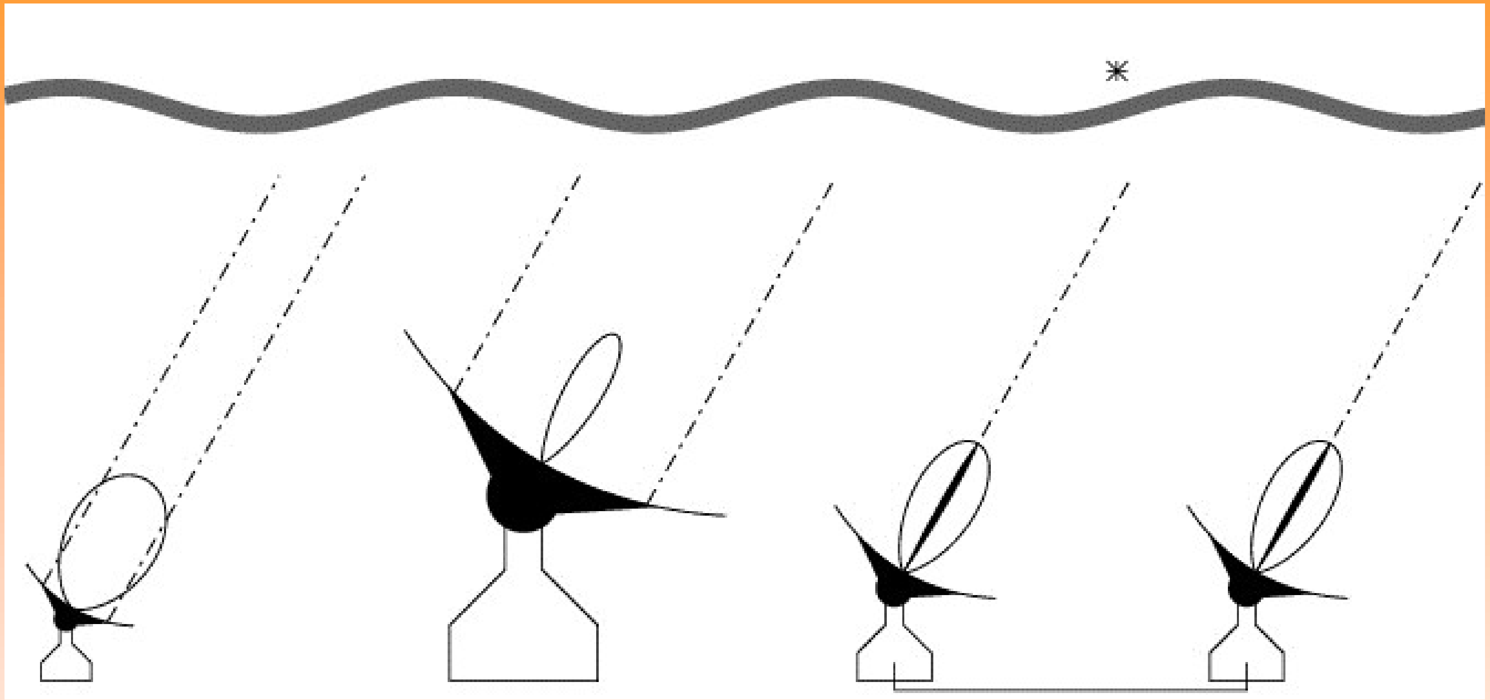
Some more details that play a role in calibration

The reduced chopper calibration:

It can be difficult to have a linear response in the detector chain over a dynamic range of more than 2-3, especially for an interferometer. Solutions:

- Use lower temperature “ambient” calibration loads
- Receiver is linear but the limitation is in the backend: switchable attenuators in the IF chain (NOEMA)
- Covering the beam only partially with absorber, rest sees the sky

Single Dish vs. Interferometers



- The single dish beam becomes the field of view.
- You need to control N antennas simultaneously
- The antennas must share a common master frequency or re-generate it from a fundamental standard
- Correlated amplitudes and phases must be calibrated

A typical project at NOEMA

- Operators and astronomer on duty (AoD) agree on a project to observe, based on meteo conditions and schedule priority
- The setup is started, the receivers are tuned.
- On a strong calibrator source, interferometric delays and gains are measured and entered into the real-time system
- RF calibrator and flux calibrators are observed
- The observing cycles start: amplitude and phase calibrators are observed before and after a target source observation.
- Each observation starts with
  BAND (spectral bandpass on the correlator noise source),
  AUTO 4 TWEAK (adjust correlator input attenuation),
  CAL (ambient/cold/sky load calibration cycle),
  then the correlations start.
- Several times per hour, pointing and focus are measured.
- The observations are pipeline-calibrated and checked by the AoD.

More about interferometry
follows after the

Lunch Break.

Thank you!