Very Long Baseline Interferometry

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VLBI Arrays

- EVN (Europe, China, South Africa, Arecibo)
- VLBA (USA)
  - EVN + VLBA coordinate joint observing => Global VLBI
- LBA (Australia)
- VERA (Japan)
- Geodetic network (Global)

VLBI in a Nutshell

- Just interferometry
- Data usually recorded on magnetic media – limited bandwidth, data transport by truck
- Independent clocks at each station – phase/delay errors
- Heterogeneous arrays (except VLBA)
  - different primary beams
  - different a priori calibration possibilities
- Longer baselines => increased time and BW smearing
  - less correlator averaging, hence bigger datasets for given FOV

VLBI Signal Path

- 2-4 cables bring IF signals from antenna to IF distributor
- Baseband Converters are fed by the IF distributor
  - BBCs have up to 16 x 16 MHz outputs
- BBCs output baseband signal to formatter
- Accessible spectrum often constrained by fixed first LO (to IF) and BBCs tunable over a range of 400-500 MHz
- BBC output digitally sampled at 1-8 x Nyquist rate (usu. 1) with 1 or 2 bits
- Sampled output goes to formatter to arrange bits into the tracks required by (tape!) recorders. (Soon to be changed).
- Data recorded on disk (Mk5A => Mk5B soon, LBA DAR)

VLBA Signal Path

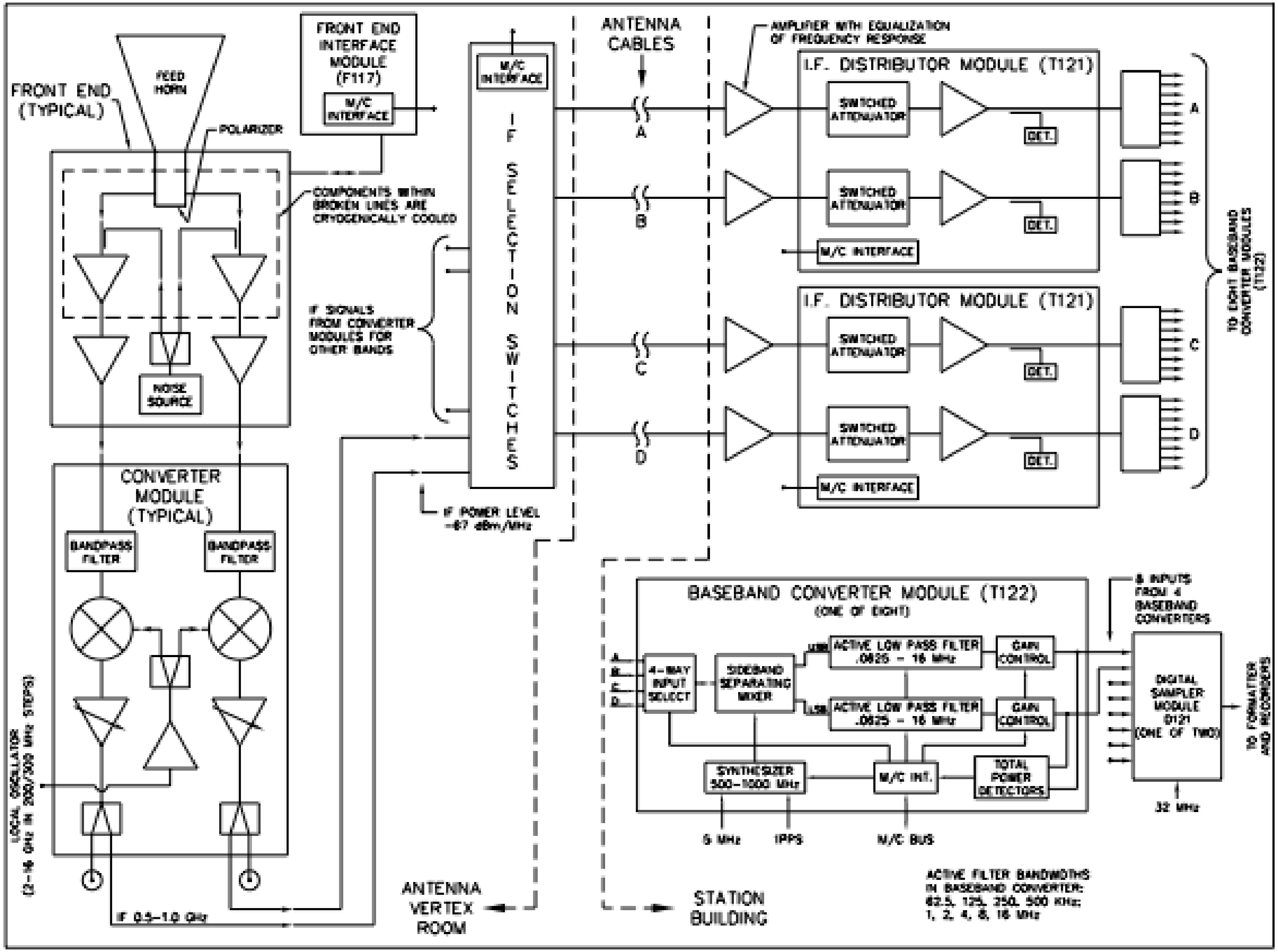
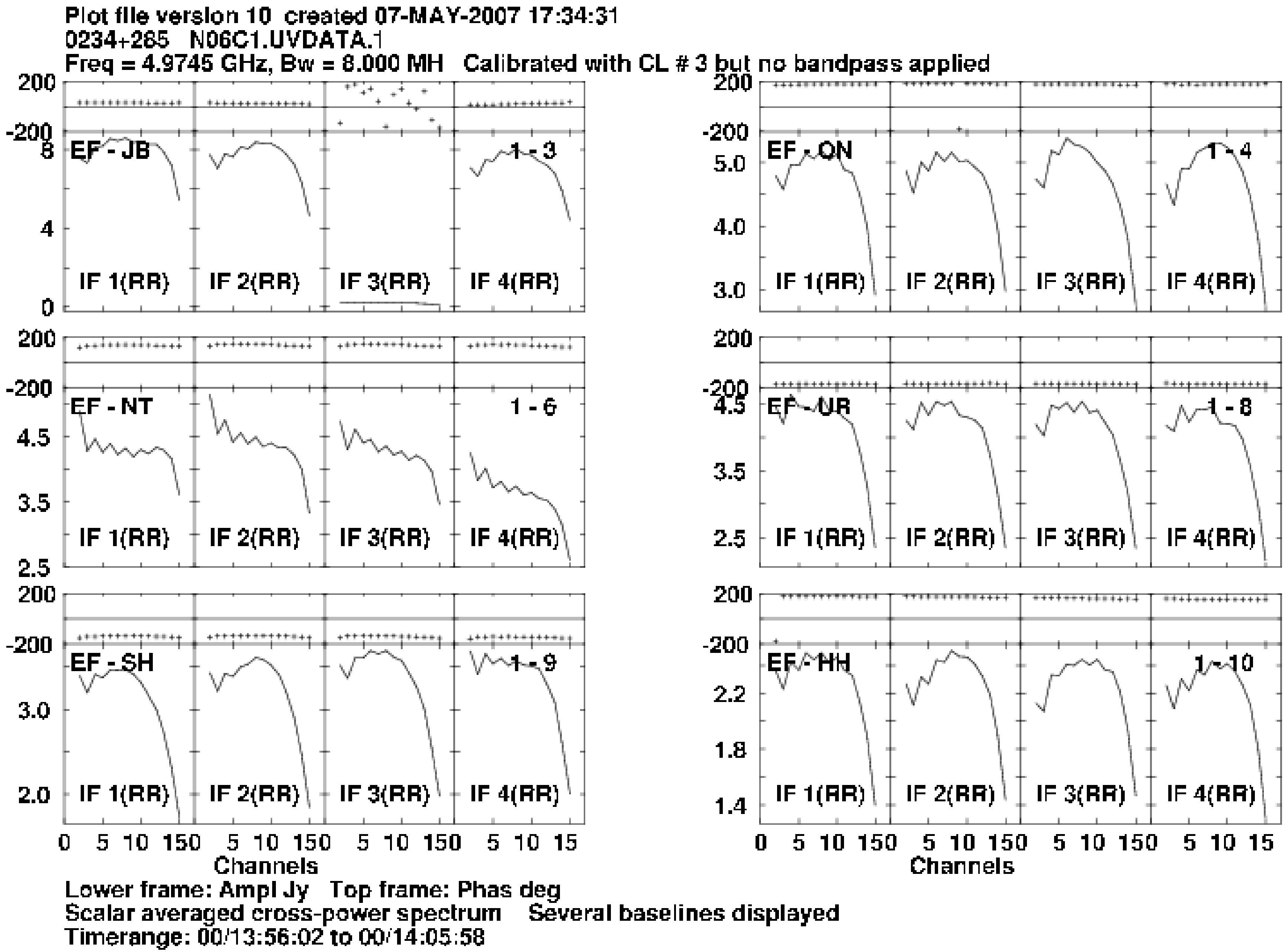


Figure 5.3: Simplified block diagram of the analog signal path at RF, IF, and baseband frequencies.

VLBI Frequency setup

- Constrained by (often fixed) first LO and limited tuning range of BBCs (approx 500 MHz with current systems)
- BBCs produce up to 16 independently tunable subbands (0.5 – 16 MHz)
  - useful when wide bandwidth coverage (RM or Spectral index mapping, improved u,v coverage – see Stewart lecture)
- Any frequency (usually) within the 500 MHz range is simultaneously available, though maximum recordable bandwidth is 128 MHz for dual-pol, 2-bit (= 1Gbps)
  - frequency switching possible on VLBA, limited on EVN
- Data within subbands also channelised (gives spectral resolution, prevents de-correlation and bandwidth smearing)

VLBI Subbands (AIPS IFs)



How Many Bits?

- VLBI observations limited by available recording rate
- 2-bit increases sensitivity by factor 1.38 over 1 bit
- Doubling bandwidth improves sensitivity by sqrt(2) = 1.41 (assuming a continuum source)
  - practicalities tend to favour 2-bit with half the bandwidth
- 4-bit only increases the sensitivity by factor 1.1 over 2-bit (TMS)
  - inefficient use of limited recording rate
  - not available on current VLBI systems
- Digitization losses are usu. compensated for at the correlator, but for VLBA should be refined with ACCOR (not required for EVN).

Fringe Fitting

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- Correlator model errors (delay)
  - atmospheric fluctuations, clock errors
- Interferometer Phase: $\phi_{t,\nu} = 2\pi\nu\tau_t$
  - τ = interferometer delay
  - phase error depends on delay error
- Linear phase model for a baseline

$$\Delta\phi_{(\tau,\nu)} = \phi_0 + \frac{\delta\phi}{\delta\nu}\Delta\nu + \frac{\delta\phi}{\delta t}\Delta t$$

  - phase error at reference time and freq, delay, delay rate
- Determined by process of fringe-fitting

Fringe-Fitting

- Can factor delay model by antenna

$$\Delta\phi_{ij}=[\phi_{i0}-\phi_{j0}]+[\frac{\delta\phi_i}{\delta\nu}-\frac{\delta\phi_j}{\delta\nu}]\delta\nu+[\frac{\delta\phi_i}{\delta t}-\frac{\delta\phi_j}{\delta t}]\Delta t$$

- Baseline fringe-fit
  - FT to delay-rate domain
  - Fit each baseline independently for delay and rate
  - Must detect source on all baselines and does not preserve closure
- Global fringe-fit (equation above)
  - Use all baselines to jointly estimate *antenna* phase, delay, rate relative to a reference antenna
  - Choice of solution time important – must have good SNR, but not exceed coherence time
  - Good a-priori source model can help...

Phase cal signals

- Stable calibration tones injected near feed
  - measure the instrumental phases and delays
- Used to improve initial alignment of phases
- “Manual” phase-cal also useful
  - fringe-fit short interval on strong calibrator
  - apply delay solutions to full experiment
  - assumes instrumental delays slowly varying (usu. true)
- VLBI data usually has multiple subbands
  - partially independent phases and delays, some calibration required before averaging.

Phase Referencing

- Transfer self-cal and/or fringe fit solutions from calibrator source to nearby target
- Must have excellent earth orientation model (antenna postions better than a few cm)
- Sources must be close - described by a single atmosphere and errors resulting from earth model increase with distance
- Switching times must be shorter than the atmospheric fluctuations (<~ 10 mins at 5 GHz)
- Should remove calibrator source structure phases before applying corrections

Self-calibration and mapping

- Similar to any other interferometer (see Lobanov demo)
  - sparse u,v coverage and poor a priori calibration can make deconvolution tricky and convergence slow

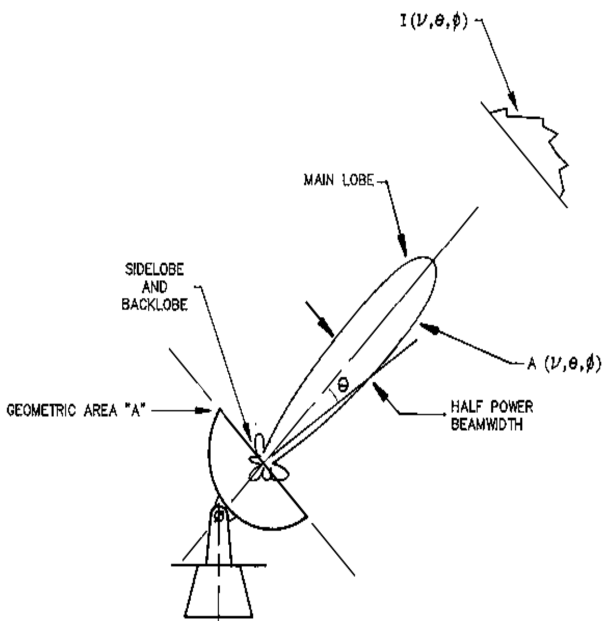
A Priori Amplitude Calibration

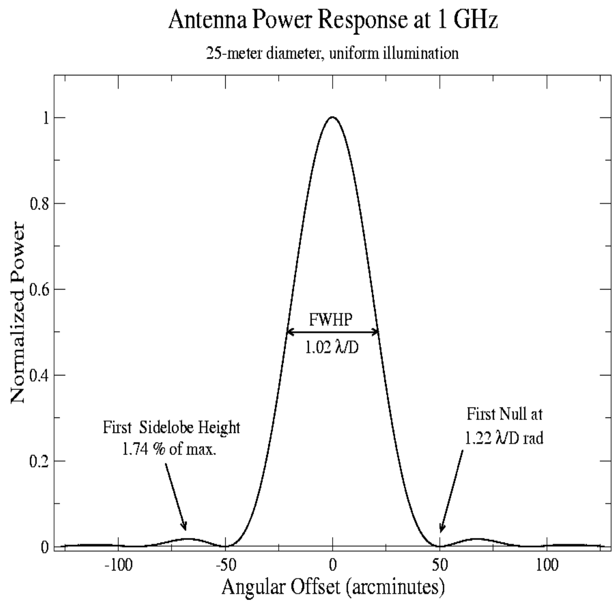
- There are no standard flux calibrators on VLBI scales
  - sources that compact are variable
- Must measure sensitivity of the individual stations
- Tsys and Gain curves distributed as additional tables with your visibility data
- Tables can be loaded with ANTAB (if not already attached) and applied with APCAL.
  - currently only available in AIPS

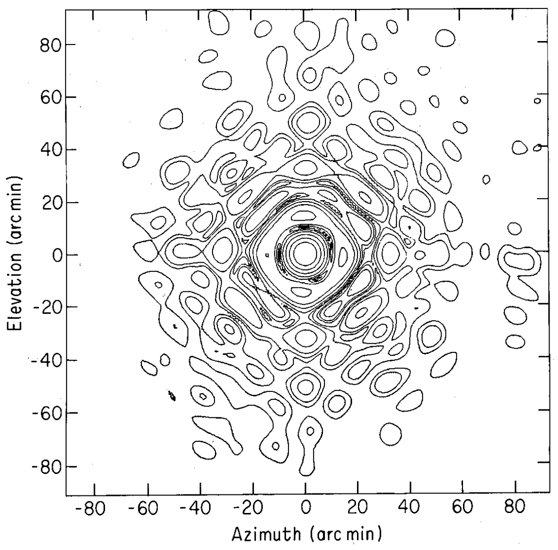
Antenna Beamwidth, Pointing & Focus

- The range of directions over which the effective area is large is the *antenna beamwidth*. From the laws of diffraction it can be shown that the beamwidth of an antenna with characteristic size *D* is approximately λ/D

- Most sensitivity is concentrated in a smaller solid angle that is often characterised by the *half-power beamwidth* (HPBW), which is the angle between points of the main beam where the normalised power pattern falls to 0.5 of the maximum







• Ideally, a radio source should be centred in the antenna main beam to prevent loss of signal

• A pointing error of 0.1 times the HPBW causes a 3% loss in signal; for an error of 0.2 HPBW, it rises to 10% and for 0.3 HPBW it becomes 22%

System Noise & Source Equivalent Flux Density (SEFD)

• In the usual case where system noise power dominates over noise power from the source, then the net amplitude of the complex correlation coefficient is

$$C_{ij} = B \frac{V_{ij}}{\sqrt{N_i N_j}}$$

where V_{ij} is the visibility amplitude in Jy, B is the dimensionless factor taking into account the effects of digitisation and N_i and N_j represent the system noise of the two antennas expressed as a *Source Equivalent Flux Density* (SEFD) in Jy

• The SEFD is defined as the source flux density that would contribute an antenna output equal to that due to the system noise, i.e. which would double the total antenna power

• Amplitude calibration is therefore about estimating the antenna SEFD values as functions of time, elevation and frequency, and applying the resulting corrections to the raw correlation coefficients to obtain V_{ij}

- The SEFD of an antenna can be divided into two parts such that

$$N = \frac{T_i}{G_i}$$

where T_i is the system temperature in K and G_i is the antenna gain in K/Jy

- T_i is defined as the physical temperature of a load in the antenna beam that contributes the same output power as the system noise

- G_i is defined as the increase in system temperature that occurs when looking at a 1Jy source. G_i changes mainly due to elevation dependent distortions of the dish due to gravity

- The SEFD therefore depends on both changes in the system temperature and in the gain

- Antenna calibration can thus be divided into two halves – the system temperature calibration and the antenna gain calibration

- For amplitude calibration of visibilities, only the *relative* values of system temperature and antenna gain are necessary, i.e. SEFD

System Temperature

- System temperature, the noise in the system, is a combination of noise from various sources;

$$T_{sys} = T_{receiver} + T_{ground} + T_{sky}$$

- System temperatures can vary unpredictably during a VLBI experiment due to changes in the receiver temperature, the spill-over, RFI etc. and so must be monitored continuously

- A secondary calibration source (usually a broad-band 'noise cal' signal) of constant noise temperature T_{cal} is periodically injected and the change in total power is compared to the power measured when this cal signal is switched off. From these measurements the system temperature T_{sys} can be derived via;

$$T_{sys} = \frac{T_{cal} P_{cal-off}}{P_{cal-on} - P_{cal-off}}$$

- VLBA systems switch the noise source continuously at 80 Hz. MkIV (EVN) systems fire a cal diode during gaps in recording

Gain Calibration

- For the purposes of calibration, *G* must be found experimentally by measuring the change in system temperature going on and off sources of known flux density

- The antenna gain can be parameterised in terms of an absolute gain or DPFU (Degrees Per Flux Unit) and an accompanying gain curve *g*, usually expressed as a polynomial function of elevation or zenith angle *z* such that the DPFU multiplied by the polynomial gives the correct antenna gain at each elevation, thus

$$G(z) = DPFU \times g(z)$$

where the polynomial *g(z)* is

$$g(z) = a_0 + a_1 z + a_2 z^2 + a_3 z^3 \ldots$$

Opacity Effects

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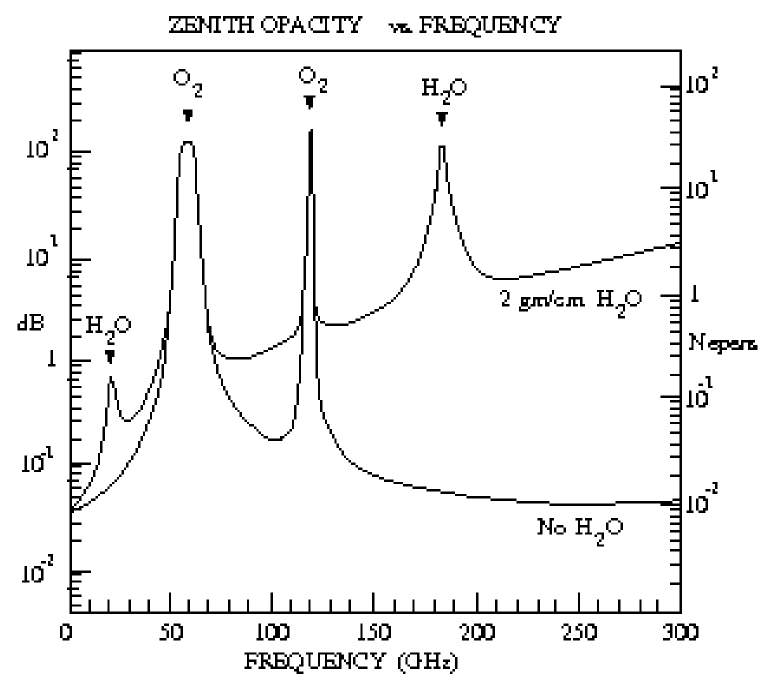
- Radio waves are also absorbed by the atmosphere
- Mostly due to spectral lines of water vapor and oxygen, hence most severe at 20 GHz and above

- Can estimate change in T_{sys} if T_{rec} and T_{atm} are known independently (APCAL)
- New techniques will use a Water Vapour Radiometer (can also estimate the atmospheric delay for phase calibration)



Atmospheric Opacity Vs freq (TMS)

A priori Amplitude calibration summary

• Essentially, the combination of DPFU, gain curve and calibration signal temperature T_{cal} are all that are required to provide accurate calibration information for a given antenna

• The absolute values of these parameters are not important, only that their *combination* reflects the actual performance of the antenna