

Seminar

Pointing and Calibration in Theory and Practice

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Chapter 1

Part 1

1.1 Introduction

In order to detect the extremely weak radio signals associated with VLBI observations, reasonably long integrations are required. However, the stronger the signal at each antenna, the more efficient will be the observations, allowing study of more sources (using less recording media) in a given time. For astronomy, not only is good sensitivity required, but the antenna also needs to be well calibrated so that the absolute radio fluxes of sources can be determined. For geodesy, the best possible signal-to-noise ratio is required. Hence, it is desirable to measure the antenna and receiver performance to assure the equipment is performing optimally or to identify areas that need to be improved. The sensitivity of an antenna depends on the aperture size and efficiency, the receiver system temperature, and whether the antenna has been properly pointed and focussed. Hence, the basic parameters of an antenna/receiver system that can be calibrated/measured are;

- The focus
- The pointing
- The aperture efficiency
- The system temperature
- The gain curve

This document introduces the basic theory of these antenna/receiver properties, their relationships and methods of measurement. I have based these notes on those of the previous TOWs by Bob Campbell (JIVE), Cormac Reynolds (then JIVE), Alastair Gunn (Jodrell Bank). Other sources of information can be found in the bibliography. More details about how these issues are dealt with practically can be found in the course notes for the maintenance workshops Automated Pointing Models Using the FS (E. Himwich), Antenna Gain Calibration (M. Lindqvist) and Generating ANTAB Tsys Files (Bach).

1.2 Fundamental Antenna Properties

1.2.1 Antenna Efficiency and Antenna Temperature

Radio antennas used in VLBI observations are normally paraboloid dishes. When such an antenna is pointed at a radio source, there will be an increase in power measured across the receiver output terminals. For a perfect antenna of area A_{eff} , the power received from an unpolarized source of flux density S (in units of Janskies $= 1 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$) in a bandwidth $\Delta\nu$ is

$$P = \frac{SA_{\text{eff}}}{2} \Delta\nu. \quad (1.1)$$

The factor of one-half results from the feed being sensitive to only one polarization of the incoming radiation. In reality, no antenna is perfect, so in practice we define the effective aperture in terms of the geometric surface area A_{geom} and an antenna efficiency η_A such that

$$A_{\text{eff}} = \eta_A A_{\text{geom}} \quad (1.2)$$

The factor η_A is the fraction of incident power that is actually picked up by the receiver/antenna system. Poor focussing or pointing cause an apparent lowering of η_A because the antenna is not collecting as much power as it could. Generally, the antenna efficiency η_A can be considered as a combination of factors such as

$$\eta_A = \eta_{\text{sf}} \eta_{\text{bl}} \eta_{\text{s}} \eta_{\text{t}} \eta_{\text{misc}}, \quad (1.3)$$

where η_{sf} is the reflector surface-accuracy efficiency, η_{bl} is the blockage efficiency, η_{s} is the spill-over efficiency, η_{t} is the feed illumination efficiency, and η_{misc} accounts for diffraction, losses and other degrading factors. In practice, the calibration of an antenna usually involves measurement of η_A rather than the individual factors by which it is determined. Note that the antenna efficiency can generally be a function of elevation (see Section 1.5). Power at the output terminals of a receiver, when observing a radio source, can be considered equivalent to power delivered by a resistive load at some temperature T . We can then designate an antenna temperature T_a such that

$$P = kT_a \Delta\nu, \quad (1.4)$$

where k is the Boltzmann constant ($1.38 \times 10^{-23} \text{ J/K}$). It follows that the antenna temperature of the radio source is

$$T_a = \frac{SA_{\text{eff}}}{2k}. \quad (1.5)$$

Larger antennas, more efficient antennas and stronger sources all give larger antenna temperatures. To find the overall antenna efficiency requires that the true

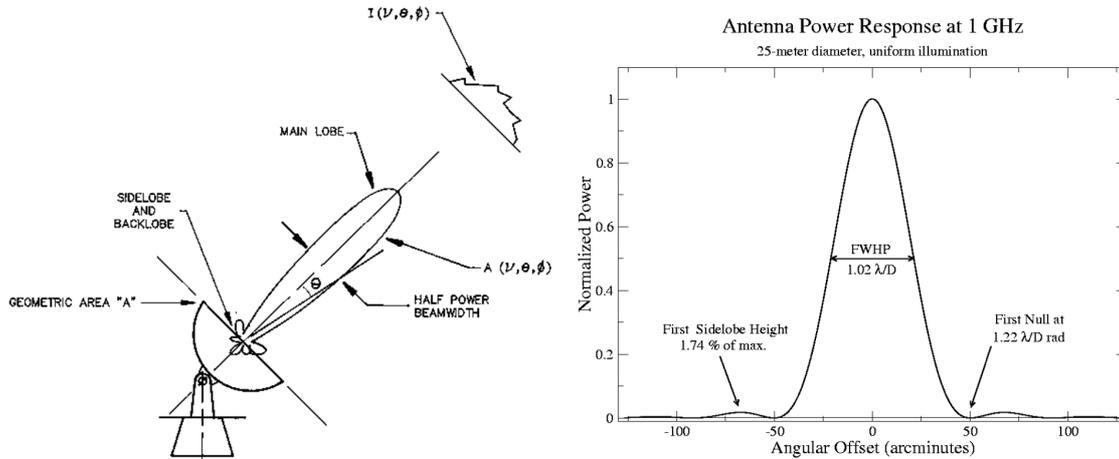


Figure 1.1: Antenna Response Patterns (left) and Half-Power Beamwidth of a Radio Telescope (right).

antenna temperature be measured. Generally, the relative amplitudes of a radio source and a calibration signal are measured. If the calibration signal is accurately known, then T_a can be found. While it is helpful to know the absolute efficiency of an antenna, it is only the ratio of system temperature to antenna temperature that determines the sensitivity. This quantity is considered further in Section 2.2. In Section 1.5, we will discuss the sensitivity, or gain, of the telescope, which in units of Janskies per Kelvin is just $A_{\text{eff}}/2k$.

1.2.2 Antenna Beam-width, Pointing and Focus

The range of directions over which the effective area is large is the antenna beam-width. From the laws of diffraction it can be shown that the beam-width of an antenna with characteristic size D is approximately λ/D . The radio telescope is not only sensitive to radiation propagating in the direction of the axis. For radiation incident from other directions, the relative sensitivity is given by the power pattern or beam of Gaussian form (see Figure 1.1).

Most sensitivity is concentrated in a smaller solid angle that is often characterized by the half-power beam-width (HPBW), which is the angle between points of the main beam where the normalized power pattern falls to 0.5 of the maximum. A source having angular size larger than the beam-width is said to be resolved, while a source of angular size much smaller than the beam-width is called an unresolved or point-like source. The HPBW is sometimes also referred to as the full-width to halfpower (FWHP). Other characterizations of the beam include beam-width between first nulls (BWFN) and the equivalent width of the main beam (EWMB). For main beams with non-circular cross-sections, values for widths in orthogonal directions are required.

Pointing calibration is fundamentally linked to the antenna response pattern (see

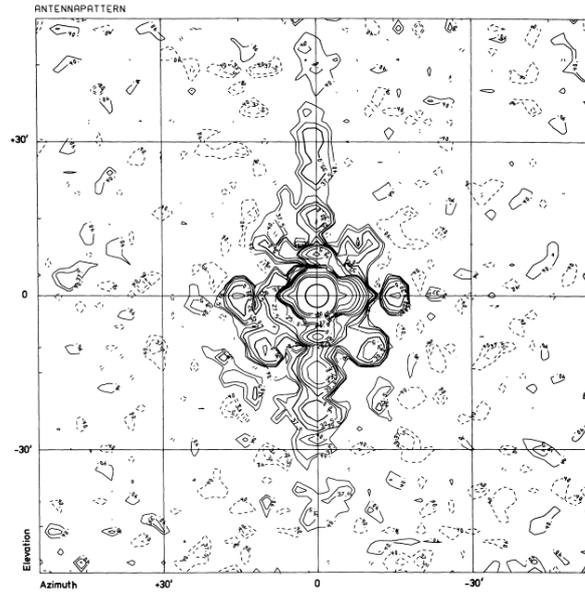


Figure 1.2: Primary beam pattern on the sky of the Effelsberg 100 m telescope at 11cm wavelength on 3C123. Contours are in decibel below the peak intensity in the center (Reich et al., 1978).

Figure 1.2). Ideally, a radio source should be centered 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%. Because of alignment errors, encoder offsets and deformation of the antenna, most antennas require a detailed analysis of pointing errors in order to derive a useful model for pointing corrections to within 0.1 HPBW across the entire sky. These measurements usually consist of a set of pointing offsets for a large number of sky positions. These offsets, which are the difference between the commanded antenna position and the position at which a strong, point-like source is properly centered in the main beam, are then used in a least-squares solution to find the coefficients of the pointing equation. The offsets may be found by scanning across a source and locating the peak response, or by finding two offsets which bracket the peak in one coordinate and show equal source response. Regular checks on pointing are essential for the continued efficiency of the antenna. A full discussion of pointing calibration, and its practical determination, can be found in the maintenance workshop Automated Pointing Models Using the FS (Himwich).

The antennas used in VLBI observations are usually reflector types with a receiver feed horn located near the primary or Cassegrain focus. For optimal efficiency, the feed must be positioned exactly at the focus. Minor lateral offsets of the feed of up to a wavelength or so will mostly effect the pointing by biasing the main beam off the electrical axis, with very little loss of gain. Radial offsets in focus position,

however, will significantly reduce the apparent gain of the antenna. Hence, for peak efficiency, the feed should be well within one-quarter wavelength of the radial focal point. For most antennas, the receiver box (or the Cassegrain subreflector) can be moved in and out with respect to the dish and its position should be adjusted for maximum response to a point-like source. Generally, the most accurate determination of the focus comes from locating two positions on either side of the peak response, which give the same power level, and taking the average of the two positions as the peak. However, since the radial motion of the receiver may also cause changes in spillover and standing wave patterns and thus cause output change independent of source effects, it is preferable to determine the focus by doing a series of on/off measurements on a source and using the resultant source deflections to find the correct focus. Focus should be checked at several different antenna positions since the focal length changes with the gravitational distortion of the dish. The focus should be determined at high and low elevation, then fixed at some convenient intermediate value.

1.3 System Noise and Source Equivalent Flux Density (SEFD)

An important fact of VLBI is that direct information about the amplitude of the received signals is lost at the stage of digitization. The correlator computes dimensionless correlation coefficients from comparing the bit-streams from each pair of telescopes. 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

$$C_{ij} = \beta \frac{V_{ij}}{\sqrt{N_i N_j}}, \quad (1.6)$$

where V_{ij} is the visibility amplitude in Jy, β is a dimensionless factor taking into account the effects of digitization, 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 which would contribute an antenna output equal to that due to the system noise, i.e. which would double the total antenna power if observed. It follows that even though C_{ij} is dimensionless we can determine V_{ij} in Jy if we know β and the SEFDs N_i and N_j in Jy. VLBI 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 at an antenna can be divided into two parts such that

$$N_i = \frac{T_i}{G_i}, \quad (1.7)$$

where T_i is the system temperature in K and G_i is the antenna gain in K/Jy (you will see this sometimes denoted by Γ). The system temperature is defined as the physical temperature of a resistive load in the antenna beam that contributes the same output power as the system noise, i.e. which doubles the output power compared to having no load. The antenna gain is defined as the increase in system temperature that occurs when looking at a 1 Jy source. The SEFD therefore depends on both changes in the system temperature and in the gain. System temperatures change because of receiver variations, changes in ground spill-over, and at high frequencies changes in the atmospheric contribution.

The antenna gain G_{ij} changes mainly due to elevation dependent distortions of the dish due to gravity. It follows that the SEFD should be highly reproducible and dependent only on elevation (and perhaps HA and Dec for polar mounted telescopes). Antenna calibration can thus be divided into two halves – the system temperature calibration and the antenna gain calibration. Such absolute calibration is important for determining whether the receivers and telescope efficiencies are at their expected values, vital information for optimizing antenna performance. However, for amplitude calibration of visibilities, only the relative values of system temperature and antenna gain are necessary, i.e. SEFD. Approximate values of SEFD for EVN antennas are shown in Table 1.1.

System temperature, the noise in the system, is a combination of noise from various sources. Generally, we can write

$$T_{\text{sys}} = T_{\text{receiver}}T_{\text{ground}}T_{\text{sky}}, \quad (1.8)$$

where T (noise from the receiver system itself – LNAs, LO mixing, etc.) ranges from a few to several tens of K (for a cooled receiver), T_{ground} (spill-over into the sidelobes from the ground) is usually a few K, and T_{sky} (noise from the sky and atmosphere) depends on frequency and the water vapour content of the atmosphere. We can parameterize T_{rmsky} as

$$T_{\text{sky}} = T_{\text{atm}} \times (1 - e^{-\tau \sin(elv)}) + T_{\text{CMB}} + T_{\text{RB}}, \quad (1.9)$$

where T_{atm} (noise from the atmosphere) can be approximately 20 K to 200 K and ($T_{\text{CMB}} + T_{\text{RB}}$) is generally a few degrees. T_{CMB} is from the Cosmic Microwave Background and T_{RB} is from the general radio background. The τ in the exponential factor is the atmospheric opacity at zenith; the $\sin(elv)$ term is assuming a plane-parallel atmosphere above the telescope.

1.4 System Temperature Calibration

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. For a system with stable receiver gains, system temperatures can be monitored by recording the variation in total power from the antenna. In

Table 1.1: Approximate SEFD values (in K) for EVN antennas from 92cm to 0.7cm (EVN status table Apr.2013).

Antenna	wavelength [cm]										
	92	49	30	21	18	13	6	5	3.6	1.3	0.7
Jb-1 (e)	132	83		36	65		80				
Jb-2 (d)				350	320		320	300		910	
Cm (a)				220	212		136	410		720	
Wb (b)	150	90	120	30	40	60	60	1600	120		
Eb/Ef	600	600	65	20	19	300	20	25	20	90	200
Mc				490	700	400	170	840	320	700	
Nt	980s	yes	1025	820	784	770	260	1100	770	800	900
On-85			900	320	320		600	1500			
On-60						1110			1000	1380	1310
Sh					670	800	720	1500	800	1700	
Ur				300	300	560	250		350	850	
Tr			2000	250	300		220	650		500	
Mh						4500			3200	2608	
Ys							160	160	200	200	
Ar	12	12	3	3.5	3	3	5	5	6		
Wz						1250			750		
Hh					450	380	795	680	940	3000	
Sv				360	360	330	250		200	710	
Zc				300	300	330	400		200	710	
Bd				330	330	330	200		200	710	
Km						350			480		
Rob70					35	20			18	83	
Rob34						150			106		
Ny						850			1255		

practice, receiver gains are insufficiently stable over long enough periods to use this method. Instead, 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 computed via

$$T_{\text{sys}} = \frac{T_{\text{cal}} P_{\text{cal-off}}}{P_{\text{cal-on}} - P_{\text{cal-off}}}, \quad (1.10)$$

where $P_{\text{cal-on}}$ and $P_{\text{cal-off}}$ refer to the output power measured with noise cal switched on or off, and T_{cal} is the noise cal system temperature. Estimating T_{sys} obviously needs an accurate estimate of T_{cal} . This can be measured using hot and cold loads such that

$$T_{\text{cal}} = (T_{\text{hot}} - T_{\text{cold}}) \frac{P_{\text{cal-on}} - P_{\text{cal-off}}}{P_{\text{hot}} - P_{\text{cold}}}, \quad (1.11)$$

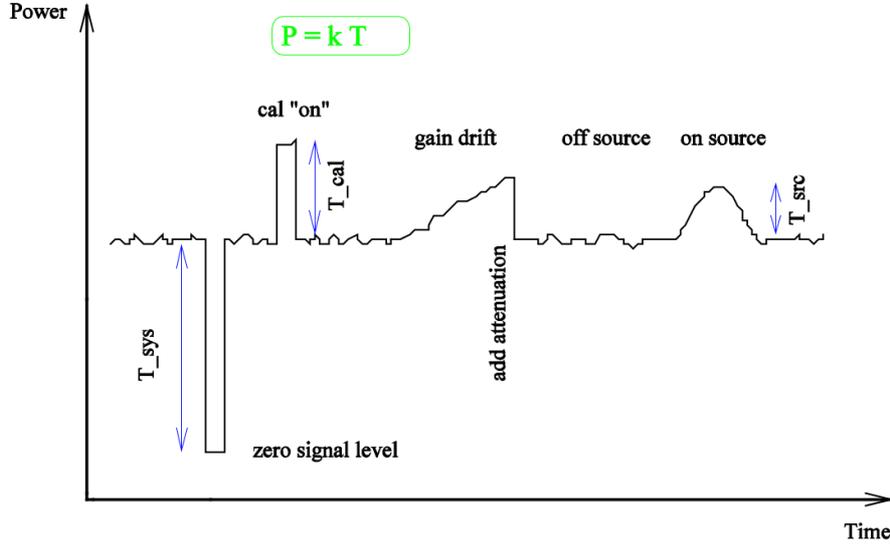


Figure 1.3: Power levels from a receiver in different situations.

where P_{hot} and P_{cold} are the output power measured with the hot and cold loads in place, and where the measurements of noise cal and hot and cold powers are separated by a short enough time that amplifier gains do not change. The most reliable results for T_{cal} probably come from laboratory measurements of the receiver and waveguide. T_{cal} can be a function of frequency and time, and part of normal calibration procedures is to determine these dependencies of T_{cal} (see Figure 1.4). Radio sources used for system temperature (and gain curve) calibration must necessarily be strong (tens of Janskies), of known flux density, non-variable and point-like for the antenna/receiver used. When performing calibration be sure that the radio source is not resolved (resulting in lower apparent peak flux density), that the receiver and/or power detectors are operating within the linear regime (or the VCs are not close to saturation), that the source is bright enough for reliable results and that the noise is not dominated by the atmosphere or adverse weather (possible at high frequencies) or RFI (possible at any frequency). Also ensure that power measurements are corrected for the zero level and that the pointing and focus are accurately determined.

1.5 Gain Curve Calibration

The gain of the antenna, expressed in K/Jy, equals the increase in total system temperature per Jansky of source flux density and depends on the collecting area

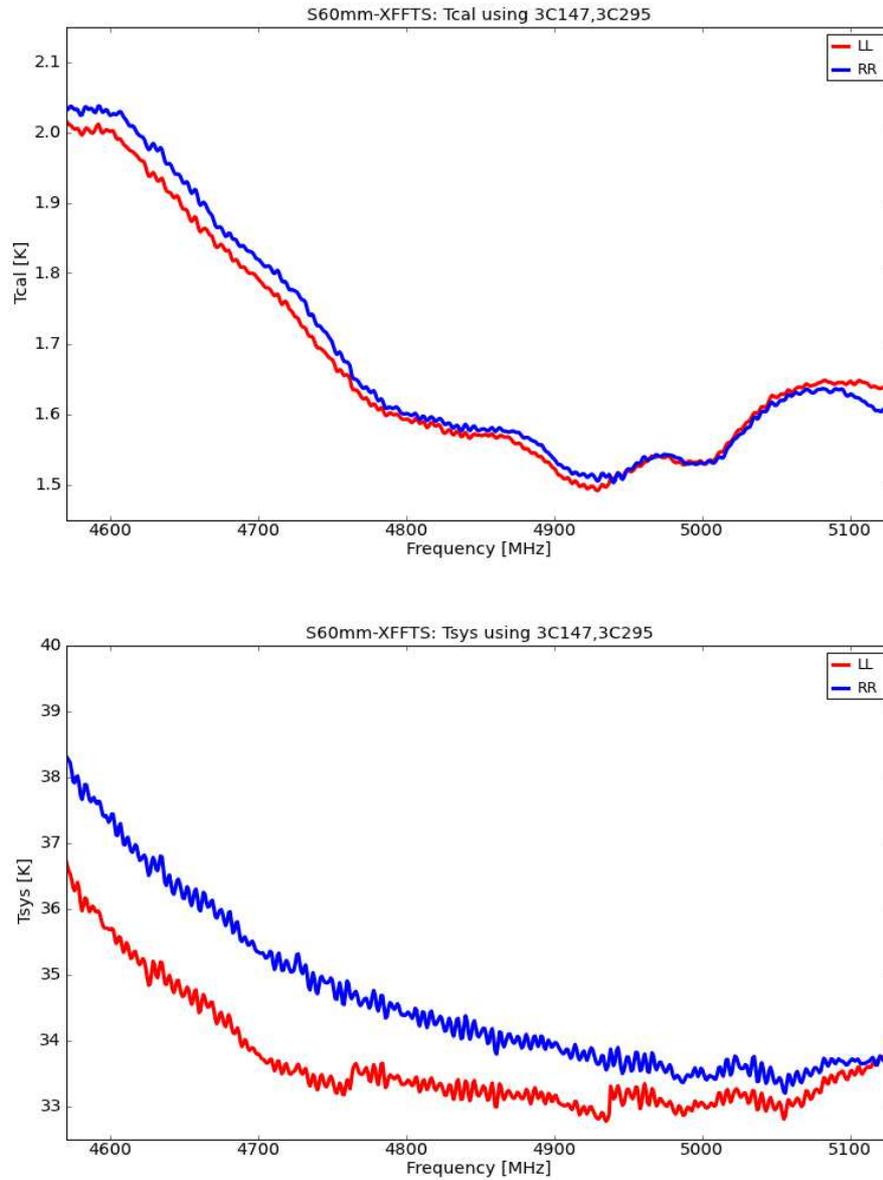


Figure 1.4: Examples of noise diode temperature and system temperature versus frequency for the Effelsberg 6 cm receiver. These curves are actually not derived from FS calibration but with the 32k channel FFT spectrometer.

of the telescope and the efficiency of the surface in focusing the incident radiation. Theoretically, this gain (in K/Jy) is proportional to the effective collecting area and equals

$$G = \frac{A \eta_A}{2760}, \quad (1.12)$$

where A is the geometrical area in square meters and η_A is the aperture efficiency (the number in the denominator has incorporated Boltzmann's constant). 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 aperture efficiency is then determined from the above equation. For most telescopes, the dominant variable factor affecting gain is the distortion due to gravity. For an altitudeazimuth mounted telescope, these gravitational effects will be solely a function of elevation. For polar mounted telescopes, this is only true to first order and more complex models may be required. The antenna gain can be parameterized 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

$$G(z) = \text{DPFU} \times g(z), \quad (1.13)$$

where the polynomial $g(z)$ is

$$g(z) = a_0 + a_1 \cdot z + a_2 \cdot z^2 + a_3 \cdot z^3 + \dots, \quad (1.14)$$

where a_i are the polynomial coefficients. Theoretically, the gain of the antenna can be determined by illuminating the dish with an artificial radio source of calibrated strength. However, it is then only possible to determine the gain at one elevation and it is very difficult to produce such a stable calibrated signal. More practically, the gain performance of a telescope can be found by making observations of the change in antenna temperature going on

and off celestial sources of known flux density. The gain is determined by comparing the change in power going on and off a source with the change in power when switching the noise cal on and off, such that

$$G = \frac{P_{\text{on-source}} - P_{\text{off-source}} T_{\text{cal}}}{P_{\text{cal-on}} - P_{\text{cal-off}} S}, \quad (1.15)$$

where T_{cal} is the noise cal temperature and S is the calibrator source flux density. A convenient way to collect gain calibration data is to use the `aquir` program in the Field System. This program cycles around a supplied list of calibrator sources making observations of all those above the horizon. For each source, it first optionally executes the `fivept` task, which makes a series of observations around the nominal pointing position and fits for the position offset giving maximum power. In order

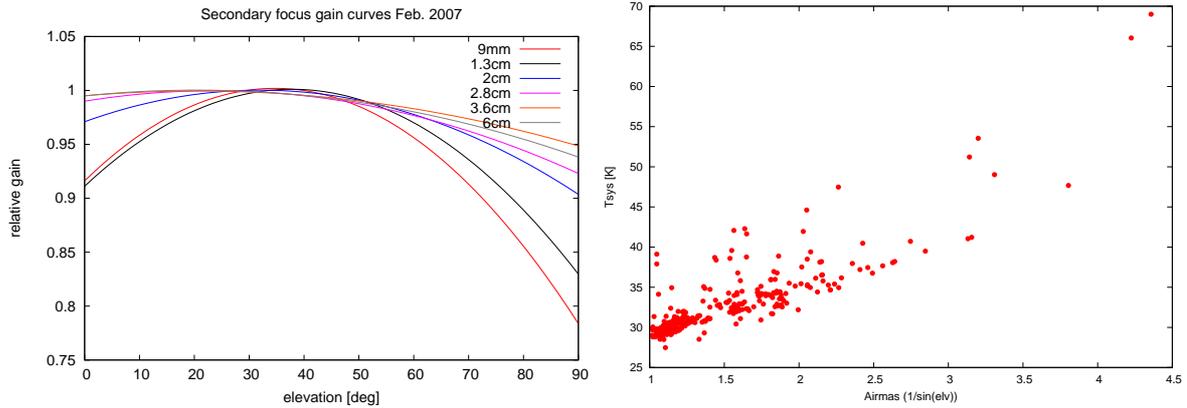


Figure 1.5: Examples of gain-elevation curves, $g(z)$, for the Effelsberg secondary focus receivers and 6cm system temperature measurements vs. airmass.

to get accurate gain-elevation information, it is clearly important to have the best possible pointing. Such data can also be used to update the pointing model used during VLBI observations. Following `fivept`, the program `onoff` can be used to determine the power ratio in the above equation. Combined with estimates of the flux densities of the calibrator sources and T_{cal} , this program can be used to collect a large database of antenna gain values allowing us to fit for the gain curve $g(z)$ and the DPFU. The accuracy of the absolute gain calibration depends on the accuracy to which T_{cal} can be determined and the calibrator flux densities are known. Choice of flux calibrator is determined by the calibrator strength (some stronger sources may saturate receivers) and/or the antenna size (large antennas may partially resolve some calibrators). The details of `onoff` are discussed in the Antenna Gain Calibration workshop (M. Lindqvist).

1.6 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. How they are determined and analyzed, in general, is described in the workshops mentioned in Section 2.1. The acquisition of accurate antenna calibration data is very much dependent on the specific features, capabilities and priorities of individual VLBI stations, but the tools are already available within the Field System.

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Chapter 2

Part 2: ANTABFS

2.1 Antenna calibration review

- A source of flux density S delivers a power to the output terminals of the receiver of

$$P = \frac{SA_{\text{eff}}}{2} \Delta\nu \quad (2.1)$$

$$= \frac{S \eta_A A_{\text{geom}}}{2} \Delta\nu, \quad (2.2)$$

where η_A is the *aperture efficiency* (the ratio between effective area and geometric area for the antenna at that frequency/pointing direction).

- A resistive load at a temperature T delivers a power of

$$P = kT\Delta\nu, \quad (2.3)$$

where k is the Boltzmann constant (1.38×10^{-23} J/K).

- The *antenna temperature* T_A is the equivalent temperature of a resistive load providing the same power at the output terminals of the receiver as the source of flux density S :

$$\begin{aligned} T_A &= \frac{1}{2k} \eta_A A_{\text{geom}} S \\ &= \frac{\pi D^2}{8k} \eta_A S, \end{aligned} \quad (2.4)$$

where the last line expresses $A_{\text{geom}} = \pi D^2/4$.

2.2 System Temperature and SEFD

- The *system temperature* T_{sys} is the equivalent temperature of a resistive load providing the same power at the output terminals of the receiver as the system noise.
- The *system equivalent flux density* SEFD is the flux density of a fictitious source providing the same power at the output terminals of the receiver as the system noise.
- These two quantities can be related to each other via a *sensitivity* Γ : $T_{\text{sys}} = \Gamma \text{ SEFD}$, with Γ in units of Kelvin per Jansky. From equation (4),

$$\Gamma = \frac{\pi D^2}{8k} \eta_A. \quad (2.5)$$

2.3 Y-method for measuring the system temperature

- One way to measure the T_{sys} of a receiver is to put two different-temperature resistive loads “into” the antenna and measure the ratio of the output powers:

$$\begin{aligned} P_{\text{hot}} &= (T_{\text{hot}} + T_{\text{sys}})g \\ P_{\text{cold}} &= (T_{\text{cold}} + T_{\text{sys}})g, \end{aligned} \quad (2.6)$$

where g is the gain of the receiver – here we take it that the receiver remains in a linear regime for both loads, such that g is independent of input/output power.

- Forming the ratio of these two output powers: $Y = P_{\text{hot}}/P_{\text{cold}}$ (Y should be > 1) and solving for T_{sys} yields:

$$T_{\text{sys}} = \frac{T_{\text{hot}} - Y T_{\text{cold}}}{Y - 1}. \quad (2.7)$$

2.4 Field-system power measurements

- The *cal signal* is a broad-band noise source at a specific temperature (`caltemp`). Ideally, this is constant, but is really a function of frequency and time – calibrating these changes is why the `rxg` files are important.

- Total-power integrators (Mark4) include:
 - `tpi`: measured when cal-source off
 - `tpical`: measured when cal-source on
 - `tpzero`: zero levels (must be subtracted from `tpi` or `tpical` before using them in calculations)
- The cal source “fires” only when there is a long-enough gap in the schedule (i.e., when the disk isn’t recording).
 - `tpi'`: a `tpi` measurement close(st) in time to the cal-source firing.
 - The difference (`tpical -- tpi'`) will be an important quantity, essentially setting the scale between TPI counts and physical temperature. Sometimes this is called `tpdiff`.

↔ How do you get T_{sys} from these FS-log quantities?

- Take the output with the cal-source off and on to be:

$$\begin{aligned} (T_{\text{sys}}) g &= \text{tpi} - \text{tpzero} \\ (T_{\text{sys}} + T_{\text{cal}}) g &= \text{tpical} - \text{tpzero}, \end{aligned} \quad (2.8)$$

- Forming the ratio of these two powers and solving for T_{sys} , and expressing the result in terms of the TPI counts leads to:

$$T_{\text{sys}} = T_{\text{cal}} \frac{\text{tpi} - \text{tpzero}}{\text{tpical} - \text{tpi}'} \quad (2.9)$$

- Representative `tpical -- tpi'` value ~ 1000 .
 - too low \mapsto larger scatter; more editing in `antabfs` may be needed
 - $\sim 0 \mapsto$ dead cal source(?)
 - jumps \mapsto change in attenuation; unstable cal source
- VLBA4 racks are slightly different, with an automatic gain control (AGC) active, keeping the power-counts in a good range for the samplers. The reported `tpgain` is an index for a look-up table for AGC gain level (256 entries). The values from this table can be used in a formula to compute a `tpi` proxy given a `tpi'` :

$$\text{tpi} = \text{tpi}' \cdot e^{0.23026 \cdot (GL' - GL)} \quad (2.10)$$

where GL and GL' are the gain-levels from the look-up table indexed by the logged `tpgain` and `tpgain'` values.

- For the DBBC, there are two available styles of T_{sys} measurements:
 1. One style is using non-continuous measurements similar to what is used with Mark4 and VLBA4 racks. There is one significant difference though. The normal approach is to make a T_{sys} measurement during shortly before each scan. After that during the observations, the `tpicd` daemon samples the `tpi` data at a user specified interval. The difference for DBBCs is that unlike the usage with the VLBA4, after the T_{sys} measurement, the IF gains are left locked until the next set-up. The set-up for the next scan will set the gains back to automatic gain control (AGC) mode so that the level can reach an appropriate level before the next scan.

This difference allows the `tpi` data sampled during the observations to be related to the gain levels in the T_{sys} measurement. This provides higher resolution than using the gains as a proxy for the signal levels (as is done with the VLBA4 rack).

2. The second T_{sys} style is continuous cal (80 Hz cal). In the continuous cal mode, all T_{sys} measurements are made by the `tpicd` daemon. This has the effect of completely removing T_{sys} related commands from FS procedures PREOB/MIDOB/POSTOB. During scans, the `tpicd` daemon samples the `tpi/tpical` values periodically. After a specified number of samples have been collected, `tpicd` calculates a T_{sys} value that is logged. In this approach T_{sys} is not measured only previous to a scan but continuously using the noise diode on a second basis and therewith provides very accurate T_{sys} measurements.

Please note for continuous cal that: (1) it is impossible to estimate T_{sys} values for the IF conditioning module detectors (no separate `tpical` value is available), but `tpicd` does report their `tpi` values (which are actually a combination of `tpi` and `tpical` values), (2) `tpicd` must be set-up to operate before `tpicd=tsys` will display anything useful, the set-up is normally done by the mode set-up procedure, and (3) the `tpicd` sampling interval should be set to 100 centiseconds.

- For the EVN, T_{cal} of the cal-sources is measured in CL experiments that take place in each frequency-band sub-session during disk-based EVN sessions. For most stations, T_{cal} has clear frequency dependence, even within a band, and can vary from session to session. The `rxg` files result from such measurements; see the *Antenna Gain Calibration* workshop (M. Lindqvist) for details.

2.5 What do the astronomer need?

- We now have $T_{\text{sys}}(t)$ within an experiment
 - `tpical-tpi` provides an physical tie to the temperature of the cal-source at gaps in the schedule
 - `tpi` provides a relative scale in between gaps
- SEFD as a function of time will give the astronomer the noise in flux-density units (Jy) of his telescopes:

$$SEFD(t) = \frac{T_{\text{sys}}(t)}{\text{GAIN}} = \frac{T_{\text{sys}}(t)}{DPFU \times POLY(elv)}, \quad (2.11)$$

where

- $DPFU$ = degrees per flux unit [K/Jy] – another measure of antenna sensitivity.
 - $POLY$ = the gain curve, above as a function elevation (could also be zenith angle [90°–elevation] or some more complicated dependencies for equatorial-mount stations). The largest contributor to gain changing with elevation is gravitation distortion of the antenna.
- The astronomer will eventually need to convert the dimensionless correlation coefficients output from the correlator into physical flux-density units, which will depend on the geometric means of the SEFDs of the two stations forming each baseline. Thus inaccuracies in any of $T_{\text{sys}}(t)$, $DPFU$, or the gain curve could translate into inaccuracies in the amplitudes of the visibility data. Since the map of the source will ultimately result from the Fourier transform of the visibility data (via various stages of image reconstruction procedures), such inaccuracies will result in errors/spurious features in the source structure in the “map plane”.

2.6 antabfs: where to get it

- `antabfs.pl` is a perl program that inputs a FS log and `rxg` files to:
 - compute/edit `tpical - tpi` values for each VC/BBC
 - compute/edit resulting T_{sys}
 - output an `antabfs` file

It needs the `pgplot` perl module for its on-screen editing and plotting functions. The path to this should be set in the environment variable `PERL5LIB`.

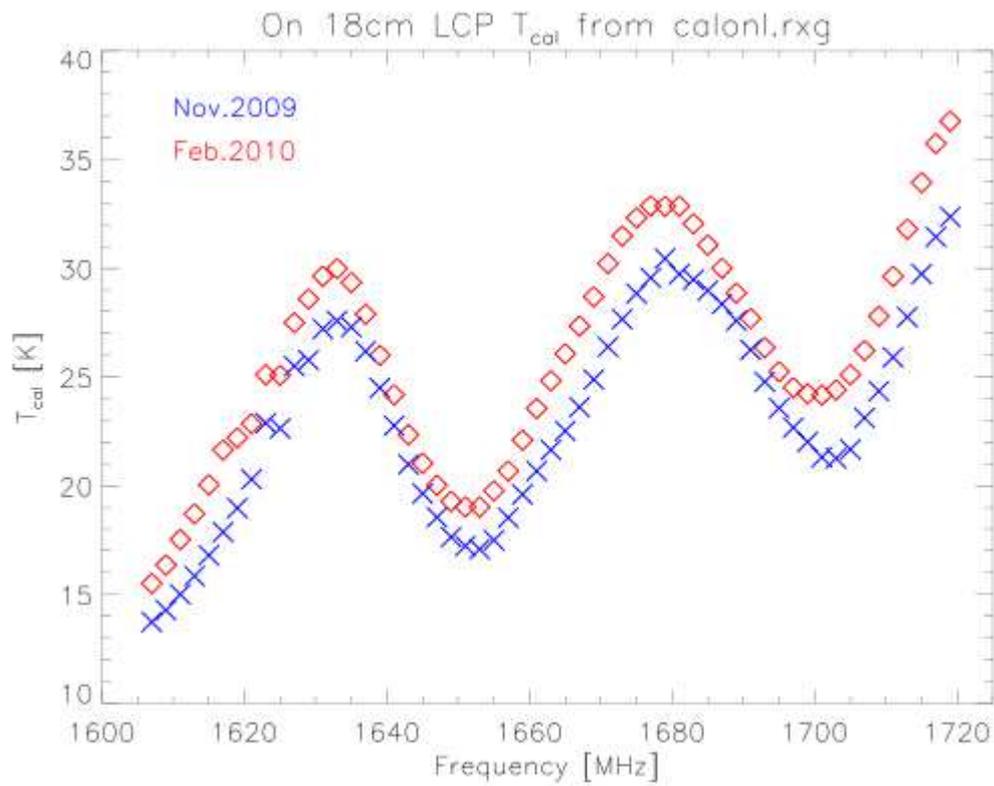
- It was written originally by Cormac Reynolds, and subsequently supported/updated by Giuseppe Cimò and Jun Yang – all at JIVE. We are always interested in getting o feedback for new features or other modifications that would improve its usefulness to the stations.
- You can get it via anonymous ftp:

```
ftp.jive.nl
cd outgoing
get antabfs.tar
```

- The current tar-ball expands to a subdirectory `antabfs` underneath your current working directory. There is a guide in this at `antabfs/docs/antabfs.tex`.

2.7 RXG files

- more authoritative information in *Antenna Gain Calibration workshop* – M. Lindqvist
- T_{cal} can be function of frequency and time (see Fig. 2.1).
- Contents of the `rxg` files per line:
 - 1st line : applicable LO-frequency range
 - 2nd line : file creation date
 - 3rd line : beam width (in terms of frequency or physical degrees)
 - 4th line : available polarizations (one of or both: rcp, lcp)
 - 5th line : DPFU [K/Jy] for each polarization listed in 4th line
 - 6th line : gain curve
 - argument = elevation or zenith angle via TYPE
 - max # coefficients = 10
 - 7th line : rows of: POL FREQ T_{cal}
 - max # rows = 100
 - group rows by polarization, then sort by increasing frequency
 - terminate with `end_tcal_table`
 - line following T_{cal} : receiver temperature (if 0, no opacity corrections used) usually 0 below K-band
 - next line : spill-over table: rows of ELEV [deg], T of spill-over noise
 - terminate with `end_spillover_table`

Figure 2.1: T_{rmcal} for On 18 cm LCP.

Example for a 4cm rxg-file from Effelsberg:

```
*4cm.rx - 3.6cm receiver parameter definition
range 7100 9000
2009 06 18
frequency 0.95
rcp lcp
1.37 1.37
ELEV POLY 0.93145303 0.0028819508 -3.0291784e-05
Oct 15, 2008, gain curve update, by UB
ELEV POLY 0.995 4.3434e-04 -1.0562e-05
rcp 8100.0 2.5000
rcp 8211.0 2.3835
rcp 8212.0 2.5230
rcp 8214.0 2.5107
rcp 8218.0 2.5223
rcp 8224.0 2.5380
rcp 8226.0 2.5493
rcp 8234.0 2.5612
rcp 8236.0 2.5707
...

lcp 8568.0 2.6720
lcp 8584.0 2.7400
lcp 8592.0 2.7970
lcp 8600.0 2.7990
lcp 8700.0 2.5002
end_tcal_table
Trec: receiver temperature
18.0 18.0
Spillover
90 0
19 1
16 2
14 3
12 8
8 120
end_spillover_table
```

2.8 Calibration feed-back for experiments correlated at JIVE

- Each experiment correlated at JIVE gets pipelined. The *a priori* amplitude calibration for this comes directly from the stations' *antabfs* output files.
- Pipeline results reside in the EVN archive, which you can access at

`www.jive.nl/select-experiment`

by clicking on the experiment you want from the pull-down menu. Go to the Pipeline tab, then to the pipeline plots link (top one of the table). Find the section beginning 'Amplitude corrections'. This will provide a list of sources in the experiment, each with a pdf, a text file, and a statistical summary.

- The pdf file plots amplitude correction factors (1 = no correction needed) by station/sub-band/polarization -- see Fig. 2.2.2
- The statistical summary tabulates by station/channel the median amplitude correction factor and related statistics. It also provides the antenna numbering that is needed to investigate the text file.
- The text file contains the raw information from which the statistical summary was computed. It tabulates per sub-band/polarization the amplitude correction factor ($\times 10000$), with time-sampling roughly on a per-scan basis. The telescopes form the columns, labeled by the antenna number in the experiment.

2.9 antabfs demo

- You may need to make a couple quick adjustments to the `antabfs.pl` program before running:
 - update the first line for the location of your perl
 - update the `$gindir` definition to reflect where your rxg files will be found.
- The basic syntax for `antabfs.pl` is just:
`antabfs.pl logfile`
A variety of command line switches are available; inclusion of the switch `-h` will produce a full listing of these.

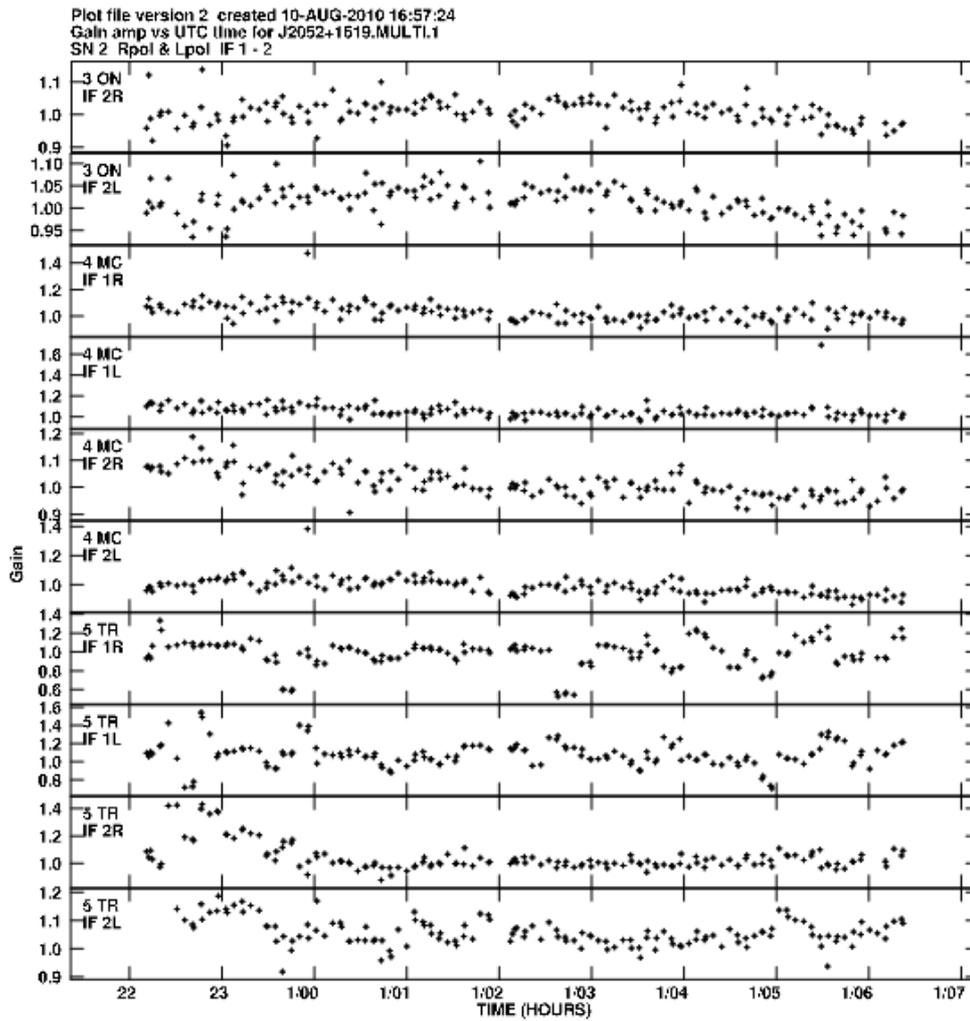


Figure 2.2: Page from an amplitude correction plot from the EVN archive (experiment ES064B, 18 cm).

- Once the FS-log has been read, you will be prompted for your plotting device for the (possibly) interactive plots. Responding with a ‘?’ returns a list of available devices. /xs is the usual response (short for /xserve -- a persistent xwindow).
1. In the first part of the program, it will loop through all VCs, showing `tpdiff = tpical-tpi` as a function of time, together with a red piece-wise linear fit (hereafter, PWLF) and lines representing ± 5 deviations from the fit (green & blue). You have some control over how the fit is made.
 - Hitting return while a plot is showing deletes the `tpdiff` values outside the green & blue range. A new PWLF will be generated and plotted.
 - You can control interactively how many deviations these lines span by simply entering a different integer and hitting return. A new PWLF will be generated, but the blue & green lines will revert to ± 5 deviations.
 - You can control interactively how many `tpdiff` points go into each PWLF bin by hitting “B” and responding to the query.
 - If you want more control over deleting `tpdiff` points, you can type “E” and hit return. You will then be able to draw boxes on the plot via:
 - left mouse button (or “A”) – selects the two opposite corners of a rectangle
 - middle mouse button (or “D”) – restarts the current rectangle
 - “C” – cancels all previously defined rectangles
 - “Z”/“U” – makes a zoom box / unzooms
 - right mouse button (or “X”) – exits, deleting all the points in all the defined rectangles
 - When you’re finally happy with this VC’s plot, enter “Y” to accept the changes made and move on to the next VC (entering “Y” as the first step bypasses any editing on the displayed VC).
 2. Once you’ve edited the `tpdiff` values for all the VCs, the program will take some time to compute T_{sys} , and then loop through the VCs again displaying $T_{\text{sys}}(t)$.
 - The only editing option you have here is the “E” option described above – interactively defining rectangles inside of which points will be deleted.
 3. Once you’ve gone through the T_{sys} for all the VCs, the program will make a color-coded plot of all the VCs’ T_{sys} plotted together, to allow a check for global consistency.

- It will prompt you whether you want to go back to step [2] to re-edit the individual-VC T_{sys} values. If you don't want to do this, then the program will finish by making the antabfs file.
- There are a couple associated plotting programs. `plot_tsys.pl` takes an *antabfs* file and generates a plot similar to that made in step [3], with the option of putting each VC onto separate panels.

Example of an Effelsberg antabfs-file:

```
! Produced by: antabfs.pl
! For antenna: EF
! ----- Tsys information for EFLSBERG
GAIN EF ELEV DPFU=1.550,1.550 FREQ=900,1740
POLY=1.0, /
TSYS EF FT = 1.0 TIMEOFF=0
INDEX= 'R1','R2','R3','R4','L1','L2','L3','L4'
/

! 061 21:18.47 scan=no0001 source=J1350+3034
!Column 1 = R1:  bbc01, 1356.50 MHz , LSB, BW= 16.00 MHz, Tcal=6.20 K
!Column 2 = R2:  bbc02, 1371.75 MHz , LSB, BW= 16.00 MHz, Tcal=6.05 K
!Column 3 = R3:  bbc03, 1387.00 MHz , LSB, BW= 16.00 MHz, Tcal=5.89 K
!Column 4 = R4:  bbc04, 1402.25 MHz , LSB, BW= 16.00 MHz, Tcal=5.57 K
!Column 5 = L1:  bbc09, 1356.50 MHz , LSB, BW= 16.00 MHz, Tcal=6.19 K
!Column 6 = L2:  bbc10, 1371.75 MHz , LSB, BW= 16.00 MHz, Tcal=6.12 K
!Column 7 = L3:  bbc11, 1387.00 MHz , LSB, BW= 16.00 MHz, Tcal=5.81 K
!Column 8 = L4:  bbc12, 1402.25 MHz , LSB, BW= 16.00 MHz, Tcal=5.25 K
061 21:30.35 34.8 36.4 38.0 36.5 37.2 36.8 34.9 31.6
061 21:30.68 34.8 36.3 38.1 36.4 34.3 37.6 35.7 32.3
061 21:31.02 34.8 36.4 38.1 36.5 34.3 37.6 35.7 32.3
061 21:31.35 34.8 36.3 38.1 36.5 34.4 37.7 35.8 32.3
061 21:31.68 34.8 36.3 38.1 36.5 34.2 37.5 35.6 32.2
061 21:32.02 34.8 36.3 38.2 36.5 34.3 37.6 35.7 32.2
061 21:32.35 34.8 36.3 38.1 36.5 34.3 37.7 35.8 32.4
061 21:32.70 34.8 36.3 38.1 36.5 34.3 37.6 35.7 32.3
061 21:33.03 34.8 36.4 38.0 36.5 34.3 37.6 35.7 32.3
061 21:33.37 34.7 36.3 38.1 36.5 34.3 37.7 35.7 32.3
061 21:33.70 34.8 36.4 38.1 36.6 34.2 37.6 35.7 32.3
061 21:34.00 34.8 36.4 38.1 36.5 34.4 37.8 35.9 32.4
! 061 21:34.00 scan=no0002 source=3C293
061 21:34.72 42.7 44.4 46.5 44.5 41.9 44.8 42.5 38.4
061 21:35.05 42.7 44.6 46.6 44.6 41.8 45.6 43.3 39.1
061 21:35.38 42.8 44.6 46.6 44.6 41.7 45.5 43.2 39.1
061 21:35.72 42.9 44.6 46.7 44.7 41.8 45.7 43.4 39.2
```

```
061 21:36.05 42.7 44.3 46.3 44.4 41.7 45.5 43.2 39.1
061 21:36.40 42.5 44.5 46.7 44.7 41.7 45.5 43.2 39.1
061 21:36.73 42.1 43.8 45.8 43.8 41.5 45.1 42.9 38.7
061 21:37.07 42.0 43.6 45.7 43.8 41.2 44.9 42.7 38.6
061 21:37.40 42.0 43.6 45.7 43.8 41.5 45.3 43.0 38.8
061 21:37.58 42.1 43.6 45.9 43.9 41.5 45.2 42.9 38.8
! 061 21:37.60 scan=no0003 source=J1350+3034
061 21:38.43 34.4 36.0 37.8 36.0 33.9 37.2 35.3 31.9
061 21:38.77 34.4 36.0 37.8 36.1 34.0 37.3 35.4 32.0
061 21:39.10 34.4 35.9 37.8 36.0 34.0 37.3 35.4 32.0
061 21:39.43 34.4 36.1 37.8 36.1 33.9 37.2 35.3 31.9
...
```