IMPROVING EVN CALIBRATION

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Version 1.0, 13th September 1996

1. INTRODUCTION

A significant area of the EVN's performance which could be improved is that of amplitude calibration. Two areas are of concern, one is the ease with which users can incorporate calibration information into AIPS and into their mapping, but a more fundamental problem is the quality and reliability of the calibration information. As revealed by the EVN calibration reports errors in overall calibration scale of up to 20% are not uncommon. This is in contrast to the situation on the VLBA where at least for frequencies of 22GHz and below calibration is now of a high quality and its use is usually transparent to users. It is clearly vital to improve the situation on the EVN.

In this report we restrict ourselves to considering the calibration of frequencies at which atmospheric opacity is is not important i.e. at EVN frequencies at or below 8GHz (a second report deals with the problems of high frequency observing). We briefly review the fundamentals of amplitude calibration in Section 2, in Sections 3 and 4 we describe methods for separately estimating the system temperature and antenna gains while in Sections 5 and 6 we describe the procedures which we think should be adopted for calibrating future EVN sessions.

2. CALIBRATION FUNDAMENTALS

Here for convenience and completeness we summarise the fundamentals of VLBI amplitude calibration. Starting from first principals, we note that an important fact of VLBI is that direct information about the amplitude of the received signals is lost at the stage of digitisation (even in 2 bit systems where the threshold levels are set by the strength of the signals). At the correlator the similarity of the two bits streams from the two telescope at the ends of each baseline are compared to create dimensionless correlation coefficients describing the degree of similarity of these bit streams. In general real and imaginary correlation coefficients are calculated on each baseline, the second corresponding to the degree of correlation after delaying the second bit stream by one quarter of a wave.

In the usual case in which system noise power dominates over noise power from the source then the net amplitude of the complex correlation coefficient

$$C_{ij} = B \frac{V_{ij}}{\sqrt{N_i N j}} \tag{1}$$

where V_{ij} is the visibility amplitude in Janskies B is a dimensionless factor taking into account the effects of digitisation and the quantities N_i and N_j represent the system noise of the two antennas expressed as a source equivalent flux density SEFD in Janskies. This SEFD is defined as the source flux density which would contribute an antenna output power 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 B and the SEFD's N_i and N_j in Jy. VLBI amplitude calibration therefore is about estimating the antenna SEFD, or N_i values as functions of time, elevation, frequency etc and applying the resulting corrections to the raw correlation coefficients to obtain $V_{i,j}$.

The SEFD at an antennas can be divided into two parts such that

$$N_i = \frac{T_i}{G_i} \tag{2}$$

Where T_i is the system temperature in Kelvin and G_i is the antenna gain in KJy^{-1}. The former quantity is defined as the physical temperature of a load in the antenna beam which 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 spillover, and at high frequencies changes in the atmospheric contribution. The antenna gain G_i changes mainly due to elevation dependent distortions of the dish due to gravity. It follows that this quantity should be highly reproducible and dependent only on elevation (and maybe also HA and Dec for Polar mounted telescopes).

In the following sections 3 and 4 we discuss in more detail the two halves of antenna calibration, system temperature and antenna gain calibration. In these two sections we concentrate on methods of calculating these two quantities absolutely. Such absolute calibration is important for determining whether the receivers and telescope efficiencies are at their expected values, vital information for optimising antenna performance, however for the purposes of amplitude calibration of data only the relative values of the system temperature and antennas gain matter (see Equ 2). Sections 5 and 6 therefore describe methods of amplitude calibration which determine only the relative quantities; such an approach has less scope for errors and is the recommended method of amplitude calibration of future EVN sessions.

3. SYSTEM TEMPERATURE CALIBRATION

3.1 Noise Cal Calibration

System temperatures can vary unpredictably during a VLBI experiment due to changes in the receiver temperature, the spillover, RFI etc, etc and so must be monitored continuously. For a system with stable receiver gains system temperatures could be monitored by recording the variation in total power from the antenna. In practice receiver gains are insufficiently stable over long enough periods to use this method, instead a secondary calibration source (presently a broad band 'noise-cal') of constant noise temperature T_{cal} must be is periodically injected and the change in total total power compared to the power measured when this cal is off. From these measurements the system temperature T_{sys} can be derived via

$$T_{sys} = \frac{T_{cal} P_{cal-off}}{P_{cal-on} - P_{cal-off}} \tag{3}$$

Where P_{cal-on} and $P_{cal-off}$ refer to the powers with noise cal on or off and T_{cal} is the noise cal system temperature.

3.2 Calibrating T_{sys}

Using equation 3 obviously requires an accurate estimate of the noise cal calibration temperature T_{cal}, which can be estimated via hot/cold load measurements via

$$T_{cal} = (T_{hot} - T_{cold}) \frac{P_{cal-on} - P_{cal-off}}{P_{hot} - P_{cold}} \tag{4}$$

Where P_{hot} and P_{cold} are the powers 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 don't change.

The most reliable results probably come from lab measurements of the receiver and waveguide. For the hot load a piece of echo absorbing material can be used to cover the input, this gives a load at ambient temperature while the cold load can be the same material soaked with liquid nitrogen. Similar tests can be done with the receiver mounted on the telescope, but in this case the loads must normally be placed in front of the feed horn, access can be difficult and it can be also be difficult to fully cover the larger feeds. An alternative for in-situ measurements is to obtain different loads of known temperature by pointing the telescope at blank sky (approx

2.7K), the ground (possible with some polar mounted telescopes) or a nearby hillside giving an ambient load. Finally if the antenna beam is sufficiently compact the Moon can be used. The Moons brightness temperature depends on its phase, and account must be take on this (see Magnum 1993), also at centimetre wavelengths the temperature used should be the weighted mean of the system temperature averaged over the Moon, taking into account sidelobes which do not lie on the Moon.

An important point in making the above calibration measurements is to ensure the receiver gives a linear response over the range of load temperatures observed. It is possible, especially when observing the ambient load to saturate a stage of amplification, in this case the derived values for T_{cal} will be inaccurate. A way to check this is to switch the noise cals on and off when looking at loads of different temperature, the change in power should be the same in all cases.

3.3 Frequency Dependence of T_{cal}

The field system calculates a T_{sys} for each VC using equation 3 but in doing so implicitly assumes that the noise tube injects a noise power which is constant over the observing band, since it uses the same value of T_{cal}, entered as parameter CALTEMP, for all VC's. In practice over typical MkIII or MkIV bands the T_{cal} can vary significantly at some telescopes and so estimates of the T_{sys} values in the different Video Converters can be significantly in error.

One solution would be to determine the T_{cal} frequency dependence and enter an array of T_{cal} values including one for each VC at each observing mode in the Field System. This solution requires significant changes to the Field System, and it is unclear that it is worthwhile entering such corrections 'online' since the T_{cal} ratios might not be determined accurately before the session starts. A better solution is to use a single value for T_{cal} in the field system which is correct at a defined reference frequency, then the frequency dependent corrections can be made when extracting the T_{sys} estimates from the Logs and formatting them in the ANCAL file. The log to ANCAL conversion program LOG2ANC already allows this option.

The values of the frequency correction factors to be applied can be determined by making careful frequency measurements when the T_{cal} is measured with hot/cold loads. An alternative and more convenient method is to compare the change in power obtained on switching the noise-cal on and off with the change in power obtained going on and off a bright flat spectrum radio source for each VC. These power ratios are independent of any differences in receiver gain for the different VC's, but since the noise power contributed from the flat spectrum celestial radio source should be almost frequency independent the measured ratios do tell us about the relative value of T_{cal} in each VC. These measurements can be made by using the Field System task ONOFF and the results entered in the input files to LOG2ANC to accomplish frequency correction of T_{sys}.

3.4 Phase-Cal Based Calibration

At present (late 1996) the noise-cal is a strong broad-band signal which is switched on for a few tens of seconds before or after each scan. This method has the disadvantage that readings of T_{sys} cannot be made continuously while observing. An alternative method is to use the injected phase-cal tones; the narrow band signals injected into the system as a 'comb' of narrow band signals each 1MHz apart. While the primary purpose of the phase-cal is to determine the phase offsets between different video converter channels, if the output power of the phase-cal is amplitude stabilised then by detecting the power at frequencies on and off the phase-cal tones it will be possible to use them for amplitude calibration. The powers 'on' and 'off' tone correspond exactly to the measurements of power with a broad band cal either on or off in equation 3. Assuming the injected phase-cal power is stable and can be calibrated with hot and cold loads T_{sys} can then be monitored continuously.

As part of the MkIV upgrade a new analogue phase-cal extractor board will be installed at each station which will allow these measurements to be made. For spectral line observations the phase-cal signal should be switched off and so for these observations the calibration must be made in gaps before and after each scan and there must be a provision for switching the phase-cal on and off under schedule control. Like the so-called 'broad-band' noise cal presently used it is likely that the amplitude of the phase-cal tones will vary from VC to VC and must be calibrated as described in Section 3.3.

4. GAIN CALIBRATION

4.1 Measuring Antenna Gain

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 area of the telescope and the efficiency of the surface in focusing the incident radiation. Theoretically this gain is proportional to the effective collecting area and equals

$$G(K/Jy) = \frac{A\eta}{2760} \tag{5}$$

where A is the geometrical area in square meters and η is the aperture efficiency. For the purposes of calibration G in K/Jy must be found experimentally by measuring the change in system temperature going on and off sources of known flux density. The aperture efficiency η is then determined from equation 5. For most telescopes the dominant factors effecting gain are the distortions due to gravity and for an altitude-azimuth mounted telescope these gravitational effects will be solely a parameter of elevation. For polar mounted telescopes this is only true to first order and more complex models may be required. In AIPS calibration format the antenna gain is parameterised in terms of a 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 such that the DPFU multiplied by the polynomial gives the correct antenna gain at each elevation i.e.

$$G(za) = DPFU * g(za) \tag{6}$$

where the polynomial $g(za)$ is

$$g(za) = (a_o + a_1 za + a_2 za^2 + a_3 za^3 ...) \tag{7}$$

where a_1 etc 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 besides 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 on switching the noise cal on and off and is calculated via

$$G = \frac{P_{on-source} - P_{off-source}}{P_{cal-on} - P_{cal-off}} \frac{T_{cal}}{S} \tag{8}$$

Where T_{cal} is calibrated using hot cold/cold load measurements as described in Section 3 and Equation 4.

A convenient way to collect gain calibration data is to use the AQUIR program on 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 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 which determines the power ratio in Equation 8, 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 and the DPFU.

4.2. Effect of Uncertain Calibrator Source Fluxes

The accuracy of the absolute gain calibration derived via Equ 8 clearly depends both on the accuracy to which T_{cal} (see Section 3.2) and the calibrator flux densities, S, are known.

For most sources their fluxes S must be derived by measuring the ratio of their flux densities to those of a small number of 'primary' calibrators whose flux densities are determined absolutely. These 'primary calibrators' comprise those few extremely bright Northern hemisphere sources e.g. Cas A, Cygnus A and Taurus A which can be observed with small antennas whose gains can either be calculated from first principles or measured on a test range. Baars et al (1977) collected such observations and therefore constructed absolutely calibrated spectra for the above three sources. One complication is that two of the three primary calibrators show steady declines in their flux densities with time and this must be taken into account when estimating the flux density at a given time and frequency. In principle the primary calibrators can be used to measure the absolute value of G using equation 8 but in practice there are number of practical problems. First the calibrators are partially resolved by the larger telescopes at higher frequencies and account must be taken of this, which introduces a source of error. Secondly the sources are so bright that they can partly saturate receivers, leading to nonlinearities in the relationship between output power and input source flux (or 'gain compression') making them useless for amplitude calibration.

To overcome these problems Baars et al (1977) provided a list of weaker secondary calibrators whose flux densities had been determined relative to one or more of the primary calibrators. These sources in general have fluxes of tens of Janskies, making them easy to detect but not so bright as to saturate receivers, and furthermore they are all compact sources so no corrections are needed for resolution effects. Unfortunately it now appears that many of the defined calibrators are variable at the 5% level over a period of a decade or so. This means that absolute calibrations based on some of the secondary calibrator spectra given by Baars will be inaccurate at this level. Ott et al (1994) identified this variability by measuring around 1990/1991 the flux density ratios of the secondary sources and comparing them with the ratios expected given the estimated spectra in Baars et al. Amongst the group of secondary calibrators however two sources stood out as having kept a constant ratio over time, namely 3C295 and 3C286. It was argued based on the size of the emission region compared to the light travel time that 3C295 is unlikely to have changed in flux density, and because the 3C286/3C295 ratio has stayed constant therefore 3C286 (the VLA primary flux calibrator) has probably also stayed constant from the 1970's to the 1990's.

Assuming the constancy of the flux density of 3C295 and adopting the spectra for this source determined by Baars et al (determined via reference to the primary calibrators) Ott et al constructed improved spectra for the secondary calibrators from the measured flux ratios to 3C295. Because these spectra are based on more recent observations (in 1990/1991) the Ott et al spectra are to be preferred over those of Baars when making absolute calibrations, however it should be noted that it is now almost 6 years since the Ott et al measurements and some sources will have varied in the interim. Continuous monitoring of some of the calibrators is being carried out by the University of Michigan at two frequencies and this monitoring can be used to obtain updated fluxes at these frequencies.

The effect of uncertainties in source flux densities is to introduce corresponding fractional errors into the antenna gains as estimated by on-off measurements via Equ 8, this can obviously effect the absolute calibration of the antenna gain and the derived value of the DPFU. More subtly such flux uncertainties may reduce the accuracy of the shape of the fitted gain curve because certain sources with either overestimated or underestimated flux densities and hence underestimated or overestimated gains will appear predominantly at either high of low elevations because of their declination. However, with a sufficiently large database of 'onoff' measurements there will many measurements of different sources which overlap in elevation so that it is possible to solve accurately for the flux ratios of these source pairs. An improved gain curve can then be derived by recalculating the gains G via Equ 8 using new source fluxes consistent with the measured flux ratios. If one of the most stable sources is included in the observations (e.g. 3C295 or 3C286) then from the measured source flux ratios it is possible to estimate absolute flux densities for all of the observed radio sources and hence determine very accurate values of the DPFU as well as the gain curve shape.

5. PROPOSED SESSION CALIBRATION

5.1 Limitations of Absolute Calibration

In sections 3 and 4 we have described how absolute calibration of both antenna gain and system temperatures can be made and then combined to estimate the SEFD in Jy, which is the relevant quantity for amplitude calibration (see section 2). In an ideal world the procedures described in sections 3 and 4 would be be performed carefully before each VLBI observing session at each frequency. In practice it is impractical to do this, usually the telescope is only available for a day or two before VLBI observations must begin and all the time is (rightly) devoted to making sure the VLBI system works. In contrast a full absolute calibration requires at each frequency a few days of pointing and gain-elevation observations and the absolute calibration of T_{cal} using hot and cold loads. In practice what generally happens is that old 'standard' versions of the gain curve, DPFU and T_{cal} are adopted and a few spot observations are made manually to check that nothing has changed significantly. However there is usually too little time to investigate and correct possible discrepancies before observing must start in earnest. For observing systems which are only installed on the telescope periodically the assumption that the T_{cal}, the absolute antenna gain and the shapes of the gain curves have not changed since the last session may not always be valid.

We suspect a major source of error in the amplitude scaling at EVN antennas comes in combining estimates of T_{sys}, T_{cal}, $DPFU$ and g made at different times and at slightly different frequencies. The T_{sys} values are of course estimated at the time of the VLBI observations but are often calculated using some assumed value of T_{cal} derived earlier at the time of the last hot/cold measurements. The g and $DPFU$ values are often measured at yet a different time and may be derived using a T_{cal} made non-simultaneously. If G or T_{cal} vary with time there is a lot of scope for errors to be introduced into the absolute calibration. An important point, first noted in Section 3.3, is that T_{cal} is often frequency dependent across the VLBI observing band and so if T_{cal} is derived using hot/cold loads at one frequency (see Equ 4) and then this value is used to estimate the gain G (see Equ 8) or T_{sys} (see Equ 3) at another frequency where it does not apply then errors result. A final source of overall calibration error is that there is no standard EVN source list of calibrators or agreement about which fluxes to use (Baars et al, Ott et al or internally derived). Different adopted values at different stations will obviously lead to inconsistent calibration, in addition as described in Section 4.2 an uncritical adoption of published source flux densities may also give errors in the derived shapes of gain-curves.

We believe the only way to ensure accurate calibration of the EVN is spend a significant effort of time outside of sessions determining gain curves and then in addition take a significant amount of calibration data *during the VLBI session*. These observations can be used to confirm that the adopted gain curves are correct, update any small changes and allow us to derive self consistent estimates of T_{cal} and antenna gain from observations made *at the time of the VLBI observations themselves*. While a full absolute calibration of the T_{sys} and gain is impossible every session, as described below this is not necessary, sufficient information can be obtained from making onoff measurements during the session to allow accurate amplitude calibration.

5.2 The Noise Cal in Janskies

As noted in Section 1 the only requirement for the purposes of amplitude calibration is to correctly estimate the system noise in Janskies, the source equivalent Flux Density or SEFD at antenna N. In AIPS an estimated SEFD, N', is calculated based on the tabulated system temperature values, T'_{sys}, estimated gain

DFPU', estimated gain polynomial g' and a multiplying 'fudge' factor, FT, via

$$N' = \frac{FT * T'_{sys}}{g' * DPFU'} \tag{9}$$

Where the primes indicate the assumed calibration quantities which not actually be their real values. The true SEFD is of course

$$N = \frac{T_{sys}}{g * DPFU} \tag{10}$$

where these unprimed qunatities refer to the actual true values of T_{sys} etc. The tabulated T'_{sys} values produced from the field systems logs are calculated from total power measurements with the noise cal on and off respectively via equation 3, assuming a certain value of the noise cal in Kelvin T'_{cal} (given by 'Caltemp' parameter in the Field System). The AIPS calculated SEFD N' can thus be written

$$N' = \frac{FT * T'_{cal}}{g' * DPFU'} \frac{P_{cal-off}}{P_{cal-on} - P_{cal-off}} \tag{11}$$

and the true SEFD is

$$N = \frac{T_{cal}}{g * DPFU} \frac{P_{cal-off}}{P_{cal-on} - P_{cal-off}} \tag{12}$$

The assumed SEFD will therefore equal the actual SEFD (i.e. $N' = N$) if we absolutely calibrate the gain and system temperatures so that all the assumed parameters equal their true values and we have $FT = 1.0$. However this is not a necessary condition, all that is required is that the assumed values are such that the combination;

$$\frac{FT * T'_{cal}}{g' * DPFU'} = \frac{T_{cal}}{g * DPFU} = T_{calJy} \tag{13}$$

This quantity T_{cal} divided by the antenna net gain $g * DFPU$ in KJy^{-1}, can be considered as the 'noise cal in Janskies' T_{calJy}. Note that T_{calJy} unlike T_{cal} depends on elevation because of the antenna gain is elevation dependent. Direct measurements of this T_{calJy} can be made by making source 'onoff' measurements, comparing the change in power obtained by switching the noise cal on and off with the change in power going on and off a source of known flux density. This observed power ratio must equal the ratio of the noise cal in Janskies to the source flux density in Janskies, it follows that

$$T_{calJy} = S \frac{P_{cal-on} - P_{cal-off}}{P_{on-source} - P_{off-source}} \tag{14}$$

Where S is the source flux. Hence by carrying out onoff measurements before, during and after the VLBI session and multiplying the observed power ratios by the source fluxes we can obtain measured values of the noise cal in Janskies. We can then check whether our adopted values of T'_{cal}, gain polynomial g', gain $DFPU'$ and factor FT give via equation 13 estimates of T_{calJy} which fit the observations, if they do then we can use these values directly when we run LOG2ANC to create an ANCAL format file from the log data, if they do not fit we must change our assumed parameters. If just the scaling of the predicted T_{calJy} versus elevation is wrong but the shape is right we could choose to change any of T'_{cal}, FT or $DPFU$ until it fits. Changing the first is inconvenient since it has already been applied by the field system, we could change $DPFU'$ but it is probably best to keep stable values for all antennas, therefore the best choice is to change FT. If it is the shape that doesn't fit then clearly we are forced to change the assumed $g'(za)$. Once we have found values that give a fit between the observed and predicted T_{calJy} we can adopt these when we run LOG2ANC to create the ANCAL format file and our amplitude calibration will be accurate.

6. Detailed Procedure

Here we summarise a step by step approach to achieving accurate calibration on the EVN during an observing session, making use the programs in the Antenna Calibration Package of the Field System to collect data and the script based tools developed by F.Rantakyrö for analysing calibration data and reformatting calibration information. The first of these tools is CAP (Calibration Analysis Package) which extracts calibration information from logs of onoff measurements and allows the fitting of improved calibration parameters. The second is LOG2ANC which uses the fitted calibration parameters and extracts T_{sys} values within the project logs, corrects their frequency dependence, and reformats the output in an ANCAL or ANTAB format file suitable for use in AIPS. The latest versions of the CAP and the LOG2ANC scripts can be found in the appropriate subdirectories on astbo1, detailed information on how to install this software and the detailed syntax for running them can be found in these directories. In addition before the October session we will supply on astbo1 all the necessary procedure files needed to run all the ACP tasks on the Field system to collected the relevent onoff input data for the calibration software. The detailed steps in calibrating a session based on this software are given below.

1) Each antenna should attempt every one to two years to estimate the absolute values of the T_{cal} at the centre of each observing band and the absolute value of the antenna gain (DPFU) and gain curve using the methods described in Sections 3 and

4. This information should be kept on astbo1 and should be changed only when observations show a very significant change has occurred in the system. It is important to document however the frequency and the date at which these observations were made. For individual VLBI experiments the effects of small variations in the T_{cal} and DPFU should be absorbed into changes in the FT parameter distributed with each ANCAL file.

2) During each session time will be set aside for amplitude calibration by the scheduler. It would be best if short gaps (say 2 hours) could be left between scheduled observations to allow for onoff calibrations to be made. In addition it would be useful to schedule 12hrs - 24hrs *after* at the end of the last project at any given frequency in order to collect further calibration data. It is much better to schedule specific time after the observations for calibration and leave the 24hrs prior to the session allocated for system setup; since at this point Friends of VLBI are understandably more concerned about checking the system works rather than collecting a large volume of calibration data, although quick checks of the calibration should of course be part of the system setup.

3) A specified 'Friend of Calibration' for the EVN should maintain and distribute via astbo1 a list of suggested calibrators to use for onoff tests at each of the upcoming frequencies, this list will be in a format suitable for use with the AQUIRE task on the field system. A list of expected source flux densities at the band enter frequency will also be sent with an indication of the accuracies of the flux estimates. The flux values will be drawn from the literature, from past EVN observations and monitoring by Bonn, Univ of Michigan, VLBA and VLA.

4) Using the suggested source list measurements of the 'src/cal' at the defined band centre frequency will be made for a large number of sources at different elevations using AQUIRE. It is useful to also run the FIVEPT program to check the pointing before running ONOFF on each source. From the logs of these ONOFF measurements the CAP script 'cap_format' will extract the values of 'src/cal' and using the estimated fluxes of the calibrators supplied in step 3 to calculate the noise cal in Jy. This can be plotted as a function of elevation or time using the script 'cap_plot', outlier points can be removed using the script 'cap_clip'.

5) The script cap_plot can be used to plot the edited T_{calJy} versus elevation. Discrepant sources with high or low values of estimated T_{calJy} with respect to other sources may have inaccurate fluxes, and the flux densities of these sources should be revised and the T_{calJy} values recalculated (see Section 4.2). The script cap_plot can also plot using equation 13 the theoretically expected T_{calJy} based on the adopted FT, $DPFU'$, T'_{cal} and gain curve g' against the observed values of T_{calJy} as a function of elevation. If this fits the observations then the adopted calibration values are

correct. If the shape is correct but the overall scaling is wrong then we just adjust the FT value until a fit is obtained. If the shape is wrong then we use an option in cap_plot to refit a polynomial to the data and calculate a revised $g'(za)$. If new values of FT or g are found these must be edited into the file that LOG2ANC uses to store its calibration parameters.

6) Steps 2 through 5 should ensure that the derived calibration is correct at the nominal band enter frequency. The final step is to take account of the frequency dependence of the noise-cal (and antenna gain) across the MkIII or MkIV observing band. As described in Section 3.3 this can be done by using supplied field system procedures to run ONOFF and measure the values of src/cal at each of the different VC bands for a bright source (e.g Cygnus A, Virgo A etc). The resulting values can be used to construct a table of correction factors to be used by LOG2ANC.

7) The script LOG2ANC (or its cousin LOG2ANT which produces the slightly different format ANTAB files) is finally run to convert the T_{sys} values in the station logs into corrected correctly formatted ANCAL data, if necessary the value of FT in each of these files is edited according to the revised parameters found in step 5. These ANCAL files are placed in the appropriate directory on astbo1 ready for the observer to retrieve them. Also placed there should be any estimates of corrected source flux densities derived in step 4, this way the values for at each station can be compared and the calibration coordinator can incorporate any changes in source flux densities into the list of source flux densities for the next session.

7. Conclusions

We believe that it is possible to achieve with the EVN the same amplitude calibration performance as presently achieved on the VLBA, however this depends on having the commitment of time to carry out the needed calibration observations, both within the VLBI sessions and additional time with the telescopes outside of sessions. This additional time is needed to obtain the full potential of the EVN observations.

We have begun to create tools to partially automate the collection and analysis of calibration data, while this software may yet evolve it can already be used to collect and analyse data and we encourage as many observatories as possible to try this software out and give us feedback during the October 1996 session and beyond.

ACKNOWLEDGEMENT The authors acknowledge many useful discussions with many members of the EVN community about calibration issues and in particular discussions with I. Pauliny-Toth and Richard Porcas about the Bonn calibration procedures.

References

Baars, J.W.M., Genzel, R., Pauliny-Toth, I.I.K., and Witzel, A., *A and A*, 1977, **61**, 99.

Magnum, J.G. 1993, *PASP*, **105**, 117.

Ott, M., Witzel, A., Quirrenbach, A., Krichbaum, T.P., Standke, K.J., C.J.Schalinski, Hummel, C.A., 1994, **284**, 331.