Amplitude calibration of Galactic plane interferometric observations with GMRT in absence of automatic system temperature measurement

BY SUBHASHIS ROY

Abstract

In this technical report, we describe two methods namely (i) Traditional method and (ii) with AGC off, which could be used to calibrate observations near Galactic plane at metre wavelengths.

1 Introduction

Amplitude calibration in radio interferometry is normally performed by observing a standard calibrator with known flux densities and spectrum. The observed visibility cross-correlation amplitudes are then compared with a secondary calibrator chosen close to the source of interest (target source) in the sky plane. The ratio of the two cross-correlation amplitudes then yields the flux density of the secondary. As the secondary calibrator is observed at regular intervals to remove the phase changes introduced by ionosphere to the incident Electromagnetic (EM) waves, these observations are also used to calibrate any change in antenna based amplitude gains. However, the above procedure holds good when the effective instrumental properties do not change from observations of the calibrators to the target sources. However, the effective temperature of the antennas increase drastically (~ 10) near the Galactic plane at metre wavelengths (this is caused by high antenna temperature due to large amount of radiation from the Galactic plane) and this could change the output power and the operating point of the amplifiers, thereby significantly changing the amplitude gains of the antennas.

This problem is normally circumvented by using automatic gain control (AGC) which is a negative feedback loop at the output of each antennas, and these keep the amplitude gains of the antennas to be inversely proportional to the output power. Then the output power is directly proportional to the system temperature (Tsys), which is defined to be a combination of antenna temperature and the effective temperature of the electronics system from antenna to correlator. Since visibility cross-correlation coefficients depend on the amplitude gains of the antennas, with AGCs working, the measured visibility amplitudes are no longer just proportional to the source flux densities, but also inversely proportional to the system temperature. Therefore, in a standard interferometer, Tsys is measured, and the software is implemented in a way which keeps the visibility data to remain unaffected with changes in Tsys. However, system temperature is not yet measured automatically at GMRT. Therefore, measuring flux densities of sources near the Galactic plane at metre wavelengths require decoupling the system temperature from the measured visibility amplitudes, and in this technical report we discuss on ways to achieve this.

2 Calibration techniques and Discussions

2.1 Traditional method

In the traditional method of observation, the AGCs are kept on during standard observation, and we discuss on methods of correcting it first.

Following the standard formulas on source visibilities (e.g., NRAO lecture series, Chap. 5) we can express the source visibilities $[(V_{ij})_S]$ (where V_{ij} which is formed from antennas i and j) as,

$(V_{ij})_S = \frac{S_{ij} \times g_i \times g_j}{(T_{sys})_S}$,

where S_{ij} is the source (S) flux density as measured by the antenna pair i,j. Antenna gain being inversely proportional to Tsys, we have expressed the actual gain as a product of a variable (g_i) independent of Tsys, and another part inverse of Tsys, i.e.,

amplitude gain of an antenna (i) $= \sqrt{\frac{g_i^2}{(\mathrm{Tsys})_S}}$.

Similarly, for the secondary calibrator (C),

$(V_{ij})_C = \frac{C \times g_i \times g_j}{(T_{sys})_C}$

(calibrator being unresolved, its flux density is independent of baseline length). Therefore, we can easily derive from above,

$S_{ij} = C \times \frac{(V_{ij})_S \times (T_{sys})_S}{(V_{ij})_C \times (T_{sys})_C}$.

If a standard calibrator (C*) is observed, C can be measured in the same way as above. Note that compared to the standard formulas given in Interferometry books, the above requires multiplying the source visibility by the ratio of effective system temperatures among calibrators and target sources. The ratio of system temperatures can be measured from total power observations of these sources after switching off the AGCs. If this ratio is the same for all antennas, then the final map can be multiplied by this correction factor. Otherwise, the Aips task VBCAL should be used to multiply the antenna based cross-correlation amplitudes by user supplied gains for each antennas in the final Single source 'uv' data files.

2.1.1 Shortcomings of the traditional technique

The shortcomings of this method are the following:

(i) Measuring Tsys requires extra observing and setup time. The typical timescale for it is about 30 minutes.

(ii) Since the time involved in estimating this ratio is significant, it cannot be done often, which leads to neglecting the variation of Tsys with time. Amplitude self-calibration technique can help to correct for small changes in the system gains with time. However, any large change in system amplitude gains degrade the source initial maps to an extent such that the target source gets improperly modelled and amplitude self-calibration may not even work.

(iii) In the above, the AGCs are modelled such that the output power remains constant despite changes in Tsys. However, it is observed that for some antennas, the output power do change significantly with changes in input power. For imperfect AGCs, total power depends on the source being observed. Therefore, we can write,
total power $(A_i)_n = (g_i^2 \times T_{\rm sys}) \times (\frac{1}{T_{\rm sys}} \times (K_i)_n)$.
Where, the subscript 'i' refers to the antenna number, the subscript 'n' refers to the source under observation, and K_n is a constant, which varies non-linearly with Tsys and consequently changes from source to source. Consequently,
$(V_{\rm ij})_S = \frac{S_{\rm ij} \times g_i \times g_j \times \sqrt{(K_i)_S \times (K_j)_S}}{(T_{\rm sys})_S}$ and
$S_{\rm ij} = C \times \frac{(V_{\rm ij})_S \times (T_{\rm sys})_S \times \sqrt{(K_i)_C \times (K_j)_C}}{(V_{\rm ij})_C \times (T_{\rm sys})_C \times \sqrt{(K_i)_S \times (K_j)_S}}$.
The ratio of $(K_i)_C$ and $(K_i)_S$ can be determined from the ratio of total power $[(A_i)_n]$ while observing the sources and the calibrators with AGC on, and
$S_{\rm ij} = C \times \frac{(V_{\rm ij})_S \times (T_{\rm sys})_S \times \sqrt{(A_i)_C \times (A_j)_C}}{(V_{\rm ij})_C \times (T_{\rm sys})_C \times \sqrt{(A_i)_S \times (A_j)_S}}$.

(iv) Effect of imperfect AGCs could be entirely eliminated without the need to compute the above if the Cross-correlation amplitude used for finding the source properties is normalised by the total power on that source. Any change in amplitude gains which affects the total power linearly can effectively be removed by a division by the total power. However, it is shown in Roy (2002) that if the antenna efficiency varies with frequency within the observing band, the bandpass function determined from observations of a calibrator away from the Galactic plane will not be applicable for a Galactic plane object with a much highest Tsys. Moreover, radio frequency interference affects the total power of antennas more than the cross correlations. Therefore, normalising the cross-correlations by the total power is not advisable, and in the rest of this report, cross-correlation always refers to the unnormalised one.

(v) We have assumed above that the total powers and the antenna gains do not change while observing one source. However, these values do change as a function of time. Even with AGC on, the total power is observed to change by $\sim 5-10\%$ in timescales of half an hour. Amplitude gain while observing the same source could also change by a similar fraction. Therefore, typical error in amplitude calibration following this method is $\sim 10\%$.

2.2 With AGC off

We can infer from the above that amplitude calibration with the Traditional technique is a time consuming procedure when done manually with AGC on. However, if the AGCs are off, then variation of Tsys does not affect the un-normalised cross correlations. Therefore, we have investigated use of this approach during standard interferometric observations. Since AGCs are off, the total power from the antennas could increase by more than a factor of 10 while observing close to the Galactic Centre. Such an increase in total power would saturate the antenna based electronics, rendering the data useless for further analysis of source properties. Therefore, while starting the observations, the antenna based attenuators need to be adjusted such that the output power is within the tolerable limit of the system while observing the strongest source during an observing run. This is achieved by using GMRT off-line programmes used by the Pulsar group (this procedure is known as Power Equalisation at GMRT). However, keeping the AGCs off causes variation in input power at the Sampler of the correlator, which could change its correlation efficiency. Since GMRT uses a 4 bit correlator, a change in input power by a factor of 4 is not expected to change the cross-correlation efficiency and hence the amplitude by large amount. Therefore, if the source and the secondary calibrators are located in such a way in the sky that the effective system temperature variation is within a factor of 4, keeping the AGCs off may be feasible. One advantage of this approach is that as the system gains do not change with source, time variation of system gain can easily be calibrated out from regular observations of the secondary calibrator. Therefore, we have tested this method at GMRT in a controlled fashion at 610 MHz using a bandwidth of 16 MHz. While observing a standard calibrator with AGCs off and output power brought to standard values, we changed the attenuators such that the total power was reduced by a factor 4. Cross-correlation data and the total power was recorded in this mode for several minutes. Then we switched on the Extra high noise calibrators at each of the antennas (noise temperature of $\sim$ 400 K), which makes the output power almost the same before changing the attenuators. Cross-correlation data and the total power was also recorded in this mode for several minutes. During the two scan recorded, only the total power had changed, but as the target source (calibrator) did remain the same, we do not expect any significant change in cross-correlation amplitude before and after the Noise calibrators were switched on. Data analysis indeed showed that for all the antennas with power level in the records within a factor of 4 less than the recommended level, the average gain for each of these scans for these antennas remain within $\sim$5% of each other.

2.2.1 Shortcomings of observations with AGC off

(i) One of the main reason for introduction of AGCs was to keep the input power to various electronics system constant. Since the transfer function of an amplifier could change with changes in their operating point, observations with AGC off could suffer from change of amplitude gain of the antenna based electronics. This change could also be a function of Tsys. However, it appears from our test that the antenna based analogue electronics gain does not change significantly when the operating point varies by a factor of a few.
(ii) At start of observations one needs to adjust the attenuators such that the system is not saturated when observing the strongest source in that observing run. However, till the Power Equalisation is completed on the strongest source, the system power could remain high which is likely to affect the Fibre optic transmissions. In several occasions we have noticed that certain arm antennas would not respond and no communication will be possible. The easiest solution of it is to increase the attenuators much higher than their standard values at the beginning of observations, and let them get properly adjusted during Power Equalisation.

3 Conclusion:

We have highlighted the various advantages and disadvantages of using the two methods to circumvent the present scenario of not having automatic Tsys measurements. However, employing any of these methods do allow us to get data which could be calibrated withing the errors quoted above. Prefering one or the other of these methods depends on the frequency band, bandwidth employed and the type of observations being pursued.

References

Synthesis Imaging in Radio Astronomy II, ASP Conf. Series, Vol. 180 (NRAO lecture series).

Roy, S., 2002, BASI, 30, 637.