J2000 co-ordinates in GMRT UV FITS Files

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1 Introduction

In this note I discuss how the visibilities measured at the GMRT are associated with (u,v,w) co-ordinates (which in turn determines the co-ordinate system of maps made with this data). A good starting point for starting this discussion is the fundamental relation between the sky brightness and the visibility. The visibility on a baseline **b** while observing an extended source centered along the unit vector $\mathbf{s}_0$ is

$$\mathcal{V} = \int I(\mathbf{s} - \mathbf{s_0}) e^{-i2\pi \mathbf{b}.(\mathbf{s}-\mathbf{s_0})} d\Omega \tag{1}$$

where $I(\mathbf{s} - \mathbf{s_0})$ is the sky brightness distributionm the integration is over all directions $\mathbf{s}$ in the sky, and we have ignored the primary beam correction. Note that this is a vector relation, and is true regardless of the co-ordinate system in which we may choose to evaluate it. Conventionally one works in a right handed UVW co-ordinate system, where the baseline vector has components $[u, v, w]$. In such a system the scalar product in the exponent in eqn(1) can be written as $u(l - l_0) + v(m - m_0) + w(n - n_0)$ where (l, m, n) and (l_0, m_0, n_0) are respectively the directon cosines of the unit vectors $\mathbf{s}$ and $\mathbf{s}_0$ with respect to the UVW axes. In such a co-ordinate system, and under certain limiting conditions (i.e. either that the field of view is small, or that the baselines are all coplanar; see e.g. Thomson, Moran & Swenson (1986)) eqn(1) reduces to a two dimensional Fourier transform. This allows one to obtain the sky brightness distribution I by a simple inverse fourier transform, i.e.

$$\tilde{I}(l, m) = \int \mathcal{V}(u, v) e^{i2\pi(ul+vm)} dl\ dm \tag{2}$$

When you do this inversion, the estimate of the sky brightness that you obtain, viz. $\tilde{I}(l, m)$ is a function of the direction cosines in the chosen co-ordinate system (i.e. the ones in which the baseline **b** had co-ordinates [u,v,w]). This means that if you want your maps to be in some particular co-ordinate system (e.g. J2000 or B1950) then you have to evaluate eqn(1) in the corresponding co-ordinate system. In this chosen co-ordinate system one can then make the appropriate approximations to reduce eqn(1) to a 2D fourier transform and then invert it. An alternative, purely image plane approach, would be to evaluate $\widetilde{I}$ in some co-ordinate system and then remap this onto a (l, m) grid in the desired co-ordinate system. These two approaches are not exactly equivalent. At the GMRT the former approach is what has been implemented, and the rest of this doccument describes this implementation.

2 Co-ordinates for GMRT data

At the GMRT the raw visibilities are stored in an *LTA* (see e.g. Chengalur 2002) file. For each integration time interval the *LTA* file has one complex number for each spectral channel of each baseline. Each baseline is identified by the numbers of the two antennas of which it is composed (e.g. C00 and C12). Therefore, each visibility is indexed by 2 antenna numbers, frequency and time, and not by uvw co-ordinates. *An LTA file has no "uvw" co-ordinates stored in it.* These co-ordinates are computed only when a FITS file is generated from the raw *LTA* file. It is at this point at which one needs to make a choice of co-ordinate system. The first fits converter that was written for GMRT data (gl2fit) did not give the user a choice of which co-ordinate system to use, but instead automatically chose a co-ordinate system that is in some sense "natural". In order to understand why this co-ordinate system is "natural" we will need to delve a little bit into positional astronomy.

Discussion of astronomical co-ordinate systems in introductory astronomy classes[1] begin and end with the idea that the location of an astronomical object[2] can be speified by giving its co-ordinates with respect to an imaginary (right-ascention, declination) grid laid out on the sky. The lines of right-ascention (usually denoted by α) are aligned with the projection on the sky of the lines of longitude used to specify locations on the earth, while the lines of declination (usually denoted by δ) are alinged with the projections of the lines of latitude. The zero point of the right-ascention is the intersection of the ecliptic[3] and the celestial equator. This is easy enough to grasp, and it is sensible for most classroom discussions to stop here. However we need

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[1] such as the ones that I took as a student, or the ones that I now teach at NCRA

[2] henceforth a "star", with due apologies to those not working in stellar astronomy

[3] more precisely the intersection at which the sun moves into the northern hemisphere, the "vernal equinox"

to go a bit further. The axis about which the earth spin is not fixed but wobbles with respect to the distant stars. This is because of the torque that the moon, sun and planets exert on the spinning earth. This wobble means that (i) the celestial equator also wobbles around and (ii) the zero point of the right-ascention also shifts around. So, in order to specify the position of a given star, it is not enough to give its (α, δ) co-ordinates, one also needs to give the epoch of time at which these co-ordinates refer to, so that the co-ordinate grid to which the co-ordinates values refer to is also specified.

The wobble of the earth's axis has components on a wide range of time scales. The component with the largest amplitude results in a complete precession of the spin axis roughly every 26,000 years. On an astronomy PhD timescale, this is (hopefully) a secular drift. In positional astronomy this component is called "precession[4]". In addition to the precession, there are also shorter time scale (and smaller amplitude) components to the wobble, these are collectively called "nutation". With this background we are in a position to take our discussion of (α, δ) co-ordinates a bit further. Star catalogs generally what are called "mean positions". Suppose for example a catalog gives you the "mean position" of a star at the equinox J2000. Then, if you want to find the mean position of that star in J2005, all you have to do is to apply the secular part of the wobble, i.e. the "precession". That is "mean positions" at different equinoxes are related to one another by precession, one needn't know the details of the nutation in order to work out the transformation. On the other hand, if you are actually observing in 2005 and want to point your telescope at this star, its not enough to know its mean position. You would need to in addition account for (i) the nutation terms, (ii) abberation of light and (iii) refraction. The position obtained after making the first two corrections is called the "apparent" position and is what is used at the GMRT for antenna pointing and fringe stopping. The refraction correction is not applied because it depends on highly variable (and unknown!) atmospheric and ionospheric conditions.

But now to get back to what might be a "natural" co-ordinate system for an array, you can readily appreciate that the apparent position which is what is actually used in observations is a natural one to work with. This is what is sometimes referred to as "DATE" co-ordinates at the GMRT. The

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[4] As far as this note is concerned the precesion being referred to is "general precession",i.e. the sum of luni-solar precession and precession due to the torque from the planets

first generation FITS conversion software (gl2fit) worked in this co-ordinate system inorder to compute the (u, v, w) co-ordinates. The next generation programme (gvfits[5]) however does allow the user to choose the co-ordinate system.

This choice of co-ordinate system was retrofitted into the programme. The procedure that is used is the following. The (u, v, w) co-ordinates are computed in the apparent system as before. These are then converted to the mean co-ordinate system on the observing date by applying the inverse of the nutation matrix on that given day. The values so obtained are then converted to the mean values on the chosen output equinox by applying the appropriate precession matrix[6].

Of course all of these corrections presuppose a model for the precession and nutation. Co-ordinates generated using the older model ("FK4", Bessel-Newcomb) are prefixed with "B" eg, B1950 co-ordinates. Since 1984 the model that has been in used is the "FK5" model, co-ordinates generated using this model are prefixed with "J", eg J2000. In gvfits at the moment only the "FK5" precession and nutation model is included.

A final practical note about the implementation is that it has been done using routines from the STARLINK positional astronomly library SLA (Wallace, 1999). Routines in this library are based on a different co-ordinate system than is used at the GMRT. The SLA co-ordinate systems have one axis pointing towards the north pole, while at the GMRT we have one axis pointing towards the current location of the source. Hence to use the precession and nutation matrices given by SLA routines one has to first convert the input (u, v, w) co-ordinates to the co-ordinate system used by SLA, then apply the precession and nutation matrices, and finally transform the resulting co-ordinates back to the co-ordinate system used at the GMRT.

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[5] Largely written by C. R. Subrahmanya and V. K. Kulkarni, with some modifications, (including the generation of J2000 co-ordinates) by me

[6] This is strictly speaking incorrect. The apparent position depends on aberration, which varies across the sky and is not a co-ordinate transformation. Ideally one should have taken out the abberation before applying the nutation correction. In practice because the differential abberation correction is small compared to the highest GMRT resolution ($\sim 2''$) it is sufficient to just do the correct transformation from apparent position to mean position for the phase center

3 Practical details

The practical details are as follows. One first has to run the programme "listscan" (which should be available if you include the standard GMRT offline analysis programme directory in your path). The command takes only one argument, viz. the *LTA* file name, and is to be run as

```
% listscan myfile.lta
```

This will generate a file called `myfile.log`, a sample of which is shown in Figure 1

This file contains control parameters for the program gvfits. The particular parameter that we are concerned with here is EPOCH. By default it is set to J2000, but any other output epoch[7] can be chosen. One can also chose to have the output be in DATE co-ordinates, in this case one should set EPOCH to have a value < 0. Historically, the co-ordinates stored in *LTA* files evolved with time. Originally only the mean co-ordinates were stored, later only the apparent co-ordinates were stored, and currently both the mean and apparent co-ordinates are stored. From the version of the *LTA* file gvfits can figure out what exactly the quantity stored in the header corresponds to and makes the appropriate corrections. If however, you wish to force gvfits to regard the co-ordinates as either mean or apparent, you can change the value of COORD_TYPE parameter from DEFAULT to MEAN or APPARENT, respectively. Once the parameters have been set, you can run gvfits by typing

```
% gvfits myfile.log
```

This will generate a FITS file (whose name corresponds to the value of the FITS parameter) which you can read into AIPS.

4 References

1. "The GMRT LTA format", Chengalur, J. N., NCRA Technical Memo, M00106, Feb. 2002.
2. "Interferometry and Synthesis in Radio Astronomy", Thompson, R.A., Moran, J.M., Swenson, Jr. G.W., John Wiley & Sons, 1986.
3. "SLALIB – Positional Astronomy Library 2.4-0 Programmer's Manual", Wallace, P. T., Starlink Project, PPARC, Oct., 1999.

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[7] but restricted to "FK5", i.e. "J"

```
   *
   * Info
   *
   DATE_OBS 2003-06-09T18:30:00 / UT
   MJD_REF 52799.7708
   *
   * I/O Files
   *
   INPUT myfile.log
   FITS TEST.FITS
   PLAN myfile.lta
   *
   * Conversion Control Params
   *
   SELF 0 !write self?  (0/1)
   CLASSIC_NORM OFF !normalize by instantaneous self?  (OFF/ON)
   NORM 0 !fancy normalization type (not debugged!!)
   CAL_SCAN -1 !scanno for fancy normalization
   CLIP OFF !(OFF/ON) [unused]
   COORD_TYPE DEFAULT !LtaFile Co-ord Type (Options:  DEFAULT/APPARENT/MEAN)
   EPOCH 2000.0000 !Output Epoch (EPOCH<0.0 ==> date co-ordinates)
   IATUTC 32.0 !(IAT-UTC [seconds])
   *
   * Data Selection
   * Edit to get a subset of STOKES,SIDEBAND,CHAN or ANTENNAS
   * FOR SIDEBAND 0==>USB, 1==>LSB
   * Delete or comment out (with '*') unwanted scans
   *
   STOKES RR LL
   SIDEBAND 0
   CHAN 0:127:1
   ANTENNAS C00 C01 C02 C03 C04 C05 C06 C08 C09 C10 C11 C12 C13 C14
E02 E03 E04 E05 E06 S01 S02 S03 S04 S06 W01 W02 W03 W04 W05 W06
   Scan 0 3C48 12:56:04 to 13:08:05 44 recs
   Scan 1 PERA 13:08:22 to 14:11:25 220 recs
   Scan 2 0303+472 14:11:42 to 14:25:20 38 recs
```

Figure 1: Example log file created by the programme listscan.