



**Robert C. Byrd Green Bank Telescope
NRAO Green Bank**

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GBT Astronomical Position Handling

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Abstract

This document summarises the different sorts of astronomical co-ordinates supported by the GBT, the transformations which are supported, and how the co-ordinates are stored in the GO and Antenna FITS files.

¹<http://www.gb.nrao.edu/GBT/MC/doc/dataprocs/gbtPosHandling/gbtPosHandling/gbtPosHandling.html>

1 Introduction

The GBT supports a variety of co-ordinate systems, for both input (specification of command positions) and output (reporting of indicated positions).

The fundamental equatorial co-ordinate system supported is mean FK5, J2000. Other supported equatorial co-ordinates are FK5 for the mean equator and equinox of a specified date, and true, geocentric apparent. Provision is also made for mean FK4 B1950, co-ordinates, albeit with some caveats as discussed in Section 2.1. In addition to equatorial co-ordinates galactic, local equatorial and horizontal co-ordinates systems may be used. Finally, the GBT provides support for “user-defined” co-ordinate systems, and specification of solar-system objects. Indicated positions are reported in mount (encoder) co-ordinates, mean FK5 J2000, and the co-ordinate system in which the telescope was commanded.

The purpose of this document is to provide a precise definition of how the GBT implements these co-ordinate systems, and the transformations between them. It also reviews how these are specified in the GO and antenna FITS files. Useful reference material includes:

- *Explanatory Supplement to the Astronomical Almanac*, ed. P. Kenneth Seidelmann (1992), University Science Books.
- *Spherical Astronomy*, Robin M. Green (1985), Cambridge University Press.
- *SLALIB - Positional Astronomy Library*, Patrick T. Wallace, Starlink User Note 67, Starlink Project.

The philosophy of the system is as follows:

- The observer provides a commanded position via GO. The antenna then either tracks this position, or performs offsets (for example cross-scans) relative to this position. The observer can specify this position in a variety of co-ordinate systems, some of which have precise, well defined meanings (i.e. FK5 J2000), others of which are more telescope-specific (e.g. “AZEL”).

The GO FITS file records only limited information about the commanded position. This information is only intended to be indicative of the observer’s intent, and might be used, for example to provide the reference position for an image made from the data. Precise position information is provided by the antenna FITS file

- for each scan, the antenna FITS file contains the actual position of the antenna, sampled at 10Hz throughout the scan, and provided in a variety of co-ordinate systems (including FK5 J2000). One of the main functions of the aips++ filler is to average the antenna positions over the times corresponding to the backend integrations, so that a single position can be associated with each integration in the scan.
- The antenna FITS file also contains detailed information on how various pointing and other corrections were applied.

2 Co-ordinate systems and transformations

The flow of transformations from input co-ordinates to servo demands, and vice versa, is shown in Figure 1 (after that of Sun/67). Co-ordinates which are accessible to the observer (either as inputs to the system, or as reported in the Antenna FITS file) have bold labels. Starting at the top, and working down, the possibilities are as follows:

GALATIC IAU 1958 galactic co-ordinates as described by Blaauw *et al.*, 1960, *Mon.Not.R.astr.Soc.*, **121**, 123. These can be converted to mean FK5 J2000 by a simple transformation, e.g. as provided by SLA_GALEQ.

JMEAN Equatorial co-ordinates with respect to the mean equator and equinox of a specified Julian epoch, in the FK5 system. These are related to mean FK5 2000 co-ordinates by allowing for luni-solar precession, as implemented for example by SLA_PRECES.

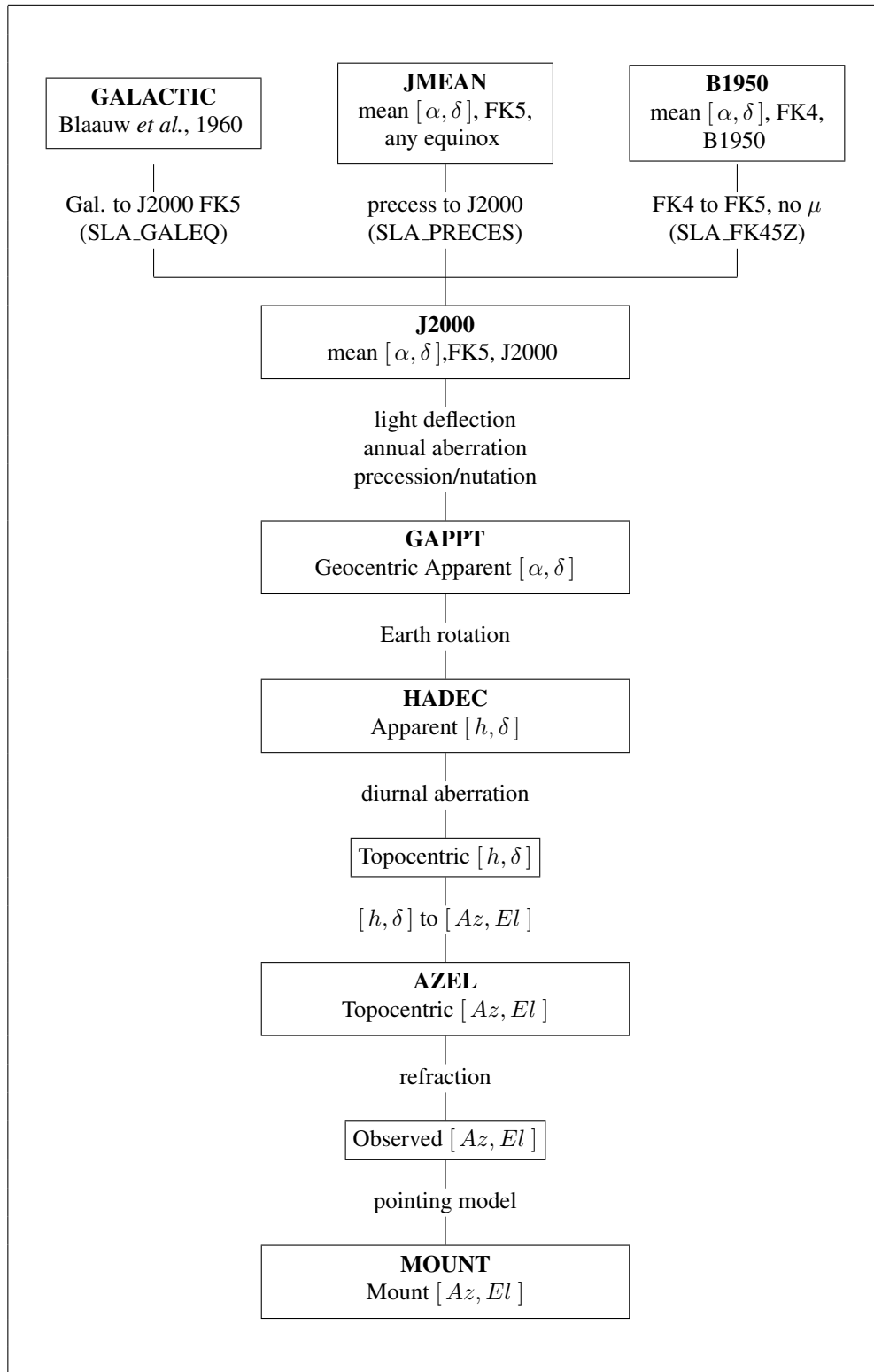


Figure 1: Relationship Between GBT co-ordinate systems (after Sun/67, Figure 1.)

B1950 Equatorial co-ordinates with respect to the mean equator and equinox of B1950, in the FK4 system. The rigorous transformation of FK4 B1950 co-ordinates to FK5 J2000 is a complex process, the GBT implementation is discussed in more detail in Section 2.1 below.

J2000 These are mean equatorial co-ordinates with respect to the mean equator and equinox of J2000, in the FK5 system. Strictly speaking, these are barycentric positions, a correction for annual parallax is required to convert to geocentric mean place. This correction is $< 1''$, and is relevant only for the nearest stars; in the GBT implementation parallax is currently always assumed to be zero, and so the **J2000** co-ordinates are effectively treated as geocentric.

GAPPT Geocentric apparent co-ordinates referred to the true equator and equinox of the start of the observation. Conversion from **J2000** to **GAPPT** requires allowing for light deflection, annual (stellar) aberration and the combined effects of precession/nutation from J2000.0 to the date of observation.

HADEC apparent $[h, \delta]$ calculated from geocentric apparent $[\alpha, \delta]$ by allowing for earth rotation via the local apparent sidereal time for the start of the observation. This input system is unlikely to be heavily used (if at all?)

Apparent $[h, \delta]$ is converted to topocentric $[h, \delta]$ on the way to topocentric $[Az, El]$ by correcting for the effects of diurnal aberration.

AZEL Topocentric azimuth and elevation. A horizontal co-ordinate system in which azimuth runs from 0° - 360° , with North at 0° , and East at 90° degrees. Again this co-ordinate system is unlikely to be used apart from for engineering purposes.

The conversion from topocentric $[h, \delta]$ to $[Az, El]$ requires the geodetic latitude of the antenna, corrected for polar motion.

MOUNT Mount $[Az, El]$ generated from topocentric $[Az, El]$ via the refraction correction and application of the pointing model. The details of this process are described elsewhere. The observer is not offered mount $[Az, El]$ as in input co-ordinate system (the *CableWrap* mode is available to engineers). Indicated mount $[Az, El]$ values are stored in the Antenna FITS files but these should not normally be used by the observer.

In addition to the above, two other input mechanisms not shown on Figure 1 are available:

USER A co-ordinate system in which the user specifies the location of a spherical co-ordinate system pole and prime meridian in J2000 co-ordinates, and optionally the first and second derivatives of these locations.

SOLAR SYSTEM Finally, the user may specify a named solar system object, and GO will automatically calculate the appropriate pole and prime meridian values and rates to centre the co-ordinate system on the (moving) solar-system object.

These will be described in more detail at a later date.

2.1 Space motion and FK4 to FK5 conversion

Space motion refers to the movement of a stellar object with respect to the fixed background. It is traditionally divided into proper motion, given as components in right ascension and declination, and radial velocity, which occurs along the line of sight.

For the vast majority of objects, the effects of proper motion are small ($< 1''$ per year), and are not usually known. The GBT has made the decision not to support these corrections. Therefore, in the (rare) case where the observer feels it important to allow for them (or for annual parallax) they should perform all of the initial co-ordinate transformations themselves, and provide adjusted input co-ordinates as true geocentric apparent co-ordinates.

Since FK4 is a non-inertial reference frame, objects (such as quasars and radio galaxies) will have a non-zero fictitious proper motion of about 0.5 per century. The correct conversion from FK4 to FK5 therefore requires

knowledge of the epoch of observation used to derive the position. In addition, star positions in the FK4 system are part-corrected for annual aberration, and embody the so-called E-terms of aberration (see Sun/67 for an excellent discussion of these effects).

The GBT conversion from FK4 B1950 to FK5 J2000 assumes inertially zero proper motion, and zero parallax and radial velocity, as performed by SLA_FK45Z, and assumes an epoch of the original observation of B1950. This conversion will therefore take care of the effects of 50 years of precession, which is the bulk of the change, but may have residual errors at the 1" level. Again, those who require the utmost precision should supply correct J2000 or GAPPT values.

2.2 Disabling co-ordinate corrections

The Antenna Manager has four type of corrections which may be enabled or disabled: polar motion, diurnal aberration, refraction and the pointing model. For all normal observations, all of these should be enabled. The state of these corrections is not recorded in the GO FITS file; however this information is recorded in the antenna FITS file, and will be used in the process of calculating derived telescope positions from encoder co-ordinates and vice versa.

If any of these co-ordinate corrections have been disabled, the celestial co-ordinate values recorded in the antenna FITS file will not in general be correct.

3 GO Input Coordinate Systems

As noted, a variety of input co-ordinate systems are available through GO. Not all of these are supported in Version 1.1 of the GO FITS file. The mapping between the labels in Figure 1 and the GO Main Screen pull-down menu is as follows (this should be checked):

GALACTIC Coordinate mode set to Galactic

J2000 Coordinate mode set to J2000

B1950 Coordinate mode set to B1950

JMEAN Coordinate mode set to RaDecOfDate (does this default the epoch to the current date? I can't find an EPOCH entry field anywhere).

GAPPT Coordinate mode set to ApparentRaDec

HADEC Coordinate mode set to HaDec

AZEL Coordinate mode set to AzEl

USER Not sure of the complete specification in GO

SOLAR SYSTEM New Origin set to planet name.

3.1 Representation in the GO FITS file

The above co-ordinate systems will be represented in the GO FITS file as follows:

The keyword COORDSYS will be used to define the type of co-ordinate system in use. The possible values in FITS version 1.1. are "GALACTIC", "RADEC", "HADEC", "AZEL", or "OTHER". OTHER will be used for any situation where the precise specification of the co-ordinate system has not yet been decided; for FITS versions 1.1 this includes user defined co-ordinates and solar system objects. Later versions of the FITS definition may include a representation of these co-ordinates, in which case a new value will be provided for COORDSYS.

For COORDSYS = “RADEC”, the standard (WCS) keyword RADESYS (note missing “C”) will be used to define the specific type of system in use.

Note that the standard FITS keyword EQUINOX is used to provide the epoch (i.e. instant of time) of the mean equator and equinox. Prior to version 1 of the FITS standard, the keyword EPOCH was used for this quantity; it is illegal to use the keyword EPOCH in new FITS files. For GAPPT, WCS paper III recommends use of the start time of the observation (via DATE-OBS or MJD-OBS) to provide the epoch of the equator and equinox.

The actual co-ordinate value used will be provided by the appropriate (long, lat) pair, depending on the value of COORDSYS.

The required FITS keywords for each of the supported input co-ordinate systems is summarised in table 1 below:

co-ordinate system	COORDSYS	RADESYS	EQUINOX	major axis keyword	minor axis keyword
GALACTIC	GALACTIC	absent	absent	GLON	GLAT
J2000	RADEC	FK5	2000.0	RA	DEC
B1950	RADEC	FK4	1950.0	RA	DEC
JMEAN	RADEC	FK5	nnnn.n	RA	DEC
GAPPT	RADEC	GAPPT	absent (1)	RA	DEC
HADEC	HADEC	absent	absent (1)	HA	DEC
AZEL	AZEL	absent	absent	AZ	EL
USER	OTHER (2)	absent	absent	absent	absent
SOLAR SYSTEM	OTHER (2)	absent	absent	absent	absent

(1) As proposed by WCS paper III, for these co-ordinate systems, the epoch of the equator and equinox will be taken as the time of the start of the observation, given by the standard FITS header keyword DATE-OBS.

(2) In the GO FITS file version 1.1 definition, we have not agreed FITS keyword mechanisms to stored information about user defined co-ordinates, not for requested to track solar system object simply by specifying name (with co-ordinates derived from the ephemerides). Accordingly, we use the COORDSYS value of OTHER to indicate this information is not available.

4 Antenna Indicated Positions

Antenna indicated positions are those derived from the values read back from the encoders. We will provide three versions of each position; MOUNT coordinates, J2000, and the co-ordinate system in which the antenna was commanded. MOUNT co-ordinates are those returned by the servo computer; they are currently the same as raw encoder units apart from the addition of the encoder offsets (which will also be stored in the antenna FITS file).

In principle any one of these three co-ordinate systems could be generated from any other off-line, given the complete description of the pointing model, the weather conditions at the time of the observation, and so on. However, to do this correctly would require not only knowing the parameters of the pointing model, but the full definition of the terms, the order in which they were applied, and so on. In practice, it will be simpler and less error prone for the antenna manager to provide all three systems (they are being calculated anyway); observers can always reproduce the calculations if they wish.

4.1 Upstream co-ordinate conversions and metrology corrections

The process of going from commanded to mount co-ordinates is commonly referred to as the “downstream” pointing transformation. The reverse process, of going from mount to commanded (or equatorial) co-ordinates is referred to as the “upstream” pointing transformation.

Currently only traditional methods are being used to determine the pointing model for the telescope. Therefore, processing the main axis encoder values through the upstream pointing transformation is the best we can do. In the

future, the laser rangefinders (or other metrology systems) may be used to provide additional pointing corrections, either in real-time for use by the servo, or after the fact to be applied at the data reduction stage. Methods for incorporating these corrections into the upstream pointing flow, and representing the data in an appropriate FITS file, is deferred to a later date.

One point should be made explicitly here. We have not yet fully thought through how offset positions for multi-beam receivers will be handled, nor fully de-coupled pointing and focus tracking effects. At this stage, the positions recorded in the antenna FITS files are therefore implicitly those for the receiver beam (prime or gregorian focus) that was used to derive the antenna pointing model in use, assumed to be at the nominal focus.

As noted, it is possible (usually for engineering purposes) to disable certain terms in the downstream pointing transformation. *In this case, the upstream transformation will not be correct, and the reported positions in J2000 and the commanded co-ordinate system will not be strictly correct.*

4.2 Representation in the FITS file

The three sets of co-ordinate pairs will be provided in a binary table, along with the time stamp and ancillary information (secondary optics positions for example) as described in the antenna FITS file document. The column names are: RAJ2000, DECJ2000, MOUNT_AZ, MOUNT_EL, MAJOR and MINOR. The first four represent J2000 and mount co-ordinates as described above. The last pair provide the antenna longitude and latitude in the commanded co-ordinate system.

Analogous to the description of the commanded co-ordinate system contained in the GO FITS file, the antenna FITS file will use the keywords INDICSYS, RADESYS, EQUINOX and DATE-OBS to fully describe the type of co-ordinate system being represented by the MAJOR, MINOR columns. The values of INDICSYS, RADESYS and EQUINOX will be provided as follows:

command co-ord system	INDICSYS	RADESYS	EQUINOX
GALACTIC	GALACTIC	absent	absent
J2000	RADEC	FK5	2000.0
B1950	RADEC	FK4	1950.0
JMEAN	RADEC	FK5	nnnn.n
GAPPT	RADEC	GAPPT	absent (Note 1)
HADEC	HADEC	absent	absent
AZEL	AZEL	absent	absent
USER	OTHER	absent	absent (Note 2)
SOLAR SYSTEM	OTHER	absent	absent (Note 2)

Note 1: For geocentric apparent co-ordinates, the indicated values provided are referred to the epoch of of the equator and equinox of the start of the observation, as given by DATE-OBS, not for the time for which the position is reported (the difference is negligible).

Note 2: We have not yet decided how to represent the USER and SOLAR SYSTEM co-ordinate systems in the FITS file. In the case of these, the MAJOR and MINOR columns in the table will simply be filled with zeroes.

DATE-OBS is the standard FITS keyword which is included in all GBT FITS files to indicate the start of the observation.

5 Acknowledgements

I'd like to acknowledge Patrick Wallace for helpful advice and comments, and for allowing me permission to base Figure 1 of this document on that in Sun/67. Any errors introduced in the modified version of the figure, or the description of it are, of course, my own.