

Library

A Protocol for Pointing Synchronization Messages

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Abstract

This document specifies the network protocol for the GBT precision pointing systems, specifically the portion of the protocol concerned with the transmission of synchronization messages from the GBT antenna control computer to the precision pointing systems. Requests, discussion and suggestions for improvements may be sent to jbrandt@nrao.edu.

1 Introduction

This document is a specification of the GBT precision pointing network protocol. The protocol consists of at least two major parts. The first part is usually referred to as commanded track, which is defined as the refracted wavefront just above the telescope. *“Commanded track is the angular position as a function of time of the normal to the telescopes plane wavefront with respect to a local, ground-based coordinate system.”*¹

However this is only one piece of the information required by the laser systems. Additional information about the current status of the telescope, and pointing model are also required in order to aid the laser systems in acquiring their targets. For purposes of discussion, I will call the messages containing both commanded track and auxiliary information “pointing synchronization messages”.

The second part of the protocol is concerned with transporting the precision pointing corrections to the GBT antenna control computer, to be used to compensate for the detected errors.

This memo will only document the format of the pointing synchronization messages. The correction feedback message format will be documented at a later date.

2 Pointing Commands

*“He knew the things that were and the things that would be and the things that had been before.”*²

This section describes a portion of the internal operation of the Antenna Manager, with respect to command generation. Commands are generated at 100ms intervals. User input

¹From GBT memos 103 and 122

²Homer, c. 700B.C.

consists of a set of piecewise parabolic trajectories for each axis of the currently selected coordinate system. Optionally offset trajectories may also be specified relative to the tracking trajectory. These inputs are interpolated for a given UTC command time t .

In some circumstances $track(t)$ may be a approximately constant. For example, the user may be observing a quasar which is essentially fixed to the celestial coordinate system (e.g., right ascension and declination of a mean catalog date). In other cases the user may choose to map a source fixed to the celestial coordinates and thus $track(t)$ will substantially change in time. In both of these examples $offset(t)$ is set to zero. An example of a constant offset might be when a user has $track(t)$ set to a cardinal position in some source (e.g., the center of a galaxy) and uses offset to measure an object displaced from the center. Moreover, there may be instances where it is desirable to have both $track$ and $offset$ be functions of time. Mapping the Moon is one example. The $track(t)$ coordinates would be set to the center of the Moon which is not fixed to the celestial coordinates, while $offset(t)$ could be used to specify the mapping scans across the Moon relative to the center.

Stated algebraically:

$$skyCmd_{\alpha,\delta}(t) \equiv track_{\alpha,\delta}(t) + offset_{\alpha,\delta}(t) \quad (1)$$

The local apparent sidereal time is then calculated, using methods described in *The Astronomical Almanac*, section B4-B7. Compensation for the drift between the UT1 and UTC time systems is read from a IERS Bulletin A data file.

Coordinate transformations are then calculated by use of the Starlink library, to convert $skyCmd_{\alpha,\delta}$ into topocentric apparent Az/El commands. Let Ω represent this transformation.

$$apparentCmd_{az,el}(t) = \Omega(skyCmd_{\alpha,\delta}, t_{LAST}) \quad (2)$$

The quantity $apparentCmd$ is then compensated for atmospheric refraction using the Starlink library `slaRefro()` function, which calculates the change in zenith distance at a given elevation. Weather data required for this calculation is usually obtained from the weather station, or may be manually entered. Refraction only affects the elevation component.

$$observedCmd_{az}(t) = apparentCmd_{az}(t) \quad (3)$$

$$observedCmd_{el}(t) = apparentCmd_{el}(t) - slaRefro(apparentCmd_{el}(t)) \quad (4)$$

For a given point source, $observedCmd_{az,el}$ would position a perfect telescope exactly on source.³

³This assumes refraction effects are faithfully modeled.

Local corrections may be entered by a user to locally redefine the azimuth and elevation zero points, based on reference observations. These small offsets are termed *localoffsets*, since they are valid only for a localized region of the sky. The azimuth correction is expressed as two terms, *localoffset_{az1}* and *localoffset_{az2}*. Localoffsets are considered to be constants, i.e., not a function of time. Therefore the net refracted commands specified by the user are:

$$AzCmdPos(t) = observedCmd_{az}(t) + localoffset_{az1} + \frac{localoffset_{az2}}{\cos(observedCmd_{el}(t))} \quad (5)$$

$$ElCmdPos(t) = observedCmd_{el}(t) + localoffset_{el} \quad (6)$$

Velocity and Acceleration are derived by evaluation of position commands at various time intervals (Note times in equations 7 through 12 are in UTC seconds):

$$AzCmdVel(t) = \frac{AzCmdPos(t + .1_{sec}) - AzCmdPos(t)}{0.1_{sec}} \quad (7)$$

$$ElCmdVel(t) = \frac{ElCmdPos(t + .1_{sec}) - ElCmdPos(t)}{0.1_{sec}} \quad (8)$$

$$AzCmdAcl(t) = \frac{AzCmdVel(t + .1_{sec}) - AzCmdVel(t)}{0.1_{sec}} \quad (9)$$

$$ElCmdAcl(t) = \frac{ElCmdVel(t + .1_{sec}) - ElCmdVel(t)}{0.1_{sec}} \quad (10)$$

Equations 9 and 10 above can also be written as:

$$AzCmdAcl(t) = \frac{AzCmdPos(t + .2_{sec}) - 2AzCmdPos(t + .1_{sec}) + AzCmdPos(t)}{0.01_{sec}} \quad (11)$$

$$ElCmdAcl(t) = \frac{ElCmdPos(t + .2_{sec}) - 2ElCmdPos(t + .1_{sec}) + ElCmdPos(t)}{0.01_{sec}} \quad (12)$$

3 Pointing Corrections

Pointing corrections consist of two major components. The first are corrections calculated by the traditional model for a given azimuth and elevation angle, which represents the repeatable variations in pointing error. The second component is a dynamic correction, which represents feedback from the precise pointing systems.

The GBT traditional pointing model, documented in GBT memos 75 and 173 is used to generate $\Delta azimuth \cos(Elevation)$ and $\Delta elevation$ corrections. (In notation of GBT memo 173, *daz* and *del* represent these quantities.) These computed deltas are denoted as *TMC_{az}* (traditional model azimuth correction) and *TMC_{el}* (traditional model elevation correction), in the equations below.

$$TMC_{az}(t) = \frac{daz(t)}{\cos(ElCmdPos(t))} \quad (13)$$

$$TMC_{el}(t) = del(t) \quad (14)$$

In phase III, additional corrections will be incorporated at this stage. These corrections are denoted as $DynCor_{az}$ and $DynCor_{el}$ in the equations below. Therefore the actual commands sent to the main axis servo system are defined by:

$$servoCmd_{az}(t) = AzCmdPos(t) + TMCor_{az}(t) + DynCor_{az}(t) \quad (15)$$

$$servoCmd_{el}(t) = ElCmdPos(t) + TMCor_{el}(t) + DynCor_{el}(t) \quad (16)$$

3.1 Message Timing

The GBT antenna control computer will send synchronization messages at a 2Hz rate. Encoder readings (time tagged at time t_1) will be within 100ms of real-time⁴ (e.g. the time the message is transmitted from the antenna control computer). Command (time t_2) will typically be 100ms ahead of real-time. Command time t_3 is currently defined as:

$$t_3 = t_2 + 0.5_{sec} \quad (17)$$

As an example for a synchronization message prepared at 12:01:00.00, time t_1 would be 12:00:59.90, and t_2 would be 12:01:00.10. The second set of commands at t_3 therefore would be 12:01:00.60.

4 Pointing Synchronization Data Elements

Pointing synchronization messages contain the data members listed in table 1.

5 Impulsive Trajectory Filtering

The GBT antenna control system will incorporate a mechanism for limiting impulsive acceleration. When a new position is desired, a trajectory that matches initial and final positions and velocities, with shaped acceleration profiles is computed. For a short period while slewing into a new position, the terms $observedCmd_{az}(t)$ and $observedCmd_{el}(t)$ in equations 5 and 6 are replaced with the shaped trajectory. During this period the status flag TrajPPActive (see table 7) is asserted. The point here is to highlight the fact that position changes will be fairly smooth continuous trajectories.

6 Azimuth-Elevation Coordinate System

The Azimuth-Elevation systems are defined in GBT Drawing C350102M081 rev B, on sheet 1. Directions of the X,Y,Z axes are: the positive Y axis points toward Astronomical North; the positive Z axis points toward the zenith; and the positive X axis points East and is normal

⁴It is most likely that t_1 will be within 20ms of real-time most of the time, however, 100ms is used to indicate an expected maximum. Encoders are sampled every 20ms, with the time of sample being accurate to a fraction of a millisecond. The reason for the ambiguity here is simply which 20ms sample is being provided.

Table 1: Pointing Synchronization Message Data Fields

Abbreviation	Description	Defined in Section
t_1	Time of encoder measurement	3.1, 6.5
$AzIPos(t_1)$	Azimuth encoder at t_1	6.1
$ElIPos(t_1)$	Elevation encoder at t_1	6.2
t_2	Command base time reference	3.1, 6.5
$TMCr_{az}(t_2)$	Traditional model azimuth correction at t_2	3 eqn 13
$TMCr_{el}(t_2)$	Traditional model elevation correction at t_2	3 eqn 14
$DyCr_{az}(t_2)$	Dynamic azimuth correction at t_2	3
$DyCr_{el}(t_2)$	Dynamic elevation correction at t_2	3
$AzCmdPos(t_2)$	Azimuth position command at t_2	2 eqn 5
$AzCmdVel(t_2)$	Azimuth velocity command at t_2	2 eqn 7
$AzCmdAcl(t_2)$	Azimuth acceleration command at t_2	2 eqn 9
$ElCmdPos(t_2)$	Elevation position command at t_2	2 eqn 6
$ElCmdVel(t_2)$	Elevation velocity command at t_2	2 eqn 8
$ElCmdAcl(t_2)$	Elevation acceleration command at t_2	2 eqn 10
$TMCr_{az}(t_3)$	Traditional model azimuth correction at t_3	3 eqn 13
$TMCr_{el}(t_3)$	Traditional model elevation correction at t_3	3 eqn 14
$DyCr_{az}(t_3)$	Dynamic azimuth correction at t_3	3
$DyCr_{el}(t_3)$	Dynamic elevation correction at t_3	3
$AzCmdPos(t_3)$	Azimuth position command at t_3	2 eqn 5
$AzCmdVel(t_3)$	Azimuth velocity command at t_3	2 eqn 7
$AzCmdAcl(t_3)$	Azimuth acceleration command at t_3	2 eqn 9
$ElCmdPos(t_3)$	Elevation position command at t_3	2 eqn 6
$ElCmdVel(t_3)$	Elevation velocity command at t_3	2 eqn 8
$ElCmdAcl(t_3)$	Elevation acceleration command at t_3	2 eqn 10

to the YZ-plane. Azimuth angles are measured from the Y-axis (Astronomical North) with positive values towards the East⁵.

$$Azimuth = \frac{\pi}{2} - \arctan\left(\frac{Y}{X}\right) \quad (18)$$

Elevation angles are measured from the XY plane, with increasing values towards the zenith.

$$Elevation = \arctan\left(\frac{Z}{\sqrt{X^2 + Y^2}}\right) \quad (19)$$

6.1 Azimuth Position Reference

Azimuth position angles are measured in radians, in the approximate range of $-\frac{\pi}{2}$ to $\frac{5\pi}{2}$ (-90 to 450 degrees). The extended range is used to indicate the state of the azimuth cable

⁵It should be noted that the astronomy community often uses a zero South convention, also many of the GBT construction drawings use a zero South convention. Do not be confused, in this document a zero North convention is used.

wrap. The azimuth position zero point is defined by the encoder zero settings, (i.e. these are basically raw servo encoder readings, unaffected by traditional model, refraction etc.).

6.2 Elevation Position Reference

Elevation position angles are measured in radians in the approximate range of 0.08 to 1.66 (5 to 95 degrees). The elevation position zero point is defined by the encoder zero settings, (i.e. these are basically raw servo encoder readings, unaffected by traditional model, refraction etc.).

6.3 Azimuth Position Command Reference

Azimuth beam position angles are measured in radians, in the range of $-\frac{\pi}{2}$ to $\frac{5\pi}{2}$ (-90 to 450 degrees). The azimuth commands are derived from the celestial coordinates of a radio source through corrections for earth rotation, precession, aberration, nutation, and atmospheric refraction. This assumes that the focus tracking system is compensating for feedarm deflection, and therefore the pointing effects due to feed misalignment are zero.

6.4 Elevation Position Command Reference

Elevation beam position angles are measured in radians, in the range of 0.08 to 1.66 (5 to 95 degrees). The elevation commands are derived from the celestial coordinates of a radio source through corrections for earth rotation, precession, aberration, nutation, and atmospheric refraction. This assumes that the focus tracking system is compensating for feedarm deflection, and therefore the pointing effects due to feed misalignment are zero.

6.5 Time Reference

Time is specified by integer modified Julian day (MJD) number, and seconds since UTC midnight. The MJD field is the integral number of days since the Julian epoch of 2400000.5. The seconds field is the number of seconds since 0:00:00 UTC, in double precision floating point format. All times in this document are referenced to UTC. As a point of terminology, monitor and control refers to the (MJD,UTC seconds) data type as a `TimeStamp`.

7 Status Information

Pointing synchronization messages also contain bit-encoded status information, as shown in table 2. Status bits are defined in the sense that a non-zero value indicates an asserted condition. For example in table 2, `EStop=0x8000` would indicate that an emergency stop has been activated.

A Message Protocol Data Structures

This appendix describes the format of the synchronization message packets. This section is directed towards the implementation details, rather than the data element definitions.

Table 2: Status Fields

Abbreviation	Description	Value (Hex)
TrajPPActive	Trajectory Preprocessor Active	0x10000
EStop	Emergency stop active	0x8000
FTEna	Focus tracking algorithm active	0x4000
GregOp	Gregorian optics deployed	0x2000
PFOp	Prime focus optics deployed	0x1000
TREna	Turret axis enabled	0x800
Z1Ena	Z1 Subreflector axis enabled	0x400
X2Ena	X2 Subreflector axis enabled	0x200
X1Ena	X1 Subreflector axis enabled	0x100
Y3Ena	Y3 Subreflector axis enabled	0x80
Y2Ena	Y2 Subreflector axis enabled	0x40
Y1Ena	Y1 Subreflector axis enabled	0x20
PxEna	Prime focus X (translation) axis enabled	0x10
PpEna	Prime focus polarization axis enabled	0x8
PpEna	Prime focus axial focus axis enabled	0x4
ElEna	Elevation axis enabled	0x2
AzEna	Azimuth axis enabled	0x1

The synchronization message protocol use the the GBT monitor system as a transport. Each data sample has the format outlined below, as a Synchronization Message record. The Monitor library provides an encapsulated interface for this protocol, and is currently available on Solaris/sparc, Linux/Intel, Windows 95/98, and Windows NT.

The header file for the Synchronization Messages is available in the file:

`/gbt1/gbt/src/devices/antenna/GBT/Access/Antenna/PointingSynchronization.h`

A.1 Data Structures

The following sections describe in C language the record format of the GBT Synchronization messages.

```

struct PVA {
    double position;
    double velocity;
    double acceleration;
};

struct AzElCommand {
    double TmCrAz, TmCrEl;
    double DyCrAz, DyCrEl;
    PVA AzCommand, ElCommand;
};

struct TimeStamp {
    int MJD;
    int flags;
    double seconds;
};

struct SynchronizationMessage
{
    TimeStamp T1;
    double AzIPos;
    double ElIPos;

    TimeStamp T2;
    AzElCommand Position_Command_at_t2;
    AzElCommand Position_Command_at_t3;

    long Axis_Status_Bits; // (See Table 2)
};

```