Doppler Tracking and the GBT Monitor and Control System

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I. Introduction

This report describes the algorithms and variables that should be used to perform Doppler tracking within the Monitor and Control System (M&C) of the Green Bank Telescope (GBT). I assume the reader already knows what Doppler tracking is, why Doppler corrections are needed in setting up an observation, and why they need to be updated during an observation.

The GBT M&C system is somewhat unorthodox in that its design places most of the astronomical calculations in the user interface or in data analysis systems and excludes most of the astronomical algorithms from within the control system itself. The design forces one to rethink how to perform Doppler tracking.

I describe in §II the user input and calculations performed by a traditional control system. §III gives my understanding of how the GBT M&C system differs from traditional systems concerning Doppler tracking and how the GBT M&C system should perform Doppler tracking. In the Appendix, I have provided a list of the variables I use in this report. You may want to read GBT memo ###, which describes a proposed user interface to the GBT I.F. and Doppler-tracking system.

II. Traditional Doppler Tracking Systems

In this section, I hope to describe how a traditional control system performs Doppler tracking. Without understanding the traditional system, I think there will be little chance of understanding the system imposed by the GBT design. I am only providing an outline of the steps, and am not getting into the details of the algorithms; a complete description would be voluminous and can be found elsewhere.

Note that, since control systems typically make many assumptions or are incapable of certain possible combination of user inputs, most telescopes do not perform all these calculations or require the user to supply complete information. Traditional control systems differ in the details of how they perform Doppler tracking. Thus, what I am describing is a theoretical Doppler tracking system that encompasses most traditional telescope control systems. Every traditional control system implicitly, more than explicitly, uses these steps and inputs for performing Doppler tracking.

II.a User Specifications for a Traditional Control System

In a traditional control system, the user supplies the following set of information:

- Positions (***X,Y***) to use for Doppler calculations. The positions need not be the telescope's current position or the position at which the observations are to be made. Having the ability to specify a position other than the observed could be useful, for example, if an observer wants to as accurately as possible cancel instrumental responses for position-switched observations.
- Coordinate System (***CS***) of (***X,Y***). Some ***CS***s have in their definition a specific epoch (***EPOCH***; i.e., a date that can be converted to a Julian Date for which the coordinate system is appropriate). Some examples of ***CS***s are: J2000, B1950, Galactic, Ecliptic, Apparent RA and DEC.
- Expected velocity (***V***) of the source. ***V*** is traditionally defined as a red shift (***z***) times the speed of light (***c***).
- A standard of rest (***SoR***) in which ***V*** is appropriate. Each standard is defined by the position (X_s,Y_s) of the apex of motion, the coordinate system (CS_s) of this position, and the velocity (V_s) of some lower-level standard of rest toward the apex. Standards of rest are hierarchal (i.e., depend upon other standards) with the frame of the telescope (topocentric) as the ultimate standard upon which all others are built. The definition of a standard should include, most often implicitly, a description of the hierarchy. For example, LSR velocities are defined in terms of heliocentric and topocentric ***SoR***s.
- The definition of red shift (***RedDef***) to be employed in the calculations (examples: Radio, Optical, Relativistic).
- A time (***t***) (which includes the date) to use for the Doppler calculation. ***t*** need not be the current time or when the observations are to be made (for the same reasons (***X Y***) need not be for the observed position).
- The time system (***tsys***) that describes ***t***. Examples of ***tsys*** are: LST, UTC, EST.
- Intermediate and Rest Frequencies (***I.F.*** and ***R.F.***) for the observations.

- The channel number (***ChanNum***) of the spectrometer that is to correspond to ***I.F.***, ***R.F.***, and ***V***.
- Center-Frequency Formula (***CFF***) that describes the relationship between ***I.F.***, Local Oscillator frequency (***L.O.***), and Sky (or Center) frequency (***SkyFreq***). The ***CFF*** is derived from how the equipment in the L.O. chain has been set up. Examples and descriptions of ***CFF*** are given in GBT memo ###.
- Number of frequency phases (***NoPhases***), frequency offsets (***FreqOffs***), and phase times (***PhaseTimes***) that are to be applied during the observations usually to perform frequency switching. A flag (***TypeOff***) should specify whether the offsets are to be applied to ***L.O.***, ***R.F.***, or to ***SkyFreq***.
- A rate (***UpdateRate***) which defines how often Doppler corrections are to be recalculated and applied. The ***UpdateRate*** depends upon how each standard in the hierarchy changes with time and upon the allowable smearing of frequencies during an observation (for example, the smearing should be a fraction of the spectrometer's channel width).

II.b Calculations as Performed in a Traditional System

The following sketches out the calculations that turn the user inputs from §II.a into oscillator frequencies.

(i) ***t*** should be converted from ***tsys*** to JD, UTC, and LST since the time in these other systems might be used in subsequent calculations.

(ii) Most ***SoR***s are a hierarchy of other ***SoR***s. For each ***SoR*** in the hierarchy, the following must be performed:

(ii.a) For some ***SoR***s, one needs to use ***t*** to calculate (X_s,Y_s) and V_s.

(ii.b) Convert (***X,Y***) from ***CS*** to CS_s. Depending upon what ***CS*** and CS_s are, one may need to use ***t*** or the ***EPOCH*** of ***CS*** or CS_s in the calculation. I'll call (***X',Y'***) the value of (***X,Y***) in CS_s. Of course if ***CS*** and CS_s are the same, (***X',Y'***) and (***X,Y***) are the same.

(ii.c) Calculate the direction cosines of (X_s,Y_s) toward (***X',Y'***). Use this result to calculate the projection of V_s along (***X',Y'***).

Sum all of the projected velocities together to form ***Vsys***, the systemic velocity (i.e., motion of the telescope with respect to ***SoR***). [For a very good but slightly outdated discussion of the calculations for a few typical ***SoR***, see M.A. Gordon, "Radial-Velocity Corrections for Earth Motion," 1976, *Methods of Experimental Physics, Volume 12, Astrophysics, Part C*; ed. M.L. Meeks; (Academic Press, New York), p. 277.]

(iii) Calculate ***SkyFreq*** by using the equation specified by ***RedDef***. Typically, the input to the equations are ***R.F.***, ***V***, and the ***Vsys*** from step (ii).

Note: (a) If the ***TypeOff*** flag specifies that the user wants frequency offsets to be in units of ***R.F.*** apply the specified ***FreqOffs*** to ***R.F.*** before performing this calculation ***NoPhases*** times.
(b) If the ***TypeOff*** flag specifies that offsets are to be in units of ***SkyFreq***, calculate ***SkyFreq*** first and then apply the specified ***FreqOffs*** to the calculated ***SkyFreq NoPhases*** times.
(c) If either of these cases is true, then ***NoPhases SkyFreqs*** will result from this step.

(iv) Using the ***CFF***, calculate ***L.O.*** from ***SkyFreq***, ***ChanNum***, and ***I.F.*** If ***TypeOff*** specifies that offsets are in units of ***L.O.***, then apply the specified ***FreqOffs*** to the calculated ***L.O.*** At this stage, ***NoPhases L.O.*** values should be available.

(v) Then, set the local oscillator's frequency to the ***NoPhases*** values of ***L.O.*** calculated in (iv). Switch between the ***NoPhases*** values of ***L.O.*** using the times specified by ***PhaseTimes***.

(vi) Since oscillators do not have infinite frequency resolution, the desired ***I.F.*** and ***L.O.*** may not be what has been set. The control system should use the actual (measured) ***I.F.*** and ***L.O.***, in combination with ***ChanNum*** and the ***CFF***, to calculate the actual ***SkyFreq***. From the actual ***SkyFreq***, and from ***R.F.***, and ***Vsys***, the control system should calculate the actual ***V*** using the equation specified by ***RedDef***. The actual (measured) values of ***V***, ***SkyFreq***, ***I.F.***, and ***L.O.*** should be recorded with the data.

(vii) Every ***UpdateRate*** seconds, repeat steps (i)-(vi). Note that the projections of V_s for some ***SoR***s may not change significantly over ***UpdateRate*** seconds, so a few of the calculations in step (ii) for these slowly-changing ***SoR***s may not need to be repeated every ***UpdateRate*** seconds.

III. How the GBT M&C System can Perform Doppler Tracking

The GBT M&C system differs from the traditional control systems in that most of the astronomical calculations do not occur in the control system but in the user interface or in data analysis software. The control system accepts positions in a limited list of coordinate systems. For example, the control system accepts from the user interface only J2000 or horizon (altitude/azimuth) coordinates. The control system will only deal with the astronomical calculations for heliocentric or topocentric ***SoR***s. Thus, if an observer wants to enter coordinates in a different system or use another ***SoR***, then the calculations outlined in §II.b will be performed partly by the user interface, partly by the control system, and the rest by the data analysis system.

III.a User-Interface Responsibilities for the GBT System

Since users will at times not want to specify coordinates in J2000 or the horizon systems, or use either the heliocentric or topocentric ***SoR***s, the user interface must perform some calculations described in §II.b. The user interface must perform the following steps from §II.b.

Step (i) may need to be performed.

Step (ii) involves descending the hierarchy of ***SoR***s. The descent need not go beyond the point where either the heliocentric or topocentric ***SoR*** is encountered, since, supposedly, the control system can take over from there. All ***SoR***s will have either of these two systems in their hierarchy. If the user interface stops the loop of step (ii) when it encounters the heliocentric ***SoR***, the remaining descent of the hierarchy from heliocentric to topocentric can be performed by the control system.

The user interface must tell the control system what the results were from its part of step (ii). I'll call the information sent from the user interface to the control system $\boldsymbol{SoR}^{UI}$ and $\boldsymbol{Vsys}^{UI}$ which, respectively, informs the control system the ***SoR*** that the user interface stopped at (either heliocentric or topocentric) and the results of the user interface's partial summation of the projection of velocities.

The control system must be passed the position to use for the remaining Doppler tracking calculations. But, if ***CS*** is not in the J2000 or the horizon systems, then the user interface must convert (***X,Y***) to either the J2000 or horizon system and pass these new coordinates to the control system. I'll call $\boldsymbol{CS^{UI}}$ the information sent to the control system that tells whether it is sending J2000 or horizon coordinates and ($\boldsymbol{X^{UI}}$,$\boldsymbol{Y^{UI}}$) the converted values of (***X,Y***).

Additionally, in order for the control system to continue the calculations of §II.b, the user interface must pass to it:

R.F.	***V***	***TypeOff***	***NoPhases***	***FreqOffs***
ChanNum	***CFF***	***I.F.***	***PhaseTimes***	***UpdateRate***
t	***tsys***			

Some of these variables need not be passed if the control system can make assumptions about default values or if the control system is locked into having to choose a particular value due to hardware restrictions (e.g., I can envision cases where the hardware restricts ***NoPhases*** to be a certain value and, thus, cannot be specified by the user). At most, 16 pieces of information must pass between the user interface and the control system.

Note that the user interface should check whether or not $\boldsymbol{Vsys^{UI}}$ or ($\boldsymbol{X^{UI}}$,$\boldsymbol{Y^{UI}}$) changes significantly in ***UpdateRate*** seconds, and, if so, the user interface must supply the control system with a table of values for $\boldsymbol{Vsys^{UI}}$ and ($\boldsymbol{X^{UI}}$,$\boldsymbol{Y^{UI}}$) as a function of ***t***.

III.b Control System Responsibilities for the GBT System

The GBT M&C system, once it has received from the user interface the information described above, can then go on with the calculations described in §II.b. First, if $\boldsymbol{CS^{UI}}$ is not topocentric (i.e., it's heliocentric), then the control system must perform the remaining descent of step (ii) down the hierarchy from heliocentric to topocentric and produce a ***Vsys*** that is the summation of the calculations performed in the user interface and control system.

The control system should then proceed with steps (iii)-(v). In step (vi), the control system must read the oscillator frequencies but it is debatable whether the rest of the calculations in the step should be performed in the control system or within the data analysis software. The control system, in principle, has all the necessary information to do the calculations, but it is up to the implementors of the M&C and data analysis systems to decide.

The control system must perform its calculations every ***UpdateRate*** seconds.

III.c Data Analysis Responsibilities for the GBT System

If the control system doesn't do the calculations in step (vi), then data analysis must. Always, it is up to the data analysis system to record the results of these calculations with the data.

IV. Conclusions

I think I have showed that the GBT M&C system can handle Doppler tracking successfully even though it employs a design different from other more-traditional telescope systems.

If the reader notices any errors or oversights in this document, please inform the author or someone from the M&C group.

Appendix: List of Symbols

The following are the variables and symbols, with brief definitions, that I have used throughout this paper.

c Speed of light.

ChanNum Channel number at which the user is specifying ***V***, ***I.F.***, and ***R.F.***

CFF Center frequency formula.

CS Name of coordinate system.

CS_s	Coordinate system of apex of motion of standard of rest.
CS^{UI}	The coordinate system for positions passed from the user interface to the control system. Can be either J2000 or horizon.
EPOCH	Epoch of ***CS***, if needed.
FreqOffs	The frequency offsets to use for frequency switching.
I.F.	Intermediate frequency.
L.O.	Local oscillator frequency.
NoPhases	Number of phases for frequency switching.
PhaseTimes	The time spent on each phase of frequency switching.
RedDef	The definition of red shift that is to be used.
R.F.	Rest Frequency.
SkyFreq	Sky frequency.
SoR	Standard of Rest.
SoR^{UI}	The standard of rest at which the user interface stops its Doppler tracking calculations. Either heliocentric or topocentric.
t	Time for which the calculation is to be performed.
tsys	The time system in which times are specified.
TypeOff	Flag describing what frequency to apply the frequency offsets for frequency switching.
UpdateRate	The rate at which Doppler corrections should be updated.
V	Velocity with respect to the desired standard of rest that the user wants to appear at a certain channel in the spectrometer.
V_s	Velocity of standard of rest with respect to some other standard of rest that is lower in the hierarchy of standards.

Vsys	The projection of velocity of the standard of rest along the line of sight to (***X,Y***).
Vsys^{UI}	The partial value of ***Vsys*** calculated by the user interface and passed to the control system.
(***X,Y***)	Position to use for Doppler tracking.
(X_s,Y_s)	Position of apex of motion of standard of rest.
(***X',Y'***)	The position (***X,Y***) converted to the coordinate system of the standard of rest.
(X^{UI},Y^{UI})	The position (***X,Y***) sent from the user interface to the control system in the coordinate system described by ***CS***^{UI}.
z	Red shift.