Specification of Frequency and Velocity Scales for Mopra Spectra

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Summary

The frequency synthesizer chain which is used to produce local oscillator signals for downconverting celestial signals at the Mopra radio telescope contains components which tune in 1 MHz quantized increments. As a result, the sky frequency corresponding to the center of the correlator bandpass can be shifted by up to ±0.5 MHz from the demanded value. The shift is well-defined, but can change from observation to observation due to changes in the Doppler correction of the motion of the telescope relative to the Local Standard of Rest, or other factors which affect the sky frequency calculation.

Unfortunately, in some cases the shifted sky frequency is incorrectly written into the .rpf datafiles. For those observations *where both polarizations are tuned to the same rest frequency*, the demanded sky frequency (rather than the true shifted sky frequency) is written into the .rpf file. The net result is that straightforward reduction of the output .rpf files will produce spectra with lines which appear at incorrect frequencies and velocities, and appear to move in velocity and/or frequency from scan to scan.

This problem can be addressed by editing the .rpf datafiles such that the recorded sky frequency is replaced by the quantized sky frequency. One can then process data normally, though co-addition of observations must be done in the velocity (rather than channel) domain. A perl script for correcting the .rpf datafiles is available.

Note that the problem is **not** one of frequency stability; the receiver chain tunes quite accurately to the quantized sky frequency. It is simply a problem of bookkeeping, which can be solved through the editing process described above.

This problem is known to affect all data in which both polarizations are tuned to the same rest frequency taken during the 2000–2003 observing seasons, and likely affects all data obtained with the Mopra radio telescope. It does *not* affect data taken in "split-mode," that is, when polarizations A and B are tuned to different frequencies.

Description of the Receiver Tuning Process

The 3mm receivers at the Mopra Radio Telescope amplify and downconvert incoming radiation with a frequency of $\sim$ 100 GHz to a baseband signal of $\sim$ 200 MHz appropriate for sampling and analysis by the observatory's correlator. The downconversion is accomplished in several stages by mixing the incoming signal with local oscillator (LO) signals.

The first stage involves mixing the sky signal down to an intermediate frequency (IF) of $\sim$ 1500 MHz with an LO whose frequency is defined by the rest frequency (F_{rest}) entered into the observatory tuning PC. The LO frequency is fixed for each tuning of the receiver, and does not change as a function of time, or during changes in telescope orientation. The output from this stage provides a bandwidth of $\sim$ 600 MHz to the subsequent downconversion stages.

The second stage involves mixing the IF down to baseband. The frequencies of the LO's used at this stage are calculated based on modifications to the rest frequency that need to be applied so that the proper frequencies are sampled by the correlator. Modifications include:

1) the difference between F_{rest} and the line frequency (F_{line}) entered into the Telescope Control System (*tcs*) software;

2) a doppler correction (ΔF_{LSR}) to account for the motion of the telescope relative to the Local Standard of Rest (LSR); and

3) another doppler correction (ΔF_{source}) for the motion of the source relative to the LSR.

The frequencies of the LOs are calculated such that radiation emitted by the source at the *tcs*-specified line frequency will appear in the centre of the correlator bandpass (stictly speaking, the line frequency will appear at the channel specified by the "CRPIX4" header variable; for a 1024 channel correlator setting, this is usually channel 513). The Mopra *tcs* calculates these second stage LO frequencies for each position observed.

Quantization Within the Receiver Chain

One of the synthesizers used in tuning the LO's for the second stage produces frequencies quantized 1 MHz steps. Rather than tuning the LO's to precisely the frequencies required to mix the IF such that line frequency emission from the source appears in the centre of the correlator bandpass, the *tcs* software tunes the LO's to the integer MHz nearest this value. The effect of this quantization is to round the the frequency corrections detailed above to the nearest MHz.

Because of this, the LO's are set so that the center of the correlator bandpass is *not* the requested sky frequency,

$$F_{sky} \equiv F_{rest} + (F_{line} - F_{rest}) + \Delta F_{LSR} + \Delta F_{source}$$

but rather a slightly different frequency

$$F_{tune} \equiv F_{rest} + \mathrm{round}\Big[(F_{line} - F_{rest}) + \Delta F_{LSR} + \Delta F_{source}\Big],$$

where "round" indicates rounding to the nearest integer MHz. This quantization produces the following consequences:

1) The requested sky frequency is displaced from the correlator bandpass center by as much as ± 0.5 MHz. At a frequency of 100 GHz, 0.5 MHz corresponds to 1.5 km/s, or

approximately 8 channels in the 64 MHz correlator configuration. Consequently, a spectral line may appear shifted by as much as this value in a given observation.

2) A spectral line will appear to wander within the bandpass from one observation to the next. This occurs because the Doppler corrections change slightly with time, due mainly to the change in the angle between the line of sight and the direction of motion of the observatory. These Doppler corrections typically amount to $\sim$ 0.1 km/s per hour, or a frequency shift of 30 kHz per hour for a frequency of 100 GHz. Because the frequency corrections are rounded to the nearest MHz, these small Doppler corrections are lost, and the line appears to move in the bandpass. For the correlator in the 16 MHz narrowband configuration, this movement is typically 2 channels per hour, so for long observations of narrow lines, direct channel-by-channel coaddition of the data will result in a smearing of the signal and potentially an artificial increase in line width. Such smearing will also occur if data from different days or different observing runs are averaged together.

A special case occurs when the computed frequency correction has a value very near to a 0.5 MHz rounding boundary. For these cases, even a small change in the Doppler correction may result in a 1 MHz change in F_{tune}, and therefore a 1 MHz shift in the center of the bandpass. Because of this effect, spectral lines can appear to shift location by 1 MHz in consecutive observations. This shift in frequency corresponds to a 3.0 km/s shift in velocity for a frequency of 100 GHz.

None of these consequences present a problem for the reduction and analysis of the data, provided that the sky frequency of each observation is properly recorded. In that case, the rest frequency and LSR velocity scales can be calculated for each observation, and coaddition of observations can be done properly in the velocity or rest frequency domain. However, as noted below, the sky frequency is not properly recorded in some cases, and it is this bookkeeping error, rather than the quantization of the LO chain, that produces problems for the reduction and interpretation of the data.

Recording the Sky Frequency in the .rpf Datafile

After calculating F_{tune} and requesting the appropriate LO settings for the second stage of the frequency downconversion, *tcs* sends this value to the correlator computer (mpccc), which writes the datafile for the observation in .rpf format. For observations conducted in “split-mode,” where polarizations A and B are tuned to different frequencies (often the case when the observer leaves polarization B tuned to the SiO maser frequency of 86243 MHz), F_{tune} is correctly passed to mpccc and written to the .rpf data file.

However, for those observations where both polarizations are tuned to the same frequency, F_{tune} is inadvertently overwritten with the value of F_{sky}, and F_{sky} is passed to mpccc and written into the .rpf data file. Thus, based on the data header information, it appears that the correlator bandpass is centered on F_{sky}, when in fact, it is centered on F_{tune}.

Reducing these .rpf files with software such as *spc* will result in the application of incorrect sky frequency and LSR velocity scales to the data, and observed spectral lines will appear with incorrect line center velocities. Moreover, because the difference between F_{tune} and F_{sky} changes with each observation, spectral lines will appear to move in velocity from spectrum to spectrum.

Addressing the Problem

It should be emphasized that this problem is **not** one involving the frequency stability of the system, nor does it fundamentally affect the quality of the observations. Rather, it is primarily a matter of bookkeeping, and as such, is correctable.

Moreover, this problem *only* affects data which were acquired with both polarizations tuned to the same frequency. The frequency of the center of the correlator bandpass is F_{tune} for split-mode data as well, but because this value is properly written to the .rpf data file, no further correction is necessary.

For those observations needing correction, the simplest fix involves replacing F_{sky} with F_{tune} in the .rpf datafile. With this fix, a spectral line will continue to appear to move around within the bandpass from observation to observation as discussed above; however, because the correct frequency will be written to the .rpf datafile, data reduction software will apply the correct LSR velocity scale to each spectrum. That is, the spectral line may appear at different channel locations, but the LSR velocity assigned to the location of the peak of the spectral line will be correct. If one is careful to add and average spectra in velocity, rather than channel by channel, the data will co-add appropriately, with no line width smearing effects.

The alternative fix — modifying the receiver chain software to tune the receiver chain in sub-MHz steps — provides the advantage that the correlator bandpass will always be centered on the calculated sky frequency. However, since the shifts in the bandpass location due to rounding are small compared to even the narrowest band regularly used (16 MHz), such modification appears unnecessary.

Correcting Existing Datasets

This bookkeeping issue is known to be present in data acquired during the 2000–2003 observing seasons, and is suspected to be present in all previous millimeter data acquired with Mopra. Correcting these datasets involves editing the .rpf datafiles to replace F_{sky} with F_{tune}. Unfortunately, this correction process is more complicated and cumbersome that it as first seems. Two problems arise:

1) Neither F_{rest} nor F_{tune} is recorded in the corrupted .rpf datafiles (Unfortunately, the variable called "RESTFREQ" in the .rpf header is filled with F_{line}, not F_{tune}). F_{tune} can be calculated from F_{rest} and F_{sky} as follows:

$$F_{tune} = F_{rest} + \text{round}\Big[F_{sky} - F_{rest}\Big].$$

Therefore, the observer must supply F_{rest} for each observation in order to perform the correction. F_{rest} is set by the tuning PC, using either a user-specified rest frequency, or a rest frequency from the PC's lookup table. The contents of that lookup table are appended to this report.

2) Editing the .rpf data file requires more than the editing of the file header found at the top of all .rpf files. Header information is also encoded within each observation block within the .rpf file. For observations containing a large number of ON-OFF pairs, there can be a large number of observations blocks to correct.

Chris Phillips and Cormac Purcell have written a perl script called *koprafix.pl* to facilitate the correction of affected .rpf files; this script, along with brief instructions for its use can be found at http://www.phys.unsw.edu.au/astro/mopra/software.php.

The corrected .rpf datafiles can then be re-processed through data reduction software such as *spc* in a normal fashion. However, the observer should keep in mind that all co-addition or averaging of observations **must** be done with respect to velocity, rather than on a channel by channel basis. *Spc* allows for such velocity-based combination using the "align" command (see http://www.atnf.csiro.au/computing/software/spc/ for details on this data reduction program).

Alternatively, one may use the *dfm* frontend to *spc* written by Cormac Purcell to reprocess the data. *Dfm* does not correct the .rpf data for the frequency quantization described here (one must still use *moprafix.pl* first); however, it ensures that data are co-added in velocity space, and it provides a graphical user interface which greatly simplifies data reduction for most observing modes. The source code and documentation for *dfm* can be found at http://www.phys.unsw.edu.au/astro/mopra/software.php.

Tuning PC Rest Frequency Lookup Table

Line Name	Frequency (GHz)	Line Name	Frequency (GHz)
C_3H_2	85.338890	$C^{34}S$	96.413000
CH_3OH_f	85.568084	CH_3OH_a	96.741420
$HCOOCH_3$	86.212000	Fe	97.600000
SiO	86.243000	CS	97.980968
CH_3OH_g	86.615578	H40a	99.023000
$H^{13}CO$	86.754300	SO	99.299879
SiO_b	86.847000	HC_3N_b	100.076389
CH_3OH_h	86.902956	CH_3NC	100.526506
C_2H	87.284156	SO_2	104.029416
HNCO	87.925238	CH_3OH_b	107.013850
HCN	88.631847	CH_3OH_d	108.893940
HCO+	89.188518	HC_3N_c	109.173643
HNC	90.663543	OCS	109.463063
HC_3N_a	90.978993	$^{12}C^{18}O$	109.782000
CH_3CN_a	91.987094	^{13}CO	110.201000
^{13}CS	92.494300	CH_3CN_b	110.383500
N_2H+	93.173505	$^{12}C^{17}O$	112.359000
CH_3OH_e	94.541000	CN	113.490982
CH_3OH_c	95.169440	CO	115.271000