Robust, realtime bandpass removal for the H I Parkes All Sky Survey Project using AIPS++

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Abstract. We present the algorithm and implementation details for the robust, realtime bandpass removal and calibration routine developed for the H I Parkes All Sky Survey project. The software is based on the AIPS++ toolkit.

1. Introduction

In Barnes (1998) we give an overview of the Parkes Multibeam Software, and the motivation for its development, that is, the desire to have robust, realtime processing software for the neutral hydrogen H I Parkes All Sky Survey (HIPASS). In this paper, we provide more details on the bandpass correction algorithm, and its implementation, based on the AIPS++ toolkit.

2. Robust Bandpass Removal

Traditionally, the bandpass that is present in single-dish 21 cm spectra is removed by observing in a "signal-reference" mode. In this mode, an extended integration (typically 3 min) is acquired while the telescope is pointed at the target position, or *signal.* A second extended integration is then acquired while the telescope is pointed towards a nearby position free of line or continuum sources—the *reference.* The bandpass is removed by dividing the signal spectrum by the reference spectrum. If longer on-source integration times are required, this process can be repeated many times, and the quotient spectra averaged.

For the HIPASS Project, where the telescope is actively driven across the sky at a rate of $\sim 1^\circ$ min^{-1}, the traditional bandpass removal technique is not suitable. Instead, a statistical estimate of the bandpass at the position and time that a particular spectrum—the *target* spectrum—was acquired is made from a set of earlier and later spectra observed by the same beam—these are the *reference* spectra. The bandpass is then removed from the target spectrum by dividing it by the statistical bandpass estimate.

This process can be formalised as follows: a particular integration will be denoted as $I_{b,p,c}$, where the subscripts b and p represent a beam-polarisation combination[1], and c is the cycle number of the integration. $I_{b,p,c}$ is a 1024-channel flux density spectrum.

For a given beam and polarization pair, the target spectrum is $I_{b,p,c_{\mathrm{target}}}$, and the reference spectra, $\mathcal{R}$, are a set of spectra which can be used to estimate the bandpass for the target spectrum. The suitability of a particular spectrum depends on a number of factors. Most importantly, a reference spectrum must be measured on a part of the sky which is independent (with respect to the telescope beam) of the part of the sky measured by the target spectrum. However, the bandpass can be expected to vary with time, so spectra taken nearby in time to the target spectrum are more useful reference spectra than those taken at greater time separations. Furthermore, any movements of the receiver with respect to the telescope dish, including rotations and axial movements, were found to introduce large phase changes in the bandpass. This lead to extreme ripple in the baseline of spectra corrected with reference spectra having varying parallactic angles or axial offsets. Thus, valid reference spectra must be from the same right ascension (or Galactic latitude) scan as the target spectrum.

Having selected the reference spectra $\mathcal{R}$, the estimate of the bandpass ($B_{b,p,c_{\mathrm{target}}}$) is given by

$$B_{b,p,c_{\mathrm{target}}} = \mathrm{median}\,(\mathcal{R}) \tag{1}$$

where the median statistic is taken channel by channel. Other, more sophisticated estimators, such as robust linear interpolation, were tested, but proved too slow for realtime reduction since in general they require minimization of non-linear functions in multi-dimensional parameter spaces.

With $B_{b,p,c_{\mathrm{target}}}$ determined, calibration of the spectral data can be done concurrently with bandpass removal. The system temperature for the target spectrum, T_{target}, is provided in the correlator file, whilst that for the bandpass estimate, T_{bandpass}, is obtained in a fashion analagous to the calculation of a single channel in the bandpass estimate. Thus the bandpass-corrected, calibrated target spectrum is

$$S_{b,p,c_{\mathrm{target}}} = \frac{I_{b,p,c_{\mathrm{target}}}}{B_{b,p,c_{\mathrm{target}}}} \times T_{\mathrm{bandpass}} - T_{\mathrm{target}} \tag{2}$$

2.1. Implementation

The BANDPASS CALCULATOR, which is our AIPS++ implementation of Equation 2, stores incoming spectra in a four dimensional buffer, of the form `Matrix<Matrix<Float>>`. The row and column in the parent matrix select a beam-polarization pair, and the row and column in the sub-matrices select cycle and channel numbers. The spectra are arranged this way to optimise access speeds, yet still provide `row()` and `column()` methods to efficiently extract spectra or time series of individual channels. Both these operations are required for bandpass correction. Since shuffling the data through the matrices would be inefficient, an indexing system is utilised to keep track of the newest spectrum added to the buffer. Spectra are discarded (overwritten) when they are no longer required.

[1] Normally, $b \in \{1, 2, \ldots, 13\}$ and $p \in \{1, 2\}$.

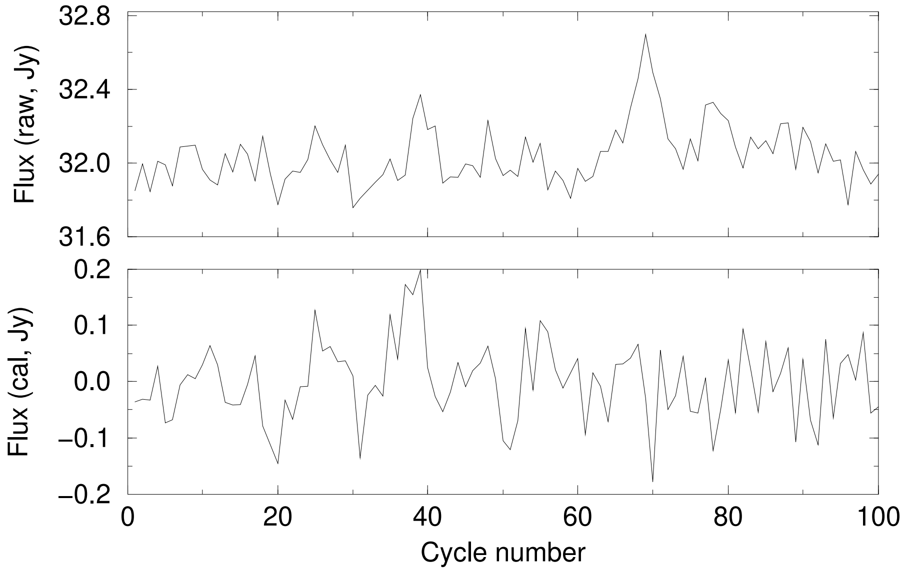

Figure 1. Raw (top) and calibrated flux densities for a selected channel of a HIPASS scan through the interacting galaxy ESO 269-IG 056 (cycles 34–41) and the continuum source PKS 1307-403 (cycles 66–73)—*see text.*

2.2. Examples

Figure 1 shows the uncalibrated and calibrated flux densities for a selected channel of a HIPASS scan through a galaxy with the central beam of the Multibeam. The galaxy appears as a rise and fall in flux density over cycles 35 to 42. This feature is preserved in the calibrated flux densities; the uncalibrated and calibrated spectra corresponding to cycle 36 are shown in Figure 2.

The feature observed near cycle 69 in the raw bandpass (Figure 1) is the continuum source PKS 1307-403 which generates an increased flux density in *all* line channels. To first order, continuum sources are removed by the bandpass removal algorithm, since the entire spectrum is rescaled according to Equation 2, and then the median value of all channels is subtracted from each channel as a simple means of baseline removal. For strong continuum sources though, there are still serious baseline ripple and curvature effects which remain in the calibrated spectra.

3. Discussion and Conclusion

The robust bandpass removal algorithm implemented for the HIPASS Project successfully produces calibrated HI emission line spectra for most of the survey data. The technique is robust to the presence of contamination by radio frequency interference and strong on-axis and off-axis continuum sources in the reference spectra. Unfortunately though, sources which emit in a particular channel over more than $\sim 2^\circ$ of declination, such as the Galaxy or associated

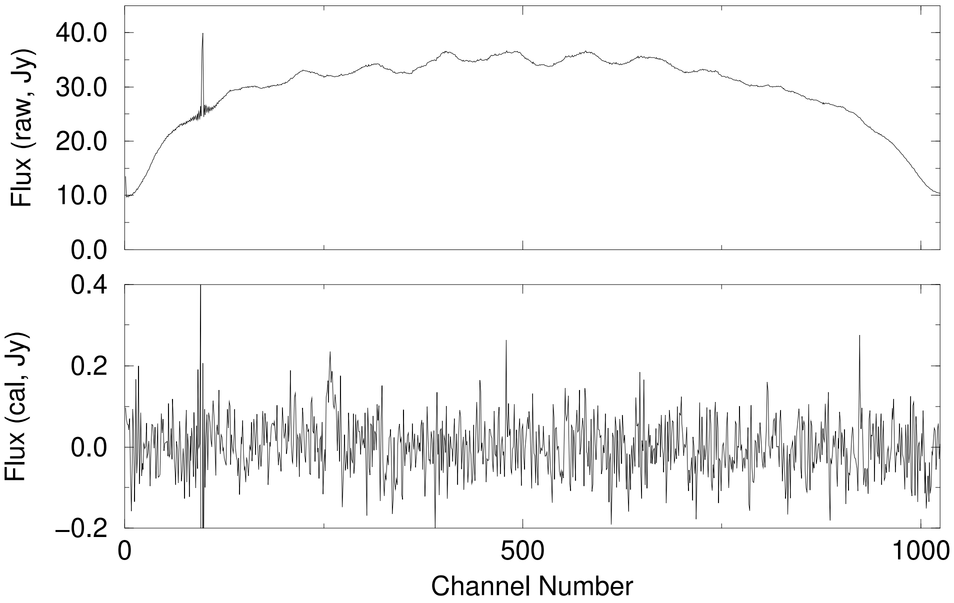

Figure 2. Raw (top) and calibrated flux density spectrum for a single integration (cycle 36) of the same HIPASS scan as shown in Figure 1—*see text.*

high-velocity clouds, are not well calibrated. This is because a trade-off between a larger set of reference spectra (yielding a better estimate of the emission-free bandpass in such cases) and a smaller set of reference spectra (yielding robustness to time-variability of the bandpass) was necessary. Conversely, the calibrated spectra of unresolved sources, which will form the bulk of the sources detected by the HIPASS, are invariably flat and of excellent quality.

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References

Barnes, D. G. 1998, this volume