Data processing of the Stratospheric TeraHertz Observatory-2 [CII] Survey

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Abstract. The Stratospheric Terahertz Observatory (STO-2) was a balloon mission to survey the Galactic Plane at [CII] transition at 1.9 THz. STO-2 surveyed approximately 2.5 deg^2 of the Galactic Plane at a spatial resolution of 1'. The STO-2 data suffer significant system drifts that are only partially addressed by the observing cadence. A slightly altered calibration scheme is presented to address these drifts. We show how it was possible to extract calibrated data from STO-2 scans and, based on the work here, make recommendations for future missions.

1. Introduction

Galaxies are dynamic structures of stars and gas: stars form in dense gas which is dispersed again by the star formation process. The gas is chemically and dynamically enriched by stellar winds from dying stars. Following abundant atoms and ions through this cycle traces the dynamics and life cycle galaxies. Singly ionised carbon, [CII], is a particularly useful ion to trace the interstellar medium of galaxies. With an ionisation potential of 11.26eV, carbon is ionised by UV radiation outside of regions of ionised hydrogen. High spatial and spectral observations of [CII] show not only where the ion is but how it is moving. The [CII] emission has recently been studied in sparse spatial sampling along 500 lines of sight throughout our Galaxy using the Herschel/HIFI spectrometer (Langer et al. 2014).

The Stratospheric Terahertz Observatory was a heterodyne spectrometer with the goal of surveying Galactic Plane at the [CII] 1.9THz transition at a spectral resolution of 0.16 km/s. In order to get significantly outside of Earth's atmosphere, STO-2 was on a high altitude balloon platform which flew at 40 km above the South Pole. The experiment carried a tank of liquid helium to cool the mixers to their operating temperature. STO-2 obtained data from December 15 to 30, 2016. In that time more that 300,000 scans of the Galactic Plane were made. Details of the STO experiment can be found in Walker et al. (2010).

2. Observations

For the [CII] survey, STO-2 made use of the On The Fly mapping (OTF) mode. OTF is a means of mapping a region by continuously scanning and intermittently reading out a detector (Mangum et al. 2000). OTF is a highly efficient means of covering a large region of the sky with single detectors or small arrays of detectors. The OTF technique uses the standard vane calibration of radio telescopes (Kutner & Ulich 1981) which makes use of a reference position free of emission (REF) as well as an integration on an internal load of known temperature (HOT). The main constraint in OTF mapping is the timing between readouts of the instrument during the scan (ON), the time between HOT measurements and the time between the REF measurements. In an OTF scan, a REF (sky) position is observed along with HOT load, the telescope moves to the beginning of the mapping region, repeats the HOT measurement then, while moving on the sky, starts integrating. The integrations are readout frequently to minimise source blurring. At appropriate intervals, the internal HOT load is observed. At the end of scanning, another HOT load is observed, followed by a REF (and HOT). This pattern continues on a new scan parallel but offset by a fraction of the spatial resolution of the instrument. Figure 1 presents a visual summary of the technique used by STO-2.

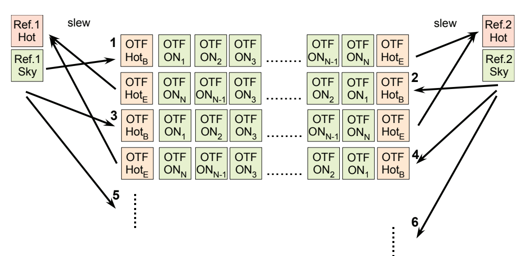

Figure 1. Observation sequence of an OTF scan.

As can be seen in the figure, the timing between successive ON readouts is the fastest, followed by the intermittent HOT scans, then by the REF measurements. This pattern comprises the observation cadence.

2.1. Standard calibration

The references (REF) and repeated hot scans (HOT) are combined to calibrate the system onto a known radiometric scale (Kutner & Ulich 1981). Reference position scans should be emission free and the system stable in time.

$$\mathrm{T}_A^* = \mathrm{T}_{sys} \frac{(ON - REF)}{REF}$$

$$\text{with, } \mathrm{T}_{sys} = 2 \times \frac{T_{HOT} - Y \times T_{REF}}{Y - 1} \text{ with } Y = \frac{HOT}{REF}$$

T_{sys} is the system noise temperature. The Y factor is the ratio of the raw HOT counts to the raw REF counts. T_{HOT} is a direct measurement of the HOT load (290K) while the second, T_{REF}, is the effective temperature of the blank sky at 1.9 THz (45K)

2.2. Radiometric noise and drift noise

The noise within radio observations can be described by two different noise sources: white noise and drift noise. White noise is independent of time and can be reduced by longer integrations. Drift noise is not uniform in time and very often shows up as 1/f noise. Drift noise cannot be reduced by longer integrations or repeated measurements.

Drift noise originates from the instability of the detector system. Understanding the timing of instabilities is needed and a proper observation sequence must be chosen to minimise drift effects. Where as white noise is simply noisy but flat over the IF bandpass, drifts result in spectra which fluctuate over the bandpass. In this case, the resulting spectra suffer from poor baselines and/or standing waves which limits the useful information present in the signal by confusing spectra features of the sky.

Figure 2 shows calibrated scan spectra for one leg of an OTF scan. The figure on the left shows the resulting spectra after applying a standard calibration.

2.3. Addressing drift

The calibration requires stability of the the entire system across the observation sequence. The reference observations are usually taken a significant time before and after the OTF scan. The drift time constant is described by the Allan time (Allan 1966) and observations should be designed with this drift time in mind. An intermittent load scan can be used to help stabilise the system by monitoring drifts that are taking place.

The frequency of the load scans (HOT load in the case of STO-2) helps make up the overall observation cadence. The other component is the reference scan. Often, the Allan stability time is short compared to the cadence of reference measurements implying that the references observations although necessary for calibration, do not correct for instrument drifts. The HOT load scan, on the other hand, can be used to address the system drift since changes in the HOT reflect the changes of the system much closer in time as the ON data were taken

To account for drifts and better use the system monitoring aspect of frequent load measurements the calibration equation can be altered to

$$\mathrm{T}_A^* = \mathrm{T}_{sys}\frac{(ON - synREF)}{synREF}$$

In this case, $synREF = HOT(t) \times \frac{REF(t_0)}{HOT(t_0)}$ and is linearly interpolated to the time of the ON integration t. t_0 is the time of the reference scan and accompanying hot.

Interpolating between standards is not new and a full discussion for OTF observations is given in Ossenkopf (2009). In the presence of significant system drifts, all calibration factors need to be interpolated in time to match the scan integration time. As can be seen in the righthand side of figure 2 a significant improvement is gained by normalising again by the HOT scan closest to the OTF integration in stead of just an interpolation between the bracketing REF/HOT sequence.

Even after altering the calibration equations, often a ripple was still present in the baseline of the spectrum. This is a common feature of heterodyne observations which could have very different causes including internal optical or electronic reflections. Common methods exist to address these fluctuations including fitting a low order polynomial or even sine waves if the pattern is periodic. However, given that a careful attention to matching calibration steps alleviated the baseline issues, perhaps the assumption of linear interpolation should be reviewed.

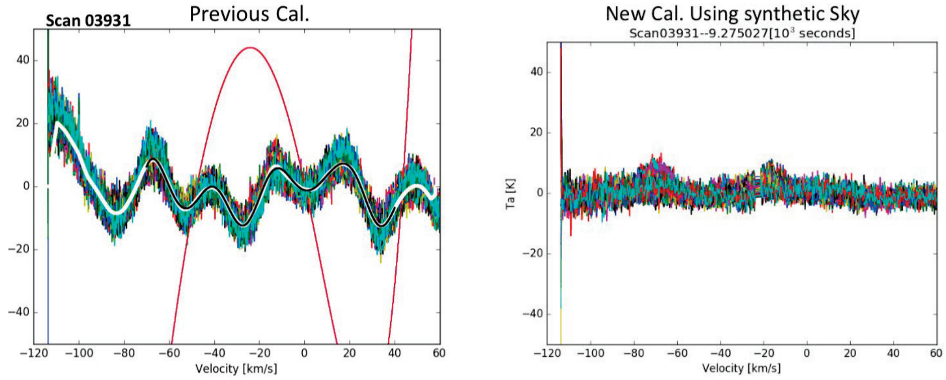

Figure 2. *Left:*Original calibration applied to a series of scans. *Right:* The same scans after applying the HOT scan stabilised calibration.

3. Conclusions

The STO-2 data has significant stability issues. One approach to mitigate this issue was to make better use of the internal calibration sources. Not all of STO-2 observations were taken in the OTF mode with frequent load calibrations. Some of the observations where OTF with far fewer loads and others were position switch modes without bracketing load sequences. Those observations present an even greater challenge.

In 2021 the Gal/X-Gal ULDB Stratospheric TeraHertz Observatory (GUSTO) will fly a long duration mission to survey inner Milky Way at CII, NII and OI transitions with heterodyne arrays of 8 pixels in each band. STO-2 was preparation for GUSTO. To help make the GUSTO survey a success, we recommend standardising observations utilising frequent load calibrations.

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