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Data Processing of the Stratospheric Terahertz Observatory-2 [CII] Survey

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Abstract. The second flight of the Stratospheric Terahertz Observatory (STO-2) was a balloon mission to survey parts of 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 presented here, make recommendations for the future GUSTO mission.

1. Introduction

Observing abundant atoms and ions traces the dynamics and life cycle of the interstellar medium (ISM) in galaxies. Singly ionized carbon, [CII], is particularly useful to trace the ISM. With an ionization potential of 11.26eV, carbon is easily ionized by the UV radiation from young hot stars. High spatial and spectral observations of [CII] show not only where the ion is but how it is moving. Sparse spatial but velocity resolved [CII] emission has recently been studied along 500 lines-of-sight throughout our Galaxy (Langer et al. 2014) and provided significant insights into the internal workings of the ISM in our Galaxy.

The Stratospheric Terahertz Observatory is a double sideband (DBS) heterodyne spectrometer with the goal of surveying parts of the Galactic Plane at the [CII] 1.9THz transition at a spectral resolution of 0.16 km/s. To minimize the influence of Earth's atmosphere, STO was put on a high altitude balloon platform which flew at 40 km above the South Pole. The second flight of STO, STO-2, obtained data from December 15 to 30, 2016. In that time more than 300,000 fully sampled 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 combines data of a sky reference position free of emission as well as data on an internal load of known temperature. STO-2 has an internal hot load. The main constraint in OTF mapping is the timing between readouts of the instrument during the scan (ON), the time between load measurements (HOT) and the time between the sky measurements (REF).

An OTF scan is shown in Figure 1. The scan begins with a sky (REF 1) observation along with a hot load (HOT). The telescope points to the beginning of the mapping region and repeats the load measurement (HOT_B). Then starts integrating on the sky while moving along the scan leg. The integrations are readout frequently to minimize source blurring. At appropriate intervals and at the end of the scan the internal hot load is observed (HOT_E). This pattern continues on a new scan parallel but offset by a fraction of the spatial resolution of the instrument.

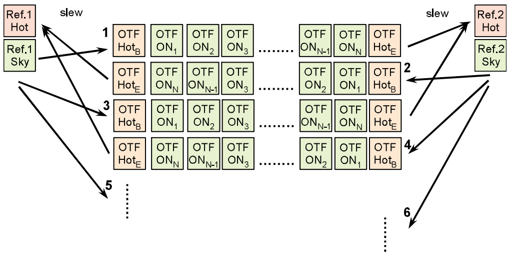

Figure 1. Observation sequence of an OTF scan. The subscripts represent increasing readouts along a scan

As can be seen in the Figure 1, the timing between successive ON readouts is the fastest, followed by the intermittent HOT, then by the REF measurements. This pattern comprises the observation cadence.

2.1. Standard calibration

The reference observations (REF) and repeated hot measurements (HOT) are combined to calibrate the system onto a known radiometric scale (Kutner & Ulich 1981). Reference positions should be emission free and the system should be stable. The calibration of a DBS receiver is give by:

$$\mathrm{T}_A^* = \mathrm{T}_{sys} \frac{(ON - REF)}{REF} \tag{1}$$

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

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 the hot load temperature (290K) while T_{REF} is the effective temperature of the blank sky at 1.9 THz (45K). The values of the Y factor and the REF measurement per channel are linearly interpolated to the time of the ON readout.

2.2. Radiometric noise and drift noise

Radio observations are afflicted with mainly two different noise types: radiometric (white) noise and drift noise. White noise is independent of frequency of observing and can be reduced by longer integrations. Drift noise increases over longer time periods and in general 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 minimize drift effects. Whereas white noise is flat across spectral channels (bandpass), drifts result in spectra which fluctuate over the bandpass. The resulting spectra suffer from poor baselines and/or standing waves. Poor baselines limit the useful information present in the signal by confusing spectral features of the sky with drift noise.

The right hand side of Figure 2 shows calibrated scan spectra for one leg of an OTF scan. The drift noise has built up spectra "features" which repeat over many scans.

2.3. Addressing drift noise

The calibration requires stability of the entire system. 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.

The frequency of the load observations (HOT) helps make up the overall cadence. Another component is the reference observation. Often, the stability time is short compared to the cadence of the reference measurements. This implies that the references observations, although necessary for calibration, may leave larger than desired drifts. The hot load can be used to address the system drift since changes in the HOT reflect the changes of the system much closer in time. In other words, an intermittent load scan can be used to help stabilize the calibration.

To account for drifts and better use the system monitoring aspect of frequent load measurements the calibration equation can be altered to create an "interpolated" REF signal.

$$\mathrm{T}_A^* = \mathrm{T}_{sys}\frac{(ON - intREF)}{intREF} \tag{2}$$

In this case, $intREF = HOT(t) \times \frac{REF(t_0)}{HOT(t_0)}$ and is linearly interpolated to the scan readout time 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. This can be seen in the right hand side of Figure 2 where a significant improvement is gained by normalizing again by the HOT scan closest to the OTF integration.

Even after altering the calibration equations, often ripples are still present in the baseline. Common methods exist to address poor baselines including fitting a low order polynomial or even sine waves if the pattern is periodic. Such baseline fits might be impractical on survey data since they require knowing which velocities should be emission free. Since the drifts build up over many scans, perhaps machine learning

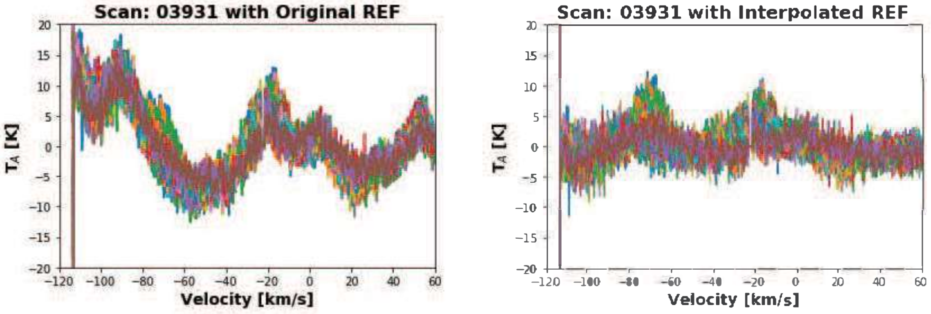

Figure 2. *Left:* An OTF scan with original calibration (Equ. 1) applied to a series of readouts along a scan. *Right:* The same scan after applying the HOT scan stabilized calibration (Equ. 2).

techniques can be adopted to address these drifts. Nevertheless, given that a careful application of calibration steps addresses some baseline issues, attention should be paid to the proper design of an OTF scan to provide frequent stabilizing observations.

3. Conclusions

In reducing STO-2 data a number of techniques were used to minimize stability issues common to heterodyne instruments. One approach to mitigate this issue was to make extensive use of the internal calibration sources. However, not all of STO-2 observations were taken in the OTF mode with frequent load calibrations. Those observations present an even greater calibration challenge.

The STO-2 mission was in preparation for the Gal/X-Gal Ultra long duration balloon Stratospheric Terahertz Observatory (GUSTO) which flies in 2021. GUSTO is a 100 day mission to survey the inner Milky Way at [CII], [NII] and [OI] transitions with heterodyne array receivers. To help make the GUSTO survey a success, we recommend standardizing observations utilizing frequent load calibrations as well as taking lessons from STO-2 about how to deal with instrument drifts in post processing.

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