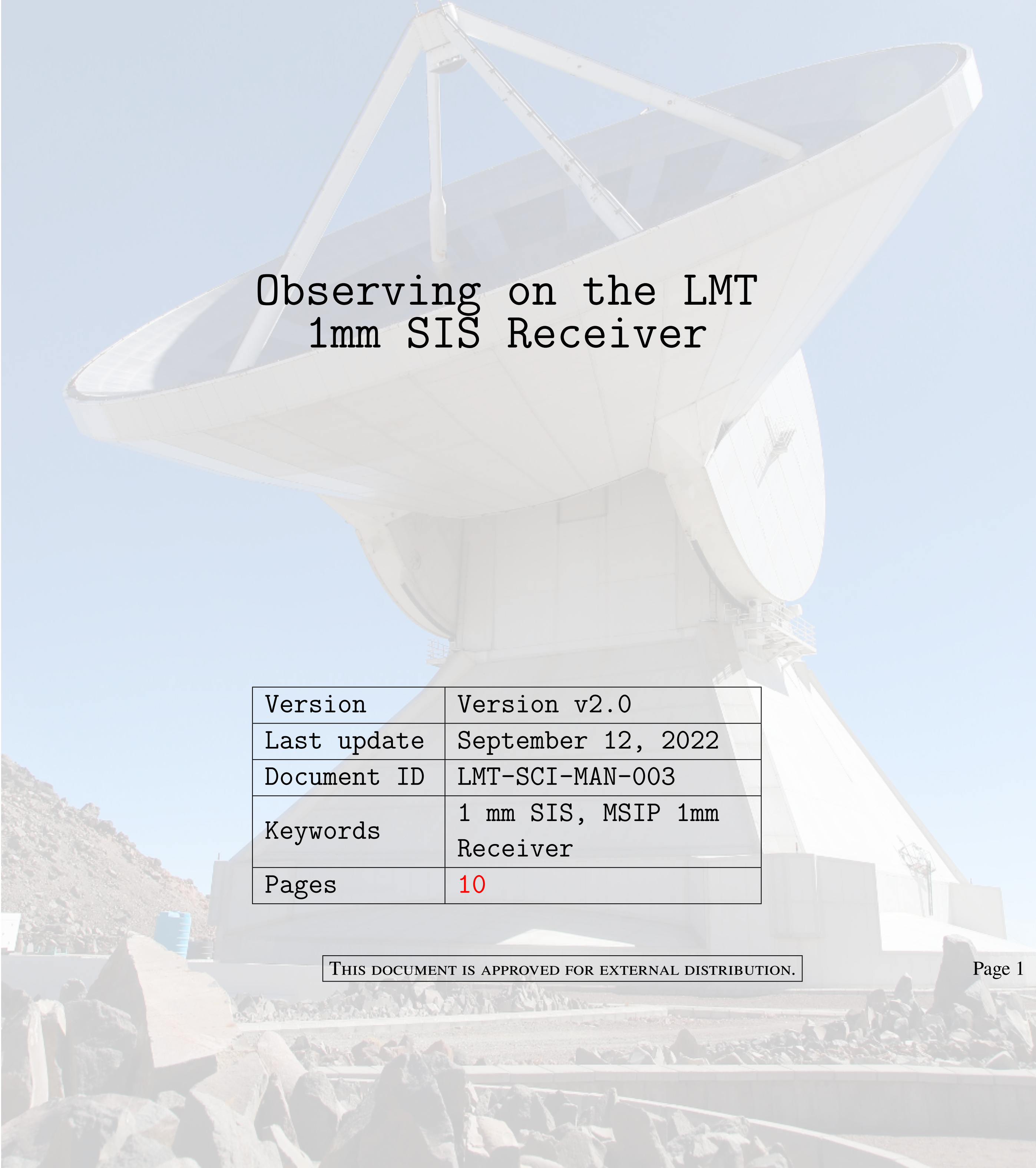

Observing on the LMT
1mm SIS Receiver

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Contents

Abstract

The 1mm SIS receiver is a dual polarization, sideband separation receiver covering the 210-280 GHz frequency range. Spectral lines from four IF outputs are processed using the WARES spectrometer system. The system is calibrated using a "chopper wheel" method, and it is not currently set up to function as a continuum instrument. It can be run in a position switching mode and an on-the-fly (OTF) mapping mode. Position switching produces a single spectrum for a single position on the sky, saved in a FITS format, while OTF mapping results in a FITS data cube with spectra for every position on the map. Detailed descriptions of mapping patterns, sensitivities, and recommended mapping strategies are described in Sections 5 and 6 of this manual.

1 Introduction

This document is intended to provide some basic information about the 1mm SIS receiver on the LMT in order to help prospective users to prepare observing proposals. It describes basic instrument parameters and presents a simple derivation of instrument sensitivity used for the instrument sensitivity calculators. Finally, some general advice about experience and best practices is summarized.

2 Instrument Description

The LMT's 1mm SIS receiver is a dual polarization, sideband separation receiver for the 210-280 GHz frequency band. As such, the receiver produces four IF outputs for processing by the WARES spectrometer, with two outputs in the receiver upper sideband for the two polarizations and two outputs in the lower sideband for the two polarization channels. The IF bands for the receivers cover 4-12 GHz. The 1mm SIS receiver makes use of the WARES spectrometer to analyse the frequencies within the band and create a spectrum.

The advantage of the two orthogonal polarization channels for the receiver is that, since they are statistically independent, they double the amount of integration time in a measurement.

The advantage of sideband separation is that, for a given setting of the local oscillator, the total range of frequencies available covers two 8 GHz frequency windows.

2.1 Spectrometer Configuration

At this time, the reciever and WARES spectrometer are configured to allow observations of two spectral windows at once, with one window in the upper sideband and one in the lower sideband. Figure 2.1 shows the range of frequencies that are accessible given a selection of the local oscillator frequency, ν_{LO}.

The WARES spectrometer can be configured to observe two spectral lines, one in the upper sideband and one in the lower sideband, simultaneously. WARES provides three possible options for taking spectra, summarized in Table 2.1, with channel bandwidths of 391 kHz, 98 kHz, and 24 kHz for the Wide, Intermediate, and Narrow modes of the spectrometer.

EXAMPLE

Suppose one wishes to observe ^{12}CO J=2-1 at 230 GHz and ^{13}CO J=2-1 at 220 Ghz. Placing the local oscillator at a frequency of 225 GHz will place the ^{12}CO J=2-1 in the upper sideband and the ^{13}CO J=2-1 in the lower sideband. This will allow the WARES spectrometer to measure both lines simultaneously.

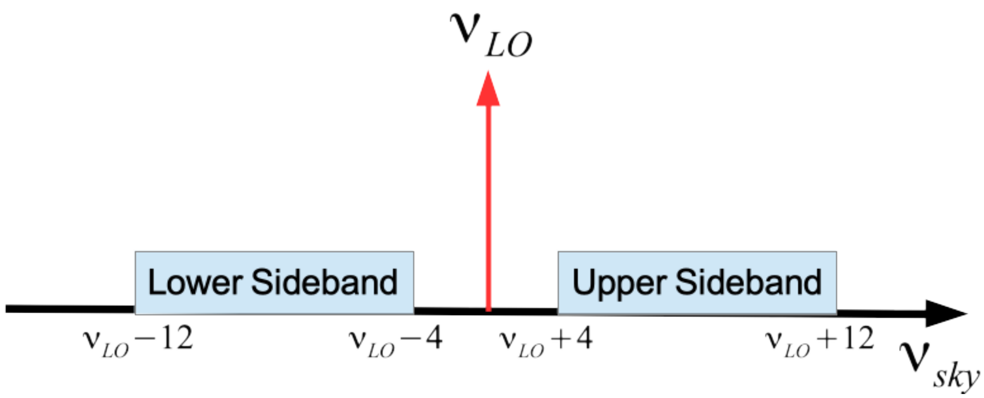

Figure 2.1: Frequency coverage of the 1mm SIS receiver. Selection of the local oscillator frequency, ν_{LO}, determines the frequency windows available for processing with the WARES spectrometer. The upper sideband window spans the range from $\nu_{LO} + 4$ GHz to $\nu_{LO} + 12$ GHz. The lower sideband window spans the range from $\nu_{LO} - 12$ GHz to $\nu_{LO} - 4$ GHz. The WARES spectrometer is configured to observe one frequency band in the upper sideband and one frequency band in the lower sideband. Each band is observed in both polarizations.

MODE	**Wide**	**Intermediate**	**Narrow**
Total Bandwidth (MHz)	800	400	200
N Channels	2048	4096	8192
Channel Bandwidth (kHz)	391	98	24
CO J=2-1 @ 230.5 GHz			
Total Bandwidth (km/s)	1041	521	260
Resolution (km/s)	0.51	0.125	0.03

Table 2.1: WARES Spectrometer Modes

2.2 Beam Size

The 1mm SIS Receiver has a diffraction limited beam. The beam is well characterized by a guassian with a half-power-beam-width (θ_{HPBW}) of approximately:

$$\theta_{HPBW} = 1.2\frac{\lambda}{D} = 6.5\left(\frac{230GHz}{\nu}\right) \text{ arcsec}$$

3 1mm SIS Receiver Calibration

The 1mm SIS Receiver is calibrated using the “chopper wheel” method. This method is in common use at millimeter-wave observatories, and it accounts for atmospheric attenuation and for some antenna losses. Antenna temperatures measured using this technique are referred to as being on the T_A^* temperature scale. We note that some observatories report antenna temperatures measured by the chopper wheel method, but include corrections for additional losses not accounted for in the method. This is not done at the LMT.

The chopper wheel system temperature measured on sky is approximately 100-150 K over much of the band, though these values depend strongly on the weather conditions. Using the T_A^* calibration, the LMT aperture efficiency at 230 GHz is approximately 26% corresponding to a gain factor of 5.4 Jy/K. The aperture efficiency and

4 Use as a Continuum Receiver

The 1mm SIS receiver is outfitted with a beam chopper which makes it possible to perform basic pointing and focus measurements on *strong* (1 Jy+) sources. The instrument is not optimized for sensitive continuum measurements.

5 Data Acquisition with the 1mm SIS Receiver

The 1mm SIS receiver is used in two basic data acquisition modes: (1) position switching; and (2) on-the-fly (OTF) mapping.

5.1 PS - Nominal Position Switching

5.1.1 Expected Sensitivity

In this mode, the receiver beam is moved between an *On* and an *Off* position on the sky and the difference is determined. Switching on and off the source leads to a single spectrum for each polarization channel of the receiver. Averaging of the two spectra leads to a doubling of the integration time on the source. Thus, when this factor is included in the sensitivity calculation for a normal position switched spectrum, the appropriate rms in a spectrometer channel would be:

$$\Delta T_{rms} = \sqrt{2}\frac{T_{sys}}{\sqrt{\beta\tau}} \text{ K} \qquad \text{(1mm SIS PS Sensitivity)}$$

where β is the channel width and is determined by the spectrometer mode selected, T_{sys} is the system temperature, and τ is the total integration time.

EXAMPLE

Let's consider a typical observation of the ^{12}CO J=2-1 line. Under moderately good weather conditions one might expect a system temperature of 125K. A 10-minute (600 s) integration using WARES in Wideband mode with a resolution of 301 kHz, corresponding to 0.5 km/s, yields an rms of 11 mK. Using the gain factor at this frequency yields an rms in flux density of 62 mJy.

5.1.2 Observing Overhead

For observations in position-switched mode, some part of the elapsed time required to make the observation is consumed by moving the telescope between the beams. In addition, calibration measurements of the system temperature are obtained as a part of an observing sequence. Position switched observations with the 1mm SIS receiver have not been extensively tested. However, for standard position-switched observations, we find that typical ratio of elapsed time on the telescope to source integration time is approximately 1.4. The LMT time calculators therefore multiply the necessary integration time to achieve a particular sensitivity by a factor of 1.4 to estimate the total amount of telescope time required for an observation.

5.1.3 Position Switching Data Product

The position switching modes described above are intended to result in a single spectrum from a single sky position. Thus, the nominal pipeline reduction of the data will provide single spectra in a FITS format data file. If two sets of spectra are obtained, for upper and lower sideband, then each will be treated as a separate spectrum.

In many observing programs, a complete project involves collection and averaging of many individual PS spectra to obtain a result. For example, a long integration is usually obtained by averaging many short integrations, and in this case, the final data product would be the single, averaged, spectrum. We note that rudimentary maps can also be obtained by making PS measurements at different positions on the source. In this case the expectation would be to produce a FITS file for each map position.

It is understood that some users may wish to receive all the individual spectra that go into a final average or map, after the initial reduction and calibration of the raw data obtained by the spectrometer. In this case, each spectrum would be prepared and transmitted to the user in a standard format; a development effort is underway to identify useful formats for the users in this case.

5.2 On-The-Fly (OTF) Mapping

The 1mm SIS receiver can be used for OTF mapping. In this observing mode, the receiver beam is scanned over the source and spectra from the WARES spectrometer are recorded at a regular cadences with a short sampling time interval of τ_{DUMP}.

5.2.1 Antenna Scanning Rate

The WARES spectrometer's fastest reliable dump time is 100 ms. Nominally, an observer seeks to scan the antenna at a rate, S, which, when sampled every τ_{DUMP} seconds results in about 4 samples of the source within a resolution element of $\frac{\lambda}{D}$. Let n_s be the number of samples in a resolution element (nominally 4), then we may compute the required scan rate:

$$S = 206265 \left(\frac{\lambda}{D}\right) \frac{1}{n_s \tau_{DUMP}} \text{ arcsec/second}$$

Nominal values for scanning at the wavelength of the ^{12}CO J=2-1 transition are based on a resolution element, $\frac{\lambda}{D}$, of about 5 arcsec. At the fastest available dump time, this would require a scan rate of 12.5 arcsec per second, which is well within the allowed range of scan rates for the LMT. It is notable that the smaller beam of the LMT at 1.3mm wavelength requires a slower scan in order to collect the nominal four samples per resolution element than is required for the SEQUOIA receiver at 3mm.

Scanning the antenna at slower rates than the nominal one computed above will provide more samples per resolution element, assuming that τ_{DUMP} is not changed. This means more integration time and sensitivity within an individual map at the cost of a longer time to complete the map. In general, for projects which need more integration time to reach a requested sensitivity limit, we recommend taking multiple maps using the nominal scanning speeds and averaging the maps together to improve the noise level.

Scanning the antenna a faster rates has the advantage of completing the map more quickly. However this is done at the cost of poorer sampling of the sky which leads to a degradation of the effective resolution of the map and lower sensitivity, due to less integration time spent in each map pixel.

5.2.2 Scanning Patterns

The 1mm SIS Receiver has not been fully commissioned for OTF observations, but no problems are anticipated because the receiever uses the same spectrometer as the SEQUOIA insrument, which has been extensively tested, and the scanning requirements for the telescope are more modest than those required for SEQUOIA.

The LMT provides the capability of making maps on a rectangular grid. One may specify the orientation of the scans on the sky in the Right Ascension-Declination system, in Azimuth-Elevation system or in Galactic Coordinates. An important consideration for scanning on a rectangular grid is the spacing between the scan rows. Nominally, one wishes to space the rows by less than one-half of the resolution ($\frac{\lambda}{D}$) in order to assure full Nyquist sampling of the spatial frequencies in the map.

The LMT is capable of scanning in other patterns as well, which may allow for more efficient sampling of small regions. For example, the AzTEC instrument used Lissajou scan patterns effectively for certain kinds of small maps, and these scanning patterns can be accomplished by the telescope. However, at the time of this writing (November 2020) maps of this sort have not been tested with the 1mm SIS Receiver.

5.2.3 Sensitivity Achieved

A standard map at the LMT will have a pixel size θ_{PIX} that is one-half of the resolution element ($\frac{\lambda}{D}$) in order to assure full Nyquist sampling of the spatial frequencies in the map. For scanning on a rectangular grid, it is rather straightforward to compute the amount of integration time in a map pixel for a map. The time spent in a map pixel (τ_{PIX}) by the 1mm SIS Receiver beam is

$$\tau_{PIX} = \frac{\theta_{PIX}}{S}\frac{\eta}{f} \text{ seconds}$$

where η is a factor that accounts for spatial filters that are applied during the production of the on-the-fly map, and f is the spacing between map rows in units of θ_{PIX}. Obviously η depends on the parameters of the filter; a nominal value for filters used at LMT during SEQUOIA commissioning tests suggested that this factor is approximately 1.5, although this needs to be confirmed for the 1mm SIS receiver.

Scanning the antenna in rows separated by f, as described above, means that both polarization channels of the receiver will see the same points on the sky. Thus, we may consider the receiver to be making two independent maps of the source with the same sampling and the result will be a factor of two increase in the integration time that goes into a map pixel. Using the radiometer equation, we may write an expectation for the rms within a map pixel:

$$\Delta T_{rms} = \frac{1}{\sqrt{2}}\frac{T_{sys}}{\sqrt{\beta\tau_{PIX}}} = \frac{1}{\sqrt{2}}\frac{T_{sys}}{\sqrt{\beta}}\left(\frac{Sf}{\theta_{PIX}\eta}\right)^{\frac{1}{2}} \text{ K} \qquad \text{(1mm SIS OTF Sensitivity)}$$

5.2.4 Observing Overhead

For observations in OTF mode, some part of the elapsed time required to make the observation is consumed by moving the telescope in its scanning pattern to observe the source. In addition, time is consumed moving the telescope to the map's reference position and there is also time used for calibration measurements of the system temperature, which are obtained as a part of an observing sequence. OTF observations wuth the 1mm SIS receiver have not been tested extensively. However, for standard OTF maps, we find that typical ratio of elapsed time on the telescope to source integration time is approximately 1.7. The LMT time calculators therefore multiply the necessary integration time to achieve a particular sensitivity by a factor of 1.7 to estimate the total amount of telescope time required for an observation.

5.2.5 OTF Data Product

A thirty minute OTF map with 1mm SIS Receiver will produce 72,000 dumps from the spectrometer which need to be reduced and "gridded" into a map. Assuming use of WARES with both sidebands and both polarization channels and configured in Narrow band mode with 8192 spectral channels, this corresponds to about 2.25 GB of data to be processed. The LMT spectral line reduction pipeline processes this raw data and produces a FITS data cube containing spectra at each position in the map.

For projects which require more integration time per pixel than can be accomplished in an individual map, we recommend taking several maps and combining their data into a single data cube. This is the nominal strategy for producing the pipeline data products for telescope users.

It is understood that some users may wish to do their own processing of the spectra obtained during the OTF mapping. For this reason, an alternative data product can be produced containing all map spectra after an initial reduction (e.g. calibration and removal of reference measurements). This data product will be provided in a standard format; a development effort is underway to identify useful formats for the users.

5.3 How do I make a small map?

The OTF mapping procedure is most effective when the scan dimension is large compared to the scale of a few beams. The large telescope takes a certain amount of time to achieve the full scan speed in maps, and for small maps, it is not efficient to reverse the direction of the high speed scan every few seconds. Accordingly, for maps smaller than approximately one-half to one arcmin, a different map strategy is recommended.

For small maps, observers should treat each map point as a separate PS observation and compute the required time for an observation based on the time necessary to achieve the required level of sensitivity. The total required time will then be given by the number of map points multiplied by the time required for each map point.

6 Experience and Best Practices

In this section we summarize some of the results of commissioning and early science observing with the 1mm SIS Receiver and suggest some best practices for using the instrument. The topics covered here are primarily of value for planning observations once observing time is assigned and a detailed observing script must be prepared.

A general comment about the 1mm SIS Receiver is that it has not been commissioned and used to the same extent as the other LMT receivers. Thus, although scientifically useful data have been obtained, there remain a number of features to be ironed out. It is hoped that this work will be completed during the period before the start of science observations.

6.1 Receiver Tuning

The 1mm SIS Receiver has the ability to tune itself to new frequencies automatically. However, at this time the procedure is not fully optimized. Generally, receiver tuning is best at frequencies that are commonly used, such as the ^{12}CO J=2-1 transition at 230 GHz.

6.2 Antenna Pointing and Focus Measurements

The small beam of the 1mm SIS Receiver places a premium on precise pointing and optimization of the antenna focus, and successful observations depend on careful measurements of these values during the observing program. This requires observations of a source near (10 degrees) the target source. The 1mm SIS Receiver has recently been equipped with a beam chopper that can be used to measure continuum flux from relatively bright (1 Jy) sources. When fully commissioned, this system should allow routine observations of bright quasars close to the target object. It is also generally possible do pointing measurements on bright CO J=2-1 lines in carbon stars.

6.3 Birdies in the WARES Spectrometer

In the Intermediate and Narrow modes of the WARES spectrometer, there are a few known "birdies" in the band. The features are intermittent and do not always cause a problem. However, since one of the features falls at the center of the band, it is a good idea to plan to place spectral lines at positions in the IF where they will not encounter a problem. A summary list is provided in Table 6.2.

MODE	Channel	IF Frequency
Intermediate	1024	100 MHz
Intermediate	2048	200 MHz
Intermediate	3072	300 MHz
Narrow	1361	33.33 MHz
Narrow	2730	66.65 MHz
Narrow	2731	66.68 MHz
Narrow	4084	99.71 MHz
Narrow	4085	99.73 MHz
Narrow	4096	100.00 MHz
Narrow	4107	100.27 MHz
Narrow	4108	100.29 MHz
Narrow	5461	133.33 MHz
Narrow	5462	133.35 MHz
Narrow	6827	166.67 MHz

Table 6.2: WARES Channels to Avoid