Observing on the LMT
Redshift Search Receiver

Version	Version v2.0
Last update	September 11, 2022
Document ID	LMT-SCI-MAN-002
Keywords	Redshift Search Receiver, RSR
Pages	9

In publications, please refer to this document as LMT-SCI-MAN-002, Version v2.0. For user support please contact the LMT HelpDesk.

Document Writing

Editors	Peter Schloerb (PS), Caleigh Ryan (CR)
Reviewers	Peter Schloerb (PS)

Revision History

Version	**Date**	**Editor**	**Reviewer**	**Section (page)**	**Notes**
v1.0	11/11/2020	PS	-	-	Initial Version - 2021-S1
v1.1	08/25/2022	CR	-	Abstract	Added abstract and updated to new template.
v2.0	09/11/2022	PS	-	-	Update for 2023-S1

Reference Documents

Document ID	**Title**
-	-
-	-
-	-

Contents

Abstract

The Redshift Search Receiver is an ultra-wideband spectrometer with four receivers, covering the frequency band from 73-111 GHz, with a fixed spectral resolution of 31 MHz in that window. The system is calibrated using a "chopper wheel" method, and it is not currently set up to function as a continuum instrument. The RSR is meant to look at point sources using a position switching technique. The instrument uses 6 spectrometers to cover the band (with overlap on the edges), and results in 24 spectra that can be used individually or combined into the complete spectrum. Detailed descriptions of expected errors, 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 Redshift Search 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 Description of the Redshift Search Receiver

2.1 Instrument Overview

The Redshift Search Receiver is a special purpose, ultra-wideband, spectrometer developed for the purpose of conducting blind searches for spectral line emission from distant objects. The receiver produces a single spectrum of the frequency band from 73-111 GHz, corresponding to most of the 3mm atmospheric window. The spectral resolution has fixed value of 31 MHz over the entire frequency band. Figure 2.1 shows a sequence of RSR observations of submillimeter galaxies.

2.2 Location and Orientation of Receiver Beams

The RSR uses the technique of "beam switching" between adjacent beams on the sky to measure the difference between the emission from the source and the emission from blank sky. The nominal separation of the beams used for most observations is 78 arcsec. However, for observations of more extended sources, there is a wide throw option which creates a spacing of 294 arcsec between the beams.

The LMT optics result in a rotation of the field, and so the orientation of the two RSR beams changes with elevation angle. With telescope pointed to the horizon, the beam switch is in the azimuth direction on the sky. This orientation changes with elevation angle until, at zenith, the beams switch is along the elevation direction on the sky.

The RSR beams are diffration limited and well characterized by a circular gaussian function with half-power-beam-width (θ_{HPBW}) of approximately:

$$\theta_{HPBW} = 1.15\frac{\lambda}{D} = 14\left(\frac{\nu}{100GHz}\right) \text{ arcsec}$$

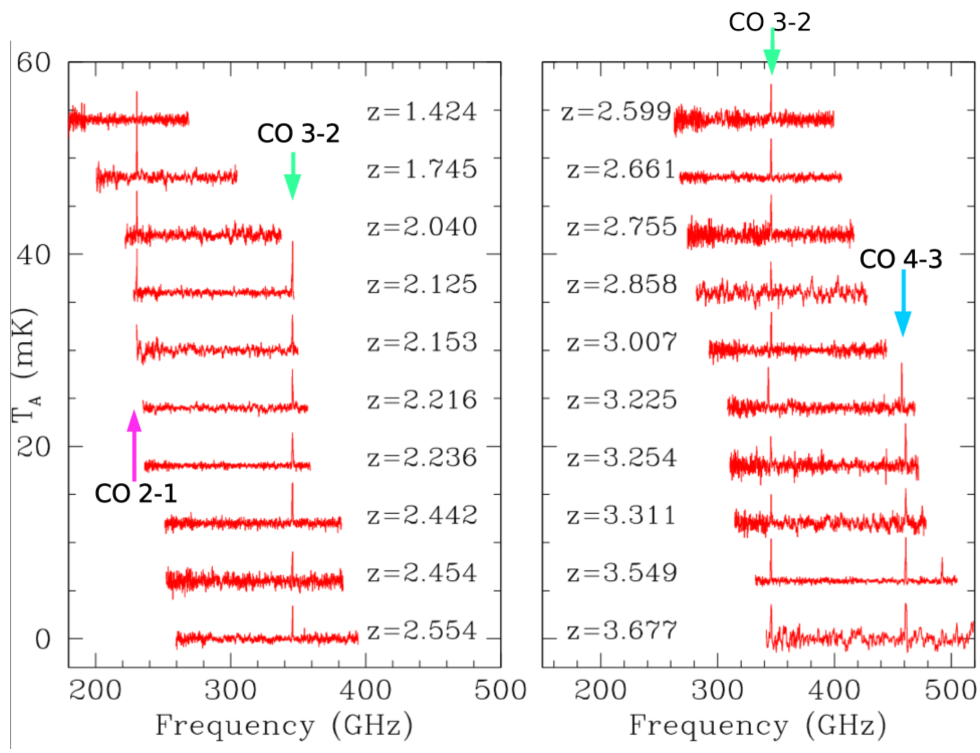

Figure 2.1: Redshift Search Receiver observations of submillimeter galaxies. Spectral lines from the CO rotational ladder are indicated. The frequency scale has been adjusted to the rest frequency of the source.

3 Calibration of the Redshift Search Receiver

3.1 System Temperature

The RSR is calibrated using the standard "chopper wheel" method that is in common use at millimeter-wave observatories. This technique corrects observations 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.

The observed system temperatures measured on the telescope do not show a strong frequency dependence across the 74-111 GHz band. Typical "chopper wheel" system temperatures in good weather conditions are at the level of 100K.

At some observatories we note that further corrections to the system temperature are made in an attempt to account for losses not included in the basic calibration and for coupling of the antenna's beam pattern to the source. These additional corrections are not applied to system temperatures measured at the LMT.

3.2 Systematic Effects in Source Measurement

The RSR receiver system has been optimized for maximum sensitivity to weak sources and not for high dynamic range observations. One feature of this optimization is that the chopper wheel calibration signal slightly saturates the system leading the system temperature measurements to be biased to lower values.

Another feature of the RSR is that the beam switched signal is not a pure square wave. There are portions of the time in the switch when the receiver sees contributions from both beams on the sky, and the result is that the full amplitude of the signal from the source is not achieved in the beam-switched spectral line system.

Both of these biases affect the value of antenna temperature that is recorded. However, the biases do not affect the overall calibration of the system, which is done by observing standard sources using the temperature scale established by the system temperature measurement.

3.3 Antenna Gain Factor

The RSR is intended to observe point sources, and so the conversion of antenna temperatures measured on the T_A^* scale to units of flux density is straight forward. This is conveniently expressed using a relationship between the number of Jansky of flux density required to produce one degree of antenna temperature. Observations of standard sources at LMT show that this gain factor is approximately 2.8 Jy/K at a frequency of 100 GHz.

A formal fit to measurements at different frequencies within the full RSR band (Yun et al 2020 memo) suggests that the following gain factor, G, should be employed:

$$G(\nu) = 2.8 \left(\frac{\nu(GHz)}{100\,GHz} \right) + 0.19 \text{ JyK}^{-1} \quad (1)$$

Given a gain factor for the 50m-diameter LMT, it is tempting to compute the aperture efficiency that is implied, and the factor of 2.8 Jy/K would imply an aperture efficiency of 50%. However, the measured antenna temperatures from the RSR suffer from the biases described in the previous section, and this leads to an underestimate of the LMT's aperture efficiency. Other observations show that the antenna is actually better than this with an efficiency of 55% at 100 GHz.

4 Use of RSR for Continuum Measurements

Continuum observations on scientific targets are not possible with the RSR at this time. Although the RSR has a mode which allows continuum measurements to be made for the purpose of pointing and focus determinations, these measurements do not require absolute calibration to be successful. Techniques are under development that will allow calibrated continuum measurements to be obtained by RSR, but at this time, this mode of observation is not supported.

5 Data Acquisition with the RSR

The Redshift Search Receiver consists of four receivers arranged as two dual polarization receivers sharing a common feed. The receiver optics direct the beam from each receiver to one of two positions on the sky, and the beam selected for a particular receiver is determined by a ferrite switch. By changing the switch, all beams may be alternated rapidly (1 kHz) between the two sky positions.

The RSR collects data in a way that combines rapid beam switching, between an on-source and off-source position, and telescope position switching which is used to alternate the position of the source between the two beams. In this way the beam switch of the receiver always has the source in one of the two beams in order to achieve the highest possible signal-to-noise ratio.

5.1 Expected Errors

To calculate the expected rms noise from an RSR obervation, let's begin with consideration of the beam switched portion of the observation. This part of the observation consists of rapidly switching the receiver between the two sky positions. We will label these positions 0 and 1. One beam is placed on the radio source with the other beam located on blank sky.

Let τ be the total integration time for a complete cycle with the source placed first in beam 1 and then in beam 0 by moving the telescope. In this case, $\tau/2$ is the amount of time with the telescope tracking one position with the source located in beam 1 and with beam 0 placed on the blank sky for a reference. The measurement is labeled T_{10}, meaning that it is the result of subtracting the observation of beam 0 from the observation of beam 1. If the source has signal T_S, then the expectation value for T_{10} is T_S. Following the expected rms error for normal position switching, it is clear that the error on this measurement will be:

$$\Delta T_{10} = 2\frac{T_{sys}}{\sqrt{\beta\frac{\tau}{2}}}$$

Now consider the observation with the telescope moved to place the source in beam 0 with beam 1 on blank sky. We'll call this measurement T_{01}. In this case, since the source has changed beams, the expectation value for the difference between beams is $T_{01} = -T_S$, and the error is:

$$\Delta T_{01} = 2\frac{T_{sys}}{\sqrt{\beta\frac{\tau}{2}}}$$

The final result is formed by taking the difference between the two measurements T_{10} and T_{01}. A straight difference of the quantities leads to $T_{10} - T_{01} = 2T_S$. So, to estimate T_S we must divide the difference by a factor of 2. Assuming independent errors between the two measurements, we have

$$\Delta T_S = \left[\left(\frac{1}{2}\right)^2 \Delta T_{10}^2 + \left(\frac{1}{2}\right)^2 \Delta T_{01}^2\right]^{\frac{1}{2}} = 2\frac{T_{sys}}{\sqrt{\beta\tau}}$$

Finally, since the above pertains to just one of the four receivers, if we assume that each receiver produces an independent measurement, the result of averaging the four measurements is equivalent to a single observation with four times the integration time. So the final error, $\Delta\bar{T_S}$, would be

$$\Delta\bar{T_S} = 2\frac{T_{sys}}{\sqrt{\beta 4\tau}} = \frac{T_{sys}}{\sqrt{\beta\tau}} \qquad \text{((RSR rms error))}$$

If we adopt the formula for the gain factor (Equation 1) to compute the sensitivity of the RSR at different frequencies within the band, then

$$\Delta S_{rms} = G(\nu)\frac{T_{sys}}{\sqrt{\beta\tau}}$$

CALCULATED EXAMPLE

The RSR channels have a frequency width (β) of 31 MHz. The system temperature (T_{sys}), measured using the chopper wheel method, is approximately 100 K in reasonable conditions. Consider a 10 minute integration time (τ), corresponding to 600 seconds. We have the error in one channel of:

$$\Delta T_{rms} = \frac{T_{sys}}{\sqrt{\beta\tau}} = \frac{100}{\sqrt{31 \times 10^6\ 600}} = 0.0007K$$

Thus, the nominal values for the RSR lead to approximately 1 mK in a 10 minute integration, which is the number used in the RSR calculator. Given the gain factor relationship in Equation 1, this then implies an rms flux density error of about 3 mJy in a 10 minute integration.

5.2 Observing Overhead

An RSR observation is a position-switched observation. Thus, some part of the elapsed time requried to take 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. For standard RSR 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.

5.3 Redshift Receiver Data Products

The RSR spectrometer section covers the full frequency range of the receiver using 6 spectrometers. The sub-bands covered by the spectrometers provide overlap at the band edges. Thus, a single observation with the RSR consists of the 6 sub-bands for each of the four receivers and a total of 24 spectra which may be analyzed separately or merged to produce the full complete spectrum.

The RSR frequency scale is “sky frequency,” meaning that no frequency corrections are made to account for Earth motions or motion of the Sun with respect to the local standard of rest. We note that these corrections are smaller than the 100 km/s resolution of the spectrometer.

Most RSR observations involve averaging of multiple individual observations to achieve a long integration time. The RSR reduction pipeline is capable of providing a FITS file for each individual observation, following reduction of the raw data and calibration, as well as a FITS file containing the complete integration merging all individual spectra obtained on the source.

6 Experience and Best Practices

Spectral line measurements over very wide bandwidths require special attention to many details. Generally, the Redshift Search Receiver provides good baselines over the full band under good weather conditions. However, there are some circumstances to consider that are known to affect the baselines and the results.

6.1 Impact of Poor Weather

The best RSR spectra require the best weather. The quality of the weather is judged not only on the optical depth of the atmosphere, but also on the stability of the atmosphere. Under unstable conditions, variations in the emission from the atmosphere can lead to large differences in the signals seen by the two beams and result in poorer quality baselines.

6.2 Spectral line observation of source with continuum emission

Some RSR targets are moderately strong (few mJy) continuum sources. The RSR is capable of detecting the continuum offset in the spectrum, but the spectral baselines are significantly poorer under these conditions than is seen in sources without underlying continuum emission. This results from the small mis-match in signal level that occurs in the switch between the RSR beams due to the extra continuum signal.

6.3 Receiver instability near 92 GHz

The receiver has an unstable region over a band of about 1 GHz near the frequency of 92 GHz which sometimes leads to poor baselines. It is important to identify poor quality spectra in this region and remove them from averages.

6.4 Sensitivity Limits

The Redshift Search Receiver noise reliably improves with the square root of the integration time for periods up to approximately two hours, corrsponding to levels of approximately 0.3 mK rms or 1 mJy rms. However, beyond this level, systematic errors in receiver baselines become important. Thus, although integrations longer than 2 hours can achieve lower rms noise levels, they do not show improvements according to the square root of the integration time.