Observing on the LMT
SEQUOIA

Version 1.1

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VERSION/CHANGE LOG

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1.0	11/12/2020	Initial Version - 2021-S1
1.1	12/08/2020	Added section to compare 2021-S1 aclculator with 2018-S1 calculator

Contents

1 Introduction

This document is intended to provide some basic information about the SEQUOIA instrument 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

2.1 SEQUOIA Array Characteristics

SEQUOIA is a 16-element focal plane array arranged in a 4 by 4 grid. The spacing between pixels in the grid is 27.8 arcsec. Thus, the diagonal distance across the array, measured as distance between the beam centers, is approximately 2 arcmin. Figure 1 shows the arrangement of the beams on the sky.

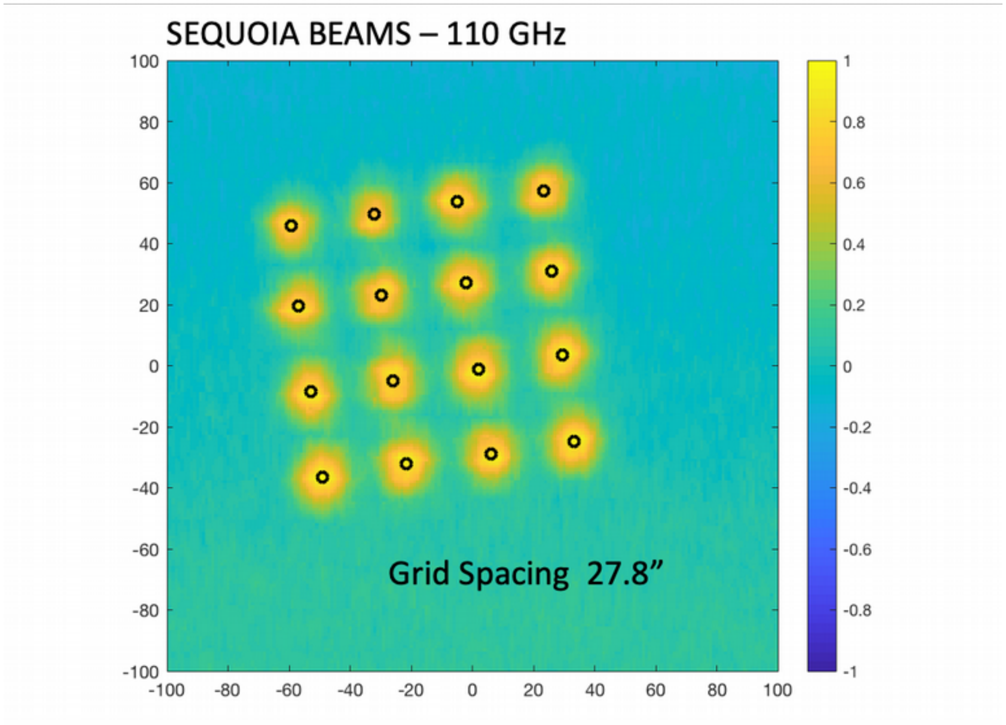

Figure 1: Observation of the SEQUOIA Focal Plane Array beams on the sky. This map is created by summing the signals from all 16 pixels of the array, so that the relative positions of the beams are shown. The black circles show the fit of the beams to a regular 4X4 grid. The coordinate system is Azimuth-Elevation in units of arcseconds.

An important feature of the array is that it rotates about its center on the sky, both with respect to the Azimuth-Elevation sky coordinate system as well as with respect to the celestial sphere, as the elevation angle changes. Thus, considering the arrangement shown in Figure 1, one must be aware that the orientation of the array will be different at other elevation angles.

The beams in the array are well represented by a gaussian function with half-power-beam-width (HPBW) that is proportional to the wavelength. A good rule of thumb is that the HPBW (θ_{HPBW}) is approximately

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

2.2 Frequency Coverage and Spectrometer Modes

SEQUOIA provides 15 GHz of instantaneous bandwidth, covering two possible frequency bands from approximately 84.5-100 GHz and 100-115.5 GHz. Spectral lines within this frequency band are observed using the WARES spectrometer system. Each pixel of the SEQUOIA focal plane array is connected to an input channel of the WARES spectrometer system. WARES provides three possible options for taking spectra, summarized in Table 1, with channel bandwidths of 391 kHz, 98 kHz, and 24 kHz for the Wide, Intermediate, and Narrow modes of the spectrometer.

MODE	**Wide**	**Intermediate**	**Narrow**
Total Bandwidth (MHz)	800	400	200
N Channels	2048	4096	8192
Channel Bandwidth (kHz)	391	98	24
HCN J=1-0 @ 88.6 GHz			
Total Bandwidth (km/s)	2709	1354	677
Resolution (km/s)	1.32	0.33	0.08
CO J=1-0 @ 115.3 GHz			
Total Bandwidth (km/s)	2082	1041	520
Resolution (km/s)	1.02	0.25	0.06

Table 1: WARES Spectrometer Modes

A new development is underway at LMT that will double the number of input channels for each SEQUOIA pixel to allow two spectral regions within the 15 GHz receiver band to be observed simultaneously. Thus, for example, with this arrangement one could observe ^{12}CO and ^{13}CO simultaneously since these lines fall within the same band form 100-115.5 GHz.

3 SEQUOIA Calibration

SEQUOIA data are calibrated using the “chopper wheel” method and all results are reported as antenna temperatures in the T_A^* system of units. Under good weather conditions, the chopper wheel system temperature measured on sky is approximately 90 K[1] over most of the band. At the high end of SEQUOIA’s frequency range, where the important ^{12}CO J=1-0 is observed, the system temperature rises to approximately 180 K[1] due to the influence of the nearby terrestrial oxygen absorption line at 118 GHz.

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[1] The LMT Observing time calculator uses a value of 100 K for $\nu < 113$ GHz and 300 K for $\nu > 113$ GHz.

Using the T_A^* calibration, the LMT aperture efficiency with SEQUOIA is approximately 55% corresponding to a gain factor of 2.6 Jy/K. The main beam efficiency is approximately 65%.

4 Use of SEQUOIA as a Continuum Receiver

SEQUOIA can collect data in total power mode, which makes it possible to observe continuum from the planets and from the brightest quasars under good weather conditions. The instrument is not optimized for sensitive continuum measurements.

5 Data Acquisition with SEQUOIA

The SEQUOIA focal plane array is used in two basic data acquisition modes: (1) a position switching mode, wherein the telescope is used to move the array between an *On* and *Off* position; and (2) an "on-the-fly" mapping mode where the telescope is scanned over the radio source to make a map. We will consider each of these below.

5.1 SEQUOIA Position Switching

5.1.1 PS - Nominal Position Switching

In this mode, the entire array is moved between an *On* and an *Off* position on the sky and the difference is determined. For observations with SEQUOIA in this mode, one usually has the telescope track one of the pixels within the array (often pixel 10). In this way, switching on and off the source will lead to a spectrum for the point tracked by pixel 10. Note that because the array rotates on the sky as the source is tracked in elevation, the other pixels in the array do not track fixed positions on the sky. Therefore, this method is best used to obtain a single spectrum at a single point on the sky for science or tracking of day-to-day calibration variations.

This observing example is a normal position switched spectrum and so the appropriate rms in a spectrometer channel would be:

$$\Delta T_{rms} \;=\; 2\frac{T_{sys}}{\sqrt{\beta\tau}}\ \mathrm{K} \qquad \text{(SEQUOIA PS Observation)}$$

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

EXAMPLE

Let's consider an observation at the frequency of the HCN J=1-0 transition (88.6 GHz). The system temperature in reasonably good conditions is 90 K. Using the wideband spectrometer mode the spectral resolution is 391 kHz, corresponding to 1.3 km/s, results in a rms antenna temperature of 11 mK in a 10-minute integration. Using a nominal gain factor of 2.6 Jy/K this corresponds to a flux density sensitivity of 31 mJy.

5.1.2 BS - SEQUOIA Beam Switching

For sources smaller than the antenna beam, a signal-to-noise advantage can be obtained by switching the SEQUOIA array back and forth between two of the pixels in the array. This observing procedure is called "beam switching" at the LMT since we are switching between two beams in the array. In this case, we can form two *On-Off* position switch pairs for the two pixels and then average the two spectra that result. Assuming the spectra from the different array pixels are statistically independent, this procedure the doubles the total integration on the source, resulting in a $\sqrt{2}$ improvement in the noise. Thus, the appropriate rms in a spectrometer channel would be:

$$\Delta T_{rms} \;=\; \sqrt{2}\frac{T_{sys}}{\sqrt{\beta\tau}}\ \mathrm{K} \qquad\qquad \text{(SEQUOIA BS Observation)}$$

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.

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 a single spectrum in a FITS format data file.

In the nominal position switching mode, where the entire array is moved fully off of the source, it is also possible to provide spectra from all 16 SEQUOIA pixels with the caveat that only one of the spectra is located at a fixed point on the sky while the other pixels will drift in their position with time as the array rotates. We note that for short duration observations the amount of rotation may be small enough to avoid smearing by the field rotation and permit useful maps to be carried out in PS mode with the full array, as described in section 5.4.

5.2 On-The-Fly (OTF) Mapping with SEQUOIA

5.2.1 Introduction

The SEQUOIA focal plane array is intended to be a mapping instrument. Maps at the LMT are constructed using the "on-the-fly" or OTF technique. We recommend a paper by Mangum, Emerson, and Griesen (https://www.aanda.org/articles/aa/pdf/2007/41/aa7811-07.pdf) which describes the basic OTF principles in detail.

In OTF mapping, the SEQUOIA array is scanned over the sky and the spectra from the SEQUOIA pixels are recorded at a regular cadence on a short sampling time interval of τ_{DUMP}, so called because it is the time between "dumps" of all the data from the full spectrometer.

5.2.2 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 necessary scan rate:

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

Nominal values for SEQUOIA scanning would consider a resolution element of about 12 arcsec at the middle of the SEQUOIA band and require a scan rate of 31 arcsec per second, which is well within the allowed range of scan rates for the LMT.

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 at 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.

5.2.3 Scanning Patterns

SEQUOIA at the LMT has been commissioned using scans made 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 a bit 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 regions on the order of the size of the SEQUOIA array footprint. 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.

5.2.4 Sensitivity Achieved

A standard map at the LMT will have a pixel size θ_{PIX} that is one-half of the resolution element ($\theta_{PIX} = \frac{\lambda}{2D}$) 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. The time spent in a map pixel (τ_{PIX}) by one of the SEQUOIA beams 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 commissioning tests is approximately 1.5.

Scanning the array in rows separated by f, as described above, means that all of the beams in a focal plane array will contribute to the integration time that goes into a map pixel. Thus, assuming independent receivers, the amount of integration time per pixel is increased by N_R the number of receivers, where $N_R = 16$ in the case of SEQUOIA. Using the radiometer equation, we may write an expectation for the rms within a map pixel:

$$\Delta T_{rms} = \frac{1}{\sqrt{N_R}} \frac{T_{sys}}{\sqrt{\beta \tau_{PIX}}} = \frac{1}{\sqrt{N_R}} \frac{T_{sys}}{\sqrt{\beta}} \left(\frac{Sf}{\theta_{PIX} \eta} \right)^{\frac{1}{2}} \text{ K} \quad \text{(SEQUOIA OTF Observation)}$$

5.2.5 OTF Data Product

A thirty minute OTF map with SEQUOIA will produce 288,000 dumps from the spectrometer which need to be reduced and "gridded" into a map. Assuming use of WARES in its Narrow band mode, with 8192 spectral channels, this corresponds to about 9 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 containing all map spectra after an initial reduction (e.g. calibration and removal of reference measurements) will be provided in a standard format. A development effort is underway to identify useful formats for the users.

5.3 Assumptions in the SEQUOIA Observing Time Calculator

The LMT provides an observing time calculator to allow prospective observers to make estimates of map RMS obtained in a given amount of observing time or the time required to achieve a particular map rms. The calculator requires adoption of a particular set of parameters described in the model of map RMS presented in the sections above. Here we describe the values adopted for the calculator associated with the 2021-S1 call for proposals. These values are then compared to values in the 2018-S1 calculators with the idea of explaining differences that result.

5.3.1 2021-S1 Calculator Parameters

The parameters for the calculator for the 2021-S1 call for proposals has benefited from the results of commissioning testing of the SEQUOIA instrument.

- System Temperature (T_{sys}) - The system temperature is assumed to be 100K for frequencies less than 113 GHz. For frequencies above 113 GHz, we assume a value of 300 K.
- Map Cell Size - The size of a map pixel is set to the size of the "Nyquist Cell" ($\theta_{PIX} = \frac{\lambda}{2D}$) in order to assure full Nyquist sampling of the spatial frequencies in the map. Note that this is one-half of (λ/D), the nominal resolution of the map.

- Scan Spacing - the spacing between scans of the array is 0.9 θ_{PIX}.
- Spatial Filtering Factor (η) - A value of 1.5 has been adopted for this factor based on SEQUOIA commissioning test results.
- Number of SEQUOIA beams that hit each map pixel - the map is set up so that *all* pixels are sampled by *all 16* SEQUOIA beams. We note that scanning patterns with fewer beams sampling the pixels can improve the speed of the map at the cost of poorer RMS per pixel.
- Spectrometer dump time (τ_{DUMP}) - The dump time is not a free parameter in 2021. We set it to the fastest possible sample time of 100 ms.
- Number of samples per resolution element (n_s) - the number of samples within the resolution element (λ/D) is adopted to be 4.
- Scan Speed (S) - Scan speed is not a free parameter in 2020 calculator. It is set by the adopted dump time and the requirement for number of samples within a resolution element.

5.3.2 Differences between 2021-S1 Calculator and 2018-S1 Calculator

For the previous call for proposals (2018-S1), a somewhat different set of assumptions was adopted for the map calculators, based on the theoretical expectations rather than actual measurements at the telescope. In addition, the basic model for 2018 mapping made some choices for the purpose of improving map speed to the greatest extent possible.

One important difference between the calculators is that the scanning pattern in 2018 assumed that only four of the SEQUOIA beams passed over each map pixel. In this scanning pattern, the array could take larger steps in the cross scan direction and reduce the map time by a factor of 4.

Comparison of the expected RMS of the map depends on more of the assumed parameters. These are summarized in Table 2 to show that the 2021 calculator should have $\sqrt{2}$ *worse* RMS than the 2018 calculator. This is largely due to the fact that the 2018 calculator averaged four Nyquist-sized pixels together, corresponding to a pixel the size of a resolution element, to estimate the RMS.

When all things are considered, the time estimate to make a map to a particular RMS is different in the two calculators. The time to make a single map is 4 times less in the 2018 calculator and the RMS estimated by the 2018 calculator for a single map is $\sqrt{2}$ better than the 2021 calculator. This means that a direct comparison of the time to achieve the same RMS will lead to a factor of 8 between the calculators.

A factor of 8 seems like a big difference, but it is just the result of: (1) different assumptions about the final resolution of the maps; and (2) a different value for the spatial filtering parameter η to use a value based on actual measurements for the 2021 calculator. To make the comparison of the calculators at the same spatial resolution, one would average four pixels in the 2021 calculation to achieve a factor of 2 improvement in the map RMS so that the 2021 calculation would now yield a net improvement in RMS of $\sqrt{2}$ compared to the 2018 value. Computing the time to achieve the same RMS in the two calculators then results in a factor of 2 difference in time. This difference is accounted for by the new (for 2021) assumption about the spatial filter parameter, η.

Parameter	**2021-S1**	**2018-S1**	**Impact**
T_{sys}	100	100	No difference
Map Cell Size	$\frac{\lambda}{2D}$	$\frac{\lambda}{D}$	2021 map RMS will be 2 times worse than 2018 value
Scan Spacing	0.9	0.9	No difference
Spatial Filter	1.5	3.0	2021 map RMS will be $\sqrt{2}$ times worse than 2018 value
Beams per Pixel	16	4	2021 map RMS will be 2 times better than 2018 map.
Scan Speed	Not Free Parameter	Free Parameter	No difference for same scan speed assumption.
Relative RMS			2021 map RMS will be $\sqrt{2}$ times worse than 2018.

Table 2: RMS Comparison of Map Calculator Assumptions in 2021 and 2018

5.3.3 This seems very confusing. What values should I use?

The 2021-S1 calculator computes the map RMS for a pixel size of $\lambda/2D$, corresponding to Nyquist sampling of the map. If that's what you want, then that's what you get from the calculator. On the other hand, this resolution might not be required for your project if a lower spatial resolution, perhaps corresponding to pixels with size of λ/D, would be adequate. In that case, we note that you could smooth over four of the Nyquist sampled pixels to improve the RMS by a factor of 2 at the cost of lower resolution. This is equivalent to a factor of 4 improvement in the length of time required to reach a particular RMS level.

Another point about the calculator is that the map RMS that is produced depends on the spectral resolution as well. The SEQUOIA calculator uses the spectrometer mode that is selected to find the spectral resolution for the RMS calculation (e.g. 1 km/s resolution for the Wide spectrometer mode). For some applications, we note that one might not require the full resolution provided by the spectrometer. For example, mapping external galaxies might only require 5 km/s resolution in which case ∼5 channels could be averaged together to improve the RMS by a factor of $\sqrt{5}$. This would be equivalent to a factor of 5 improvement in the length of time required to reach a particular RMS level.

5.4 How do I make a small map with SEQUOIA?

OTF mapping observations assume that the array is scanned across the source and the mapping sensitivity calculators assume that the scan pattern allows all elements of the SEQUOIA array to cross each pixel in the map of the source. This implies mapping scans at least as large as the array itself.

The distance between the center of the beams at the corners of the SEQUOIA array is approximately 2 arcmin. Thus, the map calculator does not produce the best estimates of observing time if the desired region is 2 arcmin or smaller. We recommend two possible strategies to make small maps: (1) just go ahead and make a bigger map using the standard OTF procedures with a size of approximately 2 times the array dimension; or (2) make use of PS observations to sample the source within the footprint of the array. For the latter case, we note that 16 PS observations spaced by the Nyquist cell size ($\frac{\lambda}{2D}$) are sufficient to complete a fully sampled map over the SEQUOIA array footprint. So, as a rule of thumb, the required integation time for a small map can be computed by requiring 16 PS observations of the source.

It is important to note that, in actual implemention of this strategy, one must account for the field rotation of the array. This can be addressed in detail when observing scripts are prepared for the observation queue.

6 Experience and Best Practices

In this section we summarize some of the results of commissioning and early science observing with SEQUOIA 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.

6.1 A Quick Tutorial about the Map Program

The concepts behind the LMT Map program are straightforward. The program is quite flexible and it is possible to specify maps with a number of different sampling properties. Here we describe what happens in a "standard" map that is scanned on a rectangular grid.

Maps are obtained by scanning the telescope across the source. The direction of the scan can be specified by the user to coincide with the source being mapped, as for example in the case of scanning along the major axis of an external galaxy. Sampling of map points within the scan is determined by the "dump time", τ_{DUMP}, and the scan speed, S, which have been described above. The length of the scan determines one of the two dimensions of the map.

In LMT nomenclature, the scan direction is the "X" axis of the map. To build up observations in the "Y" dimension, the antenna beam is offset by a small amount between scans across the source. Typically, this offset is chosen to be approximately the Nyquist cell size ($\frac{\lambda}{2D}$). The total dimension in "Y" is then determined by the number of scan rows.

Regular observations of a reference position and regular calibrations are necessary to obtain the best map data. (Considerations about these points are presented in sections below.) These observations are built into the map procedure and typically occur either every few rows of the map or even every row of the map for some types of observations.

It is straight forward to estimate the time to make a map from the time required to scan a row of the map multiplied by the number of rows of the map. This calculation is done in the map time calculator and is referred to as the "scan time" for the map. However, because the antenna is moved to the reference position periodically, the total time required to complete a map is always greater than the basic scan time.

6.2 Observations of Reference Position

Mapping observations are carried out by interleaving a sequence of spectra on the region being mapped with observations of a blank sky reference position. The selection of a reference position for the map is important. The closer the reference position is to the map the better, since it takes less time to make the observation leading to better results over all. On the other hand, it is obviously important to select a position that is known to be free of emission. For large molecular cloud complexes this can pose a problem.

For map observations of a single narrow spectral line, the source can be scanned for minutes between the blank sky reference observations without affecting the spectrometer baselines. However, when the observation requires good baselines over wide bandwidths, then it is necessary to move to the blank sky reference position more frequently, on time scales of half a minute, usually corresponding to the time to make a scan of the array across the map.

A single reference observation will be used to remove the background from many on source spectra. Therefore, it is important to allow enough integration time on the reference position so that the noise level in the on-source spectra is dominated by the noise in the on-source measurement. A rule of thumb is to set the reference integration time to be equal to the integration time for on-source spectra times the square root of the number of on-source points obtained between reference observations.

6.3 Time to Complete a Map

The reference measurements affect the amount of time to complete the observation since time is spent moving the telescope between map and reference instead of integrating on the map region. Thus, there is always a trade off that depends on the goals of a particular experiment. The SEQUOIA map calculator simply computes the time necessary to scan the region to be mapped at the rate specified, which we shall refer to as the *scan time* for the map. The *elapsed time* for a map, as measured from start to finish of the observing sequence is approximately a factor of 1.7 larger than the *scan time*.

6.4 Best Approach for Long Integrations

As noted above, one might be tempted to slow the mapping speed down in order to obtain more integration time in each pixel of the map. However, this practice is not recommended, and it is better to build integration time by making a series of short maps and then adding them together. Comparison of individual maps also allows a better assessment of possible variability in the calibration of the spectra between maps.

6.5 Importance of Calibration Updates

When the desired map gets to scales of many arcminutes, one finds that the length of time to make the map can extend to half an hour or more. During such a long time, the sky conditions are likely to change, and so we recommend either: (1) arranging your observing program to make a series of smaller maps to cover the full region to be mapped and then merge the results; or (2) defining your mapping sequence so that it will carry out system temperature measurements at regular intervals during the map.

6.6 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 3.

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 3: WARES Channels to Avoid