8. Scientific Instruments

8.1 Introduction

The LMT and its instrumentation unite to form a unique and powerful facility to pursue innovative research programs over a broad range of astrophysics. With nearly 2000 m^2 of collecting area and an accurate primary surface, the LMT when completed will have unrivaled point source sensitivity within the millimeter band. As a filled aperture telescope equipped with both bolometer and heterodyne focal plane arrays, the LMT will have optimum sensitivity to low surface brightness emission at angular resolutions of 6-12 arcsec. These sensitivity and imaging characteristics are complementary to many current and future astronomical facilities (GBT, CARMA, ALMA, HST, Spitzer, Herschel, JWST).

Cometary comae, circumstellar disks, star-forming regions, and distant galaxies are all targets which contain both gas and dust, and therefore will benefit from both continuum observations and spectral line data obtained with the LMT. Because emission from dust particles is almost always optically thin, mm continuum observations provide an estimate of the total mass along a given line of sight. Spectral line observations of a region bring knowledge of the velocity, chemistry, gas density, and temperature.

Below, we describe the first generation of continuum and heterodyne receivers being built for the LMT, and also outline ambitious plans for the next generation of instrumentation, which will be installed after the first few years of operation.

8.2 First-Generation Continuum Cameras

In the current era a primary scientific role for large mm-wave telescopes involves the ability to use array receivers (mm-wavelength "cameras") to make large surveys of the sky. In this sense, the LMT and ALMA will be highly complementary facilities. At 1.1 mm the LMT's high continuum sensitivity and 4 arcmin field of view will allow it to map large areas of sky at 6 arcsec resolution with more than an order of magnitude higher mapping speed than ALMA in its compact configuration—revealing thousands of sources for ALMA to later image at higher resolution. Furthermore, the flexible set of first-generation instruments available at he LMT allows one to quickly follow up newly discovered targets with specialized instrumentation.

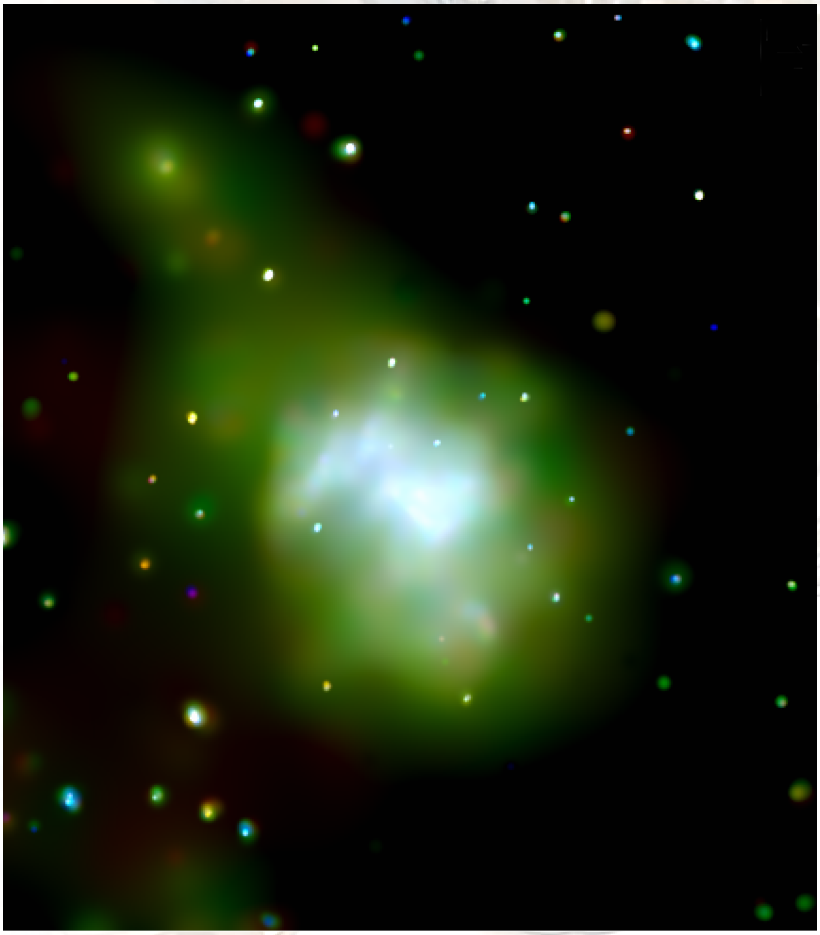

Figure 8.1 Chandra X-ray image of a galaxy cluster at z = 0.7, proposed to be imaged with AzTEC.

Herein we describe two bolometer systems currently under construction as the first-generation continuum instruments for the telescope. The Astronomical Thermal Emission Camera (AzTEC), a 144-element bolometer array, is an imaging camera designed to make deep, yet large, maps at 1.1 and 2.1 mm. The SPEctral Energy Distribution (SPEED) camera is a 16-element array of frequency selective bolometers (FSBs). Each of its four pixels simultaneously observes in four frequency bands—2.1, 1.3, 1.1, and 0.85 mm—with the same angular resolution. SPEED will be used as a follow-up instrument for photometry of sources detected in the AzTEC fields. Both instruments will be field-tested at other telescopes prior to installation at the LMT and will subsequently be used for commissioning of the telescope. Together, they will detect and characterize the mm-wave spectral energy distributions of a wide variety of sources at both low and high redshifts.

8.2.1 AzTEC

AzTEC is a large-format bolometer array camera under development at the University of Massachusetts Amherst in collaboration with the BOLOCAM instrument team at CalTech, JPL, the University of Colorado and the University of Cardiff, Wales. The instrument's detector array, comprising 144 silicon nitride micromesh bolometers fabricated on a single wafer of silicon, is nearly identical to that used in the BOLOCAM instrument[1]. The array operates at 1.1 and 2.1 mm, although only one bandpass will be available per observing run. While AzTEC is, in concept, a copy of the original BOLOCAM instrument, there are many significant changes made in an attempt to improve performance and simplify operation.

The bolometer array is cooled by a three-stage, closed-cycle ^{3}He refrigerator custom built by Chase Research Cryogenics, Ltd. The fridge utilizes the temperature-dependent adsorptive qualities of charcoal to operate its three helium pumps (^{4}He/ ^{3}He/ ^{3}He) and can operate from ambient pressure (non-pumped) liquid helium bath temperatures. The refrigerator's ultra-cold stage operates at a temperature of 250 mK and is thermally tied to the bolometer array. This stage is buffered by a 360 mK intercooler stage. All wiring and mechanical supports are thermally sunk to this intercooler stage before connecting to the 250 mK load resistors and bolometers. Lab tests show that operational temperatures are maintained for approximately 48 hours under no optical or wiring load and should last more than 24 hours when under expected loading conditions. Operation of the fridge is computer-controlled and fully automated in the complete instrument.

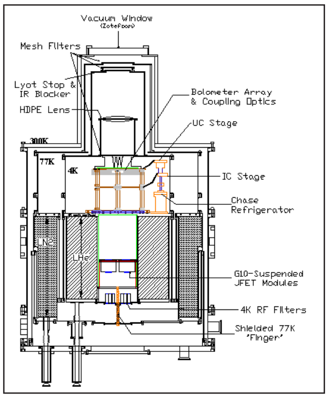

Figure 8.2 Diagram of AzTEC cryostat cross-section, complete with cold electronics, detectors, cryogenics, and cold optics[3].

We designed a robust new cryostat, custom-built by Precision Cryogenics, to house AzTEC. This flexible cryostat design will be used for future continuum instruments, including the SPEED instrument described in Section 8.2.2. The all-aluminum cryostat consists of concentric liquid helium and liquid nitrogen tanks with capacities of 23 and 26 liters, respectively.

In perhaps the largest deviation from the original BOLOCAM design, the warm readout electronics for AzTEC have been redesigned to minimize the analog signal path, simplify the electrical connections between the front-end and back-end electronics, and eliminate signal ground connections between all computers and the radiometer. The system architecture utilizes fiber optic connections carrying the AES/EBU protocol for commanding, clock distribution, and signal transmission. All clocks in the system are derived from (and phase locked to) a single master crystal that resides in the back-end electronics.

We may estimate the sensitivity of AzTEC using the bolometer noise theory of Mather[2]. For these calculations we assume a bolometer coupling efficiency of 0.15, a total telescope loading of 54 K (including receiver coupling mirrors), a telescope efficiency at 1.1 mm of 40%, and observing through an atmosphere with 2 mm of precipitable H_2O (the median value at the LMT site). Results for these calculations are shown in Table 8.1.

Since AzTEC will be completed before the LMT is ready for observations, work is under way for integration with other telescope systems. For example, a successful test run was carried out on the JCMT in June 2005.

Table 8.1 Sensitivities and optical parameters for AzTEC on the LMT at 1.1 mm given the assumptions outlined in the text[3]

NEP [aW/√Hz]	93
NET_{RJ} [mK/√Hz]	1400
NEFD [mJy/√Hz]	2.95
Beam Size [arcsec]	7
F.O.V. [$arcmin^2$]	2.4
Mapping Speed [$deg^2/hr/mJy^2$]	0.36

8.2.2 SPEED

The SPEctral Energy Distribution camera—SPEED—is capable of observing four frequency bands simultaneously[4]. SPEED is funded by NASA as a prototype instrument to demonstrate a new detector technology, the frequency selective bolometer (FSB), which is being developed by a collaboration of instrument builders at the University of Massachusetts Amherst, NASA/GSFC, and the University of Chicago. The camera is configured as a 2 x 2 array with each pixel housing a 2.1, 1.3, 1.1, and 0.85 mm detector. By sampling these wavebands, SPEED measures the mm spectral energy distribution of a source in a single pointing, eliminating the need for repeated observations of the same target. The efficiency with which SPEED obtains multi-frequency observations makes the camera ideal as a companion to a mapping instrument like AzTEC.

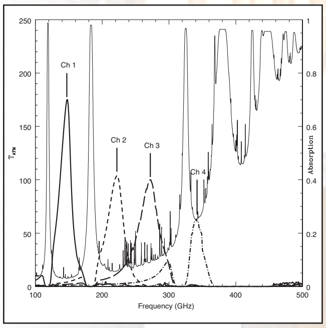

Figure 8.3. Model of the effective atmospheric temperature with 2 mm of precipitable water vapor at the LMT site. Overlaid on the model are the four predicted SPEED passbands[3].

Unlike traditional wide-bandwidth bolometers that require external filters to define the detector's bandpass, FSBs use a lossy quasi-optical interference filter as a power absorber. Each detector absorbs a narrow band of radiation and allows all radiation outside that band to pass through with low loss. By cascading FSBs tuned to different absorbing frequencies, it is possible to create a compact multi-frequency pixel so that, unlike systems that use dichroic filters, the spectral coverage of an FSB photometer is not limited by the mass and size of the cryostat but rather by the available bandwidth at the telescope focal plane.

The SPEED camera uses four FSBs to observe through the atmospheric windows at 2, 1.2, and 0.85 mm. In Figure 8.3 we show the predicted bandpass of each of the four channels of the SPEED instrument overlaid with a model of the atmosphere at the LMT site. By tailoring the geometrical properties of the interference filter and adding band-suppressing notch filters we are able to maximize the bandwidth of each SPEED channel and limit the power contribution from saturated oxygen and water lines in the atmosphere.

The FSB thermistors are voltage-biased transition edge superconducting (TES) sensors formed as a bilayer of molybdenum/gold. The TESs are cooled to 270 mK via a ^{3}He refrigerator and biased into their transition region by applying a current through a shunt resistor in parallel with the TES. Strong electrothermal feedback keeps the TES in the transition region and nearly isothermal. Characterization of prototype detectors at UMass Amherst and by colleagues at GSFC has demonstrated the repeatability of creating SPEED sensors with appropriate characteristics. SPEED's sixteen TESs will be read through a Superconducting Quantum Interference Device (SQUID) 1 x 8 multiplexer developed at the National Institute of Standards and Technology (NIST). Although multiplexing is not critical with only sixteen detectors, we are developing the multiplexing infrastructure at the LMT institutions for future large-format TES instruments.

In Table 8.2 we give the expected sensitivities derived from bolometer noise theory for each of the four channels in SPEED. As in Table 1, these sensitivities are based upon the instrument operating at the LMT with 2 mm of precipitable (ppt) water vapor and, to be conservative, assume an additional factor of 0.5 on the efficiency predicted by our optical model. Although we anticipate conditions at the LMT to be dry, we have designed our bolometers to operate with up to 8 mm of precipitable H_2O to enable diagnostic testing in high loading conditions.

The SPEED instrument is expected to be field-tested at the Heinrich Hertz Telescope in Arizona during 2005, where it will remain for scientific applications until commissioning of the LMT begins.

Table 8.2. Instrument parameters and calculated sensitivities for SPEED/LMT. See the text for assumptions impacting the sensitivity calculations[3]

	Channel 1	Channel 2	Channel 3	Channel 4
Center Frequency [GHz]	145	214	273	375
Beam Size [arcsec]	11	11	11	11
NEP [aW/√Hz]	139	194	266	324
NET_{RJ} [mK/√Hz]	593	449	382	505
NEFD [mJy/√Hz]	0.93	1.50	1.83	3.26

8.3 First-Generation Heterodyne Receivers

Spectroscopic (heterodyne) receivers can be used to produce images of molecular line emission which constrain kinematics and chemical and physical conditions in the observed gas. Focal plane arrays, like SEQUOIA, will allow LMT to perform rapid imaging with high sensitivity over large scales at the full resolution of the telescope. SEQUOIA has already been constructed and has been in use at the FCRAO 14 m telescope since 2002 (since 1998 in a partial version). Combined with the existing on-the-fly mapping technique and a suite of software that helps produce final spectroscopic cubes, SEQUOIA on the LMT will produce immediate results.

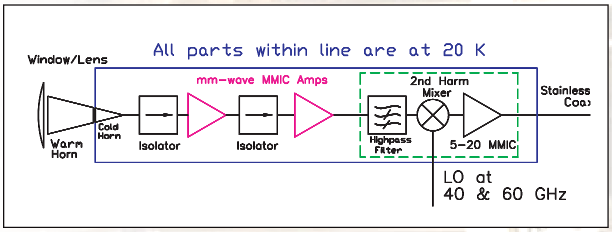

Figure 8.4 Block diagram of a single SEQUOIA pixel[5].

In the following sections, we summarize three heterodyne receivers that form the complement of first-generation spectroscopic instrumentation on the LMT.

8.3.1 SEQUOIA: The World's Fastest 3 mm Focal-Plane Array

SEQUOIA is a cryogenic focal plane array designed for the 85-115.6 GHz range. It has 32 pixels arranged in dual polarized 4 x 4 arrays. Two nearly identical dewars contain 16 pixels each, the beams from which are combined using a wire grid. A block diagram of a single pixel is shown in Figure 8.4. The array uses InP (indium phosphide) MMIC (monolithic microwave integrated circuit) preamplifiers with 35-40 dB gain, followed by subharmonic mixers with an intermediate frequency band of 5-20 GHz. The entire signal band is covered with single sideband response using just two LOs (local oscillators), at 40 and 60 GHz.

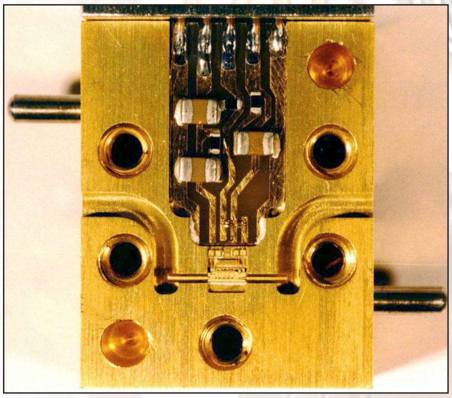

Figure 8.5 (a) Split block view of a SEQUOIA preamplifier[5]; scale is 1.5 cm left to right.

The preamplifiers using InP technology were designed at UMass Amherst, with wafer fabrication for the first stage amplifiers carried out at the company TRW and for the second stage units at HRL. The narrow band noise for these amplifiers can be as low as 27 K at 100 GHz (<40 K for 85-115 GHz), but Figure 8.5b shows more typical noise.

Square horns are used in the array since they pack together well. Each horn has a 25 mm aperture, and all of the horns are made together in a

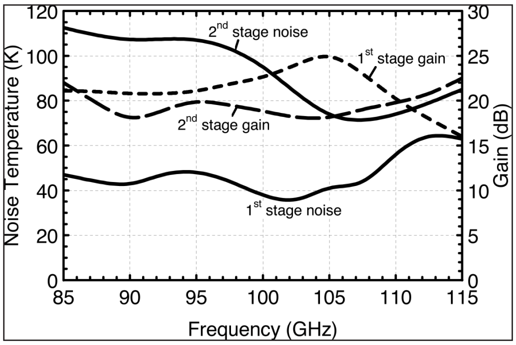

Figure 8.5 (b) Noise temperature and gain of first stage and second stage SEQUOIA preamplifiers[6].

block. With one pair of corrugated walls (and the other pair smooth), the beam patterns are symmetric with low side-lobes. This dense assembly leads to a beam spacing of twice the HPBW at midband.

Each pixel is frequency converted with a subharmonic mixer using beam-lead antiparallel-pair diodes. The required LO frequencies for full band coverage are 40 and 60 GHz, with a power of 8 mW per mixer. There are independent power amplifiers on each of the two dewars, with a common driver. LO distribution is one of the most difficult problems with array receivers, and for this receiver the relatively low frequency LO is a great help.

The array is competitive with wideband SIS receivers, and is much simpler to use. Each receiver dewar is cooled by a single refrigerator with 3.5 W cooling capacity at 18 K. While gain fluctuations are large (0.2%), they are highly correlated across a wide band, and the spectral line baseline stability is excellent. Figure 8.7 shows the noise performance across the band for 8 pixels in one dewar, as measured in the laboratory.

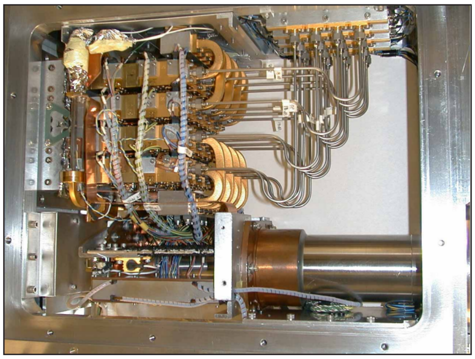

Figure 8.6 Inside details of a SEQUOIA Dewar[6]. Scale top-to-bottom is about 25 cm.

8.3.2 Redshift Search Receiver

One very important topic in contemporary astronomy is the study of the early universe, and principal indicators of the state of the universe are very highly redshifted galaxies. The Hubble expansion of the universe predicts a simple relationship between redshift and the distance to, and thus the age of, galaxies. It is fairly easy to identify galaxies using continuum receivers based on bolometers, but these detectors provide no redshift information. The receiver described here will be used to identify these redshifts.

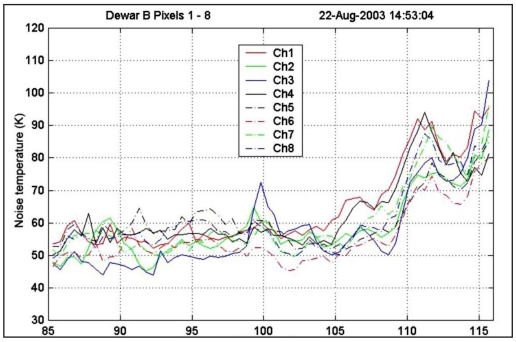

Figure 8.7 Receiver noise temperature for 8 SEQUOIA pixels[6].

Strong mm-wavelength spectral lines in galaxies arise primarily from CO and C (atomic carbon) and are fairly widely spaced in frequency. Any line search requires the detection of more than one line to uniquely identify the redshift. Thus a receiver for this work must cover the maximum possible bandwidth, and given the present technology plus the properties of the atmosphere, we have chosen 75-111 GHz for this band. As seen in Figure 8.8,

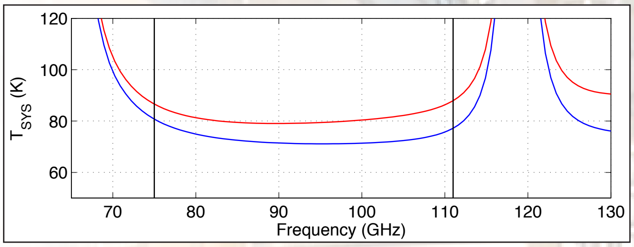

Figure 8.8 Expected on-the-sky noise temperature for the Redshift Search Receiver for conditions of 2 (blue) and 5 (red) mm of precipitable water vapor, and a 60 K receiver noise temperature[8].

this band lies between two fairly strong atmospheric absorption lines, and on either side the expected noise temperature rises fairly rapidly. Given that the galactic lines are expected to be quite weak, there is no advantage in extending the search band into frequencies of high absorption. With this choice of bandwidth, there is a very high probability of detecting one line from galaxies with redshift (z) greater than 1, and two lines for $z > 3.2$ (see Section 3.2.3).

Our receiver to perform this search is being built using several new technologies. A primary technological boost is given by the development of very low noise, wideband MMIC amplifiers. These amplifiers, the same as those employed in SEQUOIA, typically achieve noise temperatures below 50 K over much of the 75-111 GHz band (Figure 8.5b). With the cascade of two of these devices a gain of 40 dB is available, and the noise properties of subsequent stages are relatively unimportant.

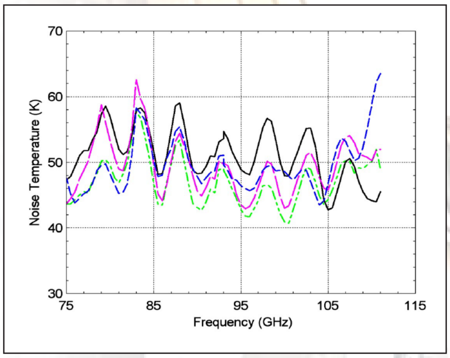

Figure 8.9 Amplifier noise temperatures for four Redshift Search Receiver pixels.

A second important development is in input waveguide components. For greatest sensitivity it is desired to use dual polarized receivers with a single feed horn. A very low loss waveguide polarization combiner has been developed which will cover the full band. This orthomode transducer (OMT) takes two single mode waveguide inputs and combines them into a circular waveguide output[7]. An additional development is a fast electrical beamswitch based on a Faraday rotation polarization switch. This dual polarization device rotates the polarization state of both inputs by 90 degrees with the application of a magnetic field. With the addition of a wire grid in front of the feed horn, this polarization switch becomes a beamswitch, since it interchanges the reflected and transmitted beams.

The noise temperatures of the new amplifiers for the Redshift Search Receiver are shown in Figure 8.9. The observed ripple is unimportant in actual receiver usage, given atmospheric contributions and on-the-fly mapping techniques.

The receiver will have two dual polarized beams, which are interchangeable using a beamswitch, so that one beam remains on the source at all times. This is a more efficient method of chopping than employing optics and a mechanical chopper, or creating dual polarized beams by using wire grid polarizers, which would add considerable size to the system. Instead the beams will be combined into dual polarized waveguide modes and then polarization switched with an electrical switch, as shown in Figure 8.10.

The four receivers making up the autocorrelation spectrometer have a combined IF bandwidth of 144 GHz, and the entire band needs to be spectrally processed simultaneously. For purposes of the line search in galaxies, a resolution of about 30 MHz is required, meaning that 5000 spectral channels are needed. This could be done with a filter bank, but the cost and complexity would be considerable. A new technique using analog autocorrelation[9] seems most suitable, and in this work the design is being refined to permit much wider bandwidth at significantly lower cost. The basic technique is to split the wide-band signal into two parts, which are sent in opposite directions down two parallel delay lines. Taps on these lines sample a small amount of the signal, and the tapped signals are then multiplied. The set of multiplied tapped signals forms the autocorrelation function, which can then be Fourier transformed to generate the spectrum.

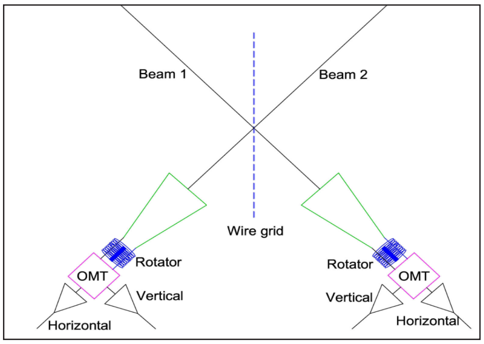

Figure 8.10 Amplifier noise temperatures for four Redshift Search Receiver Pixels.

8.3.3 One-mm SIS Commissioning Receiver

The LMT is designed to emphasize the 1.3 mm window in much of its research mission. In the first year or so of operation, it is expected that full use of this window will require a significant commissioning effort to maximize the performance of the telescope at these shorter wavelengths. A 1 mm receiver is being built to operate in the 210-275 GHz atmospheric window. It will provide state-of-the-art sensitivity using a sideband separation scheme to separate the upper and lower sidebands. In each polarization, 8 GHz of effective bandwidth per sideband (16 GHz total) will be available without the use of cumbersome mechanical tuners. This receiver will employ detectors that are based on Superconductor-Insulator-Superconductor (SIS) technology. The SIS receiver will also handle the necessary requirements of a commissioning receiver.

The receiver will be mounted at the Cassegrain focus of the LMT, and will employ a waveguide-based orthomode transducer. Two single-ended SIS junctions of the same design as that used in the ALMA Band 6 mixers will be used. The design of the entire receiver system has been optimized to allow the individual subsystems to be scaled up to an eventual large-format focal-plane array receiver system at 1 mm wavelength for the LMT. See Figure 8.11 for details of the system architecture. Table 8.3 summarizes the specifications and expected performance of the 1 mm SIS commissioning receiver.

Table 8.3. 1 mm SIS Receiver Specifications[6]

Polarizations	2
T_{SYS} (SSB)	<140 K
RF Bandwidth	210-275 GHz
IF Bandwidth	4-12 GHz (USB & LSB)
Image Rejection	> 20 dB
Beamsize	5.5-7 arcsec

8.4 LMT Wideband Spectrometer

While the Redshift Search Receiver will have its own special-purpose dedicated spectrometer, all other heterodyne receivers on the LMT will use the facility LMT spectrometer. This latter instrument is a flexible, broadband digital autocorrelator system capable of taking up to 64 IF inputs and producing spectra in several different combinations of total bandwidth and frequency resolution.

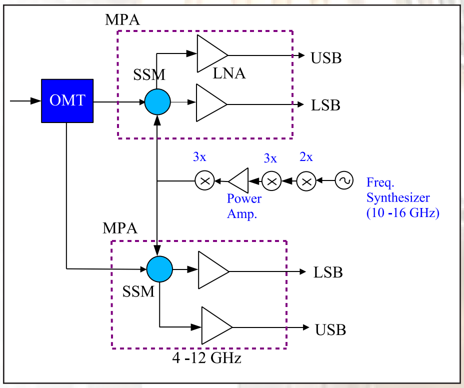

Figure 8.11 Schematic Block Diagram of 1 mm receiver. The two Mixer-Pre-amplifier Modules (MPA) are enclosed in dashed red lines[8]. OMT=orthomode transducer; SSM=sideband separation mixer; LNA=low noise amplifier.

Focal plane arrays pose significant challenges for the construction of spectrometers. The LMT must provide spectroscopic capability for the SEQUOIA system as well as for the single pixel systems and future focal plane arrays. Autocorrelation spectrometers are a common approach when a large flexible system is required, and a large, versatile correlator is the approach taken by the LMT.

An autocorrelation spectrometer computes the autocorrelation function (ACF) of the input signal. The Fourier transform of the ACF then gives the spectrum. The bandwidth is set by the sample rate (which for the LMT correlator is set to 1.6 GHz in a 3-level mode) and the resolution by the number of lags. Correlators offer stability and flexibility, although the finite sampling reduces the sensitivity (signal-to-noise ratio).

The LMT correlators must be able to support all the envisioned data collection modes, including position switching (< 1 Hz), frequency switching (~ 1 Hz), beam switching (~ 1 Hz) and on-the-fly mapping (~ 10 Hz). The bandwidth (BW) and resolution ($\delta\nu$) requirements are imposed by scientific goals, and are presented in Figure 8.12. These requirements are summarized below, with the bandwidth (BW) and resolution ($\delta\nu$) expressed in velocity units:

- Identification of unknown redshifts of primeval galaxies, BW >10000 km/s, $\delta\nu$ ~ 100 km/s;
- Extragalactic imaging, BW ~ 1000 km/s, $\delta\nu$ ~ 10 km/s;
- Galactic surveys and high velocity sources: BW ~ 300 km/s, $\delta\nu$ ~ 1 km/s;
- Giant molecular clouds: BW ~ 50 km/s, $\delta\nu$ ~ 0.1 km/s;
- Dark clouds: BW ~ 20 km/s, $\delta\nu$ ~ 0.01 km/s;
- Spectral line searches: BW ~1 GHz, $\delta\nu$~ 1-0.1 km/s.

It is seen that, depending on the scientific project, the LMT spectrometer can be optimally configured for broadband coverage or high spectral resolution, or some intermediate combination of both extremes.

8.5 Next Generation of LMT Instrumentation

Even as the first generation of instrumentation is being constructed for the LMT, scientists and engineers at UMass Amherst and INAOE are busy planning the next generation of innovative instruments. The biggest drivers for such new instruments are the significant technology developments that are occurring in the fields of continuum and heterodyne receivers. The new instruments outlined here will mean a significant improvement in the mapping speed, sensitivity, and frequency coverage of the LMT, which in turn will enable types of observations which had hitherto not been possible.

8.5.1 Next Generation Continuum Instruments

The field of continuum instrumentation is rapidly evolving. Even as the initial suite of instruments for the LMT (AzTEC and SPEED) nears completion, our continuum group is building collaborations to construct the next generation of cameras. There are three obvious areas where advancing technologies offer the promise of substantial new capabilities.

First among these is the construction of a large format, focal-plane-filling array of bolometers. To completely fill the 4 arcmin-diameter field of view of the LMT for observations at 1.1 mm requires approximately 3600 detectors. While such a camera is only one quarter the size of the SCUBA-2 instrument being built for the JCMT, this is 25 times the number of detec-

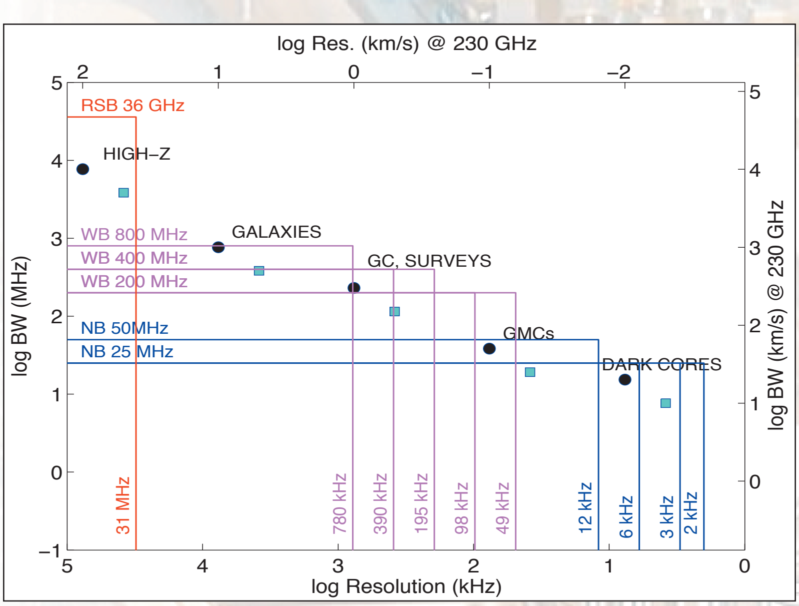

Figure 8.12 Bandwidth (BW) and resolution requirements of various scientific projects compared to the available specifications of the LMT correlator system[8,10]. The scientific requirements are shown in filled circles and squares for the 1 mm and 3 mm wavelength bands, respectively. In each case, the scientific requirements are seen to be satisfied (bounded above in bandwidth and from the right in resolution) by the available modes of the spectrometer. NB=narrow band mode; WB=wide band mode; RSB=redshift receiver spectrometer.

tors in AzTEC and would offer an improvement in mapping speed of between 12 and 20. Such an instrument would find important usages in a large variety of scientific applications.

A second type of camera being considered is a large-format array of frequency selective bolometers (FSBs) built to address such questions as the internal structure of galaxy clusters through observations of the Sunyaev-Ze'dovich effect (see Section 3.4.2). We have determined the specifications for a 1′ x 2′ field of view FSB camera in sufficient detail to support a proposal for funding from the U.S. government.

Finally, as the field of bolometer-based polarization studies explodes—largely due to the upcoming CMBPol experiment—our continuum instrumentation group is keeping a close eye on opportunities to build one or more instruments to study the polarization of dust emission at mm wavelengths.

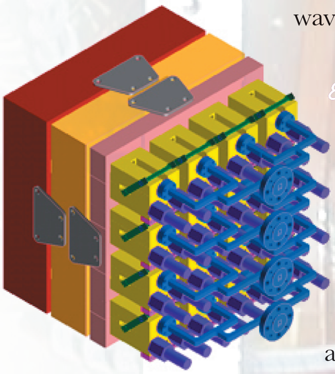

Figure 8.13 Small three-dimensional rendering of the design for OMAR. The whole assembly measures approximately 5 inches on a side and is mounted inside a cryogenic dewar and cooled to 4 K[8].

8.5.2 Next-Generation Heterodyne Instruments

The LMT will have a 3 mm focal-plane array, SEQUOIA, as soon as commissioning activities are finished. The next obvious heterodyne instrument to construct is a focal-plane array at 1 mm wavelength. Planning is well under way to build a receiver system that we call OMAR (One Millimeter Array Receiver), a dual-polarization 16-pixel array receiver for the 210-275 GHz frequency band. The array will be equipped with sideband-separation superconducting receivers modeled on the technology development of the 1 mm commissioning receiver (Section 8.3.3). In each pixel, 8 GHz of effective bandwidth per sideband (16 GHz total) will be available without the use of cumbersome mechanical tuners. Figure 8.13 shows a three-dimensional view of the proposed new receiver. The angular resolution of each pixel will be 6″, and the array will have a field-of-view (FOV) of 48″. OMAR will build on the proven experience and the heritage of success of the FCRAO instrumentation group in building focal plane arrays, providing a technically innovative instrument that will define the state-of-the-art for SIS heterodyne array receivers.

8.6 References

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