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The Science Case for the GBT 4mm Receiver

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ABSTRACT

With the recent improvements to its surface accuracy, the GBT is the most sensitive telescope operating at 90 GHz. We propose to build a traditional dual-beam feed-horn receiver which operates at the lower frequency end of the 3-4 mm atmospheric window (67–93 GHz), designated as the 4mm Receiver. The project will make use of previously acquired hardware at Green Bank. The science goals are mainly focused on molecular spectroscopic studies of star formation and astrochemistry within our galaxy and beyond, but the new receiver will be built to enable VLB observations as well. On technical grounds, the 4 mm receiver will permit further improvements to the surface accuracy and tracking performance of the GBT.

1. Introduction

The electromagnetic spectrum in the atmospheric 3-4 mm window ($\sim 67 - 116$ GHz) is exceptionally rich in molecular lines that trace the physical properties and chemistry of the material from which planets, stars, and galaxies form (Figure 1). Like nearly all telescopes operating at 3 mm, ALMA band-3 (84–116 GHz) will only cover the high frequency end of the window. At present, the only access to the complete lower part of the band (67-93 GHz) is provided by the privately funded Arizona Radio Observatory, operating the 12m telescope at Kitt Peak, Arizona. Given that there are are several key lines within the low frequency end of the band (e.g., the deuterium species which are enhanced in dark cold cores and several complex organic species), the proposed receiver would provide the GBT with a wide-range of unique science opportunities.

The 4 mm GBT receiver (67–93 GHz) is motivated on several fronts. ALMA currently lacks "band-2" (67–90 GHz) receivers. The early science results from the 4 mm receiver will demonstrate that 3–4 mm spectroscopy can be done successfully at Green Bank. There are roughly 1000 hours a year available at Green Bank for which the opacity is low [$\tau(86\,\mathrm{GHz}) < 0.1$] and the winds are acceptable for 4 mm observations (GBT Memo #267).

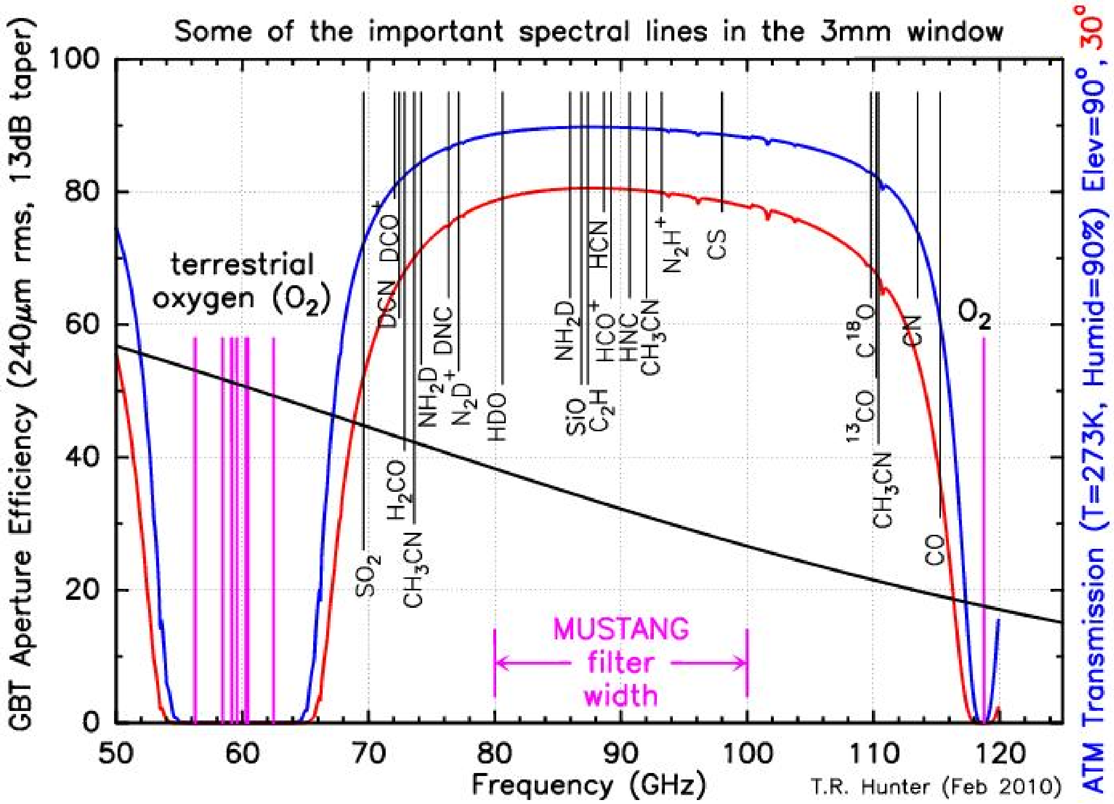

Fig. 1.— The 3 mm atmospheric window and important astronomical spectral line transitions. The atmospheric transmission in percent for Green Bank is given by the blue curve for an elevation of 90° and the red curve at 30°. The solid black curve systematically decreasing with frequency represents the aperture efficiency of the GBT assuming the current surface performance of 240μm rms. Important astronomical lines are labeled. The proposed 4 mm receiver would cover the important deuterium species at around 80 GHz and below and the dense gas tracers of HCN, C2H, HCO+, HNC, and N2H+ at around 90 GHz.

2. Justification

Based on the ASTRO-2010 Decadale Survey, four key research areas have been identified for the GBT. The 4 mm receiver would greatly enhance the science capabilities in all of these areas.

1. Fundamental Physics – With the VLBA, the GBT would allow us to probe the fundamental physics near the base of powerful black hole jets in nearby galaxies.

2. The Context of Star Formation – Studies of the structure and physical properties of cold cloud cores from which stars form will be revolutionized with molecular spectroscopy of the deuterium species and other important species within the band.

3. Origin of Life – Molecular spectroscopy of complex organic molecules and pre-biotic molecules in the ISM and comets are key for studying the conditions from which life eventually forms.

4. Galaxies Across Cosmic Time – The 4 mm band would permit the studies of CO(1-0) at intermediate redshifts where the evolution of galaxies is changing rapidly and the studies of the dense gas tracers in local star-forming galaxies.

2.1. VLB Observations

A 3–4 mm VLBI capability on the GBT would be a significant contribution to the highest resolution imaging done on a regular basis in all of astronomy. Eight antennas of the VLBA plus a number of mm telescopes elsewhere in the world are used together on a regular basis to image masers and the central regions of active galactic nuclei. Only observations at higher frequencies can achieve higher resolution and efforts to take such data are in their infancy, with no short term prospect of involving adequate numbers of antennas for imaging. Using the GBT as part of the VLBA array would increase the sensitivity of the array at 86 GHz by a factor of 5. Not only does this allow fainter objects to be studied, but it also enables fringe fitting techniques to work at much fainter levels, where fringes might not be detected between the VLBA antennas. This is essential for measuring and correcting for atmospheric fluctuations, which are the main source of errors at this frequency. The GBT is also in a desirable location for use with the VLBA. With no 3mm receiver at either Hancock or St. Croix, the eastern-most VLBA stations, the maximum baselines of the VLBA at 3mm are significantly shorter than at other frequencies. Also with nothing in the eastern U.S., there is a hole in the UV plane between the VLBA and Europe. The GBT would go a long way toward rectifying those deficiencies.

A prime target of 3 mm VLBI observations is the inner radio jet in M87. Including the GBT would significantly improve our understanding of the jet launch region. M87 is special because it has the largest angular size black hole with a jet that is bright enough for imaging observations. The global 3mm VLBI resolution of 0.20 by 0.066 milliarcsec at M87 corresponds to 28 by 9 Schwarzschild radii (R_s) at M87 ($D = 16.7\,\mathrm{Mpc}$, $M = 6 \times 10^9\,M_\odot$, Gebhardt & Thomas 2009). Models of the jet launch region typically involve magnetic fields threading an accretion disk and black hole. Material from the disk is pushed out along the field lines which splay outward at first, then collimate as they get wound up along the jet. The particles are accelerated by pressure and by "magnetic flinging". Fields threading the black hole get tightly wound and may generate a large Poynting flux down the core of the jet that is only transferred to particles some distance downstream. The M87 jet is thought to be seen at a modest angle to the line-of-sight so the highly relativistic jet core may not be seen. Instead what is seen is the sheath of material that comes from the disk. The morphology on scales under 1000 R_s will be a wide-opening-angle cone collimating into an edge brightened

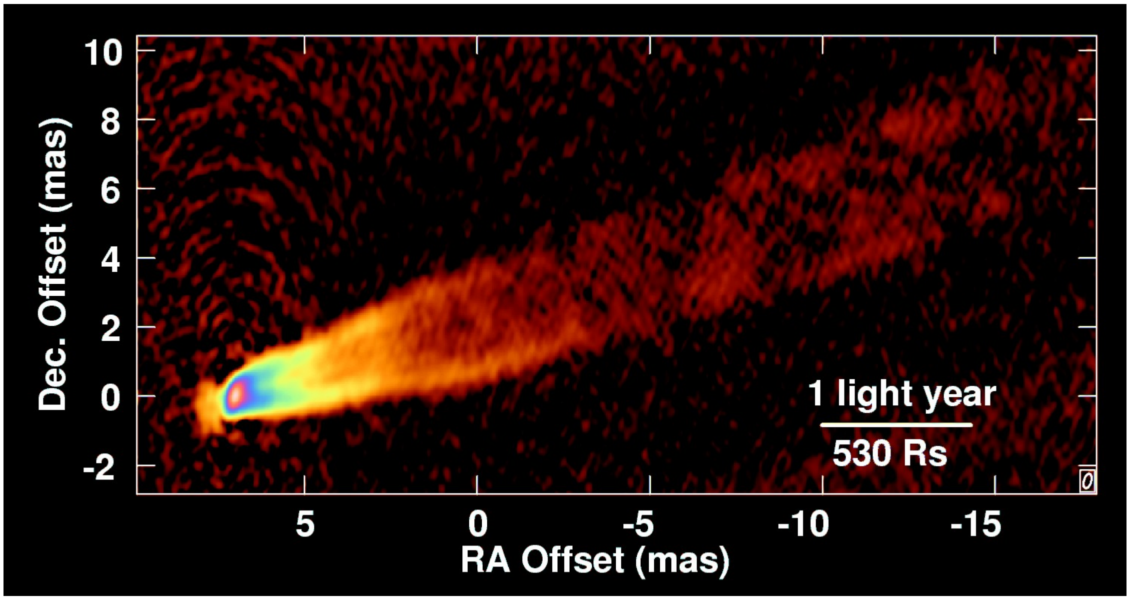

Fig. 2.— A stack of 23 images of M87 made at 43 GHz with the VLBA (Acciari et al. 2009). The resolution is 0.43 by 0.21 mas (60 by 30 R_s). Because of the stacking, detailed, time-variable structures are smeared, but the systematic structure is brought out clearly. The wide opening angle base and edge brightened are clear. The feature opposite the presumed core from the main jet is clearly real, but its nature is not yet understood.

jet. The high resolution, in gravitational units, available on M87 allows that structure to be observed (as seen by the VLBA at 43 GHz, Figure 2). With twice the cross-jet, and three times the down-jet resolution at 86 GHz, the GBT+VLBA observations would enable the study this critical structure in detail and provide improved constraints on the jet modeling.

In addition to M87, other powerful radio jets would be studied with the 4 mm receiver on the GBT. Another application is studying the structure and physics of supergiant mass-losing stars by measuring the rotational and vibrational transitions of SiO at 86 GHz.

For compatibility with the VLBA array, the 4 mm receiver for the GBT should be sensitive to a frequency range of about 80-90 GHz and be able to observe dual circular polarizations. The VLBI capabilities of the receiver system should be optimized for 86 GHz (quarter-wave plate design).

3. Star Formation

Radioastronomy at 3–4 mm provides an excellent probe of the star-formation processes producing both low and high mass stars as well as complex molecules. Low mass star formation proceeds from dense cold starless cores, whose physics may be effectively explored through investigation of less-saturated isotopes of important dense gas tracing molecules (e.g., DCN, DNC, DCO+, NH2D, CCD, N2D+, CH2D+ and their 13C or 15N isotopomers). In particular, the singly deuterated molecules have been known to be abundant in cold molecular clouds with a very high abundance enhancement as a result of fractionation (Wootten 1987). The enhancement is preferred at cold temperatures and becomes strongest in cold dense clouds without internal heat sources. Since the chemistry of deuteration is an ion-molecule chemistry, the most important lines are those of the fundamental molecular ions, DCO+ (72 GHz) and N2D+ (77 GHz). Images of molecular cloud complexes in these lines immediately identify the coldest, densest cores, the sites of the next generation of star formation. As hydrogen is an abundant constituent of astrophysical molecules, the lines of deuterated isotopomers may be used to probe the physics of these pre-stellar cores. In addition to the cornerstone molecular ions DCO+ and N2D+, several important deuterium lines are available within the planned band, including DCN (72 GHz), DNC (76 GHz), NH2D (85 GHz), HDO (80 GHz) and NHD2 (67.8 GHz).

As stars form, the core centers warm, outflows are generated, and the chemistry is altered. Owing to its fine beam, the GBT provides an excellent instrument with which to explore the ratios and abundances of these molecules in both cold and warm star-forming cores, providing information on the degree of molecule freeze-out in the coldest cores (e.g., based on the N2D+/N2H+ ratios [Emprechtinger et al. 2009]), the electron abundance (the D isotope ratio is sensitive to this parameter) and indirectly the role of the magnetic field in the collapse process, and on the excitation of the molecules–the temperature and density of the cloud cores. The 1-0 lines of N_2H^+, HCN, and HCO^+ (and their isotopologues) will be used to trace high-density (10^5 cm^{-3}) star-forming cores and infall onto them. Myers (2005) showed that measuring the velocity profile is a good way to determine the initial geometries and collapse ages of starless cores. Surveys of SiO(2-1) can be used to find well-collimated bipolar jets from the protostars. All four of these species (N2H+, HCN, HCO+, and SiO) are in the 86-93 GHz part of the spectrum, so their images will have essentially the same linear resolution. These data will reveal whether clumps are self-gravitating, how fast the clumps are moving, and which clumps have evidence of infall and outflow.

The C2H transition within the band could become very important for constraining the magnetic fields within cloud cores given that C2H is one of the few molecules which has a large Zeeman coefficient (Bel & Leroy 1998). The emission from this molecule is bright, and it has been recently mapped in nearby prestellar cores (Figure 3).

For the study of star-formation, a frequency coverage from 68.9 GHz (SO2) to 93.2 GHz (N2H+) is desired.

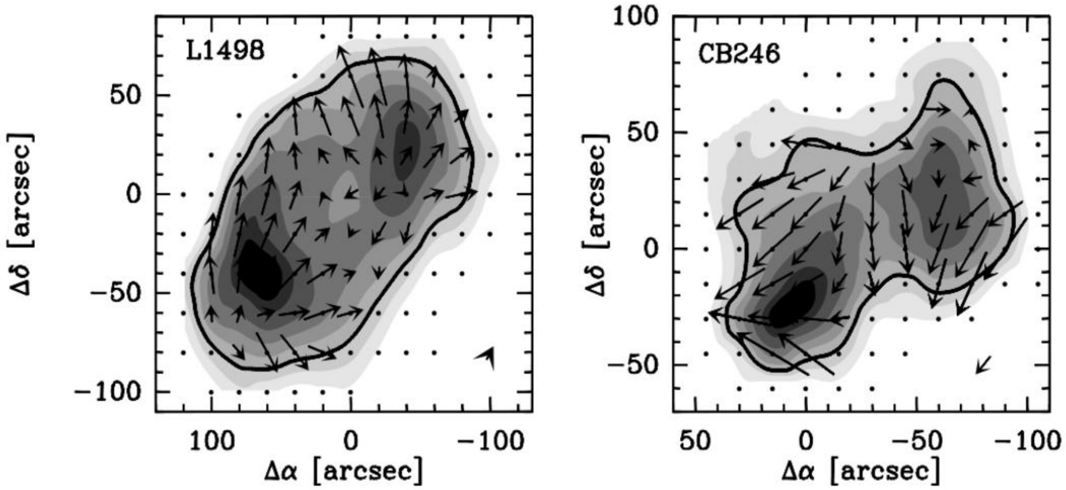

Fig. 3.— The C2H line mapped in the prestellar cores L1498 and CB246 (Padovani et al. 2009). The GBT would be able to map the stucture and velocity fields for many different molecular species found in prestellar cores to constrain the models of star formation.

3.1. Origin of Life

Transitions of complex organic molecules exist throughout the 3-mm band. Given the importance of finding the precursors to biological molecules within the ISM and within comets for our understanding of the formation and evolution of life, it is important to maximize the available frequency coverage within 3-4 mm band. Within the planned 4 mm frequency coverage, several transitions are available from the simple-sugar species glycolaldehyde CH2OHCHO and ethylene glycol HOCH2CH2OH. The existence of these species in significant quantities has been shown recently from transitions below 50 GHz with the GBT (Hollis et al. 2004a,b).

The recent GBT results also indicate that the distribution of at least a subset of the organic species are not confined to hot molecular cores. Instead, these species, including interstellar aldehydes, appear to have spatial scales on the order of 1’ – 2’. These extended molecular sources require single-dish observations and would not be detectable with interferometers.

Studies of deuterated molecules within comets are important for our understanding of the formation of the solar system. The very high deuterium fractionation observed in some cometary volatiles (more than an order of magnitude relative to the cosmic D/H ratio for water and 2 orders of magnitude for HCN) suggests chemical processes similar to those in the ISM. The large HDO/H2O and DCN/HCN ratios provide the strongest evidence that comets preserve interstellar molecular material (e.g., Irvine et al. 2000). These studies provide important insight on the formation of the solar system and the origin of life on

Earth.

In terms of instrumentation, this science application would benefit from the widest possible frequency coverage and being able to observe as many transitions as possible simultaneously for efficient line searches. The new spectrometer under develop would allow for observations of up to 16 [TBD] lines simultaneously.

4. Molecules in Galaxies

The nearby infrared-bright, star-forming galaxies will be excellent extragalactic targets for the GBT 4 mm receiver. Gao & Solomon (2004a,b) have demonstrated that the HCN is a far better tracer of the star-formation activity in galaxies than CO, given its associated with dense gas. Hence, the dense gas traces of HCN, HCO+, and HNC are key in studying the material associated with the ongoing star-formation and AGN activity. The amount dense gas traced by HCN compared to the total gas mass is a proxy for the star-formation efficiency. The nuclear regions of galaxies and ultraluminous infrared galaxies show enhanced star-formation efficiencies and much higher HCN/CO ratios in comparison to the disks of spiral galaxies.

The line ratios of dense gas tracers show significant variations between galaxies and within galaxies. The observations of Meier & Turner (2005) of IC342 have shown significant differences among the density sensitive tracers such as C2H, N2H+, HNCO, HC3N, HNC, HCN, and HCO+ (all of which are within the planned 4 mm band) on the spatial scales of tens of parsecs. These observations suggest that dense molecular clouds differ markedly in their chemical properties and, importantly, these differences correlate directly with galactic features such as large-scale shocks, dynamical resonances, and locations of intense radiation fields. Shock traces such as SiO can be used to map the location and strength of shocks induced by internal galaxy dynamics (bars, spiral arms) and external interactions, photo-dissociated region (PDR) tracers which delineate massive star formation/molecular gas interaction sites, as well as many other quiescent and ionization tracers (such as HCN, HNC, HCO+ and N2H+), to help locate and characterize the ambient dense gas properties away from shocks and massive star forming regions. A large inventory of mapped species will address additional important questions such as: over what physical scale do AGN and massive star forming regions influence the chemical and physical conditions of their surroundings? What is the average molecular complexity reached for the bulk of galaxies ISM and what constraint does this impose on basic chemical formation pathways? Does the average chemistry change with galactocentric distance? Does it change when the molecular material is transported along a bar toward the cores of starburst and active galaxies? What about the cosmic ray ionization rate? What is the ionization fraction at different galactocentric distances and is there evidence for its control of physical parameters such as cloud support and star formation? Can the chemical state of the gas be used to clock the age of molecular

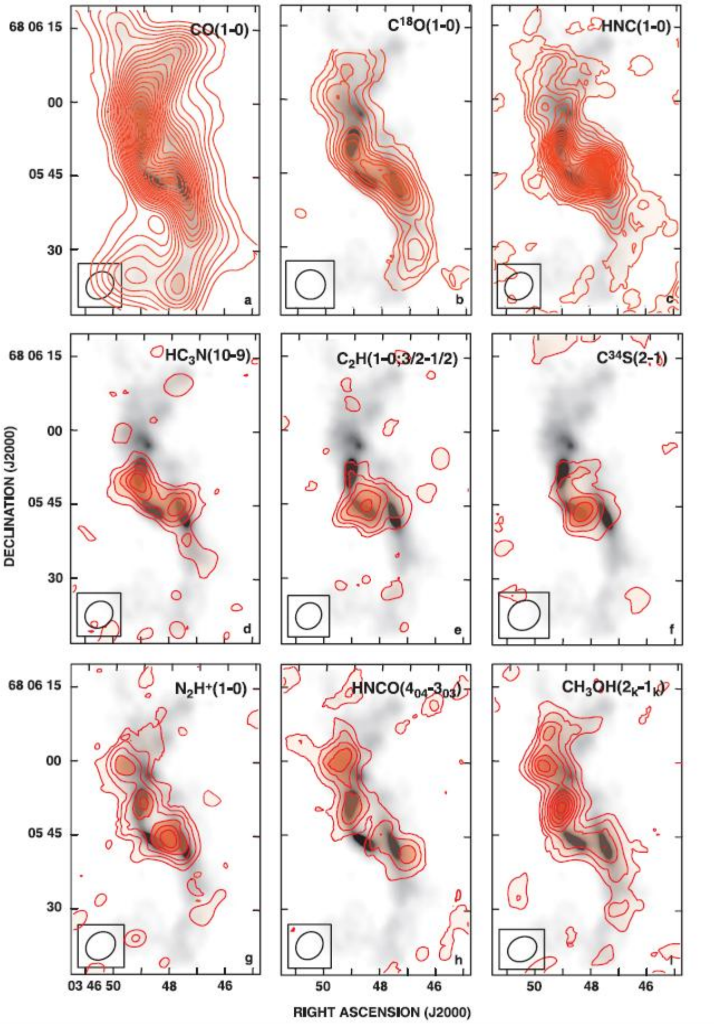

Fig. 4.— The integrated intensities of nine tracer molecules observed in IC 342 at a resolution of 5″ (Meier & Turner 2005). The GBT would have sufficient resolution to study the large-scale molecular variations in nearby galaxies.

clouds with position in a galaxy?

For nearby galaxies (D $<$ 5 Mpc), the 7″ beam of the GBT will be sufficient at $<$ 100 pc to separate individual GMCs. The resolution of GBT is well matched to the ongoing VLA HI surveys at 6″ resolution (THINGS, ANGST, and the local volume "LITTLE THINGS" survey) and the $\sim$ 6″ CO interferometric surveys such as SONG. The combination of the GBT HCN surveys with the CO and HI surveys will allow the study of the spatial distribution and relative fractions of dense molecular gas, total molecular gas, and neutral gas within several types of nearby galaxies. In addition, this resolution is well matched to the SINGS survey of local galaxies in the mid-infrared with the Spitzer 24μm band and the Herschel KINGFISH survey of local galaxies in the the far-infrared (70, 100μm at 6–8″ resolution).

Besides providing a basic inventory of the gas at different densities and the dust at different temperatures as a function of galaxy type and environment, these matched resolution data will provide insight into the mechanisms whereby the gas and dust is transferred between the neutral and molecular gas phases of the ISM and provide estimates of the lifetimes of molecular clouds and star formation efficiency.

5. Intermediate-Redshift Galaxies

Studying the molecular properties of intermediate galaxies is key for our understanding of galaxy evolution. At intermediate redshifts ($0.37 < z < 0.7$), CO(1-0) will not be available with ALMA band-3. Studying sources at these intermediate redshifts is crucial in understanding the strong evolution of the galaxies from today to $z = 1$. Although upper-ladder CO transitions are observable at intermediate redshifts with ALMA and other instruments, the ground state CO(1-0) line is key for measuring the total amount of the cold molecular gas. Large samples of low and intermediate redshift ULIRGs and LIRGS have been uncovered by the Spitzer and Herschel surveys and could be observed in CO(1-0) at $0.24 < z < 0.7$ and HCN(1-0) at $z < 0.3$ with the 4 mm receiver. However, the detection of faint broad lines may require a nutating tertiary which is currently not available for the GBT.

6. Technical Benefits for PTCS

A traditional, feedhorn-coupled HEMT receiver operating at 4 mm on the GBT would be of great benefit to the PTCS project as it attempts to provide further improvements to the telescope performance at high frequency. In particular, improvements will be made in two important areas (1) surface efficiency, and (2) the tracking performance.

6.1. Surface Efficiency

During the holography campaign of 2009, the telescope gain has increased by a factor of 1.4 at 43 GHz, and 2.4 at 90 GHz. The aperture efficiency is now so good at 43 GHz (64%) that further refinements of the surface will be difficult to confirm at this frequency. The current Q-band efficiency suggests a surface accuracy of 235 microns rms. A modest reduction to 210 microns rms would boost the gain by a factor of only 1.038. However, at 93 GHz, the factor would be 1.2 which is detectable (and would provide a 40% reduction in observing time).

At present, we can only use MUSTANG to compare the relative improvement from various surface adjustment strategies. However, it cannot provide an absolute efficiency because that number is degenerate with the optical throughput and the value of the shunt resistors on the detectors. Also, this receiver does not illuminate the surface in the same manner as every other receiver, and its availability is more limited than the other receivers. With a dual-beam 4 mm receiver outfitted with a movable ambient temperature load (similar to the Q-band receiver), we will be able to measure accurate planetary brightness temperatures, which will allow us to make valid predictions for the antenna performance all the way up to 115 GHz. Furthermore, the spectral line capability of the 4 mm receiver will allow observers to measure and correct the residual large-scale surface deformations by performing out-of-focus holography using the strong SiO(2-1) maser line. This technique was recently proven using the 43 GHz SiO(1-0) line, and despite the reduced efficiency at 86 GHz, the smaller beamsize will deliver spectra with higher brightness temperatures.

6.2. Tracking Performance

The tracking performance of the GBT is about 2" rms in calm wind conditions. The performance is limited by a resonance in the servo system, the source of which has been identified as a combination of torque ripple internal to the motors and tachometer misalignment. These issues will be corrected in the new digital servo currently under construction and planned for deployment in FY11. At that point, we will have to test the system in order to prove without a doubt that the tracking performance has met the requirement of $< 1"$ rms. The best way to do this is to track sources at the half-power point of the beam and measure the receiver output power variation. Performing this test at Q-band provides a signal change of only 8% for a 1 arcsec tracking error. The same test run at 93 GHz would provide a healthier signal change of 17% for the same 1 arcsec tracking error. For this test, a dual-beam receiver would be desired so that sky variations can be removed from the continuum datastream. A single beam receiver could in principal be used if one instead processed the spectral datastream from a sufficiently strong SiO maser.

7. Preliminary Specifications

- Frequency range: 68.9 — 93.2 GHz. The high-frequency end is set by the N_2H^+ line at 93.17 GHz, and the low frequency end is set by the SO2 transition at 68.9 GHz.
- Instantaneous IF Bandwidth: 2 GHz or more
- Number of beams: two
- Beam separation: 4.7 arcmin with the current plate
- Dual beam linear polarization with selection of circular polarization for VLB observations

- VLB observations optimized at 86 GHz (for continuum and SiO line transition), assuming a quarter-wave plate for the selection circular polarization
- Chopper wheel/mirror calibration based on ambient load and sky

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