An 800 GHz SIS Receiver for the RLT Incorporating a HIFI Band 3-type Mixer and SiGe LNA

A. Hedden, H. Li, E. Tong, S. Paine, R. Blundell, J. Kawamura, C. Groppi, C. Kulesa, C. Walker, G. de Lange, T. Klapwijk, T. Zijlstra, H. Mani, and S. Weinreb

Abstract—**We have constructed an 810 GHz receiver system incorporating a superconductor-insulator-superconductor (SIS) mixer developed for Band-3 of the HIFI instrument for Herschel space observatory and a wide-band SiGe low noise amplifier (LNA) designed at Caltech. The instrument is currently installed at the RLT telescope (elevation 5500 m) in northern Chile. Hot/cold (280K/72K) load measurements performed at the telescope yield noise temperatures of 225 K (Y-factor = 1.7) including receiver optics. First-light observations indicate that the receiver is highly sensitive and functions stably. We present details of the receiver system, its performance at the telescope, and first-light observations with a Herschel mixer.**

Index Terms—**radio astronomy, submillimeter wave receivers, submillimeter wave spectroscopy, superconductor insulator superconductor mixers**

I. INTRODUCTION

A key goal of upcoming space-based and airborne missions is improving our understanding of the structure of the Galactic interstellar medium (ISM) and the life cycle of interstellar clouds as a stepping stone to understanding the internal evolution of galaxies. Through the efforts of many researchers, the far-infrared (FIR) and terahertz (THz) atmospheric window, harboring important spectral line probes of molecular clouds and star formation, including high-J CO lines and N+ at around 1.3 and 1.5 THz, is becoming accessible with unprecedented sensitivity and resolution capabilities [1]-[4]. Complementary observations of key species in the 800 GHz atmospheric window are needed over large spatial scales (multiple square degrees) both for a more complete picture of the lifecycle of the ISM and for producing finder charts enabling the efficient use of new and upcoming THz observatories.

We have constructed and deployed (December 2008) a highly sensitive 810 GHz heterodyne receiver system to the RLT telescope in northern Chile [5] capable of making these much needed observations. At the heart of the receiver is an 800 GHz SIS mixer developed for Band-3 of the HIFI instrument [6, 7] to be launched in 2009. The mixer unit is connected to a wide-band SiGe LNA designed at Caltech [8]; the first of its kind to be used in a submillimeter (submm) receiver functioning at a telescope. The system operates with a 1-2 GHz IF capable of simultaneously observing important spectroscopic probes of star formation including neutral atomic carbon $^{12}C^0$ and $^{13}C^0$ J = 2-1 and carbon monoxide CO J = 7-6 lines near 809 GHz and 806 GHz, respectively.

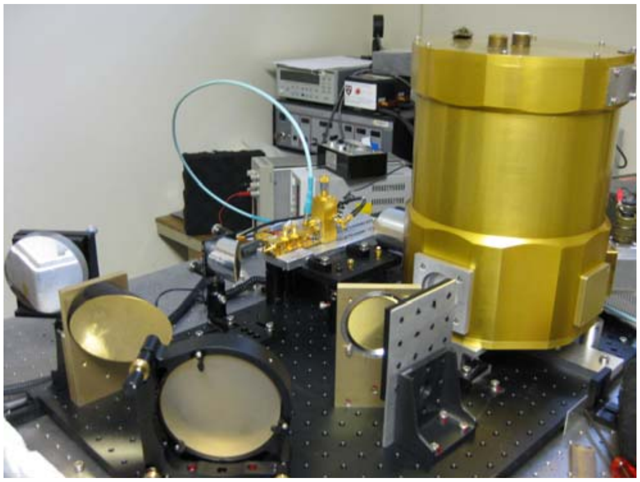

Fig. 1. Layout of the 810 GHz receiver system: view of receiver system operating in the laboratory complete with LO unit and all optics needed to couple the beam to the RLT.

Equipped with a spectrometer affording high spectral resolution (< 0.5 km/s) and coupled with a telescope beamsize of 1.9’ at 810 GHz, this new RLT receiver system will provide important complementary observations to planned large-scale C+ and N+ surveys of the Galactic plane made by STO, an upcoming balloon-borne spectroscopic mission [9] in which

---

Manuscript received 20 April 2009.

A. Hedden*, H. Li, E. Tong, S. Paine, and R. Blundell are with the Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138 USA (*corresponding author; phone: 617-495-7487; e-mail: ahedden@cfa.harvard.edu)

J. Kawamura is with the California Institute of Technology Jet Propulsion Laboratory, Pasadena, CA 91109 USA

C. Groppi, C. Kulesa, and C. Walker are with the University of Arizona Steward Observatory, Tucson, AZ 85721 USA

G. de Lange is with SRON, 9700 AV Groningen, the Netherlands

T. Klapwijk and T. Zijlstra are with the Kavli Institute of Nanoscience, Faculty of Applied Sciences, Delft University of Technology, Delft, the Netherlands

H. Mani and S. Weinreb are with the Dept. of Electrical Engineering, California Institute of Technology, Pasadena, CA 91125 USA

members of our team are involved. We present details of the receiver system, including results and performance at the RLT, and first-light observations obtained with a Herschel mixer.

II. OVERVIEW OF THE RECEIVER SYSTEM

A. HIFI Band-3 Type Mixer Unit

The mixer assembly is a pre-flight spare for Band-3 of the HIFI instrument modified for use over a 1-2 GHz intermediate frequency (IF) range. The mixer is specified to operate between 800 and 960 GHz. It is projected to achieve a noise temperature of about 150 K at 800 GHz in the spacecraft under typical operating conditions. The details of the design and construction of the mixer are described in [10]. We have installed the mixer block in a liquid helium cooled cryostat equipped with an anti-reflection coated quartz vacuum window and infra-red blocking filters. Two off-axis parabolic mirrors, one placed inside the cryostat and a second one mounted outside the cryostat couple the beam emerging from the corrugated feed of the mixer block to the main telescope optics. The optical design was carried out with the use of the ZEMAX software package. The layout of our instrument is shown in Fig. 1.

B. SiGe Low Noise Amplifier

The mixer is connected to a SiGe IF amplifier [8] by a 10 cm long coaxial cable. This is the first use of a SiGe amplifier in a submm receiver system deployed on a telescope. Housed in a small package of about 3 cm x 2 cm x 1 cm, it has very low noise from 0.2 GHz to 4 GHz in addition to low power dissipation. Unlike most cryogenic HEMT amplifiers which require a servo loop to adjust the gate voltage so as to maintain a constant drain current and hence a stable gain, this SiGe amplifier can simply be operated with a fixed drain voltage. We have chosen a drain voltage of 1.4 V, which represents a compromise between several considerations (see Fig. 2). At lower bias voltage, the power dissipation is reduced and the gain flatness is improved. However, by increasing the bias voltage, higher gain and a lower noise temperature can be obtained. At our operating voltage, the power dissipation is only about 7 mW for a noise temperature of close to 4.5 K over the 1-2 GHz IF range. The gain of the amplifier is 38 dB at 1 GHz, decreasing to 36 dB at 2 GHz and to 33 dB at 4 GHz. The gain slope is further accentuated by the 1 meter long stainless steel coaxial cable connecting the amplifier to the output port of the cryostat. Gain equalization is achieved using the external IF processor resulting in a 2.5 dB variation in the power output spectrum.

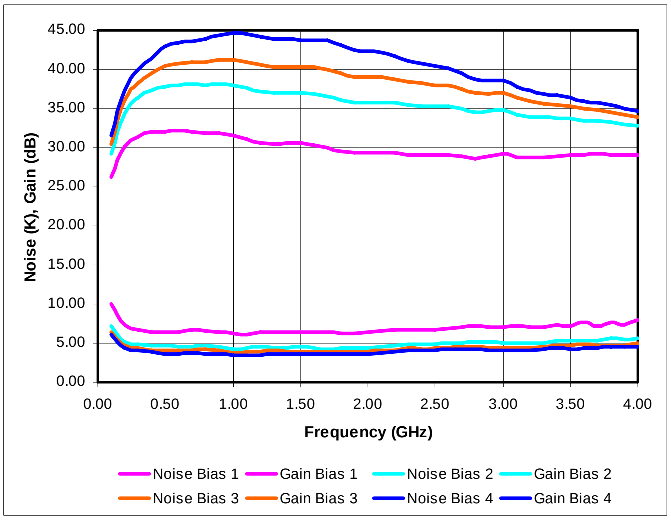

Fig. 2. Gain (top 4 curves) and noise (bottom 4 curves) characteristics of the SiGe LNA operated at 20 K with different drain voltages (cases 1-4 correspond to 1.1 V, 1.2 V, 1.3 V, and 1.6 V drain voltage). For operations with the 810 GHz receiver, a drain voltage = 1.4 V was used.

C. 810 GHz Local Oscillator Unit

The local oscillator (LO) unit used in this system incorporates a fixed-tuned planar diode doubler cascade developed by Jet Propulsion Laboratory for the Herschel space mission [11, 12]. The primary source is a Gunn oscillator operating at around 101 GHz. After passing through a compact coupler with an integrated harmonic mixer diode for phase-locking purposes, the output power of the Gunn oscillator is amplified by 2 stages of a W-band power amplifier to about 200 mW. This drives a cascade of 3 stages of frequency doublers to yield ~0.2 mW of radiated output power at 808 GHz. An off-axis mirror couples the LO power to the mixer through a wire grid polarizer oriented to reflect a small fraction of the LO output power which can be controlled by varying the drain bias voltage on the power amplifiers.

D. IF Setup and Backend Spectrometer

The purpose of the receiver is achieving simultaneous observations of three astronomically significant lines including neutral atomic carbon and carbon monoxide lines at around 809 GHz and 806 GHz, respectively. For this reason, the SIS mixer is operated in double-side-band mode at a fixed LO frequency of about 808 GHz. Using a 1-2 GHz IF, the carbon lines appear in the upper-side-band, and the CO line appears in the lower-side-band. A digital autocorrelator made by Spaceborne, Inc. with 1024 channels and a maximum bandwidth of 1 GHz was used as a backend spectrometer, resulting in a channel width of 1 MHz and a corresponding spectral resolution of 0.4 km/s at 810 GHz.

III. RESULTS

A. Lab Measurements and Characterization

The SIS mixer operates best with a magnetic field that delivers 2 quanta of magnetic flux to the junction. This corresponds to a coil current of around 15 mA. At higher field strength, the quality of the SIS device is visibly degraded while at lower levels, receiver stability is poor. The optimal operating bias point of the mixer is found to be at 2.1 mV and 50 μA. To achieve this operating condition, we set the wire grid polarizer angle at about 5 degrees to the LO for signal coupling. This is equivalent to about 1.5% LO coupling and results in minimal loss to the signal beam. Even at this low coupling level, the LO unit does not need to be operated at full power. Standard hot/cold load sensitivity measurements were performed at the input pupil of the complete receiver system. A Y-factor of 1.7 was recorded, which translates into a receiver system noise temperature of 235 K (Rayleigh-Jeans temperature), averaged over the entire IF pass-band. This sensitivity compares favorably to lab measurements reported by the HIFI Band-3 development team [10] given that our bath temperature is at 4.2 K, the entire optics train is included in our measurement, and the mixer is being operated over an IF range different to the Band-3 design.

Before installation of the warm optical components, the beam emerging from the cryostat was mapped both in amplitude and phase by a near-field scanner with an open waveguide probe. Adjustments were made so that the axis of the measured beam coincided with the normal to the center of the cryostat window. Then the warm optical components were positioned after careful optical alignment. Finally, the receiver beam profile at the input pupil of the receiver system was measured for final adjustment and verification. This two-step radio/optical alignment procedure was introduced in the deployment of a 1.5 THz superconducting receiver [13] but this work confirms the utility of this method by the reproducibility and validity of the near-field measurements. In practice, this method has proven to be invaluable for producing good, repeatable alignment between the cryostat, SIS mixer, and the receiver / telescope optics, in addition to minimizing optical alignment efforts at high elevation.

B. Performance at the Telescope

The RLT telescope is located 40 km north of the ALMA site in northern Chile at an elevation of 5525 m, one of the best ground-based sites for terahertz astronomy with atmospheric transmission as high as 50% above 1 THz [5,14]. A Fourier Transform Spectrometer (FTS) is also located at the site and operates continuously, providing measurements of sky brightness to determine atmospheric opacity over the 350 GHz – 3 THz range [15] and calibration information for RLT spectroscopic observations. The telescope's primary mirror is 80 cm in diameter, resulting in a 1.9' beam at 800 GHz. The excellent observing conditions and modest beamsize (~5 pc at the Galactic center, capable of resolving star-forming clumps in nearby Giant Molecular clouds) make this telescope well suited to conducting large-scale surveys in the 800 GHz atmospheric window. To this end, the SIS receiver system described in this work was deployed to the RLT in early December 2008 and began its first observing campaign.

Fig. 3 shows receiver response measured at the RLT, including plots of mixer current vs. bias voltage with and without the local oscillator signal (pumped and unpumped IV curves) and receiver output power as a function of bias voltage for ambient temperature (280 K) and liquid nitrogen (72 K) blackbody loads (PV hot/cold curves) positioned at the input pupil of the receiver system. Optimal receiver response was achieved at a mixer bias of 2.3 mV and 55 μA, yielding a 225 K (Y = 1.7) receiver noise temperature at 808 GHz, an improvement of 10 K over lab performance and a factor of 5 better than noise levels achieved with the 800 GHz HEB receiver that this system replaced. This new receiver achieves a performance that is comparable to 800 GHz SIS receiver systems currently operating at similar sites, including CHAMP+ [16] on the APEX telescope (SSB noise temperatures of ~700 K at 810 GHz) and the SMART array [17] on NANTEN 2 (DSB noise temperatures of 200-400 K after recent upgrades).

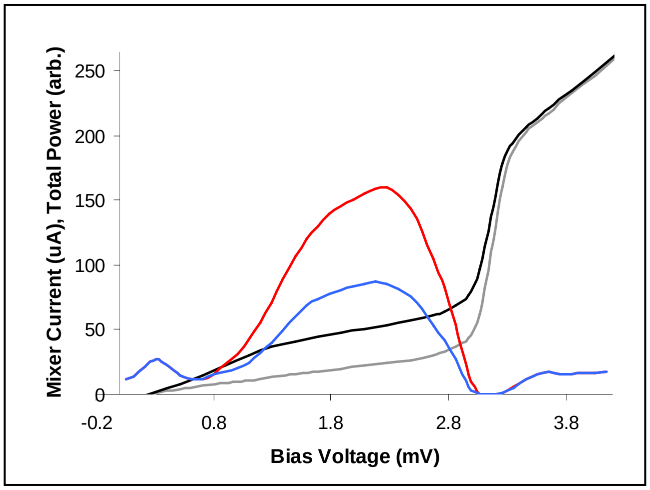

Fig.3. Performance at the RLT at 808 GHz, including pumped (black) and unpumped (gray) IV curves and hot (red) / cold (blue) total power measurements (PV curves; note that total power is in arbitrary units, arb.) Optimal performance (Y = 1.7) was achieved at a mixer bias of 2.3 mV and 55 μA, resulting in receiver noise temperature of 225 K.

The weather during the December 2008 observing campaign was good overall, with a zenith transmission equal to year-round median levels (40% at 810 GHz) throughout the run. This resulted in system noise temperatures of 1000-2100 K at the elevation of our sources (~60°) throughout the observing run. First light observations made with the new SIS receiver system toward the NGC 2024 star-forming region indicate that the receiver is sensitive and reveal its power as a large-scale mapping instrument (see Fig. 4). The spectrum shown represents a total on-source integration time of 0.6 minutes and clearly shows both CO J = 7-6 (left, LSB) and weaker neutral carbon line (right, USB) with a high signal-to-noise (S/N) ratio, > 15 at the $^{12}C^{0}$ line center and ~4-5 in the

CO line wings. The LO frequency was changed during observations to verify the identity of these lines. The resolution of this spectrum is 0.4 km/s, adequate for resolving features in complex line profiles, enabling multiple clouds along the line of sight to be distinguished, and disentangling signatures of bulk gas motions such as rotation and outflow. This spectrum is part of a larger 20’×20’ map made toward NGC 2024 in ~8.5 hours of total observing time, including telescope overhead, with the new SIS receiver on the RLT.

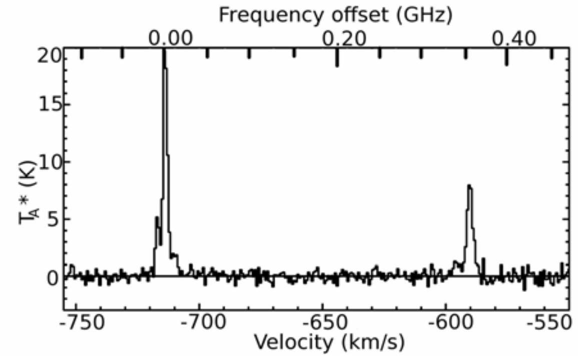

Fig. 4. Spectrum showing CO J = 7-6 (*left*, LSB) and $^{12}C^0$ J = 2-1 (*right*, USB) toward NGC 2024 made with the 810 GHz SIS receiver at the RLT. Axes show observed antenna temperature corrected for optical depth at source elevation and telescope scattering efficiencies (T_A*) as a function of frequency offset from the CO line center (GHz), *top*, and velocity (km/s), *bottom*. These are first light observations for a Herschel Band-3 type mixer at a telescope.

IV. CONCLUSION

We have constructed and deployed an 810 GHz receiver system incorporating a HIFI Band-3 pre-flight spare SIS mixer developed for Herschel and a wide-band SiGe LNA to the RLT telescope (elevation 5500 m) in northern Chile. Receiver sensitivity achieved at the telescope is slightly improved over laboratory measurements, resulting in noise temperatures of 225 K (Y = 1.7) measured at the input pupil of the receiver system. This compares favorably to measurements reported by the HIFI Band-3 team, given differences in operating conditions, and to the performance of 800 GHz SIS instruments currently operating at similar sites. We present first-light observations with a Herschel Band-3 type mixer at a telescope and the results indicate that the 810 GHz SIS receiver system is sensitive, stable, and functions as a good large-scale mapping instrument. The location of the RLT and its primary beamsize at 800 GHz coupled with the sensitivity of this new receiver system and high spectral resolution capabilities add to its appeal as a survey instrument. Our team is embarking on a CO/C^0 selective survey of molecular clouds in the Galactic plane, providing an important complement to upcoming THz spectroscopic surveys with the STO balloon-borne mission.

REFERENCES

[1] D. P. Marrone, J. Battat, F. B. Bensch, R. Blundell, M. Diaz, H. Gibson, T. Hunter, D. Meledin, S. Paine, D. C. Papa, S. Radford, M. Smith, and E. Tong, “A Map of OMC-1 in CO J = 9-8,” *Astrophysical Journal.,* vol. 612, no. 2, pp. 940-945, September 2004.

[2] D. P. Marrone, R. Blundell, E. Tong, S. N. Paine, D. Loudkov, J. H. Kawamura, D. Luhr, and C. Barrientos, “Observations in the 1.3 and 1.5 THz Atmospheric Windows with the Receiver Lab Telescope,” *Proc. 16th Int. Symp. Space THz Tech.*, S04-05, May 2005.

[3] M. C. Wiedner, G. Weiching, F. Bielau, K. Rettenbacher, N. H. Volgenau, M. Emprechtinger, U. U. Graf, C. E. Honingh, K. Jacobs, B. Vowinkel, K. M. Menten, L. A. Nyman, R. Güsten, S. Philipp, D. Rabanus, J. Stutzki, and F. Wyrowski, “First observations with CONDOR, a 1.5 THz heterodyne receiver,” *Astronomy & Astrophysics.,* vol. 454, no. 2, pp. L33-L36, August 2006.

[4] C. E. Oberst, S. C. Parshley, G. J. Stacey, T. Nikola, A. Löhr, J. I. Harnett, N. F. H. Tothill, A. P. Lane, A. A. Stark, and C. E. Tucker, “Detection of the 205 μm [NII] line from the Carina nebula,” *Astrophysical Journal.,* vol. 652, no. 2, pp. L125-L128, December 2006.

[5] D. P. Marrone, R. Blundell, H. Gibson, S. Paine, D. C. Papa, and C. E. Tong, “Characterization and status of a Terahertz telescope,” *Proc. 15th Int. Symp. Space THz Tech.*, pp. 426-432, April 2004.

[6] M. Harwit, “The Herschel mission,” *Advances in Space Research.,* vol. 34, no. 3, pp. 568-572, 2004.

[7] T. de Graauw, and F. P. Helmich, “Herschel-HIFI: The Heterodyne Instrument for the Far-Infrared”, *The Promise of the Herschel Space Observatory*, ESA SP-460, pp. 45-51, 2001.

[8] S. Weinreb, J. C. Bardin, and H. Mani, “Design of cryogenic SiGe low-noise amplifiers,” *IEEE Trans. Microwave Theroy Tech.,* vol. 55, pp. 2306-2312, November 2007.

[9] C. K. Walker, C. A. Kulesa, C. E. Groppi, E. Young, T. McMahon, P. Bernasconi, C. Lisse, D. Neufeld, D. Hollenbach, J. Kawamura, P. Goldsmith, W. Langer, H. Yorke, J. Sterne, A. Skalare, I. Mehdi, S. Weinreb, J. Kooi, J. Stutzki, U. Graf, C. Honingh, P. Puetz, C. Martin, and M. Wolfire, “The Stratospheric Terahertz Observatory (STO) an LDB experiment to investigate the life cycle of the interstellar medium,” *Proc. 19th Int. Symp. Space THz Tech.*, pp. 28-32, April 2008.

[10] G. de Lange, B. D. Jackson, M. Jochemsen, W. M. Laauwen, L. de Jong, M. Kroug, T. Zijlstra, and T. M. Klapwijk, “Performance of the flight model HIFI band 3 and 4 mixer units,” *Proc. SPIE* , vol. 6275, pp. 627517, July 2006.

[11] I. Mehdi, E. Schlecht, G. Chattopadhyay, and P.H. Siegel “THz local oscillator sources: performance and capabilities,” *Proc. SPIE,* vol. 4855, pp. 435-446, 2003.

[12] I. Mehdi, G. Chattopadhyay, E. Schlecht, J. Ward, J. Gill, F. Maiwald, and A. Maestrini, "Terahertz multiplier circuits," *IEEE MTT-S Symposium Digest*, pp. 341-344, June 2006.

[13] C. E. Tong, D. N. Loudkov, S. N. Paine, D. P. Marrone, and R. Blundell, “Vector measurement of the beam pattern of a 1.5 THz superconducting HEB receiver,” *Proc. 16th Int. Symp. Space THz Tech.,* pp. 453-456, May 2005.

[14] R. Blundell, J. W. Barrett, H. Gibson, C. Gottleib, T. R. Hunter, R. Kimberk, S. Leiker, D. Marrone, D. Meledin, S. Paine, D. C. Papa, R. J. Plante, P. Riddle, M. J. Smith, T. K. Sridharan, C. E. Tong, and R. W. Wilson, “Prospects for Terahertz radio astronomy from northern Chile,” *Proc. 13th Int. Symp. Space THz Tech..*, pp. 159-166, March 2002.

[15] S. Paine, R. Blundell, D. C. Papa, J. W. Barrett, and S. J. E. Radford, “A Fourier Transform Spectrometer for measurement of atmospheric transmission at submillimeter wavelengths,” *Publications Astron. Soc. Pacific,* vol. 112, pp. 108-118, January 2000.

[16] C. Kasemann, R. Güsten, S. Heyminck, B. Klein, T. Klein, S. D. Philipp, A. Korn, G. Schneider, A. Henseler, A. Baryshev, T. M. Klapwijk, “CHAMP+: a powerful array receiver for APEX,” *Proc. SPIE*, vol. 6275, pp. 62750N, July 2006.

[17] U. U. Graf, S. Heyminck, E. A. Michael, S. Stanko, C. E. Honingh, K. Jacobs, R. T. Scheider, J. Stutzki, and B. Vowinkel, “SMART: the KOSMA Sub-Millimeter Array Receiver for Two frequencies,” *Proc. SPIE*, vol. 4855, pp. 322-329, June 2003.