Versatile Radiometric Testbed for the Submillimeter Wave Instrument

Mikko Kotiranta*[1], Karl Jacob[1], Michael Olberg[2], Paul Hartogh[3], and Axel Murk[1]

***Abstract*— This paper presents a radiometric testbed for the characterization of the 600-GHz and 1200-GHz double side band heterodyne receivers of the Submillimeter Wave Instrument on the Juice mission of ESA. The testbed enables measurements of receiver noise temperature, gain stability, side band ratio, and beam coalignment in a thermal-vacuum chamber. Receiver spectral response and spurious signal investigations are possible with an optional transmitter. Measurement results obtained for engineering and protoflight models of the instrument are presented.**

***Keywords*— Beam coalignment, Juice, microwave radiometry, side band ratio, Submillimeter Wave Instrument, testbed**

I. Introduction

The Submillimeter Wave Instrument (SWI) [1] on the Jupiter Icy Moons Explorer (Juice) spacecraft of ESA consists of two double side band heterodyne receivers that are independently tunable in the frequency bands 530 GHz - 625 GHz and 1080 GHz - 1275 GHz, respectively. The Schottky diode mixers and IF low-noise amplifiers of the receivers are cooled passively to a temperature of 150 K. The instrument backend consists of broadband autocorrelation spectrometers (ACS), high-resolution chirp transform spectrometers (CSH), and continuum channels.

In addition to the receiver noise temperature and gain variations that limit the receiver sensitivity and the accuracy of absolute brightness temperature determination, knowledge of the receiver side band ratio (SBR) is necessary for obtaining exact spectral line intensities present in the upper and lower side bands. The SBR of Submillimeter Wave Satellite (SWAS) receiver system [2], the Odin radiometer [3], and the Heterodyne Instrument for the Far Infrared (HIFI) on board the Herschel Space Observatory [4],[5] were determined before the launch using a gas cell that enables observations of known molecular spectral lines in a laboratory. The SBR of submillimeter wave receivers has also been determined with a setup based on a Martin-Puplett interferometer [6].

The 600- and 1200-GHz beams of SWI must be well coaligned to allow simultaneous observations without excessive signal loss in either of the channels. A facility such as the Low-temperature Near-field Terahertz Chamber (Lorentz) [7] allows beams to be characterized by a two-dimensional RF near-field measurement in space-quality vacuum in a wide range of temperatures. The beam positions inside the instrument, for example during the alignment process of the receivers and the relay optics, may be determined with a compact setup described in [8].

A radiometric testbed allowing the characterization of the SWI receivers in a realistic environment prior to the launch is essential for maximizing the science output during the mission. This paper presents the design and operation of such a testbed.

To understand how the testbed can be used for characterizing the SWI receivers, the instrument optics is briefly reviewed in Section II. The design of the testbed is then described in Section III, the employed test methods are presented in Section IV, and the measurement results demonstrating correct operation of the testbed are given in Section V. Finally, conclusions based on the results are drawn in Section VI.

II. SWI Optics

SWI receives thermal radiation from Jupiter's atmosphere with a 29-cm off-axis paraboloid antenna that is steerable in the angular range ±72°. The primary (M1) and secondary (M2) mirrors are mounted on a rocker that is attached to the receiver unit box with two bearings that allow the rocker to be tilted up to ±4.3°. There is a cut-out in the rocker to allow the signal from M2 to enter the receiver unit (RU) box, in which relay optics consisting of planar and elliptical mirrors (M3-M5) and a free-standing wire grid (WG) guide the signal to the 600- and 1200-GHz receivers. The signal of the 600-GHz channel is collected by a corrugated feedhorn with a nonlinear profile whereas the 1200-GHz receiver is equipped with a smooth-walled, spline-profile horn. Further, a planar flip-mirror (MF) allows the receivers to view a conical calibration hot load (CHL). The beam path is illustrated schematically in Fig. 1.

III. Testbed Design

The testbed is built around a Martin-Puplett interferometer (MPI), and its main parts are depicted schematically in Fig. 2a. The testbed is attached to the receiver unit (RU) box using an interface part that fits one of the bearing holes. The rocker and the mirror M3 are not present during the tests, so instead of reflecting from the mirror M3, the 600-GHz and 1200-GHz receiver beams exit the RU box through the bearing hole. After entering the testbed, they first meet a parabolic mirror from which they are reflected to a photolithographic polarizer that splits the signals to a fixed

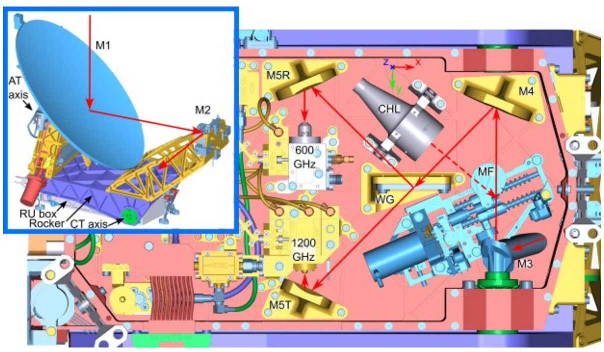
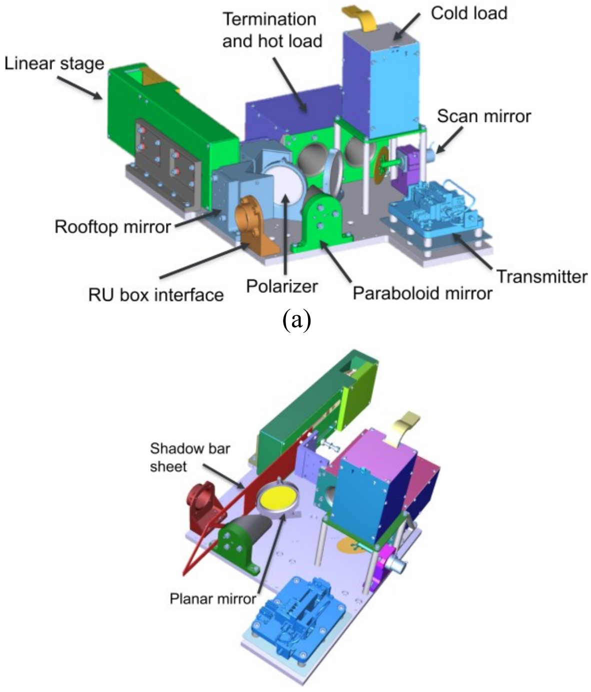


Fig. 1. Overview of the SWI optics with the beam path.

[1]University of Bern, Bern, 3012, Switzerland; [2]Chalmers University of Technology, Onsala, 43992, Sweden; [3]Max Planck Institute for Solar System Research, Göttingen, 37077, Germany



(b)

Fig. 2. CAD model of the SWI testbed: configuration for measuring a) side band ratio, b) beam coalignment.

rooftop mirror and to a movable rooftop mirror that is mounted on a vacuum-compatible linear stage. After reflecting at the roof top mirrors and recombining at the polarizer, the signals then meet a second photolithographic polarizer at the output of the MPI. Only the vertical components are transmitted to a scan mirror that reflects the signals either towards a hot or cold conical cavity blackbody calibration target. The targets have a nonlinear profile and utilize an epoxy-based composite material for efficient microwave absorption. The cold target stands on thermally insulating supports, and its metal housing is connected to a cryo-cooler. A third scan mirror position allows a signal from a transmitter to be injected towards the receivers to investigate the receiver spectral response and generated spurious signals.

While a receiver side band ratio measurement calls for an interferometric setup, a more direct beam path to the calibration targets is sufficient for noise temperature and stability measurements: instead of the polarizers, a single planar mirror is mounted to the testbed, as shown in Fig. 2b. The planar mirror configuration is employed also during beam coalignment measurements. The movable roof mirror is replaced with a heated shadow bar sheet. The receivers view the cold load, and the sheet with two shadow bars that are oriented in an angle of ±45° with respect to the vertical are then moved across the 600-GHz and 1200-GHz beams. The geometry of the shadow bars is illustrated in Fig. 3. Beam offsets at least up to 10 mm with respect to optical axis can be determined.

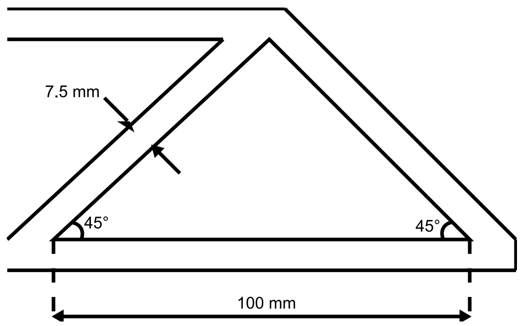


Fig. 3. Geometry of the shadow bars.

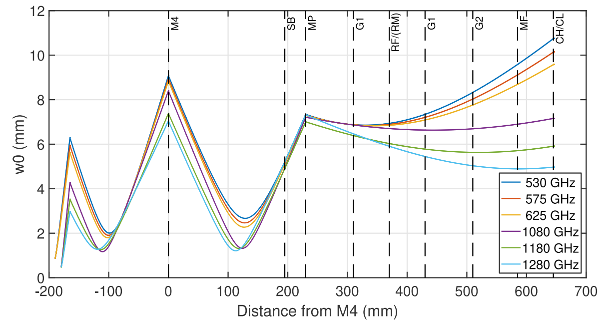


Fig. 4. Beam radius in the testbed computed using Gaussian beam mode propagation. SB: shadow bar sheet; MP: paraboloid mirror (reflected focal length 101.6 mm); G1/G2: polarizer; RF/RM: fixed/movable rooftop mirror; MF: scan mirror; CH/CL: hot/cold load.

The propagation of the receiver beams in the testbed was determined using Gaussian beam mode analysis (Fig. 4). The radii of both beams are about 5 mm at the plane of the shadow bar. The shadow bars have a non-projected width of 7.5 mm, so at the linear stage position, where the greatest beam blockage is obtained, more than 98 % of the power should hit the shadow bar if ideal Gaussian beams are assumed.

IV. Measurement Methods

A. Beam Coalignment Measurements

The horizontal and vertical offsets of the beams with respect to the optical axis are determined with the relations given in [8]:

$$\Delta h = \frac{(\Delta x_1 + \Delta x_2)}{2}, \tag{1}$$

$$\Delta v = \frac{(\Delta x_1 - \Delta x_2)}{2}, \tag{2}$$

where $\Delta x_1 = x_1' - x_1$, $\Delta x_2 = x_2' - x_2$, x_1' and x_2' are the linear stage coordinates at which the peak IF power is measured, and x_1 and x_2 the reference coordinates defined by the testbed mechanical design. The peak IF power is measured at the position where the blockage of the cold load view by the warm shadow bar is the greatest.

The beam coalignment, or the positions of the beams with respect to each other, can be determined also from a relative measurement: the measured coordinates of one beam are used as the reference coordinates during the measurement of the second beam.

B. Side Band Measurements

In a double side band receiver both the upper and lower side bands contribute to the IF spectrum. In an ideal DSB receiver one half of the signal originates from the upper side band and the other half from the lower side band. In case of SWI, an equal contribution of both side bands is not important but rather that the fractions are known so that the spectral line intensity calibration may be performed correctly.

Signal transmission through the MPI is dependent on the electrical path length and follows a cosine curve. When the rooftop mirror position is swept and the transmission curves

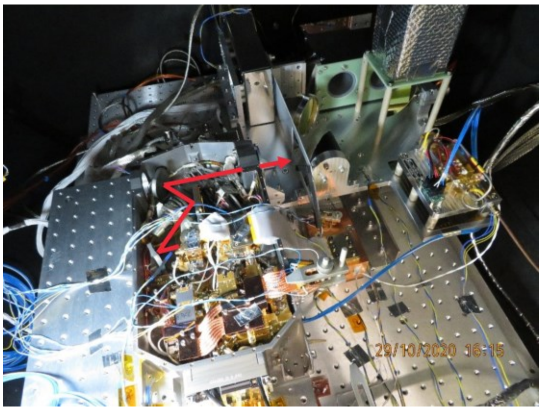


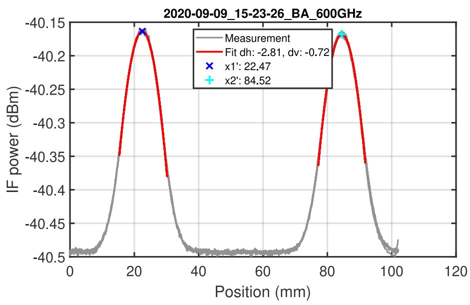
Fig. 6. Beam coalignment measurement with the testbed in a thermal-vacuum chamber. 600-GHz receiver beam path is indicated with a red line.

at USB and LSB frequencies are superimposed, a beat pattern is formed. Following the procedure presented in [6], the USB and LSB conversion gains are computed by fitting two cosine functions to the beat pattern that is obtained by measuring the Y-factor for each ACS channel at different rooftop mirror positions. The Y-factor is obtained by looking at the hot and cold loads through the MPI and by computing the power ratio. The USB and LSB gains g_{USB} and g_{LSB} are determined from the amplitudes of the cosine-functions. The side band ratio is then

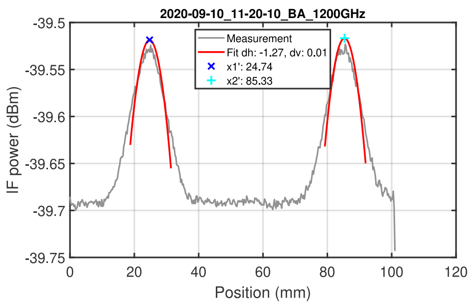
$$SBR = \frac{g_{USB}}{g_{LSB}}. \quad (3)$$

V. Results

Fig. 6 shows the RU box that is attached to the testbed in a TVAC during a beam coalignment measurement. It was first performed on the 600-GHz receiver of the SWI engineering model (EM) at room temperature. The 1200-GHz receiver was not switched on due to concerns related to the degradation of mixer lifetime. The measurement was then repeated with both receivers when the RU box was



(a)



(b)

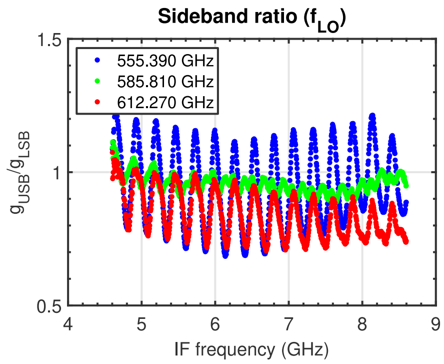
Fig. 7. SWI EM receiver beam coalignment measurement at -80°C after feedhorn-mixer block elevation correction by shimming: a) 600-GHz, b) 1200-GHz.

TABLE I
HORIZONTAL AND VERTICAL BEAM OFFSET WITH RESPECT TO THE NOMINAL BEAM AXIS AND THE DISTANCE *D* BETWEEN THE BEAM CENTERS.

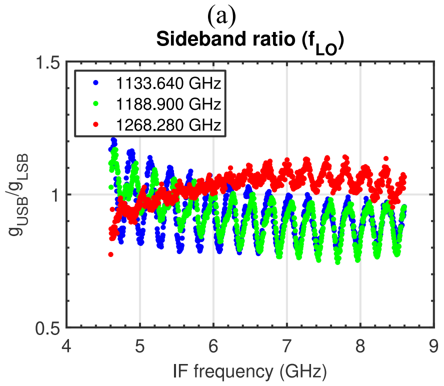
	600 GHz		1200 GHz		*D* (mm)
	Δh (mm)	*Δv* (mm)	*Δh* (mm)	*Δv* (mm)	
Room temp.	-2.9	-3.3	n/a	n/a	n/a
Cold	-2.7	-3.3	-0.4	-3.5	2.3
Cold, shimmed	-2.8	-0.7	-1.3	0.0	1.7

cooled down to a temperature of -80 °C. Coordinate measurement machine measurements had shown that the feedhorn-mixer blocks of the receivers had a misalignment of about 400 µm in the elevation direction with respect to the mounting surface. This misalignment was corrected by shimming, and the shadow bar measurement was repeated. Fig. 7 shows as an example the measured IF power as a function of the linear stage position for both receivers at a RU box temperature of -80 °C. The measured beam offsets as well as the distance between the beam centers *D* are summarized in Table I.

The side band ratios of the SWI protoflight model (PFM) receivers are presented in Fig. 5 at three LO-frequencies near the center and edges of the operating frequency bands. The ratios vary between 0.68 and 1.23 in the 600-GHz band and between 0.74 and 1.36 in the 1200-GHz band. They exhibit a ripple, the magnitude of which is dependent on the LO-frequency.



(a)



(b)

Fig. 5. SWI PFM receiver side band ratio for several LO-frequencies in a) 600-GHz and b) 1200-GHz channel.

VI. Conclusions

A versatile testbed for radiometric characterization of SWI has been built and successfully employed in the testing of SWI EM and PFM receivers in a thermal-vacuum chamber (TVAC).

The shadow bar measurements show that the cooling of the receiver unit box has only a minor effect, -0.2 mm in horizontal direction, on the beam position at 600 GHz. Further, the results confirm the reduction of vertical beam offset as the feed horns of both channels were shimmed in the elevation direction. The final measured distance between the beams centers, 1.7 mm, applies only in the shadow bar plane if the beams are not propagating parallel to each other.

The side band ratios of both SWI receivers have been determined successfully. A ripple in the results with respect to the IF frequency has been observed and further investigations of its origin are on-going.

Acknowledgments

The work at the University of Bern has been funded by the Swiss National Science Foundation under the Grant No. 200020-165744 and the ESA PRODEX program PEA 4000111892.

References

[1] M. Kotiranta, et al., "Optical Design and Analysis of the Submillimeter-Wave Instrument on JUICE," in IEEE Trans Terahertz Sci, vol. 8, no. 6, pp. 588-595, Nov. 2018.

[2] V. Tolls et al., “Submillimeter Wave Astronomy Satellite Performance on the ground and in orbit,” ApJS, vol. 152, no. 1, pp. 137-162, May 2004.

[3] U. Frisk et al., “The Odin satellite - I. Radiometer design and test,” A&A, vol. 402, no. 3, pp. L27-L34, May 2003.

[4] Teyssier, D., Dartois, E., Deboffle, D., *et al.*, “A Multi-path Far-Infrared and Sub-millimetre Gas Cell for Spectral Tests of HerscheL/HIFI,” in ISSTT 2004, Northampton, Massachusetts, USA, 2004.

[5] Higgins, R., Teyssier, D., Borys, C. et al., “The effect of sideband ratio on line intensity for Herschel/HIFI,” Exp Astron no. 37, pp. 433-452, May 2014.

[6] M. Renker, et al., "Sideband characterization and atmospheric observations with various 340 GHz heterodyne receivers", Rev. Sci. Instrum. 85, 084706, 2014.

[7] P. Moseley et al., “Introducing LORENTZ: A Novel Low-temperature Near-field Terahertz Chamber for Instrument Characterisation,” in ISSTT 2022, Baeza, Spain, 2022.

[8] U. U Graf, “A Compact Beam Measurement Setup”, J Infrared Milli Terahz Waves, no. 37, pp. 770–775, Mar. 2016