Radiometric Performance of the 530 to 625 GHz Receiver Unit of the Submillimetre Wave Instrument on JUICE

Karl Jacob[1, *], M. Kotiranta[1], P. Sobis[2], A. Emrich[2], V. Drakinskiy[3], J. Stake[3], A. Maestrini[4], J. Treuttel[4], B. Thomas[5], M. Philipp[5], P. Hartogh[6], and A. Murk[1]

[1]Institute of Applied Physics, University of Bern, CH-3012, Bern, Switzerland

[2]OMNISYS Instruments AB, SE-421 32, Västra Frölunda, Sweden

[3]Chalmers University of Technology, 41296, Göteborg, Sweden

[4]LERMA, Observatoire de Paris, 75014, Paris, France

[5]Radiometer Physics GmbH, Meckenheim, Germany

[6]Max Planck Institute for Solar System Research, D-37077, Göttingen, Germany

*Contact: karl.jacob@iap.unibe.ch.

***Abstract*— The upcoming Submillimeter Wave Instrument on the JUICE spacecraft is a passive radiometer/spectrometer instrument with two heterodyne receivers which are independently tunable in the frequency bands 530 to 625 GHz and 1080 to 1275 GHz. It will study Jupiter's atmosphere as well as the atmospheres and surface properties of the Galilean moons. This work presents the results of first radiometric tests with a prototype of the 600 GHz receiver. In this context, the baseline ripples caused by the internal calibration target have been characterized using two conical prototypes with a linear and an exponential absorber coating profile. A significant reduction of the baseline ripple amplitude has been measured with the target having the exponential cone profile. The spectroscopic baseline has been characterized for various frequency steps when applying frequency switching as an alternative calibration mode. At some operating frequencies a very flat switching baseline has been measured for frequency throws up to 90 MHz, while at other frequencies significant spectral distortions are measured even with a step size of 22.5 MHz. The first radiometric tests of the sideband gain ratio with a passive Fourier Transform Spectroscopy method demonstrate the general applicability in the 530 to 625 GHz band.**

I. INTRODUCTION

The JUpiter ICy moons Explorer (JUICE) is a L-class mission of the European Space Agency (ESA) to investigate Jupiter and the Galilean satellites Ganymede, Callisto and Europa. The launch of the spacecraft is scheduled for 2022 and the scientific payload consists of 10 instruments. One of these instrument is the Submillimetre Wave Instrument (SWI). SWI is a passive heterodyne radiometer/spectrometer instrument that is going to observe the atmospheres and surface properties of the Jovian objects with two orthogonally polarized receivers which can be independently tuned in the frequency ranges from 530 to 625 GHz and from 1080 to 1275 GHz [1]. The two double sideband (DSB) receivers are based on sub-harmonic mixers which will be passively cooled to a temperature of about 140K to improve the sensitivity of the instrument. The back-end of SWI includes two Chirp Transform Spectrometers (CTS), as well as two Auto Correlation Spectrometers (ACS) and two continuum channels. SWI will be calibrated with views to cold space and using an internal conical blackbody calibration target (CHL) which acts as the hot reference [2]. A planar flip mirror can be activated to allow the 600GHz and the 1200GHz receivers to view the CHL. This internal calibration target should exhibit a homogeneous temperature distribution, as well as an emissivity close to unity. The coherent backscattering S_{11} of the internal calibration target leads to standing waves between the calibration target and the receivers, that cause periodic baseline ripples in the calibrated spectra. This limits the absolute accuracy of the calibration and complicates the evaluation of the spectra. Since the flip mirror mechanism has a relatively slow switching time and a limited lifetime, alternative calibration modes need to be considered to overcome gain drifts of the receivers. Hence, it is also planned to apply frequency switching as an alternative calibration mode that requires a less frequent calibration with the CHL. A flat spectroscopic baseline is necessary over the entire intermediate frequency (IF) band and large frequency throws are preferable for the data evaluation. Additionally, an accurate analysis of the observed spectral lines requires a precise knowledge of the sideband gain ratio of the double sideband mixers. Therefore, determining the receiver characteristics before the launch is crucial. This paper first presents the design of the 530 to 625 GHz receiver unit of SWI and then reports the results of the first radiometric measurements obtained with a receiver prototype.

II. RECEIVER UNIT DESIGN

A view from the bottom into the receiver unit box together with the optical beam path is illustrated in Figure 1. More detailed information about the optical design and the components can be found in [3]. The 600 GHz receiver chain consists of an E-band

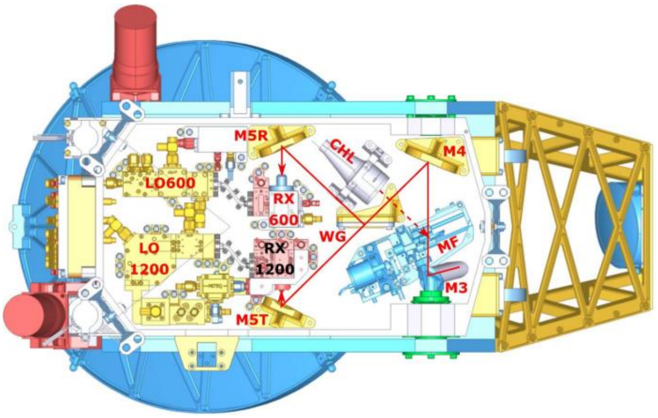

Figure 1. Bottom view of the receiver unit box with optical beam path.

tripler and an E-band power amplifier (MPA) from Radiometer Physics GmbH (RPG) in Meckenheim, Germany. The elements are followed by a chain of two varactor diode multipliers, a 140 GHz doubler from RPG and a 280 GHz doubler from LERMA in Paris, France. The local oscillator (LO) delivers a maximum power between 4 and 10 mW at ambient temperature operation across the entire SWI frequency range from 265 to 312.5 GHz. The sub-harmonic DSB mixer has been developed by Omnisys Instruments AB in Västra Frölunda, Sweden. The mixer block consists of a broadband GaAs Schottky membrane diode and a commercial low noise amplifier (LNA) that has been designed by the company Low Noise Factory, which are both optimized for cold temperature operation. The mixer is based on Terahertz Monolithically Integrated circuits (TMIC) and cryogenic InP High Electron Mobility Transistor (HEMT) LNA MMIC from Chalmers University of Technology. Both chips are integrated into a single block including the bias connections for the LNA in order to reduce the size and mass. The mixer block with the LNA will be passively cooled to a temperature of about 150 K in order to improve the signal-to-noise ratio by a thermal strap that is connected to an external cold space radiator. In addition, the last doubler is cooled in order to improve the efficiency and extend its lifetime. Since the other components (LO600 in Fig. 1) of the receiver unit will be operated at the temperature of the spacecraft of about 220 K, the cooled components (RX600 in Fig. 1) are insulated by an additional titanium waveguide. More information about the receiver unit design can be found in [4].

III. RADIOMETRIC CHARACTERIZATION

A. *Standing Waves to Calibration Target*

The baseline ripples, which are caused by a small but non-zero reflectivity of the CHL, have been determined in combination with a prototype of the 600 GHz receiver unit integrated into a breadboard model of the receiver unit optics and a prototype of the CHL. Two prototypes of the CHL with different geometries have been designed and manufactured, one with a commonly used linear and one with an exponential profile of the absorber coating to reduce the reflectivity of the CHL as described in [5]. The IF signal has been measured with the prototype of the SWI ACS, resolving a bandwidth of 4.4 GHz with 256 channels. The measurement setup is calibrated with a Y-factor measurement using a liquid nitrogen and an ambient temperature reference. The differences of two calibrated spectra, one of them measured with an axial movement of the target of 1/4λ, is calculated to make sure that only the standing waves caused by the test object are observed. At a fixed central frequency and distance to the calibration target, the double sideband detection of the standing wave leads to destructive and constructive superposition in the lower (LSB) and the upper sideband (USB) in the IF spectrum. Because the absolute position of the target is not clearly defined and the location at which the reflection at the target occurs is difficult to identify, measurements at only two positions are not sufficient to determine the amplitude in the worst case, where the resulting baseline ripples in the two sidebands superimpose constructively. Therefore, the resulting spectra are measured at two additional target positions, which are shifted by 1/8 λ to the first set of measurements. The amplitude in the worst case is calculated with the root sum square (RSS) of both amplitudes. Figure 2 depicts the baseline ripples determined with the linear CHL prototype at the central frequency of 590 GHz. Additional measurements with a commercially available TK-Ram absorber from Thomas Keating Ltd., UK, and a state-of-the-art pyramidal calibration target have been performed for a comparison. The pyramidal target is the on-board calibration target of the ice cloud imager (ICI) instrument as part of the second generation of the meteorological operational satellites (MetOP-SG) [6]. All results are summarized in Table 1. The amplitudes determined with both CHL prototypes and the ICI target are significantly smaller in comparison to the TK-Ram absorber. The worst case amplitude of the linear prototype is a factor of four higher compared to the worst case amplitude of the exponential cone.

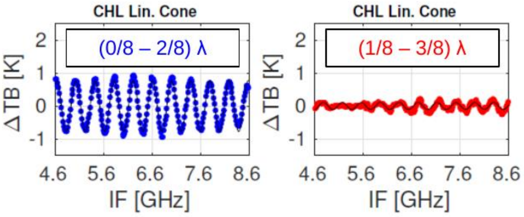

Figure 2. Baseline ripple determined with the linear CHL prototype.

Table 1. Extracted standing wave amplitudes of the measured targets.

Target	**ΔTB [K] (0/8 – 2/8)λ**	**ΔTB [K] (1/8 – 3/8)λ**	ΔTB [K] RSS
SWI CHL lin.	**0.78**	**0.11**	0.79
SWI CHL exp.	**0.10**	**0.16**	0.19
MetOp-SG ICI	**0.43**	**0.15**	0.46
TK-RAM	**9.1**	**8.7**	12.6

B. *Frequency Switching Baseline*

The frequency switching method will to be implemented as one of the SWI calibration modes and, therefore, the quality of the difference spectra has been investigated with the SWI 600 GHz receiver unit prototype and the prototype of the SWI ACS. The

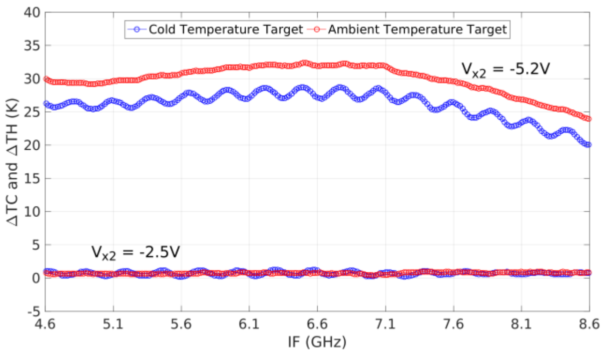

Figure 3. Switching baseline at 590 GHz when looking onto a liquid nitrogen and a room temperature target for two bias voltages of the last LO stage with the same LO power and for a stepsize of 22.5 MHz.

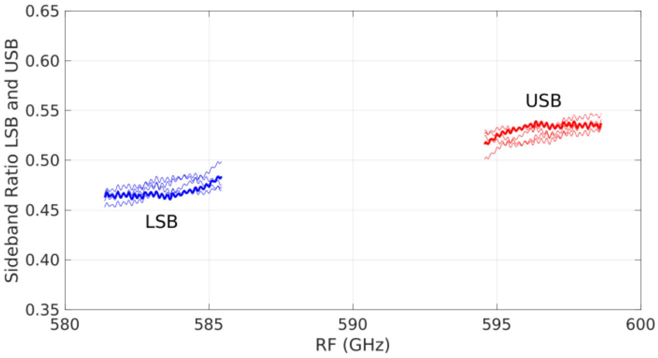

Figure 4. Fitted sideband ratio at 590 GHz with different path length. of the MPI. The results obtained with the distance showing the highest condition number of the coefficient matrix is shown with the thick line.

minimum frequency step of the SWI synthesizer is 1.875 MHz and with the harmonic number of 24, this results in the total step of the subharmonic LO of 22.5 MHz. The measurements were carried out by applying a similar frequency step and multiples of the step size using a laboratory synthesizer. The beam of the receiver was periodically directed onto a liquid nitrogen and a conical ambient temperature target for one second and the LO frequency was switched at each position. As an example Figure 3 shows the switching baseline at a LO frequency of 295 GHz for different bias settings of the last LO stage with the same LO output power and for the smallest stepsize of 22.5 MHz. In both cases the receiver has been optimized for the minimum noise temperature by changing the bias voltage setting of the 280GHz doubler according to a pre-determined look-up table. At a LO frequency of 295 GHz the optimum is reached at two different bias voltages while maintaining the bias voltage setting of the remaining LO components. The bias voltages -2.5 V and -5.2 V result in a similar LO output power of about 1.8 mW. While an almost flat switching baseline is observed at a voltage of -2.5 V, the switching baseline at a voltage -5.2 V shows significant spectral baseline distortions. In the second case a more complex calibration scheme would be needed in which the bias settings are also changed at each LO frequency step. The periodic ripple on the cold target are an artifact due to a standing wave from reflections at the liquid nitrogen surface. This result shows that the voltage settings cannot be selected solely on the basis of an optimal noise temperature if frequency switching will be used.

C. *Sideband Gain Ratio Measurements*

The frequency dependent sideband gain ratio of the 600 GHz receiver prototype has been measured with a scanning Martin Puplett Interferometer (MPI). The used polarizing dual-beam interferometer consists of three polarizing wire grids, a fixed rooftop reflector, and a second rooftop reflector mounted on a translation stage. Behind the MPI a flip mirror is used to switch between an ambient temperature and a liquid nitrogen target. From the resulting oscillations of the Y-factor with varying path length difference in the two interferometer arms, the frequency response can be determined with a Fourier transformation. In contrast to similar test setups using a single power detector with relative wide IF bandwidth, the measurement setup uses the prototype of the SWI ACS. This allows a more detailed Fourier transform of the interferogram, that results in a much higher frequency resolution and reveals more details on the variability of the sideband response [7]. In a first approximation of the sideband ratio between the USB and LSB the resulting beating pattern can be fitted with two cosine functions of a periodicity corresponding to the LO and IF frequencies. The amplitude and phase of the two cosines is derived using a linear least squares fitting algorithm. The ratio of these amplitudes correspond to the sideband ratio, whereas the fitted phase is only needed to compensate the uncertainty of the zero path length position. The detailed description of the used setup, which has been placed in front of the SWI receiver unit optics, and the data analysis can be found in [7]. Figure 4 gives an example of the fitted sideband response at a central frequency of 590 GHz at room temperature operation. The minimum path length used in the fit were fixed to a value where the interference pattern of the lowest IF shows at least one zero-crossing of the envelope of the beating pattern. As a quality criterion the condition number of the coefficient matrix was determined, which indicates the highest value with 12 mm path length. The result of the corresponding fit is plotted with the thick line. The fast periodic ripple on the traces are an artifact due to standing waves in the measurement setup. The main reasons for these standing waves are the reflections at the liquid nitrogen surface of the cold reference load, as well as the alignment errors and other imperfections of the MPI elements.

IV. CONCLUSIONS

Radiometric measurements of the baseline ripples caused by the CHL demonstrate a reduction of the standing wave amplitude with the exponential prototype. On the basis of these test results the geometry with an exponential cone profile has been selected as the internal calibration target for SWI. Frequency switching as alternative calibration mode, which requires a less frequent gain calibration with the CHL, was investigated, showing very promising results with an almost flat switching baseline at the smallest possible stepsize of the SWI synthesizer and even at larger frequency steps. However, these tests have demonstrated that suitable bias voltages of the LO chain components need to be selected to avoid large baseline distortions. The presented FTS test method allowed to determine the frequency dependent sideband gain ratio, enabling the possibility of a pre-launch calibration of the sideband response over the full IF bandwidth and a wide range of LO settings. The verification of the FTS technique with gas cell measurements is planned in the future and a more compact, vacuum-compatible setup for cryogenic sideband gain ratio tests at 600 and 1200 GHz is in construction.

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