# Characterization of the 530-625 GHz receiver unit for the Jupiter mission JUICE/SWI

# CHARACTERIZATION OF THE 530 GHZ TO 625 GHZ SWI RECEIVER UNIT FOR THE JUPITER MISSION JUICE

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## ABSTRACT

The Submillimetre Wave Instrument (SWI) is being developed for the Jupiter Icy moons Explorer (JUICE) mission of the European Space Agency (ESA). In this paper we give an overview of the 530 GHz to 625 GHz receiver unit of SWI and present the first noise temperature measurements covering the complete receiver bandwidth at room temperature operation. In this context we will point out the difficulties with the highly variable local oscillator power within the bandwith, which needs a careful tuning of the multiplier bias voltages in order to optimize the noise temperature and to avoid damage of the mixers. In addition we show initial results at cold temperature operation. Furthermore we will present a first stability measurement showing the temperature dependence of the receiver gain at room temperature operation.

Key words: JUICE; SWI; Submillimetre Wave Radiometer; Heterodyne Receiver;.

## 1. INTRODUCTION

The Submillimetre Wave Instrument (SWI) has been selected as one of the scientific instruments on the upcoming Jupiter Icy moons Explorer (JUICE) mission of the European Space Agency (ESA). JUICE is the first L-class mission in the Cosmic Vision programme designed to explore the Galilean satellites and the Jovian atmosphere. The launch of JUICE is scheduled in 2022 and arrival at Jupiter in 2030 [1, 2]. SWI is a passive heterodyne spectrometer whose primary scientific goals are to investigate the chemistry, isotopic composition, structure and general circulation of Jupiter's stratosphere and how it couples the lower and upper atmosphere and to investigate the sources and sinks, composition, isotopic composition, kinetic and hydrodynamic behavior of the atmospheres of the Galilean satellites. Furthermore SWI will investigate the thermo-physical properties of the surfaces of Ganymede, Callisto and Europa. In the current baseline configuration SWI consists of two orthogonally polarized heterodyne receivers which are independently tunable between 530 GHz and 625 GHz. This frequency range is rich in emission and absorption lines, especially the water line at 557 GHz, whose detection and mapping are important to understand the atmospheric circulation dynamics of Jupiter. In a second version of SWI one of the receivers is tunable between 1080 GHz and 1275 GHz. This would allow to determine the ortho-to-para ratio of water and improve the temperature retrieval by observing the methane line at 1256 GHz [3].

Figure 1 shows the CAD model of the current SWI concept. The antenna of the instrument has a projected aperture of 300 mm and can be rotated around two axes in along track and across track direction. The front-end receivers are cooled with a cold space radiator to a temperature of about 150 K in order to improve the sensitivity of the instrument. The back-end includes two high resolution Chirp Transform Spectrometers (CTS) with

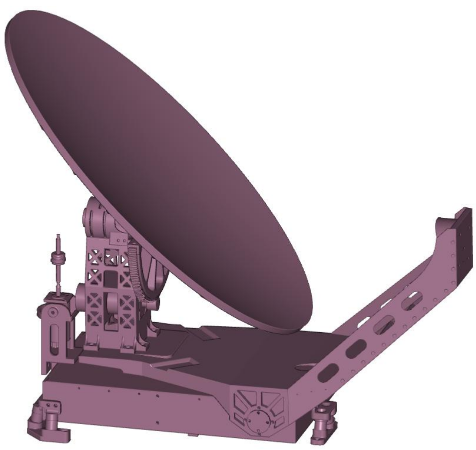

*Figure 1. CAD model of SWI for the ESA mission JUICE.*

1 GHz bandwidth and 100 kHz spectral resolution for precise line observations, two Autocorrelation Spectrometers (ACS) with 4 GHz bandwidth and 16 MHz spectral resolution for fast line surveys, and two broadband continuum detectors for polarimetric surface observations of the moons.

Details on the development of the different receiver elements are presented elsewhere at this conference. In this paper we show an overview of the receiver unit and first test results of the complete SWI 600 GHz front-end receiver chain.

## 2. RECEIVER UNIT

A CAD model showing the insight of the SWI receiver unit (RU) module with two 600 GHz channels can be seen in Figure 2. It contains the optical coupling network with focusing reflectors and a polarizing beam splitter, as well as a conical black body target which is used for the radiometric calibration of SWI. The flipping mirror mechanism which is used to direct the beam periodically onto the calibration hot load (CHL) is not shown in the figure. The two orthogonally polarized 600 GHz heterodyne receivers are placed on the left of the RU.

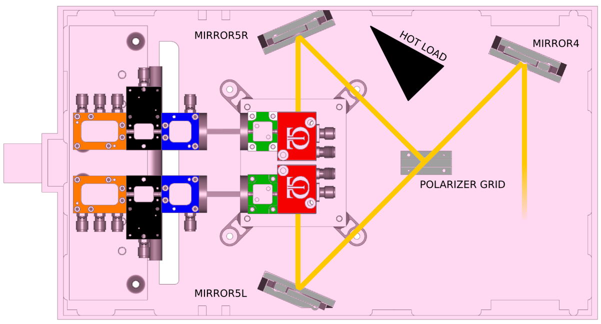


*Figure 2. CAD model showing the insight of the SWI RU module containing two orthogonally polarized 600 GHz heterodyne receivers, optics and the calibration hot load.*

A more detailed view on the assembled 600 GHz front-end receiver chain is given in Figure 3 showing a schematic diagram and a photograph. In the current baseline the local oscillator (LO) source consists of an E-band tripler and an E-band power amplifier from RPG. The E-Band tripler is a planar Schottky varactor diode based device delivering about 6–10 mW in the range between 67 GHz and 78 GHz with an average efficiency of about 7–12 %. The E-band power amplifier is based on an commercially available MMIC chip delivering 90–100 mW in the range from 67 GHz to 78 GHz. In the current version both components have to be biased from constant voltage supplies.

These components are followed by a chain of two varactor diode multipliers, a 140 GHz doubler from RPG and a 280 GHz doubler from LERMA with an estimated combined efficiency of about 6 %. Results of a prototype

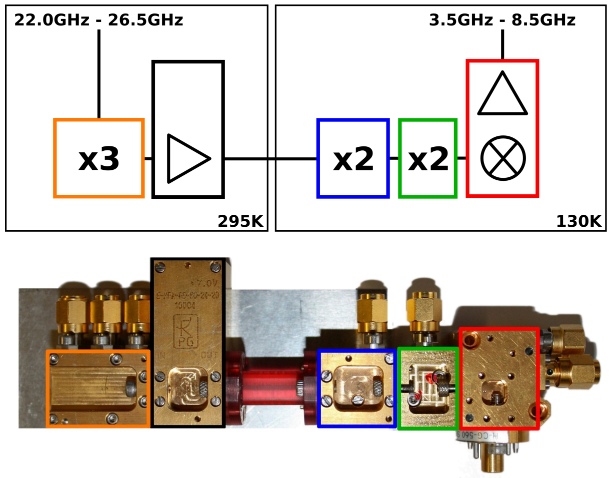


*Figure 3. Schematic diagram and photograph of the integrated SWI 600 GHz receiver chain used for the first performance tests at room and cold temperature operation.*

of the 280 GHz doubler from LERMA are reported elsewhere [4]. The LO chain can provide output powers between 4 mW and 10 mW at room temperature operation within the full SWI bandwith from 265 GHz to 312 GHz.

The sub-harmonic double sideband (DSB) mixers have been developed by Omnisys Instruments. The SWI mixers are based on Terahertz Monolithicaly Integrated circuits (TMIC) and cryogenic InP HEMT LNA MMIC from Chalmers University of Technology. Detailed information on the used diode technology and the development of a 557 GHz membrane Shottky diode mixer with a state-of-the-art performance is published elsewhere [6]. Further state-of-the-art subharmonic membrane Schottky diode mixers in the SWI frequency range of the 600 GHz channel have already been developed [7]. The SWI mixer blocks include a broadband GaAs Schottky membrane diode and a cryogenic LNA designed from Low Noise Factory, both optimized for a cold temperature operation. The chips are integrated into a single receiver module including the bias connections for the LNA in order to reduce size and mass of the blocks. Details on the mixer development are shown elsewhere [5]. The input of the mixers is connected to a corrugated feed horn which was optimized to match the frequency independent SWI optics.

In order to improve the signal to noise ratio the mixers and their integrated low noise amplifiers (LNA) will be cooled passively by thermal straps to an external cold space radiator to a temperature of about 150 K. In addition the last doubler will be cooled to improve its efficiency. Since the rest of the RU will be operated at the spacecraft temperature of about 220 K the cooled components have to be thermally isolated trough an additional wave guide. In the final SWI RU version the two doublers will be connected with a Titanium waveguide, which acts as a thermal break between the cooled parts and the LO components at ambient temperature. Since this component was not available for the initial measurements a 3D printed plastic waveguide from Swissto12 was inserted between the power amplifier and the 140 GHz doubler to provide thermal isolation during the cold measurements.

## 3. EXPERIMENTAL SETUP

Figure 4 shows a schematic diagram of the experimental setup for the performance measurements of the 600 GHz receiver chain. In the flight instrument the LO chain will be driven with a custom made 22–26.5 GHz synthesizer with 17 dBm output power. Since this module was not available for the current tests it was replaced by an Agilent 83624B synthesizer followed by an active doubler from SpacekLabs. The LO input powers then range between 50 mW and 80 mW. At the IF output different bandpath filters have been used to limit the IF bandwith. The filtered IF band was amplified with a broadband post-amplifier from Millitech and detected with either a broadband power meter N8485 from Agilent or with a spectrum analyser FSP-30 from Rhode&Schwarz with a resolution bandwidth of 10 MHz.

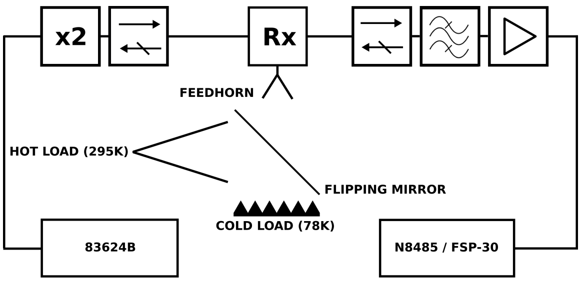


*Figure 4. Schematic diagram of the test setup. The component Rx represents the entire 600 GHz front-end chain.*

The noise temperature of the receiver chain was determined with a Y-factor measurement using a hot and a cold calibration target. The hot target is an injection molded conical absorber at ambient temperature, the cold target a pyramidal foam absorber immersed in liquid nitrogen. A flipping mirror allows a fast switching between the two loads to avoid drifts in the measured powers. The complete test setup, including the settings of the synthesiser and bias supplies, the flip mirror and the recording of the IF signals and housekeeping data such as the temperature at different locations or bias currents was fully automated with a Labview user interface.

The cryogenic measurements were performed in a thermal vacuum chamber (TVC) in which the cold components are mounted on a copper plate under a liquid nitrogen bath. The temperature of this plate can be controlled with additional resistive heaters between 78 K and 450 K. Due to the limited space the hot and cold calibration targets had to be placed outside of the TVC. They were viewed through a vacuum window consisting of a low loss TOPAS-8007 foil supported by a rigid polystyrene foam. The window has a measured loss of $-0.84$ dB at 560 GHz. With an assumed window temperature of

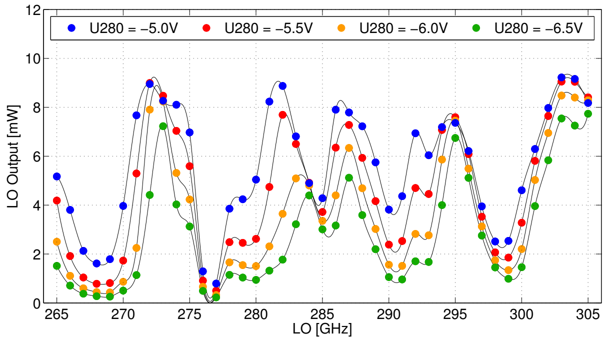


*Figure 5. Output power of the LO chain for different voltages of the 280 GHz doubler and with fixed bias voltages of the remaining elements at room temperature operation.*

295 K the effective temperature of the cold load behind the vacuum window is 116 K which was used to correct the cold Y-factor measurements.

## 4. MEASUREMENT RESULTS

### 4.1. LO Output Measurements

The output powers of the LO chain have been measured with a photo-acoustic power meter from Thomas Keating over the complete bandwith for different bias voltages of the 280 GHz doubler at room temperature operation. For this purpose a corrugated feed horn has been connected to the LO output, a Signal Recovery DSP Lock-In Amplifier SR7265 and a chopper wheel at 30 Hz have been used to measure the resulting LO chain output powers. Figure 5 gives an example of the results at room temperature operation where the output power varies over the band between 0.5 mW and 9.5 mW.

This result demonstrates the difficulties when operating the integrated front-end chain. At some frequencies the output power is limited to small values and the multiplier bias needs to be optimized for a high efficiency, whereas in other frequency bands the LO power can significantly exceed the maximum allowed mixer input of about 3 mW. For that reason a careful tuning scheme of the bias voltages of each of the multipliers needs to be established based on frequency and temperature dependant lookup tables.

### 4.2. Noise Temperature Measurements

Figure 6 presents the first noise temperature measurement results of the 600 GHz SWI receiver front-end chain from 530 GHz to 630 GHz obtained at room temperature operation. Plotted are the calculated DSB noise temperatures at optimum operation, which are found with a successive increase of the LO pumping powers. Each data point in this figure is the mean value of 10 independent measurements while the error bars represent the extreme values of these measurements.

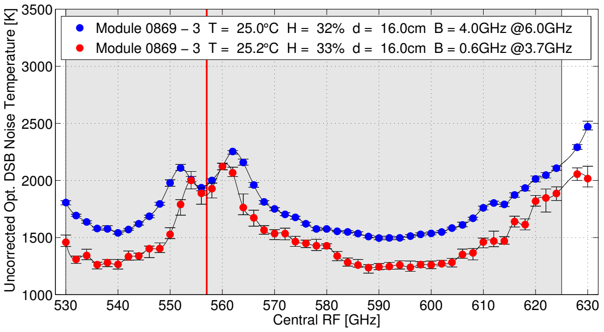


*Figure 6. Optimum DSB noise temperature of the integrated 600 GHz front-end chain at room temperature operation measured with two different bandpath filters. The red line marks the centre of the 557 GHz water vapour transition.*

The measurements have been performed with two different bandpath filters behind the IF output. The first test series (•) was obtained with a 4 GHz to 8 GHz filter, corresponding to the complete IF bandwith of SWI. In this case a minimum DSB noise temperature of 1496 K was observed at 590 GHz. For the second (•) the IF output was limited to a narrower band between 3.3 GHz and 4.0 GHz, showing a minimum DSB noise temperature of 1236 K at 588 GHz. This indicates that the noise temperature is not flat over the IF bandwidth, which is shown in more detail by the spectrally resolved measurement at in the following figures.

The atmospheric absorption can have a significant effect on the Y-factor measurements, in particular around the rotational transition line of water vapour with a centre frequency of 557 GHz. This effect has not been corrected in the calculation of the noise temperature in Figure 6, which results in two peaks around 557 GHz. These peaks occur when the centre of the absorption line falls in either the upper or the lower sideband of the DSB mixer. The correction of this effect requires knowledge of the atmospheric state and of the frequency dependent sideband ratios of the mixer. For that reason only the uncorrected noise temperatures are used in the following.

The LO pumping powers which are needed to reach the best noise performance of the receiver chain are plotted in Figure 7. They vary significantly between 0.70 mW at 568 GHz and 2.35 mW at 612 GHz over the full bandwith. Because of the different impedance matching in the integrated configuration and the LO output measurement configuration with the feedhorn attached to the LO chain the real powers needed to reach optimum operation can be different. It is obvious again that a careful tuning of the LO powers with bias tables is essential for a correct operation since the variation of the optimum pumping powers is remarkable.

Figure 8 shows the spectrally resolved optimum DSB

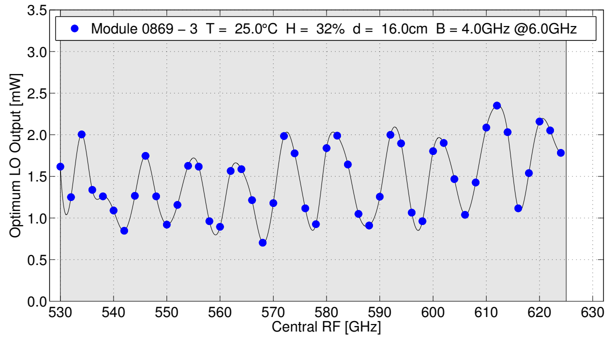


*Figure 7. LO powers at optimum operation of the integrated 600 GHz front-end chain at room temperature operation.*

noise temperature of the integrated 600 GHz front-end chain within the full bandwidth between 530 GHz and 625 GHz again without corrections. The two regions showing an increased DSB noise temperature are again caused by the water absorption line at 557 GHz, indicated with the horizontal red line. An absolute minimum DSB noise temperature of 1190 K was observed at an IF of 4.1 GHz and a centre frequency of 590 GHz where the effect of the water absorption is small. Above 310 GHz the LO chain doesn't provide enough power to measure a measurable IF output power.

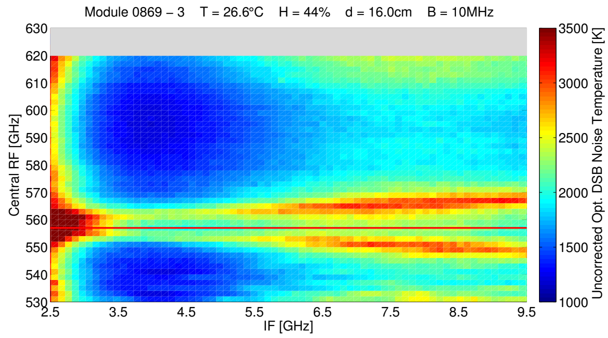


*Figure 8. Uncorrected DSB noise temperature of the integrated 600 GHz front-end chain over the entire IF spectrum at ambient temperature operation. The red line marks the centre of the 557 GHz water vapour transition.*

Figure 9 shows the measured hot and cold IF powers at the top and the resulting noise temperature distribution at the bottom at a central RF of 590 GHz and at room temperature operation when looking at the hot load. The IF output power changes within $-45$ dBm and $-37$ dBm showing the receiver gain over the entire IF bandwith. In good agreement to the measurements in Figure 6 a minimum in the noise temperature of 1200 K at an IF frequency of about 4 GHz can be observed.

The initial measurements at cryogenic temperatures were performed with a second identical mixer block (Serial No. 0869-4) and the same LO chain in the TVC. Figure 10 compares the noise temperatures at room temperature and at 140 K operation depending on the LO input

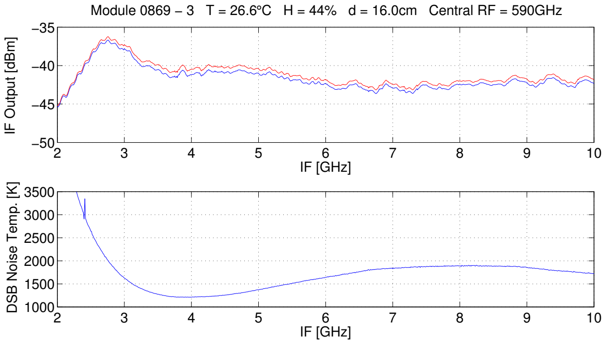


*Figure 9. Measured hot and cold powers and the resulting DSB noise at a center RF of 590 GHz and at room temperature operation.*

power for an RF center frequency of 560 GHz. At ambient temperature an optimum of the uncorrected DSB noise temperature of 2750 K is reached at an LO power of 1.17 mW, which is in good agreement with the previous results in Figure 7. When the receiver is cooled to 140 K it requires a two times higher LO power of 3.246 mW to reach a minimum of DSB noise temperature of 1540 K. The effect of the vacuum window was corrected in both measurements, but not the atmospheric attenuation of the 557 GHz water vapor line. Since the measurements were performed over the full bandwidth of the LNA and close to the line center, the true noise temperature will be significantly better. However, the results at both temperatures can be compared with each other because the measurements have been performed with the same setup and at stable laboratory conditions within some hours.

### 4.3. Performance Stability Measurements

A long term measurement with more then seven hours was performed at ambient temperature operation and 590 GHz. The ambient temperature change, measured with a PT100 attached to the mixer block, is plotted in Figure 11 as a function of time. The plot shows also the

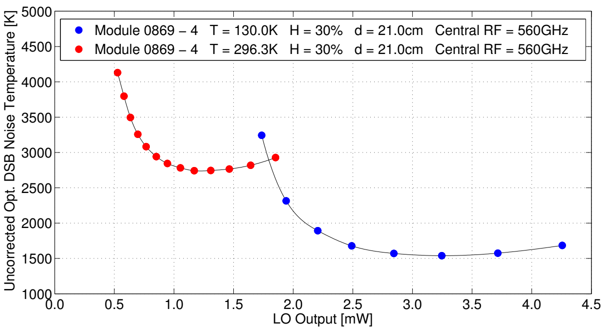


*Figure 10. Uncorrected DSB noise temperature of the 600 GHz SWI receiver front-end chain at room temperature and cold temperature operation at a central RF of 560 GHz.*

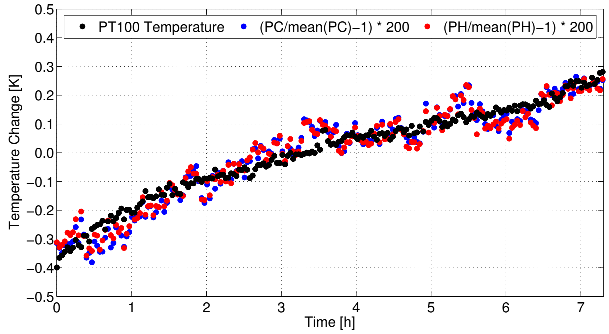


*Figure 11. Temperature change of the receiver chain and the gain variances of the receiver at room temperature operation measured when looking at the hot and cold calibration target.*

relative gain drift of the SWI receiver chain when looking at the cold and the hot target as an average over the full IF bandwith. It correlates well with the temperature with a slope of $\Delta G/\Delta T = +0.022$ dB/K.

In Figure 12 the relative drifts of the measured hot and cold powers and the relative drift of the resulting noise temperature is shown within the entire IF bandwidth and as a function of time. A relative change in the measured powers of 1 % when looking at the cold load and the hot load can be observed, but the changes are within the full IF band. No standing waves can be observed when looking at the cold load. The relative drift of the calculated noise is about 5 %. The observed drifts are mainly related to the measured temperature change of the receiver.

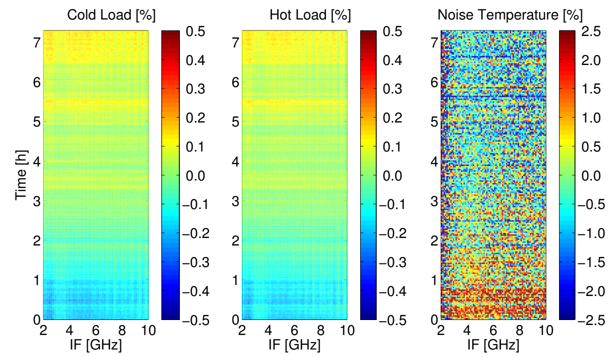


*Figure 12. Relative drifts of the measured hot and cold powers and relative drift of the resulting DSB noise temperatures in the long term test at a center RF of 590 GHz and at room temperature operation.*

## 5. CONCLUSION AND OUTLOOK

We have presented the first noise temperature measurements of the 530 GHz to 625 GHz SWI receiver front-end chain at ambient temperature operation covering the entire bandwith. In this context we demonstrated some difficulties in optimizing the noise temperature and avoiding damages of the mixers because of the LO output variations within the complete bandwith. The measured optimum DSB noise temperatures at room temperature operation are below the target value of 1500 K at cold temperature operation [8]. In addition we presented initial measurements at a temperature of 130 K, indicating an even improving DSB noise temperature at optimum operation.

Continuing measurements covering the complete bandwith between 530 GHz and 625 GHz are ongoing to characterize the performance of the front-end receivers in vacuum environment and at temperatures reachable with passive cooling in space.

Furthermore we presented first results of a long term measurement showing the temperature dependence of the receiver gain at room temperature operation. Since the instrument calibration procedure is repeated in time intervals of about 30 min the temperature caused drifts in the measurements are a main limitation of the measurement precision and thus a more detailed investigation of these aspects such as Allan Variance measurements are needed.

The characteristics of the integrated RU will be measured as soon as it is available. Besides the performance measurements this includes detailed antenna pattern measurements of the corrugated feed horns and beam pattern measurements of the entire optics at room and cold temperature operation in a TVC. The development of the calibration hot load is an ongoing work at the IAP and the progress is presented elsewhere at this conference. First performance tests on this task are planned in the close future.

## ACKNOWLEDGMENTS

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