PHOCUS Radiometer Payload

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Abstract— **PHOCUS – Particles, Hydrogen and Oxygen Chemistry in the Upper Summer Mesosphere is a Swedish sounding rocket experiment with the main goal of investigating the upper atmosphere in the altitude range 50-110 km. This paper describes the radiometer instruments (SondRad) in the PHOCUS payload, which are intended to explore the water vapour concentration in connection with the appearance of noctilucent (night shining) clouds. The design of the radiometer system has been done in collaboration between Omnisys Instruments AB and the Group for Advanced Receiver Development (GARD) at Chalmers University of Technology where Omnisys was responsible for the design, implementation, and verification of the radiometers and backend and GARD was responsible for the optics and calibration systems.**

The radiometers cover the water absorption lines at 183 GHz and 557 GHz with 67 kHz backend resolution. The 183 GHz channel is a side-looking radiometer while the 557 GHz radiometer is placed along the rocket axis looking in the forward direction. Both channels employ sub-harmonically pumped Schottky mixers and FFT spectrometer back-ends. The 183 GHz channel employs a CW-pilot signal calibrating the entire receiving chain while the IF-chain of the 557 GHz channel is calibrated by injecting a signal from a calibrated noise source through a directional coupler.

The instrument will collect complete spectra for both the 183 and 557 GHz with 300 Hz rate for the 183 GHz channel and 10 Hz for the 557 GHz channel for about 60 seconds reaching the apogee of the flight trajectory and 100 seconds after that. With lossless data compression using variable resolution over the spectrum, the data set is reduced to 2 x 12 MByte.

***Index Terms*—Radiometer, calibration, water vapour, and Noctilucent clouds.**

I. INTRODUCTION

PHOCUS – Particles, Hydrogen and Oxygen Chemistry in the Upper Summer Mesosphere is a Swedish[1] sounding rocket experiment with the goal of investigating the upper atmosphere in the altitude region 50-110 km and in particular the circumstances under which noctilucent (night shining) clouds (NLC) appear [1]. The NLC are restricted to a thin layer around 82 km, the highest clouds in our atmosphere, and are only present during the summer months and at high latitudes. The clouds are known to consist of water ice but the exact details of their formation are uncertain. Three criteria are needed to form ice clouds: cold temperatures, water vapour, and condensation nuclei. The nature of the condensation nuclei is not fully understood but two important suggestions are meteoric smoke particles and ions [2].

Measurements of the water vapour amount in the tenuous atmosphere at 82 km altitude is challenging. The heterodyne technique is probably the only method that can provide these measurements in the presence of sunlight. The water vapour measurements on board PHOCUS are performed by two microwave radiometers (SondRad) shown in Figure 1, operating at the 183 GHz and 557 GHz water absorption lines. The PHOCUS payload carries in total 18 instruments from 8 different research groups, investigating different properties of the mesosphere. The instruments measure optical (spectral-, angular- and polarization) properties, chemical composition (O- and H-probes), charged particles, temperature and pressure, and water vapour, to mention a few [2].

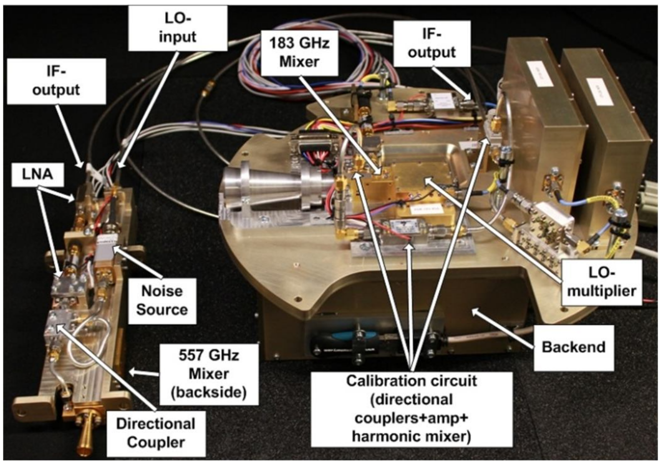

Figure 1. Picture of the two radiometers (557 GHz left). The backend with FFT-spectrometer located under the 183 GHz receiver (right).

II. TECHNICAL DESCRIPTION

SondRad comprises two radiometers covering the water absorption lines at 183.31 GHz and 556.936. The 183 GHz receiver is side-looking and is placed in the middle section of the rocket, Figure 2. Approximately 2 m above, the 557 GHz receiver is placed, pointed along the rocket axis looking in the forward direction, Figure 2. Both radiometers employ sub-harmonically pumped Schottky mixers where the 183 GHz mixer is provided by RPG [3] and the 557 GHz mixer is provided by VDI [4]. The LO sources at 85 GHz and 95 GHz for both radiometers employ active multiplier chains that have been developed by Omnisys Instruments AB [5]. The active 85 GHz multiplier pumps the 183 GHz mixer directly whereas

[1] PHOCUS rocket experiment is funded by the Swedish National Space Board. The radiometer instrument was funded by the Swedish Research Council, Vetenskapsrådet.

the 91 GHz chain is followed by a power amplifier with x3 multiplier stage that sub-harmonically pumps the 557 GHz mixer.

The FFT-spectrometer backend provided by Omnisys Instruments AB, processes a 275 MHz band with 4096 channels.

The two radiometers employ two different calibration techniques described in section III. A block diagram of the complete system is shown in Figure 3, with the 557 GHz radiometer located in the so called “Particle module” and the 183 GHz frontend located below the “Mid recovery module” (Figure 3). The backend, with the FFT spectrometer, and the control unit is placed on the same platform as the 183 GHz receiver.

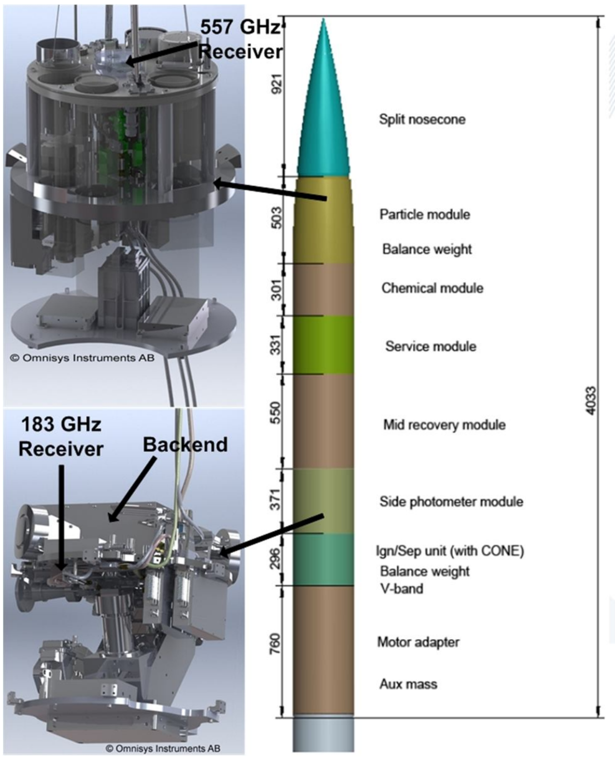

Figure 2. 3D-drawings of the 557 GHz and the 183 GHz radiometers and their respective placement on the rocket. ***The rocket figure is provided by SSC*** **[6].**

During the observation, starting at nose cone ejection, about 60 seconds after liftoff until reaching the apogee, and 100 seconds on the returning flight trajectory, the instrument will collect data with 300 Hz sampling rate for the 183 GHz receiver and 10 Hz sampling rate for the 557 GHz receiver. For the 183 GHz channel 183.310 GHz ±19.3 MHz will be saved of the FFT backend data and in addition 182.264 GHz ±0.5 MHz for the calibration signal. For the 557 GHz channel, 556.936 GHz ±19.3 MHz will be saved of the FFT backend data. The reason for limiting the spectral width is to reduce the amount of the data stored. Initially the data are stored locally in SDRAM, with limited capacity, and are dumped to non-volatile data storage at the apogee, as well as after the return to an observation stop altitude. A further step to reduce the amount of data is to vary the spectral bandwidth of the channels by keeping a high resolution, 67 kHz, at the centre of the band and decrease the resolution by combining channels towards the band edges. By doing this, the number of channels is reduced from 576 to 184. With lossless data compression using the variable resolution over the spectrum, the recorded data set is reduced to approximately 12 MByte/100s observation.

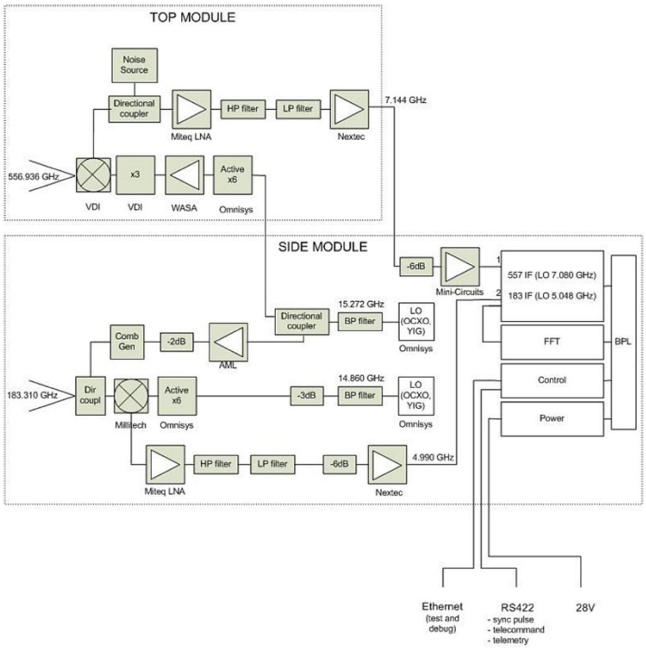

Figure 3. Block diagram of the complete system with the 557 GHz module at the top. LOs for both receivers are located at the 183 GHz base plate as well as the FFT-backend [7].

III. Receiver Calibration

A typical application for a radiometer in atmospheric or radio astronomical observation is to detect very weak signals, buried in noise. If the system noise is completely uncorrelated, i.e. white noise, signal integration over time will reduce the noise according to the radiometric equation [8]:

$$\sigma = \frac{T_{System}}{\sqrt{B\,\tau}} \tag{1}$$

where T_{system} is the total system noise ($T_{antenna} + T_{receiver}$), B is the detection bandwidth, τ is the integration time, and σ is the resulting standard deviation. In reality, the noise in a radiometer is a combination of white noise, the DC drift, and 1/f noise. The DC drift and 1/f noise limit the possibility of reducing the noise by integration and an optimum integration time can be calculated from the Allan variance [9]. This means that further integration will not improve the signal-to-noise ratio. Apart from the noise-originated instability of the receiver, the gain of the receiver varies over time. This can, for instance, vary if the physical temperature of the receiver changes and it implies that a calibration of the receiver is needed in order to be able to compensate for the gain drift over the entire observation period. The time periods between calibration sequences should be well within the characteristic time of the gain instability.

The most common calibration technique for radiometers is use of a Dicke-switch [10], where the reference signals are radiation from a black body at two different and specific temperatures, P_{Hot}/P_{Cold}. The received power can be calculated according to Planck's black body radiation law in the Rayleigh-Jeans limit [8], and, assuming a perfectly matched single-mode waveguide, the received power can be calculated as

$$P = k_B BT \quad (2)$$

where k_B is the Boltzmann's constant, B is the detection bandwidth, and T is the brightness temperature of the black body. The receiver noise temperature is then calculated according to a well-known relation

$$T_e = \frac{T_{Hot} - Y * T_{Cold}}{Y - 1} \quad (3)$$

where Y is the ratio P_{Hot}/P_{Cold}, i.e. the IF output power of the radiometer when exposed to the different loads. This technique calibrates the entire receiver chain (optics, mixer, and LNAs) and is usually implemented by employing a chopper wheel or a mechanical switch placed in the receiver input beam. A common problem of the standard Dicke-switch calibration technique is that no measurements can be performed during the calibration cycle, hence precious observation time has to be sacrificed.

However, due to a very harsh environment on board the rocket, in terms of shock and vibration, as well as space constraints and extremely short observing time, a calibration system without any moving parts, a fully electronic calibration system, is preferred for PHOCUS. For example, a signal from a broadband calibrated noise source, instead of the hot load, could be injected through a directional coupler between the RF-horn and the mixer as in [11], but unfortunately at 183 GHz and 557 GHz such noise source is not commercially available.

The driver for the 183 GHz calibration system on the PHOCUS rocket was to consider the above mentioned criteria, e.g. no moving parts and the space constraints. To achieve this, a calibration system with a stable pilot signal injected through a directional coupler [12] (-13dB coupling) between the RF-horn antenna and the mixer was introduced. The pilot signal is placed 40 MHz away from the 183.31 GHz water absorption line, the target for the observation, and thus allows continuous calibration without any loss of observation time. With this calibration technique it is assumed that all receiver back-end channels experience the same gain variations in the time domain. The pilot signal is generated from the LO source for the 557 GHz radiometer, which has a base frequency of 15.727 GHz. The reference signal is extracted from the LO through a 20 dB directional coupler, amplified and fed to a harmonic mixer generating the pilot signal at 183.264 GHz (12th harmonic). The block diagram of the radiometer with its calibration system can be seen in Figure 4. The amplifier operates in saturation in order to keep the amplitude of the generated output calibration signal insensitive to small fluctuations in the reference signal supplied.

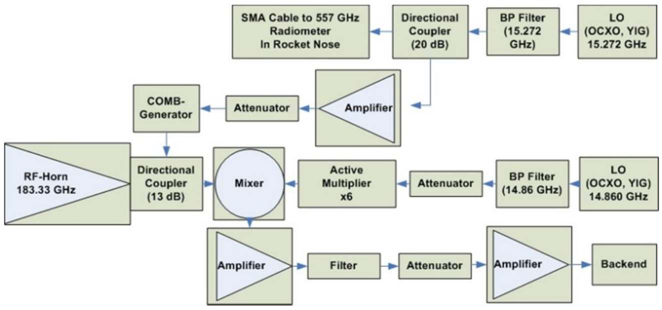

Figure 4. Layout of the 183 GHz system with the calibration signal extracted from the LO-path for the 557 GHz radiometer.

Right before the launch, the receiver noise temperature is measured by standard Y-factor technique in order to obtain an absolute temperature reference. This is done by placing a hot and cold load outside the rocket at the signal window. During this calibration, the level of the pilot signal referenced to the noise floor (ratio should be the same for hot- and cold loads) is recorded. During the flight, any drift of the gain in the receiver chain will result in a level change in the pilot signal relative to the baseline noise level.

The receiver temperature and the pilot signal measurements performed in the laboratory are presented in Figure 5 and Figure 6. The mean value and standard deviation are plotted together with the noise temperature, where the mean is calculated for the central channels where the resolution is the highest, 67 kHz. At the band edges, the channels are combined in order to reduce the data storage. The data in Figure 5 and Figure 6 are integrated over 10 seconds and the calibration accuracy (repeatability) is estimated to less than 2 % and is calculated as

$$\Delta = (Peak\ Hot - Baseline\ Hot) - (Peak\ Cold - Baseline\ Cold) \quad (4)$$

$$Uncertainty\ (\%) = \frac{\Delta}{Peak - Baseline} \times 100 \quad (5)$$

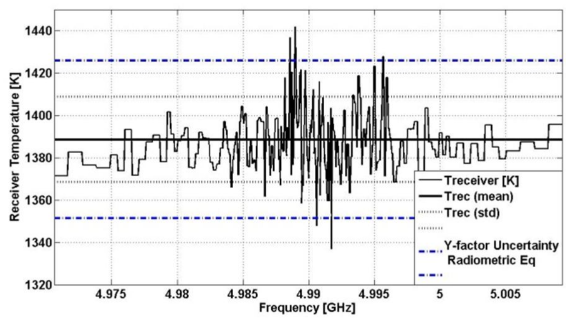

Figure 5. Laboratory measurements of the 183 GHz receiver noise temperature.

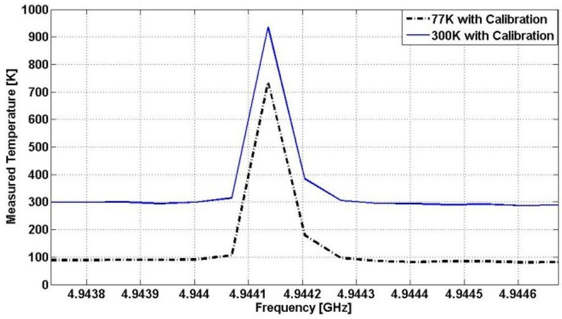

Figure 6. Pilot signal with liquid nitrogen and room temperature loads.

During the observation period the measurement rate is 300 Hz, resulting in an integration time of 3 ms per spectrum. Notice that the integration time in order to obtain a stable pilot signal is independent on the integration time used for the observation data, which might be shorter in order to dissect the mesosphere and obtain the desired altitude profile. The observations will typically be in blocks of 0.1 s, i.e. integration over 30 spectra.

The 557 GHz radiometer calibration utilizes a different technique. Also this calibration system is fully electronic for the same reasons as pointed out in the previous section. The much higher frequency of this channel makes it more difficult and expensive to generate signals that could be used as a pilot signal while, most importantly, introducing a directional coupler with its associated loss in front of the mixer would substantially increase the system noise. Following these considerations, the 557 GHz radiometer calibration is done by injecting broadband noise from a calibrated noise source, [13], through a directional coupler between the mixer output and the first IF Amplifier (LNA), Figure 7. This scheme limits calibration of the 557 GHz receiver channel to the gain of the IF and back-end parts, the parts probably mostly affected by changing the ambient temperature.

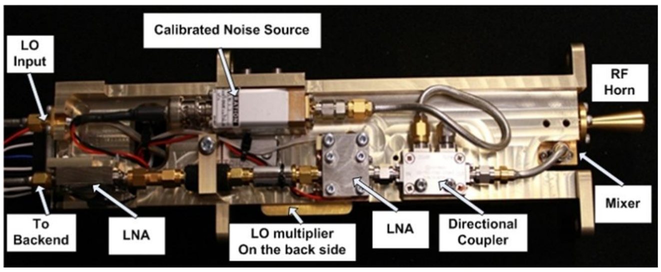

Figure 7. Picture of the 557 GHz radiometer with the horn, noise source, coupler, and LNAs. The mixer and LO-multiplier is located on the back side.

Since any measurements during the calibration would not be feasible, in contrast to the calibration system for the 183.31 GHz radiometer, the calibration is performed before the rocket reaches the altitude where the measurements should start. A second calibration is performed at the trajectory apogee, and the third calibration sequence is done once the rocket has reached an altitude below the region of interest. The drift in the receiver gain is measured between the calibration periods by measuring the difference between the baseline (independent on the load temperature) and the level with the calibration noise source is switched on. A decrease in the receiver gain would result in a smaller difference between the on/off calibration signal cases. Figure 8 and Figure 9 show the receiver noise temperature of the 557 GHz receiver and the measured temperature levels with the noise source switched on/off for liquid nitrogen and room temperature loads.

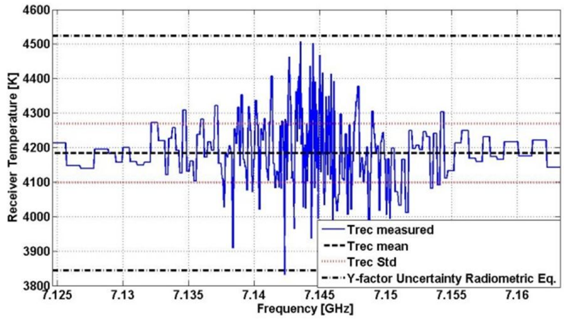

Figure 8. Laboratory measurement of the 557 GHz receiver noise temperature.

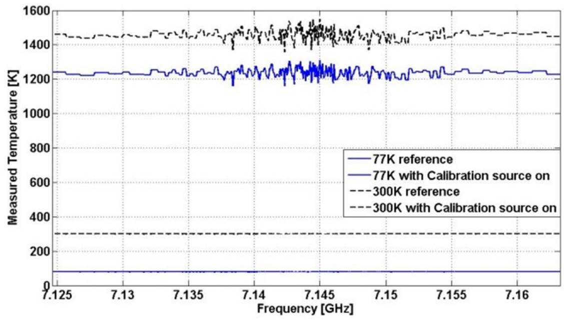

Figure 9. Measured temperatures with calibration source on/off for liquid nitrogen and room temperature loads.

IV. Conclusion

In this paper, we present the 183 GHz and 557 GHz radiometers for the PHOCUS sounding rocket experiment, with launch date between 4 July - 4 August, 2011. The receiver system together with its specific calibration techniques is described.

Acknowledgment

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