550-650 GHz spectrometer development for TELIS

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***Abstract*—In this paper we present design and experimental results of the 550 - 650 GHz channel for the Terahertz Limb Sounder (TELIS), a three-channel balloon-borne heterodyne spectrometer for atmospheric research. This frequency channel is based on a phase-locked Superconducting Integrated Receiver (SIR). SIR is an on-chip combination of a low-noise SIS mixer with quasioptical antenna, a superconducting Flux Flow Oscillator (FFO) acting as Local Oscillator (LO) and SIS harmonic mixer (HM) for FFO phase locking. The microcircuit is designed as a quasioptical mixer. We report first results of the SIR mixer sub-assembly noise temperature and beam pattern measurements. We have also tested flight configuration of the 550-650 GHz receiver, which includes cold optics, flight electronics and digital backend spectrometer, to measure emission line of the OCS gas in the laboratory gas cell.**

***Index Terms* — Josephson mixers, integrated receiver, superconducting devices**

I. Introduction

TELIS (Terahertz Limb Sounder) is a cooperation between DLR (Institute for Remote Sensing Technology, Germany), RAL (Rutherford Appleton Laboratories, UK) and SRON (National Institute for Space Research, the Netherlands), to build a three-channel balloon-borne heterodyne spectrometer for atmospheric research. The three receivers utilize state-of-the-art superconducting heterodyne technology and will operate simultaneously at 500 GHz (channel developed by RAL), at 550-650 GHz (SRON in collaboration with IREE), and at 1.8 THz (DLR). TELIS is designed to be a compact, lightweight instrument capable of providing broad spectral coverage, high spectral resolution and long flight duration (~24 hours duration in a flight campaign). The combination of high sensitivity and extensive flight duration will allow evaluation of the diurnal variation of key atmospheric constituents such as OH, HO_2, ClO, BrO together will longer lived ones such as O_3, HCL and N_2O. The balloon platform on which TELIS will fly also contains a Fourier transform spectrometer MIPAS-B developed by the IMK (Institute of Meteorology and Climate research of the University of Karlsruhe, Germany). MIPAS-B will simultaneously measure within the range 680 to 2400 cm^{-1}. The combination of the TELIS and MIPAS instruments will provide an unprecedented wealth of scientific data and will also be used to validate other instruments and atmospheric chemistry models. First flight is foreseen in April 2007.

II. TELIS Configuration

The optical front-end of TELIS consists of a pointing telescope, calibration blackbody and relay optics, common for the three channels: 500 GHz, 550-650 GHz and 1.8 THz [1]. The telescope is a dual offset Cassegrain antenna. Primary parabola has an elliptical cross-section of 260x140 mm. 2:1 anamorphicity is introduced by the cylindrical tertiary mirror. An anamorphic design was selected to improve telescope compactness, mass, and moment of inertia. A vertical (elevation) resolution at the tangent point is about 2 km at 500 GHz (FWHM), inversely proportional to the frequency. The limb scans range from upper troposphere (10 km) to stratosphere (30-40 km). Horizontal (azimuth) resolution is about a factor of 2 worse but not of prime importance for this mission as the atmospheric properties within the beam depend only on the altitude.

Calibration of the radiometric gain of the spectrometers is done with two blackbody reference sources at submillimeter wavelengths: the hot-load, which is a conical black-body at the ambient temperature, and the cold sky.

Frequency separation between the channels is performed quasioptically, allowing simultaneous observations by all receivers. First, one linear polarization of the incoming signal is selected by a wire grid and is reflected into the 500 GHz channel. The other linear polarization, which is transmitted by the grid, is then split between two other frequency channels by a dichroic filter. After the splitting, the three beams enter a custom designed liquid helium cooled cryostat. A number of off-set reflectors are used to interface the optics from the telescope to the cryogenic channels. Fig. 1 shows schematics

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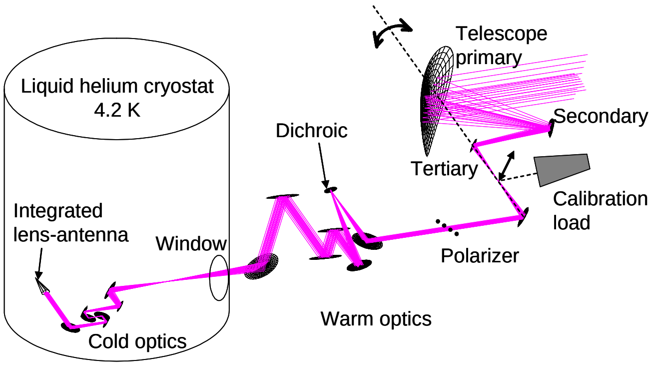

Fig. 1. Schematics of the 550-650 GHz channel optics. The telescope is rotated around the axis coinciding with the direction of the output beam. Wire grid polarizer and dichroic plate are used to separate this receiver from the two other frequency channels (not shown). The cold optics and mixer element are located inside the cryostat at the ambient temperature 4.2 K.

of the optics directly related to the 550-650 GHz channel. The optical beams of the two other frequency channels after the splitting as well as their dedicated optical elements are not shown here.

Inside the cryostat the receivers have dedicated cold optics, mixing element and IF amplifiers. Three amplified output IF signals are fed to an IF processor which converts the IF to the input range of the digital autocorrelator of 2 x 2 GHz bandwidth. An on-board microcontroller controls the instrument and interfaces with the ground station.

III. SIR Design

A key element of the 550-650 GHz channel is Superconducting Integrated Receiver (SIR) [2], which comprises in one 4 x 4 x 0.5 mm^3 chip a low-noise SIS mixer with quasioptical antenna, superconducting Flux Flow Oscillator (FFO) acting as Local Oscillator (LO) and SIS Harmonic Mixer (HM) for FFO phase locking. The SIR microcircuits are traditionally fabricated on a Si substrate using Nb-AlOx-Nb tri-layer [3].

Performance of all-Nb devices, however, is very critical to the ambient temperature, which should not exceed 4.5 K, and also to its stability. This is very difficult to control on a balloon platform since the TELIS liquid helium cryostat should be over-pressurized (p>1 Bar) due to safety reasons. To overcome this problem, we have developed and studied Nb-AlN/NbN-Nb circuits with a gap voltage Vg up to 3.7 mV and extremely low leakage currents (Rj/Rn > 30). Based on these junctions integrated microcircuits comprising FFO, SIS and harmonic mixer have been designed, fabricated and tested; the radiation from such circuits has been measured at frequencies up to 700 GHz. Employment of NbN electrode does not result in the appearance of additional noise. For example, FFO linewidth as low as 1.5 MHz was measured at 595 GHz, that allows us to phase lock up to 85 % of the emitted by FFO power and realize very low phase noise of about –93 dBc. It is important to note that for Nb-AlN-NbN FFO there is a possibility to tune permanently the FFO frequency even in the Fiske regime, since Fiske steps are bended and overlapping. From the other hand, for Nb-AlN-NbN junctions there is a considerable increase of the FFO linewidth just above of the Vg/3 (of about 600 GHz) due to self-adsorption of the FFO radiation [4] (effect of Josephson self-coupling).

The receiver chip is placed on the flat back surface of the 10 mm diameter elliptical Si lens, forming an integrated lens-antenna. SIR feed antenna is positioned at the more distant focus of the ellipse. To minimize the reflection loss at the lens-air interface, the curved surface of the lens is coated with a 74 micron thick Stycast antireflection coating, optimized for the center frequency 600 GHz. Further shaping of the beam is done by means of a number of curved and fold mirrors, all located at the cold plate of the liquid helium cryostat [5].

IV. Mixer Noise Temperature and Beam Pattern

Most of the experimental results discussed here have been obtained with the SIR device based on the Nb-AlN-NbN technology. SIR chip is mounted in a flight configuration mixer block surrounded by a magnetic shield. No other optical elements of the cold channel were installed for the noise temperature (NT) and beam pattern measurements reported in this section. All tests were done in a liquid helium cooled cryostat at 4.2 K ambient temperature. NT measurements are done using Y-factor technique by chopping between hot (295 K) and cold (80 K) loads in the signal path of the receiver. IF response of the mixer is amplified by a cryogenic InP based 4-8 GHz LNA amplifier followed by a 60 dB gain GaAs RT amplifier. The signal is detected by a fast power meter in 40 MHz bandwidth, selected by tunable YIG filter. We have also used flight configuration of the PLL system and could lock the FFO practically at any frequency in the 550-650 GHz range.

Fig. 2 shows results of the NT measurements, which are not corrected for any loss. The DSB NT below 400 K is measured in about 100 GHz wide frequency range. Rise of the NT

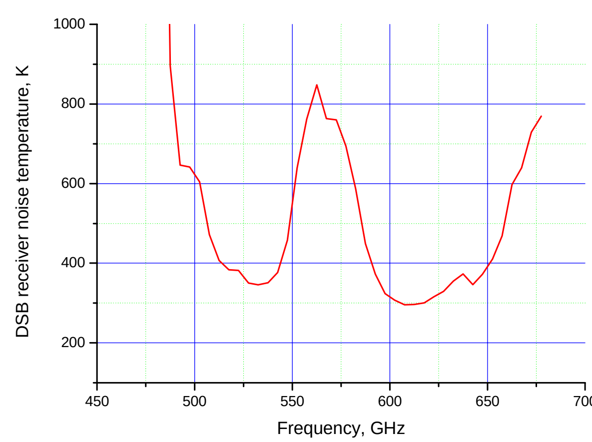

Fig. 2. Uncorrected DSB noise temperature of the SIR. Rise of the noise temperature around 560 GHz could be to a large extent explained by absorption in the atmosphere due to the strong and broad water line around that frequency.

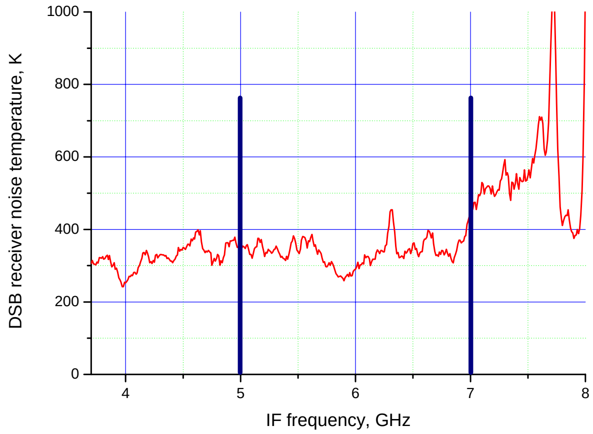

Fig. 3. DSB noise temperature of the SIR as a function of the IF frequency.

around 560 GHz could be to a large extent explained by absorption in atmosphere due to the strong and broad water line around that frequency. Vacuum hot/cold measurements are planned for the future to exclude this effect from the measurement results.

Fig. 3 shows measured NT vs. IF of the receiver. One can see that the response is fairly flat in the 5-7 GHz frequency range, the input bandwidth of the SIR channel backend spectrometer. Further optimization of the coupling between the mixer and IF board should minimize ripples in the response which are probably due to the standing waves in the IF circuitry.

V. Integrated Antenna Beam Pattern

Far-field amplitude beam pattern of the integrated antenna has been measured at 625 GHz in a heterodyne mode. The submillimeter source is a harmonic multiplier [6] driven by a microwave source. The dewar is placed on a rotation/tilt table to allow for the angular measurements [7]. The tilt movement is referred to as the vertical scan and the rotation as the horizontal scan. The angle resolution of the system is 0.1°. The integrated antenna is located at the center of rotation. The measured beam pattern of the antenna is therefore expected to be independent of the beam pattern of the signal source. Nevertheless, to exclude influence of a possible beam asymmetry in the measured results, we have rotated the source by 180 degrees and obtained similar pattern. There are no focusing elements between the signal source and the receiver and the distance between them is about 70 cm. Signal source is positioned with ±0.2 deg and ±0.2 mm accuracy relative to the reference plane of the mixer block using He-Ne laser alignment system. The measured beam pattern includes thus information about boresight error of the beam.

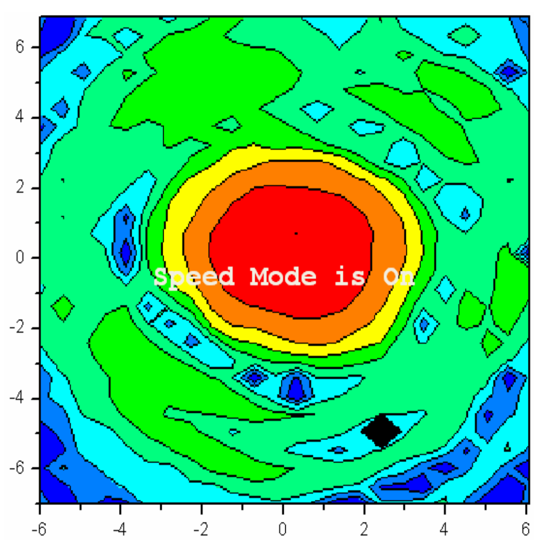

Fig. 4. Far-field 2D scan of the integrated lens-antenna beam pattern. The isolines are at -3 dB, -6 dB, -10 dB, -15 dB etc.

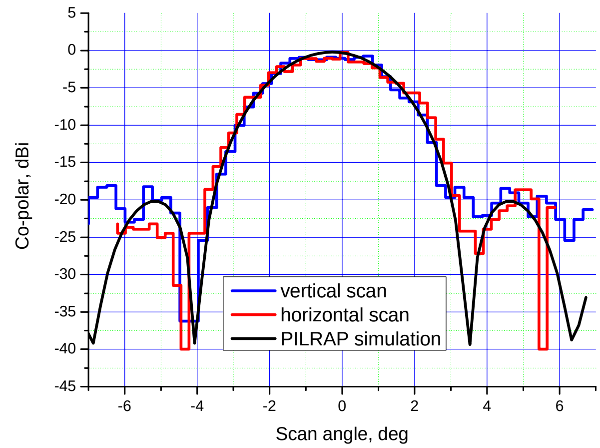

Fig. 5. Vertical (blue curve) and horizontal (red curve) far-field scans. The fit (black curve) is diffraction pattern calculated by PILRAP.

Results of the measurements for the double dipole antenna coupled SIR are shown in the Fig. 4 and Fig. 5. The pattern is symmetric with the first sidelobe level of below -17 dB. It is close to the theoretically predicted diffraction pattern calculated by PILRAP [8] and similar to the patterns measured with the double slot or double dipole antennas at these frequencies. The full width half maximum (FWHM) is 3 deg.

VI. Laboratory Gas Cell Measurements

Gas cell measurements were done using a prototype cryostat which accommodates complete cold channel. Only SSB filter was not installed at this moment to allow DSB operation of the receiver. As a back-end spectrometer we used Digital AutoCorrelator (DAC). SIR was operated in a phase-locked mode. Spectra are integrated from about 20 individual calibrated spectra. DAC integration time of individual spectrum is 1 sec. Recorded by the DAC spectrum is a convolution product of the signal (gas emission lines) with the FFO line spectrum. To recover the signal, we apply a simple direct deconvolution process using the measured FFO line shape.

Photo of the measurement setup is shown in Fig. 6. Receiver beam is focused by an off-axis parabola. For radiometric calibration we used room temperature (300 K) and

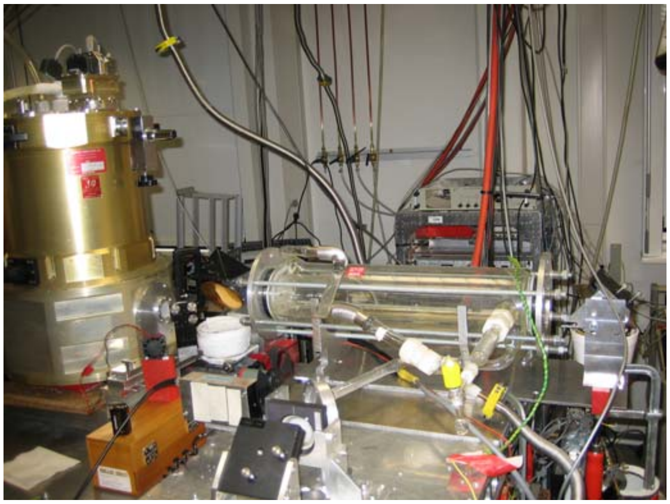

Fig. 6. Photo of the measurement setup. Switching mirror selects between "cold" load (receiver beam is directed downwards, as in the picture), "hot" (beam is directed upwards), or "signal" (beam is directed towards the gas cell).

liquid nitrogen (77 K) cooled blackbodies (Eccosorb). Switching between two calibration loads and a signal (gas cell) is done by a computer controlled flat mirror. After the gas cell the beam is reflected by a flat mirror towards another cold (77 K) load. Gas cell windows are made from 2 mm thick HDPE. Measurements are done in a sequence Hot-Signal-Cold-Signal-Hot-Signal-…

For the measurements two OCS lines at 619.6213651 GHz and 631.7429035 GHz were selected. These lines could be observed at the same time, one in the upper and the other in the lower sideband of the receiver. The FFO was thus tuned at 625.240 GHz. The IF frequencies of these lines are 5618.6 MHz and 6502.9 MHz.

We have measured emission lines at different gas pressures, ranging from 0.2 mBar to 8 mBar. Example of the deconvolved spectrum at a gas pressure of 1.2 mBar is shown in Fig. 7. At this pressure both lines are expected to be saturated, pressure broadened and probably also saturation broadened. Modelling of these gas lines and comparison with the measured data is in progress. One can note that the two lines have different strength. We have measured the same levels also at higher gas pressures, proving that the lines are indeed in saturation. The difference in lines strengths should thus reflect the sideband ratio of the receiver.

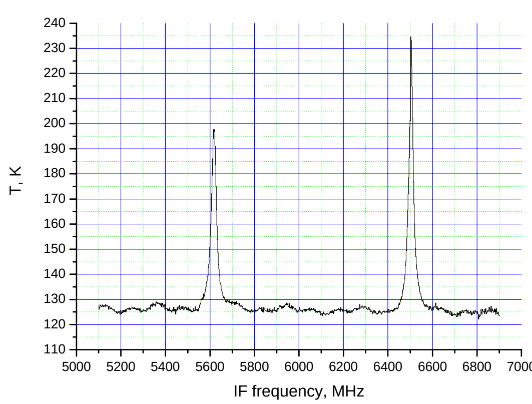

Fig. 7. Deconvolved spectrum of the OCS emission lines at a gas pressure 1.2 mBar. LO frequency 625.24 GHz. Lines are saturated, the difference in line strength reflects the sideband ratio of the receiver.

There are ripples in the measured baseline which we believe have optical origin. In our lab test setup the calibration blackbodies are made from flat Eccosorb, the cryostat and gas cell windows have no antireflection coatings. Reflections of the optical beam from different surfaces cause appearance of the standing waves, which are then seen back in the measured spectrum. It is possible to exclude them from the line spectrums by measuring the baseline only (empty cell) and using these data to subtract the ripples (not done in Fig. 7). The baseline temperature is about 125 K, higher than the background temperature 77 K (cold load behind the cell) mainly due to the loss in the gas cell windows.

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