Superconducting Integrated Receiver on Board TELIS

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***Abstract*— In this paper we present configuration and performance of the 480 - 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. The SIR channel has been integrated into the TELIS system in the end 2006 and fully characterized during 2007/2008 in preparation for the flight campaign. In May 2008 TELIS was shipped to Brazil where it was integrated into the MIPAS-B gondola. The TELIS-MIPAS test flight took place in June 2008 in Teresina, Brazil.**

I. INTRODUCTION

TELIS (Terahertz Limb Sounder) is a cooperation between DLR (Institute for Remote Sensing Technology, Germany), RAL (Rutherford Appleton Laboratories, UK) and SRON (Netherlands 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 operate simultaneously at 500 GHz (channel developed by RAL), at 480-650 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 shall allow evaluation of the diurnal variation of key atmospheric constituents such as OH, HO_2, ClO, BrO together with long lived species such as O_3, HCl and N_2O. The balloon platform on which TELIS is integrated 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 simultaneously measures within the range 680 to 2400 cm^{-1}. TELIS and MIPAS together cover a wide range of important atmospheric species to improve our understanding of atmospheric processes, investigate changes in the atmosphere

due to anthropogenic emissions, and to validate satellite instrumentation.

In this paper, the science and technology of TELIS will be discussed with emphasis on the 480-650 GHz channel developed by SRON and IREE.

II. ATMOSPHERIC SCIENCE IN THE THZ REGION

The millimeter and sub-millimeter (terahertz, THz) region of the electromagnetic spectrum is well suited for the study of the composition of the upper Earth's upper atmosphere. Many of the atmospheric trace gases have their rotational transition lines in this spectral region. The very high resolution required (in excess of 10^6) in order to fully exploit the spectral signature, can be obtained by heterodyne detection techniques.

Application of the heterodyne detection technique in atmospheric observations from space has been pioneered by the Microwave Limb Sounder on board the UARS satellite [1], operational between 1991 and 1999. UARS/MLS measured stratospheric ozone, ClO, water vapor, pressure, and temperature using bands at 63 GHz, 183 GHz, and 205 GHz. Its improved successor MLS on board of EOS-Aura has been launched July 2004 [1] and performs very successfully. The frequency bands have been extended to 118 GHz (for temperature and pressure), 190 GHz (H_2O and HNO_3), 240 GHz (O_3 and CO), 640 GHz (for HCl, ClO, BrO, HO_2, and N_2O), and 2.5 THz (for OH).

In Europe, the Swedish ODIN satellite [2] carries the Sub Millimeter Radiometer instrument which is used for atmospheric research as well as for astronomical observations. Its frequency bands are located at 118.25 - 119.25 GHz, 486.1 - 503.9 GHz, and 541.0 – 580.4 GHz. ODIN was launched in 2002 and is still operational.

Two satellite instruments are currently under development that employ SIS and HEBM mixers: JEM/SMILES [3] for observing the Earth' atmosphere and Herschel/HIFI [4] for astrophysical research. The Japanese

SMILES instrument (Superconducting Submillimeter-Wave Limb Emission Sounder) for the Japanese Experiment Module (JEM) of the International Space Station will be used for the observation of many atmospheric species around 625 and 650 GHz. This instrument is currently planned to be launched in 2008. The HIFI instrument (Heterodyne Instrument for the Far Infrared) instrument is being integrated onto the Herschel satellite and will be launched in 2009.

Newly proposed to the US National Research Council is the SMLS instrument (Scanning MLS) on board CAMEO [1]. Here, superconducting SIS mixers are proposed for the millimeter channel 180-280 GHz and two sub-millimeter channels 580 – 680 GHz. The huge gain due to the low-noise characteristics of these mixers is used to reduce the integration time for one single measurement to a few milliseconds, allowing for two orders of magnitude more observations in comparison to the standard mixers used in MLS. With SMLS a full 3-D characterization of the atmosphere is possible. When selected, CAMEO/SMLS will be launched in the 2015-2018 timeframe.

Extrapolating the current trends towards the future, we foresee Earth limb sounding from a satellite platform with superconducting receivers operating at millimeter, and sub millimeter wavelengths.

Several balloon and aircraft instruments anticipate space application of cryogenic technologies, as well as ground based astronomical observatories. Without being complete a few examples are given. Already operationally flying instruments for Earth observation using SIS mixers are: PIROG [5], ASUR [6] and BSMILES [7].

III. The Science of TELIS

An extensive list of molecular species will be targeted by TELIS: BrO, ClO, HCl, HOCl, CH_3Cl, O_3 (normal and isotopic), H_2O (normal and isotopic), OH, HO_2, HNO_3, NO, N_2O, NO_2, HCN, and O_2. Vertical profiles of even very weak individual lines can be determined as the TELIS receivers combine limb sounding with a high frequency resolution and low noise observations. An example of a spectrum to be measured by the SIR channel at 495 GHz LO frequency is shown in Figure 1.

With respect to stratospheric ozone depletion both the halogen chemistry and HO_x chemistry can thoroughly be

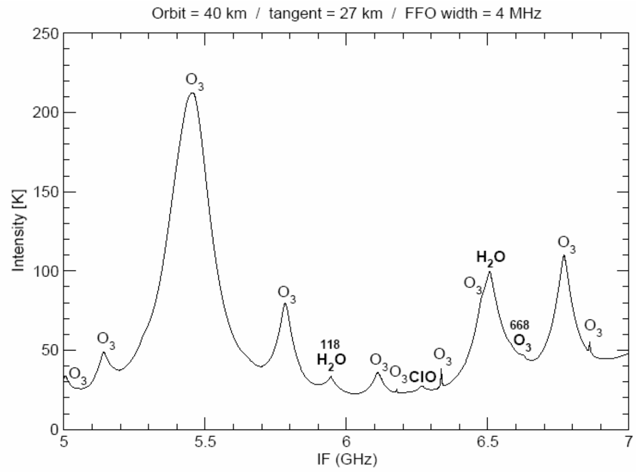

Fig.1 Example of spectrum to be measured by the SIR channel at LO frequency 495 GHz in DSB mode

investigated. Ozone isotopes may give insight in hidden and unknown chemical reactions and isotopic water may shed light on the origin of stratospheric water, which is connected to ozone through the HO_x cycle and Polar Stratospheric Clouds (PSCs).

A key question in stratospheric sciences is whether ozone will recover in the coming decades as a result of international regulations on ozone depleting substances. In the lower and middle stratosphere ozone depletion is governed by halogen chemistry (chlorine and bromine), which is fairly well understood. The fact that TELIS and MIPAS can retrieve almost all species appearing in the catalytic halogen ozone depletion cycles will put the existing atmospheric chemistry models to stringent tests. In the upper stratosphere also HO_x and NO_x become important catalytic ozone depletion forces. Here atmospheric chemistry models are less accurate: ozone concentrations are underpredicted, OH is underpredicted, and HO_2 is overpredicted. Observing all species simultaneously will shed light upon the production and loss mechanisms of HO_x and the partitioning between OH and HO_2 [9, 10].

Stratospheric water vapor plays an important role in the ozone chemistry as a source gas for the production of HO_x. The origin of stratospheric water is still not completely understood. Stratospheric water is transported from the troposphere, but also formed in situ by the oxidation of species, for instance, methane. The accurate measurement of water isotopologues may give insight in the relative weights of the water loading mechanisms of the stratosphere, as the different masses and energy level structures of the isotopologues result in differences in evaporation, condensation, and chemical reactions.

IV. TELIS Instrument Configuration

A design drawing of the TELIS instrument is shown in Figure 2. The optical front-end of TELIS is common for the three channels and consists of a pointing telescope, calibration blackbody, and relay and band-separating optics. Details of the optical design can be found in [11, 12, 13].

The telescope is a dual offset Cassegrain antenna. All three telescope mirrors are mounted on a common frame that can be rotated around the axis coinciding with the direction of the output beam. The 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 the upper troposphere (10 km) to flight altitude at about 37 km with 1 to 2 km steps. Horizontal (azimuth) resolution is about a factor of 2 less, due to the anamorphicity of the telescope but not of prime importance for this mission as the atmospheric properties within the beam hardly depend on the azimuth.

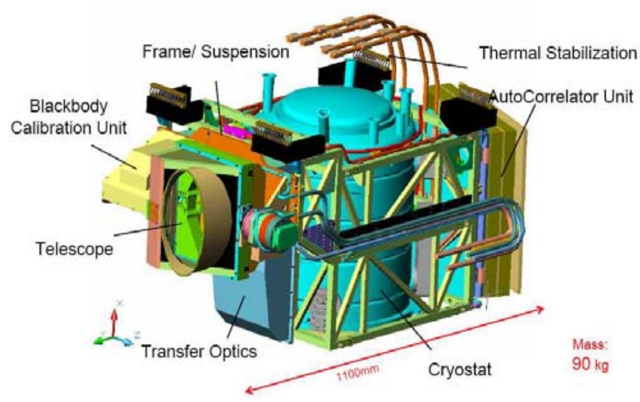

Fig.2 Design drawing of the complete TELIS instrument

Calibration of the radiometric gain of the spectrometers is done with two blackbody reference sources. The hot-load consists of a conical black-body at ambient temperature that can be viewed by a small switching mirror in the warm optics. The cold sky reference is measured with the telescope set at 60 degree upwards with respect to the limb position. The two references are measured once or twice in every limb scan.

Frequency separation between the channels is performed quasioptically, allowing simultaneous observations by all receivers. For this, the beam is first split in two polarization components by a wire grid. The 500 GHz channel uses the reflected beam. The beam is then split 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, see Figure 3.

Inside the cryostat, each receiver has dedicated cold optics, mixing element and IF amplifiers.

The 500 GHz receiver channel is being developed by RAL [14]. It is a highly compact unit consisting of a fixed-tuned waveguide SIS mixer, cryogenic solid-state local oscillator (LO) chain and a low-noise Intermediate-Frequency (IF) chain. Single sideband operation is achieved through the use of a miniature cryogenic dichroic filter that provides a 4K image termination and image band rejection of >25dB. For optimization of the performance of the dichroic single-sideband filter a high IF is chosen: 14 – 18 GHz.

The 480-650 GHz receiver channel is being developed in cooperation between IREE and SRON and is based on a single-chip Superconducting Integrated Receiver (SIR) that comprises on one substrate a low-noise SIS mixer with quasi-optical antenna and a superconducting Flux Flow Oscillator (FFO) acting as LO [15, 16, 17]. Tunability of the FFO shall allow for a wideband operation of this channel, with a goal to obtain 150 GHz instantaneous rf bandwidth or even more. The SIR channel is discussed in detail in the next section.

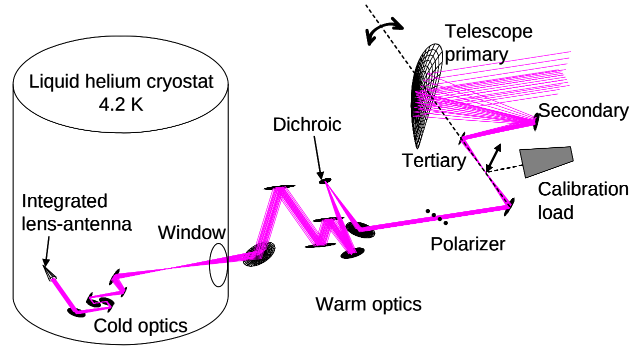

Fig.3 Schematics of the 500-650 GHz channel optics. The telescope is rotated around the axis coinciding with the direction of the output beam. Wire grid polarizer and dichroic plate are used to separate this receiver from the two other frequency channels (not shown). The cold optics and mixer element are located inside the cryostat at the ambient temperature of 4.2 K

The 1.8 THz channel is based on a phonon-cooled NbN HEB mixer technology and is being developed by DLR, also acting as Principle Investigator (PI) for the TELIS mission. It is similar to that under development for SOFIA by MSPU and DLR [18,19]. It utilizes a cryogenic solid-state LO that is loss-less coupled to the mixer via an optical interferometer (Martin-Puplett type).

Three amplified output IF signals are fed to an IF processor which converts the IF to the input frequency range of the digital autocorrelator of two times 2 GHz bandwidth. Both IF processor and digital autocorrelator are developed by the Swedish Omnisys company [20].

An on-board PC-104 computer interfaces with the control electronics of the three receiver channels and the instrument, with the digital auto correlator, with the host instrument MIPAS, and with the ground segment through a radio link. The ground segment consists of a server computer interfacing with three dedicated client computers through TCP/IP socket connections.

The complete system is battery powered and is designed for 24 hours flight duration. The total instrument is about 1x1x0.6 m^3 and has a weight of 90 kg (see Fig. 2).

V. The Superconducting Integrated Receiver

A key element of the SIR channel is the Superconducting Integrated Receiver (SIR) chip developed at IREE [15, 16, 17]. SIR comprises on one 4 x 4 x 0.5 mm^3 chip a low-noise SIS mixer with quasioptical antenna, a Flux Flow Oscillator (FFO) acting as Local Oscillator (LO) and a SIS Harmonic Mixer (HM) for FFO phase locking, see Figure 4.

All components of the SIR microcircuits are fabricated from a high quality Nb-AlN/NbN-Nb tri-layer on a Si substrate [21]. The receiver chip is placed on the flat back surface of the Silicon lens with antireflection coating, forming an integrated lens-antenna. As the FFO is very sensitive for the external electromagnetic interferences the SIR chip has to be placed inside two cylindrical shields. The outer shield is made from cryo-perm and the inner shield is copper covered with 100 um of superconducting lead.

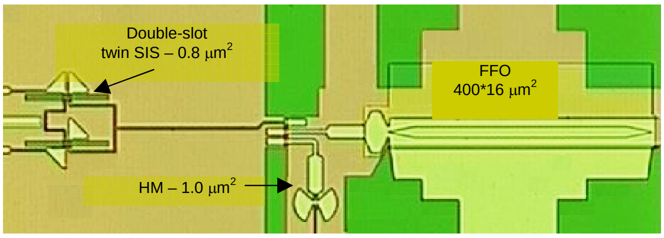

Fig. 4 Micro photograph of the central part of the SIR chip with double slot antenna

The spectral resolution of the TELIS backend spectrometer is 3 MHz, in order to resolve the exact shape of the atmospheric lines. The FFO lineshape and stability should ideally be much better than this. As the free-running linewidth of the FFO can be up to 10 MHz, the FFO is locked to an external reference oscillator using a Phase Lock Loop (PLL) system. For this, a small fraction of the FFO power is directed to a so-called Harmonic Mixer (HM). The scheme of this system is shown in Figure 5. The HM is pumped by a tuneable reference frequency in the range of 19-21 GHz from the Local oscillator Source Unit (LSU), phase locked to the internal ultra stable 10 MHz Master Oscillator. The HM mixes the FFO signal with the n-th harmonic of the 19-21 GHz reference. The frequency of the LSU is chosen such that the difference frequency signal is about 4 GHz. This signal is amplified by a cryogenic low-noise HEMT amplifier, and downconverted to 400 MHz, where its frequency and phase are compared with a reference of 400 MHz. Both reference signals at 3.6 GHz and at 400 MHz are phase locked to the 10 MHz Master Oscillator. Finally, the phase difference signal generated by the PLL is used as a feedback to the FFO control-line current to compensate for the phase error. Wideband operation of the PLL (15 MHz full width) is obtained by minimizing the cable loop length. The result of the PLL on the FFO spectrum is shown in Figure 6. The impact of the non-perfect FFO spectrum on the retrieval accuracy is discussed in [22].

TELIS is setup to measure spectra in the sub-millimeter and THz range. From the spectra vertical profiles of trace gases will be determined in an off-line retrieval process. The retrieval is based on a comparison between a calculated spectrum and the measured spectrum [23]. The calculated spectrum is determined by a so-called forward model and takes into account the observation geometry. The emission spectrum is calculated by integrating the radiative transfer equation along the line of sight (LoS), for a given temperature and pressure profile, and for assumed molecular

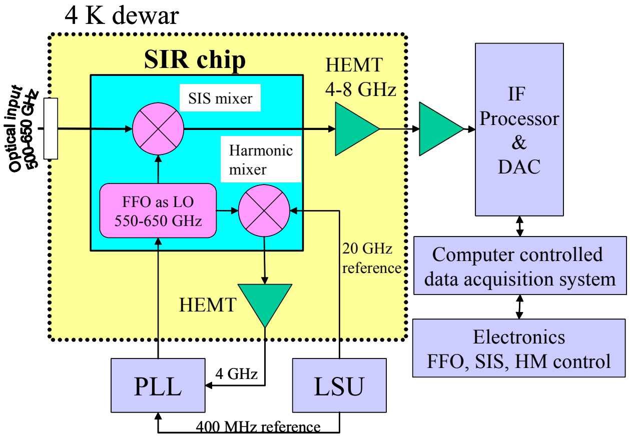

Fig. 5 Schematics of the SIR with a phase-locked LO. The FFO frequency is mixed in the Harmonic Mixer with the 19-21 GHz reference. The mixing product is amplified, down converted and compared with the 400 MHz reference in the PLL. The phase difference signal generated by PLL is used to feedback the FFO control line

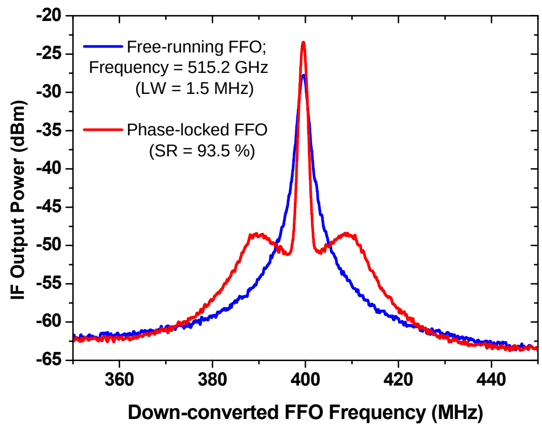

Fig. 6 Spectrum of a frequency-locked FFO (blue curve) and phase-locked FFO (red). Due to limitations of the spectrum analyzer the central delta-peak of the PL-FFO appears broadened

density height profiles. The instrument model adds instrument features such as the instrument lineshape and the integration over the Field of View (FoV) to determine the calculated TELIS spectrum.

In the so-called inverse model, the calculated spectrum will be compared to the actual measured spectrum and the molecular density profiles will be altered to iteratively obtain the best match between modeled and observed spectrum. All limb scans are evaluated simultaneously to enhance the accuracy for the height profile.

VI. SIR Performance

The TELIS-SIR channel has been integrated and tested in the TELIS flight cryostat in 2006. All experimental results discussed here have been obtained with the SIR device selected for the first flight. The measured double sideband (DSB) receiver noise temperature, uncorrected for any loss, is presented in Figure 7 as a function of LO frequency, and in

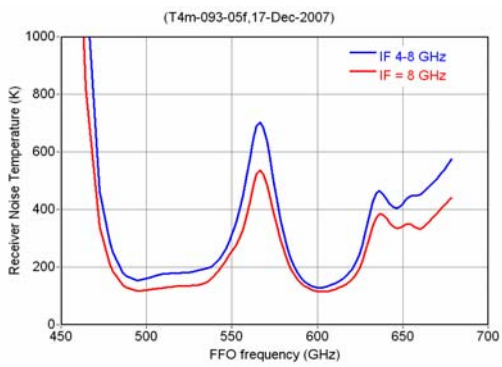

Fig. 7 Measured DSB receiver noise temperature of the SIR device selected for flight at 8 GHz IF frequency (red line) and integrated in the 4-8 GHz IF range (blue curve)

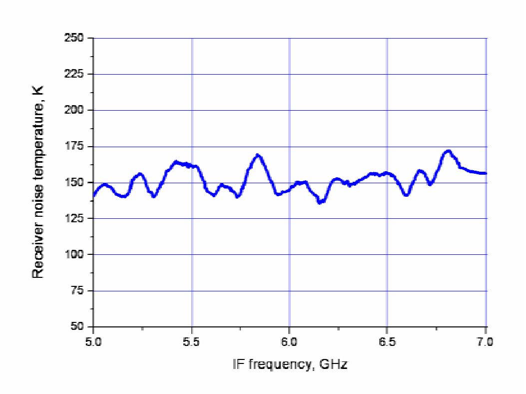

Fig. 8 Receiver noise temperature as a function of IF frequency, taken at 600 GHz

Figure 8 as a function of IF frequency. As can be seen, the averaged in the 4-8 GHz IF band noise is below 200 K over > 100 GHz input bandwidth of the receiver, with a minimum of 120 K at 600 GHz. The noise peak around 540-575 GHz is partially caused by absorption of water vapor in the path between calibration sources and cryostat, and partly due to properties of the mixer matching circuits. The relatively high noise in this part of the band is not a concern since this part of the atmospheric spectrum is almost completely blocked by the presence of a very strong atmospheric water-vapor line. The noise as a function of IF is fairly flat in the designed frequency range 5-7 GHz, as can be seen in Figure 8.

The near field beam pattern of the SIR cold channel has been measured using the ALMA measurements setup at 600 GHz. Results of the FFT transformed amplitude and phase distribution are shown in Figure 9. The measured beam waist is 2.25 mm (within 1% of the designed value), Gaussisity of the measured beam is 92.4%.

The SIR is a complicated device; it contains a few interactive superconducting elements: an SIS mixer, an FFO, and an HM for the FFO phase locking. Special algorithms and procedures have been developed and tested to make possible characterization of the SIR in a reasonable time scale and ensure SIR control during the flight. Some of these routines are listed below:

- fast definition of the FFO operational conditions (both on the Fiske step and in the flux-flow regimes);
- measurements of the free-running FFO linewidth;
- optimization of the LSU and HM parameters;
- optimization of the PLL operation;
- minimization of the SIR noise temperature;
- setting all predefined SIR parameters in the proper sequence for control during the flight;
- continuous monitoring of the main SIR parameters, adjustment (or recovering) the SIR operational state.

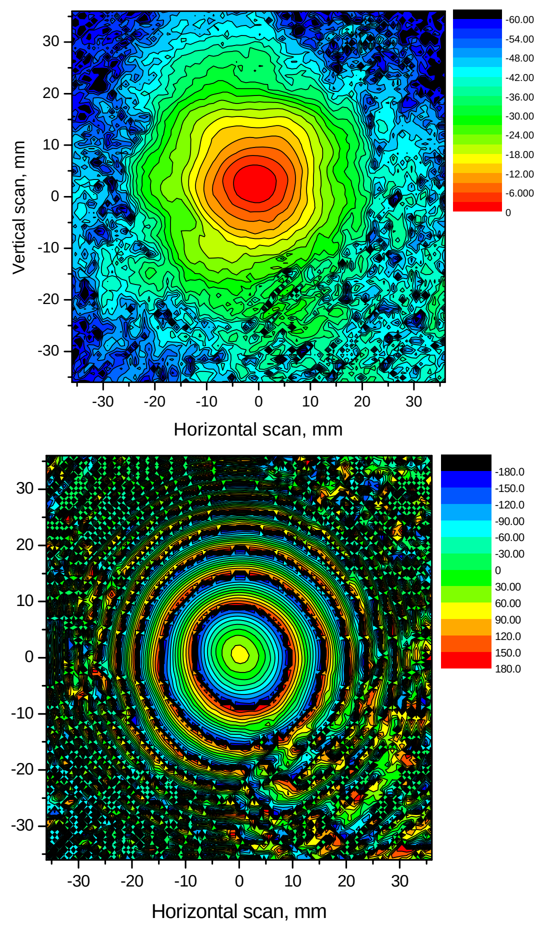

Fig. 9 SIR cold channel amplitude (upper panel) and phase (lower panel) distribution. Distance from the beam waist is 110 mm. Frequency is 600GHz

For the measurement strategy it is important to know the stability of the complete receiver chain. The stability determines the measurement time and thus the frequency of the calibration cycle. The stability of the complete TELIS-SIR system has been determined with a noise-fluctuation bandwidth of 17 MHz and the results are presented in Figure 10. For the two IF channels that are used to determine the Allan variance it is found that the Allan stability time is about 13.5 seconds. When the difference of the two channels is taken to determine the Allan variance (this is the so-called spectroscopic (differential) mode), the Allan stability time of 20 seconds is found.

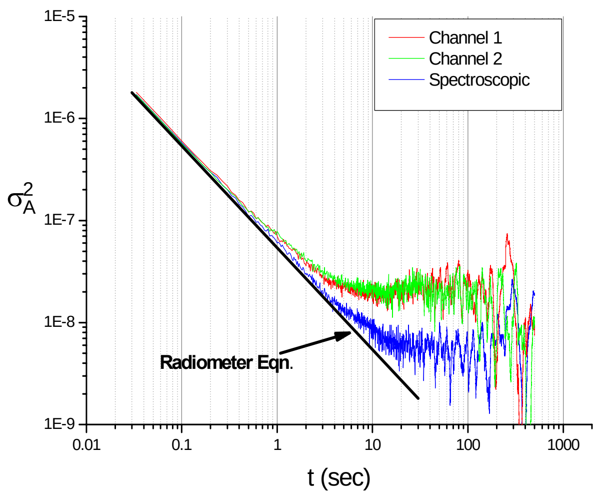

Fig. 10 System stability of the SIR channel. FFO is phase locked at 600 GHz. Green and blue lines present individual channels variance, the black one is representative for the spectroscopic variance

To prove the capabilities of the TELIS-SIR channel for high resolution spectroscopy we have successfully measured line profiles of OCS gas around 600 GHz. The tests were done in a laboratory gas cell setup at a gas pressure down to 0.2 mBar, corresponding to the FWHM linewidth <5 MHz. Figure 11 shows an example of the measured spectrum at a gas pressure of 2.6 mBar. In this case the FFO frequency was tuned to 601 GHz so that the two OCS lines have their lines in the 5 – 7 GHz IF range, one in the upper side band and the other one in the lower side band. The flat lower level of the spectrum is due to the 77 K cold reference and the residual emission of the warm windows of the gas cell. One can see two strong lines, which are calculated to be saturated. The 4 weaker lines are isotopes (not saturated). For the saturated lines the signal level is expected to be at 210 K for an ideal receiver. The deviation from this value is due to the sideband ratio of the receiver being different from 1.0.

Knowledge of the instrument sideband ratio with an accuracy of better than 10% is required for the retrieval as the spectrum is taken in the DSB mode. We have set-up Bruker

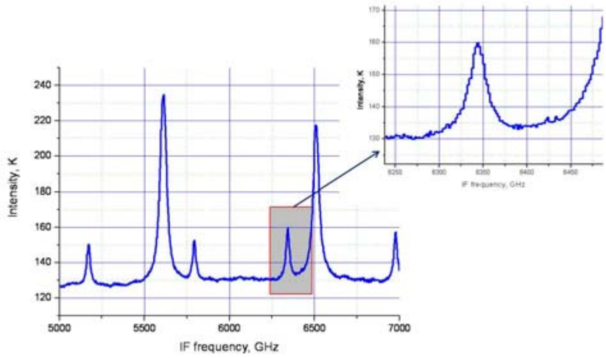

Fig. 11 Deconvolved spectrum of the OCS emission lines at a gas pressure 2.6 mBar. LO frequency 601 GHz. Two strong lines are saturated; weaker lines are not saturated isotopes. The lines are detected, one in the LSB, the other one in the USB

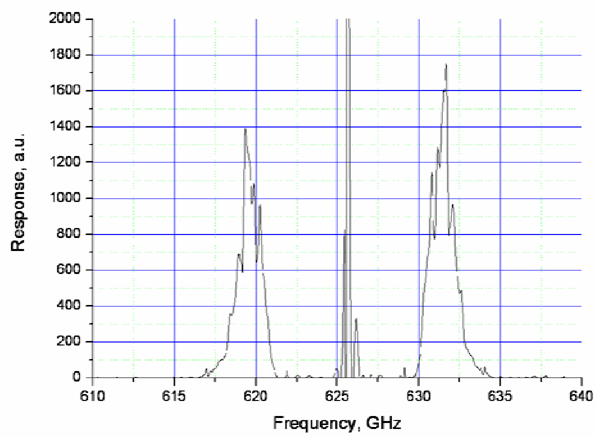

Fig. 12 FTS spectrum of the receiver. LO frequency is 626 GHz. Two sidebands of the receiver are mirrored around the LO frequency.

Fourier Transform spectrometer to measure the receiver response in the heterodyne mode. One of the results is presented in Figure 12. The LO frequency for this experiment was set around 626 GHz. One can see a strong peak in the data due to self-emission of the LO radiation towards the FTS system. The sidebands of the receiver are detected separately, so that the sideband ratio of the instrument can be calculated.

VII. First Flight

The TELIS instrument had its maiden flight during the Teresina 2008 campaign within framework of the SCOUT-03 project. It arrived in Teresina in May 2008 and was successfully assembled and integrated into the MIPAS-B gondola within two weeks. A number of tests, including communication link with the ground segment, telescope control (compensation for gondola motions), line of sight characterization with respect to elevation and azimuth, have been successfully accomplished by the TELIS and MIPAS teams. Special attention was paid to electro-magnetic compatibility of the two instruments. Figure 13 shows the TELIS instrument integrated into the MIPAS gondola.

All SIR sub-systems were operational on the launch site; no degradations or failures have been detected.

For the test flight seven micro-windows have been selected with the following LO settings:

- 495.04 GHz and 496.96 GHz for the water isotopes;
- 506.56 GHz for BrO;
- 515.25 GHz for the pointing and also H_2CO, H_2O_2;
- 519.25 GHz for BrO and HNO_3;
- 607.78 GHz for HCN and the ozone isotopes;
- 619.10 GHz for HCl, HOCl and ClO.

The SIR was characterized at these frequencies and pre-set operating parameters for the FFO, SIS and HM mixers have been determined. Specially developed control algorithms allowed fast switching between the frequencies and final optimization of the SIR for each particular frequency. A typical time for a frequency switch is about 2 minutes.

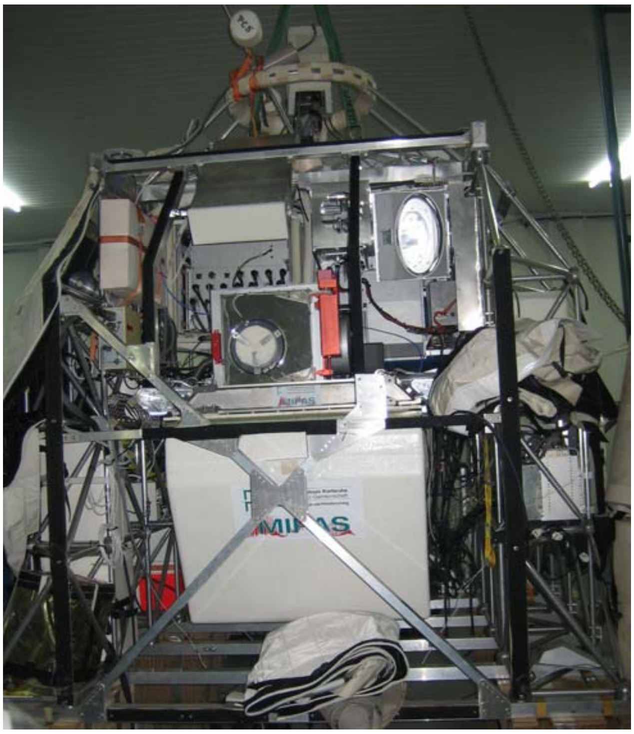

Fig. 13 TELIS (upper right corner in the gondola) is integrated into the MIPAS gondola. TELIS electronic boxes are located in the gondola structure (right side)

The balloon was launched on 05.06.2008 at around 10:30 pm. In the first two hours of the flight the gondola ascended to about 30 km altitude. During this time it went through very cold atmospheric layers with temperatures as low as 180 K at the tropopause. Although the instrument was insulated, the TELIS electronics and battery boxes cooled down to temperatures as low as 240 K. This was much lower than anticipated and also lower than the minimum temperatures we observed in previous Thermal Vacuum tests. Nevertheless, it was still possible to operate the SIR channel and switch between frequencies using the automatic on-board algorithms to compensate for the drifts and offsets developed in the electronics.

Unfortunately, the cold temperatures of the cryostat and optics also resulted in a malfunctioning of the telescope mechanics and calibration source. Therefore, no limb sounding and no deep space view for calibration could be done. Furthermore, due to the low temperature the cryostat developed a leak. As a result, the liquid helium evaporated quickly and the channels warmed up after about 3 hours of flight.

After the flight the gondola was recovered and both instruments survived the landing, no major mechanical problems were found. The housekeeping data is currently being analysed to identify problems in order to improve the thermal design for the next flight, which is currently scheduled for winter 2009 in Kiruna.

CONCLUSIONS

Capability of the SIR for high resolution spectroscopy has been successfully proven in a laboratory environment. The receiver has been installed into TELIS and integrated in the MIPAS gondola for the first flight. The maiden flight took place in June 2008. During the first few hours of the flight the instrument behaved normally, could be commanded and frequency switching algorithms worked well. However, due to thermal-mechanical problems no scientific data have been obtained. The housekeeping data is currently being analysed to identify problems in order to improve system thermal design for the next flight, which is currently scheduled for winter 2009 in Kiruna.

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