TELIS: TErahertz and subMMW LImb Sounder – Project Summary After First Successful Flight

Manfred Birk[1]*, Georg Wagner[1], Gert de Lange[2], Arno de Lange[2], Brian N. Ellison[3], Mark R. Harman[3], Axel Murk[4], Hermann Oelhaf[5], Guido Maucher[5] and Christian Sartorius

[1] *German Aerospace Center (DLR), Germany*
[2] *Netherlands Institute for Space Research (SRON), The Netherlands*
[3] *Rutherford Appleton Laboratories (RAL), United Kingdom*
[4] *University Bern, Switzerland*
[5] *Karlsruhe Institute of Technology (KIT), Germany*

*Contact: manfred.birk@dlr.de, phone +49-8153-28-3084

***Abstract*— The TELIS instrument is a balloon-borne cryogenic three-channel heterodyne spectrometer for limb sounding of stratospheric trace gases. The instrument is flown on the MIPAS gondola together with the MIPAS-B Fourier-transform spectrometer of the Institute of Meteorology and Climate Research (IMK) of the Karlsruhe Institute of Technology (KIT). The MIPAS gondola is equipped with a precise GPS-aided inertial navigation system providing attitude and heading data of the gondola movements with 128 Hz that are also used as input for the TELIS pointing system. TELIS was developed by a European consortium involving research institutions, universities and industrial partners.**

Thermal emission radiation is coupled in by a 26x13 cm dual offset Cassegrain telescope controlled to maintain constant tangent height during measurement. Radiometric calibration is achieved by a blackbody and deep space view. The radiation is divided into three channels by means of a polarizer and a dichroic. Within a special lightweight cryostat three complete heterodyne receivers are kept at liquid helium temperature: THZ channel, 1750-1890 GHz, hot electron bolometer mixer, DLR; SIR channel, 480-650 GHz, integrated receiver, SIS mixer, SRON (see poster 'TELIS instrument performance analysis'); subMMW channel, 497-504 GHz, SIS mixer, RAL. A digital autocorrelator spectrometer with 4 GHz bandwidth and ca. 2 MHz resolution serves as backend shared among the channels.

The first successful flight was in March 2009 and the second in January 2010, both launched from Esrange near Kiruna, Sweden. Calibrated spectra are so far only available as quicklook data. Sideband ratios have been characterized. The radiometric accuracy of the autocorrelator is under investigation (see poster 'Characterisation of the TELIS autocorrelator spectrometer').

This paper will present the instrument as well as first results from the flight campaigns.

I. Introduction

In order to investigate stratospheric trace gas distributions associated with ozone destruction and climate change, TELIS (TErahertz and submillimetre LImb Sounder) has been developed, a new state-of-the-art balloon-borne three channel (500, 480-650, 1800 GHz for RAL, SRON and DLR respectively) cryogenic heterodyne spectrometer. The instrument applies state-of-the-art superconducting heterodyne technology operated at 4K and is designed to be compact and lightweight, while providing broad spectral coverage within the submillimetre and far-infrared spectral range, high spectral resolution and long flight duration (~24 hours during a single flight campaign). The TELIS instrument is operated together with the MIPAS-B Fourier Transform spectrometer on the same balloon platform. MIPAS was developed by the Institute of Meteorology and Climate Research of the Karlsruhe Institute of Technology, Germany, and has completed 18 successful flights (see e.g. [1] and references cited therein). The combination of TELIS and MIPAS instruments covers all relevant atmospheric species:

TELIS species (limb sounding: height range 10-40 km, altitude resolution 2 km)

DLR: OH, HO_2, HCl, NO, NO_2, O_3, H_2O, O_2 (pointing, temperature), HOCl, $H_2{}^{18}O$, $H_2{}^{17}O$, HDO

RAL: BrO, ClO, O_3, N_2O

SRON: ClO, BrO, O_3, HCl, HOCl, H_2O, HO_2, NO, N_2O, HNO_3, CH_3Cl, HCN, $H_2{}^{18}O$, $H_2{}^{17}O$, HDO, O_2 (pointing, temperature)

MIPAS-B species (incomplete list)

Ozone relevant: O_3, NO, NO_2, HNO_3, HNO_4, N_2O_5, ClO, ClOOCl, HOCl, $ClONO_2$, $BrONO_2$

Water isotopologues: HDO, $H_2{}^{16}O$, $H_2{}^{17}O$, $H_2{}^{18}O$

Tracers: N_2O, CH_4, CO, SF_6, CF_4, CCl_4, CFC-11, CFC-12, CFC-113, HCFC-22, CH_3Cl

Short-lived source gases: NH_3, acetone, PAN, H_2CO

NMHCs: C_2H_6, C_2H_2

Species involved in cloud physics: H_2O, HNO_3, NH_3, OCS, ...

Cirrus cloud parameters: extinction, volume, bulk composition, coarse size dist.

The species marked in red are measured by TELIS alone and are thus complementary to the MIPAS observations. Several species can be used for cross validation. In case of the water isotopologues the DLR channels measures strong isolated lines which are suited for MIPAS/ENVISAT validation.

II. TELIS Instrument Overview

Fig. 1 shows the block diagram of the TELIS instrument. Three heterodyne receivers are installed inside the cryostat fabricated by RAL which is lightweight and has two optical benches (ca. 30 cm diameter), one below and one above the helium vessel. The 480-650 GHz channel developed by Netherlands Institute of Space Research (SRON) utilizes the Super-Integrated-Receiver (SIR) combining the Superconductor-Isolator-Superconductor (SIS) mixer and its quasi-optical antenna, a superconducting phase-locked Flux Flow Oscillator (FFO) acting as LO and SIS Harmonic Mixer (HM for FFO phase locking [2],[3]). The 500 GHz channel developed by Rutherford Appleton Laboratory (RAL) is a highly compact heterodyne receiver. It uses a fixed tuned SIS mixer, with a junction provided by the Institut de Radioastronomie Millimetrique, France and a solid state LO [4]. The 1.8 THz channel [5] uses a solid state local oscillator and a hot electron bolometer as mixer.

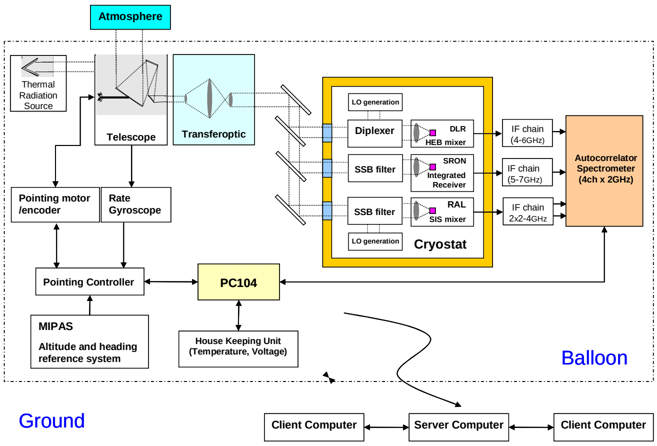

Fig. 1 Block diagram representing the TELIS instrument

The atmospheric signal is transmitted from the telescope through the front-end transfer optics where the signals are separated and coupled into each channel through dedicated windows. For radiometric calibration a cone-shaped blackbody [6] is used together with an up-looking spectrum (ca. 65° elevation angle). The input of the channels is switched to the warm blackbody by a flip mirror between telescope and transfer optics. For on-ground operation, a second flip mirror is installed to couple radiation from a cold load (Dewar lined with Eccosorb filled with liquid nitrogen). The telescope was designed to yield 2 km vertical resolution at 500 GHz. To avoid edge taper effects the vertical size of the mirror is 4ω. The size of primary of the dual offset Cassegrain is 26 cm in vertical and 13 cm in horizontal direction. The anamorphicity is introduced by a cylindrical tertiary. The RAL channel signal path is separated by means of a polarizer (manufactured by RAL) which transmits the SRON and DLR beams. SRON and DLR beams are further separated by a dichroic filter plate (also manufactured by RAL) transmitting 84-93% of the THz spectral signal to the DLR channel.

The telescope is positioned by a limited angle torque motor powered by an H-bridge. The angle is measured with a high-accuracy angular encoder. Furthermore, the angle change with respect to a space-fixed coordinate system is measured with a rate gyro. A real time processor controls the telescope using a digital control loop to keep an earth-fixed pointing angle of the telescope. Data for this control to relate the gondola and earth-fixed systems is supplied by the AHRS (attitude and heading reference system) of MIPAS. The AHRS is a precise GPS-aided inertial navigation system with gyros and accelerometers providing attitude and heading data of the gondola movements with 128 Hz. The pointing stability is 1' peak-to-peak in absence of large gondola oscillations. For a single measurement the pointing angle is held constant.

The Intermediate Frequency (IF) output of each channel is fed to a digital autocorrelator spectrometer developed by the OMNISYS company (Sweden), having a resolution of about 2 MHz and two independent spectrometers with an input frequency range of 2 GHz each. The total bandwidth is either shared by DLR and SRON channels or entirely dedicated to the RAL channel, which uses a 14 GHz to 18 GHz IF downconverted to two separate 2 GHz channels.

All devices of the TELIS instrument are controlled by a computer (based on PC/104). Device drivers running in a Linux environment control the hardware. Communication between flight and ground segment servers is done via telemetry supporting TCP/IP. The ground server uses a MySQL database to store all sent and received commands and data. The data received from the instrument are raw autocorrelation as well as housekeeping data, e.g. temperatures, voltages, pointing data.

During flight, the TELIS instrument is powered by lithium sulfuryl chloride batteries offering high energy density. The instrument is also surrounded with PE foam insulation and heat from the autocorrelator unit is transferred to a radiator plate by ammonia-filled heat pipes. Table 1 contains summary details about the instrument. Figure 2 shows the optical module of TELIS including the telescope, blackbody unit, transfer optics, and cryostat (blue). The autocorrelator unit (Figure 3) contains IF pre-amplifiers for SRON and DLR channel and an IF box which converts channel outputs to 1.75-3.75 GHz for the autocorrelator. This box also controls the autocorrelator and variable attenuators. The local oscillator synthesizer for the 1.8 THz channel (output frequency ca. 16 GHz), the autocorrelator, and the DC/DC power supply for all components on this unit are also on this plate which is mounted on the back of the optical module. Beside the optical module, there are four small racks: digital rack, analogue rack, battery rack, and a rack controlling the SRON channel. All racks are stored in compartments (40x40x25 cm) of the gondola structure.

TABLE I
TELIS Specifications

Dimensions optical module	120 x 70 x 72 cm
Total mass	140 kg
Total power consumption	240 W
Liquid helium	15 l
Liquid nitrogen	7 l

Telescope	
Size	26 cm vertical x 13 cm horizontal
Design	Dual offset Cassegrain, anamorphic
Field of View	Ca. 2 km FWHM at tangent point
Spectrometer	
Type	Digital autocorrelator, 1.5 bit
Bandwidth	2 x 2 GHz
Resolution	2 MHz
Measurement cycle	
Duration	30-50 s
Calibration	Hot load + deep space view
Measurement time per microwindow	10-20 min
DLR Channel	
Frequency range	1750-1890 GHz
LO power	>200 nW
Noise temperature	3000-4000 K DSB
Mode	Double sideband
SRON Channel	
Frequency range	480-650 GHz
Noise temperature	200 K DSB
Mode	Double sideband
RAL Channel	
Frequency range	497-504 GHz
Noise temperature	2000 K DSB
Mode	Double sideband

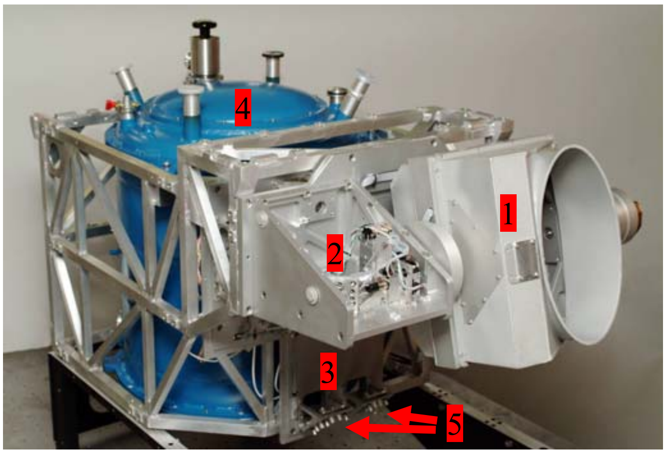

Fig. 2 Optical module of TELIS. The module is based on a welded aluminium frame. The oval opening on the right belongs to the telescope (1) and has about the size of the primary which is behind the opening. The blackbody unit (2) with the flip mirrors and one imaging mirror is left of the telescope. The warm blackbody itself is under the unit and cannot be seen. The transfer optics plate (3) is between telescope, blackbody unit, and cryostat (blue vessel, 4). The only elements of the transfer optics which can be seen are the coupling mirrors (5) to the RAL and SRON channels.

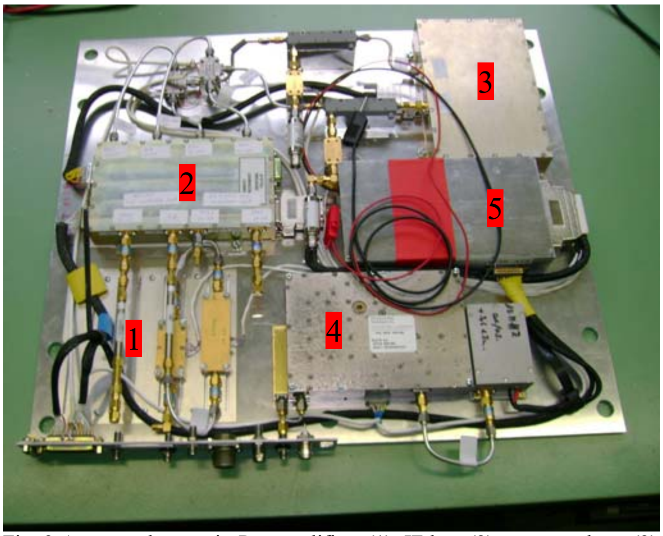

Fig. 3 Autocorrelator unit. Pre-amplifiers (1), IF box (2), autocorrelator (3), LO synthesizer (4), power supply (5).

III. CHARACTERIZATION

A. Radiometric accuracy

Gas cell measurements offer a radiometric check of the entire system. Opaque lines of ambient temperature gas have a known line contrast when measured against a cold background. By adjusting the total pressure atmospheric signals can be simulated. In the case of unknown sideband ratio opaque lines may be selected with a difference frequency in the range $2xIF_{lower}$ to $2xIF_{upper}$, where IF_{lower} and IF_{upper} are the IF boundary frequencies. The local oscillator can then be adjusted to position the lines from both sidebands at the same IF frequency. Thus, the IF signal represents the sum of both sidebands and the radiometric accuracy can be investigated without knowing the sideband ratio.

Cell measurements (OCS for SRON channel, methanol for DLR channel) showed radiometric errors in the auto-correlator (see Fig. 4). The errors affect the signal intensity and signal spectral shape. Radiometrically calibrated spectra with broad spectral signatures, similar to the shapes in the calibration spectra, do not show any errors. When the spectrum to be calibrated has a spectral shape which differs from that of the calibration measurements errors occur depending on the difference of calibration and target spectral shape. The OCS spectra in Fig. 4 could be fitted by using a multiplicative and additive correction in radiance in each of the 500 MHz autocorrelator segments. The scalar increased from narrow to broad lines from 0.8 to 1.0. To characterize the spectrometer, identical measurements were performed with an FFT spectrometer for comparison. A final analysis is in progress.

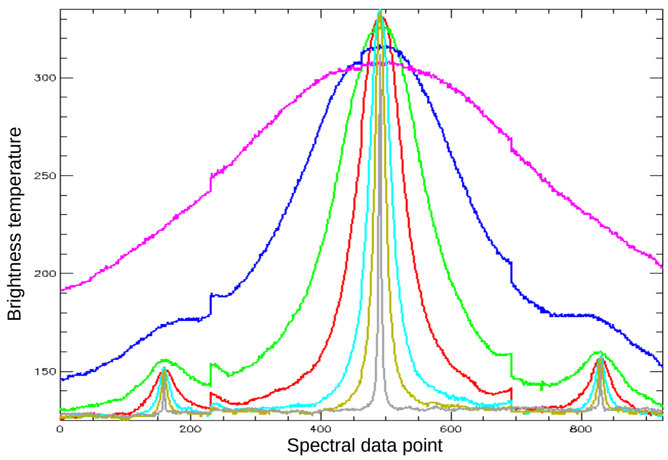

Fig. 4 Measured OCS spectra at different gas pressures. There was a saturated line in each sideband. All lines should peak at 300 K (gas temperature) and there should be no steps in the line profile.

A method was developed to measure sideband ratios using a high resolution Fourier-transform spectrometer (6 m maximum optical path difference, corresponding to 30 MHz resolution). The heterodyne channel is used as detection unit of the FT-spectrometer and the IF power diode output is fed into the Fourier-transform analogue electronics. Several iterations were required to optimize the procedure and to obtain reproducible results. With this method the sideband ratios of both the DLR and SRON channel were measured. Figure 5 shows an example of the spectral dependence of the sideband ratio for two independent measurement campaigns (new positioning of detector unit). Worst case differences of 10% occur. On average, the method is accurate to 5%. The spectral shape indicates that some small interference (Fabry-Perot) effects are still present in the optics of the heterodyne spectrometer.

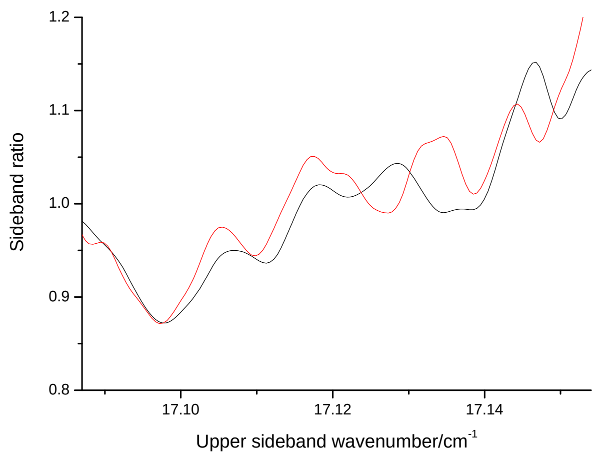

Fig. 5 Example of sideband ratio from two different measurement campaigns

B. *Antenna beam profile*

The influence of the telescope on the beam profile was measured by Fürholz and Murk [7]. The azimuthally collapsed antenna beam profile (ACAP) of the entire system was measured according to a method developed by Pickett [8]. For this a copy of the telescope was built omitting the tertiary and using a mercury arc lamp slit source where the arc is imaged into the focal plane of the telescope copy equipped with a well-defined slit. Antenna beam profiles are measured by placing the telescope copy in front of the telescope, and recording the total IF power as function of telescope angle. A typical beam profile of the SRON channel is shown in Fig. 6.

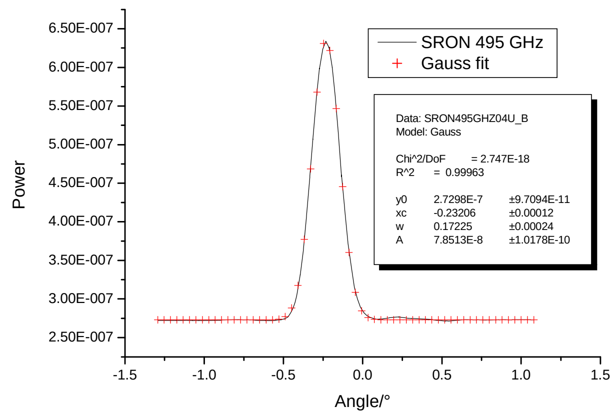

Fig. 6 SRON ACAP at 495 GHz and fitted Gauss profile. The ω is 0.17° corresponding to 0.2° FWHM corresponding to a width of 1.8 km at a distance of 550 km (typical distance sensor to lowest tangent point).

IV. Campaigns and Results

TELIS participated in two successful campaigns, one in March 2009 and the second in January 2010. Both campaigns were in Esrange near Kiruna, Sweden. The flight altitude was between 30 and 35 km. In contrast to the MIPAS Fourier-Transform spectrometer the different species to be measured cannot be simultaneously covered since they require different local oscillator settings. The optimum LO frequency was determined by simulating the double sideband spectra using standard atmospheric trace gas profiles and the HITRAN spectroscopic database. The selection criterion was to have mostly isolated lines for the target species. The different spectral regions to be covered are called microwindows. The different microwindows were tested in the same cryostat cooling cycle as the flight itself was performed. In case of the THz channel it was confirmed that the optical path difference setting for the diplexer (Martin Puplett interferometer) did not drift between characterisation and flight outside the specification. The diplexer setting influences the sideband ratio and is selected for optimum transmittance of the atmospheric signal.

A single microwindow was measured for a time period of about 10-20 minutes. The measurement sequence includes individual atmospheric measurements and the calibration measurements (hot load, up-looking 65°). The atmospheric measurements consist of a series tangent spectra (spaced by 1.5 or 2 km) from 10 km to flight altitude, 2 up-looking spectra 6° and 12°. Each spectrum was measured for 1.5 s, calibration spectra were measured about every 30 s. The measured data are directly transmitted to the ground and processed to so-called "quick look" products. Fig. 7 shows a computer screen with quick look data. On the left DLR and on the right SRON results are shown. The upper graphs shows power spectra, the next single calibrated spectra and the lower co-added spectra for all tangent heights and up-looking angles.

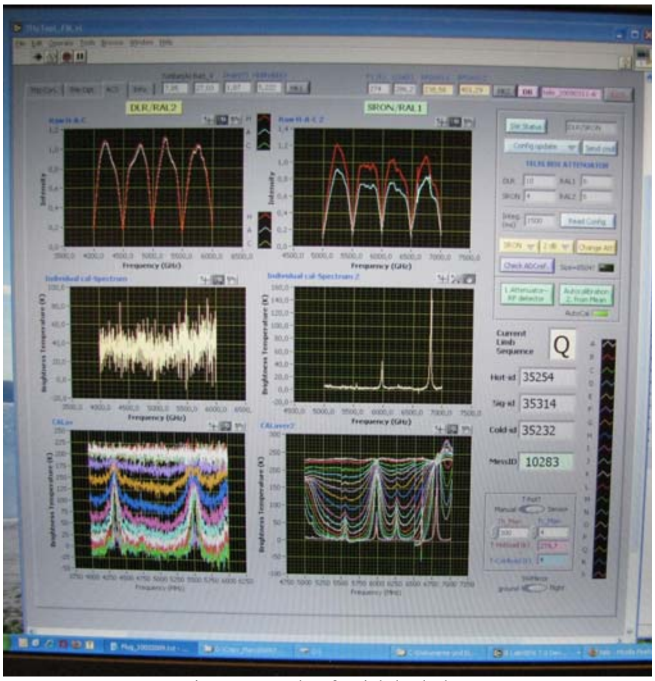

Fig. 7 Example of quick look data

Figure 8 shows an example for the THz co-added spectra for the OH microwindow together with model calculations. It can be seen that the modelled baseline is significantly lower than the measured one. Investigations on the reason are in progress. It was found that the noise temperature which was usually of order 3000-4000 K increased in the flight up to 7000 K. This happened during both flights. However, during the first flight, and when the instrument was bathed in sunlight and warming up, the noise temperature decreased to the nominal values. The likely cause of this effect is ice formation on the tertiary telescope mirror which, in turn, introduces increased attenuation in the signal path. Whether the increase in noise temperature is correlated with the large baseline values observed in the measured spectrum is still under investigation.

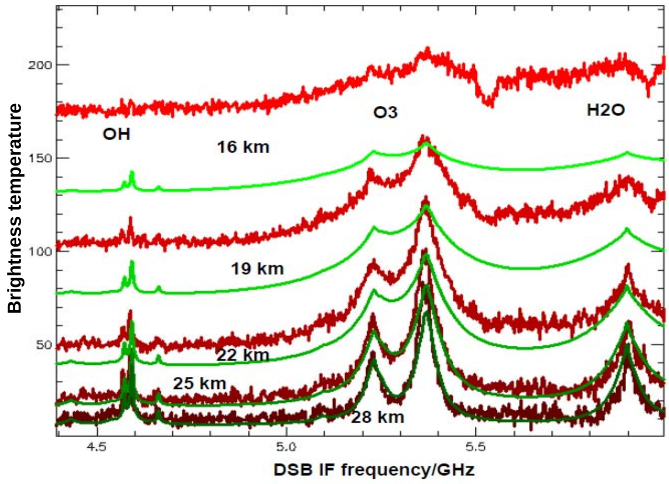

Fig. 8 Measured (shades of red) and modelled (shades of green) double sideband quick look spectra of THz channel OH microwindow at 16, 19, 22, 25 and 28 km tangent altitude

Figure 9 and 10 show spectra measured with the SRON channel during the recent flight. These spectra are very important in improving our understanding of atmospheric chemistry. In Figure 9 the time dependence of the ClO signal can be seen, with the most recent flight located inside the polar vortex during perturbed chemistry. Since MIPAS measures ClOOCl, both instruments MIPAS and TELIS can measure the time dependence of the most relevant chlorine species in perturbed chemistry which would finally quantitatively close open issues about the polar ozone hole. Figure 10 shows, also for the first time, a subMMW measurement of BrO in the polar vortex. To date in situ and UV remote measurements have provided contradictory results regarding the bromine budget. This new measurement will help to quantify the atmospheric bromine content and its consequent impact upon the global ozone budget.

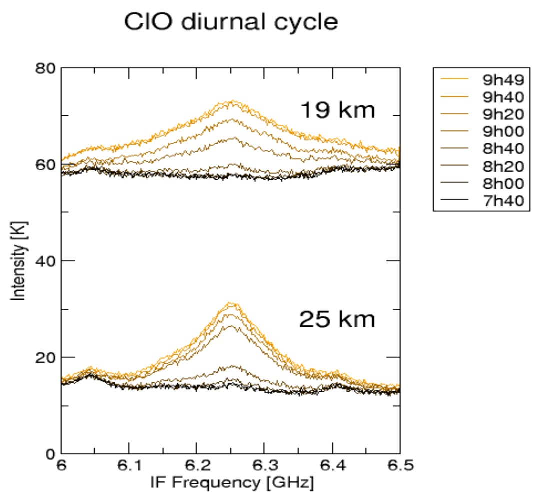

Fig. 9 The perturbed chemistry diurnal cycle of ClO recorded by the SRON channel of the TELIS instrument during the 2010 flight from Kiruna. The quick look spectra measured at 19 and 25 km tangent altitude are shown at intervals of 20 minutes

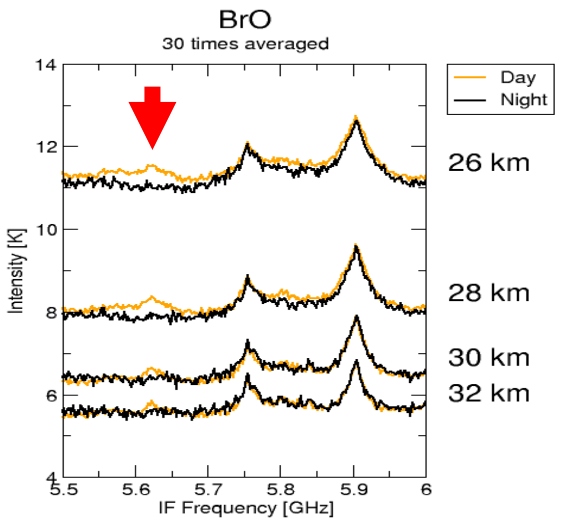

Fig. 10 BrO recordings by the SRON channel of the TELIS instrument during the 2010 flight from Kiruna. The quick look spectra measured at 26, 28, 30, and 32 km tangent altitude are shown.

V. Outlook

The next step is the generation of calibrated spectra which requires the correction of the autocorrelator error, the implementation of sideband ratios and the solution of the problem of too high baselines in SRON and DLR channel. Scientific exploitation of the data will help to improve atmospheric models and the data quality of remote sensing instruments.

TELIS is currently being modified to allow installation on the new German HALO research aircraft.

References

[1] Friedl-Vallon, F., Maucher, G., Seefeldner, M., Trieschmann, O., Kleinert, A., Lengel, A., Keim, C., Oelhaf, H., and Fischer, H., *Design and characterization of the balloon-borne Michelson Interferometer for Passive Atmospheric Sounding (MIPAS-B2)*, Appl. Opt., 43, 3335-3355, 2004.

[2] Yagoubov, P. et al., *Superconducting Integrated Receiver on Board TELIS,* in proc 19th International Symposium on Space Terahertz Technology, Groningen, 28-30 April 2008, pp. 268-275.

[3] Hoogeveen, R. W. M., Yagoubov, P. A., de Lange, A., Selig, A. M., Koshelets, V. P., Ellison, B. N., Birk, M., *Superconducting integrated receiver development for TELIS*, SPIE Proceedings Vol. 5978 (2005) 59781F.

[4] Ellison, B. N., et al., *Development of a compact sub-millimetre wave SIS receiver for terrestrial atmospheric sounding Infrared and Millimeter Waves,* proc. 12th. International Conference on Terahertz Electronics. (2004), pp. 445-446.

[5] Suttiwong, N., Birk, M., Wagner, G., Krocka, M., Wittkamp, M., Haschberger, P., Vogt, P. and Geiger, F., *Development and characterization of the balloon-borne instrument TELIS (TErahertz and Submm LImb Sounder): 1.8 THz receiver*, Proc. 19th ESA Symp. on European Rocket and Balloon Programmes and Related Research (Bad Reichenhall) 2009, in press.

[6] Murk A., Wylde R., Spurrett R., Fürholz P., Kämpfer N., *Blackbody Calibration Targets with Ultralow Reflectivity at Submillimeter Wavelengths*, 4th ESA Workshop on Millimetre-Wave Technology and Applications, Volume WPP-258, pp. 359-364, 2006.

[7] Fuerholz, P. and Murk, A., *Phase-Corrected Near-Field Measurements of the TELIS Telescope at 637 GHz*, IEEE Transactions on Antennas and Propagation, Volume 57, Issue 9, Sept. 2009, pp. 2518-2525.

[8] Pickett, H.M., *Microwave Limb Sounder THz module on Aura*, IEEE Transactions on Geoscience and Remote Sensing, Volume 44, Issue 5, May 2006, pp. 1122-1130.