TELIS – development of a new balloon borne THz/submm heterodyne limb sounder

U. Mair, M. Krocka, G. Wagner, M. Birk
Remote Sensing Technology Institute, DLR, Germany
H.-W. Hübers, H. Richter, A. Semenov
Institute for Space Sensor Technology and Planetary Exploration, DLR, Germany
P. Yagoubov, R. Hoogeveen, T. de Graauw, H. van de Stadt, A. Selig
Space Research Organisation of the Netherlands (SRON), The Netherlands
V. Koshelets, S. Shitov
Institute of Radio Engineering and Electronics (IREE), Russia
B. Ellison, D. Matheson, B. Alderman, M. Harman, B. Kerridge, R. Siddans, J. Reburn
Rutherford Appleton Laboratory (RAL), United Kingdom

Abstract

We present a design concept for a new state-of-the-art balloon borne atmospheric monitor that will allow enhanced limb sounding of the Earth's atmosphere within the millimetre and submillimetre wavelength spectral range. The instrument, called TELIS (TErahertz and submm LImb Sounder), is being developed by a consortium of major European institutes that includes the Space Research Organisation of the Netherlands (SRON), the Rutherford Appleton Laboratory (RAL) in the United Kingdom and the Deutschen Zentrum für Luft- und Raumfahrt (DLR) in Germany (lead institute). The TELIS will utilise state-of-the-art superconducting heterodyne technology and is designed to be a compact, lightweight instrument capable of providing broad spectral coverage, high spectral resolution and long flight duration (~24 hours duration during a single 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, ClO, BrO together will longer lived constituents such as O_3, HCL and N_2O. Furthermore, the TELIS will share a common balloon platform to that of the MIPAS-B Fourier transform spectrometer, developed by the Institute of Meteorology and Climate research of the University of Karlsruhe, Germany. MIPAS-B will provide simultaneous and complementary spectral measurements over an extended spectral range. The combination of the TELIS and MIPAS instruments will provide atmospheric scientists with a very powerful observational tool and, in addition, will act as a prelude to future spaceborne instruments planned by the European Space Agency (ESA).

Introduction

A recent ESA study of observational requirements for future atmospheric chemistry missions concluded that improved observations from space of ClO, BrO and other trace gases would be required to understand how stratospheric ozone will respond to changing chlorine and bromine loadings and changing climate beyond 2008, and that a sub-millimetre wave limb-sounder with superconducting (SIS) receivers cooled to 4K could meet these requirements. It also concluded that the sensitivity of a hot electron bolometer (HEB) receiver cooled to 4K would be required to observe OH in the lower stratosphere (i.e. <20km) and stratospheric HBr for the first time. These observations by 4K sub-mm and terahertz limb-sounders would be unique within the proposed timeframe as well as improving substantially on preceding satellite missions.

As a prelude to future spaceborne atmospheric sounding missions and in support of the above scientific rationale, funding has been secured by three European national institutes (DLR, SRON and RAL) to develop a high sensitivity, balloon borne atmospheric sounder that will allow simultaneous measurement of key molecular constituents within the stratosphere. The instrument is called TELIS (TErahertz and submm LImb Sounder) and will provide measurement of atmospheric constituents including OH, O_3, N_2O, CO, HCl, HOCl, ClO, and BrO that are associated with the depletion of atmospheric ozone and climate change.

In addition to the TELIS instrument, the balloon platform (i.e. gondola) will also contain a Fourier transform spectrometer (MIPAS-B developed by the Institute of Meteorology and Climate research of the University of Karlsruhe, Germany) that will simultaneously measure within the range 680 to 2400cm^{-1} The combination of the TELIS and MIPAS instruments is unusual and although there is no interdependency between the two, simultaneous operation will provide a wealth of scientific data as both a stand alone chemistry mission and in complement to existing spaceborne instruments, e.g., ODIN and Envisat.

The ambitious spectral coverage of the TELIS instrument is accomplished by use of three frequency channels: 500 GHz, 650 GHz and 1.8 THz. All channels will use a state-of-the-art superconducting SIS and HEB mixer technology. The 500 GHz channel is being developed by the RAL and is based on a highly successful instrument previously used for airborne measurements of the lower stratosphere [1]. 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 a prerequisite for this channel and is achieved through use of a miniature cryogenic dichroic filter that provides a 4K image termination and image band rejection of >25dB. The 650 GHz 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 quasioptical antenna and a superconducting Flux Flow Oscillator (FFO) acting as LO [2]. Tunability of the FFO shall allow for a wideband operation of this channel, with a goal to obtain 100 GHz instantaneous rf bandwidth or even more. The 1.8 THz channel is based on a phonon-cooled NbN HEB mixer technology, similar to that under development for

SOFIA by MSPU and DLR [3]. It will ultilise a cryogenic LO coupled to the mixer via an optical interferometer (Martin Puplett type). The channel is designed to allow future upgrade to 2.5 THz.

Design concept

The general design concept of TELIS is shown schematically in Fig. 1:

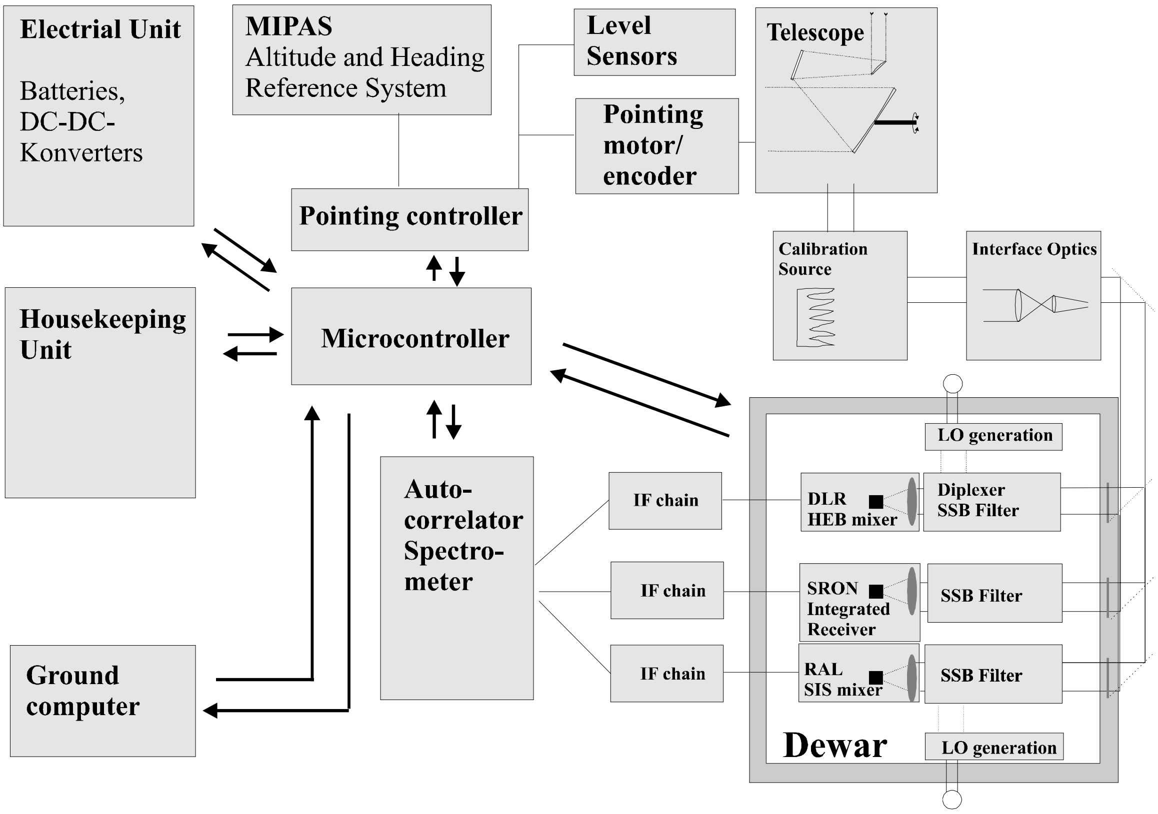

Figure 1. Schematic block diagram of the TELIS instrument.

The TELIS has a common optical front end for all three channels. A dual offset cassegrain design is used for pointing. In order to reduce size and weight an anamorphic design is applied. After the telescope a warm 300 K blackbody source can be switched in for radiometric calibration. Further quasioptical elements allow beam shaping and channel separation: The THz channel is separated from the submm channels by a dichroic filter and the submm channels are separated by a polarizer. The three heterodyne receivers are located inside a custom-made 4 K Helium cooled dewar with each channel having a separate optimised channel window. The down-converted signals are preamplified and further down-converted in three separate intermediate frequency chains. Digital autocorrelator spectrometers are utilised for spectral analysis.

A specially designed microcontroller unit is used for control and readout of all instrument components, for data storage and for telemetry. A real time pointing controller will allow to accurately address different tangent heights. The attitude information is taken from the MIPAS altitude and heading reference system. Level sensors will determine the relative angles between the TELIS and MIPAS frame.

The raw data is transmitted from the microcontroller to a ground computer system where several users can access the data and higher data products are formed.

500 GHz Receiver

The 500 GHz channel will target a range of atmospheric molecular species, but a primary goal is the evaluation of ClO, BrO and N_2O in the lower stratosphere. A calculated example of the spectral range to be observed is shown in Fig. 2 for a tangent of 20 km. In addition to encompassing the ClO, BrO and N_2O emissions, the spectral range also allows observation of O_3 which is essential to allow precise atmospheric retrievals of the more minor species.

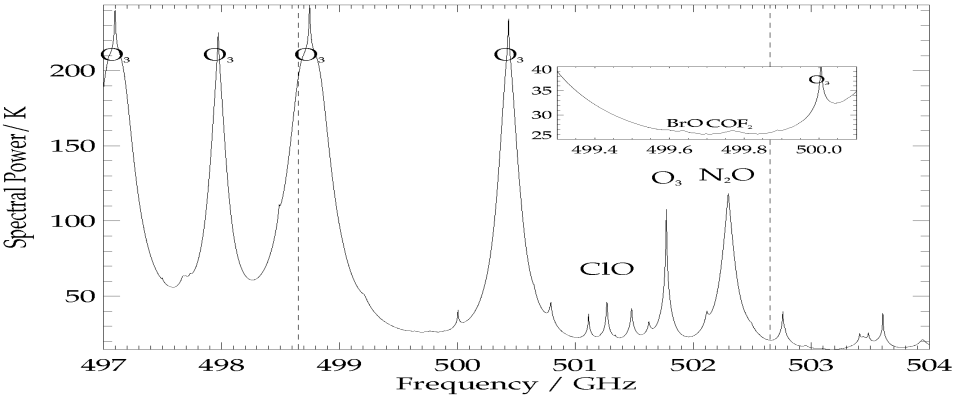

Figure 2. Calculated spectral emission features encompassed by the TELIS 500 GHz.

The spectral range to be observed places technical demands on both the 500 GHz channel and the overall TELIS instrument concept. For example, an instantaneous bandwidth of 4 GHz is necessary to encompass the primary target range (shown by the dotted lines in Fig. 2). This necessitates multiplexing of the IF and spectrometer chain and also the use of a broad-band low noise amplifier. Furthermore, it is essential that spectral contamination from the image sideband of the mixer is reduced to an extremely low value and a goal of 25 dB image band rejection has been set. Achieving this goal requires the introduction of a quasi-optical filtering element into the signal path and the use of a high IF centre frequency.

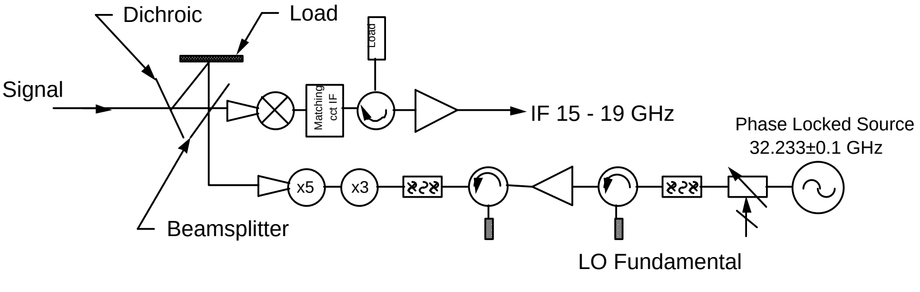

Figure 3. RAL 500 GHz compact SIS receiver channel.

The conceptual design of the 500 GHz channel shown in Fig. 3. Within this concept a dichroic plate filter (DCP) is used to separate the mixer signal and image sidebands prior to direction of the signal band into a reduced height, fixed tuned, single mode SIS waveguide mixer. The image band is directed towards and terminated by a cold (~4 K) load that ensures contaminating spectra are rejected and noise contribution from the image sideband is minimised. The use of the DCP filter necessitates the use of an IF centred at ~16 GHz which is both demanding and unusual requirement for an SIS mixer.

The LO chain is formed from a x3x5 varactor multiplier combination that up-converts a fundamental frequency of ~ 32.3 GHz (derived from a phase locked dielectric tuned resonator) to a nominal LO centre frequency of ~ 484 GHz. With the exception of the fundamental frequency source, the LO chain is placed inside the receiver cryogenic vessel and cooled to ~ 15 K. The available power from the LO is injected into the SIS mixer through a simple dielectric membrane beamsplitter with typically a 1% coupling factor. It is possible to tune the LO over a narrow range ±1.7 GHz in order to increase the instrument spectral coverage to a nominal 7 GHz. The total spectral coverage of the 500 GHz channel, limited by the frequency response of the DCP, extends from 497 to 504 GHz with a goal for the system single sideband equivalent noise temperature of 600 K.

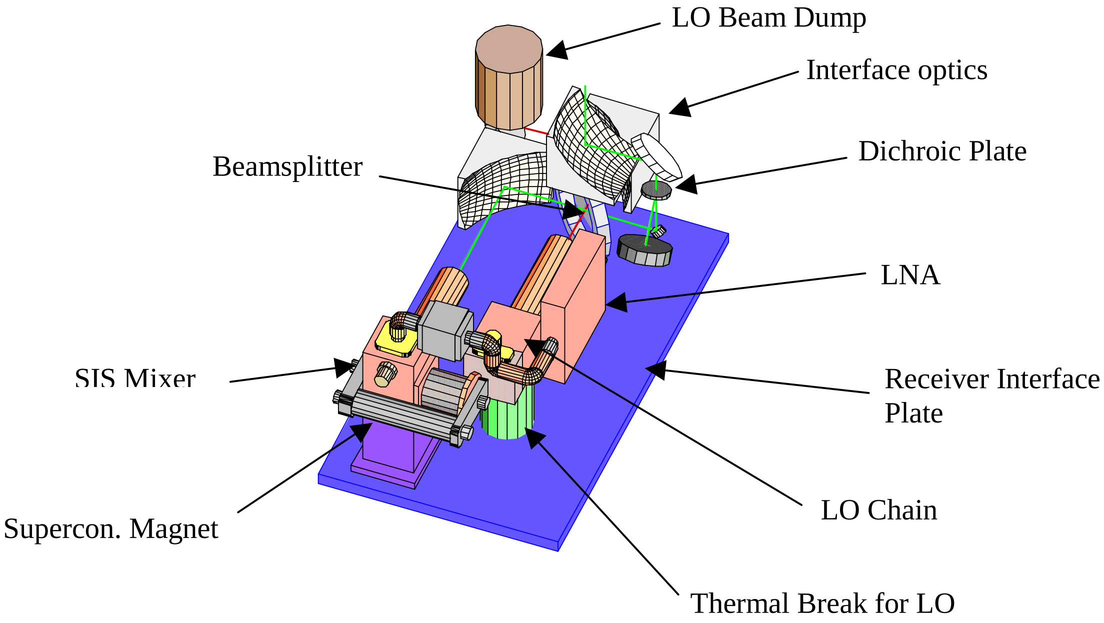

Figure 4. Three-dimensional concept of the RAL 500GHz compact TELIS channel.

Although similar in concept to a previously developed airborne instrument [1], the new TELIS 500 GHz radiometer reflects the requirements associated with a balloon borne environment and remote operation: that is, it must be simple, lightweight and reliable. In fulfilment of these aims we have developed a novel design concept that integrates the majority of receiver components, including the optical interface, SIS mixer, LNA, DCP, beamsplitter and LO, onto a single mounting plate that can be easily installed into the

TELIS cryogenic system. The plate will be cooled to 4 K along with the majority of the components, but a suitable thermal insulator is incorporated between the LO and the plate to avoid excess vaporisation of the cryostat liquid helium reservoir. Fig. 4 shows the proposed concept and indicates the primary receiver components that are encompassed within a volume of 90x95x170 mm^3.

650 GHz receiver

A key element of this channel is Superconducting Integrated Receiver (SIR), that comprises on one chip a low-noise SIS mixer with quasioptical antenna and a superconducting Flux Flow Oscillator (FFO) acting as LO [2]. The FFO is a long Josephson tunnel junction in which an applied dc magnetic field and a bias current drive a unidirectional flow of fluxons, each containing one magnetic flux quantum. The velocity and density of the fluxons and thus the power and frequency of the emitted mm-wave signal may be adjusted independently by joint action of bias current and magnetic field. The FFOs based on Nb-AlOx-Nb junctions have been successfully tested from about 120 to 700 GHz (gap frequency of Nb) providing power sufficient to pump a SIS-mixer.

The SIR microcircuits for quasioptical mixers are fabricated on a Si substrate on the base of a high quality Nb-AlO_x-Nb tri-layer. The technological procedure does not require any additional equipment compared to conventional SIS junction technology. Each individual chip with size of $4\,\mathrm{mm} \times 4\,\mathrm{mm} \times 0.5\,\mathrm{mm}$ contains an SIS mixer incorporated in a double-dipole antenna and a FFO with matching circuits. The FFO-based LO is placed just outside the two-wavelength “hot” spot of the antenna and connected to the mixer with a microstrip transmission line, which contains a number of rf coupling and dc blocking elements. Both the SIS mixer and FFO are provided with local magnetic fields via integrated control lines. The receiver chip is placed on the flat back surface of the elliptical lens from silicon. To achieve a beam of high efficiency and good symmetry, a quarter-wave back reflector chip is installed at the double-dipole antenna so there is no back-lobe radiation.

The concept of SIR looks very attractive for TELIS, foremost due to a wide tuning range of the FFO. Presently the frequency coverage of most practical heterodyne receivers is limited by the tuning range of LO and the fractional input bandwidth typically does not exceed 10-15 %, maximum feasible with a solid state multiplier chain. In the SIR the bandwidth is basically determined by SIS mixer tuning structure and matching circuitry between SIS and FFO and may achieve 30-40 % with a twin-junction SIS mixer design. In a baseline TELIS concept, the SIR channel will operate from 600 to 650 GHz, eventually aiming at a larger coverage, 500 to 650 GHz, with a single device. The goal single side band receiver noise temperature is 400 K within this band.

Schematically layout of the SIR front-end is shown in Fig. 5. The input sky signal is fed through the IR filter and passes through a Single Side-Band (SSB) filter based on Martin-Puplett polarization rotating interferometer. Further the beam is focused onto a mixer by two mirrors, “M1” and “M2”. The unwanted sideband of the mixer is reflected by two wire grids and terminated by a 4 K cold load. The intermediate frequency of the mixer is amplified by a wideband, 4-8 GHz, cryogenic HEMT amplifier ("SIR IF amplifier") with a noise temperature of 5 K. In order to reduce external magnetic interference to the sensitive FFO, the mixer block is shielded by two coaxial cans. The external layer is made from cryo-perm and the internal one is copper covered with 100 μm of superconducting led. The SIR chip is positioned far enough from the opening of the shielding can, which is the only aperture for entering the signal beam and all electrical connections.

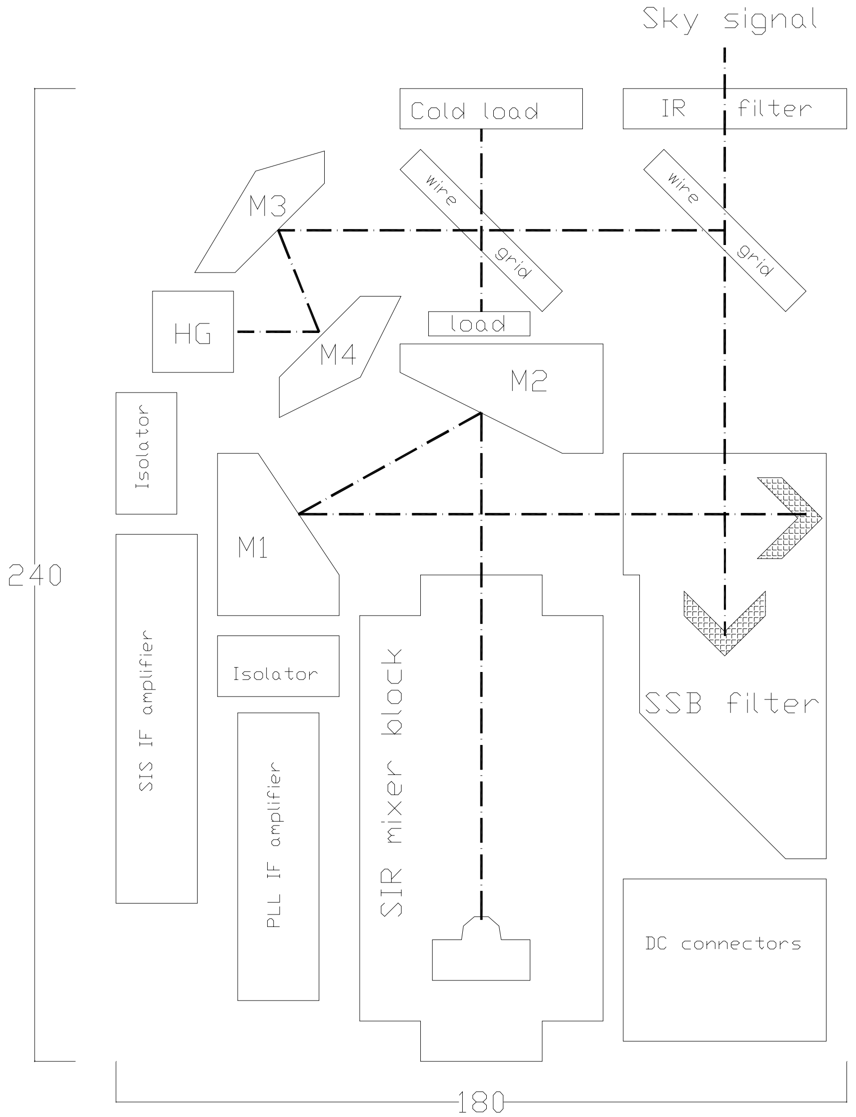

Figure 5. Mechanical and optical layout of the SIR receiver.

Initially FFO is not a very stable frequency source with an intrinsic linewidth of > 1 MHz, limiting the ultimate spectral resolution of the receiver. However, the FFO is a voltage controlled oscillator and its frequency can be stabilized by locking to an external reference oscillator using a Phase-Lock Loop (PLL) system. There are currently two concepts of PLL system under investigation and the final choice between those will be made at a later stage. Presently all the components needed to realize either system are envisaged in the design and shown in the schematic layout. In a first approach a submm-wave signal from a harmonic generator (HG), driven by a 20-22 GHz synthesizer, is focused by mirrors "M3" and "M4" and applied directly to the receiving mixer. A small part of the IF band, 4±0.05 GHz, is used to monitor the mixing product between the n-th harmonic of the synthesizer signal and the FFO signal. This down-converted signal, after narrow-band filtering, controls the phase-locking loop (PLL) system while the rest of the IF band is used to analyze the downconverted sky signal. In a second approach the chip receiver contains an additional harmonic SIS mixer which is used to mix a part of the FFO signal with the n-th harmonic of the synthesizer. In this case one more IF amplifier ("PLL IF amplifier") is used, but the "HG" and mirrors "M3" and "M4" can be omitted from the design.

All receiver components depicted in the Fig. 5 will be mounted on a single 4 K plate. The complete receiver with a size 240x180x80 mm^3 will be pre-aligned and fully tested before mounting into a TELIS system.

1.8 THz Receiver

Measurements with the 1.8 THz receiver will focus on the OH triplet at 1.8 THz. However, within a range of 80 GHz a variety of species of particular interest for atmospheric chemistry can be observed (e. g. HO_2, HOCl, NO, NO_2). Therefore the goal is to design the receiver for the frequency band from 1.76 THz to 1.84 THz. At DLR a 2.5 THz airborne heterodyne receiver for the detection of OH is in operation. This receiver is based on a gas laser LO and a Schottky diode mixer [4]. An example of an OH emission detected with this receiver is shown in Fig. 6. Although the OH emission at 1.8 THz is about a factor of four weaker than at 2.5 THz, the former one was chosen for TELIS because of risks associated with the development of a 2.5 THz solid state LO. In addition, the weaker emission at 1.8 THz is partly compensated by the higher sensitivity of the mixer at 1.8 THz.

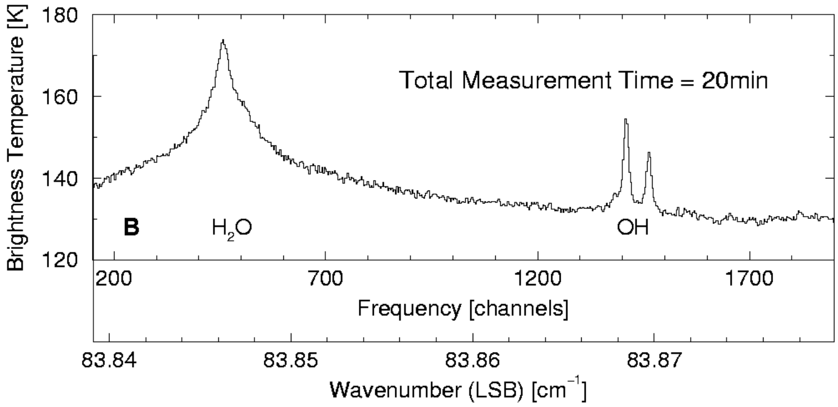

Figure 6. OH and H_2O measured with the DLR 2.5 THz airborne heterodyne receiver.

The preliminary front-end design is shown in Fig. 7. A SSB filter will be used to suppress the unwanted sideband. Coupling of LO and signal radiation is done by a polarizing diplexer. Three beam shaping mirrors, one for the LO and two for the mixer, are used. All optical components, the mixer and the IF system up to the first amplifier are mounted at the 4 K stage of the dewar. The multiplier chain of the LO is mechanically connected to the same plate but thermally well isolated. The size of the front-end is about 220 mm × 260 mm.

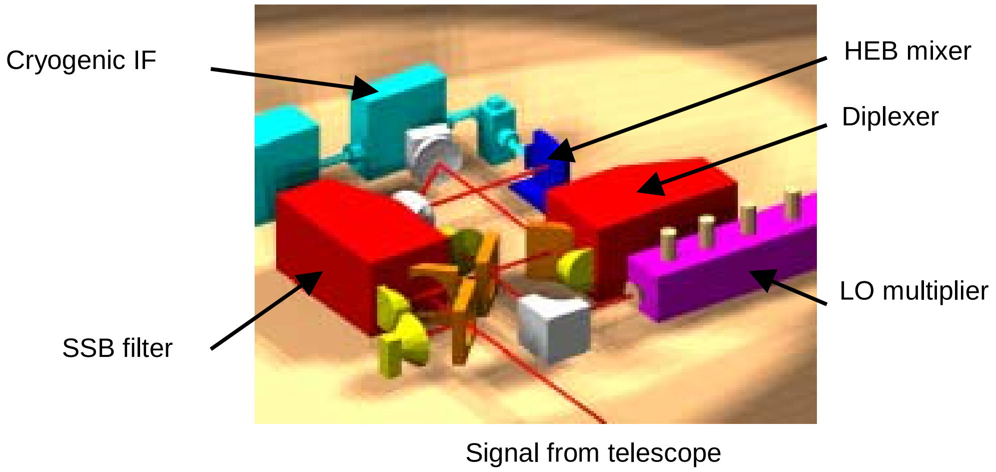

Figure 7. Preliminary design of the 1.8 THz front-end.

The mixer is a phonon cooled hot-electron bolometer similar to the one described in [3]. The HEB is incorporated in a quasi-optical hybrid antenna with a planar double-slot feed antenna and a 6 mm diameter lens. The lens is coated with a Parylene antireflection (AR) coating optimized for 1.8 THz [5]. It has been shown that the response of a HEB with a logarithmic-spiral antenna is linear to at least 400 K [5]. With the more narrow-band design of the TELIS HEB mixer we expect even higher dynamic range. The IF band is from 4 GHz to 6 GHz. A total bandwidth of 2 GHz is necessary in order to have sufficient baseline for the retrieval of the OH line The band was chosen as a compromise between the IF bandwidth of the HEB which is expected to be about 7 GHz (-3 dB DSB noise bandwidth), and the bandwidth of the SSB filter and LO diplexer. The baseline SSB noise temperature in the IF band is 4,000 K to 6,000 K.

The LO will be a multiplied ≈100 GHz source (Gunn oscillator or a synthesizer which is multiplied and amplified up to ≈100 GHz). Three multiplication stages (×3×3×2) are necessary to yield 1.8 THz. Since the efficiency of these multipliers increases with decreasing operation temperature they will be mounted inside the dewar and cooled to about 80 K. The power required by the HEB for optimum operation is about 100 nW [6]. However, this power is determined by a method known as isothermal method. It is an estimate of the power which is absorbed inside the superconducting bridge. Taking coupling losses into account the output power (goal) of the multipliers should be at least 2 μW between 1.76 THz and 1.84 THz.

References

1. Ellison, B.N., Moyna, B.P., Matheson, D.N., Jones, A., Claude, S.M.X, Mann, C., Kerridge, B.J., Siddans, R., Munro, R., and Reburn, W.J., “Development of a high sensitivity airborne SIS receiver to detect ClO and BrO”, Proceedings of 2nd ESA Workshop on Millimetre Wave Technology and Applications, Espoo, Finland, May 1998

2. V. P. Koshelets and S. V. Shitov "Topical review: Integrated superconducting receivers", Supercond. Sci. Technol., **13**, R53–R69, 2000

3. A. D. Semenov, H.-W. Hübers, J. Schubert, G. N. Gol'tsman, A. I. Elantiev, B. M. Voronov, E. M. Gershenzon, "Design and Performance of the Lattice-Cooled Hot-Electron Terahertz Mixer", J. Appl. Phys. **88**, 6758-6767, 2000

4. C. R. Englert, B. Schimpf, M. Birk, F. Schreier, M. Krocka, R. Nitsche, R. Titz, M. Summers, "The 2.5 THz heterodyne spectrometer THOMAS: measurement of OH in the middle atmosphere and comparison with photochemical model results", J. Geophys. Res. D 105, 22211-22223, 2000

5. H.-W. Hübers, J. Schubert, A. Krabbe, M. Birk, G. Wagner, A. Semenov, G. Gol'tsman, B. Voronov, G. Gershenzon, Parylene Anti-reflection Coating of a Quasi-Optical Hot-Electron Bolometric Mixer at Terahertz Frequencie, Infrared Phys. and Technol.42, 41-47, 2001

6. S. Cherednichenko, M. Kroug, H. Merkel, P. Khosropanah, A. Adam, E. Kollberg, D. Loudkov, G. Gol'tsman, B. Voronov, H. Richter, H.-W. Hübers, "1.6 THz Heterodyne Receiver for the Far Infrared Space Telescope", Proc. of the European Conf. on Appl. Superconductivity, Copenhagen, September 2001