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

P.L. Yagoubov, R.W.M. Hoogeveen, A.M. Maurellis
National Institute for Space Research (SRON), The Netherlands

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

G. Gol`tsman, B. Voronov
Moscow State Pedagogical University, Russia

V. Koshelets, S. Shitov
Institute of Radio Engineering and Electronics (IREE), Russia

B. Ellison, B. Kerridge, D. Matheson, B. Alderman, M. Harman, 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 submillimeter and far-infrared wavelength spectral range: TELIS, TErahertz and submm LImb Sounder. The instrument 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). 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, HO_2, ClO, BrO together will longer lived constituents such as O_3, HCL and N_2O. Furthermore, 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. TELIS will serve as a testbed for new cryogenic heterodyne detection techniques, and as such it 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 [1]. A sub-millimeter 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.

The history of heterodyne detection of species of the Earth atmosphere is rather brief. The Micrwave Limb Sounder on board the US Upper Atmosphere Research Satellite (MLS/UARS) was the first mission [2] to measure stratospheric ozone, ClO, water vapor and pressure and temperature using heterodyne detection at 63, 183 and 205 GHz. It was active between 1991 and 1994, and employed room temperature Schottky diodes. Its highly improved successor on board the EOS-Aura satellite will be launched early 2004 [2]. Although the frequency range has been extended up to 2500 GHz, it still employs uncooled Schottky diodes, and a double gas laser to pump the 2.5 THz mixer.
The Sub Millimeter Radiometer (SMR) on board the Swedish Odin satellite, launched in February 2002, measures up to 580 GHz with Schottky diodes operating at 100 K, thereby gaining significantly in noise performance. Instead of filterbanks, 2 digital auto correlators and one Acousto-Optic Spectrometer are used as back-end [3].
Only the planned Japanese Superconducting Submillimeter-wave Limb Emission Sounder on board the Japanese Experimental Module (JEM/SMILES) [4] of the International Space Station features two low-noise cryogenic superconducting mixers.

Extrapolating the current trends towards the future we foresee Earth limb sounding from satellite platform with superconducting receivers operating at sub millimeter and Terahertz frequencies. Instead of gas lasers only solid state local oscillators are to be employed to reduce system complexity. As back end the most likely candidates are complete spectrometers such as Acousto-Optic Spectrometers or Digital Auto Correlators.

Anticipating such future space borne 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, HO_2, O_3, N_2O, CO, HCl, HOCl, ClO, and BrO that are associated with the depletion of atmospheric ozone and climate change. In addition, TELIS will serve as a testbed for a number of novel technologies in the field of low-noise cryogenic heterodyne detection.

The balloon platform on which TELIS will fly also contains a Fourier transform spectrometer (MIPAS-B developed by the Institute of Meteorology and Climate research of the University of Karlsruhe, Germany). MIPAS 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 independent 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 [5]. 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 quasi-optical antenna and a superconducting Flux Flow Oscillator (FFO) acting as LO [6]. 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 [7]. It will ultilise a cryogenic solid-state LO coupled to the mixer via an optical interferometer (Martin Puplett type). The channel is designed to allow future upgrade to 2.5 THz.

Instrument design concept

The general design concept of TELIS is shown schematically in Fig. 1. 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. As a calibration cold load a deep space view will be used by pointing the telescope up by about 50 degrees. Further quasi-optical elements allow beam shaping and channel separation: The 500 GHz channel is separated from the two other channels by a polarizerer and the remaining submm and the FIR channel are separated by a dichroic filter. The three heterodyne receivers are located inside a custom-made 4K Helium cooled dewar with each channel having a separate optimised vacuum 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. All three channels will be operated simultaneously. From the opeartional point this requires good coordination in the observation plans. From technical point of view it requires very careful electronic design avoiding both emmisions and pick-up of spurious signals.

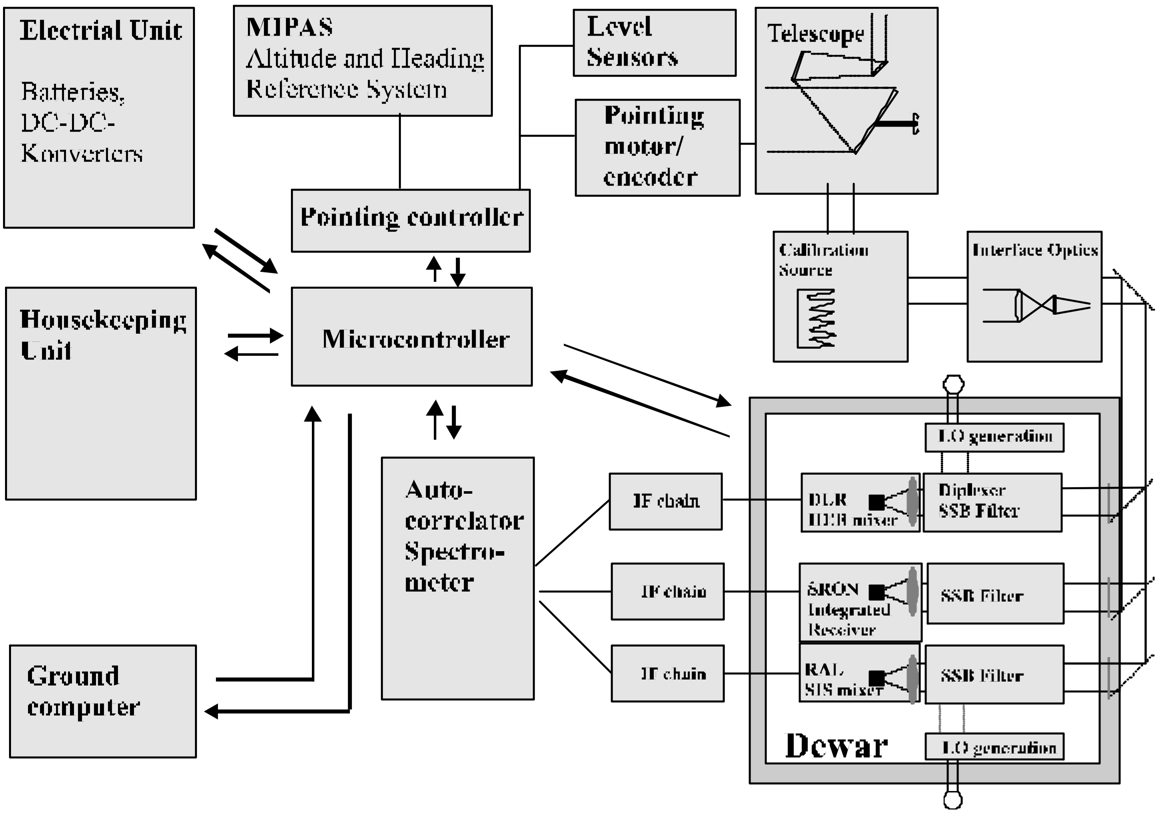

Figure 1. Schematic block diagram of the TELIS instrument.

A PC board together with specially designed microcontroller units are used for control and readout of all instrument components, for data storage and for telemetry. A real time pointing controller will allow accurately pointing to 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.

The 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.

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.

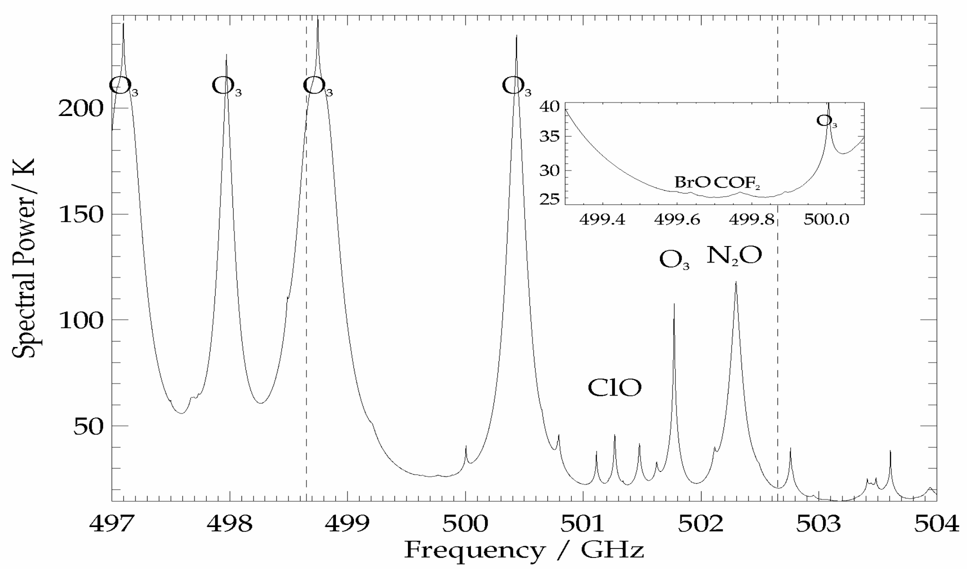

Figure 2. Calculated spectral emission features encompassed by the TELIS 500 GHz.

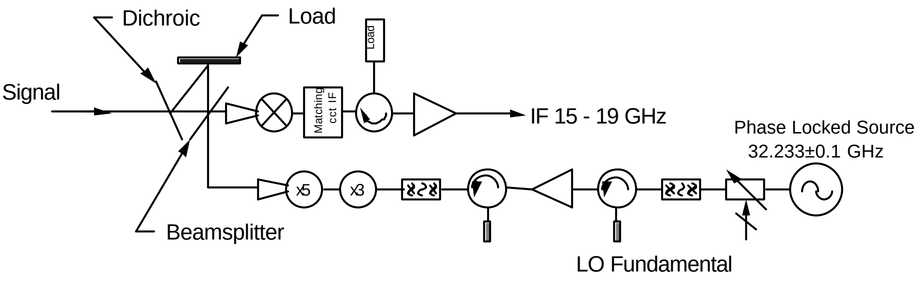

Figure 3. RAL 500 GHz compact SIS receiver channel.

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 ~17 GHz which is both a 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 noise temperature of 600 K.

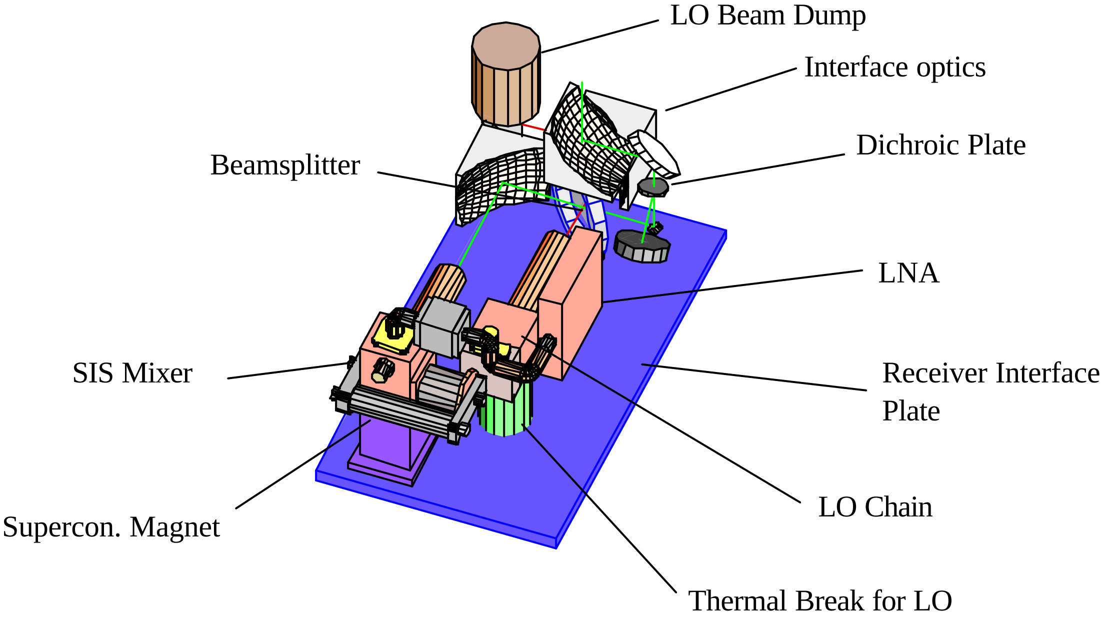

Figure 4. Three-dimensional concept of the RAL 500GHz compact TELIS channel.

Although similar in concept to a previously developed airborne instrument [5], 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.

The 650 GHz Superconducting Integrated Receiver

A key element of this SRON-provided channel is 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 [6]. 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 mm × 4 mm × 0.5 mm contains a 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.

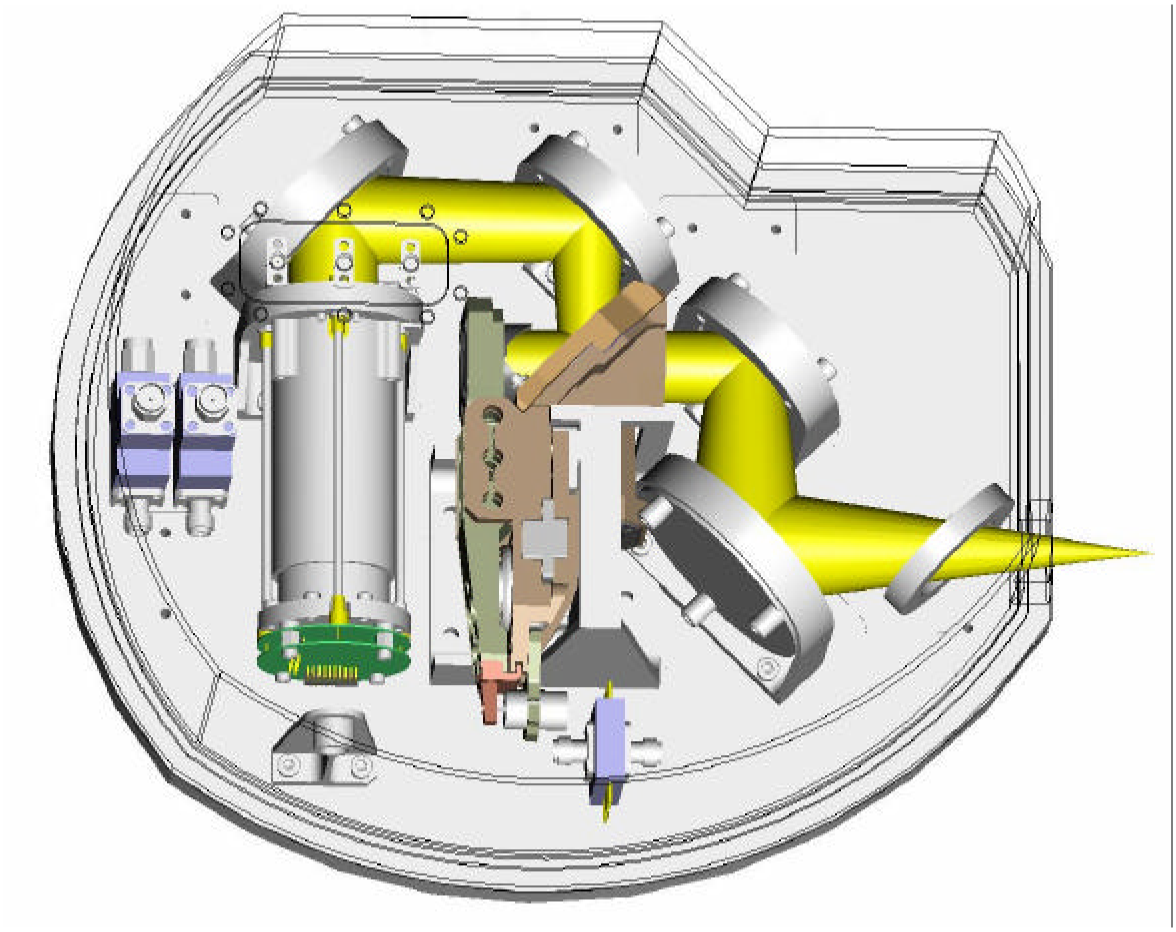

Figure 5. Mechanical and optical layout of the SIR receiver. The beam quasi-optical beam is shown in yellow; the diplexer is located in the centre, while the SIR with its superconducting and antimagnetic shields is located at the left. Some IF components are placed. The Harmonic Generator will be located at the upper right corner.

The concept of SIR looks very attractive for TELIS, foremost due to a wide tuning range of the FFO. Presently, the frequency range of most practical heterodyne receivers is limited by the tunability of the LO. For a solid state multiplier chain the fractional input bandwidth typically does not exceed 10-15 %. In the SIR the bandwidth is basically determined by SIS mixer tuning structure and matching circuitry between SIS and FFO and up to 30-40 % may achieved 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.

A schematical layout of the SIR channel 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 the 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 5K. 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 cans, which is the only aperture for entering the signal beam and all electrical connections.

Initially FFO is not a very stable frequency source with an intrinsic linewidth of typically a few MHz, thereby limiting the ultimate spectral resolution of the receiver. However, the FFO is a voltage controlled oscillator and its frequency can be stabilized by locking it 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 an external 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 at 4 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.

The 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 room temperature Schottky diode mixer [8]. 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.

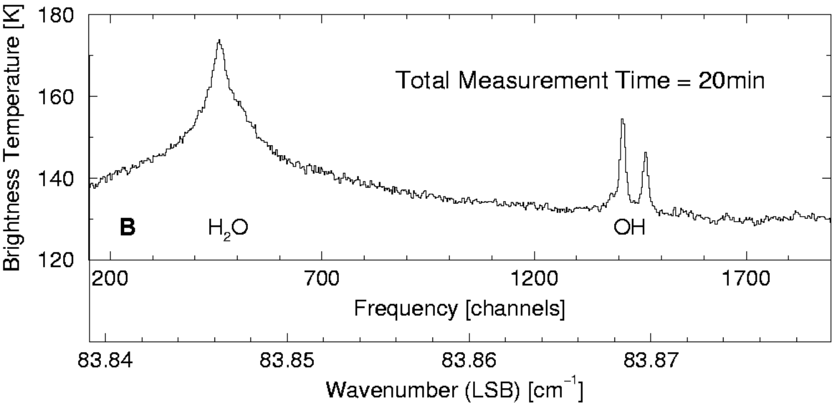

Figure 6. OH and H_2O measured with the DLR 2.5 THz airborne heterodyne receiver.

The preliminary cryogenic design is shown in Fig. 7. An 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.

The mixer is a phonon cooled hot-electron bolometer developed by Moscow State Pedagogical University and similar to the one described in [7]. 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 [9]. It has been shown that the response of a HEB with a logarithmic-spiral antenna is linear to at least 400 K [9]. 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 IF band was chosen as a compromise between the IF bandwidth of the HEB mixer 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.

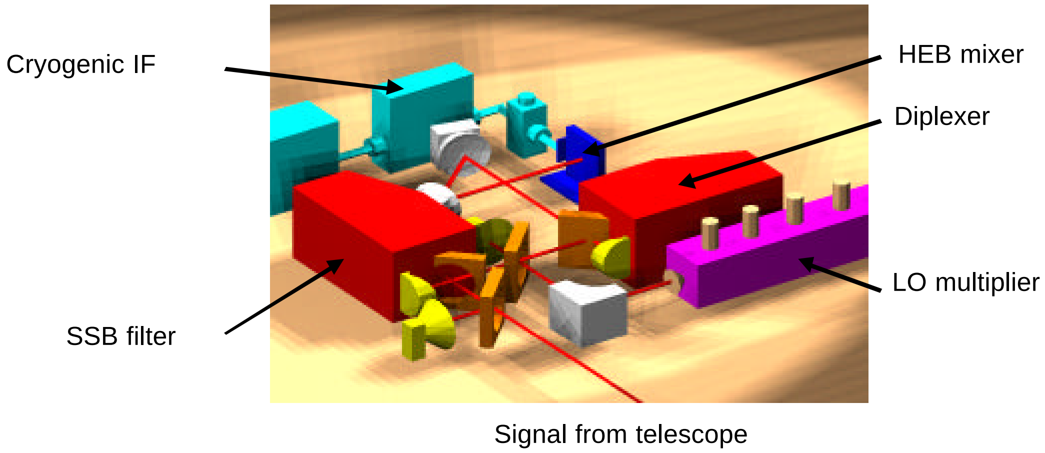

Figure 7. Preliminary design of the 1.8 THz front-end.

The 1.8 THz LO will be a PLL-stabilized syntheziser multiplied and amplified to ~100 GHz. Three additional multiplication stages 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 mixer for optimum operation is about 100 nW [10]. 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.

Conclusions

Within the framework of the TELIS project three European institutes are building a balloon borne cryogenic heterodyne instrument. Three receivers will operate at 500 GHz (RAL channel), at 600-650GHz (SRON channel) and at 1.8 THz (DLR channel). The combination of the MIPAS and TELIS instruments will provide a unique balloon platform for atmospheric sounding. TELIS itself will be a testbed for new cruogenic heterodyne detection techniques. To name a few innovations of TELIS: The compactness of the 500 GHz channel, with its challenging high intermediate frequency of 15-19 GHz; the first field demonstration of the Superconducting Integrated Receiver; the 1.8 THz HEB mixer with its solid state Local Oscillator; the cryogenic low-noise IF amplifiers and the application of 2 GHz and 4 GHz digital auto correlators as back end spectrometers.

TELIS is presently in the phase of detailed design and early production. The three individual channels will de designed assembled and tested after which system integration and test will start in 2004. A test flight is foreseen in 2005.

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