TELIS: A novel three-channel cryogenic heterodyne receiver for stratospheric research

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Abstract

TELIS (TErahertz and sub millimeter LImb Sounder) is a three-channel balloon-borne cryogenic heterodyne receiver on which a number of novel features are tested. It will fly together with the MIPAS-B2 instrument and the combination will yield the most complete map of atmospheric species ever measured from one platform. The three channels are selected at 500 GHz, tunable between 500 and 650 GHz and at 1.8 THz, and employ a SIS mixer, a Superconducting Integrated Receiver and a HEBM. First flight is foreseen in 2006.

Introduction

Traditionally, instruments that study the Earth's atmosphere take their measurements in the UV/visible region of the spectrum, where reflected sun light carries the spectral absorptions of trace gases. Band pass filters and/or gratings provide spectral discrimination. Examples are the SBUV and TOMS instruments [1], and more recently full spectrometers such as ERS-2/GOME [2], ENVISAT/SCIAMACHY [3] and EOS-Aura/OMI [4]. Another possibility is to measure the emission of the atmosphere in the thermal infrared part of the spectrum, as is employed by ENVISAT/MIPAS [5]. Here a Michelson interferometer provides the spectral discrimination.

A third technique is applied in the millimeter and sub millimeter wavelength region and is based on radio techniques. Here the incoming radiation is mixed with a strong Local-Oscillator (LO) signal and a non-linear detector outputs the difference frequency at a convenient intermediate frequency (IF) where signal amplification is easy. Standard radio techniques can then be employed to create a spectrum which contains all the information of the incoming atmospheric signal. This heterodyne technique has been pioneered by the Microwave Limb Sounder on board the UARS satellite, launched in 1991. Its successor MLS on board EOS-Aura has been launched July 2004 [6].

The key element of a heterodyne receiver is the mixing element. Up to now, the mixer consists of Schottky diodes. They can be operated both at room temperature (MLS) or cooled down to 100 K, as is done in the Sub Millimeter Radiometer on board the Swedish ODIN satellite [7]. Cooling significantly reduces the noise temperature of the mixer. A major drawback of Schottky mixers is the LO power needed. Especially at the higher frequencies the LO-power requirement excludes the use of solid-state devices and necessitates cumbersome gas lasers.

A huge performance improvement can be gained if the mixer would operating at cryogenic (4 K) temperature. In fact, two such satellite instruments are currently under development: the Japanese JEM/SMILES Earth observing instrument [8], and the HIFI instrument on board the astrophysical Herschel satellite[9]. Both are foreseen to be launched in 2007, and both employ Superconductor-Insulator-Superconductor (SIS) mixer devices.

Extrapolating the current trends towards the future we foresee Earth limb sounding from a 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 spectrometers the most likely candidates are Acousto-Optic Spectrometers or Digital Auto Correlators, in contrast to filter-bank spectrometers.

TELIS instrument description

Anticipating such future space-borne atmospheric-sounding missions DLR, SRON (in collaboration with IREE) and RAL are developing a highly sensitivity, balloon-borne atmospheric sounder that will allow simultaneous measurement of key molecular constituents of the stratosphere. The instrument is called TELIS (TErahertz and submm LImb Sounder) [10] 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 test bed 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 [11]. MIPAS-B will simultaneously measure within the range 680 to 2400 cm^{-1}. The combination of the TELIS and MIPAS instruments will provide an unprecedented wealth of scientific data that will be used to validate other instruments, and to validate atmospheric chemistry models.

TELIS contains three independent receiver channels, selected to yield the maximum science output. The channels are located inside one helium cooled cryostat and operate at 500 GHz, 500 - 650 GHz and at 1.8 THz. The common front end optics consists of a dual offset anamorphic Cassegrain pointing telescope, followed by beam-separating optics. A switch mirror can point the beam towards a warm black-body calibration source. Beam separation is provided by a polarizing beam splitter and a dichoic filter.

Inside the cryostat the three receivers have dedicated cold optics, mixing element and IF amplifiers. Three amplified output IF signals are fed to an IF processor which converts the IF to the input range of the three digital auto correlators of 2 x 2 and 4 GHz bandwidth. Both the IF processor and the autocorrelators have been developed by the Swedish Omnisys company [12].

An on-board microcontroller controls the instrument and interfaces with the ground station.

TELIS receiver channels

The 500 GHz channel is being developed by the RAL and is equal to band E of the MASTER instrument on board the

proposed ACECHEM mission [13]. The frequency covers 499 – 503 GHz where ClO, BrO and N_2O have their emission, together with Ozone that is measured to allow precise retrieval of the minor species.
The highly compact unit consists of a fixed-tuned waveguide SIS mixer, cryogenic solid-state local oscillator (LO) chain and a low-noise IF-chain. Single sideband operation is a prerequisite for this channel and is achieved through use of a miniature cryogenic dichroic filter that provides an image band rejection of >25dB. The high IF of 15 – 19 GHz, needed for the dichroic filter, is a challenge for the IF amplifiers.
The LO chain comprises a phase-locked dielectric-tuned fundamental at 32.3 GHz, up converted by a x3x5 varactor multiplier to ~484 GHz.
The complete receiver channel, including LO chain, is mounted on a base plate and measures 90x95x170 mm^3. Anticipated single-sideband receiver noise temperature is about 600 K.

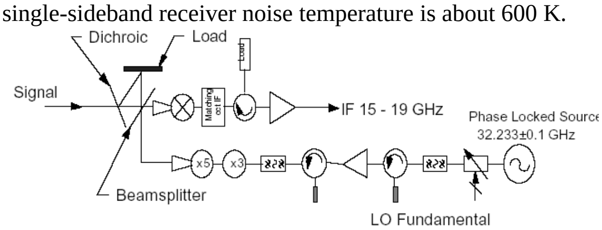

Figure 1: The very compact design of the RAL 500 GHz channel. Only the LO fundamental is placed outside the cryostat.

The 1.8 THz channel is developed by the PI institute DLR and will focus mainly on the OH triplet. The receiver is designed to be tunable over +/- 40 GHz, such to allow the detection of trace gases e.g. HO_2, HOCl, NO, NO_2.
The mixer used is a phonon-cooled NbN Hot Electron Bolometer Mixer (HEBM), developed by DLR, Berlin and MSPU, Moscow. As a second source (??), a similar HEBM device developed by SRON may be mounted.
The LO chain starts with a PLL stabilized synthesizer, multiplied and amplified to ~100 GHz. In the cryo channel, but operating at about 80 K, are x3x3x2 multipliers delivering about 100 nW at 1.8 THz. LO injection is performed by a polarizing diplexer, based on a Martin-Puplett Interferometer (MPI). A similar device is used a single side band (SSB) filter. The IF is 4 – 6 GHz, based on a trade-off between HEBM noise performance and SSB and diplexer bandwidth.
Anticipated single side band receiver noise temperature is about 5000 K. The channel is designed to be upgraded later on to 2.5 THz, where OH has a much stronger emission line. Bottle neck here is the 2.5 THz LO.
The SRON channel targets a breakthrough in receiver development: an integrated receiver with on one single chip the low-noise mixer and its quasi-optical antenna, together with a Flux-Flow Oscillator as an on-chip LO. As the tunability of the FFO ranges from 120 GHz up to 700 GHz, the operational RF bandwidth is basically limited by the antenna/SIS-mixer design, chosen here to be about 500 – 650 GHz. The Superconductive Integrated Receiver (SIR) [14] is developed by IREE, in close collaboration with SRON. Within the RF range many molecules can be detected, but first target species will be ClO and HCl, and possibly CO, HOCl, HNO_3, N_2O. Under study are the isotopomers of water vapor and ozone.
Figure 2 shows the layout of the SIR cold channel. The atmospheric beam enters from the top, and is combined with a frequency-reference beam from a Harmonic Generator. Via a SSB filter the beam is directed to the SIR, housed inside superconducting and anti magnetic shields.

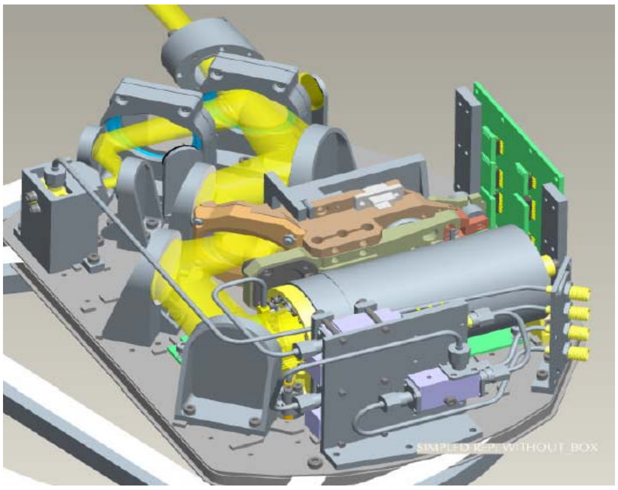

Figure 2: SIR cold channel.

The free running line width of the FFO is typically a few, up to 10 MHz. As this would limit the resolution of the receiver, the FFO is phase locked to a stable reference frequency. Shown in Figure 2 is the option where a 20-22 GHz signal is fed to an off-chip Harmonic generator. Its n^{th} harmonic (n= 24 – 30) is combined with the atmospheric beam to mix with the FFO output. The IF is fed to a PLL system and coupled back to the FFO. It is also possible to integrate on chip a Harmonic Mixer that combines the 20-22 GHz stable reference and the FFO output. This option would significantly reduce the optical design.
The Single side band receiver noise temperature is foreseen to be 500 K.

Conclusions

TELIS is developed for balloon-borne atmospheric research from 2006 onwards. Its three receiver channels at 500 GHz, 500-650 GHz and at 1.8 THz are all very innovative in design, and will act as a test bed for new cryogenic heterodyne detection techniques. Together with the MIPAS-B instrument, TELIS will yield the most complete set of atmospheric species ever measured simultaneously from one platform.

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