Implementation of the Superconducting Integrated Receiver on TELIS

P. Yagoubov[1], S.V. Shitov[2], V.P. Koshelets[2], R. Hoogeveen[1]

[1]National Institute for Space Research (SRON), the Netherlands

[2]Institute of Radio Engineering and Electronics (IREE), Moscow, Russia

Abstract. We present a design concept for a new heterodyne spectrometer that will utilize state-of-the-art superconducting technology: TELIS, TErahertz and submm LImb Sounder. TELIS will be operated on a balloon platform and will measure a variety of important atmospheric constituents within the lower stratosphere. In addition it will provide validation measurements for existing and planned spaceborne instruments and it will be an experimental platform for field testing new sensor technologies. In order to cover the most important atmospheric species three frequency channels have been selected: 500 GHz, 600-650 GHz and 1.8 THz. The 600-650 GHz channel is based on a Superconducting Integrated Receiver (SIR), which is developed in cooperation between IREE and SRON. SIR is the on-chip combination of a low-noise SIS mixer with quasioptical antenna and a superconducting Flux Flow Oscillator (FFO) acting as Local Oscillator (LO). SIR on board of TELIS will be the first implementation of the Superconducting FFO in a practical instrument and an important step in realization of a future full superconducting heterodyne spectrometer.

1. TELIS scientific objectives

A recent ESA study of observational requirements for future atmospheric chemistry missions concluded that improved observations from space of ClO, BrO, OH 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 submillimeter wave limb-sounder with highly sensitive frontends could meet these requirements. Anticipating future space borne atmospheric sounding missions and in support of the 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), it will provide measurement of many atmospheric constituents 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.

2. TELIS design concept

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 [2]. It is a highly compact unit consisting of a fixed-tuned waveguide SIS mixer, solid-state local oscillator (LO) chain and a low-noise intermediate frequency (IF) chain. 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 [3]. 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 [4]. It will utilise a solid-state LO coupled to the mixer via an interferometer (Martin Puplett type). The channel is designed to allow future upgrade to 2.5 THz.

TELIS will have a common optical frontend for all three channels. A dual offset Cassegrain telescope design is used for pointing. Further quasioptical elements allow beam shaping and channel separation: The 500 GHz channel is separated from the two other channels by a polarizer and the remaining channels are separated by a dichroic filter. The three heterodyne receivers are located inside a custom-made 4 K Helium cooled dewar with each channel having a separate optimised vacuum window. The downconverted signals are preamplified and further downconverted in three separate intermediate frequency chains. Digital autocorrelator spectrometers are utilised for spectral analysis. All three channels will be operated simultaneously. From the operational point this requires good coordination in the observation plans. From technical point of view it requires very careful design avoiding both emissions and pick-up of spurious signals.

3. SIR design concept

A key element of the SRON-IREE provided 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 [3]. 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 submm-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 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 [5]. 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.

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.

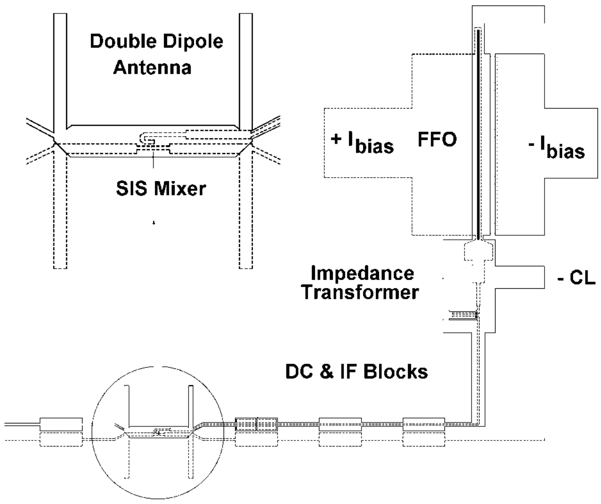

Figure 1. *Schematic of the SIR chip. Planar antenna coupled SIS mixer is pumped by an integrated on the same chip Local Oscillator - Flux Flow Oscillator (FFO).*

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. 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. All receiver components will be mounted on a single 4 K plate. The complete receiver has a size 240x180x80 mm^3.

4. FFO frequency stabilization

SIR channel will detect the atmospheric signal at frequencies between 500 GHz and 650 GHz with a spectral resolution of the order 1 MHz. The immediate consequence of such high spectral resolution is the requirement for high frequency stability of the LO.

Next to that, SIR is using extremely sensitive SIS mixer, therefore the LO must have excellent noise behaviour and highly limited spurious signals.

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 [5]. However, the FFO is a voltage controlled oscillator and its frequency can be stabilized by locking it to an external frequency standard using a Phase Lock Loop (PLL) system [3].

4.1 *Internal Harmonic Mixer option*

In a baseline concept of SIR PLL configuration one more superconducting element is integrated on the SIR chip - Harmonic Mixer (HM). Main consumer of the FFO power at 500-650 GHz is the SIS mixer. A small fraction of the FFO is also directed towards the HM. The latter mixes the FFO with the n-th harmonic of the 22-24 GHz reference standard signal provided by the Local Source Unit (LSU). The mixing product is amplified by a cryogenic low noise amplifier and then downconverted to 400 MHz in a PLL system. Frequency and phase of the mixing product are compared in the PLL system with the reference 400 MHz, which is also provided by the LSU. Finally, the phase difference signal generated by the PLL is used to feedback the FFO bias to compensate for the phase error. The SIR chip, including FFO, SIS mixer and HM are located in the cryostat. The PLL resides right outside the cryostat to minimize the total PLL loop length.

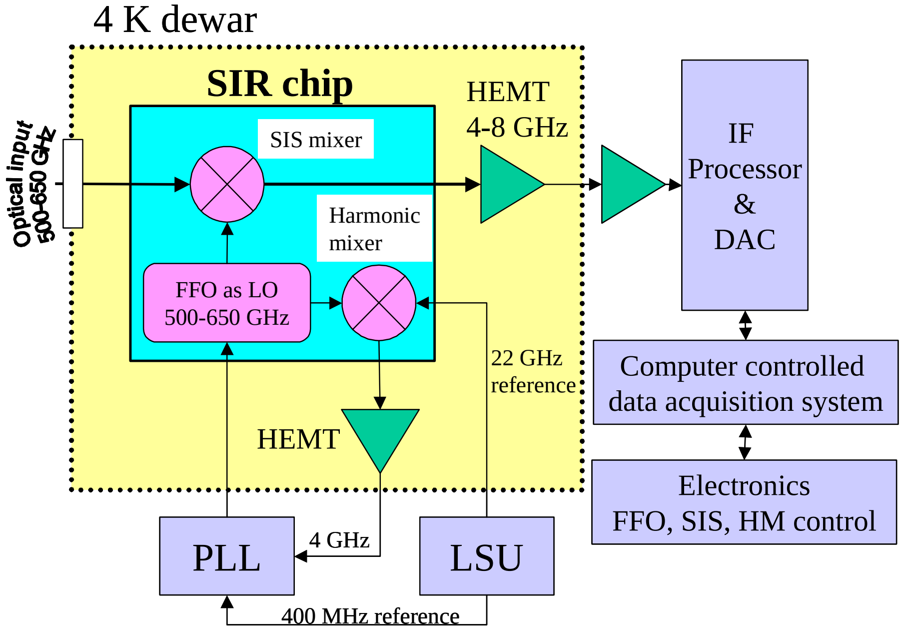

Figure 2. *PLL configuration of the HM option. Planar antenna coupled SIS mixer is pumped by an integrated FFO. A small fraction of the FFO is directed towards the HM. The latter mixes the FFO with the n-th harmonic of the 22-24 GHz reference standard signal. Frequency and phase of the mixing product are compared in the PLL system with the reference 400 MHz. Finally, the phase difference signal generated by the PLL is used to feedback the FFO bias to compensate for the phase error.*

4.2 *External Harmonic Generator option*

Anticipating a certain risk associated with increased complexity of the chip due to integration of an extra element we also envisage in the design a safety option that will utilize an external submm frequency reference – "Harmonic Generator (HG) option". Harmonic Generator is a non-linear device which produces high order submm harmonics of the 22-24 GHz signal of the LSU. Frequency of the LSU is tuned in such a way that there is a harmonic 4 GHz apart from the desired LO frequency of the FFO. This harmonic is quasioptically injected into an SIS mixer sky signal path. It is downconverted by the SIS mixer and amplified in a first stage IF amplifier together with the sky signal. About 90% of the total power is then directed into a "sky signal" chain, and 10% into a "PLL" chain. The PLL signal is further amplified and processed by a PLL system exactly the same way as in the HM option.

5. Conclusion

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 600-650 GHz (SRON-IREE channel) and at 1.8 THz (DLR channel). 600-650 GHz channel will utilize a Superconducting Integrated Receiver, that comprises on one chip a low-noise SIS mixer with quasioptical antenna and a superconducting Flux Flow Oscillator (FFO) acting as LO.

TELIS will provide a unique platform for atmospheric sounding and will also serve as a testbed for new cryogenic heterodyne detection techniques. The instrument is presently in the phase of detailed design and early production. A test flight is foreseen in 2005.

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