

AN AIRBORNE SIS-RECEIVER FOR ATMOSPHERIC MEASUREMENTS AT 625 TO 720 GHz

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Abstract

A heterodyne receiver using a SIS waveguide mixer with integrated horn and single backshort tuner has been built. It has been used for a series of airborne measurements of atmospheric trace gases, like HCl and ClO, above northern Europe during the winter of 1993/94. The receiver is suitable for measurements in the range of 625-720 GHz and shows stable performance in an airplane combined with high sensitivity. The best achieved noise temperature in the laboratory was $T_{DSB}=310$ K at 708 GHz and an all-over single sideband system noise temperature of $T_{SSB}=1500$ K at 625 GHz in the airplane.

Introduction

In a collaboration between the Laboratory for Space Research (SRON, Groningen) and the Institute of Environmental Physics (Bremen) the former submillimeter atmospheric sounder (SUMAS) [1,2,3,4] of the University of Bremen has been significantly improved by the use of a SIS junction as detection element instead of the conventional Schottky diode used before. First test flights of the new ASUR (Airborne Submillimeter SIS Radiometer) experiment onboard the German research aircraft FALCON were successfully performed in December 1993. Later, in February 1994 a flight campaign to northern Scandinavia was undertaken in order to measure atmospheric trace gases like ClO and HCl at the polar vortex. The system shows a significantly reduced overall noise temperature and good stability during flight. Due to this fact the emission lines of ClO and HCl could be measured with high temporal and spatial resolution.

Schottky diodes have been proven to be reliable heterodyne detectors for atmospheric and astronomical receivers over a wide range of frequencies up to several THz. However, Nb-tunnel junctions made out of a sandwich of superconductor-isolator-superconductor (SIS) offer today a significantly better sensitivity and wider bandwidth as non-linear mixing elements at frequencies up to 750 GHz than any other detector [5,6,7]. They were first used at lower frequencies only. Since then, the frequency range of SIS-mixer receivers could be highly increased - up to the superconducting gap frequency of Nb and above. This is due to great improvements in precision mechanical engineering, junction fabrication, and in the development of local oscillators for higher frequencies. This improvement in sensitivity is connected with the small disadvantage of lower operating temperatures (LHe₄) in comparison to Schottky diodes which can be operated at temperatures above 20 K. In this campaign it has been the first time that an airborne receiver with a SIS tunnel junction mixer has been used for atmospheric measurements of trace gases, like HCl and ClO, in the range of 625-720 GHz.

SIS-waveguide mixers are being developed at SRON for space applications like FIRST (far-infrared satellite telescope). Mixers have been made for 350 GHz [8], and in scaled versions [9] for 500 GHz and 750 GHz. A 1000 GHz mixer is under development. These mixers contain an integrated horn and a single backshort tuner and show besides a good beam pattern an excellent performance over the whole frequency band of the waveguide. Direct detection measurements with a Michelson spectrometer of Nb-junctions with integrated tuning elements demonstrate a broadband power incoupling. The bandwidth varies with the type of tuning network and can be as large as 170 GHz at 670 GHz. Heterodyne response has been obtained up to 840 GHz. Y-factor measurements in the laboratory show best double sideband noise temperatures of $T_{\text{DSB}}=310\text{K}$ (250K after correction for the beamsplitter transmission losses) at 708 GHz [10]. Single sideband noise temperatures of the complete receiver system can be as low as $T_{\text{SSB}}<1700\text{K}$ in the range of 625-650 GHz measured during flight.

We will illustrate the sensitivity of our SIS-mixer around the gap-frequency and give an overview about the receiver design and its system performance. We will also show results of trace gas measurements during the flight campaigns.

Experiment description

Nb/Al₂O₃/Nb-tunnel junctions at SRON have an area of about 1 μm^2 and are fabricated with a Selective Niobium Over-Etch Process (SNOEP) [11]. Embedded in a matching and transforming network out of superconducting microstrips the junction impedance can be matched to the waveguide impedance at a broad range of frequencies. The mixer described here consists of a full-height wave guide measuring

300x150 μm^2 , with a single backshort and an integrated diagonal horn. The quartzchip with the junction lies across the waveguide and contains on-chip low-pass filter sections that prevent signal currents from leaking into the substrate channel.

We have successfully designed and fabricated several kinds of integrated tuning structures for different frequency regimes and bandwidths using SIS tunnel junctions as detectors. We studied the frequency response of waveguide mixers by means of a Fourier transform spectrometer (FTS) of the Michelson type. Video response could be obtained up to 750 GHz and quasiparticle heterodyne response was measured up to 850 GHz.

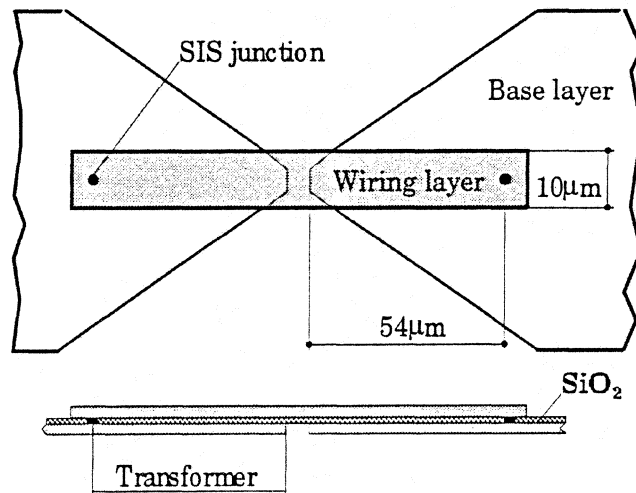


Fig. 1: Quartz chip with SIS-junction, tuning network and low-pass filter

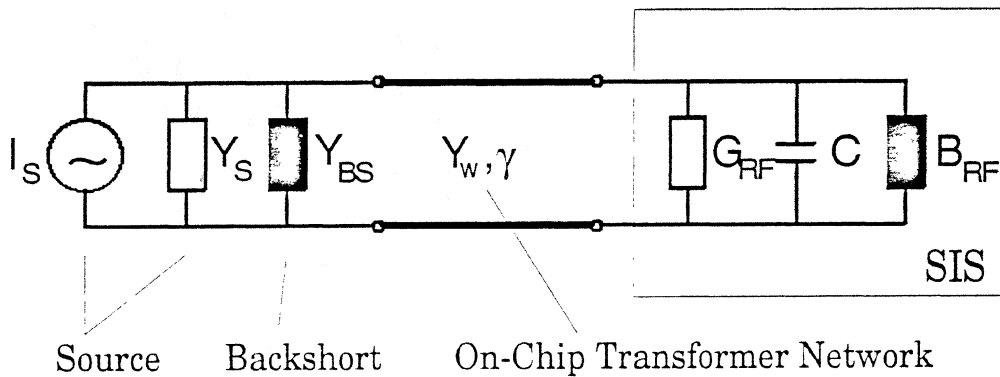


Fig. 2: Equivalent RF-circuit of the junction and environment.

Spectrometer measurements and tests in heterodyne experiments of various designs show that one-step transformers are most suitable for our purposes. This simple design, shown in Fig. 1, offers not only a broadband power incoupling to the junction but also a high sensitivity. It has been shown that transformer designs are most appropriate also for other detectors and environments. Two-step transformers offer up to 30% bandwidth in antenna-coupled designs. Complete on-chip filter structures with bandpass characteristics, e.g. Chebyshev filters, made out of superconducting striplines are possible [13].

Fig. 2 shows a simple equivalent electronic RF-circuit of a SIS junction and its surrounding waveguide. The junction is represented by the geometrical capacitance C , the non-linear admittance G_{RF} , and the susceptance B_{RF} . The latter are caused by internal quantum effects. The transformer network is represented by a lossy microstrip line with the characteristic admittance Y_w and wavenumber γ . The superconducting microstrip designs were calculated by means of the Mattis-Bardeen theory [12]. The admittance of the waveguide is assumed to be real and the influence of the backshort purely imaginary. Two FTS spectra show (Fig. 3) the video response due to the coupling of the SIS junction to an integrated tuning network. In both cases single-step transformers, $10\ \mu\text{m}$ wide and $54\ \mu\text{m}$ long, are used for coupling to the waveguide. The single element B6 shows a broad 3dB-bandwidth of about 125 GHz and sample B3 with two junctions in series with 90 GHz a somewhat smaller bandwidth. Both samples have the same resonance frequency of about 640 GHz.

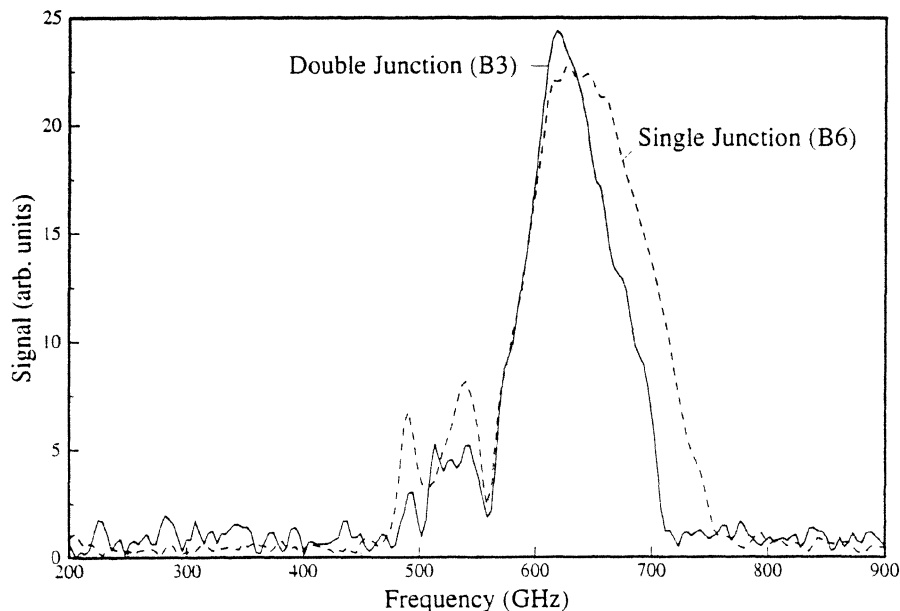


Fig. 3: FTS response of single junction B6 and double junction B3.

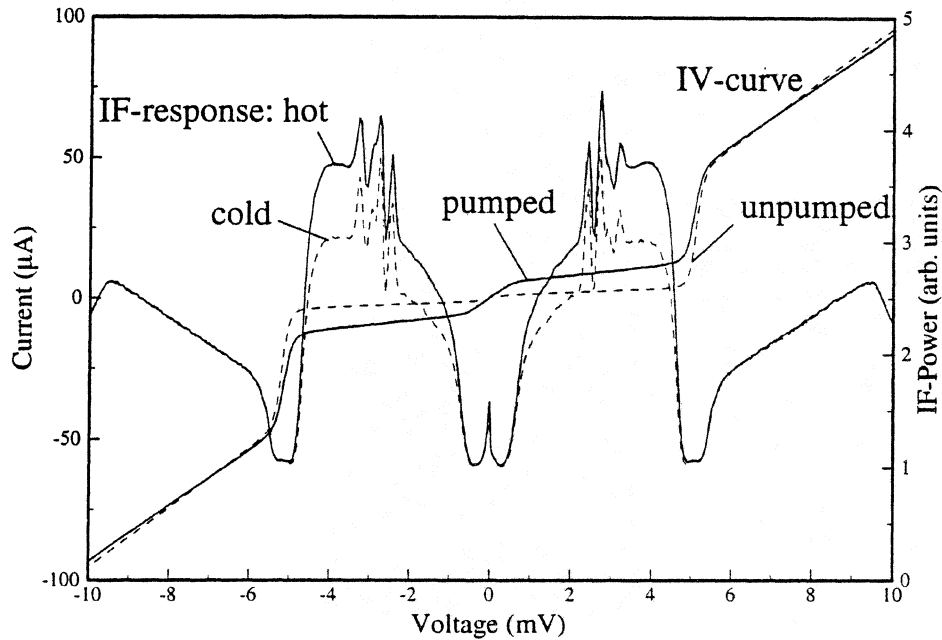


Fig. 4: Pumped and unpumped IV-curve of sample B3 with hot (300K) and cold (80K) IF-response at 680 GHz.

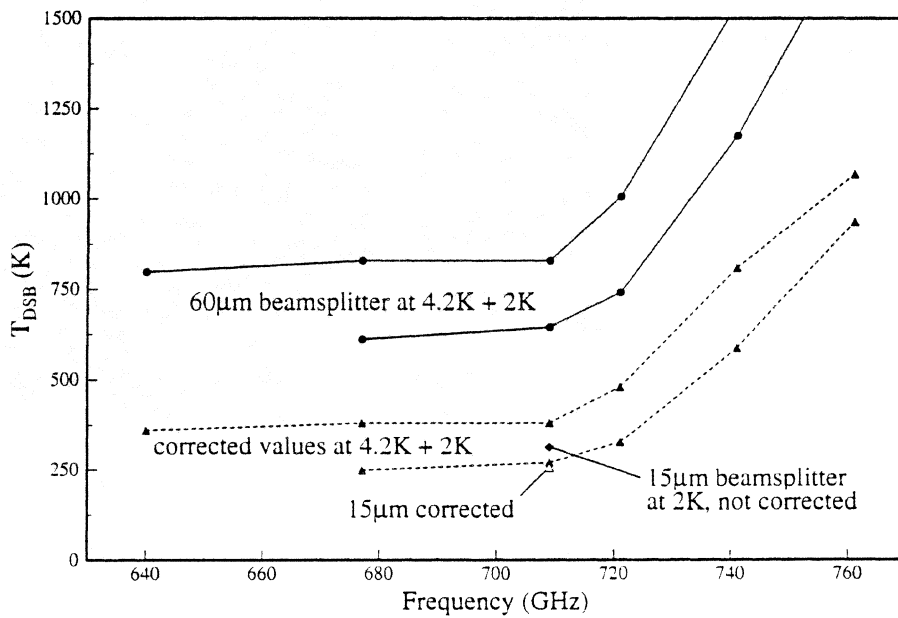


Fig. 5: Double sideband noise temperature T_{DSB} of sample B3 for different operating temperatures and frequencies from 640-750 GHz. The corrected values for T_{DSB} are also shown if the beamsplitter losses are taken into account.

Laboratory heterodyne tests showed a slightly better performance of the sample B3. Therefore sample B3 was used during all further laboratory tests and flight experiments. Fig. 4 shows its DCIV-curves, unpumped and pumped by the local oscillator at 680 GHz, together with the IF heterodyne response arising from a hot (300K) and cold (80K) load. The IF response shows also some remaining structures of the Josephson effect that could not be suppressed completely by the applied magnetic field.

Fig. 5 shows the laboratory heterodyne performance characterized by the double-sideband noise temperature T_{DSB} for different operating temperatures and frequencies from about 640 GHz up to 750 GHz. The two upper curves show measurements with a mylar beamsplitter of 60 μm thickness at 4.2 and 2 K He bath temperature. Curves that are corrected for the losses of the beamsplitter are shown below. To verify these corrections a measurement with a 15 μm thin beamsplitter was investigated. This measurement yields $T_{\text{DSB}}=310$ K at 708 GHz at 2 K physical temperature and is the lowest value above the gap frequency reported. The corrected value of this measurement is 250 K and lies within 5 K of that of the measurement with the 60 μm thick beamsplitter. Due to the lack of oscillator power more measurements with the 15 μm beamsplitter at other frequencies could not be performed. The tuned heterodyne bandwidth is rather wide (630-720 GHz), but could not be completely measured for the same reason.

Quasi-optics

The atmospheric signal was entering the airplane through a wedge-edged window especially designed for that frequency range to avoid standing wave problems. A rotating mirror was pointing in an alternating cycle to the window and to calibration loads at 300 and 80 K. A corner-cube wavelength modulator was used to eliminate the remaining standing wave problems. Two Martin-Puplett type interferometers were used as a single sideband filter (SSB) and as a diplexer in order to combine the atmospheric and the LO signal. A combination of an elliptical mirror and a cooled high-density polyethylene (HDP) lens in front of the mixer determined the optical system. The complete optical system was calculated with Gaussian beam optics to minimise losses in the optical system. The beam radius along the optical path was always smaller than 12.5 mm, since the aperture diameter of most optical components was 50 mm. The asymptotic angle of growth of the receiver beam radius is 0.7° .

The LO power requirement of a SIS junction is much smaller than that of a Schottky diode and the LO emits far more power than necessary for a SIS junction. We implemented therefore in the LO path a polarising wiregrid that can be rotated to attenuate the signal. The location of the grid in the LO path is just before the signal path entry. Fig. 6 shows a schematic layout of the optics.

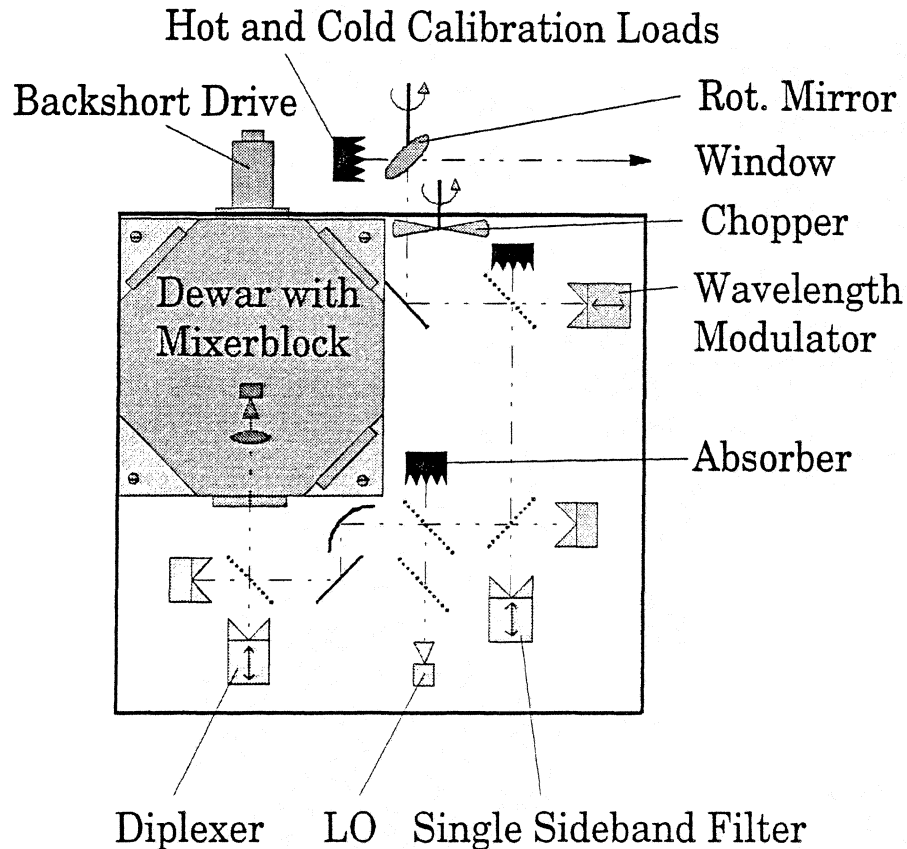


Fig. 6: Schematic layout of the quasi-optics.

Detector and IF-system

The electrical layout of the receiver system is shown in Fig. 7. Two solid state oscillators from Radiometer Physics served for the different frequency bands as local oscillator (1. LO) and were exchanged in various flights. One operated at 637-639 GHz to serve the lower frequency bands while the other radiated at 675 GHz for the higher frequency bands. The IF frequency was chosen to be 11.08 GHz, to cover with both sidebands interesting molecular lines. Switching between measurements of those lines can be done by adapting the single sideband filter (SSB).

The junction IF output was coupled over a commercial bias tee and an isolator directly to the first IF amplifier. As a first stage served a low-noise HEMT amplifier from Berkshire Technologies that was mounted inside the dewar at the 4K stage. The noise temperature of this amplifier is below 15 K for the

whole frequency band, from 10-12 GHz. The IF signal was amplified one more time and filtered before it was mixed down to 3.7 GHz by means of a second mixer.

The IF output towards the backend is centred at $f_{IF}=3.7$ GHz with a bandwidth of 1200 MHz. The power level varies between 0 and 10 dBm. The backend consists of an acousto-optical spectrometer (AOS), two filterbanks and a UNIX system for the data retrieval. The power is distributed via directional couplers to the different spectrometers and two sensors that register the power level. One fast detector, a RF Schottky diode, is used for bias sweeps made visible on an oscilloscope to optimise the SIS mixer. The slower sensor is a HP power meter whose measurements are taken permanently as housekeeping data by the computer system.

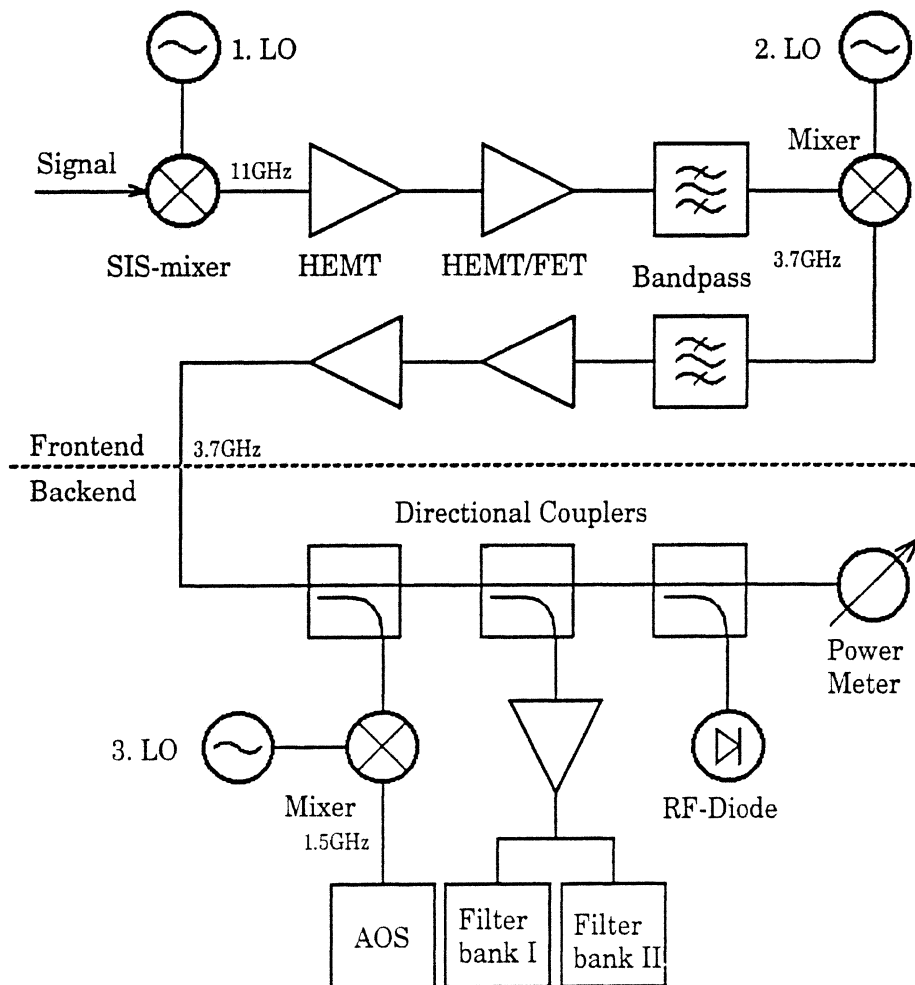


Fig. 7: IF-system

The resolution and the bandwidth of the AOS are described later in the chapter about the system performance. One of the filterbanks has been on loan from the Max-Planck-Institute for Aeronomy in Lindau/Katlenburg. The filterbanks have a central frequency of 3.7 GHz with 28 channels. The 8 channels in the centre have a bandwidth of 8 MHz each. On both sides of the centre are 4 channels with 40 MHz and 5 channels with 80 MHz bandwidth, respectively. This is done to cover a large bandwidth with a small number of channels, while simultaneously obtaining a high resolution in the centre.

The UNIX system is used to control important parts, e.g. the rotating mirror, of the experiment and to retrieve the data. It stores the data on tape together with housekeeping data from various sensors and gives an on-line quick-look of the obtained data and spectra.

Measurement campaign

The receiver system was built into a Falcon aircraft operated by the German space agency DLR in Oberpfaffenhofen. During the winter 1993/94 a total of 8 observation flights were made, five solely in an observation campaign to Kiruna in northern Sweden and above the polar sea. The flight campaign to Kiruna covered the time from February 7th to 18th, 1994. The typical flight time was about 2.5-3 h and covered a distance of about 2000 km. Measurements of 4 molecules were made at 6 different frequencies ranging from 625-686 GHz as listed in Table 1.

The flights were coordinated for comparison of the data with other experiments, like the balloon borne Submillimeter Limb Sounder (SLS) of the Jet Propulsion Laboratory, the MLS experiment on-board the UARS satellite² and a German research aircraft (Transall), which contained several instruments for trace gas measurements (O₃, ClONO₂, HNO₃, ...).

System Performance

During all flights the receiver frontend and the filterbank system showed an excellent performance. Only the acousto-optical spectrometer was not operational during the first flights due to electronic problems. However, the complete measurement program could be successfully completed as planned.

The overall system noise temperature (single sideband) were measured continuously by a powermeter during the flights and stored by the computer system on tape. These data compare well with the noise temperatures obtained from single channels of the AOS and the filterbanks. During a typical flight usually several molecules were measured. Switching from the upper into the lower sideband was done by tuning the SSB filter. The observation of ClO and HCl in one flight was of greatest interest and made it

² Microwave Limb Sounder on-board the Upper Atmospheric Research Satellite

also necessary to tune the LO to a new frequency. In either case optimisation of SIS bias voltage, back-short and diplexer position, and LO power level was necessary. In general, tuning to a new frequency band needed about 5-10 min.

The noise temperatures achieved for each molecule are shown in Table 1. Since the receiver has had to be tuned in a relatively short time the listed numbers may not represent the lowest reachable noise temperatures. The system noise temperature increased, as expected, towards higher frequencies. The over-all single sideband noise temperatures T_{SSB} given in Tab. 1 are somewhat higher than the laboratory measurements in Fig. 5. To compare both measurements the double sideband noise temperatures T_{DSB} have to be doubled and 300 K added for the warm sideband termination. Because the laboratory measurements have been performed using a simple set-up the residual differences can be explained by losses due to polarisation selection and in the optical system.

The AOS covers about 880 MHz containing 2000 channels with an effective resolution of 1.4 MHz. Fig. 8 shows the system noise temperature over the AOS bandwidth. For data analysis the bandwidth is restricted to 620 MHz where the noise temperature is relatively constant. In Fig. 8 four channels at a time are added to one data point to increase the signal to noise ratio. This results in an effective resolution of 2.8 MHz. The outer channels are not taken into account, because of their higher noise level.

Molecule	Frequency [GHz]	T_{sys} [K]
HCl	625.913±0.6	1.500
N ₂ O	627.286±0.6	1.500
O ₃	648.073±0.6	1.900
ClO	649.448±0.6	1.700
O ₃	664.300±0.6	1.950
ClO	686.460±0.6	2.300

Table 1: Mean system noise temperature (single sideband) for different molecules over the measured frequency band

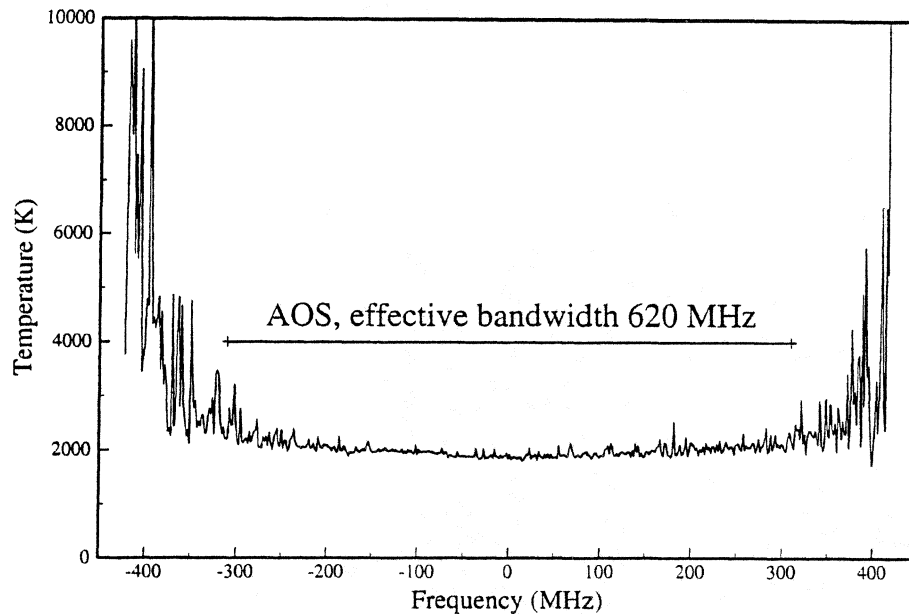


Fig. 8: System noise temperature over the AOS bandwidth. For data analysis the outer channels are not taken into account, because of the higher noise level there.

Measurements

To obtain the submillimeter emission spectra the raw data were calibrated with the measurements of the hot and cold calibration load. They were corrected for the window transmission and integrated to obtain sufficiently low signal to noise ratio. Only spectra above 30,000 feet with a roll angle lower than three degrees and a stable power level were used. Fig. 9 shows as an example the spectrum of HCl with an integration time of 630 sec together with a calculated spectrum at 625 GHz. Differences in the power levels of the measured and calculated spectra are due to different water vapour levels. The spectrum of ClO at 649 GHz was integrated during 562 sec and exhibits an amplitude of ~ 1.5 K (Fig. 10). There is also some indication for an additional, weak $^{18}\text{O}_3$ line in the vicinity of ClO.

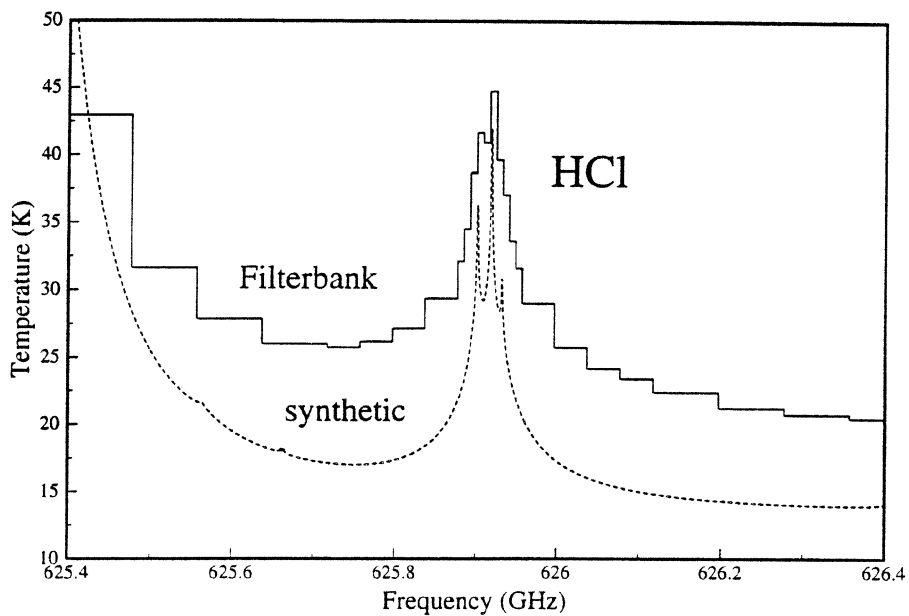


Fig. 9: Synthetic and measured spectra of HCl at $f=625.9168$ GHz measured on February 15, 1994. The integration time is 630 sec and the rms error 0.07 K.

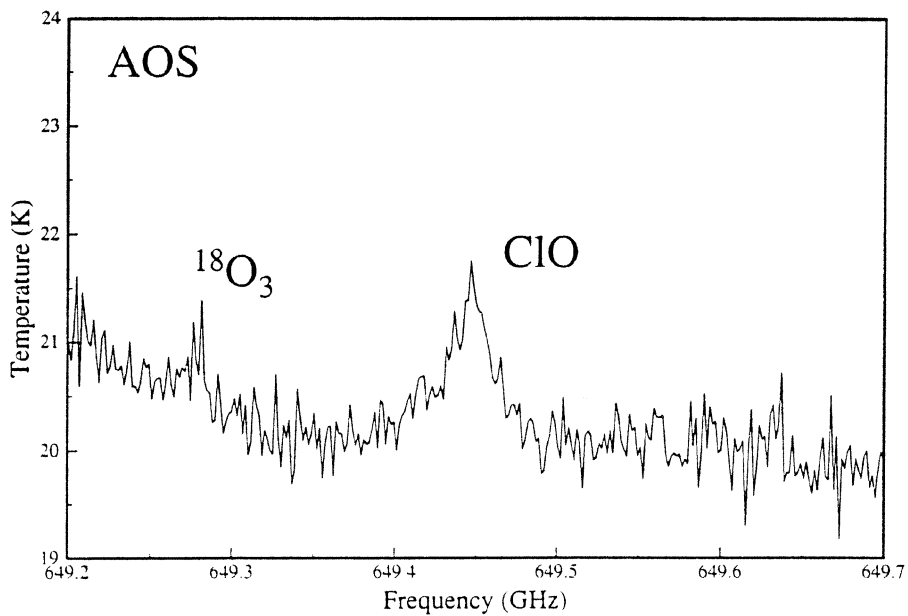


Fig. 10: AOS spectrum of ClO at $f=649.448$ GHz measured on February 15, 1994. The integration time is 562 sec and the rms error 0.1 K.

Conclusions

The application of a SIS tunnel junction mixer in airborne measurements in the frequency range from 625 to 720 GHz has been successfully demonstrated. The sensitivity compared to the former Schottky detector is about three times higher. The broadband response is due to the use of an integrated tuning network with a single-step microstrip transformer. During a series of eight flights in winter 1993/94 measurements of four different molecules at six different frequency bands could be performed with high spectral and spatial resolution. The lowest noise temperatures so far achieved are about $T_{\text{DSB}}=310$ K at 708 GHz in the laboratory and $T_{\text{SSB}}=1500$ K at 625 GHz for the complete receiver system in the airplane. This successful campaign has shown that airborne measurements using an appropriate extremely low-noise receiver is a convenient technique for fast and accurate investigation of trace gases in situations of disturbed atmospheric chemistry.

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Emission spectrum of HCl at 625.917 GHz

ASUR campaign Feb. 1994, 630 sec. integration time

