A Dual-Frequency 183/380 GHz Receiver for Airborne Applications

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Abstract—**A complete dual-frequency cryogenic heterodyne receiver operating at 183 and 380 GHz is described. The cooled mixers are whisker-contacted GaAs Schottky diodes mounted in reduced height fundamental-mode waveguide. The local oscillators are Gunn-oscillator-driven multipliers using GaAs varactor diodes as the harmonic generators. Quasi-optical techniques are used extensively for coupling the remote and local oscillator signals into the mixers. The overall system temperature is 320 K DSB for the 183 GHz receiver and 650 K for the 380 GHz receiver.**

I. Introduction

A CRYOGENICALLY COOLED dual-frequency heterodyne radiometer that allows simultaneous observations near 183 and 380 GHz has been developed for use aboard the Kuiper Airborne Observatory (KAO) [1]. The radiometer is used for spectral line studies of astrophysical sources and the earth's atmosphere [2]–[4]. In its present configuration the instrument has been used to observe the $3_{13} \rightarrow 2_{20}$ and $4_{14} \rightarrow 3_{21}$ transitions of water vapor at 183.3 and 380.2 GHz in several interstellar clouds, in Halley's comet, and on Venus. The mixing elements are whisker-contacted GaAs Schottky diodes mounted in waveguide structures. The local oscillator (LO) sources are multipliers driven by Gunn oscillators. The instrument is designed for optimum noise performance (320 K DSB at 183 GHz and 650 K DSB at 380 GHz) and features Dicke stabilization, low-loss folded Fabry–Perot LO diplexers, and dielectric phase wobblers for baseline ripple reduction in both channels.

Cooled GaAs Schottky diode based waveguide receivers have been used extensively in ground-based radio-astronomy observatories. The frequencies of these receivers have been selected for the rotational transitions of CO, some of the strongest interstellar lines, at 115, 230, and 345 GHz. At 115 GHz these receivers have system temperatures as low as 80 K DSB [5]. At 230 GHz typical performance for laboratory-based cooled GaAs receivers is 200 K DSB [6], [7]. The receivers at 345 GHz have system temperatures of about 500 K DSB [8], [9]. At higher frequencies the atmosphere becomes too opaque for ground-based observations except in a few discrete frequency windows. Furthermore, waveguide structures become much harder to fabricate, so very few single-ended fundamental waveguide receivers have been constructed. A room-temperature harmonically pumped waveguide mixer at 550 GHz has been reported to have a 3000 K DSB noise temperature [10]. Mixers mounted in corner cubes have been reported at much higher frequencies with significantly higher noise temperatures. Precursors of this dual-frequency cooled airborne instrument have been reported by Gustincic [11], Kerr [12], and Batelaan [13]. A similar receiver operating at 205 GHz has been qualified for operation on the Upper Atmospheric Research Satellite [14].

This paper will describe the instrument system, with a detailed discussion of the quasi-optics, the cooled front end, and the spectrometer subsystem. There will also be a discussion of instrument performance.

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II. System Description

Fig. 1 shows functionally the major portions of the system, which consist of the calibration subsystem, the input and LO optics, the cryogenic mixers, the LO sources and associated phase lock circuitry, the intermediate frequency (IF) subsystem, and the spectrometer subsystem.

This instrument is designed to be flown on the Kuiper Airborne Observatory. RF signals from the radio source are collected by the KAO 91-cm-diameter Nasmyth telescope and focused at f/d 17.3 into the radiometer. On entering the radiometer, the incoming RF beam first passes the calibration subystem, consisting of a chopper wheel and ambient and liquid-nitrogen-cooled loads. Then it is separated into vertical and horizontal polarization components. The vertical component is used for 183 GHz while the horizontal polarization component is used for 380 GHz. Each signal beam is combined with the beam from the appropriate LO source. Then the combined signal and LO beams are fed to the corresponding cryogenic mixer. The output IF of each mixer, centered at 1390 MHz, is amplified 27 dB in a cryogenic FET amplifier, further amplified by room-temperature amplifiers about 80 dB,

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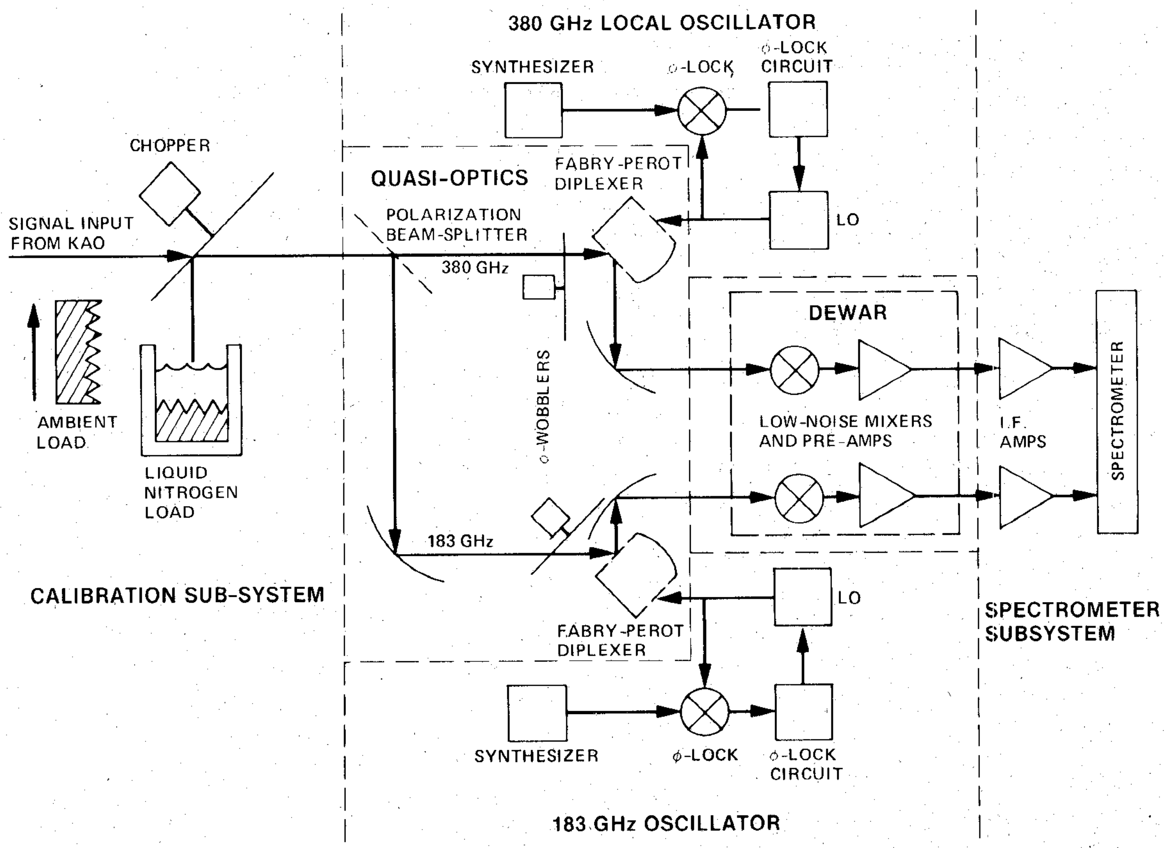

Fig. 1. A functional block diagram showing the major radiometer subsystems.

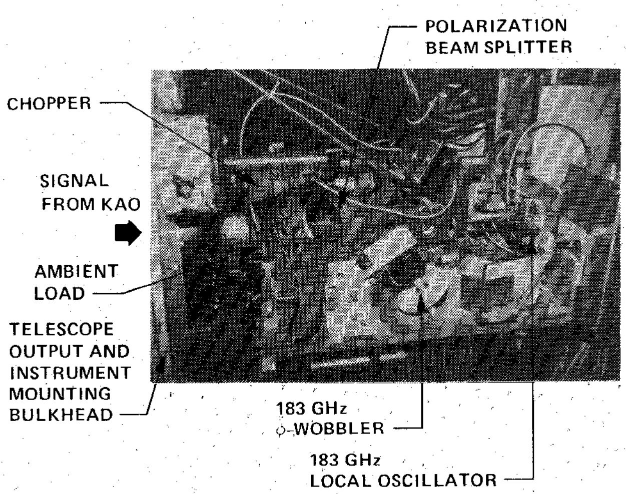

Fig. 2. The radiometer front end mounted on the KAO telescope.

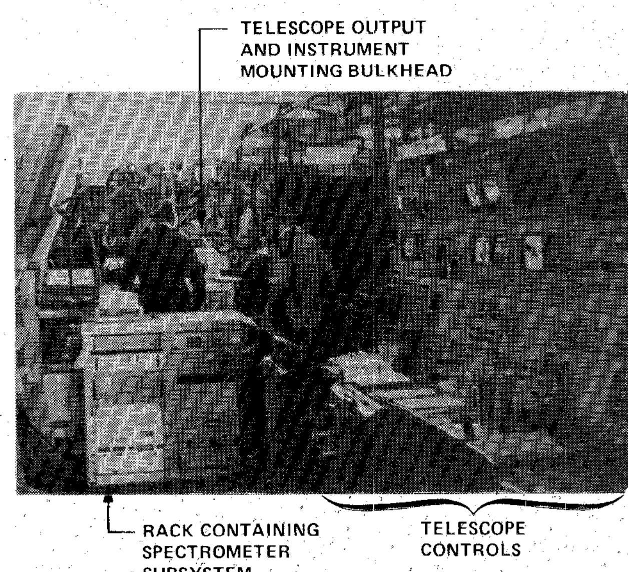

Fig. 3. An operational scene aboard the KAO.

and then distributed to the various inputs of the spectrometer subsystem. Fig. 2 is a photograph of the front end mounted on the KAO telescope while Fig. 3 shows a typical operational scene aboard the KAO.

III. The Front End

For the water vapor transitions the instrument is tuned to 183.3 GHz and 380.2 GHz. Each IF is centered at 1390 MHz with 300 MHz bandwidth. Each LO chain is tunable over an adequate range to allow operation at either upper or lower sideband and to correct for the maximum Doppler shift of about ± 100 km s^{-1}.

Each mixer is a single-ended fundamental waveguide mount using a whisker-contacted GaAs Schottky diode as the nonlinear element, as shown in Fig. 4. The diode is mounted in quarter-height waveguide to improve impedance matching. A sliding, contacting backshort made of gold-plated phosphor bronze shim stock is located behind

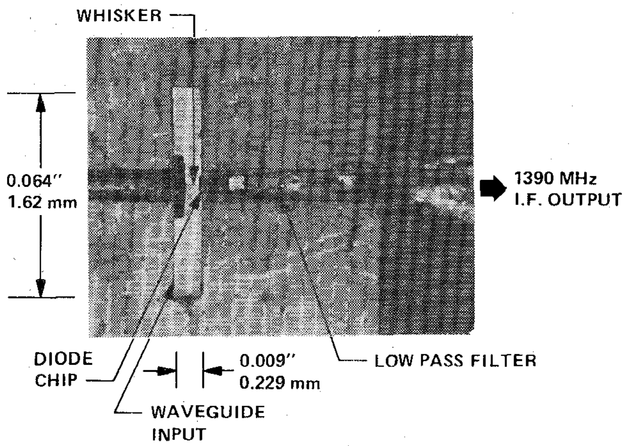

Fig. 4. A photomicrograph of the 183 GHz mixer looking into the waveguide.

the diode to optimize coupling of the signal into the diode. The feedhorns for the cooled mixers are smooth wall dual-mode Potter horns, as modified by Pickett [15], of 6.4-wavelength aperture diameter. Each feedhorn consists of a conical flared section connected via a step into circular waveguide followed by a smoothly tapered, 5-wavelength-long transition to reduced-height rectangular waveguide. While patterns of these specific horns have not been taken, there is adequate testing and history of scaled horns of this design to claim that horn beam efficiency is 90 percent at 14° half angle, and the pattern is Gaussian down to the 10 dB level. At these high frequencies, losses in waveguide can be substantial; therefore, each feedhorn is mounted directly to its mixer block without any additional waveguide, allowing the diode to be located only about 5 wavelengths further along the reduced-height rectangular waveguide. The signal traverses at most 10 wavelengths in waveguide, minimizing losses.

The GaAs Schottky diodes were fabricated by Prof. R. Mattauch (University of Virginia) and are designated 1H-30. The anodes are 1 μm in diameter with a zero bias capacitance of 1.8 fF and a room-temperature series resistance of 16 Ω. These diodes show at least a factor of 2 sharpening of the steps in their $I-V$ curves, as measured by the change in voltage for a current change from 10 μA to 100 μA, when cooled from room temperature to 15 K. Similarly, a factor of 2 to 3 decrease occurs in the mixer noise by cooling. The diodes are contacted by gold-coated phosphor bronze whiskers that have been etched to a submicron diameter point. The spring constant of a wire varies as its radius to the fourth power, so thin whiskers, being less stiff than thick wires, will form a contact to the diode more tolerant to thermal cycling. The whisker for the 183 GHz mixer has a 6 μm diameter and is about 120 μm long. The whisker for the 380 GHz mixer is about 75 μm long with a 4 μm diameter.

The IF is coupled out of the mixer by an RF microstrip choke structure formed on 3-mil-thick quartz substrate located in an 8×8 mil channel. Each RF choke is a low impedance–high impedance filter in which the diode forms the first capacitive element. The choke sections are about 1 mm and 0.85 mm long for the 183 and 380 GHz mixers, respectively. The IF impedance at the output of the RF choke was measured to be between 200 and 250 Ω over the 300-MHz-wide IF band centered at 1390 MHz. To facilitate matching the IF output of the mixers to the FET amplifiers, coaxial lines are provided with movable Macor "slugs," which are accessible through longitudinal slots in the outer conductors. A $VSWR$ of less than 1.5 and 1.3 was achieved for the 183 and 380 GHz mixers, respectively. Each mixer is followed by a two-stage cooled GaAs FET low-noise amplifier. These amplifiers are broad-band, operating from 1.1 to 1.6 GHz, with about 27 dB gain and 10 K noise temperature at the physical temperature of 13 K.

The cryogenic mixers and IF amplifiers are mounted on the second stage of a CTI-Cryogenics model 350 closed-cycle helium refrigerator within a $15 \times 15 \times 37$ cm rectangular dewar and are cooled to approximately 13 K. A 21 layer thermal "space blanket" surrounds the cooled components to minimize the radiative thermal load on the cold stage. The dewar has Teflon windows of 5/2 wavelength (4.10 mm) and 7/2 wavelength (2.76 mm) thickness for the 183 and 380 GHz beams, respectively. The thicknesses were chosen to minimize reflection loss while providing adequate mechanical stability and strength. The dewar housing was designed to allow for its removal from the refrigeration structure for access to the internal parts without disturbing the remainder of the system. The mixer backshort adjustments are via stainless steel shafts passing through vacuum feedthroughs. For minimum heat transfer during system operation, the feedthrough shafts are pulled away from the mixers except when necessary to tune the backshorts. To allow proper engagement of the mixer backshorts with the feedthrough shafts for tuning, visual windows are provided in the sides of the dewar. Mixer bias is supplied through flexible coax while the IF output of the FET amplifiers is by RG-141 semirigid stainless steel coax which is thermally sinked to the 77 K refrigerator first stage at midpoint. These lines pass through the dewar wall via hermetic SMA connectors. A multipin hermetic connector passes the required dc power and temperature sensor connections into the dewar.

The LO for the 183 GHz channel is generated by a times-three multiplication of a Gunn oscillator operating at about 60.6 GHz. The Gunn oscillator is a GaAs type made by Central Microwave with 60 mW output power. The output power is set with a waveguide attenuator and applied to the Millitech manufactured tripler to get an LO power of 1 mW (1.7 percent efficiency) at 181.9 GHz. Similarly, the LO for the 380 GHz channel is generated by a times-four multiplication of a Gunn oscillator operating at about 95 GHz. This Gunn oscillator is an InP type with 40 mW output power on a common mount with the frequency quadrupler. Power output is 400 μW, for an efficiency of 1.0 percent. This assembly is also from Millitech. The Gunn oscillator can be changed in the field to accommodate large frequency changes required for various observational programs. A previous version of this instrument used a phase-locked carcinotron as the LO for the 380 GHz channel. The system temperature of the present 380 GHz radiometer is about 50 percent lower when using the solid-state source than when using the carcinotron as the LO source.

Since the instrument is a spectrometer, it is necessary to stabilize its frequency, in this case to 2 parts in 10^8. A small amount of LO power is coupled from the fundamental output of each Gunn oscillator and routed to a harmonic mixer. Signals from separate frequency synthesizers are multiplied to about 10 GHz in commercial phase locked oscillators, and these signals are then applied to the appropriate harmonic mixers. A harmonic of each 10 GHz signal, the 18th harmonic for the 183 GHz channel and the 38th harmonic for the 380 GHz channel, mixes with the LO sample and produces an IF of 50 MHz. Each 50 MHz output is amplified, limited, and compared to a 50 MHz crystal source in an ECL phase lock circuit to generate an error signal. Signal-to-noise ratio is greater than 40 dB and loop filters were chosen to match the modulation sensitivity of each LO for a minimum sideband level over a lock frequency from 25 MHz to 100 MHz at the phase detector. The 380 GHz LO used a 150 kHz loop bandwidth, for a modulation sensitivity of 500 MHz/V, giving sidebands at the −30 dBc level. The 183 GHz LO was designed for a 30 kHz loop bandwidth, with a modulation sensitivity of 300 MHz/V, giving sidebands at the −20 dBc level. Each resulting error signal is then applied to the appropriate Gunn oscillator bias voltage to correct the frequency. Each synthesizer can be reset as the appropriate LO is tuned through the moderate frequency changes required by the Doppler shifts of the sources observed.

IV. Quasi-Optics Description

The RF quasi-optics of the receiver, Figs. 5 and 6, accomplish several functions. They

1) match the KAO telescope to the cooled mixers,
2) separate the 183 GHz and 380 GHz beams,
3) match and combine the LO signals with each RF beam, and
4) reduce baseline effects caused by telescope–radiometer interactions to an acceptable level.

With the telescope adjusted for an f/d of 17.3, its nominal design value, the collinear 183 and 380 GHz RF beams from the KAO telescope have $1/e$ amplitude beamwaist radii of 22.9 mm and 11.5 mm at 200 mm and 447 mm aft of the mounting bulkhead respectively, while the visible wavelength focus is at 530 mm. The mounting bulkhead contains a pressure window which is made of 20-mil-thick high-density polyethylene. This thickness closely approximates an integral number of half wavelengths at both frequencies to minimize reflection losses.

At a point near the beamwaists, the beam is separated into horizontal and vertical polarization components by a polarization beam splitter consisting of a grating of tungsten grid wires of 10 μm diameter suspended with 100 μm spacing. Because a 3 dB polarization loss of a randomly

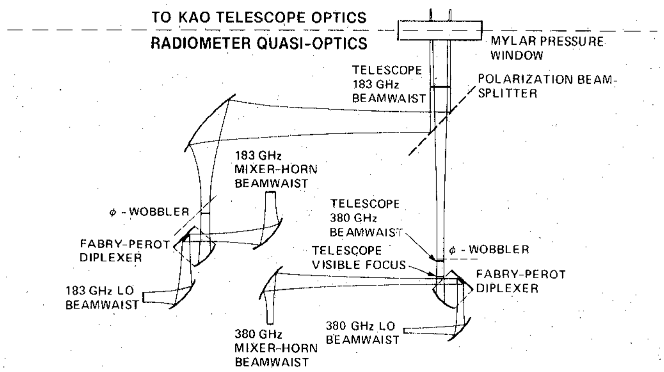

Fig. 5. A schematic depiction of the radiometer quasi-optics. The signal flow is described in the text.

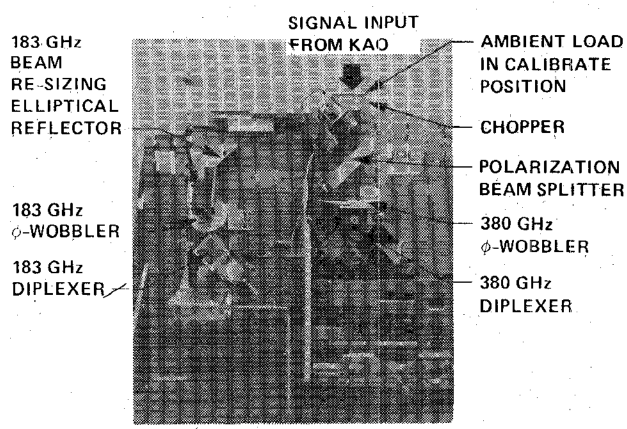

Fig. 6. This laboratory photograph of the radiometer front end shows the quasi-optics layout.

polarized signal by a linear feedhorn is intrinsic, the polarization beam splitter is an ideal means of diplexing two randomly polarized signals for subsequent reception by two orthogonally arranged, linearly polarized feedhorns. No additional losses are incurred except ohmic losses in the wire structure. The measured loss for the transmitted horizontal polarization is less than 0.3 dB at 380 GHz.

After passing through the polarization beam splitter, the 380 GHz RF signal is combined with the LO power in a Fabry–Perot ring resonant structure (16) and then matched to the required 1.54 mm beamwaist of the feedhorn mixer by an off-axis elliptical reflector. The 380 GHz signal channel contains only this single beam resizing reflector to match the KAO output to the mixer feedhorn since the beamwaist size from the KAO telescope was suitable to directly match the beam size requirement of the Fabry–Perot diplexer.

In contrast, the 183 GHz signal channel beam after reflection from the polarization beamsplitter is first resized by an off-axis elliptical reflector to fit its diplexer. The combined 183 GHz signal and LO beam from the Fabry–Perot diplexer are then matched to the required 3.19 mm beamwaist of the feedhorn mixer by a second elliptical reflector. Off-axis elliptical reflectors are also used to match each LO beam from its source feedhorn to its respective Fabry–Perot diplexer. The mirrors used in the quasi-optical beam routing are sections of ellipsoids designed with the foci at the center of the radius of curvature of each applicable wavefront. Each mirror is machined with a numerically controlled lathe to about one hundredth wavelength and hand polished to allow alignment verification using a helium–neon laser. All instrument feedhorns are smooth-wall dual-mode Potter horns, described above.

The Fabry–Perot ring resonant diplexer was chosen for its good LO noise rejection and broad signal reflection band [16]. These units were originally designed for a 1 GHz IF with a free spectral range of 2 GHz but worked just as well at 1.39 GHz IF. Due to the original 1 GHz IF, the physical length and width were fixed at 53.04 mm. The KAO telescope 380 GHz 11.00 mm beamwaist fits directly into this size cavity with a Rayleigh length of 482 mm. This dictated the horizontal and vertical radii of curvature of the toroidal surface to be 4470 mm and 2235 mm.

The 183 GHz diplexer has the same 53.04 mm length and width. The KAO telescope 183 GHz 22.8 mm beamwaist is resized, as mentioned previously, to 3.6 mm. This yields a Rayleigh length of 24.83 mm and radii of curvature of the toroidal surface of 117.28 mm and 58.64 mm. The mesh grid densities chosen were determined experimentally, trading off between LO transmission loss and noise filtering: finer meshes have better LO noise filtering (higher finesse or Q) but higher LO transmission loss.

In observing spectra with the KAO telescope, a significant, almost sinusoidal amplitude response as a function of frequency is observed. The periodicity of this "baseline ripple" is related to the feedhorn-to-subreflector distance. The amplitude of this signature is several times the data signal level for observations of this type, so its suppression was of paramount concern in this instrument. The method chosen was to shift the signal phase periodically by one quarter wavelength by intercepting the beam with a stepped dielectric disk made with this differential quarter-wavelength feature [17]. The required phase shifting disk is mounted in each signal beam near its beamwaist where the rays are collimated and is motor driven at about 1350 rpm. For the 183 GHz beam the disk is mounted at the Brewster angle to minimize reflective insertion losses but, for mechanical reasons, the 380 GHz disk is mounted with its surface orthogonal to the beam. Because the 183 GHz disk is mounted at an angle, it laterally displaces the beam 0.46 mm when passing through the thin part of the disk and 0.71 mm when passing through the thick part of the disk. No attempt to correct for this beam shift is made because its ultimate effect is to cause a pointing error on the 183 GHz antenna beam of about 3 percent of a beamwidth and a beam switching of about 1 percent. Since the 380 GHz disk is mounted normal to its beam, there is no lateral displacement.

Because observing time on this telescope is at such a high premium, little time can be spent doing engineering evaluation of the experimenter's equipment while actually installed on the telescope. For this reason, only a laboratory evaluation of the hardware solution to this problem was possible prior to the actual experiment. To simulate the KAO telescope reflections, the instrument was pointed at a laboratory ceiling and spectra were taken at each frequency with and without the "phase wobbler" in place. The results showed a significant improvement. Without the phase wobbler operating, the peak-to-peak baseline signature was 100 K. With the phase wobbler operating the peak-to-peak signature was 6 K, a 12 dB improvement. It should be noted that this was an artificially harsh test, looking directly at a reflective surface. In subsequent operation on the KAO telescope the RF baseline ripple was less than the instrument noise level of 0.05 K ($\Delta T_{\min}$) with the phase wobbler operating.

In conjunction with the baseline improvement there was also a bad side effect attributed to the phase wobbler. With the phase wobbler in place and running, the system noise temperature degraded about 100 K compared to the value with it in place and not running. It was concluded that as the quarter-wavelength differential thickness step passed through the beam it was acting as a zoned wedge lens and causing the beam to point off axis and "see" some hot parts of the surroundings. For mechanical balance, the dielectric disks had been made symmetrically with two thick areas opposite each other and two thin areas opposite each other, each with equal angles. This meant that the beam incurred four edge transitions per disk revolution. A partial cure was to remake the disks with only two regions, one half thick and one half thin. This halved the number of undesired beam transitions and improved the degradation caused by the phase wobbler to about 50 K. The disks were no longer circularly symmetrical and hence were badly out of balance, but balance was restored using external weights. While this technique of reducing baseline ripple worked well, because of the noise degradation side effect, future systems will use a different scheme to control the baseline ripple.

V. Spectrometers and Data System

Analysis of the received signals is performed using a number of spectrometers having various bandwidths and resolutions, which can be connected in various ways as dictated by the requirements of the measurements. Two filter banks, one of 16 and the other of 36 tubular filters, can be tailored by selecting the individual filters. These banks operate at a center frequency of 160 MHz after down-conversion from the 1390 MHz IF. The outputs of the 52 detectors are read by voltage-to-frequency convertors (V/F) in a unit designated the Massively Parallel Counter (MPC). The MPC includes an autocorrelator, clocking at 30 MHz, consisting of 96 lag channels which can be connected in various combinations of 24 channel groups to any or all of three samplers. In addition, there is a bank of 256 1 MHz channels built on the NRAO pattern [18] by Millitech, which includes a multiplexing V/F, and short term accumulators. These accumulators are read out approximately every tenth second by the MPC and integrated for periods up to 6 minutes.

The MPC is connected via an IEEE-488 bus (HP-IB) to an HP9825T computer, which calibrates the spectra, converting filter bank counts to antenna temperatures, normalizing the autocorrelator data, and applying a van-Vleck correction. The data, along with header data such as scan number, time, receiver frequencies, and integration time, are recorded on magnetic tape cartridge.

The data are then passed into the KAO computer network (or its equivalent at JPL) on a GPIO bus. An HP21MX computer, designated the DATA CPU, merges the data with observatory housekeeping data from the central EXEC CPU. These data include the name, coordinates, Doppler velocity, and rotation angle of the celestial object under observation, the position, altitude, heading and speed of the observatory, the temperatures in various parts of the telescope, the boresight water column density derived from an IR radiometer, and other environmental factors. These merged data are stored on 1/2 inch digital magnetic tape. The program then separates the data into two records, one for each receiver. These records are passed to the EXEC CPU.

The EXEC CPU stores the records passed from the DATA CPU into two disk files, one for each receiver. Multiple copies of a data reduction program are used by the various investigators to monitor and reduce the incoming data. The same program is used at JPL for postflight data analysis.

VI. Noise Performance

Receiver noise measurements are made using a conventional Y-factor technique by chopping at 4 Hz between a room-temperature load and a load immersed in liquid nitrogen. The loads are located at the input to the instrument and at the output of the KAO telescope and hence measure noise temperature performance from that point onward. Losses in the telescope itself and from the atmosphere must be measured by other means to calibrate the scientific observations. Both loads were made from Eccosorb AN-72 absorber. Measured physical temperatures of the loads are used in the calibration and emissivities are assumed to be unity. The mixer tuning was optimized by varying the dc bias, the LO power level, and the backshort tuning position. The best operational performance for the 183 GHz receiver was an end-to-end system temperature of 320 K DSB. The mixer dc bias current was 0.3 mA at a voltage of 0.8 V. For the 380 GHz receiver, the best performance was an end-to-end system temperature of 650 K DSB. The optimum bias current was about 0.4 mA dc with a voltage of 0.5 to 0.7 V depending on the frequency of operation. Less than 200 μW of LO power was required for best noise temperature in both the receivers. The radiometer exhibits end-to-end system performance on the aircraft comparable to that of similar receivers in ground-based observatories.

VII. Conclusions

We have designed and built a cryogenically cooled 183/380 GHz receiver that has flown several times on the Kuiper Airborne Observatory to observe water emission in the interstellar medium. Quasi-optical techniques are used extensively to couple the remote signal and local oscillator sources into the mixers. The cooled mixers are GaAs Schottky diodes mounted in waveguide structures. The LO's are multipliers employing GaAs varactor diodes as harmonic generators and driven by phase-locked Gunn oscillators. The overall system temperature is 320 K DSB at 183 GHz and 650 K DSB at 380 GHz, performance comparable to that obtained at ground-based observatories.

Acknowledgment

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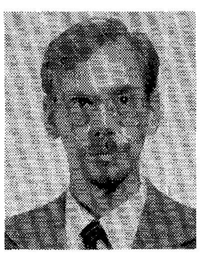
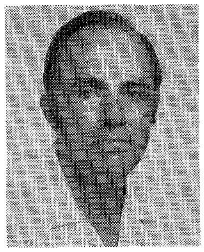
Dr. Frerking is a member of the American Astronomical Society, Sigma Xi, and Phi Beta Kappa.



Thomas B. H. Kuiper obtained the B.Sc. degree in physics (with honors) from Loyola College, Montreal, and the Ph.D. degree in astronomy from the University of Maryland.

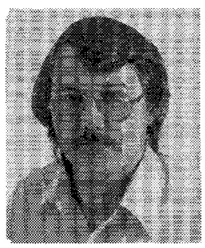
He joined the JPL staff in 1975, after a two-year tenure as NRC Resident Research Associate. He was a founding member of the JPL study team that originated the concept of the Large Deployable Reflector. He was also a member of the first team to conduct a millimeter-wave spectral line investigation with the NASA Kuiper Airborne Observatory. He is Friend of the telescope for the DSN Goldstone complex. He has served as a member of the NASA Astronomy/Relativity Management Operations Working Group.

Dr. Kuiper is a member of the American Astronomical Society, the Canadian Astronomical Society, the International Astronomical Union, the International Radio Science Union, and the American Association for the Advancement of Science.



Herbert M. Pickett (M'83) was born in Baltimore, MD, on April 2, 1943. He received the A.B. degree from Williams College in 1965 and the Ph.D. degree in physical chemistry from the University of California, Berkeley, in 1970. From 1970 to 1973 he was a postdoctoral fellow at Harvard with E. Bright Wilson, Jr. In 1973 he was a Miller Fellow at the University of California.

From 1973 to 1978 he was an Assistant Professor at the University of Texas at Austin. Currently he is Senior Research Scientist and Supervisor of the Molecular Spectroscopy Group at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.



Mark M. Schaefer received the B.S.E.E. degree from the California State Polytechnic University, Pomono, in 1979. He holds a First Class Radiotelephone license and was Transmitter Engineer for radio station KROQ-FM Pasadena, CA. He also holds an Extra Class Amateur radio license.

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Peter Zimmermann (M'77), photograph and biography not available at the time of publication.

N. C. Luhmann, Jr, photograph and biography not available at the time of publication.