A 2.5-THz Receiver Front End for Spaceborne Applications

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Abstract—The OH radical is an important player in known ozone depletion cycles; however, due to its location in the atmosphere, it must be studied from either a balloon or spaceborne platform. For long-term mapping over large portions of the earth, a spaceborne platform is the most desirable. NASA's Earth Observing System Microwave Limb Sounder instrument is slated to house a 2.5-THz Schottky-diode receiver for such measurements. In this paper, we describe the design, fabrication, and testing of the receiver front end. Measured double-sideband (DSB) *receiver* noise temperatures of better than 9000 K are reproducibly achieved with all devices of our best design. Estimated *mixer* noise is 3500-K DSB for optimal bias conditions and at *room temperature*. Selected components will be used in the first terahertz heterodyne receiver to be flown in space.

Index Terms—Antenna radiation patterns, atmospheric measurements, diplexers, heterodyning, horn antennas, membranes, micromachining, noise measurement, reliability, satellite applications, Schottky diode mixers, semiconductor device noise, space technology, submillimeter-wave receivers, terahertz.

I. INTRODUCTION

THE OH radical plays a significant role in a great many of the known ozone destruction cycles, and has become the focus of an important radiometer development effort for NASA's Earth Observing System (EOS) Chem I satellite, which will monitor and study many tropospheric and stratospheric gases, and is scheduled for launch in 2002 [1]–[3]. The Microwave Limb Sounder (MLS) instrument on this satellite is the only near-term opportunity to obtain global measurements of this important radical.

The lowest energy OH doublets at 2510 and 2514 GHz fall fortuitously close to a strong methanol laser line at 2522 GHz. A receiver noise of 20 000-K single sideband (SSB) is expected to provide enough sensitivity for daily global stratospheric maps of OH above 35 km and monthly global maps to 18 km from a limb-sounding satellite in polar orbit. These requirements are consistent with the performance that can be obtained
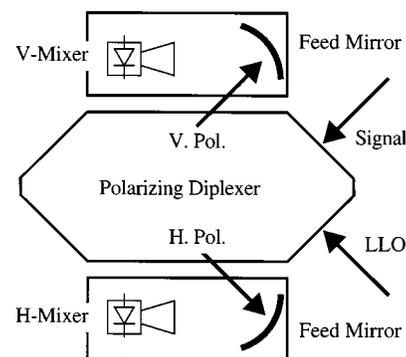
Fig. 1. Schematic diagram of the quasi-optical components in the 2.5-THz receiver front end.

from state-of-the-art room-temperature Schottky diode mixers. The molecular oxygen line at 2502 GHz can also be monitored as a pressure/altitude indicator.

The challenges of producing such sensitive mixers are numerous, but for this application, there is the added challenge of designing a robust receiver that can withstand the environmental extremes of a rocket launch and five years in low earth orbit. In this paper, we discuss the design and implementation of the first terahertz heterodyne receiver scheduled to be flown in space.

II. RECEIVER FRONT-END DESIGN

The receiver front end used to detect the OH radical at 2.5 THz consists of the following components and is schematically outlined in Fig. 1:

- diplexer to combine the OH signal and the laser local oscillator (LLO);
- off-axis elliptical feed mirrors to shape the beams of the mixer feedhorns;
- room-temperature fundamental Schottky-diode mixers for horizontal and vertical polarizations;
- support structures allowing simple rugged alignment
- room-temperature low-noise IF amplification chain (not pictured) from 7 to 22 GHz;
- mixer bias circuitry (not pictured).

Note that the space-qualified LLO is a complex subsystem in itself, and is not included here as part of the front end. However, it should be mentioned that the LLO technology is quite well developed, and will deliver over 20 mW of 2.5-THz power for only 140 W of spacecraft power. The LLO is $75 \times 30 \times 10$ cm in size, and 20 kg in mass [4].
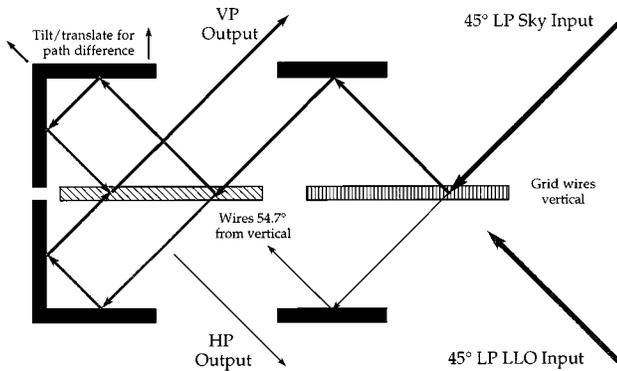
Fig. 2. Diplexer principle of operation. The right-hand-side grid splits the two input beams into two components for each beam. The heavy line follows the reflected half of the sky input (vertically polarized sky radiation). The left-hand-side grid splits this into two components, and interferometrically combines them after these two components are subjected to slightly different path lengths. The path length difference is adjusted such that the vertically polarized sky input at 12.8-GHz IF will pass through the "VP output" port. Sky inputs at 8.4- and 20.4-GHz IF will exhibit some cross-pol component due to compromises in the choice of path length. The LLO appears nearly horizontal at the HP port and nearly vertical at the VP port.
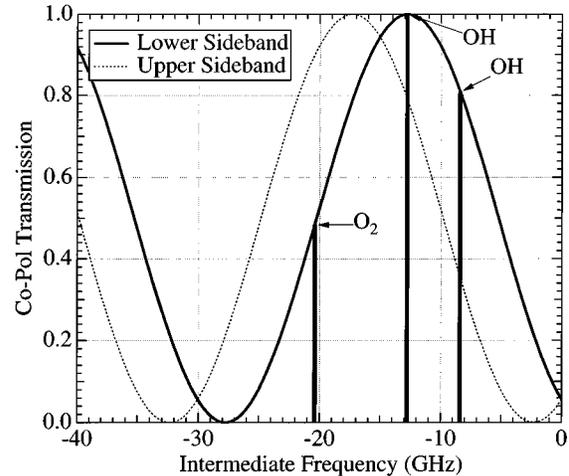

Fig. 3. Designed co-pol transmission of the sky signal through the 2.5-THz diplexer. The LLO beam will behave similarly, but with transmission curves identical to one minus the sky transmission. Note the opposite sideband rejection obtained for the OH channels by choice of path length difference (9.972 mm).

A. Diplexer

The principle of operation of the protoflight model (PFM) diplexer is shown in Fig. 2. It is a dual-polarization four-port version of the commonly used Martin–Puplett diplexer. The diplexer's dual-polarization operation serves to lower the system noise by $\sqrt{2}$ and provide the redundancy important to space flight missions. (The atmospheric radiance is not expected to be significantly polarized.) The four-port configuration is made possible with an input grid (the right-hand-side grid in Fig. 2), which splits incoming radiation into two equal portions. The difference in path length between the two roof mirrors determines output polarization at a given IF. If just one signal IF were employed, it would be straightforward to optimize coupling of the LLO and signal simultaneously. Unfortunately, for reasonable path length differences, one cannot simultaneously optimize coupling of the LLO and the three IF's of interest.

This is apparent from Fig. 3, which plots the sine-squared behavior of the diplexer with IF for our chosen nominal path length of 9.972 mm. Sensitivity is most important for the two OH IF's, but one cannot place the transmission peak directly between them without severely compromising the oxygen signal. The nominal path length results ideally in 94% local oscillator (LO) coupling, 82% coupling at 8.4-GHz IF, 99% at 12.8-GHz IF, and 49% at the less-critical 20.4-GHz oxygen line IF band. At 8.4-GHz IF, 82% of the horizontal polarization (HP) mixer's beam will couple to horizontally polarized sky radiation, but the remaining 18% will come from vertically polarized (VP) radiation originating in the approximately constant 300-K LLO port. Although a folded Fabry–Perot-type diplexer could be constructed to offer better coupling at all frequencies of interest simultaneously, stability and ease of use made the Martin–Puplett our first choice.

In practice, we fold the diplexer diagram of Fig. 2 into three dimensions so as to make a more compact, rugged design. Fig. 4 shows the "VP" half of the diplexer, to which are mounted the two polarizing wire grids and the "adjustable"

Fig. 4. Polarizing grids mounted on half of the 2.5-THz diplexer . The adjustable path length mechanism is visible in the upper left-hand side. The wheel presses against an invar spacer.

roof mirror. The two 45-mm free-aperture wire grid polarizers incorporate 5-μm-diameter gold-coated tungsten wire on 12.5-μm centers in stainless steel frames.[1] The adjustable roof mirror is spaced from the diplexer body by the nominal distance of (9.972/2) mm with invar spacers. To allow for machining tolerances, a mechanism is used to give ± 200 μm in fine adjustment of this path length. The adjustment is accomplished with a circular "adjuster wheel," which rotates about a shoulder bolt 200 μm off center. The wheel contacts one of the invar spacers, and is eccentrically rotated to tilt the rooftop mirror mount against a flexure, causing a change in path length with a negligible effect on beam location. The wheel is made of aluminum with a Teflon-impregnated anodized coating, designed to withstand abrasion while rotating against the invar spacer. This mechanism is secured with epoxy before flight, and the rooftop mirror mount is spring-loaded against the wheel to withstand vibration.

Fig. 5 offers two views of the fully assembled PFM diplexer. The "HP" half of the diplexer is symmetrically spaced from the VP half with respect to the grids with stainless steel standoffs. The "fixed" roof mirror bolts directly to the HP half of the diplexer. The optical design places the beam waist ($\approx$4.1-mm radius) close to the flat turning mirror visible at bottom center
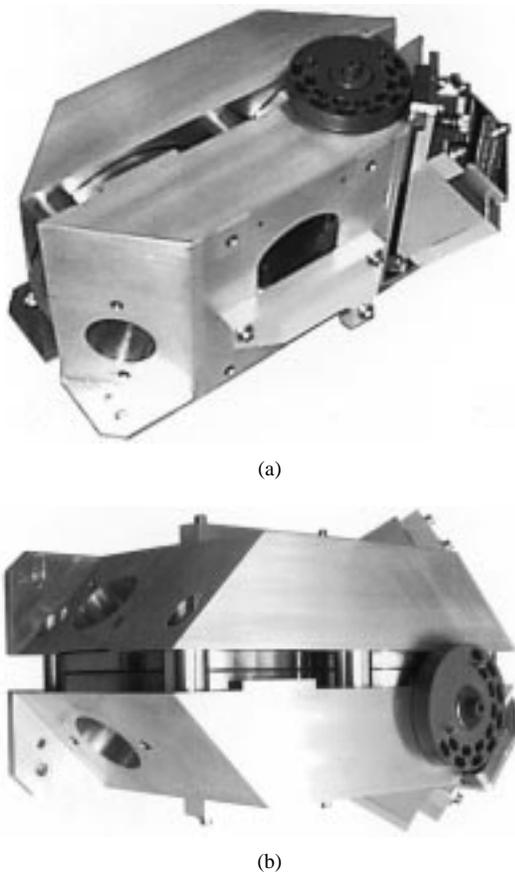
[1]Graseby Specac, Smyrna, GA.

(a)

(b)

Fig. 5. Two views of the assembled 2.5-THz diplexer. (a) LO input port at bottom left-hand side, the vertical-polarization output in the center, and the adjuster wheel with tilting roof mirror at the top right. (b) Sky input at top left-hand side, a hint of the fixed roof mirror at top right-hand side, and the wire grid polarizer frames along the center.

of Fig. 5(a). Apertures of ≥ 22.5-mm diameter are used to avoid truncation effects. All components not previously discussed are made from the same alloy of aluminum to minimize effects due to thermal expansion. The design has been optimized for ruggedness, mass, volume, thermal stability, and alignment procedures.

B. Receiver Front End

The receiver front-end components are pictured for the HP mixer in Fig. 6. The VP mixer is essentially identical, but with the mixer and IF chain rotated 90° clockwise, and the whole assembly mirror imaged. The feed mirrors are diamond-turned off-axis ellipsoids, which convert the rapidly diverging feedhorn beam to a well-collimated beam suited for best diplexer performance. The angle of incidence is 22.5°, a compromise between optimal on-axis operation and beam truncation requirements. The feed mirrors (and diplexer mirrors) are optically accurate, allowing the difficult receiver alignment to include the use of an HeNe laser and an optical autocollimating alignment telescope.

We use dual-mode Pickett–Potter conical feedhorns [5] electroformed on aluminum mandrels. Figs. 7 and 8 show an image/contour plot and E- and H-plane cuts for one of the horns. To date, two Jet Propulsion Laboratory (JPL), Pasadena, CA, horns have been tested and found to be essentially identical in beam pattern. A nominally identical horn, fashioned from a
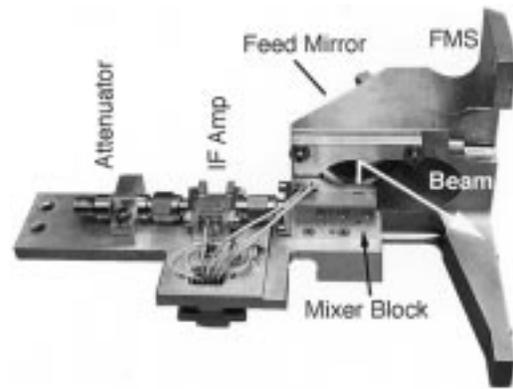

Fig. 6. Close-up of receiver front-end components. The chain includes an off-axis elliptical feed mirror, the mixer, a 7–22-GHz IF amplifier, and a clamped attenuator. Thermometry, amplifier power, and dc bias for the mixer passes through the connector at bottom. The feed mirror support (FMS) face to the right-hand-side bolts to a long edge of the hexagonal diplexer.
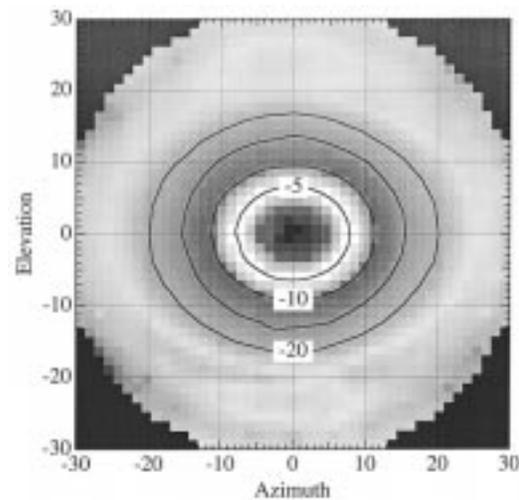

Fig. 7. JPL 2.5-THz Pickett–Potter horn beam pattern. Contours are in decibels.
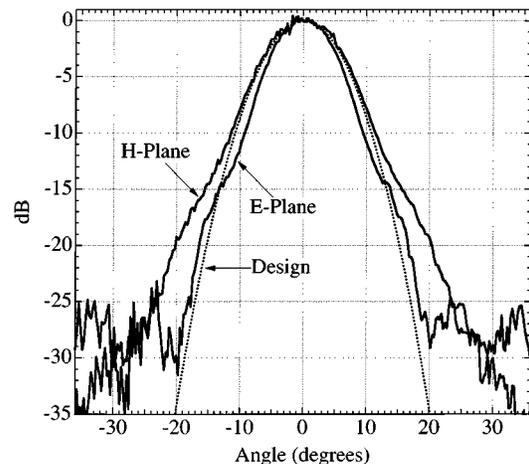

Fig. 8. JPL 2.5-THz Pickett–Potter horn beam pattern cuts in E- and H-planes, compared with the nominal design.

stainless-steel mandrel by the Rutherford Appleton Laboratory (RAL), Chilton, Didcot, U.K., gives slightly more symmetric beam patterns [6]. The cause of the asymmetry evident in these
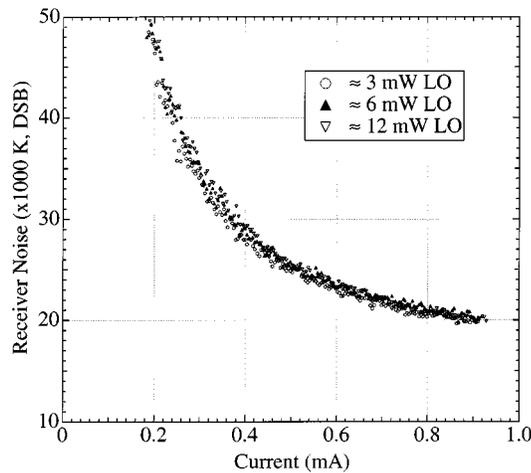
Fig. 9. Receiver noise versus current at an IF of 8.4 GHz, demonstrating the use of current bias to reduce sensitivity to LO fluctuations. A factor of ≈ 4 in LO power results in virtually no input noise temperature change.
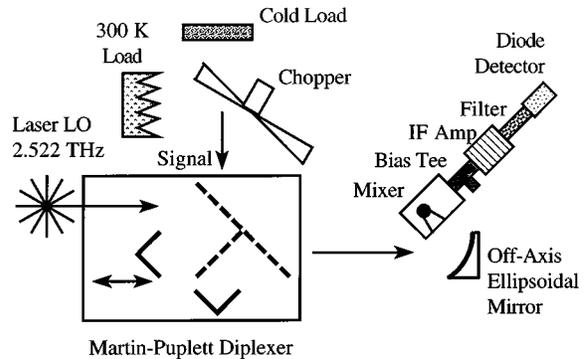

Fig. 10. Schematic of the 2.5-THz mixer test system. It is designed for sensitive measurement of high-noise devices, flexibility, and rapid computer-controlled measurements.

horns is not currently understood, but similar behavior has been seen for such horns if oversized for the test frequency [5]. Perhaps nonideal electrical conductivity at the surface of the horn gives an apparent increase in the horn's "electrical" size.

The radiation collected by the feedhorn passes through a single-mode 2.5-THz rectangular waveguide, which, in turn, feeds a mixer. The mixers are GaAs Schottky monolithic membrane diodes (MOMED's), designed and fabricated at JPL [7]. The mixers utilize a new fabrication technique, which offers more robust construction than existing whisker-contact corner-cube designs, while maintaining state-of-the-art noise performance. Comparable performance has been achieved as well with planar-whisker-contacted waveguide mixers from RAL [8]. The LO power requirements of these mixers (≈ 5 mW) is modest enough to permit use of a low-power LLO. Fluctuations of laser power will be kept below 1% through the use of dithered feedback loops.

A resistive bias-tee arrangement has been chosen to protect the mixers while providing a dc-bias path for the Schottky diode with minimal impact on the IF throughput. We have designed and implemented a differential feedback circuit to provide a stiff current bias with good immunity to noise pickup. The current bias also serves to reduce sensitivity of the device to LLO power fluctuations. A simple explanation is that, for an ideal Schottky diode, current bias is equivalent to curvature bias, and curvature is the dominant contributor to mixing, as seen in a simple Taylor expansion argument. As shown in Fig. 9, for one of the early JPL mixer designs, a factor of four change in LO power results in virtually no change of input noise temperature. Conversion gain behaves similarly. More recent device designs exhibit somewhat more sensitivity to LO power. Our current thinking is that the IF transformer match is not as good for these devices, and the LO power fluctuations result in device impedance changes that have a nonnegligible effect on the receiver characteristics. The IF transformer is a 7–22-GHz quartz suspended-substrate stripline step transformer, typically 100 Ω at the mixer end, and 50 Ω at the amplifier. Higher impedance transformers have been tested, offering better mode matching to the MOMED output, but results have not been encouraging. We are experimenting with al-

ternative transformer materials and designs to offer good mode and impedance matching simultaneously.

Low-noise (150 K at 8.4 and 12.8 GHz, and 200 K at 20.4 GHz) room-temperature IF amplifiers with ac-coupled inputs[2] amplify the downconverted mixer output by 32 dB. A 125-μm-thick piece of indium is sandwiched between the amplifier and mounting plate, and provides adequate heat sinking for an operational temperature close to 30 °C. The final component in the front-end signal chain is a low VSWR broad-band attenuator.[3] The attenuation value (typically 2–6 dB) is selected at test to provide the precise signal level required for best spectrometer sensitivity without saturation. A thermistor is located adjacent to the amplifier for diagnostic purposes.

III. 2.5-THz MIXER TEST SYSTEM

Accurate RF noise measurements at 2.5 THz are complicated by several factors, e.g.,

- high mixer noise temperatures;
- variable atmospheric attenuation;
- poorly calibrated "absolute-power" detectors;
- unavailability of matched attenuators;
- "gray" body loads;
- imperfect Gaussian beams.

The measurement test system used here to overcome these difficulties is schematically shown in Fig. 10. At this time, relatively few measurements have been made in demonstrating the successful operation of the flight-type diplexer, as a more flexible Martin–Puplett-type diplexer[4] was used for most receiver measurements. Comparison of measurements between the protoflight (PF) diplexer and the test system diplexer verify that the PF diplexer performance is at least as good as the test-system diplexer performance.

The noise temperatures are measured using the standard Y-factor technique on the full receiver only (i.e., including the diplexer and atmospheric losses, and the addition of noise by the bias tee and IF amplifier). A chopper switches the signal beam between a hot and cold load during the measurement.
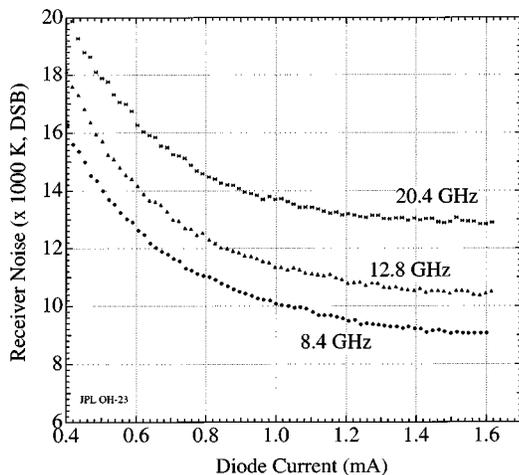
Fig. 11. Receiver noise versus current at intermediate frequencies of 8.4, 12.8, and 20.4 GHz. Filters with bandwidth of ≈700 MHz were used to separate the intermediate frequencies. The LO power coupled to the mixer was approximately 7 mW.
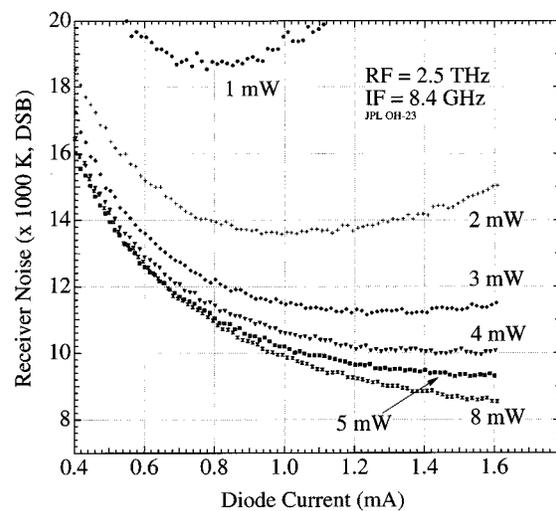

Fig. 12. Receiver noise versus current for various LO power levels. The IF is 8.4 GHz. Respectable performance is achieved with only 2 mW of coupled power.

A lock-in detector at the 100-Hz chopper frequency extracts a hot/cold-load power output variation from a crystal diode detector. A filter is placed in front of the crystal diode detector to select the IF band of interest: i.e., 8.4, 12.8, or 20.4 GHz. The filter bandwidth is approximately 700 MHz.

After converting the lock-in signals from rms to peak-to-peak values, we combine with the average dc output power to give the hot and cold powers needed for an accurate Y-factor calculation. This technique can be used to evaluate receivers with noise in excess of 500 000-K DSB. It has been demonstrated that the noise temperature measured with the test system is consistent with averaged dc-type Y-factor measurements, and also consistent with measurements using the actual PFM diplexer.

IV. MOMED SCHOTTKY DIODE MIXERS

The Schottky-diode mixers and the mixer-block housings have been previously described [7]. To date, we have extensively RF tested over 40 different devices of varying designs. The best devices are consistently of the same design, and devices of the same design offer very similar performance. Reliability and reproducibility of the devices and device performance has been quite good, and highlights the benefits gained by using a planar device technology. Measured anode sizes of ≈0.35 μm × 1.0 μm on 7 × 10^{17} cm^{-3} material, and wide tapered waveguide probes are the defining characteristics of the best MOMED's. Smaller and larger anodes, higher doping, and more narrow waveguide probes have been tested and give poorer performance. Our fabrication effort is now focussed on device yield and reliability for flight applications.

Fig. 11 compares receiver performance at 8.4, 12.8, and 20.4 GHz. The receiver performance measured here is competitive with that of the best reported in the literature [9], particularly when one considers the fine quality of the beam from the Pickett–Potter horn. The performance at 20.4 GHz is notably worse than at the other IF frequencies, in part because of amplifier noise. Although sideband ratio measurements have not yet been performed, the large RF/IF ratio would suggest

that this should not account for the remainder of the differences between the three IF bands.

We currently believe the IF match to be a major cause of performance variation between the IF bands. RF match may not be optimal either, but the similarity in appearance of the three curves would suggest a relatively constant RF match across the full IF range. The slopes of the curves suggest that the combined RF and IF match is best at high current (low dynamic resistance). For this device, we also find the noise performance to degrade as LO power is reduced (reduction of LO power by a factor of ≈2 results in ≈10% noise increase). Better performance at higher LO power also suggests the need to lower the mixer impedance. However, we find lower noise temperatures when using lower impedance IF transformers. It seems that the waveguide probe configuration performs better with a lower impedance device for best RF match (or wider probe for constant impedance), but the IF transformer is currently tuned to match a higher impedance device. We have not yet tested transformers with less than 100 Ω Ω input impedance, and are somewhat wary of mode matching between the very small MOMED beam lead and the huge 100-Ω quartz section. Indeed, network analyzer measurements of the return loss looking in the mixer output port show significant variation across the full IF range, and show dramatic sensitivity to the quality of the wire-bond connections made within the mixer block.

Fig. 12 indicates that the LO power requirements for the planar MOMED devices are relatively modest. Although best performance is achieved at LO power of at least 8 mW, adequate performance is found with only 5 mW. The best measured receiver noise of ≈8250-K DSB is found for LO power greater than 8 mW, and for diode current slightly more than 1.6 mA. Operation of the receiver in flight may use bias current levels of less than 1 mA, and LO power of ≈5 mW to extend the MOMED lifetime against electromigration and other heat-sensitive degradation processes. Subtracting estimated and calculated noise contributions from atmospheric attenuation, bias-tee attenuation, and IF amplifier input noise results in an
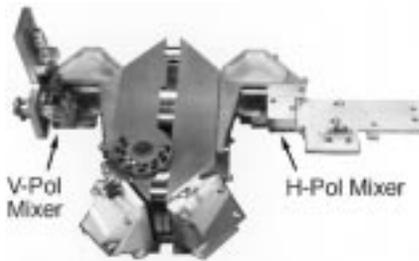
Fig. 13. Assembled receiver front end, in the configuration that was mounted on the electrodynamic shake table. Note the "vertical" mixer on the left-hand side, and the "horizontal" mixer on the right-hand side. The diplexer adjuster wheel is atop the roof mirror on the left-hand side.

estimated *mixer* noise temperature of only 3500-K DSB. This is competitive with superconducting mixers and, considering the simplicity of Schottky diode mixer operation, makes this technology attractive even for such high-sensitivity applications as astronomy.

V. QUALIFICATION FOR SPACEFLIGHT

Although it is possible to create a low-noise terahertz receiver in the laboratory, a serious challenge exists in making it robust enough for practical use. Much effort has gone into the design of the receiver front end so that it will withstand the environmental extremes of vibration during launch. It is yet another chore to ensure the five-year lifetime of the mission. The nature of the device and its mounting fixtures make the other environmental effects less difficult to deal with: thermal, vacuum, and radiation effects are not a serious problem in the EOS-MLS instrument.

The spaceflight qualification of the front end began with a balloon flight of a breadboard model front end. The front end performed without a problem, and some useful OH measurements were performed [10]. A gondola coolant pump failure prevented extensive data collection.

To further establish the reliability of the mixers, the mixer blocks were subjected to thermal testing. Rapid thermal cycling (four cycles from -50 C to $+100$ C, 20-min dwell times at each extreme) was performed on six devices, and found to have no noticeable effect on the dc device characteristics. As thermally induced damage is potentially the most difficult problem to circumvent, the test results offer a good deal of reassurance that the JPL MOMED mixers will perform well in a flight environment. The predicted flight survival temperature range for the EOS MLS terahertz receiver front end is from $-30\,^{\circ}$ C to $+55\,^{\circ}$ C.

The small size of the MOMED mixers makes them relatively insensitive to the low-frequency vibration experienced during launch. The rest of the front end is quite susceptible to damage. To test the robustness of the design, the assembled front end was subjected to the following random vibration for 3 min each in x, y, and z axes (expected to mimic the launch environment):

20–50 Hz	$+6$ dB/octave.
50–500 Hz	0.2 g^2/Hz.
500–2000 Hz	-6 dB/octave.
overall	13.0 g (rms).

Fig. 13 shows the assembled front end in the configuration that was subjected to the vibration test. The front end survived vibrational testing quite well, with the only defect noted to be the cracking of a substandard epoxy joint used to secure the horizontal mixer block SMA connector. RF coupling, noise temperature, and dc I–V characteristics were otherwise identical before and after the test.

The burden of operation in a vacuum environment primarily places requirements on the types of epoxies allowed, and on the thermal difficulties due to lack of convection. Simulations have been performed to estimate temperatures around the receiver front end and predict no problems. The diplexer is designed to be insensitive to overall temperature, and harmful thermal gradients (primarily imposed across the fasteners between diplexer components) are being minimized.

The predicted total radiation dose over the five-year mission life is 60 krad (Si). Proton irradiation of the device will not be an issue because it is surrounded by ≈ 5 mm of brass mixer block. In addition, GaAs diodes are known to be relatively immune to total-dose effects resulting from the deposition of ionizing energy [11].

To ensure mixer lifetimes in excess of the five-year mission, accelerated life tests with fit to an Arrhenius-lognormal degradation are planned to begin in early 2000. Parameters used to define a device failure are expected to include I_{sat}, R_s, η, as well as the low-frequency noise signature of the device. Long-term plans for life testing will use the low-frequency noise as a diagnostic as well as a measure of degradation [12].

VI. SUMMARY

Excellent performance of fixed-tuned Schottky-diode receivers in a robust receiver configuration has been demonstrated. Receiver noise of 8250-K DSB has been measured for JPL MOMED mixers at 8.4-GHz IF and 2.5-THz RF. High-quality beam patterns in close agreement with theory have been measured at 2.5 THz on Pickett–Potter dual-mode horns. This noise and beam quality is required for monitoring of atmospheric chemistry, and can facilitate the development of several important remote-sensing and *in-situ* applications [13]. With the concurrent development of low-power compact terahertz LLO's, this technology is realizable in a spaceborne platform. Work in the near future will concentrate on integration of the engineering model (EM) and protoflight model (PFM) components, component reliability, environmental testing, and device lifetime testing.

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