DEVELOPMENT AND PERFORMANCE OF A LASER HETERODYNE SPECTROMETER USING TUNEABLE SEMICONDUCTOR LASERS AS LOCAL OSCILLATORS

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ABSTRACT

A diode-laser based IR heterodyne spectrometer for laboratory and field use has been developed for high efficiency operation between 7.5 and 8.5 microns. The local oscillator is a PbSSe tuneable diode laser kept continuously at operating temperatures of 12-60K using a closed-cycle cooler. The laser output frequency is controlled and stabilized using a high-precision diode current supply, constant temperature controller, and a shock isolator mounted between the refrigerator cold tip and the diode mount. Single laser modes are selected by a grating placed in the local oscillator beam. The system employs reflecting optics throughout to minimize losses from internal reflection and absorption, and to eliminate chromatic effects. Spectral analysis of the diode laser output between 0 and 1 GHz reveals excess noise at many diode current settings, which limits the infrared spectral regions over which useful heterodyne operation can be achieved. System performance has been studied by making heterodyne measurements of etalon fringes and several Freon 13 ($CF_3C\ell$) absorption lines against a laboratory blackbody source. Preliminary field tests have also been performed using the Sun as a source.

INTRODUCTION

To date, a number of studies have been made involving infrared heterodyne detection using tunable diode lasers (TDL's). The first effort was made in 1974 by Mumma et al. (ref. 1), where a limited tunability device and an 8-channel bank of 25 MHz filters were used to obtain blackbody continuum measurements of the Moon and Mars, and the detection of a laboratory N_2O line. Subsequent work included the detection of stratospheric ozone features by Frerking (ref. 2) and spectroscopy of C_2H_4 in the laboratory by Ku and Spears using a TDL heterodyne radiometer (ref. 3). Recently, Harward and Hoell have detected lines of several stratospheric species between 9 and 11 microns using a swept single channel TDL radiometer (ref. 4).

While there are a variety of problems associated with tunable diode lasers as local oscillators, they have the potential of continuous spectral tunability, which is not possible with gas laser systems. Current TDL technology allows coarse selection of operating wavelengths in regions between 4-20μm, with single mode output powers marginally sufficient for useful heterodyne operation in spectral regions below 12μm. The instrument discussed here has been developed as a general purpose TDL heterodyne spectrometer for high resolution ground based studies of the stratosphere and of astrophysical sources.

SPECTROMETER LAYOUT

A schematic diagram of the diode laser heterodyne spectrometer is shown in Figure 1. With the exception of the 50 percent reflecting - 50 percent transmitting ZnSe beamsplitter, which is used as a beam combiner, the use of off-axis parabolic mirrors provides an all reflecting system. This eliminates transmission losses and dispersion effects and improves the quality of focal images throughout the system.

The optical system is matched to the GSFC 48-inch telescope and an f/30 input beam. The incoming beam from the telescope results in a diffraction limited spot size (full width at half maximum) of about 300 microns at the telescope focus when the operating wavelength is near 8 microns. The telescope beam is collimated using a 30 inch focal length parabolic mirror and combined with the laser local oscillator beam at the beamsplitter. The combined beams are then demagnified and focussed onto the HgCdTe detector using f/4.5 collecting optics.

The TDL local oscillator is kept continuously at operating temperature (12-60K) using a closed cycle cooler and provides multi-mode output powers of a few mW near 1200 cm^{-1}, with a frequency separation of about 1.4 cm^{-1} between adjacent longitudinal modes. Using a 150 line/mm grating as a mode selector in the local oscillator beam results in a mode spacing of about 150 microns in the detector focal plane. This effectively isolates single modes of the laser L.O. The TDL is mounted so that the polarization of the $\vec{E}$ field vector is horizontal (in the plane of the figure). In this configuration the grating efficiency in first order exceeds 85 percent at wavelengths between 8 and 12 microns, and should be suitable regardless of the diode used.

A synchronous detection process is employed whereby a rotating blade chopper in combination with a stationary flat mirror provides signal and reference beams from the source in alternate half-cycles of the chopping cycle. By means of dual kinematic mirrors near the telescope focus, a blackbody reference source can be placed in either the signal or the reference beam for sensitivity measurements and instrument calibration. This blackbody source is also used for laboratory studies of subject gases by placing a gas cell in the blackbody beam.

In the remote observation mode, any remaining systematic errors, either in the telescope or in the synchronous detection scheme, can be removed by changing the signal and reference beam paths using a translatable dichroic mirror. The transmitted visible beam from this mirror also provides a conjugate image for guiding on remote sources.

HETERODYNE DETECTION ELECTRONICS

Two methods are now being employed for heterodyne detection using the instrument. Most of the initial heterodyne measurements were obtained in the manner shown in Figure 2. Here the total I.F. signal from the IR detector is amplified (50 dB) using a low-noise wideband (0-1.5 GHz) amplifier. A portion of this output is again amplified and band limited using a 150 MHz low pass filter. The filter output is square-law detected and the D.C. signal is delivered to a lock-in amplifier and recorder. Using a high precision TDL current supply, the diode laser can be slowly tuned to scan the desired spectral region. The current supply delivers a voltage to the recorder X-axis which is proportional to the diode current. This produces a single channel scan of heterodyne signal as a function of diode current. By repeating the scan using a calibration etalon, a relative frequency scale can be assigned to the X-axis. The I.F. bandwidth, 150 MHz in this configuration, is the filter cutoff frequency. The wavelength resolution is therefore roughly 300 MHz and the effective integration time is the time constant setting on the lock-in amplifier, typically 1.25 seconds.

Recently, an RF filter bank spectral line receiver has been added to the system which provides multiplexing and time integration capability for measurements on weak astronomical sources. Using this method, the I.F. output is split into 32 contiguous frequency channels each 25 MHz wide, for a total coverage of 800 MHz in the I.F. This block of filters can be steered to any portion of the I.F. by mixing with a second RF local oscillator. The output of each filter is then digitized synchronously with the chopper and the output can be displayed and printed after each integration period. A variation of this spectral line receiver design is discussed in detail by Buhl and Mumma (ref. 5) and Mumma et al. (ref. 6). In the future this spectral line receiver will be extended to 1600 MHz coverage at 25 MHz resolution and a separately tunable high resolution filter bank of 32, 5 - MHz filters will be added.

DIODE LASER LOCAL OSCILLATOR

The TDL oscillator currently installed in the instrument is a PbSSe device manufactured by Laser Analytics, Inc. The output power in a single mode from this laser has been measured to be as large as 1 mW, although typical single mode powers for heterodyne work lie below 200 μW. The operating frequency of this device varies from about 1170 cm^{-1} at a diode current of 0.20 A and mount temperature of 12 K, to nearly 1290 cm^{-1} at 2.0 A and 60 K.

The TDL is mounted on a vibrationally and thermally isolated platform that is enclosed in an evacuated shroud, as illustrated in Figure 3. This design scheme is discussed by Jennings and Hillman (ref. 7) and has been used successfully to stabilize a diode for direct absorption spectroscopic studies. The laser and copper mount are maintained at cryogenic temperatures by coupling the diode mount through a flexible braid to the second stage of a two-stage closed-cycle helium refrigerator. This braid, together with a metal bellows on the vacuum shroud isolate the diode mount assembly from mechanical shock associated with cooler operation. The entire assembly is enclosed in a 50 K radiation shield attached to the refrigerator first stage. This serves to lower the minimum mount temperature by reducing the conducted heat load on the second stage. A high-precision temperature controller is used to preset the diode mount temperature anywhere between the cooling limit of 11 K, and the maximum recommended diode temperature of about 70 K. With a properly positioned temperature feedback loop, consisting of a sensor and heater at the diode mount, the temperature has been stabilized to within $\pm$ 1.0 mK over a 1 hour period. Since the temperature tuning rate for our present diode has been found to be approximately 10 MHz/mK, this corresponds to a frequency stability over the same time period of about $\pm$ 10 MHz. Stability better than $\pm$ 5 MHz is expected over shorter time periods.

Once the temperature has been set, the diode output frequency is fine tuned by varying the diode current, as previously described, or the diode frequency may be preset to some fixed value. The PbSSe device now in use exhibits a current tuning rate of about 1.2 cm^{-1}/A near 1200 cm^{-1}. This rate is slow enough so that contributions to the frequency drift from current supply instabilities are negligible.

INITIAL RESULTS

Figure 4 illustrates the current tuning procedure applied to a single channel scan of a 15 percent absorbing feature, near 1180 cm^{-1}. The results of two heterodyne scans are shown, obtained by first placing a 10 cm cell containing 25 Torr of Freon 13 in front of the blackbody and then replacing the cell with a 1 inch etalon. Roughly 150 μW of single mode laser power was available when these measurements were made. The inset at the upper right shows direct absorption measurements that were made by placing the same two objects in the local oscillator beam and current tuning again over the same region. The baseline in both heterodyne and direct scans refers to the absorption feature, and not to the etalon fringe pattern which has been shifted down in both cases and is used here to establish a relative frequency scale. The lack of any observable structure in the absorption line during the heterodyne scan of the type seen in the direct mode is due mainly to the system resolution of 300 MHz, comparable with the line spacing in the multiplet.

The best achievable double side-band signal to noise ratio (SNR) in this experiment was found to be about 250, for an IF bandwidth of 150 MHz, integration time of 1.25 sec, and blackbody temperature of 1273 K. The expected SNR for an ideal system under these same conditions is about 19,000, making the measured system delta (Δ) (ref. 6) about 80 in this region of the scan. A more typical value of achievable SNR is 140 in the noisier portion of the scan, which yields a delta of approximately 145. This increased noise, which turns on at the same current value in both heterodyne scans has been found to originate in the diode laser output. Studies using a spectrum analyzer show that this noise results from the generation of small satellite modes close enough in frequency to the primary mode to be seen in the I.F. These small modes show amplitude modulations that are correlated with vibrations of the diode cooler second stage, which is mounted on the optical bench. As might be expected, the noise superimposed on the resulting spectrum is strongly time coherent with a frequency of about 2.5 Hz, which is the cycling period of the refrigerator second stage. Many of the modes which are otherwise suitable for heterodyne detection are much more sensitive to cooler vibrations than the example shown here, so that a large fraction of the available diode tuning range is made unsuitable for heterodyne work with the present system. Plans are being made to install a new diode in the near future. Test results obtained at that time will reveal whether the diode we are currently using is unusually vibration sensitive, or whether further de-coupling of the diode from the closed cycle cooler is required.

After interfacing the spectrometer with the R.F. spectral line receiver, the same gas cell with 40 Torr of Freon 13 was placed in the beam of a 1270 K blackbody, producing the results shown in Figure 5. 25 RF channels of 25 MHz width were used in these preliminary measurements. The features shown here lie in the same wavelength region (near 1180 cm^{-1}) as the weaker lines discussed earlier. Both spectra in Figure 5 were obtained using the same diode laser mode and a total power of about 200μW on the detector. By first locating the lines in direct absorption and tuning the diode to the line center position, the line could be positioned properly for heterodyne detection by shifting the diode current a predetermined amount. In so doing, the feature is moved an appropriate distance out in either sideband from the zero of I.F. Each result consists of an average of four consecutive runs for a total effective integration time of 3.2 minutes. The spectrum is divided by the average of four scans taken during the same time period with the gas cell removed, yielding a quotient spectrum with fractional transmittance as the ordinate. This eliminates the effect of gain variations with frequency from the amplifiers and detector.

The instrument has very recently been placed in operation at the Coude focus of the 48 inch reflecting telescope at the Goddard optical site and additional 25 MHz filters were added to the filter bank for a total I.F. coverage of 800 MHz.

The first observational test performed was a comparative measurement of detector response in the heterodyne mode using the Sun and a local blackbody source at a number of temperature settings. Figure 6 is a composite of these blackbody measurements, taken sequentially, with all system parameters held constant during the duration of the tests. Each measurement was made with an integration time of about 45 seconds and an LO power of $\sim$ 200μW. The modulations observed in each scan are caused by standing waves in the RF cables and can be removed by ratioing as was done in Figure 5.

The positive slope for all curves is predominantly due to the detector and preamplifier roll-off at high I.F. The ratios of heterodyne signals for any two temperatures have been found to be close to the expected values at the high frequency end. Closer to the zero of I.F., however, the high temperature curves grow anomalously large. This effect is due to the absence of an infrared filter in the blackbody (or Sun) beam. For the temperatures of interest here, a large fraction of the total energy flux is converted to shot noise power by the detector and synchronously detected. Since the bolometric (T^4) term increases much more quickly with temperature than the heterodyne signal term at these wavelengths, the synchronously detected blackbody shot noise becomes large compared to the signal as the source temperature increases. This result emphasizes the importance of a relatively narrow band filter in the signal beam when making measurements against hot sources.

SUMMARY

These results show that diode laser heterodyne spectroscopy has evolved to the point where remote sources other than the Sun can be detected with adequate signal-to-noise. From the level of system performance achieved so far at 8 microns, one can expect signal to noise ratios in excess of 10 at > 10^6 resolving power for a continuum temperature of 250 K and less than 30 minutes integration time, making planetary spectroscopic observations feasible. In addition, grating and Fabry-Perot spectrometer studies of several compact HII regions reveal large fluxes in the fine structure lines of SIV and ArIII near 10.51 and 8.99 microns respectively. Calculations show that these features, if narrow in linewidth, should be easily observable for integration times of less than 1/2 hour.

One of the major remaining problems is the lack of a satisfactory method of absolute frequency calibration to within the accuracy required. Careful calibration of an IR monochromator allows a frequency determination to within about ± 0.1 cm^{-1}. This uncertainty is equal to about $\pm$ 3 GHz, which is still considerably broader than the 800 MHz filter bank recently interfaced with the system, and more than two orders of magnitude broader than a single resolution element of 25 MHz.

A supplemental scheme for frequency calibration uses a transfer standard (gas) having numerous lines of established rest frequencies in the region of interest. By interpolating between the diode current settings at the centers of these standard lines, the operating wavelength may be established with high precision. In the 1200 cm^{-1} region, the recently available N_2O calibration standards can produce the desired < 0.001 cm^{-1} calibration accuracy. (Data from work (as yet unpublished) by W. B. Olson, A. G. Maki, and W. J. Lafferty, National Bureau of Standards, Gaithersburg, Md.)

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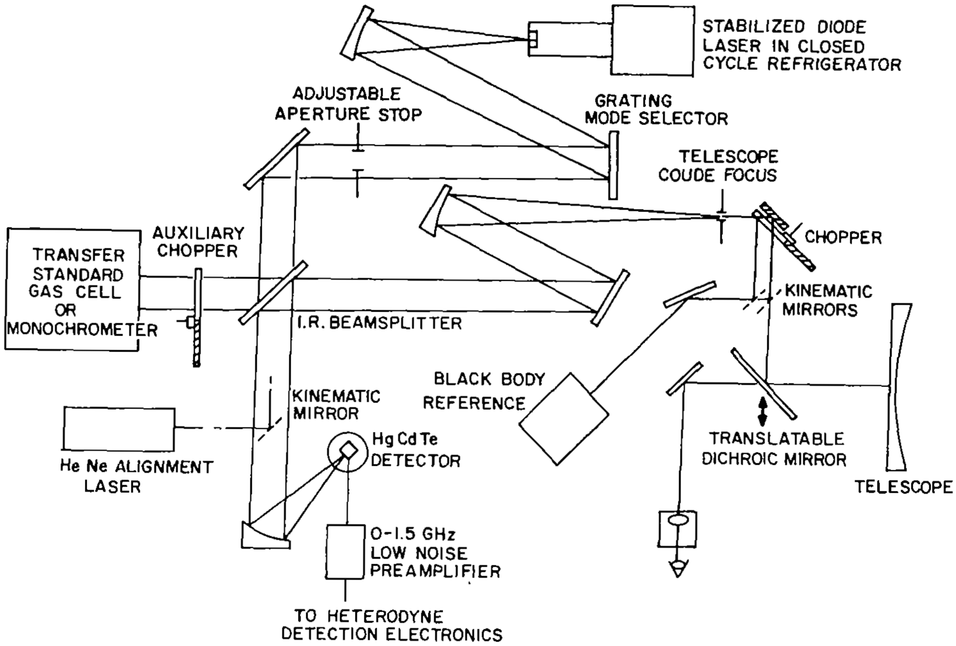

Figure 1.- Schematic diagram of diode laser heterodyne spectrometer optical front end.

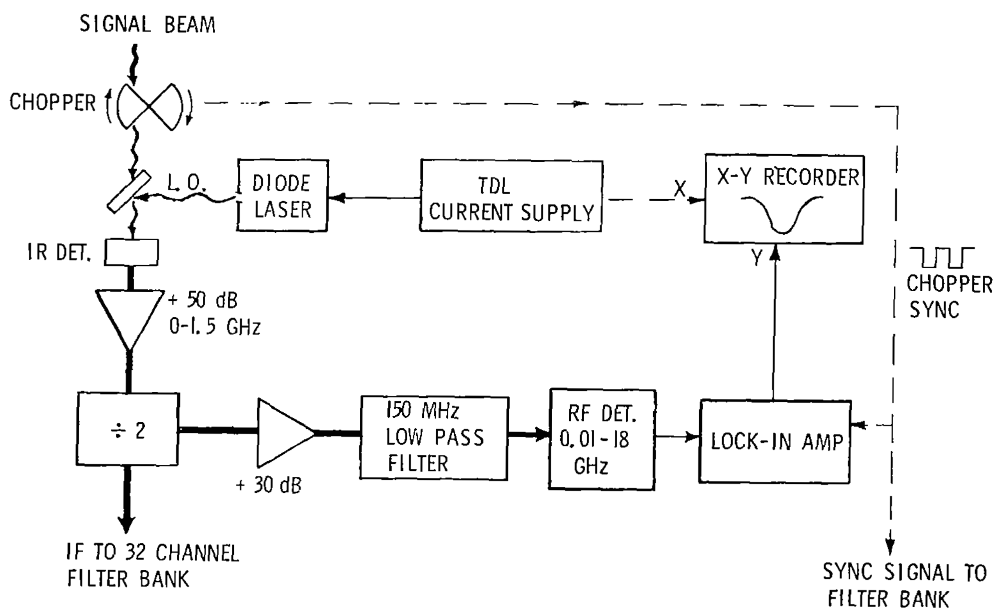

Figure 2.- Diagram of current tuning method for producing heterodyne spectra.

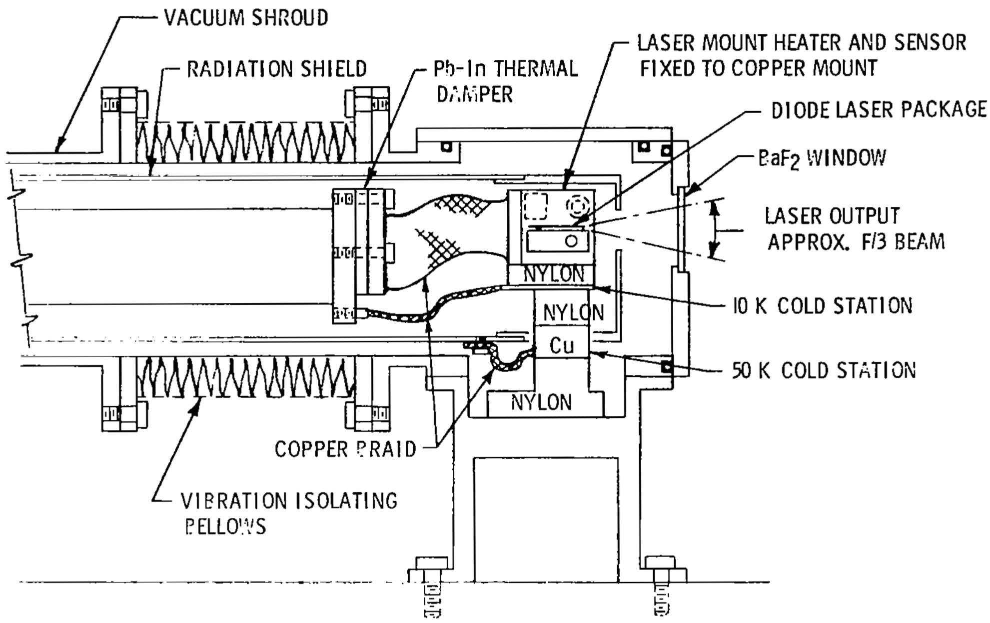

Figure 3.- Diode laser mounting scheme.

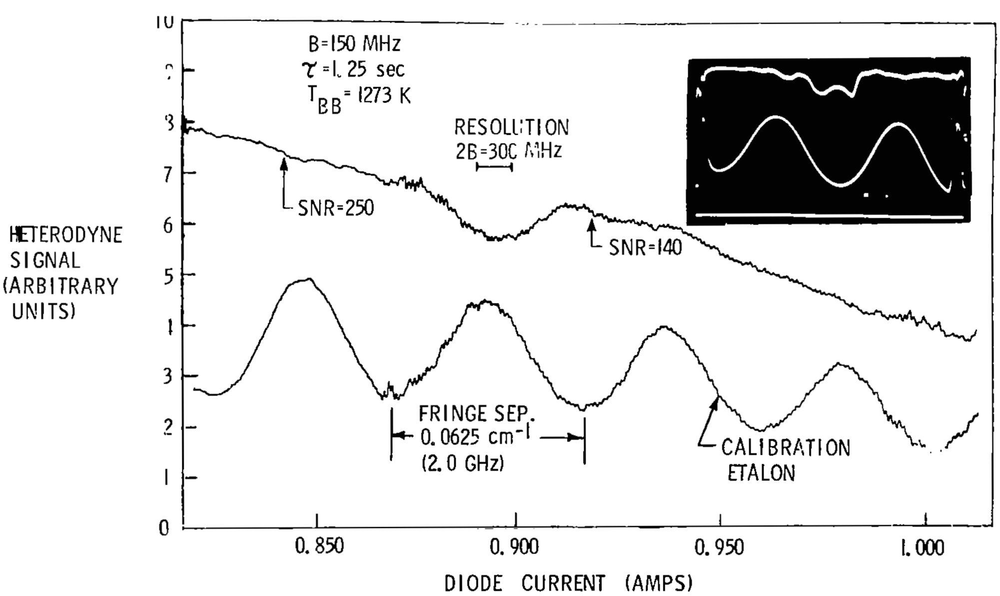

Figure 4.- Single channel heterodyne scan and direct absorption scan (inset) of Freon 13 multiplet and 1 inch etalon near 1180 cm^{-1}. The baseline of the etalon scan has been shifted for clarity. The etalon scans are shown below the $CF_3C\ell$ absorption scans in each case.

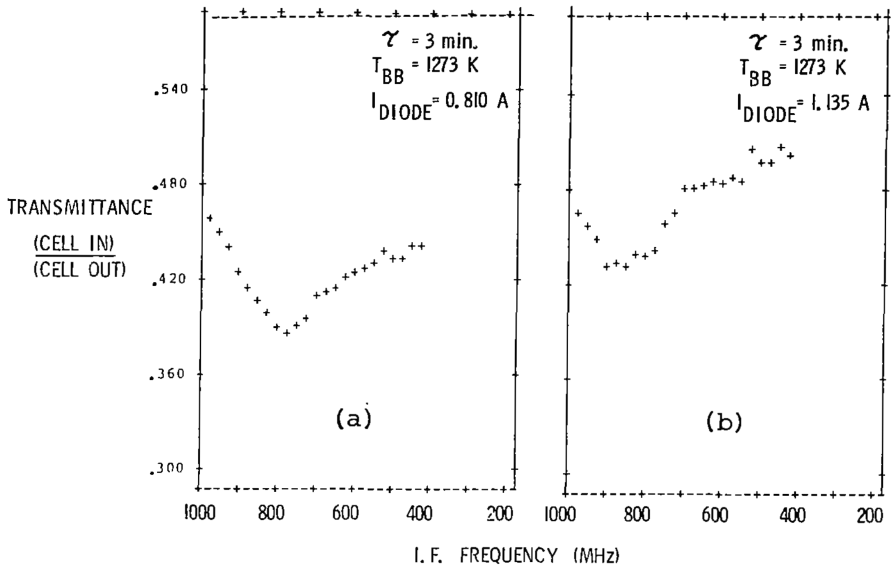

Figure 5.- Heterodyne measurements of pressure broadened Freon 13 ($CF_3C\ell$) lines near 1180 cm^{-1} using a 23 channel RF spectral line receiver and 10 cm absorption cell. Trace (a) shows a blend of several discrete lines while trace (b) is an isolated feature.

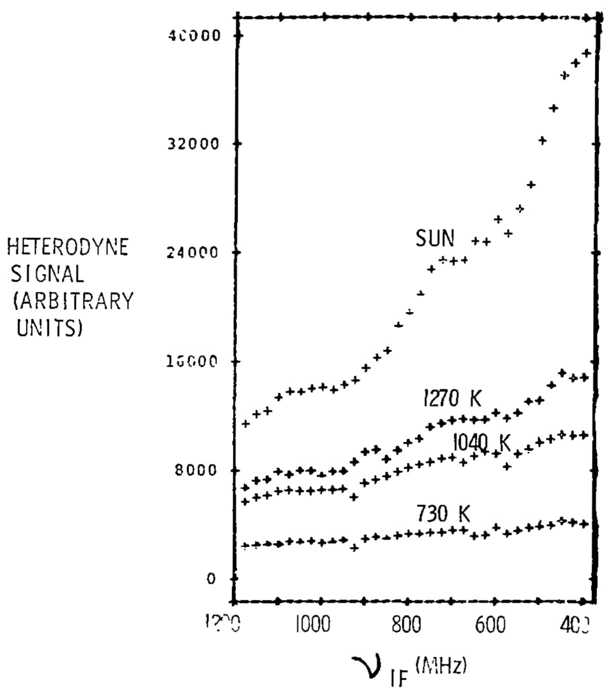

Figure 6.- Preliminary blackbody heterodyne efficiency measurements using spectral line receiver.