X-524-65-461

55396

10.6 MICRON COMMUNICATION SYSTEM

BY
NELSON McAVOY

NOVEMBER 1965

NASA — GODDARD SPACE FLIGHT CENTER — GREENBELT, MARYLAND

10.6 MICRON

COMMUNICATION SYSTEM

November 1965

Approved:

Henry H. Plotkin
Head, Optical Systems Branch

Robert J. Coates
Chief, Advanced Development Div.

Goddard Space Flight Center

Greenbelt, Md.

10.6 MICRON COMMUNICATION SYSTEM

Extensive investigation has been made by industrial concerns and NASA personnel on the utilization of lasers for NASA deep space communication requirements. Most of this analysis has been speculative in that it has been made on projected development of new lasers, new optical receivers, new modulators, improved tracking telescopes, and large defraction limited optics. The analysis made herein and the resulting proposed communication system is based on either equipment which is presently available or equipment which is to be modified by tried and proven methods. It is felt that the experiment to be discussed in conjunction with similar experiments on the optical technology satellite now being studied under contract NAS8-20115 can result in sufficient know-how to design a communications transmitter and auxiliary equipment for a Mars probe which will transmit a real time TV signal to Earth.

It is first necessary to establish the capability of optical receivers. This is done in Appendix I. Appendix I shows that the minimum detectable signal power is

$$P = \frac{Rh\nu B}{\eta} . \tag{1}$$

R is the signal to noise ratio, η is the quantum efficiency of the detector, B is the receiver bandwidth, and $h\nu$ is the energy per quanta. The limit shown in equation 1 results from fluctuation in the number of quanta in the local oscillator in case of heterodyne reception and fluctuation in the number of signal quanta in the case of envelope reception. The minimum detectable signal of equation 1 is a practical limit for heterodyne reception and a theoretical unattainable limit for envelope detection.[1,2,3] Shannon's law requires

$$P = \frac{R' h\nu B'}{\eta} \tag{2}$$

watts of signal power for an information bit rate B'. In practice it is convenient to have R' photons per bit approximately equal to ten to eliminate sophisticated data processing. It is interesting to note that obtaining equation 2 does not require the assumption of boson statistics while equation 1 does not require the assumptions of information theory. From information theory, one can establish that the bit rate, B', of equation 1 requires at least a bandwidth B.

It is seen from equation 1 that for a given power incident on the receiver and a given receiver bandwidth, one will have a larger signal to noise ratio, R, for lower frequency lasers. It should be noted that equation 1 and the latter statement do not hold when

$$e^{\frac{h\nu}{kT}} \approx 1 + \frac{h\nu}{kT}$$

i.e., not in the rf microwave or millimeter wave range. Parenthetically, neither does equation 2 remain valid in the rf microwave and millimeter range. This is illustrated in Figure 1, which shows receiver capability over the useful spectral range.

---

1. B. J. McMurtry, Sylvania Electronics Systems, El Segundo, California, Lecture Notes prepared for the AGARD Lecture Series on Orbit Optimization and Advanced Guidance Instrumentation, Dusseldorf, Germany, October 1964, G. Locovsky, R. F. Schwarz and R. B. Emmons, Proceedings of the IEEE, Vol. 51, No. 4, April 1963.
2. N. McAvoy, Advanced Development Division, GSFC Quarterly Report No. 6, March 1965, p.2.
3. F. Arams and Marie Wang, Proceedings of the IEEE, Vol 53, p. 329, March 1965.

One can conclude from equation 1 that neglecting availability of lasers, transmitter pointing accuracy, transmitter antenna gain, atmospheric absorption, and atmospheric coherence disturbance, one is better off working at frequencies in the range $h\nu \approx kT$ or $\nu = 6 \times 10^{12}$ cps (λ = 50 microns). At this wavelength thermal noise begins to predominate.

We next concern ourselves with the two practical parameters: 1) practical telescope apertures and consequently laser transmitter antenna gains; 2) practical limitations of pointing laser transmitters. It is reasonable to assume that pointing apparatus presently exists to either track from the ground or a satellite to within two arc seconds. We also assume that presently existing fabrication methods permit the use of infrared diffraction limited telescopes with apertures of at least one meter. Still neglecting the practical limitation of the availability of lasers throughout the spectral range, we are forced to ask the question: To how low a frequency can one go with one meter aperture telescopes and have laser transmitter antenna gains equivalent to two arc seconds beam divergence? The answer, from the diffraction limit equation, is a laser transmitter in the 10 micron region. I would like to stress that the preceding analysis is not an ipso facto result from recent startling laser developments in the 10 micron region - the carbon dioxide lasers which are capable of high power efficiency and monochromaticity.[4]

There are three major remaining problems with which to be concerned: 1) atmospheric absorption and scatter; 2) distortion of the plane isophasel

4. C. K. N. Patel, Bell Telephone Laboratories, Inc., Murray Hill, New Jersey, CW High Power N_2-CO_2 Laser, Applied Physics Letters, Vol. 7, No. 1, July 1, 1965.

surface of the transmitted beam by the atmosphere; 3) doppler shift of the transmitted beam causing large difference frequency in the optical mixer. The first of these problems can be dismissed from the results of the many DOD infrared propagation studies which have shown the 10 micron range to exhibit less absorption and scatter than the visual range. As to the second of these problems, it has been shown theoretically[5] and verified experimentally[6,7] that the coherence aperture of a beam propagated through the atmosphere varies with the 6/5 th power of the wave length. This results in a projected coherence area at ten microns larger than the one meter aperture telescopes to be proposed. The third of these problems, but the most stringent, is the requirements on response time of optical mixers. In the experiments that will be discussed, doppler shifts up to 500 megacycles will be experienced. Bulk photodetectors do exist in the 10-micron range which have sufficiently fast minority carrier mobilities to obtain 450 megacycles bandwidth photomixers.[8] It is theoretically possible, although it has not been verified in the infrared range, to generate optically tracking local oscillators from Brillouin scattering (parametric interaction) by rotating the interaction crystals.[9,10] This will alleviate the problem of needing photomixers with response times higher than 10^{-8} seconds.

5. D. L. Fried, North American Aviation, Electro-Optical Laboratory, Tech. Memo 118, Optical Heterodyne Detection of an Atmospherically Distorted Signal Waveform, July 1964.
6. M. Harwit, Phy. Review, Vol. 120, p. 1551, 1960.
7. Private communications, Dr. Frank Low, National Radio Astronomy Observatory, Greenbank, W. Va.
8. J. T Yardley and C. B. Moore, "Response Time of Ge:Cu Infrared Detectors", to be published, Applied Physics Letters.
9. R. Y. Chico, B. P. Stoichett and C. H. Townes, Physics Review Letters, Vol. 12, p. 592 (May 25, 1964)
10. D. A. Sealer and H. Hsu, "Parametric Interaction of Light and Hypersonic Waves" The Ohio State University R search Foundation Report 1579-16, Oct. 15, 1964.

In brief summation, the reasons for choosing the 10 micron range for optical communication experiments in contradistinction to the visual range are: 1) better lasers 2) large coherence areas 3) coherence areas compatible with diffraction limit of scopes 4) diffraction limit of scopes compatible with their tracking accuracy 5) high quality (accuracy) optics are not needed 6) best atmospheric window 7) smaller doppler shifts 8) less watt per information bit required at the receiver.

The following parameters are within the realm of realization for telemetry links between a Mars probe borne laser and receivers on the Earth:

Transmitter:

Pointing accuracy of laser - two arc seconds

Laser output power at 10.6 microns - 100 watt cw

Electrical power input to the laser - 2000 watts

Laser modulator power - 50 watts

Laser modulator bandwidth - 2 mc

Laser transmitter gain antenna - 1 meter aperture

Receiver:

Receiver antenna - 1 meter aperture (Cassegrainian)

Receiver tracking accuracy - two arc seconds

Optical mixer quantum efficiency - 20%

Optical mixer missmatch - VSWR of 5

Optical mixer bandwidth - 1 Gc

Optical local oscillator power - 20 dbm

IF tracking bandwidth - 10 mc

Information bandwidth - 5 mc

Base bandwidth - 1 kc (laser short term stability of 3×10^{10})

Figure 2 shows the parameters of the range equation for a typical $10.6\,\mu$ laser system and receiver capability.

In order to develop equipment for and establish the practicality of the previously discussed telemetry link, we propose to transmit signals to Echo II, and to receive the echo of these signals at various locations on the Earth. The first experiments will be done using a receiver superimposed with the transmitter and with only audio modulation of the transmitted signal. In this mode of operation, a portion of the transmitted, unmodulated signal can be used for a local oscillator. Thus, phase, frequency, and amplitude fluctuations caused by laser instability, atmospheric perturbations and nonspecularity of Echo II can be established.

Although extensive development is required in general for the instrumentation discussed, equipment is presently almost ready to do the first phase of the Echo II experiment, i.e., the transceiver mode of operation.

Figure 3 shows the return signal power from Echo II for tracking conditions that will be expected. Figure 4 shows the transceiving equipment which has already been designed for coherent receiver studies with helium-neon lasers. With only slight modification, this equipment can be used with $10.6\,\mu$ lasers. Figure 5 shows a block diagram of a possible configuration of the equipment needed.

In the receiving system, one has a choice between (1) using a 450 mc wide I.F. amplifier and detector, (2) tuning sidebands of part of the transmitted signal for a tracking L.O. and consequently having a fixed I.F. or (3) tuning the I.F. of the optical mixer from 0 to 450 mc. The three choices are in order of increasing difficulty and will be tried in that order.

APPENDIX I

Signal and Noise Relations in Optical Detectors

A detector, such as a photoemissive diode, photo-junction diode, or an extrinsic photo-resistor, gives off an electron for an absorbed photon. An ideal detector is one which produces at the output terminals of the detector one electron for every photon incident.* The basic circuit used in the detection process is shown in Figure 1.

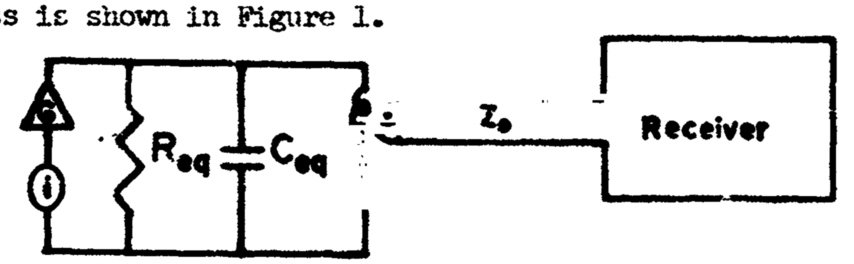

Figure 1. Basic circuit for current source detector. i is the current source equivalent to the current generated in the photoemission process. G is an equivalent amplifier for the photomultiplication. R_{eq} and C_{eq} are the equivalent capacitance and resistance of the photodetector.

It will be assumed that the frequency of the current, ω, will satisfy

$$\frac{1}{\omega} \gg R_{eq} C_{eq}$$

i.e. we are not limited by the time constant of the detector.

Photoresistive detectors such as the metal doped germanium cannot be represented with the equivalent circuit of Figure 1. There is no diode effect and a bias is required since the resistivity is changed by the incident light. The minimum detectable signal for coherent detection and the noise analysis is only slightly different than that for diodes.[1,2]

*Those who approach detection from the quantum electrodynamic point of view where detection electrons are obtained from the creation and annilation of photons also put the restriction on the ideal detector that its dimensions be less than the photon wavelength. We chose to deal with the practical detector sizes and degrade our output signal power by the phase difference between the current generated at two points on the detector separated by an appreciable part of a photon wavelength.

1. G. Lucovsky, R. F. Schwarz, R. B. Emmons, Photoelectric Mixing of Coherent Light in Bulk Photoconductors, Proc. IEEE, Vol. 51, No. 4, Apl. 1963.
2. H. Levinstein, "Extrinsic Detectors", Applied Optics, Vol. 4, p.639, June 1965.

Suppose a steady stream of photons is incident on a detector at an average rate $\bar{n}$ photons/sec. The root mean square deviation of the number of photons from the average, at a rate between ν and $\nu + \delta\nu$ is[3,4]

$$n_{\delta\nu} = \sqrt{2\bar{n}\,\delta\nu} \tag{1}$$

The same statistics apply for photoelectrons emitted from the photocathode. The current resulting from a flux of $n(t)$ photons/sec. on the photosurface before amplification is

$$i(t) = n(t)e\eta \tag{2}$$

e is the electronic charge and η is the quantum efficiency.

In terms of current, expression (1) is

$$n = \sqrt{2\frac{\bar{I}}{e\eta}\delta\nu} \tag{3}$$

Again applying equation (2), the root mean square deviation of the current at a rate between ν and $\nu+\delta\nu$ is

$$i_{\delta\nu} = e\eta\sqrt{2\frac{\bar{I}}{e\eta}\delta\nu} \tag{4}$$

With proper matching to the receiver, the power input to the receiver between frequencies ν and $\nu + \delta\nu$ will be

$$\frac{1}{2}i_{\delta\nu}R_{eq}G^2 = R_{eq}G^2 e\eta\bar{I}\,\delta\nu$$

The current may be due to several sources: i_s , due to the laser signal; i_{lo} due to a laser local oscillator (if any); i_b due to background illumination;

3. K. R. Spangenberg, Vacuum Tubes, McGraw Hill Book Co., New York, 1948.
4. M. Ross, Optical Receivers, To be published by J. Wiley and Sons, Inc.

or i_d due to dark current. The total shot noise power to be expected in the receiver with bandwidth B is

$$P_{\text{shot noise}} = G^2 R_{eq} e \eta B (T_s + T_{lo} + T_d + T_b) \tag{5}$$

Another contribution to the noise is the current arising from the beating of the local oscillator with the background radiation having the same isophasels and wavelength as the signal. In practice this contribution is too small to consider further here.

Finally, we must include the thermal contribution to the noise. The noise out of the receiver of Figure 1 due to thermal effects is

$$P_{th} = K T_{eq} B \tag{6}$$

where K is Boltsman's constant, and B is the bandwidth of equation (5). T_{eq} is the temperature of a fictitious resistor with value Z_o of Figure 1. The noise power within the bandwidth B at RF from a resistor R delivered to a matched load is KTB. Therefore, the T_{eq} is defined as the temperature of a fictitious resistor on the input terminals of the receiver which will simulate the noise generated inside the receiver, plus the actual thermal noise of the detector[5]. The receiver thermal noise will be the dominate thermal source in most cases except, perhaps, when liquid helium cooled masers, and parametric amplifiers in the UHV range are used. Notice that this noise appears at the output of the detector and, therefore, is not acted upon by its gain.

5. See Noise Figure Standards, Proc. I.R.E.

For establishing the current due to the signal we consider first a situation in which the detector is illuminated simultaneously by a signal and local oscillator; they are plane polarized in the same direction and have the same isophasel surface. The power absorbed by the detector is

$$P(t) = (E_s(t) + E_{lo}(t))^2 A\sqrt{\frac{\epsilon}{\mu}} \qquad (7)$$

where E_s is the signal electric field at the detector,

E_{lo} is the local oscillator electric field at the detector,

$\sqrt{\frac{\epsilon}{\mu}}$ is the admittance of free space, and,

A is the detector area.

This is equivalent to the arrival of photons at a rate $\frac{P(t)}{h\nu}$ photons per second, and the resultant generated current would be

$$i(t) = e\eta\left|\frac{P(t)}{h\nu}\right| \qquad (8)$$

Equations (7) and (8) give

$$i(t) = \frac{e\eta}{h\nu} A\sqrt{\frac{\epsilon}{\mu}}\left(E_s^2(t) + E_{lo}^2(t) + 2E_s(t)E_{lo}(t) \right) \qquad (9)$$

Only the last term in the brackets contributes to signal current at the IF frequency, $|\omega_s - \omega_{lo}|$. If the electric field at the various frequencies is represented as

$$E = E_0 \sin(\omega_i t + \frac{\omega_i}{c}x + \theta_i),$$

$$i(t) = i_s(t) + i_{lo}(t) + i_{if}\cos|\omega_s - \omega_{lo}|t \qquad (10)$$

where

$$i_{if} = \sqrt{2 I_s I_{lo}} \qquad (11)$$

The average output power delivered to a matched load, after the tube gain acts upon the current, would be

$$\overline{P}_{if} = \frac{1}{2} i_{if} R_{eq} G^2 \qquad (12)$$

The signal-to-noise ratio can now be obtained by combining eq. (12), eq. (5) and eq. (6).

$$S/N = \frac{1/2\, i_{if} G^2 R_{eq}}{K T_{eq} B + e G^2 B R_{eq} (i_s + i_{lo} + i_b + i_d)} \qquad (13)$$

or, from eq. (11)

$$S/N = \frac{\overline{i}_s \overline{i}_{lo} G^2 R_{eq}}{K T_{eq} B + e G^2 B R_{eq} (\overline{i}_s + \overline{i}_{lo} + \overline{i}_b + \overline{i}_d)} \qquad (14)$$

This is the general expression usually seen for photodetector S/N.[6,7,8]

The usual conditions of heterodyne detection require that the L.O. be sufficiently intense that

$$i_{lo} > i_s + i_b + i_d$$

and

$$e G^2 R_{eq} B \overline{i}_{lo} > K T_{eq} B$$

Under these conditions, eq. (14) reduces to

$$S/N = \frac{\overline{i}_s}{e B} \qquad (15)$$

---

6. B. J. McMurtry, Sylvania Electronics Systems, El Segundo, Calif., Lecture Notes prepared for the AGARD Lecture Series on Orbit Optimization & Advanced Guidance Instr., Dusseldorf, Germany, Oct. 1964, G. Lucovsky, R.F.Schwarz & R. B. Emmons, P. of the IEEE, Vol. 51, No. 4, April 1963.
7. B.M. Oliver "Signal-to-Noise Ratios in Photoelectric Mixing", Proc.IRE (Correspondence), Vol. 49, pp.1960, 1961; Dec. 1961.
8. G. Lucovsky, M.E. Lasser, & R.B. Emmons, "Coherent Light Detection in Solid State Photodiodes", Proc. IEEE, pp. 166 - 172, Jan. 1963.

Incorporating eq. (8),

$$S/N = \frac{\eta \bar{P}_s}{h\nu B} \tag{16}$$

The incident power which results in a S/N of unity is

$$\bar{P}_{min} = \frac{h\nu B}{\eta} \tag{17}$$

The results are very similar for the extrinsic semiconductor for photoresistive detectors. When the detector time constants are taken into consideration, one will get[1]

$$S/N = \frac{\eta \eta_a P_s}{h\nu \,\Delta B(1+\omega_{if}\tau_o)} \tag{18}$$

where τ_o is the carrier lifetime, η_a is fractional absorption by the detector.

This treatment also includes the case of direct (or incoherent) envelope detection, in the absence of a local oscillator. Instead of an IF signal, we consider detecting a signal at a modulation frequency, within a bandwidth B. In equation (13), we should replace i_{if}^2 with $m^2 \bar{i}_s^2$, where m is the modulation index, and set $i_{lo} = 0$. The expression for S/N becomes

$$S/N = \frac{1/2\, m^2 \bar{i}_s^2 G R_e}{K T_{eq} B + 2eG^2 R_{eq}(\bar{i}_s + \bar{i}_b + \bar{i}_d)} \tag{19}$$

In the absence of a local oscillator, we cannot arbitrarily neglect terms in the denominator. If the detection process were limited by thermal noise,

$$K T_{eq} B \gg 2 e G^2 B R_{eq} (i_s + i_b + i_d) \tag{20}$$

Equation (19) becomes:

$$S/N = \frac{\frac{1}{2} m^2 (\frac{e\eta}{h\nu} \bar{\bar{P}}_s)^2 G^2 R}{K T_{eq} B} \tag{21}$$

The power which is equivalent to the noise in this case is

$$P_{nep} = \frac{h\nu}{m e G \eta} \sqrt{\frac{2KTB}{R}} \tag{22}$$

This is the common parameter used for a figure of excellence in IR detectors.

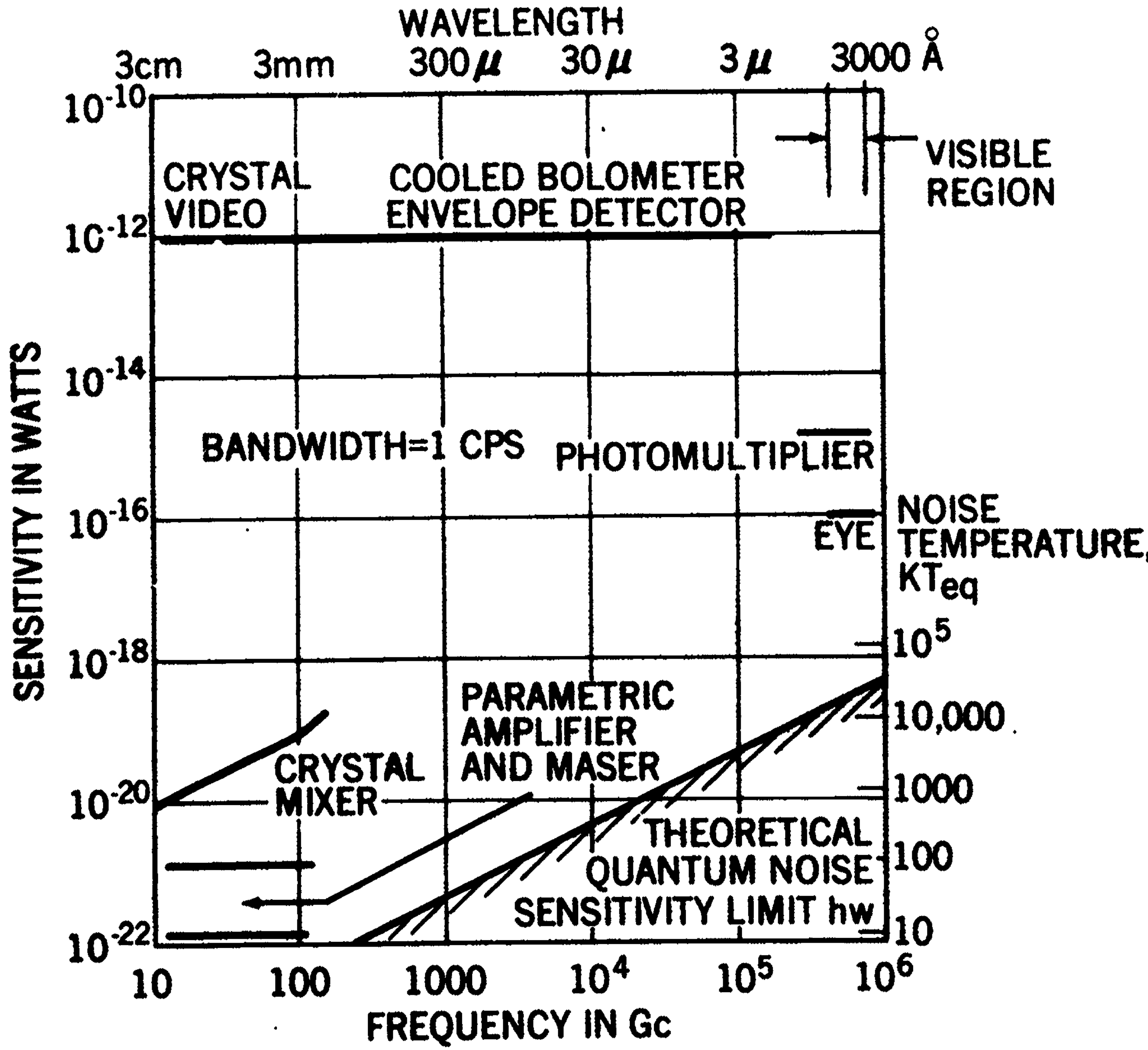

FIGURE 1. SENSITIVITY OF RECEIVERS FROM RF TO VISUAL RANGE

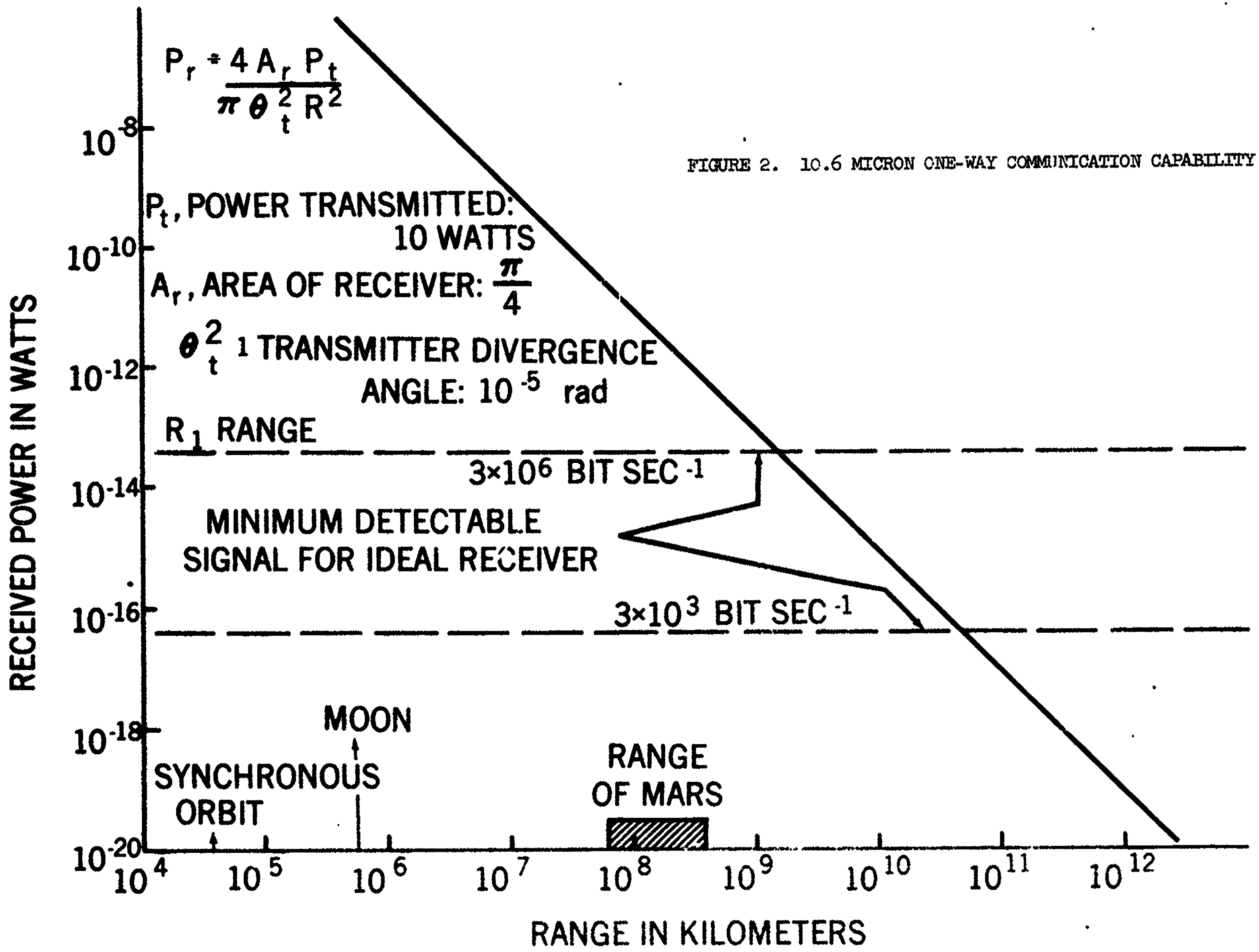

FIGURE 2. 10.6 MICRON ONE-WAY COMMUNICATION CAPABILITY

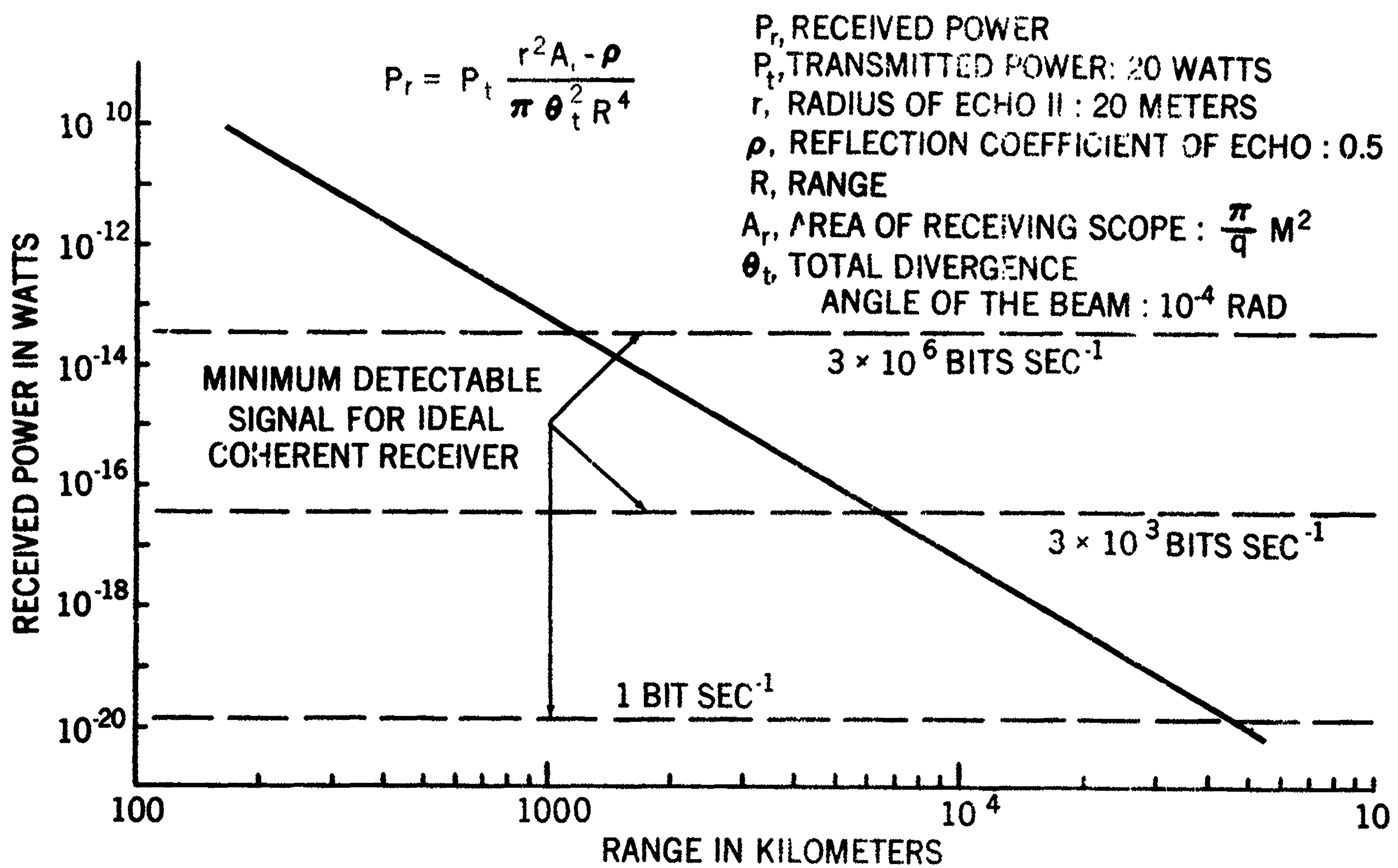

FIGURE 3. POWER RECEIVED IN A REFLECTED BEAM FROM ECHO II USING A 10.6 MICRON TRANSCEIVER

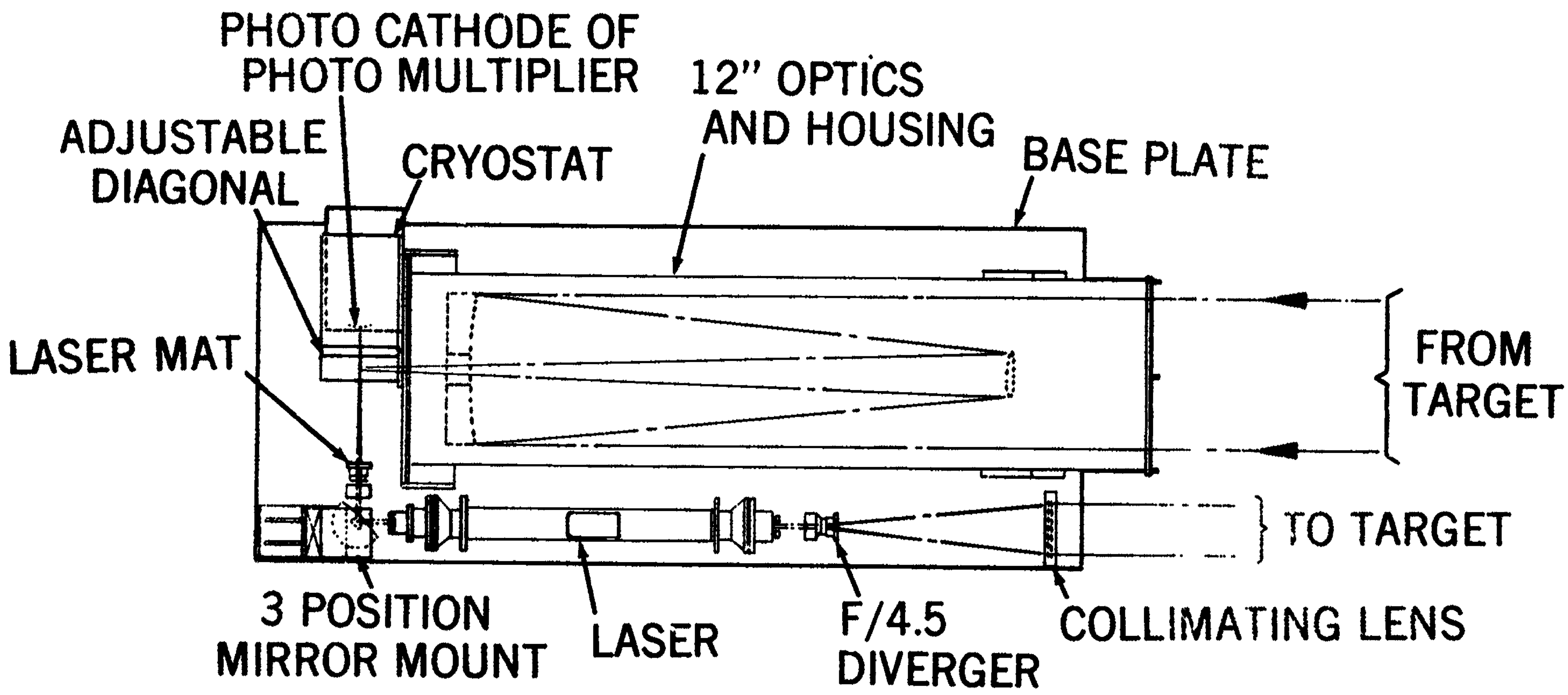

FIGURE 4. HOMODYNE TRANSCEIVER FOR 6328 Å LASER WITH 12-INCH APERTURE RECEIVER TELESCOPE.

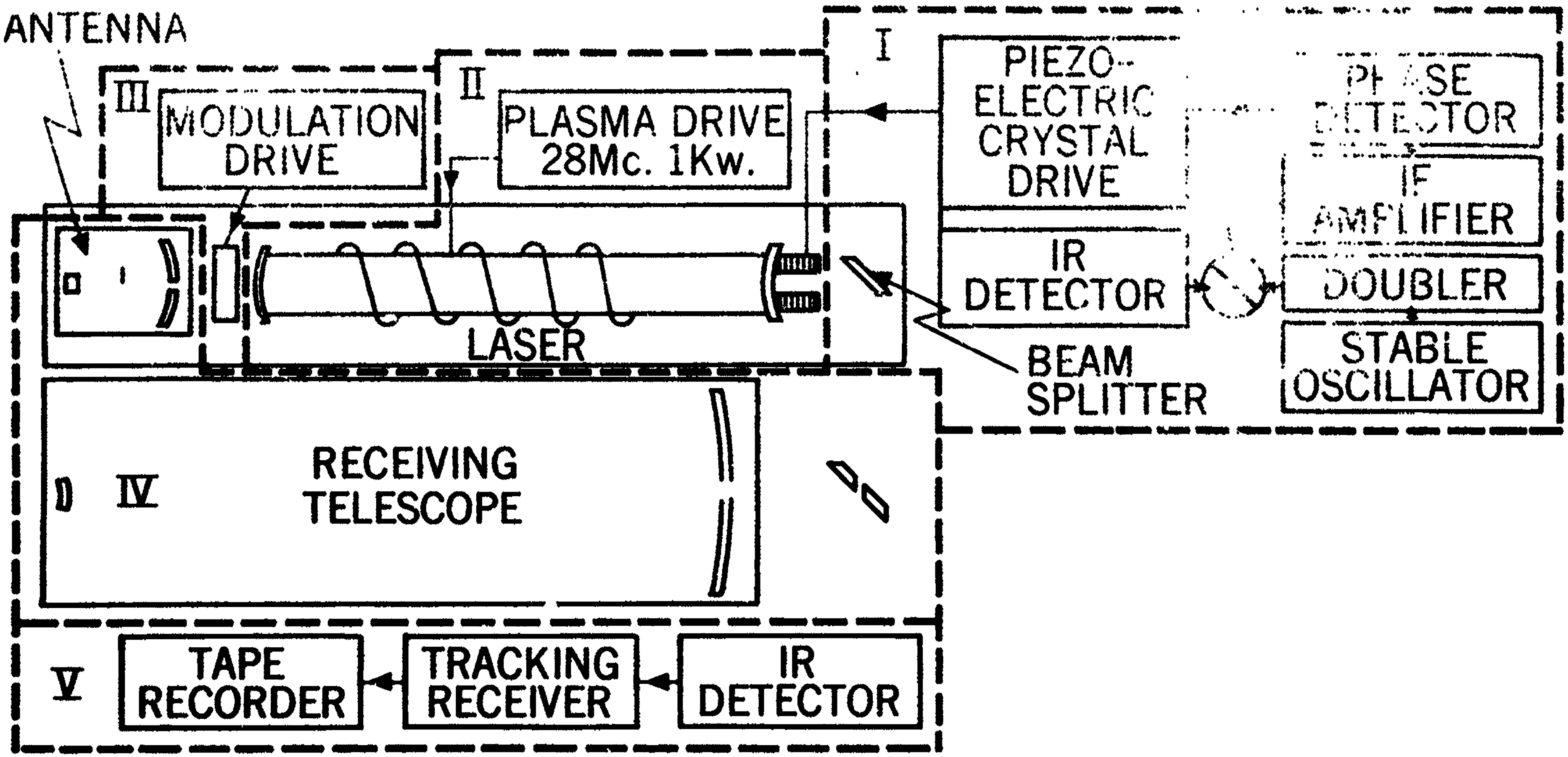

FIGURE 5. BLOCK DIAGRAM OF 10.6 MICRON HOMODYNE TRANSCEIVER. THE MODULES ARE: I LASER STABILIZER, II LASER, III LASER MODULATOR, IV MIRRORS AND PLATFORM, V OPTICAL HETERODYNE RECEIVER.

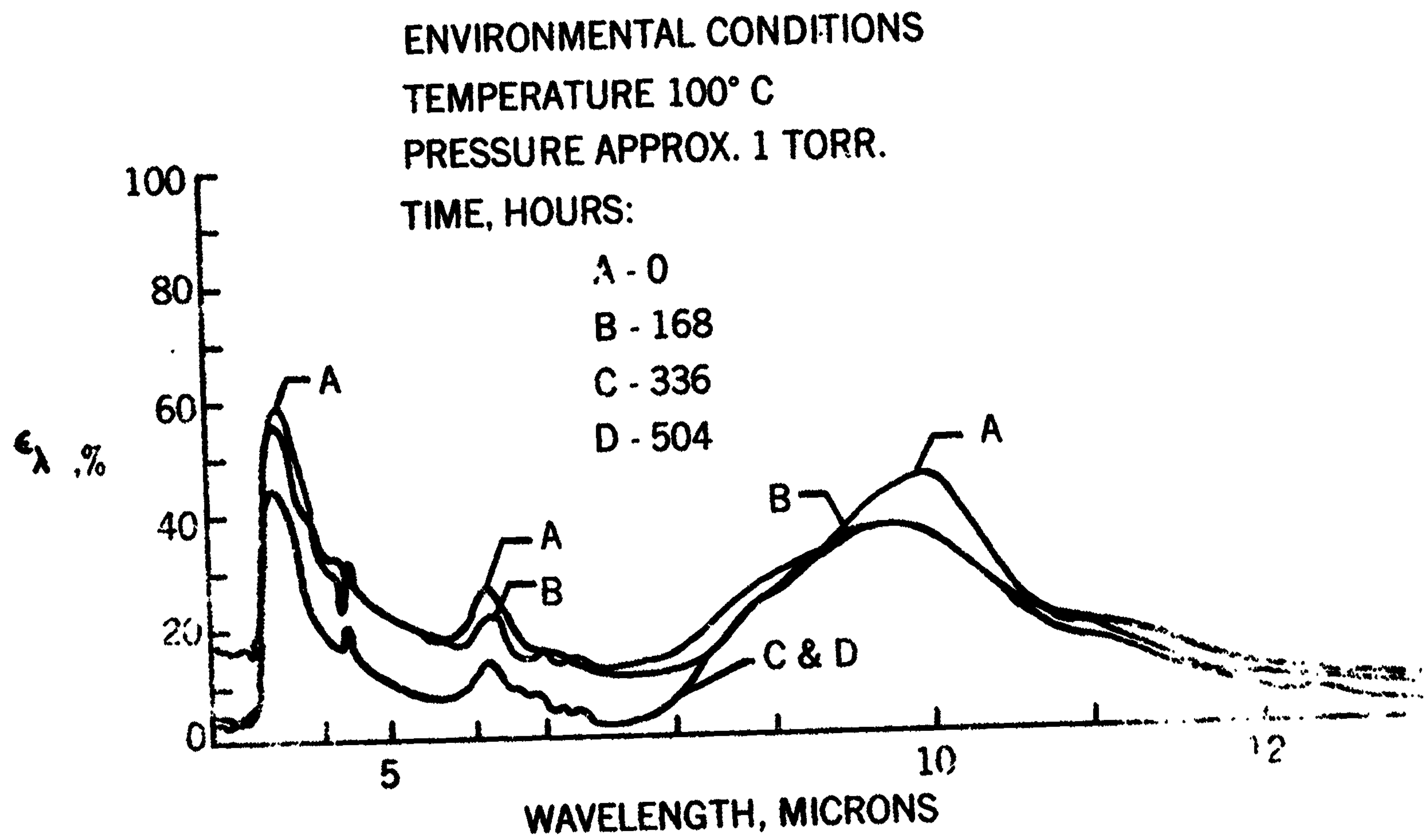

FIGURE 6. THERMAL EFFECTS IN THE INFRARED SPECTRA OF ECHO II.