A 10.6 μm TERRESTRIAL COMMUNICATION LINK*

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Summary This paper reports the development of an experimental type 10.6 μm laser communication system, consisting of a transmitter terminal and a receiver terminal, designed to operate one wav over a nominal five-mile path. The system provides a 5 MB/s digital data channel using a frequency shift keying format and optical heterodyne detection with a mercury cadmium telluride detector operating at a temperature of 77°K.

The system is the first CO_2 laser heterodyne communication system which is capable of hands-off, uninterrupted operation in a nonlaboratory environment. The achievement of single frequency operation of a laser transmitter and local oscillator in a field system is the result of more than seven years of research and development. Laser frequency purity, stability and control, all questions of primary concern previously, have been proven satisfactory with the development of this system.

This paper reports the operation of the system during environmental tests, over a 4.1-mile test range, a 19.5-mile test range at the Hughes facility, and over a three mile test range at Ft. Monmouth, N.J. over a period of several months. During a period of 1320 hours of continuous operation, the system was inoperable for 65 hours due to weather conditions, demonstrating a reliability of 95%.

Introduction A detailed description of the system was given at ITC-72. However, at that time, the system had not been in operation a sufficient length of time to provide operational data. This paper, therefore, is devoted entirely to reporting on the system performance through real atmospheres.

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The reliability of the system has been improved to the point where only weather factors seriously interrupt the performance. The improvement in reliability of the system over prior art is the result of a number of technical factors:

- Metal ceramic laser discharge tube provides added strength and reliability to the laser

- Sealed-off laser life is extended to more than 3000 hours

- Air cooling of laser transmitter and local oscillator laser eliminates cooling water failure problems

- Laser “grating” mirror on local oscillator provides simplified transition control of LO laser

- Intracavity optical FM using cadmium telluride-low loss material and excellent coatings provide good laser performance with modulator in cavity

- Long holding time dewar permits operation for 50 hours on 1 liter of liquid nitrogen.

The 10.6 µm heterodyne laser communication system has high operating margin by virtue of its high power capability, high source efficiency, and near ideal detection capability. Its potential for use through the atmosphere, where extreme variations in atmospheric transmission loss may occur, offers greater promise than any other laser communication system.

During the period from 27 October through 3 November 1972, communication system tests were conducted using the system over a 20-mile path between Malibu and El Segundo, California. The transmitter was located at the Hughes Research Laboratories at Malibu and the receiver located on the eleventh floor of the Hughes Space and Communications Group building at El Segundo. About two-thirds of the path was over water at an average elevation of 300 ft. The data taken during this period included signal spectrum, carrier-to-noise ratio and bit error rates for various weather conditions.

During the period from 1 December to the present, the system has been under test over a three-mile path at Ft. Monmouth, N.J. For this short distance, the beamwidth of the transmitter was broadened out to make the alignment less critical. The transmitter is located in a tower which is subject to movement from variable wind loading and requires a broader beam to maintain pointing under these conditions. Operational tests were performed for a variety of weather conditions including rain, snow and fog.

Performance and Testing: Predicted Performance If all the transmitted signal is captured by the receiver optics, the carrier to noise (C/N), is calculated to be 116 dB. In practice there are a number of factors which prevent this high carrier to noise ratio from being reached; detector saturation and damage, amplifier saturation, and local oscillator noise. In addition, for path lengths longer than a few thousand feet, propagation and diffraction losses play a part in the C/N ratio. For a path length of 8 km for which the system was designed, the path loss due to diffraction is 21 dB, and that due to attenuation in clear air is 4 dB. Combining these numbers, the C/N for clear air operation with full collimation will be 91 dB.

For a bit error rate of 10^{-6} or less, a demodulated signal-to-noise ratio of 14 dB is required, or a carrier-to-noise ratio of about 17 dB. For these conditions, the system margin, that is the excess signal available over that required for a 10^{-6} bit error rate is 74 dB. Table I lists these predicted performance values.

Table I
Predicted Performance Values

Transmitter Power	1 W
Receiver NEP	2.5×10^{-19} W/Hz
Data Rate Requirement	5 MB/s
i. f. Bandwidth	10 MHz
Carrier to Noise Ratio 5 mile path, clear air	91 dB
System Margin (excess, of 14 dB required for 10^{-6} bit error rate)	74 dB
Extinction in rain and fog	20 mg/m^3 liquid water content or 20 mm hour rainfall

Environmental Tests The transmitter and receiver were set up in the test chamber (Fig. 1(c)) pointed at each other, with the shutter closed and the manual attenuator in place, simulating a signal level at about five miles. The system was cold soaked for 5 hours at an indicated temperature of 35°F (1°C), which was as near 32° as the chamber would regulate. The refrigeration plant caused vibration of the entire chamber, and the system had to be repainted at the beginning of the test. Despite the vibration, the system locked up and began transmission within twenty minutes of activation and operated normally.

The system was allowed to warm up to 50°F (10°(C) and tests were repeated. The refrigerator was switched off for these tests to eliminate the vibration. The system was operated at 68°F (20°C).

To operate above ambient, space heaters were placed in the chamber. No regulation was available and the chamber air temperature measured as high as 110°F (43°C) with a laboratory thermometer. Again, at this elevated temperature no operational problems were encountered.

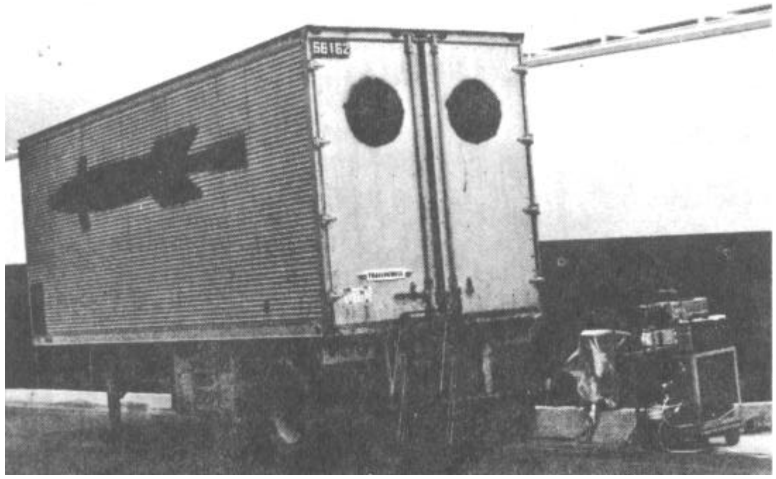
Figure 1 shows the equipment during the environmental testing.

Performance over 4.1-Mile Test Path For this test the transmitter was set up on a Hillside fully exposed to the weather with the receiver located inside a laboratory at the Hughes Malibu facility. Tests were conducted over an 8 hour period from 9:45 a.m. to 5:45 p.m. on 18 October 1972. Weather observations made at the receiver site are shown in Table II.

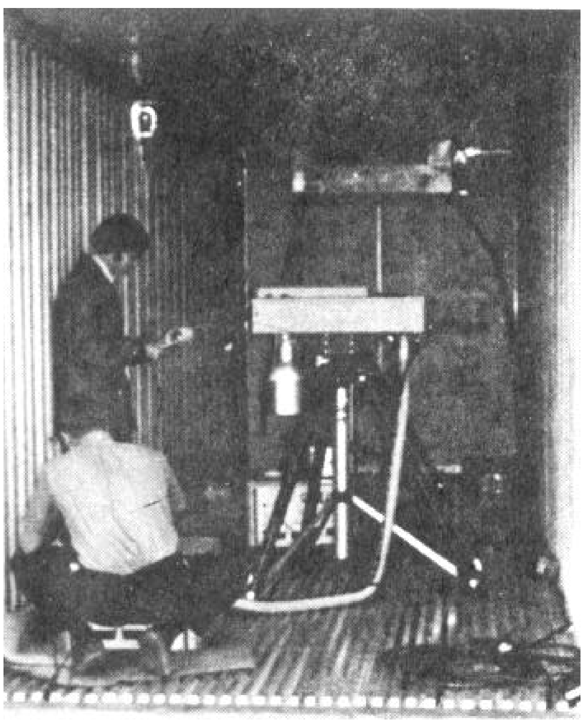
Communication from the transmitter to the receiver was maintained using the laser equipment once acquisition was complete. Figure 2 shows the system set up for the 4.1-mile tests.

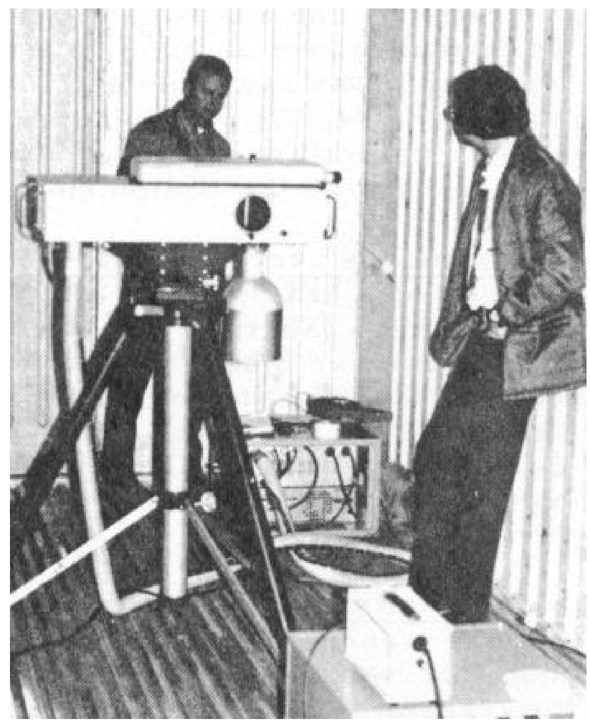
- <u>Acquisition</u> The receiver was set up and waiting in the laboratory before the transmitter arrived at the remote site. Set-up time for the transmitter was about 5 min; during this period the receiver was aimed at the transmitter. Five min after turning the transmitter on, communication was established over the laser link.

- <u>C/N Margin</u> Measurement of C/N requires accurate attenuation in the signal path. Attenuation at the i.f. amplifier in the receiver is not practical due to nonlinearities in the detection process at high signal levels. Calibration of thin mylar sheets is not accurate at high attenuation due to interference between the many required layers and due to phase distortion caused by varying thicknesses across the larger aperture. The most practical attenuator for field testing consists of a calibrated variable aperture placed in front of the transmitter aperture. Accuracy of this form of attenuation is dependent only upon knowledge of the power distribution across the aperture. Minimum aperture setting available was 2 mm, corresponding to an attenuation of 58 dB. C/N at this setting (estimated from the AGC voltage at the i.f. amplifier) was 7 dB. The total C/N is thus 65 dB.



(a)





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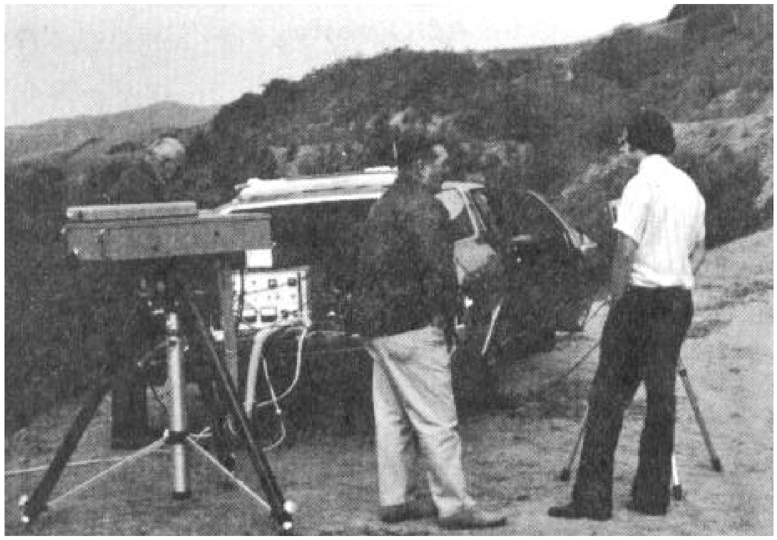
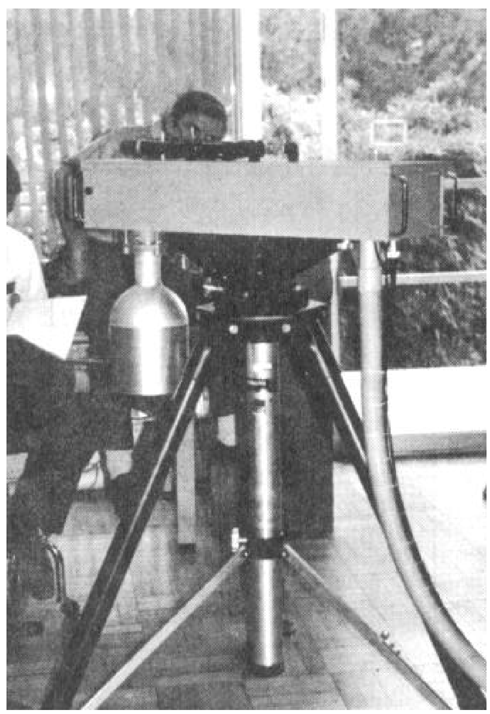
(c)

Fig. 1. Environmental testing.



(a) Transmitter



(b)

Fig. 2. 4.1-mile test range.

Table II
Weather Conditions During 4.1-mile 8-Hour Test

Time	Temperature, °F	Relative Humidity,	Pressure, in.	Wind, mph
9:00 a.m.	65	66	30.00	0 to 5
10:00 a.m.	66	62	30.00	0 to 5
12 noon	70	56	30.00	0 to 5
2:00 p.m.	70	56	30.00	0 to 5
4:00 p.m.	73	54	29.96	0
6:00 p. m.	71	64	29.93	0
Notes: Morning overcast, clearing about noon. Drop in pressure followed by thunderstorm in late evening.				

Considering attenuation and range, the predicted C/N for this condition should have been about 88 dB. The measured value of 65 dB had an uncertainty of ± 3 dB. At best, then, 20 dB was lost due to scintillation, misalignment, and imperfect collimation. The estimated scintillation effects were 12 to 16 dB, leaving 4 to 8 dB unexplained.

Waveform measurements are shown in Fig. 3. Figure 3(a) is a sample of the bit stream after transmission through the system at 1.5 mB/s, with Fig. 3(b) showing the “eye pattern” output. Attenuation in the beam at this time was 33 dB.

Performance over 19.5-Mile Path The tests described in the following paragraphs were conducted over a 19.5-mile path Although this distance is considerably greater than the design range of the equipment, it was advantageous to conduct such an exercise.

Description of Experiment The transmitter was located at the Malibu facility operating through an open door in a laboratory exposed to the east. Aiming of the transmitter was achieved on a day when the weather was clear and when the receiver terminal was visible through the sighting optics. The transmitter terminal included two sources of signal information: a black and white TV camera and a pseudo-random word binary signal generator having a NRZ data rate of 1.5 MB/S.

The receiver terminal was located on the eleventh floor of the Hughes Space and Communications Group building, (366) in El Segundo, California. The window pane on the west exposure was removed and replaced with a plexiglass panel with a 6-in. diameter hole cut for the beam to enter. The receiver head was situated to receive energy through the 6-in. hole. Peripheral equipment at the receiver terminal included a television monitor, a HP 8553 spectrum analyzer and a chart recorder. A view from the eleventh floor window is shown in Fig. 4.

A map of the geographic area is shown in Fig. 5. The distance between the two terminals was 19.5 statute miles. The weather was variable from slight haze to moderate haze, visibility varied from 1/2 to 5 miles. Temperature in morning hours was near 55°F, warming to 72°F by midafternoon. Humidity varied from 70% in the morning hours to about 40% in the midafternoon hours. About 2/3 of the path was over water an an average elevation of 300 ft.

- **Channel Quality** The following series of channel quality tests were conducted on 31 October:

  - 30 MHz i.f. Spectrum (Fig. 6) - Using a digital input signal, the i.f. spectrum was recorded for various drive levels of the transmitter input.

  - Video Spectrum - The video spectrum of the digital data was measured on the spectrum analyzer for a full transmitter modulator drive level.

  - Digital Waveform (Fig. 7) - The digital waveform was measured at the output of the discriminator.

  - Eye Pattern Tests - Eye patterns were photographed for various exposures showing clear decision areas.

  - Bit Error Measurements (Fig. 8) - Difficulty of measuring bit errors was encountered because error detector would lose synchronization when the signal level dropped to a certain level and more than a few bits are lost. Thus, these measurements consisted of measuring the average time between drop-outs during which time no bit errors occurred. The average time between errors was 32.4 s. If one assumes at least 1 bit error during each dropout, the calculated minimum bit-error rate is 2.05×10^{-8}. If 100 bits are lost during each dropout, the bit-error rate is 2.05×10^{-6}.

- C/N Measurements. - The logarithmic i.f. amplifier section of the spectrum analyzer was used to provide a calibrated C/N output. The spectrum analyzer was connected to the output of the detector preamplifier. A test signal was injected in order to provide the calibration of the chart recorder.

- C/N Calibration - Using a test signal injected at the output of the detector preamplifier, a C/N calibration was made. The level of the injected signal is shown in dBm in Fig. 9.

- Continuous 1-hour run (Fig. 9) - Using a reduced chart speed, a continuous 1-hour run was conducted. Figure 9 shows three 8-min samples from this run. This run started at 4 p.m., one hour before sunset, with scintillation depths reaching 10 dB. At 4:15 p.m. a sheet of saran wrap was stretched over the port hole in the window to help eliminate gusts of cold air entering the port. An immediate reduction in the scintillation amplitude was noticed.

  At 5 p.m. the turbulence was reduced to significantly less than I dB peak-to-peak variation.

- C/N Measurements - 2-Hour Run Without Repointing The previous measurements required periodic repointing of the receiver in order to stay in alignment with the incoming beam. Typically, repainting is required every 30 min during the morning hours or during the evening hours. During the period from 9:45 a.m. to 11:45 a.m., 2 November 1972, a run was conducted where the receiver was not repainted. The initial C/N was the order of 55 dB with scintillation amplitude reaching 20 dB. Pointing was out of alignment after 2 hours of operation. The cause of the misalignment of the receiver is not known. During the 5 days of operation, the transmitter required no repainting. It has been suggested that the eleventh-f-loor of an industrial building may be sufficiently unstable to account for these variations.

Performance Over 3-Mile Test Path at Ft. Monmouth, N.J This section describes the collection of data and system performance tests conducted in a field environment over a nominal three-mile path in the vicinity of Fort Monmouth, New Jersey. After approximately 1750-hours of operation, including a period of continuous operation from 2 March 1973 through 23 April 1973, no degradation of the system's performance characteristics was observed that could be attributed to any of the electronics, optical or mechanical components. The system performed satisfactorily during heavy rain, fog with a visibility of approximately 3/8 of a mile, and light to moderate snow.

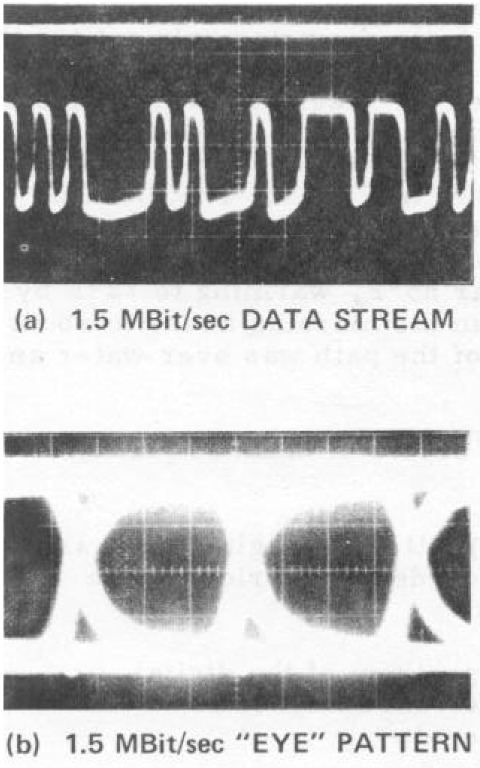


Fig. 3. Waveforms over 4.1 mile link with 33 dB attenuation in beam.

Fig. 4. View from 11th floor window of Space and Communication Building 366. Malibu transmitter location shown by arrows.

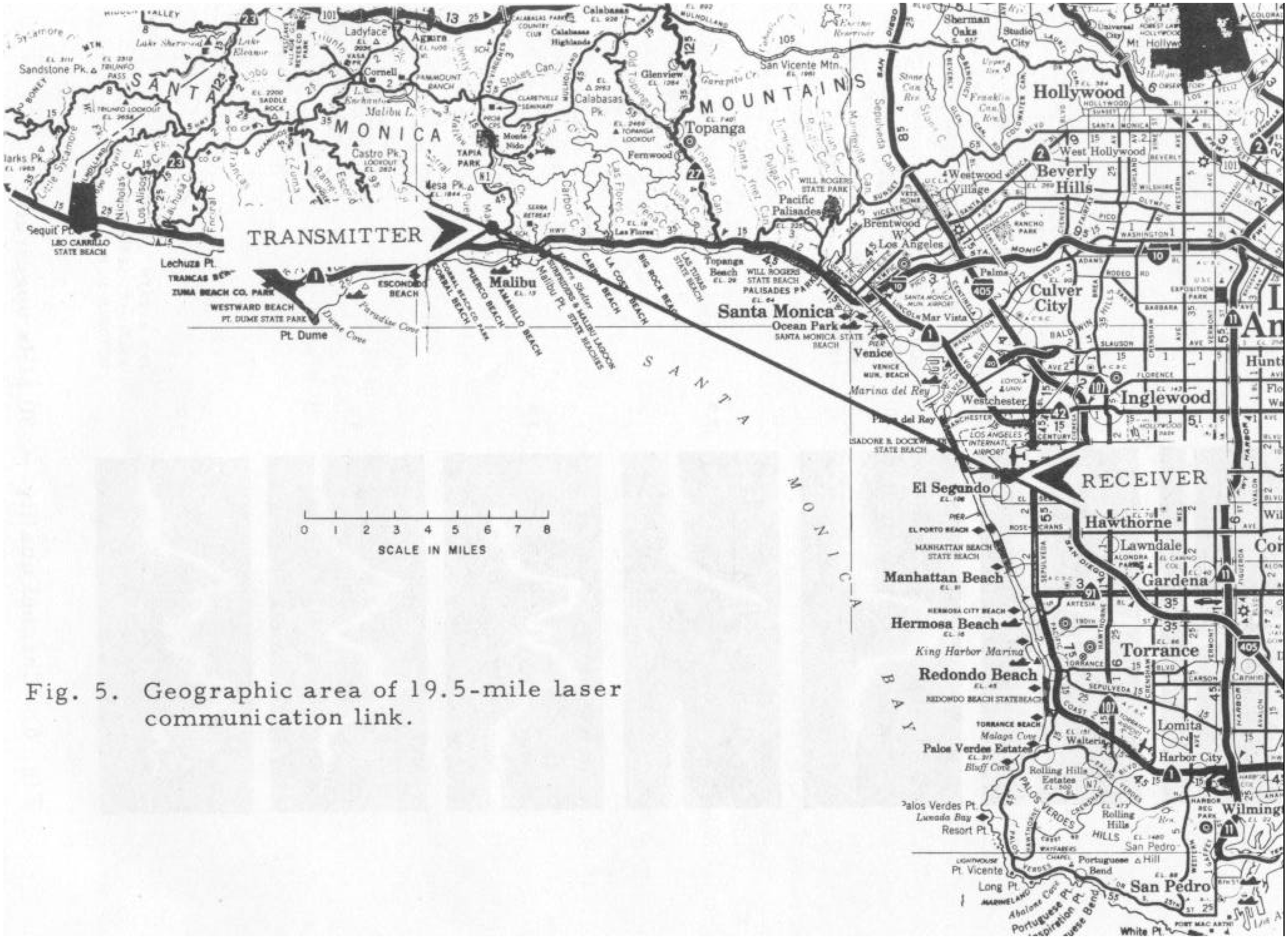


Fig. 5. Geographic area of 19.5-mile laser communication link.

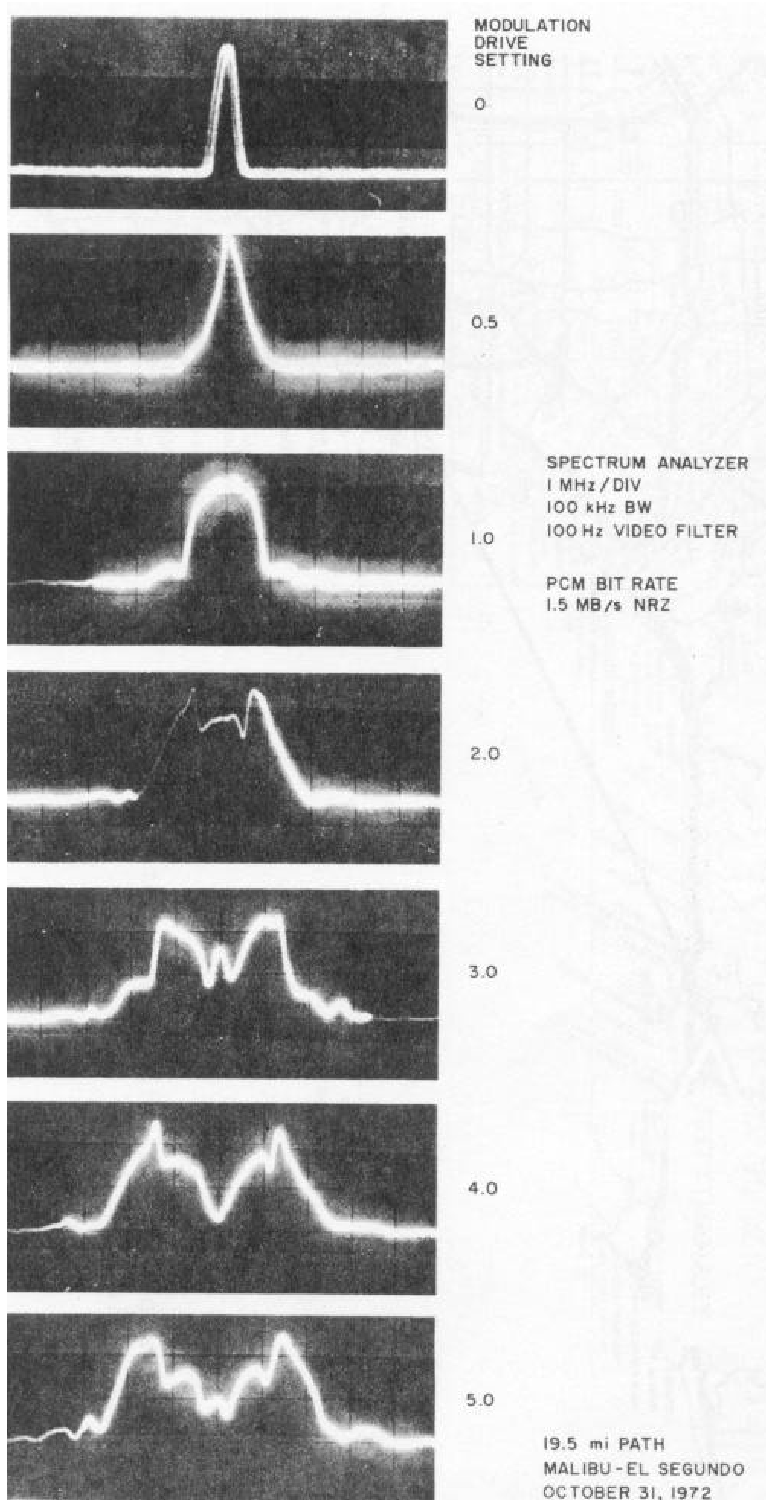


Fig. 6. Channel quality - 30 MHz spectrum.

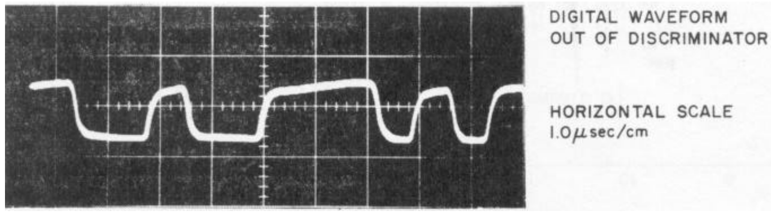


Fig. 7. Channel quality - digital waveform.

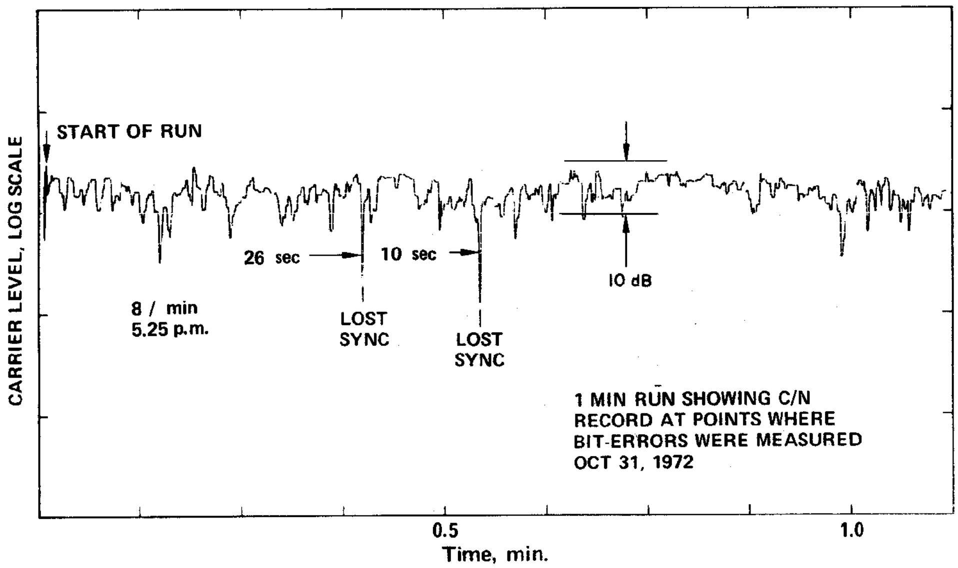


Fig. 8. Bit-error measurements (one minute sample).

3-Mile Test Range The line-of-sight atmospheric test facility, located at Fort Monmouth, consists of two shelter installations and meteorological measurement equipment. Figure 10 shows the path profile between the terminals; a photograph of the path as seen from the receiver shelter, a photograph of the transmitter shelter, and the receiver shelter located atop a four story building.

In order to conduct long term measurements of the average carrier level it was necessary to broaden the transmitter bearnwidth to approximately 1 mrad. In addition, the exit port of the transmitter, the entrance port of the receiver and the 6-in. hole cut in the window in front of the receiver were each covered with stretched membrane of Saran wrap. The ports were covered in order to prevent condensation on the telescope optics, while the hole in the window was covered to eliminate severe fading caused by the turbulent interface of air currents at the hole in the window. The receiver's liquid nitrogen dewar was refilled automatically at 24-hour intervals, thus permitting continuous unattended operation.

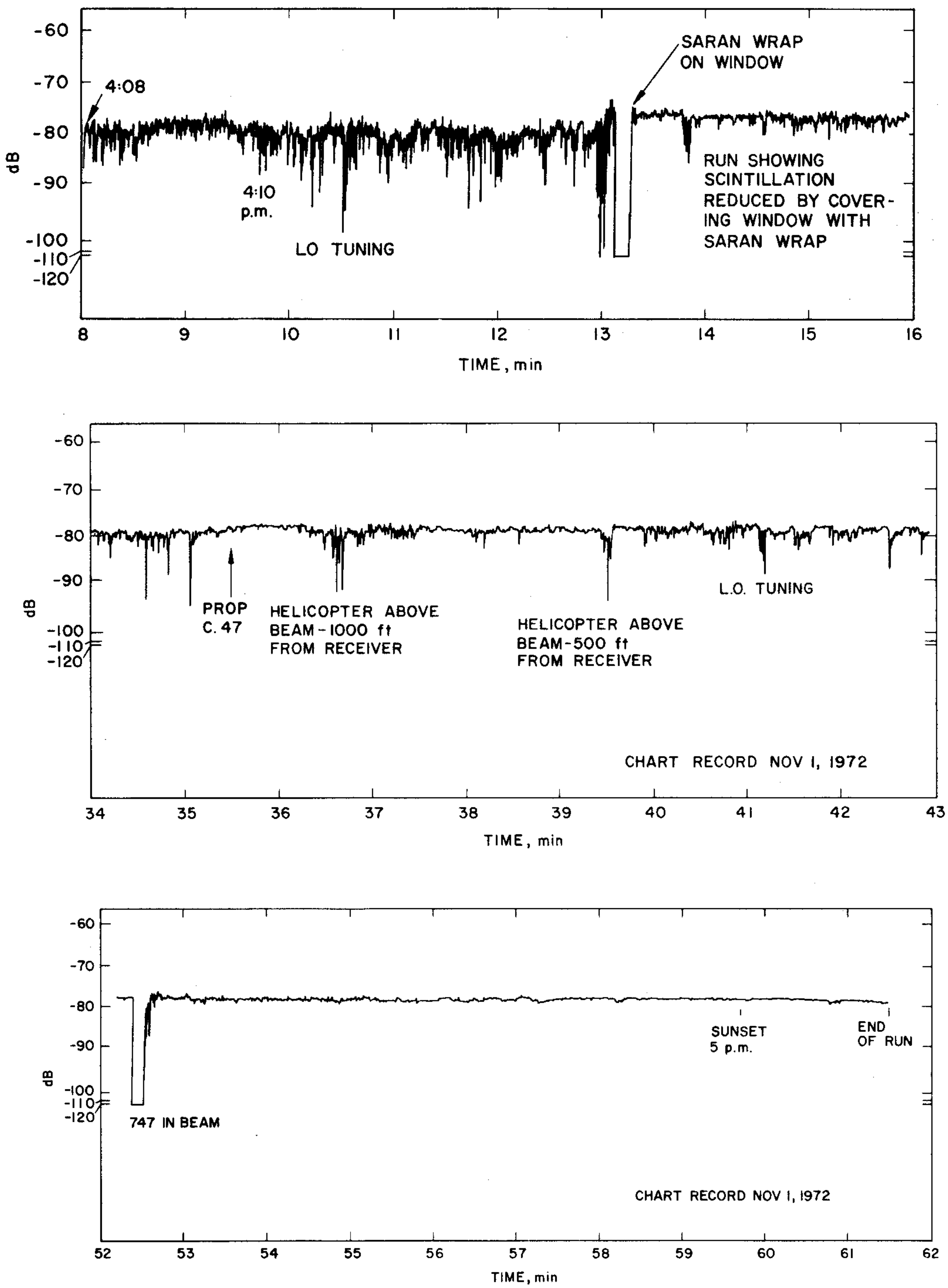
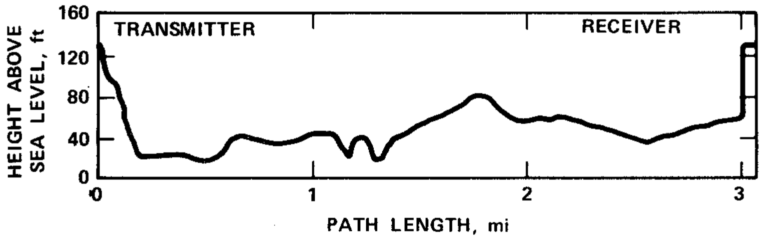


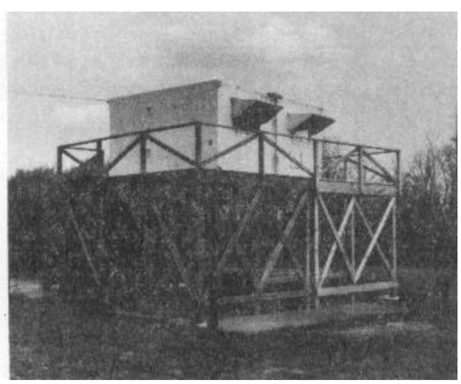
Fig. 9. C/N measurements - continuous 1-h run (8-min samples).



Path profile

View of path from receiver site

Receiver shelter



Transmitter shelter

Fig. 10. Fort Monmouth 3-mile test range.

System Performance The performance characterization tests were divided into three phases: (1) frequency spectrum analysis for digital and analog TV signals; (2) eye pattern photographs to provide an estimation of signal to noise ratio; (3) long term recording of the average carrier level. In general, these tests verified that this system performance conformed to the theoretical analysis of a binary, frequency modulated (FM), low modulation index communications system.

- **Frequency Spectrum Tests** The received pseudorandom bit sequence as photographed from an oscilloscope is shown in Fig. 11(a), and its demodulated baseband spectrum is shown in Fig. 11(b). Figure 11(c) shows a TV picture of the transmitter via the link.

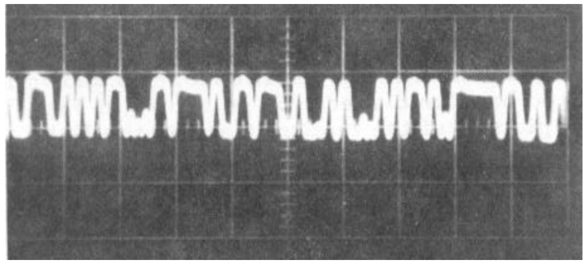
- **Eye Pattern Tests** The eye pattern tests were conducted by transmitting the pseudorandom bit sequence and observing multiple traces on an oscilloscope sweeping at a submultiple of the bit rate. Figure 12(a) shows an eye pattern at 4.608-MB/s rate with a sequence length of 511 bits in a direct back-to-back test. A typical received eye pattern through the system, Figure 12(b), shows a very clean decision center even with approximately 15 dB fades due to scintillations. In general, the eye pattern measurements have indicated an excellent average error rate under clear weather conditions. During heavy rain or fog with visibility of less than 3/8 of a mile the eye pattern was much poorer indicating poor error rate. It has beep estimated that with full collimation, error rate of better than 1×10^{-6} would be achieved for all but the most severe weather conditions.

- **Carrier Level Tests** During long term average carrier level measurements, a pseudorandom bit sequence was transmitted and the receiver AGC level recorded on a strip chart recorder.

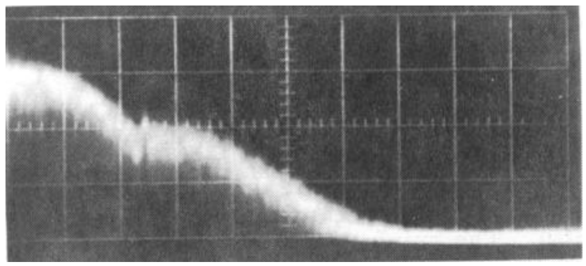
The typical chart recording for moderate to heavy rain showers is shown in Fig. 13(a). The rainfall rate for this particular example is approximately 3/8 in. /hour. Light to moderate rain caused very little signal degradation while heavy fog almost inevitably caused a loss of signal. Figure 13(b) shows the typical pattern for heavy fog where the fog temporarily lifts and then returns. It is interesting to observe the last part of this recording where the system is attempting to relock.

Only light to moderate snowfall occurred during the test period and is shown in Fig. 13(c). In this chart the signal loss was approximately 10 dB.

During the test period diurnal variation of temperature average was 10°F, several days of 20°F, and one day with a change of 34°F. The alignment of the transmitter and receiver units were maintained up to about 30° changes.



(a) Digital waveform at 4.608 MB/s.



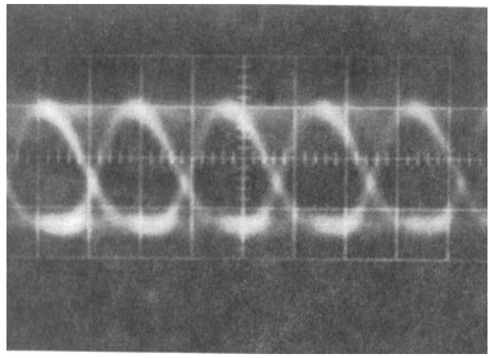
(b) Baseband spectrum for 4.608 MB/s digital signal

(c) TV picture of transmitter over three mile link

Fig. 11. Signal characteristics.

Wind conditions varied from very light to approximately 35 mph duringa rainstorm, with the system maintaining communications in winds up to about 30 mph.

Experience with the system has indicated that as in the example of fog data, a relock would be possible if either the AFC threshold level had been preset lower or a manual lock-in attempted. It is estimated that approximately half of the loss of signal occurrence could have been prevented or corrected by one of the methods given. Approximately 65 hours were lost of the total of 1320 hours of continuous operation for a transmission reliability of 95%.



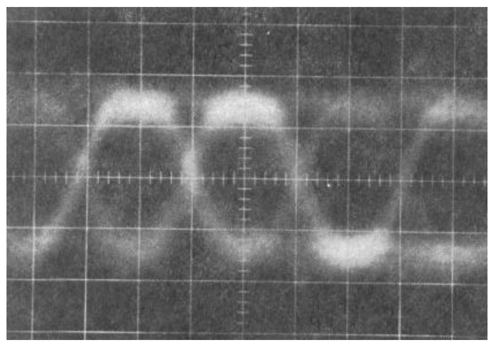


Fig. 12. Eye patterns of 4.608 MB/s signal direct (top) and through system (bottom).

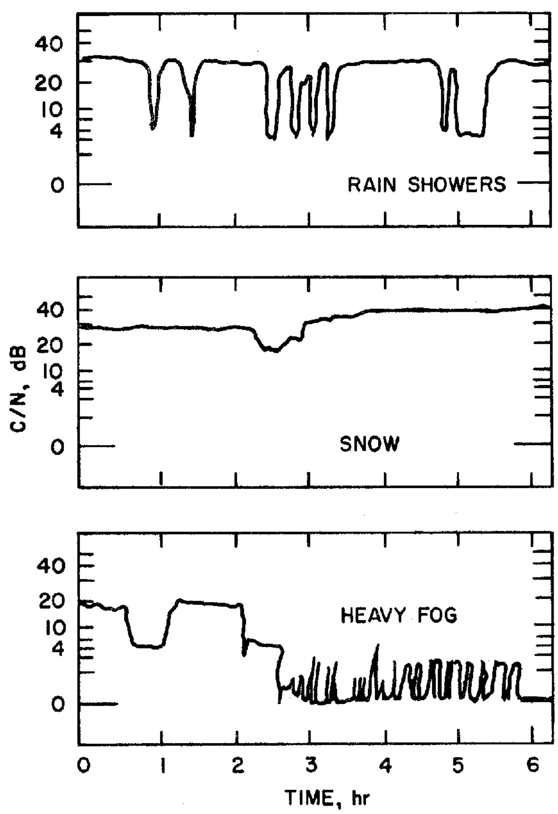


Fig. 13. Average carrier level during various weather conditions.