A Review of Operational Laser Communication Systems

FRANK E. GOODWIN, MEMBER, IEEE

Abstract—Laser communication systems which have been built into serviceable units are reviewed. Although systems built prior to 1965 were more of a breadboard nature, some early experiments of historical interest are described. After 1965, techniques and component reliability were sufficiently improved to permit the development of several interesting and sophisticated systems. Performance characteristics of the more representative of these systems are listed. Recent trends show the use of infrared wavelengths, injection lasers, mode-locked/pulse-code modulation systems, optical heterodyne detection, and automatic pointing and tracking.

Introduction

THIS paper discusses the performance characteristics of laser communication systems which have actually been developed into serviceable systems. Some of the systems developed during the past five years introduce new concepts and provide important operational data. The discussion will, therefore, center around these representative systems.

The term "operational" as used here must be carefully qualified, since none of the systems described is operational in the military sense of the word. The word was chosen to be stronger than "demonstrated," to convey that the systems included are serviceable, reliable, and useful. Thus, breadboard experimental systems are omitted except for references to a few cases of particular interest.

In order to put the description of operational systems in the proper perspective and to fully appreciate the significance of the concepts demonstrated, some early experiments of historical interest will be described. These experiments generally cover the period from 1962 to 1965, prior to the availability of reliable lasers.

Some Experiments of Historical Interest

The first communications with light beams did not use lasers, but rather reflected sunlight with a heliograph, a modern version of which is the signaling mirror. For many generations blinker signals using incandescent and arc lights provided communications between ships. Modulated arc lights provided voice communications links 30 years ago. A spectacular demonstration of transmitting television over 30 miles, using a light emitting GaAs diode, was given by M.I.T. Lincoln Labs. as early as 1962, prior to a significant laser communication demonstration.

Perhaps the first demonstration of long distance laser communication through the atmosphere was performed by a Hughes group in November 1962 over a range of 30 km (18 miles). This experiment was performed shortly after the 6328-Å helium–neon (He–Ne) laser was discovered. The laser was excited by an RF source high-frequency amateur radio transmitter; intensity modulation of the laser was easily achieved by modulating the intensity of the RF source. Detection was achieved with a photomultiplier. Intelligible voice communications were obtained through the use of a high-pass filter to reduce the effects of scintillation noise.

Shortly thereafter in May 1963 an all-time distance record was set by a group from Electro-Optics Systems who transmitted a voice modulated 6328-Å beam 190 km (118 miles) from Panamint Ridge near Death Valley, Calif., to a point in the San Gabriel Mountains near Pasadena. The modulation and detection schemes were similar to those of the Hughes experiment.

The first transmission of TV over a laser beam was reported by a group at North American Aviation in March 1963. Modulation was achieved through an interferometer which was driven with piezoelectric elements having a modulation bandwidth of 1.7 MHz. Later in 1963, electro-optic modulation of 5-MHz band TV signals was achieved at Hughes through the use of an eight element interdigital potassium di-hydrogen phosphate (KDP) modulator. However, both the North American and Hughes demonstrations were not suitable for transmitting signals through turbulent atmosphere. The spectral character of atmospheric turbulence interferes severely with vertical synchronization.

A significant step in avoiding the effects of atmospheric scintillation on laser modulation was demonstrated in late 1963 by a group from IBM with pulse-rate modulation of a GaAs injection laser. The pulse-rate was 8 kHz, and a pulse frequency discriminator produced a modulation bandwidth near 6 kHz. Variations in the amplitude of the received pulses were not demodulated in the output.

After the initial flurry of activity in 1962 and 1963, it was realized that amplitude modulation (AM) of laser beams with analog information was not practical in the presence of atmospheric-turbulence noise. Although experiments suggested several techniques which might be suitable to reduce the effects of atmospheric turbulence, they were as yet unproven. Some of the techniques were: 1) optical frequency modulation with optical heterodyne detection; 2) frequency modulation of a subcarrier on the laser beam; and 3) pulse code modulation.

The problem of getting useful information through a turbulent atmosphere on an optical beam became one of

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The author is with Hughes Research Laboratories, Malibu, Calif. 90265.

providing enough signal margin so that a continuous flow of information was available even with deep fading in the amplitude of the received beam. If this condition were met, any of the several techniques just outlined could have been used to remove the amplitude noise. In spite of early knowledge of the necessary techniques to build a system with a channel free from atmospheric noise, the usefulness and practicality of a laser communication system was questionable for many reasons. First, existing communications systems were adequate to handle concurrent demands. Second, considerable research and development were required to improve the reliability of components to assure reliable system operation. Third, a system in the atmosphere would always be subject to interruption in the presence of heavy fog. Fourth, use of the system in space where atmospheric effects could be neglected required accurate pointing and tracking optical systems which were not then available. In view of these problems, it is not surprising that the rate of progress in the early 1960's in building operational laser communication systems was slow.

After 1965, as reliable laser sources became available, several interesting and sophisticated laser communications systems were built and evaluated. The following discussion describes the salient features of some of these systems.

Operational Systems—Description and Performance

The following systems are described because they illustrate a particular new concept or technique. The system chosen for each illustration is considered particularly representative. It is possible that there are systems unknown to the author which may have served as a better illustration; any such oversight was unintentional.

Several trends and developments of interest occurred during the period from 1965 to 1970. First, there was a general movement toward the infrared, stimulated by the development of reliable He–Ne lasers at 1.15 μm and 3.39 μm, helium–xenon at 3.5 μm, gallium arsenide at 0.9 μm, and (most important) the Nd:YAG laser at 1.06 μm and the CO_2 laser at 10.6 μm. Second, the development of optical heterodyne techniques for detection in the infrared took place. Third, there was the development of the necessary sophisticated pointing and tracking techniques which make optical space communications feasible.

The anticipated needs of future communications systems with high quality channels having extremely large dynamic range and a high degree of linearity, as required, for example, by cable television, has introduced another trend. Electrooptic amplitude modulation, polarization modulation, and some forms of phase modulation are inherently nonlinear and cannot provide sufficient linearity to meet these requirements. The trend, therefore, has been toward optical FM, subcarrier FM, and pulse code modulation (PCM). Optical FM and subcarrier FM can provide a dynamic range up to about 55 dB. PCM, of course, limited only by available bandwidth. Dynamic ranges required in some future communication needs will exceed 55 dB, requiring the use of digital techniques. Systems which use these later techniques are described in the paragraphs which follow.

TABLE I

	Hughes/U.S. Army Electronics Command SSB FM System [1]
Wavelength (μm)	0.6328
Power (watts)	0.003
Photodetector	Philco L4501 silicon photodiode
Modulator	SSB quadrature using KDP
Modulation	Subcarrier FM (FSK), 876 MHz $\pm$ 1 MHz
Coding	PCM
PCM Bit Rate	250 kbit
Base Bandwidth	1 MHz
Range Performance	Useful for 1 mile paths for PCM error count studies

Single Sideband FM—Optical Heterodyne Detection—1965

Single sideband (SSB) FM offers a means of avoiding the effects of amplitude fading and electrooptic modulation nonlinearities. The method is described as the single sideband modulation of the optical beam with an RF carrier, usually the output of a conventional FM transmitter. With the suppression of the original optical carrier, a new optical signal is generated which is offset in frequency from the original frequency by that of the RF carrier. Frequency modulation of the RF carrier produces true frequency modulation of the optical carrier. The receiver must be an optical hterodyne receiver in order to recover the information from the signal.

The first system of this type was a single-ended system built by Hughes for the U.S. Army Electronics Command in 1965 for PCM error rate studies [1]. The FM transmitter and receiver were elements of the AN/GRC-50, a military communication set, having a carrier frequency of 876 MHz. The system utilized a 6328-Å laser oscillator and a silicon photodiode tuned to the RF carrier frequency. Although the system was single ended, having to derive the local oscillator from the transmitter oscillator, it demonstrated techniques which were rather advanced for the time and served a useful purpose in the study of PCM error rates in the presence of atmospheric turbulence. Data for this model are given in Table I.

PCM/Pulsed Laser (PL)—1966

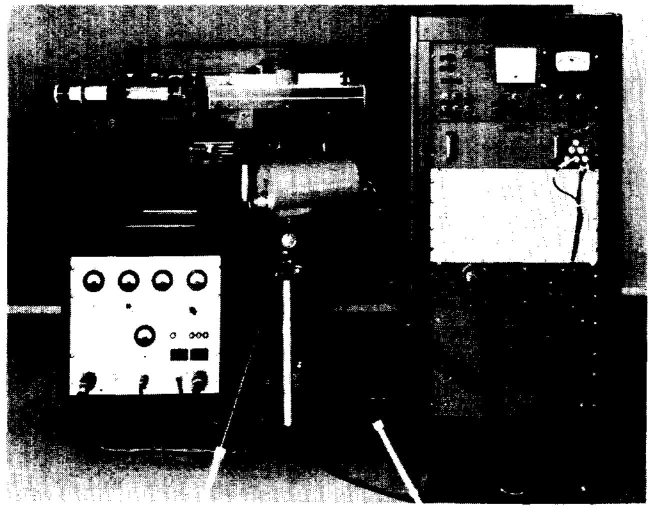
Wide-band PCM was first used in two laser communication systems developed in 1966. One (using the He–Ne 0.6328-μm wavelength) was built for NASA Marshall Space Flight Center (MSFC) by ITT Federal Laboratories [2], [3] and the other (using the argon ion 0.4880- or 0.5145-nm wavelengths) was built for NASA Manned Spacecraft Center (MSC) by Hughes [4], [5]. Both systems utilized orthogonal polarization modulation with balanced photomultiplier detectors to obtain symmetrical binary detection to help reduce the effects of atmospheric turbulence. Extensive measurements with the ITT system over atmospheric paths during the past two and one-half years have yielded correlation data between bit-error rates, TV picture quality, atmospheric turbulence, transmitter power, and receiver

TABLE II

	ITT/NASA MSFC System [2], [3]	Hughes/NASA MSC System [4], [5]
Wavelength (μm)	0.6328 He–Ne	0.4880/0.5154 argon ion
Power (watts)	0.005	5
Photodetector	S-20 Photomultipliers (two)	S-11 Photomultipliers (two)
Modulator	20 cm transverse field KDP	50 cm transverse field KD*P
Modulation	PCM/PL (polarization)	PCM/PL (polarization)
Coding	PCM delta	PCM
PCM Bit Rate	30 Mbit $\cdot$ s^{-1}	30 Mbit $\cdot$ s^{-1}
Base Bandwidth	10 MHz	10 MHz
Bit-Error Rate	$<10^{-6}$	$<10^{-6}$
Range Performance	Tested extensively over 5 mile path	Tested over 4.2 mile path with 50-dB system margin
	Theoretical maximum operating range = 50 000 mi	Theoretical maximum operating range = 1 500 000 mi

aperture size. Conclusions are that TV picture quality is satisfactory with bit-error rates of 10^{-4}; the laser systems can obtain bit-error rates of less than 10^{-6} for typical atmospheric paths. The system specifications are listed in Table II.

Fig. 1(a) shows the transmitter terminal of the Hughes system. Fig. 1(b) shows the Hughes 5-watt argon laser beam in the night sky. Fig. 2 shows the receiver terminal of the ITT system (the spot of light in the background is the transmitter station).



(a)

(b)

Fig. 1. (a) Hughes wide-band PCM argon laser transmitter. (b) Hughes 5-watt argon beam at night.

Pulse Frequency Modulation—1965 Through 1969 (GaAs–9000 Å)

A gallium arsenide injection laser operating near room temperature (-4°C) was designed and built by IBM for optical communication experiments on Gemini VII [6]. The system utilized pulsed frequency modulation (PFM) for coding information; it had a pulse repetition frequency (PRF) of 8 kHz and a demodulated voice bandwidth of 6 kHz. Although the Gemini experiment was unsuccessful, the techniques employed have created a whole family of laser communication devices.

The first pulsed gallium arsenide injection lasers, operating at or near ambient 300°K temperature, were unreliable because of metallurgical flaws in the junction and lack of understanding of the material limitations by the systems designers. Continuous efforts by RCA (Sommerville) have resulted in significant improvement in the reliability of laser diodes [7]. This improvement was achieved 1) through a close confinement construction which sharply reduces internal optical loss and 2) through better material and heterojunction diode fabrication processes.

Systems designers have now learned that the improved low-threshold diodes last longer only when they are operated at lower currents and lower temperatures. Lower design PRF rates have been a key factor in extending the life of these devices.

Recently (1968) RCA (Camden) developed a reliable field communication unit for the U.S. Army Electronics Command. Optronix, Holobeam, Saab, and Avionics Santa Barbara Research Center (SBRC), now have productized versions of this type of laser communication system (see Fig. 3). The specifications listed in Table III are typical of these systems, although they refer in detail to the SBRC unit.

Wide-Band PCM Subcarrier Frequency Shift Keying—1967 (3.39 μm)

Subcarrier FM offers another means of avoiding the effects of amplitude fading and electrooptic modulation nonlinearities. The method can be simply described as the

Fig. 2. Receiver terminal of ITT system. (Courtesy of ITT Aerospace.)

Fig. 3. Santa Barbara Research Center's gallium arsenide laser communicator.

TABLE III

	SBRC Infrared Laser Communicator
Wavelength (μm)	0.9040
Power (watts)	2 W peak, 0.003 W average, duty cycle $\cong 10^{-3}$
Photodetector	Silicon avalanche photodiode
Modulation	Direct modulation of diode current
Coding	PFM
PCM Bit Rate	6 kbit $\cdot$ s^{-1}
Base Bandwidth	2.3 kHz
Range Performance	6 miles (good seeing conditions)

amplitude modulation of the optical beam with an RF subcarrier. At the receiver, the output of an optical amplitude detector is fed into a conventional FM receiver tuned to the subcarrier frequency.

The FM subcarrier idea was applied to wide bandwidths with a 50 Mbit $\cdot$ s^{-1} frequency shift-keying (FSK) system built by Hughes for the NASA MSC. Here the subcarrier center frequency was 125 ± 25 MHz. FSK, the digital form of FM, was used. Amplitude modulation of the subcarrier was provided by a gallium arsenide crystal located inside the cavity of the 3.39-μm laser. Modulating voltage applied to the crystal produces coupling of the intracavity energy off a Brewster plate [8] (see Fig. 4). The specifications are listed in Table IV.

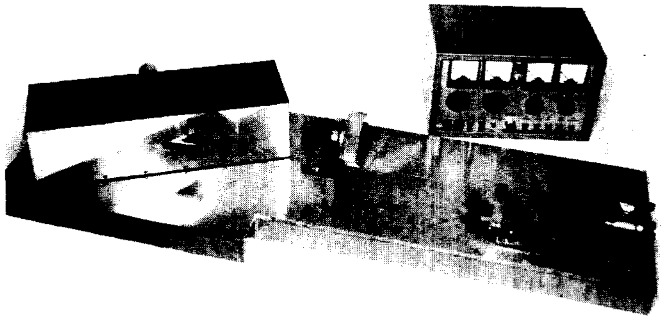


Fig. 4. Hughes 3.39-μm wide-band subcarrier FSK system.

TABLE IV

	Hughes/NASA MSC 3.39-μm Wide-Band Subcarrier FSK System [8]
Wavelength (μm)	3.39 He–Ne
Power (watts)	0.002
Photodetector	Indium arsenide (300°K) photodiode
Modulator	Gallium arsenide (intracavity coupling)
Modulation	Subcarrier FSK (125 MHz$\pm$MHz)
Coding	PCM
PCM Bit Rate	50 Mbit $\cdot$ s^{-1} (nonreturn to zero)
Base Bandwidth	25 MHz
Range Performance	1 mile (good seeing conditions)

A recent experiment by a group at Lockheed Palo Alto [9] has demonstrated the FM-subcarrier technique using a 2.8-GHz subcarrier frequency, a lithium niobate modulator, and a silicon avalanche photodetector. Sufficient linearity was obtained to transmit a band of frequencies from 54 to 216 MHz, i.e., all of the VHF TV channels simultaneously.

Optical FM—Optical Heterodyne Detection—1968 (10.6 μm)

Experiments in optical heterodyne detection have been conducted at various laboratories since 1963, although improved sensitivity in heterodyne detection was not demonstrated until 1966 [10]. Workers at Honeywell built an optical heterodyne communication system for the NASA Marshall Space Flight Center in 1968 which employed optical FM for two voice channels; the modulation was provided by mechanical motion of the laser mirror [11]. This system demonstrated the vastly improved receiver sensitivity obtainable through the use of optical heterodyne detection. Concurrent with the development of the Honeywell system the author and his coworkers at Hughes demonstrated intracavity FM modulation using an electrooptic

TABLE V

	Honeywell/NASA MSFC 10.6-μ Heterodyne System [10]	Hughes Breadboard [12]
Wavelength (μm)	10.6 CO_2	10.6 CO_2
Power (watts)	5	1
Photodetector	HgCdTe (77°K) heterodyne	Ge:Hg (21°K) heterodyne—30 MHz IF
Modulator	Piezoelectric (mechanical)	Gallium arsenide phase modulator
Modulation	Optical FM	Optical FM, intracavity
Coding	Analog	Analog
Base Bandwidth	1 MHz—2 voice channels	5 MHz—TV channel
Range Performance	Test range = 3 miles	Demonstration range = 18 miles; $S/N = 50$ dB

crystal, and the transmission of TV over an 18 mile path through the atmosphere [12]. The performance characteristics are given in Table V.

The demonstration of optical heterodyne detection at 10.6 μm, along with the high power and high efficiency CO_2 laser oscillators available at this wavelength, has signaled a new era in laser communications technology. The ratio of transmitter power available to minimum detectable power in the system is already up to 170 dB and is likely to increase still more as available CO_2 laser powers increase.

Wide-Band Optical FM—Optical Heterodyne Detection—1970 (3.39 μm)

Wide-band optical FM is employed in a field-ruggedized communication system developed at Hughes (see Fig. 5). This system is ultimately capable of handling information bandwidths up to 50 Mbits $\cdot$ s^{-1} in either direction through the system, one direction at a time (simplex). Time sharing permits coded information to flow in two directions simultaneously. The prototype system was designed with one TV channel or four voice channels multiplexed to be available in both direction simultaneously.

This system illustrates the use of optical heterodyne detection in a ruggedized package. Heterodyne detection was (and still is) believed by many to be impractical. The frequency stability requirements for both the transmitter and receiver local oscillators are severe, but have been achieved in this system through good engineering principles. The performance specifications are given in Table VI.

Significant Achievements in Pointing and Tracking

The implementation of the laser in space communications required gimballed optical systems which will track the incoming beam and point the outgoing beam to a high degree of accuracy. Under the sponsorship of the NASA MSFC, workers at Perkin-Elmer have developed an optical system which has a dynamic tracking stability of approximately 0.3 μrad [13]. The techniques are thus available to point and track with diffraction limited beams from fairly large optical systems. Fig. 6 illustrates tracking experiment at Perkin-Elmer. Here the large tube on the upper left is the

TABLE VI

	Hughes 3.39-μm Two-Way Laser Communicator (1970)
Wavelength (μm)	3.39 He–Ne
Power (watts)	0.001
Photodetector	Indium arsenide (heterodyne)–30 MHz IF
Modulator	Gallium arsenide
Modulation	Intracavity, optical FM
Coding	Analog
Base Bandwidth	to 25 MHz
Range Performance	3 miles (good seeing) / 1 mile (poor seeing) — Picture S/N greater than 40 dB.

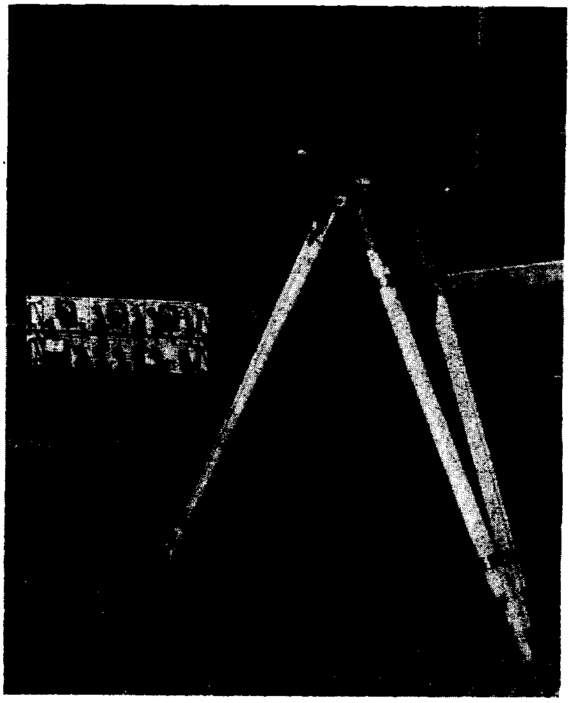


Fig. 5. Hughes 3.39-μm optical heterodyne two-way laser communicator.

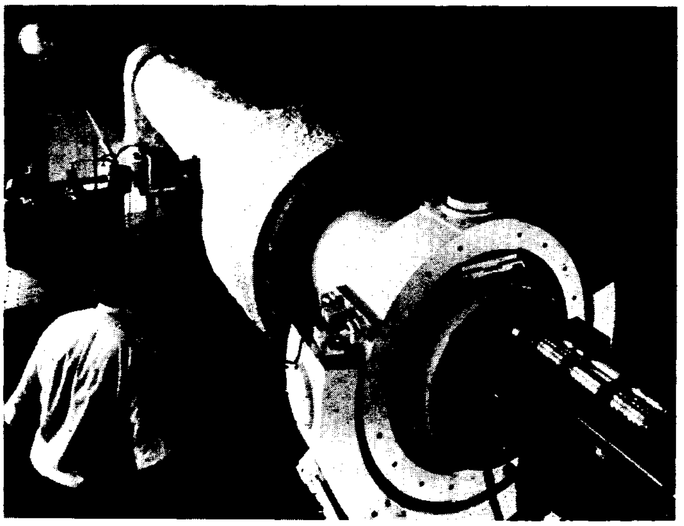


Fig. 6. Perkin-Elmer fine pointing and tracking test facility. (Courtesy of Perkin-Elmer Co.)

TABLE VII

	Sylvania ARL Two-Way System (1967) [14]
Wavelength (μm)	0.6328 He–Ne
Power (watts)	0.001 nominal
Photodetector	S-20 photomultipliers, (2)
Modulator	Sylvania VP2, KD*P
Modulation	Polarization
Coding	Analog
Tracking Sensor	Image dissector, photomultiplier
IMC Element	Magnetic
Base Bandwidth	5 MHz
Range Performance	1-km test range

collimated source, simulating a signal from a distance. The telescope on the lower right is tracking the source to within less than half a microradian while the base on which the telescope is mounted is moving with a programmed motion of $\pm 2°$.

Generally speaking, laser communications equipment designed for point-to-point use on the ground does not required tracking optics. The beam is usually spread out sufficiently to provide for atmospheric image motion and diurnal refraction. An exception to this is a tracking capability included in a portable communication system built by Sylvania Applied Research Laboratory (ARL) in 1967 [14]. In this system, compensation for image motion and maintenance of fine pointing was achieved as an integral part of the system. The performance specifications are listed in Table VII.

PCM/AM PCM via Mode-Locked Lasers (1970)

The recent work of Kinsel, Denton, and Guesic [15]–[19] with amplitude PCM utilizing mode-locked laser pulses has opened the way to obtaining extremely high data rates. This work at Bell has been followed at Nippon Electric Co. (NEC) [20], by a truly monumental effort in the development of a fully operational four-leg two-way laser communication link between Yokohama and Tamagawa, a distance of 14 km. Three repeater stations are utilized in the system in addition to the two terminals. The longest leg of the link is a distance of 4.25 km. Communications occur simultaneously in both directions. To the author's knowledge, this is the first laser link built which will handle commercial traffic. Operational reliability through the atmosphere is estimated to be 99 percent for a 24 hour period (mean annual statistics) and 99.6 percent for daytime operation. Fig. 7 shows one of NEC's laser communication terminals. The performance specifications are listed in Table VIII.

New Systems Under Development

There have been many "false starts" in the development of laser communication systems during the past decade, due mainly to the lack of laser component reliability. For example, the first He–Ne lasers had lifetimes of 100 hours; they now have lifetimes exceeding 20 000 hours. Thus, operational laser communication systems are paced for the most part by the laser technology. It would seem to make good sense to do as the group at Nippon Electric has done and base a system design around a component with proven reliability.

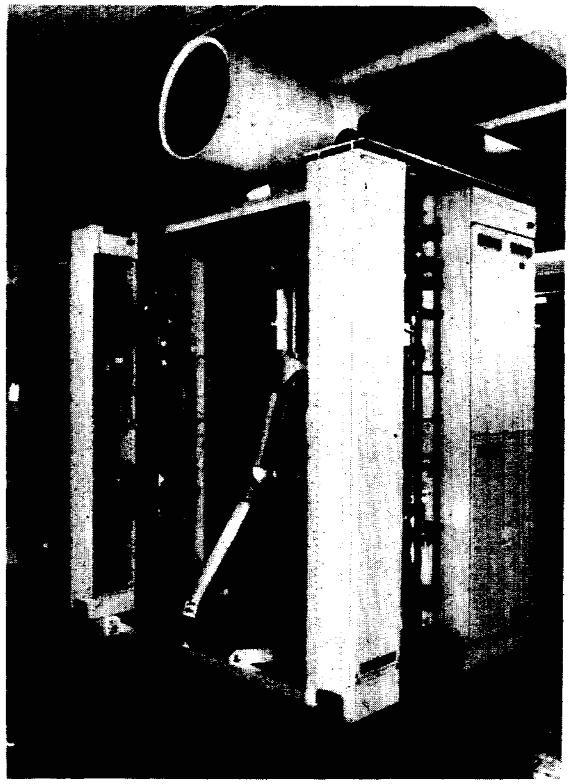


Fig. 7. Nippon Electric's PCM/AM laser communication terminal. (Courtesy of Nippon Electric Company, Ltd.)

TABLE VIII

	Nippon Electric Co. PCM/AM System [20]
Wavelength (μm)	0.6328 He–Ne
Power (watts)	0.003 in each of two redundant transmitters
Photodetector	Silicon avalanche photodiode (single)
Modulator	Lithium tantalate
Modulation	PCM/AM
Coding	PCM delta
PCM Bit Rate	123.492 MHz
Base Bandwidth	13.7 MHz per channel, 3 channels
Number of Lasers in System	16
Range Performance	Test ranges 2.5 km, 4.1 km, 4.25 km, 3.2 km. Total 14 km. 99 percent reliability 24 hour operation; 99.6 percent reliability business hours

The first sealed-off CO_2 lasers had lifetimes of less than 100 hours, and are now approaching the 10 000 hour mark. The CO_2 laser is, therefore, now available for an operational system. The vehicle for the test is the ATS-F laser communication experiment designed to establish a two-way link between a synchronous orbit and the earth's surface. The system is being built by Aerojet General Corporation for NASA Goddard Space Flight Center (GSFC) [21]. Due to be launched in 1973, the Laser Communication Experiment (LCE) will be the first illustration of the user of lasers

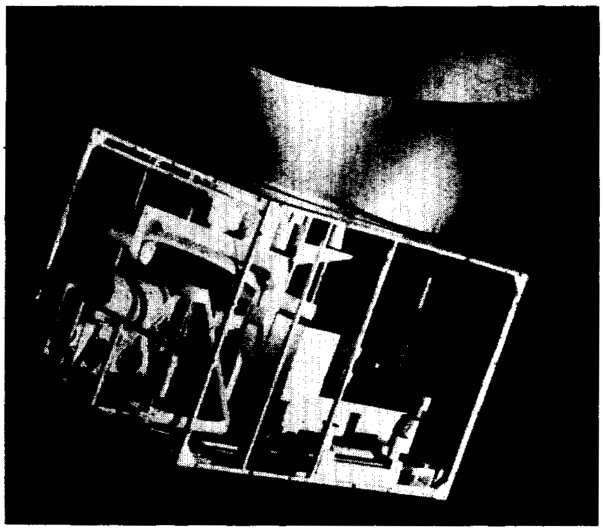


Fig. 8. Mock-up of Aerojet General's flight package for ATS-F laser communication experiment. (Courtesy of Aerojet General Corp.)

TABLE IX

	Aerojet General/NASA GFSC Laser Communication Experiment [21]
Wavelength (μm)	10.6 CO_2
Power (watts)	1.0
Photodetector	HgCdTe (100°K) optical heterodyne
Modulator	Gallium arsenide
Modulation	Intracavity FM or external AM
Coding	Analog
Base Bandwidth	5 MHz
Range Performance	3.6×10^{-7} m (23 000 mi) $S/N = 25$ dB

for space communications. To date, the configuration selected is constrained by size, weight, and power. No laser other than the CO_2 system can even approach meeting the requirements. A mock-up of the LCE is shown in Fig. 8. The large horn on top is the radiation cooler for the detector. The performance specifications are listed in Table IX.

Conclusions

Most of the techniques required to create a useful and practical laser communication system in the atmosphere or in space have been demonstrated with the model systems described in this paper. Anticipated needs for future space communication channels requiring large dynamic range and a high degree of linearity can be met with laser systems. In addition, eventual shortage of microwave channels for point communications through the atmosphere will require other modes of communication. Laser systems may be ideal to fill the needs which cannot be met with these conventional systems, since they have the inherent advantage of not creating interference with conventional systems or with other laser systems.

Present trends indicate that laser communications systems of the future will have large dynamic range, a high degree of linearity, and will utilize PCM of extremely high data rates.

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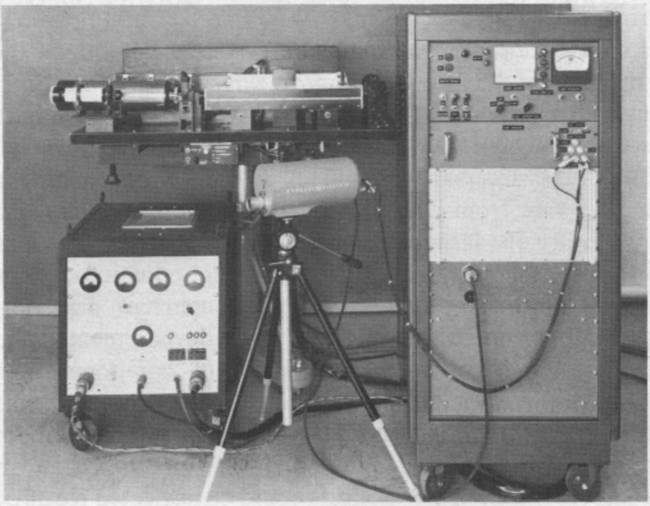
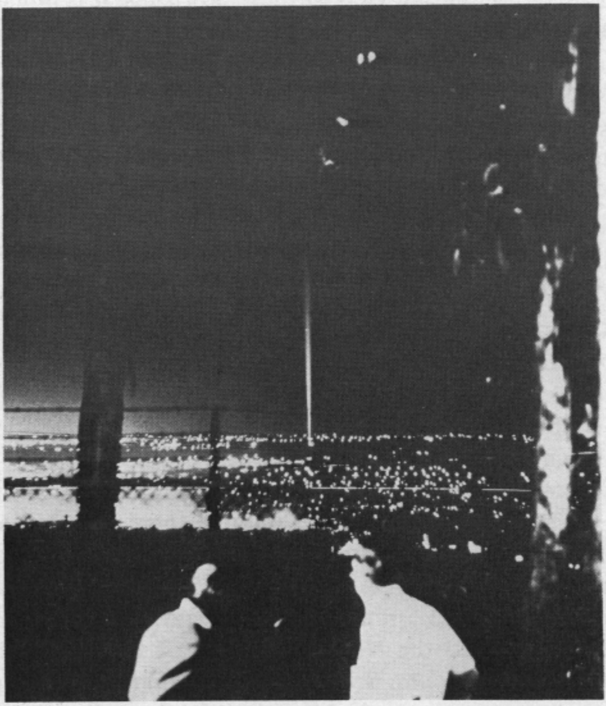


(a)



(b)

Fig. 1. (a) Hughes wide-band PCM argon laser transmitter.
(b) Hughes 5-watt argon beam at night.

Fig. 2. Receiver terminal of ITT system. (Courtesy of ITT Aerospace.)

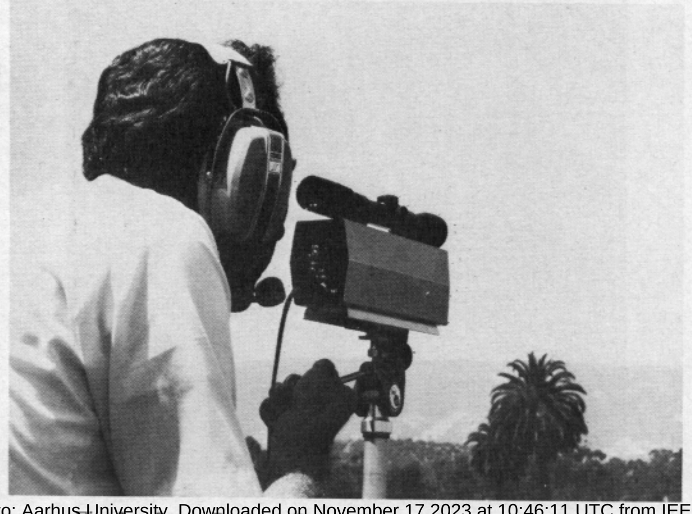


Fig. 3. Santa Barbara Research Center's gallium arsenide laser communicator.

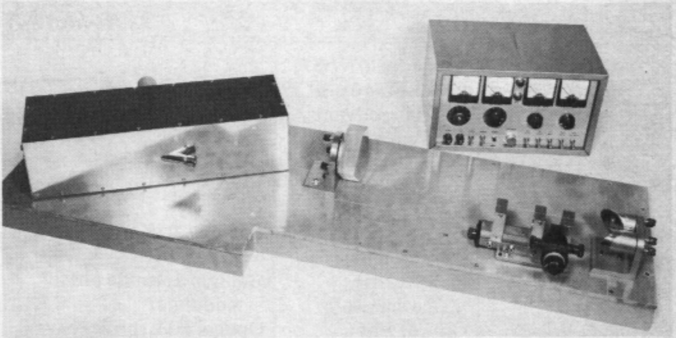


Fig. 4. Hughes 3.39 μm wide-band subcarrier FSK system.

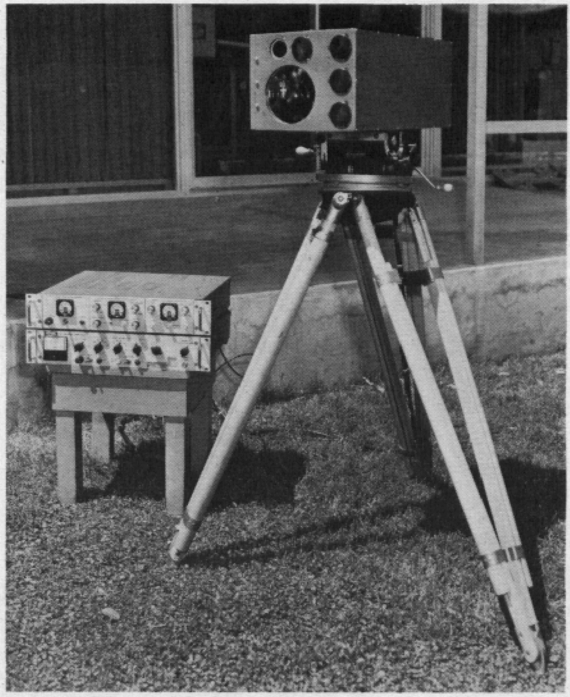


Fig. 5. Hughes 3.39-μm optical heterodyne two-way laser communicator.

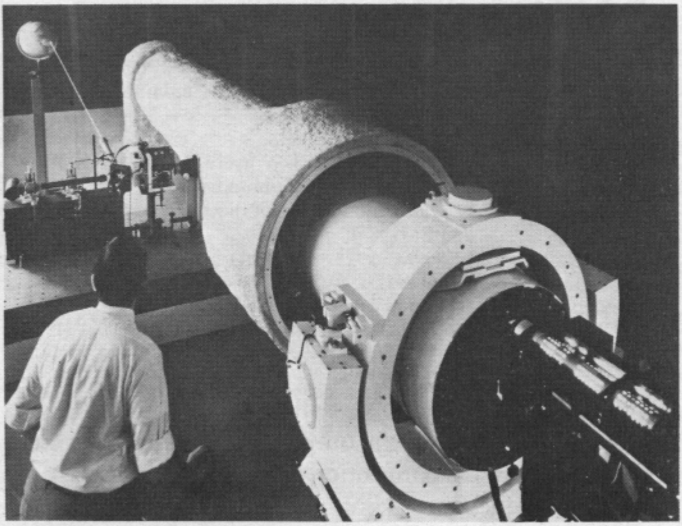


Fig. 6. Perkin-Elmer fine pointing and tracking test facility. (Courtesy of Perkin-Elmer Co.)

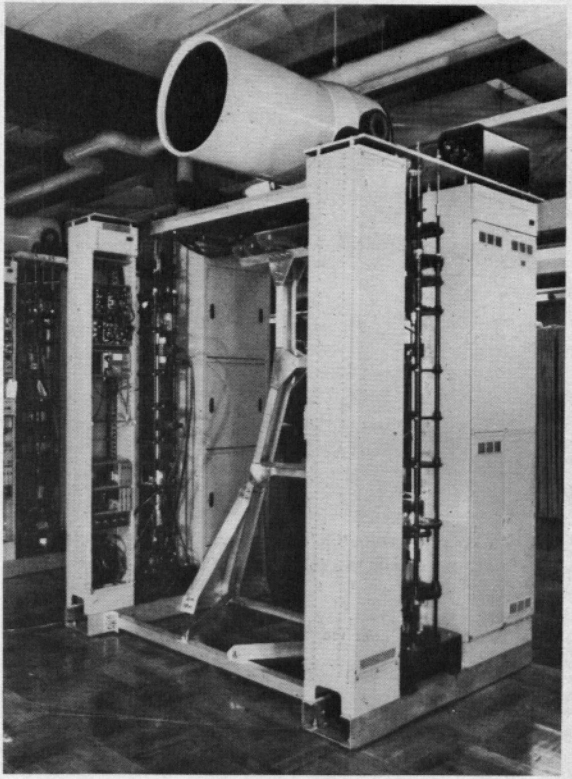


Fig. 7 Nippon Electric's PCM/AM laser communication terminal
(Courtesy of Nippon Electric Company, Ltd.)

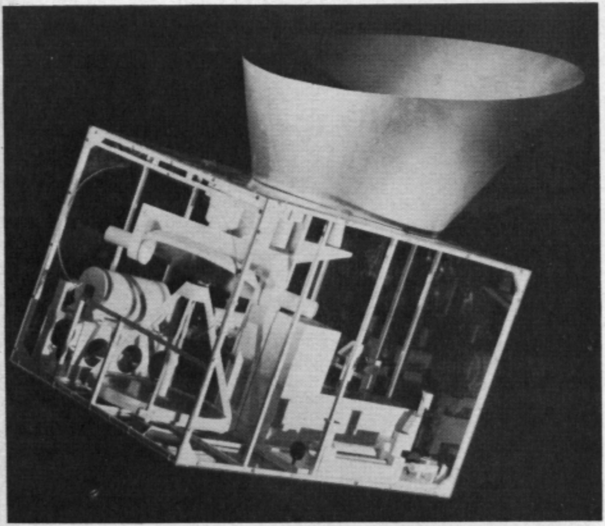


Fig. 8. Mock-up of Aerojet General's flight package for ATS-F laser communication experiment. (Courtesy of Aerojet General Corp.)