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Topics in Millimeter-Wave and Optical Space Communication

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LINCOLN LABORATORY

TOPICS IN MILLIMETER-WAVE AND OPTICAL SPACE COMMUNICATION

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ABSTRACT

Many comparative studies have been made of millimeter-wave and optical space-communication systems. The applications considered have been diverse, including links between satellites in low Earth orbits, satellites in synchronous orbits, deep-space probes, and Earth terminals, with data-rate requirements from a few bit/sec to Gbit/sec. We present in this report not just another such comparison, but rather a short tutorial account of the common and of the distinctly different features of some millimeter-wave and optical space-communication systems. For example, the design of the transmitting antennas is governed by the same electromagnetic theory, which accounts for diffraction at an aperture. However, the signal-to-noise relationships in the receivers may not be the same (Gaussian vs Poisson noise statistics).

Possible satellite applications are surveyed briefly, with mention of the favorable and the unfavorable factors associated with millimeter-wave and optical space-communication systems. Candidate systems are postulated and link calculations are given.

Accepted for the Air Force
Joseph R. Waterman, Lt. Col., USAF
Chief, Lincoln Laboratory Project Office

CONTENTS

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

CONUS	Continental United States of America
DCA	Defense Communications Agency
DoD	Department of Defense
DSIF	Deep-Space Instrumentation Facility
EHF	Extremely-High Frequency, 30-300 GHz
EIRP	Effective Isotropically Radiated Power
EOS	Earth Observational Satellite
ERTS	Earth Resources Technology Satellite
IMPATT	Impact Ionization Avalanche Transit Time
INTELSAT	International Telecommunications Satellite Consortium
IR	Infra-Red, the optical spectrum in the approximate range 0.7-100 μm
LSA	Limited Space-Charge Accumulation
NASA	National Aeronautics and Space Administration
Near-IR	the optical spectrum in the approximate range 700-2000 nm (0.7-2 μm)
nm	nanometer (10^{-9} meter). 1 nanometer ≡ 10 Ångstrom
PCM	Pulse-Code Modulation
PIN	Positive Intrinsic Negative
SHF	Super-High Frequency, 3-30 GHz
TDRSS	Tracking and Data-Relay Satellite System
TWTA	Traveling-Wave-Tube Amplifier
V-band	50-75 GHz
Visible	the optical spectrum in the approximate range 400-700 nm (0.4-0.7 μm)
WARC/ST	World Administrative Radio Conference on Space Telecommunications
X-band	6.20-10.90 GHz
μm	micrometer (10^{-6} meter). 1 micrometer ≡ 1000 nanometer

TOPICS IN MILLIMETER-WAVE AND OPTICAL SPACE COMMUNICATION

I. INTRODUCTION

Back in 1961, Bob Hansen (Ref. 1) told how to write a series of versions of a famous paper that might be entitled "Optimum Frequencies for Space Communications." Hansen's recommended procedure was both simple and speedy. Each aspiring author had only to manipulate the standard range equation using off-the-top-of-the-head guesses about antenna-gain restrictions, vehicle weight/power restrictions, capabilities of transmitting tubes and devices, and antenna-noise-temperature characteristics. Provided no one else had used exactly the same boundary conditions (including the assumed modulation format), the author could generate his own contribution to the professional literature in about 12 hours.

Hansen's famous paper could be counted on in 1961 to yield optimum frequencies in the range 1 to 10 GHz, with a maximum likelihood in the vicinity of 3 GHz. Nowadays, advances in the state-of-the-art – coupled with extraordinary growth in the projected data-rate appetites of the users – make it possible for the optimum frequencies to come out in the high microwave region, or even in the optical domain. In writing this report, we have explicitly tried to avoid writing yet another of Hansen's famous papers. The reader will search here in vain for an unequivocal statement of the optimized superiority of millimeter-wave over optical space communication, or vice versa. What he will find is a short presentation of the common and of the distinctly different features of some millimeter-wave and optical space-communication systems. There is nothing mysterious or magical about either frequency range. Most of the basic concepts of electromagnetic communication at much longer wavelengths apply in these novel domains. The few familiar basic concepts that do not apply here can be replaced by others that will become equally conventional in time.

Any reader who needs to go deeper into the subjects of this paper will find a large literature awaiting him. Our bibliography is by no means exhaustive, but it should give useful leads. Omission of any particular book, paper, or report from it does not imply that we consider that contribution to be just another version of Hansen's famous paper. Several professional periodicals have published recent special issues devoted to millimeter-wave technology (Refs. 2-3), optical communication (Ref. 4), and satellite communications (Ref. 5). There are many books on conventional microwave space communication (Ref. 6, for example); the number of books on optical communication (Refs. 7-8, for example) is growing rapidly. The literature of expository reports and journal articles on millimeter-wave and optical space communication is already large (Refs. 9-23, for example).

II. MILLIMETER-WAVE SPACE COMMUNICATION

There are several motivations for moving to higher frequencies as new demands for communication arise. In the busier parts of the world, where demands are growing, the electromagnetic spectrum for cm-and-longer wavelengths has already been completely allocated and is relatively crowded by users in the popular bands. The technology of equipment development there is rather mature, so order-of-magnitude improvements in system performance (or reductions in system cost) are not likely. On the other hand, going to mm-and-shorter wavelengths appears at first sight to be very attractive; there are vast stretches of little-used spectrum and appealing possible economies. The greater directivity attainable — in principle — with a fixed-aperture antenna at higher frequency allows increasing dramatically the effective isotropically radiated power (EIRP) of a terminal for a given transmit power, with corresponding system improvement (we will see below that the narrower antenna beam can present some troublesome problems, however). Furthermore, the millimeter-wave technology (and even more so the optical technology) is new, different, and exciting.

A. Millimeter-Wave Frequency Allocations

During the summer of 1971, the World Administrative Radio Conference on Space Telecommunications met in Geneva to act on proposed and recommended frequency allocations. The resultant allocations in the millimeter-wave region are listed in Table I through the courtesy of Dr. R. K. Crane, Lincoln Laboratory, one of the US representatives to the Conference. As can be seen, these frequency allocations cover a total bandwidth in excess of 100 GHz. The most significant ones for immediate and near-future utilization are probably those below 100 GHz, since this is the region where the millimeter-wave technology development is most advanced. For the purposes of this report, the allocations in the oxygen-absorption region are of particular interest for inter-satellite (cross-link) applications.

B. Millimeter-Wave Propagation Phenomena

The millimeter-wave bands currently proposed for space communication suffer from adverse propagation effects in traversing the atmosphere. These effects arise from molecular absorption by atmospheric gases — principally oxygen — and by water vapor, from scattering by hydrometeors, and from refraction and scattering by spatial variations in the refractive index. These phenomena can cause signal attenuation, fading in amplitude and/or phase, and increased antenna noise temperature. They may impose limitations on the maximum useful bandwidth and antenna size.

The absorption by oxygen and water vapor and the attenuation by rain, clouds, and fog reduce the signal strength. The theoretical one-way attenuation from sea level straight up (or down) through the atmosphere (after Ref. 24) is shown in Fig. 1. Variations in the refractive index reduce system performance by defocusing the transmitting beam on the one hand and by producing wavefront tilt and phase decorrelation across the receiving aperture on the other. Rather than reiterate here the results of the many theoretical and experimental investigations, we refer the reader to some of the excellent review articles on this subject in the literature (Refs. 24-26).

C. Millimeter-Wave Systems

We include under space communications three possible links: ground-to-satellite, satellite-to-satellite, and satellite-to-ground. As we will see in the survey of applications (Sec. V), the latter two will be needed before the first

TABLE I

FREQUENCY ALLOCATIONS BY THE 1971 WARC/ST

Frequency (GHz)		Region*	Allocation Primary/Secondary	Fixed and Mobile	Fixed† Satellite Up	Fixed† Satellite Down	Broadcast Satellite
23.0	23.6	W	Fixed, Mobile	EA			
23.6	24.00	W	Radio Astronomy				
24.0	24.05	W	Amateur, Amateur Satellite				
24.05	24.25	W	Radiolocation/Amateur				
24.25	25.25	W	Radionavigation				
25.25	27.5	W	Fixed, Mobile	EA			
27.5	29.5	W	Fixed, Mobile, Fixed Satellite	A	A		
29.5	31.0	W	Fixed Satellite		EA		
31.0	31.3	W	Fixed, Mobile/Space Research				
31.3	31.5	W	Radio Astronomy				
31.5	31.8	1 & 3	Space Research/Fixed, Mobile				
		2	Space Research				
31.8	32.3	W	Radionavigation/Space Research				
32.3	33.0	W	Radionavigation				
33.0	33.4	1	Radio Astronomy, Radionavigation				
		2 & 3	Radionavigation				
33.4	34.2	W	Radiolocation				
34.2	35.2	W	Radiolocation/Space Research				
35.2	36.0	W	Radiolocation				
36.0	40.0	W	Fixed, Mobile	EA			
40.0	41.0	W	Fixed Satellite			EA	
41.0	43.0	W	Broadcast Satellite				EA
43.0	48.0	W	Aeronautical and Maritime Mobile Satellite; Aeronautical and Maritime Radionavigation Satellite		AMS	AMS	
48.0	50.0	W	Not Allocated				
50.0	51.0	W	Fixed Satellite		EA		
51.0	52.0	W	Earth Exploration Satellite, Space Research		EES	EES	
52.0	54.25	W	Space Research (Passive)				
54.25	58.25	W	Intersatellite				
58.25	59.0	W	Space Research (Passive)				
59.0	64.0	W	Intersatellite				
64.0	65.0	W	Space Research (Passive)				
65.0	66.0	W	Earth Exploration Satellite, Space Research		EES	EES	

TABLE I (Continued)

Frequency (GHz)		Region*	Allocation Primary/Secondary	Fixed and Mobile	Fixed† Satellite Up	Fixed† Satellite Down	Broadcast Satellite
66.0	71.0	W	(See 43-48)		AMS	AMS	
71.0	84.0	W	Not Allocated				
84.0	86.0	W	Broadcast Satellite				EA
86.0	92.0	W	Radio Astronomy, Space Research (Passive)				
92.0	95.0	W	Fixed Satellite		EA		
95.0	101.0	W	(See 43-48)		AMS	AMS	
101.0	102.0	W	Space Research (Passive)				
102.0	105.0	W	Fixed Satellite			EA	
105.0	130.0	W	Intersatellite				
130.0	140.0	W	Radio Astronomy, Space Research (Passive)				
140.0	142.0	W	Fixed Satellite		EA		
142.0	150.0	W	(See 43-48)		AMS	AMS	
150.0	152.0	W	Fixed Satellite			EA	
152.0	170.0	W	Not Allocated				
170.0	182.0	W	Intersatellite				
182.0	185.0	W	Space Research (Passive)				
185.0	190.0	W	Intersatellite				
190.0	200.0	W	(See 43-48)		AMS	AMS	
200.0	220.0	W	Not Allocated				
220.0	230.0	W	Fixed Satellite (Direction not specified)		EA	EA	
230.0	240.0	W	Radio Astronomy, Space Research (Passive)				
240.0	250.0	W	Not Allocated				
250.0	265.0	W	(See 43-48)		AMS	AMS	
265.0	275.0	W	Fixed Satellite (Direction not specified)		EA	EA	

* Regions: 1. Europe, Russia, and Africa
2. North and South America
3. Rest of World
W. Worldwide

† Fixed Satellite: Point-to-Point Satellite Service

A: Allocated

AMS: Aeronautical Mobile Satellite, Maritime Mobile Satellite, Aeronautical Navigation Satellite, Maritime Navigation Satellite

EA: Exclusive Allocation

EES: Earth Exploration Satellite

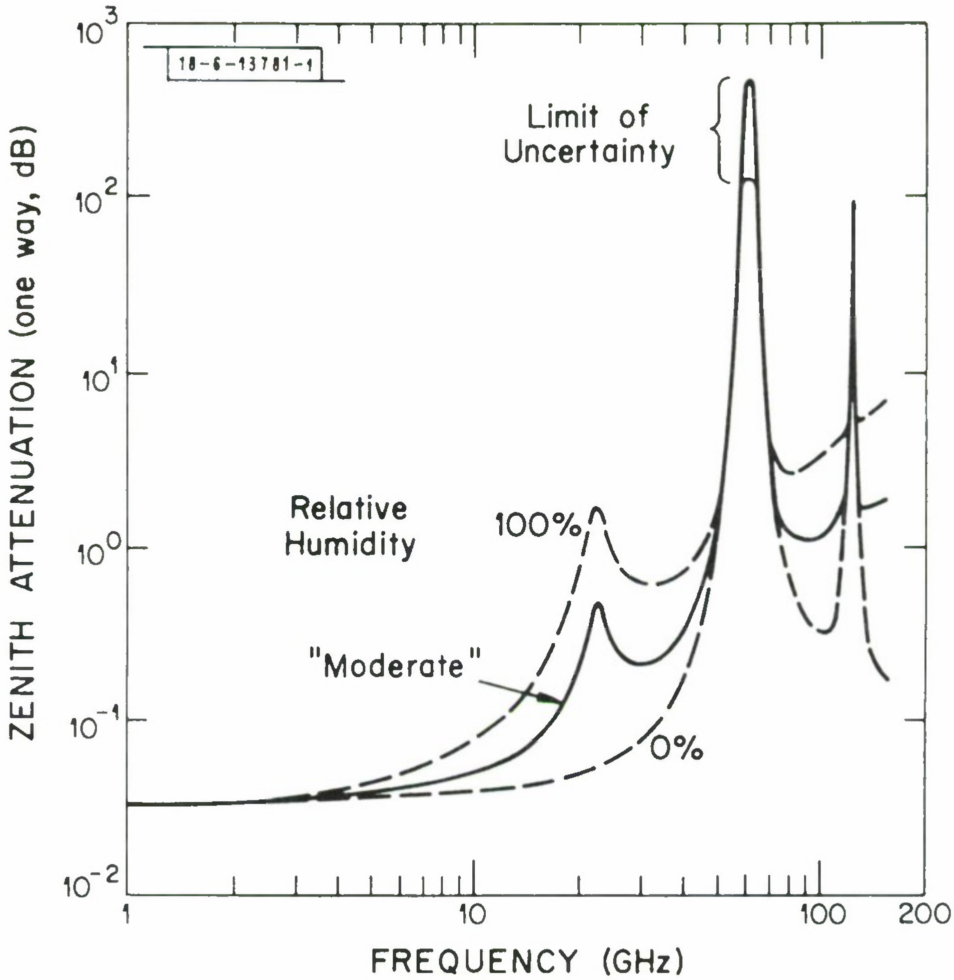

Fig. 1. Zenith attenuation vs frequency. (After R. K. Crane, Ref. 24.)

one. A satellite-borne transmitter is required for each of these two links, so the usual limitations on size, weight, available prime power, and heat-dissipation capability confront the transmitter designer. The satellite-to-satellite millimeter-wave link is somewhat more challenging than a satellite-to-ground link of equivalent capacity. The development of large satellite-borne antennas having precise surfaces is subject to rigorous size and weight constraints. Furthermore, the pointing problem (mutual acquisition and tracking in angle) must be solved by two satellite-borne terminals in the satellite-to-satellite case.

When one of the terminals is to be on the ground, such limitations are not usually imposed on its designers. Although the propagation effects can adversely influence maximum antenna size and can increase path loss on the space-to-ground link, these problems at least have indicated solutions in phased apertures of a few large antennas, and in space-diversity combining of received signals. In the following paragraphs we concentrate our attention on some of the salient issues related to a satellite-to-satellite communication link at millimeter wavelengths.

The proposed frequency allocations for satellite-to-satellite relaying (Table I) include frequency bands near 60 GHz. In these regions the minimum theoretical one-way attenuation for a vertical path all through the atmosphere exceeds 100 dB (Fig. 1), and it varies as the cosecant of the elevation angle. A satellite-to-satellite link operating at these frequencies would be completely private; it would not be detectable from the ground, and it would be relatively impervious to jamming or interference, whether deliberate or unintentional. Considering the proposed frequency allocations and the current status of the millimeter-wave technology, it is our opinion that the oxygen-absorption region around 60 GHz is a prudent and promising choice for satellite-to-satellite communication in the near future (about five years). Other portions of the millimeter-wave region could be used, however.

D. Millimeter-Wave Technology

We now briefly review the important areas of technology in the 60-GHz region as they would affect a satellite-to-satellite communication link (Ref. 27).

These critical areas are the generation, modulation, amplification, transmission, radiation, and reception of signals.

Sources of low-level millimeter-wave power in the frequency range of interest include tubes and solid-state devices. Klystrons and backward-wave oscillators tend to be bulky and massive and to require special cooling and high operating voltages. Tubes in this instance are not seriously considered for space applications. Solid-state devices in frequency-multiplier chains are used for indirect generation of power. The output power is normally limited by the final multiplier diode, the over-all bandwidth tends to be narrow, and the DC-to-RF conversion efficiency is low. Direct generation of millimeter-wave power has also been demonstrated with LSA diodes and more significantly with silicon IMPATT diodes (Ref. 28). Devices such as the IMPATT diode have potential applications beyond their use as local oscillators, exciters, or pump sources. We can speculate on the possibility of arraying a number of these diodes for use as the final stage in an all-solid-state transmitter.

Modulation of the frequency of the source used for the exciter of the transmitter can be implemented in a number of ways, such as by varying the bias voltage of a solid-state oscillator or that of a varactor diode inserted in the oscillator cavity. Modulation of the phase of the source can be accomplished by varying the transmission-line length between the oscillator and the output. This latter method naturally lends itself to digital techniques; it seems that high data rates (>100 MHz) and low insertion loss (<1 dB) are well within the state-of-the-art (Ref. 29). Another method of modulation is to carry out this complex task in a separate modem and then to combine this signal with the carrier in an up-converter. This method, as well as the preceding ones, may require high-level post-modulator amplification.

Amplification of millimeter-wave power is a requisite for high-data-rate communications. It is also one of the more critical areas in the development of technology. A number of millimeter-wave traveling-wave-tube amplifiers (TWTA's) have been made at Hughes Research Laboratories (Ref. 30). The operating frequencies are 55 and 95 GHz, with output powers from 150 W to 6 kW, gains of 20 dB, and efficiencies of about 25%. None of these tubes is space-qualified. However, they could probably serve as prototypes from which a suitable design could be evolved.

Transmission of millimeter wave power requires, for efficiency and power conservation, that all guide runs be kept short. The standard rectangular guide in this frequency band has a calculated insertion loss of 0.5 dB/ft. Passive components such as couplers, diplexers, and comparators are also rather lossy. Dissipation losses can be reduced by using circular guides and by increasing the principal dimension of the guide to several wavelengths. Using a pipe four wavelengths in diameter and the TE_{01} mode of propagation would decrease the attenuation by about two orders of magnitude relative to the attenuation in a standard-size guide (Ref. 31). Mode purity in oversized guides can become a problem; losses due to spurious modes could offset the reduction in dissipation losses. With millimeter waves, high dissipation losses are likely to remain an unpleasant reality.

Radiation of millimeter-wave power requires efficient antennas with uncommon dimensional tolerances. Using the Ruze (Ref. 32) formalism, the rms value of the random surface deviations should not exceed 0.02 λ (0.004 inch at 60 GHz) for the gain degradation to remain below 0.5 dB. A millimeter-wave antenna made of a relatively new material which reportedly has the desired thermal characteristics in addition to being lightweight has been reported (Ref. 33). This material (which has promise for space applications) consists of graphite fibers embedded in an epoxy resin. The thermal-expansion coefficient is between 0.4 and 0.6×10^{-6} per °F over the temperature range −300 to +100°F. The predicted gain degradation because of thermal distortion was computed for a 6-ft-diameter antenna to be 0.2 dB at 70 GHz. A 19-inch scale model was built; it was tested and appeared to be satisfactory.

A 6-ft-diameter antenna at 60 GHz has a computed power gain of +58.5 dBI (η = 55%) and a 0.20° beamwidth between half-power points in the E-plane, 0.18° in the H-plane. In order to maintain full link capacity, the boresights of the antennas should be aligned with the line-of-sight within one-tenth (0.02°) of their beamwidths. This requirement obviously dictates an angle-tracking system and possibly an angle-acquisition scheme. In addition to angle acquisition

TABLE II

CHARACTERISTICS OF A MILLIMETER-WAVE SPACE-COMMUNICATION LINK

Operating wavelength $\lambda = 5$ mm
Operating frequency $\nu = 60$ GHz
One-way Doppler effect = 200 Hz/(m/sec)

Transmitter output power P_t (TWTA, 25 W)	+14 dBW
$\eta_t = 0.2$, $P_{in} = 125$ W , $P_{diss} = 100$ W	
Antenna power gain, transmitter (6-ft, $\eta_a = 0.55$)	+58.5 dBI
Half-power beamwidth = 0.2° (3.5 mrad)	
EIRP = +72.5 dBW	
Antenna power gain, receiver (same)	+58.5 dBI
Path loss $(\lambda/4\pi R)^2$, R = 73,000 km*	−226 dB
Total guide losses	−3 dB
Received power P_r	−98 dBW
Power density at receiver = 1.3×10^{-10} W/m^2 [−99 dB(W/m^2)]	
Effective receiving area = 1.4 m^2(+1.5 dBm^2)	
Standard noise power density ($kT_{ambient}$) [one-sided]	−204 dB(W/Hz)
Noise figure of receiving system	+7 dB
System noise power density $N_o = kT_{sys}$ [one-sided]	−197 dB(W/Hz)
Energy quantum $h\nu = 4 \times 10^{-23}$ J(−224 dBJ)	
P_r/N_o for the system	+99 dBHz
Required E_b/N_o for bit-error probability $< 10^{-5}$†	+13 dB(Hz-sec/bit)
Maximum data rate $\mathcal{R}_{max}$	+86 dB(bit/sec) (400 Mbit/sec)

* Two geostationary satellites 120° apart.

† Assumed modulation is Four-Level Phase-Shift Keying (QPSK).

and tracking, it may be necessary to have a frequency-acquisition-and-phase-tracking scheme also. This area presents quite an engineering challenge; the problems cannot be considered solved without a successful demonstration in space.

Reception of millimeter-wave power in space will require reliable low-noise receivers. Parametric amplifiers at 60 GHz are not yet available, although their development should be feasible (Ref. 34). At the present time, the receiver front end is invariably a mixer. Current research in millimeter-wave mixers is oriented toward various techniques for improving the noise figure. By properly terminating the image harmonic frequencies, by operating the mixer diodes as ON/OFF switches, by using very low-loss waveguide circuits, ultra-low-noise IF amplifiers, and high-quality diodes with low series resistance and low junction capacitance, mixer conversion losses and system noise figures could be minimized. The future projection, based on current research, is that a mixer with a conversion loss of 7 dB at 60 GHz is achievable (Ref. 35).

On the basis of the foregoing discussion, we postulate a candidate system and compute the link performance for a millimeter-wave satellite-to-satellite link. The salient parameters and performance numbers are given in Table II.

From Table II we gather that our space-to-space link capacity with 0 dB link margin is 400 Mbit/sec. A formidable capacity indeed, but the result is no better than the assumptions on which we based our calculations. We regard Table II as an interesting exercise aimed at demonstrating the capability of a millimeter-wave space-to-space link. The system components and black boxes are almost available. Given the right amount of motivation (plenty of money) such a high-capacity data-relay system could surely be built in the very near future (less than five years). In the meantime, satellite-to-satellite relaying, if it is to be demonstrated at millimeter-wave frequencies, will probably be done with more modest equipment, on a less ambitious scale. Scaling our postulated output power and antenna gain downward and noise figure slightly upward, it seems that a link capacity of tens or hundreds of kbit/sec could be fairly readily demonstrated. We conclude this critique of millimeter-wave links by saying that the potential for very-wide-bandwidth communications is certainly there; this is the region where the gigahertz are. The equipment could soon become available; all that is needed is the proper motivation to achieve the postulated performance.

III. OPTICAL SPACE COMMUNICATION

Many of the attractive aspects of millimeter-wave space communication (Sec. II) apply even more strongly in the optical domain. For example, there is now no frequency-allocation problem for optical communication systems in the USA, for there is no governmental regulation (other than from the standpoint of safety) of operation in that part of the electromagnetic spectrum. This carefree situation cannot be expected to persist when optical communication becomes popular.

A. Optical Propagation Phenomena

Optical signals are subject to all the vagaries of propagation through the atmosphere that plague millimeter-wave signals. It often happens that the signals are of wide-band character, perhaps originating in the optical transmitter (Q-switched, mode-locked, or current-pulse-injection lasers, for example) or set by the requirements of high-data-rate users. Such signals are susceptible to degradation by the dispersive effects of high-order multiply scattering channels such as clouds, fog, or haze between transmitter and receiver. Signals that leave the transmitter in a tightly collimated, mode-controlled, frequency-stabilized beam of radiation may reach the receiver with a decidedly non-uniform phasefront, spread out in time of arrival, in angle of arrival, and in Doppler-shifted frequency. Much theoretical and experimental work has been done (review articles Refs. 36-38, for example) to establish understanding of optical propagation through the turbulent clear atmosphere. Comparatively little has been done (Refs. 39-40) to come to grips with the coarse practical problems presented by bad weather. Some space/ground-link users can wait for better weather; others must rely on the statistical improbability that all of a multiplicity of well-separated terminals will be blanked out simultaneously, at a critical time.

B. Optical Systems and Technology

Under space communication we include three possible links: ground-to-satellite, satellite-to-satellite, and satellite-to-ground. The first and last of these have been tried (a receiver matched to the green wavelength of the argon laser was carried on NASA's GEOS-II satellite; a voice-modulated GaAs laser transmitter was carried on Gemini VII), though with only limited success.

The status of optical-communication technology is even less well developed than for EHF. Discussion of it often centers on the state-of-the-art in laser development (transmitters). There is a substantial body of opinion favoring gas lasers such as CO_2 (10.6-μm radiation). Power-conversion efficiency is high, frequency-stabilization has been pushed to extraordinary lengths, and long-lived units have been demonstrated. Unfortunately, when one looks beyond the transmitter to consider the entire communication system, one finds that a receiving system matched to a CO_2 transmitter has some drawbacks. Energy detectors such as photomultiplier tubes and photodiodes perform very poorly at 10.6 μm. The system designer could elect to frequency-multiply (with consequent inefficiencies) the output of the CO_2 laser manyfold, getting it into the visible spectrum, where these energy detectors work well. Alternatively, he could elect to mix the received signals optically with a CO_2 local-oscillator signal, processing the RF difference frequency by conventional techniques thereafter. The heterodyning approach presents some real challenges: the receiver must now generate the local-oscillator signal, and the mixer must be operated at cryogenic temperatures.

This year's favorite for wide-band/high-data-rate optical space communication is the solid-state Nd:YAG laser (1.06 μm). Energy detectors at 1.06 μm leave something to be desired, so some system designers frequency-double the Nd:YAG output to 0.53 μm, where much better detectors are available. The doubling is touchy; better detectors at 1.06 μm would allow foregoing that complication and inefficiency. The partisans of CO_2 have not given up; they will surely be heard from again (Ref. 41). The field of quantum electronics is developing so fast that both Nd:YAG and CO_2 might be displaced by something else. It is too soon to declare any particular segment of the optical spectrum to be the long-term preference for space communication.

Looking at the matter from the standpoint of the over-all system, we suggest that the role of the laser (transmitter) as it affects the system design will change. It will not be enough (as at present) to choose a laser that can be modulated readily and that operates efficiently in a wavelength band where sensitive, quiet detectors can be built. For example, it will be profitable in applications where there is substantial background light (when receiving optical signals from a satellite that is very near the Sun in view angle, or even seen against it) to restrict the narrow receiver pass band to the very minimum set by the transmitter output spectrum. It could turn out that the desired ultra-narrow-band filters would determine the other characteristics of the system, including the transmitted wavelength. The transmitter might be tunable, locked to a reference filter element. Furthermore, the provision of full-duplex communication (simultaneous two-way communication between two terminals; see Sec. V) would be facilitated if a selection of transmit/receive wavelengths in a common band were available. Neither of these degrees of transmitter freedom (wavelength tunability, wavelength selectability) is readily provided by lasers such as Nd:YAG and CO_2.

The surface tolerances required on optical antennas are much tighter than for millimeter-wave antennas, but — paradoxically — they are easier to meet. The 6-ft-diameter, 60-GHz, +58.5-dBI, antenna discussed in Sec. II-D has an aperture-to-wavelength ratio of about 365. By comparison, a 10-cm-diameter, 1-μm, antenna has a ratio of 100,000 with a maximum power gain larger than +100 dBI. Optical components of this size and quality have been made for many years. The saving grace for optical antennas is the element of <u>scale</u>. An optical mirror, for example, can hold its shape without excessive penalties in size or weight by virtue of the rigidity achieved in rather ordinary materials having a thickness of many thousands of wavelengths. We hasten to point out that the tremendous directivity achievable with an optical antenna of modest physical size carries with it excruciatingly difficult problems of beam-pointing on transmission, of acquiring and tracking in angle on reception. The beamwidth of an antenna having a power gain of +100 dBI cannot exceed about 40 μrad (8 $\widehat{\text{sec}}$).

Table III contains a simplified calculation of system performance for an optical space communication link. The calculations of Table III are made using the natural physical concepts of power flux, receiving area (cross-section), etc. Path-loss and receiving-gain numbers are supplied for those who prefer them. The assumed system losses are implicit in the numbers for P_t and A_r. The detection parameter N_b plays a part in Table III parallel to the noise-power density N_o in Table II. Some people define an equivalent noise-power density for this optical-detection case. We are uncomfortable with that procedure; the detection takes place in Poisson, not Gaussian, noise (see Sec. IV).

This system is an even more extreme extrapolation of the state-of-the-art than the millimeter-wave one presented in Table II. Of particular note is the dismal inefficiency of the optical transmitter. Pointing the 10-μrad transmitting beam will be a challenge. The resolution field-of-view (beamwidth) associated with an effective receiving area (set by the aperture stop) of $0.1\,m^2$ is about 2 μrad, but it is not necessary to point the receiving aperture to that precision. The receiving optical system focuses incoming radiation from a much wider field-of-view (set by the field stop) onto the photosurface of the detector. Radiation arriving within a single resolution field-of-view is imaged as a tiny spot (blur circle). The photosurface may be tens or even thousands of wavelengths wide (unlike a conventional microwave antenna feed). Assuming reasonable uniformity of photoelectric properties, it does not matter very much just where on the photosurface the image is formed, so the angle-tracking requirements on the receiver are correspondingly relaxed.

IV. SOME POINTS OF COMPARISON

Now that we have reviewed the performance calculations for millimeter-wave and optical satellite-to-satellite communication, we can make some instructive comparisons between them. The electronics engineer who has had experience in the calculation and measurement of communication-system performance in the conventional microwave region will find no particular surprises awaiting him in the millimeter-wave domain. For example, the V-band (EHF) system calculations presented and discussed in Sec. II are not significantly

TABLE III

CHARACTERISTICS OF AN OPTICAL SPACE-COMMUNICATION LINK

Operating wavelength $\lambda = 530$ nm
Operating frequency $\nu = 5.7 \times 10^5$ GHz
One-way Doppler effect = 1.9 MHz/(m/sec)

Transmitter output power P_t (doubled Nd:YAG) 200 mW(−7 dBW)

$\eta_t = 0.002$, $P_{in} = 100$ W , $P_{diss} = 99.8$ W

Transmit beamwidth $\Theta_t = 10\ \mu$rad(2 $\widehat{sec}$)

Power gain = +112 dBI

EIRP = +105 dBW

Range R = 73,000 km*

Path loss $(\lambda/4\pi R)^2 = -305$ dB

Effective receiving area A_r 0.1 m^2(−10 dBm^2)

Power gain = +126.5 dBI

Power density at receiver = 5×10^{-7} W/m^2 [−63 dB(W/m^2)]

Received power $P_r = 4P_tA_r/\pi R^2\Theta_t^2 = 5 \times 10^{-8}$ W(−73 dBW)

Energy quantum $h\nu = 3.75 \times 10^{-19}$ J(−184 dBJ)

Quantum efficiency $\eta_q = 0.2$(S-11 PMT, +20° C)

Signal-photoelectron rate $\bar{n}_{sig} = P_r\eta_q/h\nu = 2.6 \times 10^{10}$ pe/sec

Background (cathode dark current) $\bar{n}_{cdc} = 5 \times 10^4$(pe)/sec(negligible)

Background from Sun, stars, etc., assumed negligible

For $Prob_{error} \approx 10^{-5}$, $N_b \approx 20$ pe/decision , average†

Maximum data rate $\mathcal{R}_{max} = \frac{\bar{n}_{sig}}{N_b} \approx 10^9$ bit/sec

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* Two geostationary satellites 120° apart.

† Assuming simple ON/OFF (1/0) modulation.

different from those that are routinely made (and verified) for systems operating at wavelengths several thousand times greater (in the HF region). As we saw in Sec. III, however, the study of optical communication systems, operating at wavelengths several thousand times shorter than for V-band (in the visible and near-IR), requires different outlooks in certain respects. The underlying electromagnetic-physics and detection-theory bases for all these calculations are, of course, the same.

A. Noise Statistics and Detection

The major conceptual differences between these calculations come from the detection processes. For millimeter-wave communication, we can consider that we are still in the familiar land of Gaussian noise statistics, for the external as well as the internal backgrounds. This territory has been explored in depth. The paramount significance of the (E_b/N_o) ratio in digital signal detection is well understood. That is to say, given receiver noise of spectral density N_o (W/Hz), each bit decision (detection) made with a specified level of reliability in a particular modulation format requires at least energy E_b (J). Using a simple example, it does not matter in well-designed systems, all other things being equal, whether the transmitted pulses are short, with high peak power, or long, with low peak power, so long as the received energy per pulse is the same.

The rules can be different for optical detection. The availability of quiet, sensitive energy detectors in the visible-light region allows observation of individual photoelectron-emission events. Although it would be stretching a point to say that these optical receivers count photons, they can count discrete current pulses. The pulses correspond to photoelectron emission caused by reception of signal and external-background energy on the one hand, and by internal-background phenomena (dark current, for example) on the other. The preferred, analytically tractable, model for a shot-noise process of this sort is the Poisson one. In that regime, the choice of waveform makes a big difference. All other things being equal, it is advantageous to transmit short, high-peak-power pulses rather than long, low-peak-power ones of equal energy if the system has a direct-detection ("photon-bucket") receiver. If the received pulses are sufficiently short, the receiver need be gated ON only during the time when a pulse might be received, with consequent reduction in the level of background noise. The energy-detection process then becomes essentially noiseless insofar as background is concerned. Nature, being a jealous wench, does not allow us to make error-free detections, however, The emission of photoelectrons in response to incident light is a statistical process; the distribution of possibilities gives rise to uncertainties that are called "quantum noise."

We pointed out in Sec. III the principal differences between optical receivers working in the visible and in the IR. Nowadays, the latter invariably rely on heterodyne detection. A well-designed receiver for 10.6-μm CO_2 radiation can also be essentially noiseless insofar as background is concerned, though at the price of equipment complexity, and with some sensitivity to the phase-front "purity" of the received radiation. The use of a strong optical local-oscillator signal for the mixing-down from optical to IF frequencies sets the character of the noise statistics (Gaussian).

These differences between the detection processes have marked influence on the choice of modulation formats. For millimeter-wave communication, it is generally desirable to transmit constant-level, modulated-CW signals, for the usual RF-system reasons (maximum energy per bit for given peak-power level in the transmitter). For optical space communication in the context of state-of-the-art technology, the detection advantages of short, high-peak-power, transmitted pulses are very persuasive if the signals to be transmitted are available in binary form (Ref. 42). On the other hand, if the signals are available in analog form, or if a high-total-rate data stream is composed of several independent, unsynchronized, lower-rate streams, there may be an over-all system advantage to subcarrier modulation of a CW, "single-frequency," laser (Refs. 43-44). Each case must be decided on its own merits.

The study of optical communication systems from the standpoint of quantum mechanics is being pursued (Ref. 45). These studies have not yet had a significant impact in the applications area.

B. Antennas

The performance of both millimeter-wave and optical antennas can be understood in terms of the same electromagnetic theory, which accounts for diffraction at an aperture. The term "diffraction-limited optics" deserves a little explanation. Long ago, sources, lenses, and detectors were not good enough to achieve the results predicted by diffraction theory. As the state-of-the-art improved, the theoretical beamwidths, resolutions, etc., were realized. Further improvement was then impossible, the results being limited by diffraction effects. To say that a lens, mirror, antenna, or whatever is "non-diffraction-limited" is not to imply that such a component can do better than a diffraction-limited one; the situation is exactly the opposite. Most microwave and millimeter-wave communication antennas are diffraction-limited.

The statement is sometimes made that optical antennas "have no side lobes." This viewpoint is an understandable exaggeration. The near-in side lobes have the same quantitative relationship to the main-beam gain (perhaps a few tens of dB down) as for a millimeter-wave antenna of similar aperture illumination. The near-in side lobes occupy only a very small solid angle, so it may be plausible to discount them. It is most difficult to measure the low, far-out side lobes of an optical antenna, far harder than for a similar millimeter-wave antenna (which is not an easy task). Nevertheless, they are – they must be – there. Control of the far-out sidelobe level is particularly important for optical receiving systems in space because they must usually operate in the presence of a powerful jammer – the Sun. This jammer is less important for millimeter-wave receiving systems.

The procedures for beam-pointing on transmission and for acquiring and tracking in angle on reception are conceptually much the same for millimeter-wave and for optical antennas (telescopes). The optical-system designer sometimes enjoys flexibilities that the millimeter-wave hardware does not readily afford. In an optical receiving system, the resolution in angle (the beamwidth) and the field-of-view (the solid angle throughout which beams can be formed) can be specified independently without introducing great complexity of equipment. On the other hand, the millimeter-wave-system designer has an easier time of it than the optical-system designer when it comes to illuminating a transmitting antenna by means of a focal-point feed (power source) that is to be less than a wavelength across.

One feature that gives optical space communication systems good potential for wide-band/high-data-rate applications is the relative ease with which the transmitted and received beams can be made very small in angle. Unfortunately, this helpful system improvement brings with it a new problem. The classical velocity-aberration effect (point-ahead angle) becomes significant (Refs. 46-47). Consider two satellites in coplanar, geostationary, Earth orbits, 120° apart in longitude. They move with the same (scalar) speed, but their (vector) velocities differ by a (tangential) component of magnitude $v_t \approx 5.3$ km/sec. The point-ahead angle is approximately $\Theta_{pa} = 2(v_t/c) \approx 11\,\mu$rad. If the antenna beamwidths are of this size or smaller, the two spacecraft cannot communicate by transmitting and receiving along the line of sight between them. Each spacecraft must "lead" the other (much as in hunting) by $(\Theta_{pa}/2)$ in order that its transmission can be received, and it will receive transmissions from the other at an angle $(\Theta_{pa}/2)$ behind the line connecting the two satellites. This problem is not insuperable, but it adds complexity to a high-performance optical communication system. Θ_{pa} is much smaller than the minimum beamwidths calculated in Sec. II for millimeter-wave space communication systems, so the point-ahead effect can be neglected in that context.

C. Practical Factors

Anyone working in millimeter-wave or optical space communication enjoys the thrills of pioneering, together with some of the hardships. The current status of millimeter-wave technology can be likened to the status of X-band (~ 8 GHz) technology about a decade ago. Most all of the devices, components, and test equipment have been developed or are being developed on a small scale in laboratories. The relative scarcity of test equipment, RF components, etc., in the millimeter-wave bands makes it hard to do things which are now done with relative ease at longer wavelengths (where are the V-band equivalents of the stable, broad-band, high-resolution spectrum analyzers that now serve as well-calibrated frequency-domain oscilloscopes at frequencies as high as 1 GHz?).

In the optical region, the availability of components and test equipment is far worse. The components that do exist are for the most part the outgrowths of a tradition of small-quantity production, often directed to the specialized needs of a particular field such as spectroscopy.

Theoretical and applied optics and the associated subjects in the physics of matter were already well-developed fields when the invention of the laser (c. 1960) led to their current renaissance. The effective utilization by the communication-system designer of the vast store of relevant information that has already been accumulated and is steadily increasing is made difficult by the diversity of its origin. Consider, for example, a particular, salient system characteristic: receiver sensitivity. The same physical device might be described in radiometric terms or in photometric terms (Ref. 48). The photometric terms (which should be avoided) are intimately related to the "standard" response of the human eye, a factor of very small significance for optical space communication. The radiometric terms are often given in forms of very limited applicability, offering plentiful opportunities for confusion (Ref. 49).

V. APPLICATIONS

Our discussion of millimeter-wave and optical space communication thus far has been almost entirely technical in content. Now it is time to look beyond these familiar, comfortable concerns and face a larger question: To what constructive uses might we put these technologies?

A. Wide-Band/High-Data-Rate Systems

There are both civil and military uses for the wide-band/high-data-rate communication systems for which the millimeter-wave and optical domains hold promise.

1. INTELSAT

A future need for inter-satellite trunking in the INTELSAT environment has already been foreseen (Ref. 50). Such "switchboards in the sky" (Fig. 2) will extend the flexibility of the INTELSAT network as more ground terminals

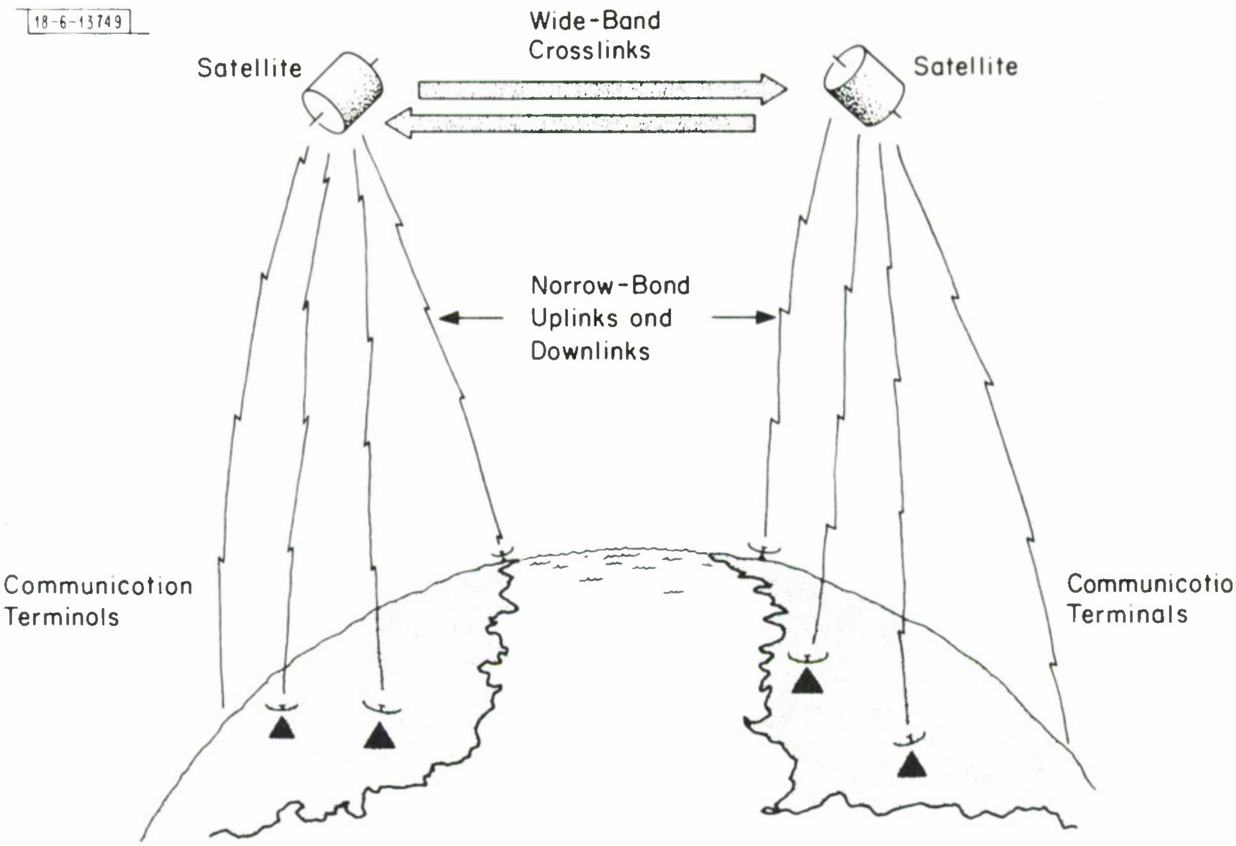

Fig. 2. Satellite-to-satellite data relay in the INTELSAT environment.

come into use and intercontinental traffic builds up. Although it is easy to be misled by optimistic extrapolations of growth curves, there is little doubt that this traffic will grow substantially.

2. NASA

The NASA concept for a tracking and data-relay satellite system (TDRSS) is based on geostationary satellites that perform multiple relaying functions (Ref. 51). These relay satellites serve as intermediaries between a few centrally located ground stations (within CONUS and perhaps at the two principal overseas DSIF sites) and satellites in orbits ranging in altitude from a few hundred to tens of thousands km. The TDRSS satellites retransmit commands from ground stations to specific satellites and the data outputs (including telemetry and tracking signals) from these satellites to the ground stations. The successful implementation of the TDRSS concept would allow better, faster, and more convenient service to the ultimate user as well as economic gain.

The techniques of millimeter-wave and optical space communication find obvious applications in the cases for which the data stream coming from a specific satellite is of high rate (Fig. 3). The Earth Resources Technology Satellite (ERTS) is a case in point. The ERTS A and B satellites (Refs. 52-54) will carry high-resolution TV cameras and scanners for the collection of Earth-resources survey data from space. The output from the two ERTS remote sensors (each of which has multispectral characteristics) are a 3.5-MHz video signal and a 15-Mbit/sec PCM signal. The data output from an operational successor Earth Observational Satellite (EOS) might be as much as 300 Mbit/sec.

3. Military

The military uses are essentially the same as those cited for INTELSAT and NASA.

(a) The Defense Communications Agency (DCA) now leases many channels provided by the INTELSAT system. When new capabilities (such as satellite-to-satellite trunking, Fig. 2) become available in that system, DCA will be able to take advantage of them.

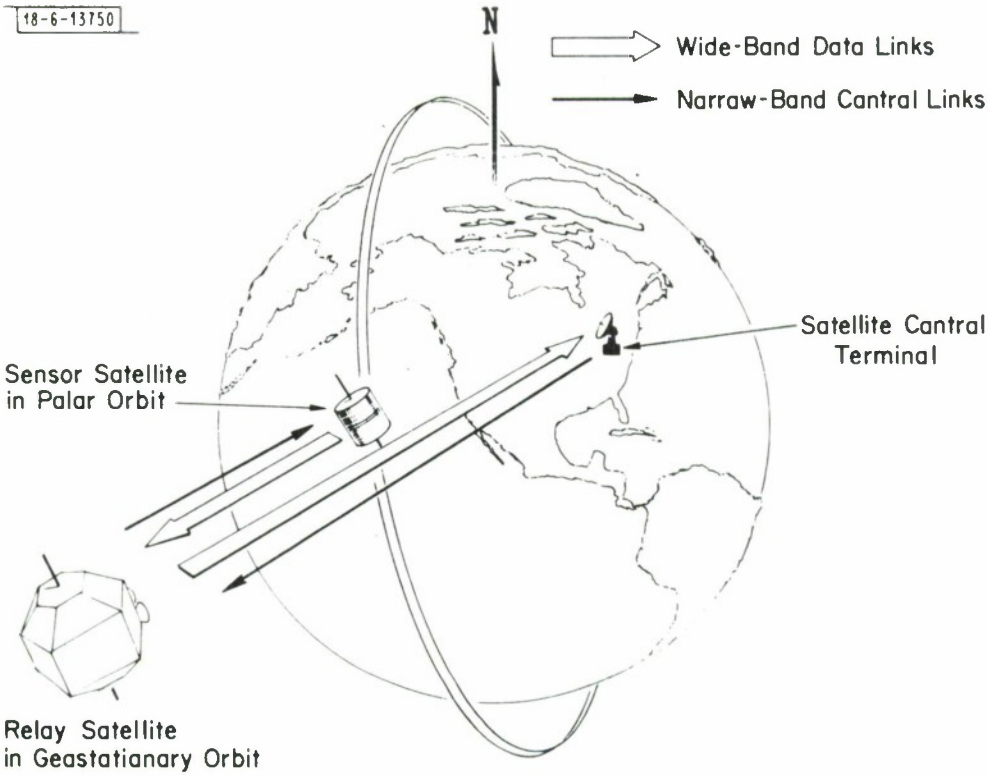

Fig. 3. Satellite-to-satellite data relay in the NASA environment.

(b) There are military needs for satellite relay of high-rate data, much as in the NASA environment (Refs. 55-59). The immediate relay to Command Centers of data from surveillance and reconnaissance sensors (Fig. 3) is of vital importance, not only for the waging of war but also for the preservation of peace.

(c) The desire of NASA to monitor and control its satellites in orbit from a CONUS location via relay satellites (TDRSS) has a close military counterpart. Many of the same reasons apply (Ref. 60).

B. Narrow-Band/Low-Data-Rate Systems

We expect that the first satellite-based experiments in millimeter-wave and optical communication will yield channels having rather limited capacity (say, 10 to 100 kbit/sec). The results of these initial experiments, coupled with the available technology, will permit advances in later experiments to the 100-Mbit/sec-to-1-Gbit/sec range. It is doubtful that there will be any significant applications in the civil area for the initial low-rate links. There are, however, credible military applications for them in the area of assured communication for command-and-control purposes.

C. Historical Note

It is interesting to note that satellite-to-satellite data relay was first suggested, along with the geostationary communication satellite itself, in Arthur Clarke's remarkable 1945 article (Ref. 61). This applications-oriented article furthermore contains the thought that ". . . . . (communication satellites) might be linked by radio or optical beams. . . . . "

VI. SUMMARY AND CONCLUSIONS

We have seen – on paper – some of the things that could be done with millimeter-wave and optical space communication. Each of these portions of the electromagnetic spectrum has in turn been proclaimed "the wave of the future." They are indeed of great promise, but these promises of great things will not be kept without strong motivation and substantial financial encouragement. We recognize here another of many provocative areas in contemporary technology, areas in which useful operational systems will be developed as they are needed and can be accepted.

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13. ABSTRACT

Many comparative studies have been made of millimeter-wave and optical space-communication systems. The applications considered have been diverse, including links between satellites in low Earth orbits, satellites in synchronous orbits, deep-space probes, and Earth terminals, with data-rate requirements from a few bit/sec to Gbit/sec. We present in this report not just another such comparison, but rather a short tutorial account of the common and of the distinctly different features of some millimeter-wave and optical space-communication systems. For example, the design of the transmitting antennas is governed by the same electromagnetic theory, which accounts for diffraction at an aperture. However, the signal-to-noise relationships in the receivers may not be the same (Gaussian vs Poisson noise statistics).

Possible satellite applications are surveyed briefly, with mention of the favorable and the unfavorable factors associated with millimeter-wave and optical space-communication systems. Candidate systems are postulated and link calculations are given.

14. KEY WORDS

space communication
optical communication
millimeter-wave communication
satellite-to-satellite relay