Non-Conventional Communication

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Summary

The problem of acquiring and tracking a distant terminal for long-range laser communications is defined and solutions suggested. Factors considered include the effects of the atmosphere, the transit time, and the inherent limitations of optical systems.

Various parametric tradeoffs can be made in the synthesis of a system capable of the required accuracies. Some of the parameters have basic, or inherent, limitations while others are limited by size, weight, or cost considerations. These parameters are defined and their magnitudes established.

Finally, various system components are examined and their necessary characteristics defined to provide guidelines for the future development of equipments capable of performing the required tasks.

Introduction

The advantages to be gained from the inherent broadband capabilities of the laser in long-range communications require solutions to the acquisition and tracking problems associated with the use of extremely narrow beams. In order to evolve acquisition and tracking logic, it is necessary to examine in detail the various factors which govern system characteristics and to choose a transmitting beamwidth on the basis of available laser power, detector sensitivity, area of receiving aperture, and atmospheric perturbations (if transmission through the earth's atmosphere is to be considered). Knowledge of the magnitude of these parameters together with coarse acquisition information is then used to formulate acquisition systems.
Three acquisition systems are considered in this paper: one which holds the transmitter and receiver beamwidths constant throughout the acquisition cycle, one which holds the transmitter beamwidth constant but varies the instantaneous field of view of the receiver, and one which uses a storage device with memory. Common to all systems is the problem of external noise caused by the stars, earth and planets. These noise sources complicate the acquisition problem by adding the requirement of target discrimination.

The tracking problem is characterized by the high degree of precision necessary and the generally slow angular scanning rates. Ideally, the error-signal generation portion of the system should be compatible with the acquisition scanner to reduce interface and switch-over problems. A difficulty encountered in tracking extremely narrow beams with moving systems lies in the requirement that the transmitter "lead" the target to compensate for the error caused by the time it takes for the beam to travel the distance between transmitter and receiver. Additional complications arise when transmission through the atmosphere is necessary.

It is the purpose of this paper to examine the spectrum of system considerations outlined above which impact upon the total acquisition and tracking problem. As developed in the paper, the successful solution of the acquisition and tracking problem requires extreme precision in the various components which comprise the system. Most of the components can be made available now but others, such as precision beam deflectors, require further development.

The Acquisition Problem

The problem of acquisition is one of locating and illuminating a target with a narrow beam in a field of view which may be larger than the width of the beam. The size of the field of view is governed by the accuracy to which the position of the target is known.

The narrow beam associated with a system of this type makes the laser unsuitable for a general search over large volumes. For example, a laser beam with an angular width of 5 seconds by 5 seconds requires $1.3 \times 10^{10}$ beam positions to search out a hemisphere. A beam position here is defined as the solid angle subtended by the half power points of the beam. If a dwell time of one microsecond is allowed at each beam position, a total time of 3.6 hours is required to complete the search. Because the relative motion between a space vehicle and an earth station does not permit this length of time to establish contact, it is necessary to perform coarse acquisition by some means external to the optical system.

If the acquisition is to be performed for a ground terminal, one of the precision radars can be used for coarse acquisition. The following list shows the angle accuracies of some of the radars presently in use. After a space vehicle has been tracked for several days, its position can be computed to much greater accuracies, certainly less than 1 second of arc.
<table>
<thead>
<tr>
<th>Radar</th>
<th>Angular Accuracy</th>
<th>Frequency Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>AN/FPS-16</td>
<td>0.012°</td>
<td>C</td>
</tr>
<tr>
<td>Modified AN/FPS-16</td>
<td>0.0084°</td>
<td>C</td>
</tr>
<tr>
<td>AN/FPQ-6</td>
<td>0.006°</td>
<td>C</td>
</tr>
<tr>
<td>Tradex</td>
<td>0.017°</td>
<td>UHF</td>
</tr>
</tbody>
</table>

Since the space vehicle will not have the benefit of a high resolution radar, it will have to rely on an attitude stabilization system or far body tracker. The following list shows the presently attainable accuracies of several basic attitude stabilization systems.

- Gravity Stabilization without Damping: ±6°
- Gravity Stabilization with Damping: ±1°
- Spin Stabilization: ±1°
- Horizon or Area Scanning: ±1° or less
- Sun, Moon, or Star Tracking: ±1' to ±1°

It is also useful to examine the attitude control requirements for the OAO satellite. Not all of the accuracies shown in the following list have been achieved in flight but all are felt to be within or near the state of the art.

**Initial Orientation**

<table>
<thead>
<tr>
<th>Action</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Align toward Sun</td>
<td>0.5° to 1°</td>
</tr>
<tr>
<td>Acquire Star</td>
<td>0.5°</td>
</tr>
<tr>
<td>Acquire Earth</td>
<td>several degrees</td>
</tr>
</tbody>
</table>

**Attitude Stabilization**

<table>
<thead>
<tr>
<th>Direction</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toward Sun</td>
<td>1 second to several degrees</td>
</tr>
<tr>
<td>Toward Star</td>
<td>0.1 second</td>
</tr>
<tr>
<td>Toward Vertical</td>
<td>0.1° to several degrees</td>
</tr>
<tr>
<td>Zero Yaw Angle</td>
<td>1° to several degrees</td>
</tr>
</tbody>
</table>

These, then, represent the magnitude of coarse acquisition information which can be available for use on a laser based system.
A situation may occur in which a space vehicle looking toward the earth is pointed with great precision toward the earth's center without knowing the location of the target on the earth's surface. Since the solid angle occupied by the beam will generally be much smaller than the solid angle subtended by the earth, a search will be necessary throughout the latter.

In order to develop an acquisition logic, it is first necessary to define the following parameters governing the system:

\[ \omega_t = \text{solid angle beamwidth of the transmitter}; \]

\[ \Omega_t = \text{solid angle field of view of the transmitter, i.e., the solid angle representing the uncertainty to which the position of the target is known}; \]

\[ \omega_r = \text{instantaneous field of view of the receiver}; \]

\[ \Omega_r = \text{total field of view of the receiver, analogous to } \Omega_t \text{ but not necessarily of the same size}; \]

\[ T_a = \text{acquisition time.} \]

It is useful to examine the factors governing the size of each of these.

The transmitter beamwidth \( \omega_t \) must be selected on the basis of the power available from the laser, the distance to the target, and the required power density at the target. The smaller the power available from the laser, the smaller the beamwidth necessary to realize the same power density at the receiver. Figure 1 is a plot of the maximum range obtainable as a function of the solid angle of the transmitted beam for the following parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitted Power</td>
<td>1 watt</td>
</tr>
<tr>
<td>Receiving Aperture</td>
<td>1 ft²</td>
</tr>
<tr>
<td>Receiver Bandwidth</td>
<td>1 Mc</td>
</tr>
<tr>
<td>S/N Ratio</td>
<td>5 db</td>
</tr>
<tr>
<td>Losses</td>
<td>5 db</td>
</tr>
<tr>
<td>Detector Sensitivity</td>
<td>( 3 \times 10^{-12} \text{ dbw} ) (Sensitivity of the best uncooled photomultiplier for 6328A wavelength.)</td>
</tr>
</tbody>
</table>

This plot is, of course, representative and may be shifted up or down for other values of the above-listed parameters.
At this stage of development, it is difficult to predict the magnitude of CW power available from lasers in the future. It appears as though power outputs of the order of watts or tens of watts may be obtained but probably not hundreds or thousands of watts. New developments may greatly alter this prediction. Higher output power remains a prime requisite for very long range communications, such as deep space probes, and the course of development must be aimed toward higher powers because beamwidth narrowing to increase power density cannot be exploited ad infinitum.

In addition to the difficulties of aiming such narrow beams, a ground based station must contend with scintillations caused by air turbulence. These scintillations have plagued astronomers since early time and are of the order of one half to two seconds of arc at night and greater in the day. The lower beamwidth limit for a ground based station will therefore be about one to five seconds of arc.

A receiving aperture of one square foot is taken as the size that can conveniently be carried aboard a space vehicle; weight and size of optical telescopes increase rapidly as the aperture is increased beyond this point. Greater ranges might be achieved if a large aperture is used on the ground and is accompanied by a laser of correspondingly greater power. Since it is unlikely that the output power of a single CW laser will be limited by input power considerations, the higher power can be achieved only by ganging several lasers in an array. If the problems associated with arraying lasers can be solved, then greater distances than those
indicated in Figure 1 can be obtained. For example, the range can be doubled by increasing the transmitted power by a factor of four, or by doubling the receiving aperture.

Detector sensitivity has two limitations: (1) that caused by noise in the receiver itself which can be reduced by cooling, and (2) that caused by quantum noise which is a basic limitation. Quantum noise is a part of the signal itself and is due to the random times of arrival of the individual photons. Since the energy of a photon at light frequencies is large compared to the energy of a photon at microwave frequencies, fewer photons are required to achieve a given power level. At low power levels, the averaging effect of large numbers of arriving photons is lost and the randomness of arrival of the individual photons becomes important.

Quantum noise rises linearly with bandwidth while detector noise (for photomultipliers) varies with the square root of the bandwidth. Quantum noise, therefore, becomes dominant for large bandwidths. Figure 2 shows plots of the noise level of both quantum noise and detector noise as a function of wavelength for bandwidths of 1 Mc and 10 Mc. The detector noise curve is plotted from data on commercially available photomultipliers. Each point on the curve represents the best available photomultiplier for that particular wavelength. Since the measured points for the detectors do not vary by more than a factor of two from the curve, it is felt that this curve is representative of uncooled detectors.

The total field of view $\Omega_t$ of the transmitter is expressed in steradians. It represents the area of uncertainty in the knowledge of the exact location of the target. This information may be obtained, as discussed previously, from high resolution radars, attitude stabilization systems, star trackers, or combinations of these. For the case in which the position of the earth is known, but not the location of the target on the earth, $\Omega_t$ becomes the solid angle subtended by the earth with its vertex at the space vehicle.

The receiver beamwidth $\omega_r$, or instantaneous field of view, must be small enough at some time during the acquisition phase to permit pointing the laser transmitter associated with it with sufficient accuracy to ensure illumination of the distant target. Although $\omega_r$ may be initially broad, it must eventually assume the same order of magnitude as the transmitter beamwidth on the same end of the communication link.

The total field of view $\Omega_r$ of the receiver is selected on the same basis as that of the transmitter and is numerically equal to that of the transmitter at the same location.

The acquisition time $T_a$ is the time allowed to acquire and identify the target, based on convenience and the relative motion between the earth and the space vehicle.
Figure 2. Receiver Sensitivity
Three types of acquisition systems – constant beamwidth, variable field of view, and storage – were studied in detail and are treated at length in the following discussion.

Constant Beamwidth Acquisition System

In this system, the transmitter and the receiver beamwidths remain constant throughout the acquisition cycle. The most general applications of this concept are represented by the relations \( \omega_t < \bigcap_t \) and \( \omega_r < \bigcap_r \). In this case the transmitter and the receiver must both scan out their respective field of view in such a manner that, at some time during the period allotted for acquisition, the transmitter and receiver must point at each other. In order to accomplish this, one terminal, say the receiver, scans at a very slow rate \( R_r \), so that it requires the entire acquisition time \( T_a \) to scan its field of view \( \bigcap_r \). At the same time, the other end, the transmitter in this example, scans at a fast rate \( R_t \), so that it scans its entire field of view \( \bigcap_t \) once for each beam position of the receiver. The respective scan rates are then given by

\[
R_r = \frac{\bigcap_r}{T_a} \text{ steradians/second}
\]

and

\[
R_t = \frac{\bigcap_t \bigcap_r}{T_a \omega_r} \text{ steradians/second},
\]

or

\[
R_t = R_r (\frac{\bigcap_t}{\omega_r}).
\]

The dwell time, or the time required for the transmitter beam to cross the receiver, is given by

\[
t_d = \frac{\omega_t}{R_t} = \frac{T_a \omega_t}{\bigcap_t \bigcap_r}.
\]

A specific acquisition of interest occurs for the case represented by the relations \( \omega_t = \bigcap_t \) and \( \omega_r < \bigcap_r \). An example would be the situation in which the position of the space vehicle is known with great accuracy, say within a second of arc. The ground based transmitter could be immediately aimed at the space vehicle, illuminating it at all times. It is then only necessary for the receiver on the vehicle to search out its field of view until the far transmitter is detected. The receiver then begins tracking and directs the beam of its associated transmitter toward the ground to commence communications.

Variable Field Scan System

Optical receiver systems which are not diffraction limited can quite easily be made to have a variable instantaneous field of view. For example, a variable iris, placed at the image plane of the primary lens or mirror, acts as a field stop to
change the field of view. This characteristic can be used to advantage in an optical acquisition system to conserve bandwidth and/or acquisition time.

Consider the total field of view of the receiver to be divided into quadrants and the instantaneous field of view to be the solid angle subtended by one of the quadrants. The receiver will examine only four beam positions for the presence of the transmitter and the transmitter will scan its field of view at least once for each receiver beam position. Upon detecting the signal, the receiver narrows its field of view by a factor of two in each direction and again scans. This time its total field of view is the quadrant in which the signal was originally detected. This procedure is repeated until the target position is located within a receiver instantaneous field of view of the desired size. The following relations describe this type of scan and compare it to the fixed field scan.

Let \( n \) be the number of beam positions of the fixed field scan in the total field of view; then

\[
\omega_r = \frac{\pi}{n}. 
\]

If, in the variable field scan, \( \omega_r \) is successively divided into quadratures as previously described, then

\[
\omega_r = \frac{\pi}{4^m} 
\]

where \( m \) is the number of divisions into quadratures. Then

\[
n = 4^m
\]

and

\[
\log n = m \log 4 \\
= 0.602 m.
\]

For a number of values of \( n \), \( m \) takes the following values:

<table>
<thead>
<tr>
<th>( n )</th>
<th>( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^2 )</td>
<td>3.32</td>
</tr>
<tr>
<td>( 10^3 )</td>
<td>4.98</td>
</tr>
<tr>
<td>( 10^4 )</td>
<td>6.65</td>
</tr>
<tr>
<td>( 10^5 )</td>
<td>8.30</td>
</tr>
</tbody>
</table>

Since \( m \) can take only integer values, the next higher whole number would be used.
On the average, with a fixed field scan system, the target would be located when only half the total \( n \) beam positions had been scanned. Even so, it is obvious that the scanning of the field need be accomplished with only a few quadrature divisions compared with the high number of fixed field elements.

The disadvantages of this method are the greater complexity of the scan system due to the zoom nature of the optics and the greater amount of external noise which can enter the receiver with the wide field of view.

**Storage Type Acquisition System**

The storage type system employs a device such as an image orthicon together with a memory matrix and computer. The entire field of view is imaged on the face of the image orthicon with the position of the target read into the memory. This arrangement is necessary because there may be optical noise sources in the field of view in addition to the target. The image orthicon is an integrating device so that high frequency recognition modulation cannot be placed on the target beam to aid in target discrimination. A low frequency modulation can be placed on the target emission, however, so that a large number of frames will reveal the presence of the identification modulation. The longer acquisition time engendered by this system is offset by the greater sensitivity of the detector due to the long integration time. The disadvantage of this system lies in the need for a memory and computer.

**Noise**

External noise in an optical system originates from two principal sources, that of the optical signal itself and that from sources which are self-radiating or are reflecting energy from other sources. This noise both deteriorates the sensitivity of the receiver and necessitates discrimination of the target from the other sources.

For an ideal receiver, regardless of frequency, the total noise spectral density is given by the relation

\[
\phi(f) = \frac{\hbar \nu}{e^{\frac{\hbar \nu}{kT}} - 1} + \hbar \nu,
\]

where \( \phi(f) \) = total noise spectral density per cycle of bandwidth,

\( \hbar \) = Planck's constant \((6.625 \times 10^{-27} \text{ erg/ sec})\),

\( k \) = Boltzman's constant \((1.38 \times 10^{-16} \text{ erg/ deg})\),

\( T \) = Absolute temperature,

\( \nu \) = Frequency of radiation.
At optical frequencies, the first term disappears and the $h\nu$ term becomes dominant; at radio or microwave frequencies, $h\nu \ll kT$ and the first term goes to $kT$.

It is convenient, in the microwave region, to speak in terms of equivalent temperature of the receiver. As a matter of interest, the same calculation can be made at optical frequencies by setting $h\nu = kT$; then

$$T = \frac{h\nu}{k}.$$  

For a frequency of $4.75 \times 10^{14}$ cps (6328Å),

$$T = 22,800^\circ K$$

and

Noise Figure $= 78.5$

$= 19$ db.

This noise figure is that of an ideal receiver and assumes a unity quantum efficiency of the receiver. Even if the receiver is noiseless, its quantum efficiency is poorer than one, and this noise figure will be effectively degraded further.

Other noise entering the receiver is due to bodies radiating or reflecting energy in the spectral region of interest. At night these sources are principally the moon, planets and stars, although the phenomena known as air glow, aurora and zodiacal light add a low-intensity, but detectable background. The earth is a large noise source for reflected light. This factor is important for a space vehicle looking toward the earth.

In daytime, the brightest source by far is the sun, but the atmosphere too is very bright and may be $10^{-7}$ to $10^{-8}$ watts at zenith in a 10Å bandwidth and a one-square-foot aperture having a $0.5^\circ$ field of view.

The spectral distribution of both self-radiating and reflecting extra-terrestrial sources are taken to be that of the sun; this is a fairly good approximation except for reflection from the earth which will be discussed in more detail later.

To assess the problem of noise from extra-terrestrial bodies, it is most convenient to use data compiled by astronomers. Unfortunately for this use, the brightness unit most often employed is that of stellar magnitude. The curves plotted on the graph shown in Figure 3 are used to convert stellar magnitude (abscissa) into power density in watts/meter$^2$ (ordinate). The upper curve is the observed values of brightness without spectral filtering. The monochromatic nature of laser light makes it possible to reduce greatly the effect of external noise sources by passing all received light through a narrow bandpass filter. The filter greatly attenuates the light from unwanted noise sources by passing only a
Figure 3. Power Density as a Function of Stellar Magnitude
narrow band of the emitted light with very little attenuation of the laser light. The lower curve in Figure 3 is a plot of the noise passing through a 10Å bandpass filter. A filter of this width can be obtained without too many problems resulting from frequency shifts due to temperature variations. Even narrower filters can be built, but these usually require a controlled temperature environment. It is seen that this filter reduces noise by a factor of $10^3$.

Plotted on this curve is the stellar magnitude of the moon, Venus and Mars. Also plotted is the detector threshold for a one-square-foot aperture, which is at a stellar magnitude of 0 order when the 10Å filter is used. The only sources in the sky brighter than this magnitude, hence the only sources which will be seen through an aperture of 1 square foot, are:

<table>
<thead>
<tr>
<th>Object</th>
<th>Stellar Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>-26.7</td>
</tr>
<tr>
<td>Moon</td>
<td>-12.6</td>
</tr>
<tr>
<td>Venus</td>
<td>-4.4</td>
</tr>
<tr>
<td>Mars</td>
<td>-2.8</td>
</tr>
<tr>
<td>Jupiter</td>
<td>-2.5</td>
</tr>
<tr>
<td>Mercury</td>
<td>-1.2</td>
</tr>
<tr>
<td>Saturn</td>
<td>-0.4</td>
</tr>
<tr>
<td>Sirius</td>
<td>-1.58</td>
</tr>
<tr>
<td>Canopus</td>
<td>-0.86</td>
</tr>
</tbody>
</table>

From these data the brightness of the moon appears to be too great to make optical communications possible; however, this brightness is from the whole moon and can be cut down considerably if only a portion of the moon is viewed. The sun is so bright that communications are not feasible if it is part of the background.

The brightness of the earth is rather difficult to define since there is so little data available on it. Venus owes its brightness to its ever present cloud cover which reflects equally over its surface. The earth, on the other hand, is composed of large masses of water and land. The water reflectivity depends on the surface roughness and will vary from 0.03 to 0.40. Land reflectivity depends greatly on the region from which the reflections occur, the season of the year, and the cloud cover in the field of view. Because the space vehicle will use a receiver with a narrow field of view, it will look at only a small portion of the earth at a time and will receive reflected solar energy which varies greatly with location. The approximate reflectivities of various surfaces listed below are taken in the visible
region and are not valid in the near infrared since reflection from vegetation increases greatly in that spectral region.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh Snow</td>
<td>0.80</td>
</tr>
<tr>
<td>Old Snow</td>
<td>0.40 (approx.)</td>
</tr>
<tr>
<td>Grass</td>
<td>0.1 - 0.23</td>
</tr>
<tr>
<td>Rock</td>
<td>0.12 - 0.15</td>
</tr>
<tr>
<td>Dry Earth</td>
<td>0.14</td>
</tr>
<tr>
<td>Wet Earth</td>
<td>0.08 - 0.09</td>
</tr>
<tr>
<td>Water (Sea)</td>
<td>0.03 - 0.40</td>
</tr>
<tr>
<td>Forests</td>
<td>0.05</td>
</tr>
<tr>
<td>Deserts</td>
<td>0.25</td>
</tr>
<tr>
<td>Clouds</td>
<td>0.5 - 0.75</td>
</tr>
</tbody>
</table>

The large variations of albedo might make it worthwhile to locate ground based stations in regions of low albedo. For example, if operation is in the visible region, the most suitable area might be forest areas, but these would be among the worst locations for near infrared operation.

The average albedo for the earth as a whole, if it occupies the entire field of view, ranges from 0.32 to 0.52 which varies with the season and greatly with the amount of cloud cover.

The effect of these noise sources on the acquisition and tracking function of an optical communications system is twofold. First, it raises the noise level of the receivers, thus necessitating a greater signal level at the receiver. Secondly, the sources require a means of target discrimination so that a false target is not acquired and tracked.

Spectral filtering, as previously mentioned, is helpful in greatly reducing the external noise problem, but still leaves a few sources at least as bright as the laser signal. In order to provide discrimination from these sources, it will be necessary to place identification modulation on the signal during the acquisition phase. The received signal can then be passed through a narrow bandpass filter so that it can be recognized.
The Tracking Problem

The problem of tracking with very narrow beamwidths centers about the need for precision. In order to operate a successful optical communications system, it is necessary to track within a small part of the beamwidth of the transmitter. Precision of tracking, therefore, must be of the order of 0.1 to 1.0 second of arc. In addition, the use of extremely narrow beams tends to accentuate the refraction and scintillation effects of the atmosphere. Compensation for these effects may require tracking which is rapid as well as precise.

Tracking Rates between Earth Station and Space Vehicle

The tracking rates associated with relative tangential motion between the opposite ends of the communication system may vary widely depending upon the precise geometry of the system. For example, the tracking rates may vary from 0.06 radian/sec for an earth satellite as viewed from the ground to $7 \times 10^{-5}$ radian/sec, the rate given by the angular velocity of the earth's rotation. Higher rates than these might be encountered between two earth satellites or space vehicles.

Error Signal Generation

There are a number of error signal generation methods used today which are capable of the high degree of accuracy necessary for a laser communication system. The various types of devices used for applications, such as precision star tracking, are well covered in the literature and will not be further discussed here. One characteristic none of these has, however, is a clear-cut capability for dual use in both acquisition and tracking. A high-speed beam deflector which works upon the application of an electrical signal to steer or deflect the beam is well suited to such a dual role. This beam deflector, if it has the capability of both relatively large and small, precise deflections can be used both for acquisition scanning and for error signal generation in a conical scan mode. This type of beam deflector, if it can be made inertialess as discussed later, appears to be the best suited to perform this function.

Bradley and Transit Time Errors

If the laser transmitter and distant receiver are moving with respect to each other, the transmitter will appear to be at an angle $\alpha$ from its true position given by

$$\alpha = \frac{v_p}{c},$$

where $v_p$ is the relative velocity component perpendicular to the line of sight between transmitter and receiver, and $c$ is the velocity of light. This deviation is called the "Bradley error" or "transit time error" of the communication link.
It is convenient to remember that a relative velocity of 1 mile/sec results in a Bradley error of 1.107 second of arc. Thus, relative tangential velocity in miles per second is approximately equal to the Bradley error in seconds of arc.

The orders of magnitude of Bradley error that would be encountered in optical communications links are:

<table>
<thead>
<tr>
<th>Communication Link</th>
<th>Bradley Error (seconds of arc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth to Earth Satellite</td>
<td>1 to 7</td>
</tr>
<tr>
<td>Earth Satellite to</td>
<td>3 to 8</td>
</tr>
<tr>
<td>Lunar Satellite</td>
<td></td>
</tr>
<tr>
<td>Earth to Planetary Probe</td>
<td>5 to 25</td>
</tr>
</tbody>
</table>

It is seen that these errors are significant when considering beamwidths less than 10 seconds of arc.

Atmospheric Effects

When one portion of an optical communications system is located within the atmosphere, its propagation path is subject to losses and perturbations caused principally by scattering of the light by particles and absorption by the various gases. The subject of scattering has been under study, both theoretical and experimental, for quite some time. Rayleigh, in 1871, made the first quantitative study of scattering by small particles. Scattering by particles much smaller than a wavelength is commonly called "Rayleigh scattering" and shows a wavelength dependence such that the scattered intensity is proportional to $\lambda^{-4}$. Thus, when white light is scattered by smoke or haze, it has a bluish color as does the sky.

The scattering caused by particles which are about the same size as a wavelength is known as "Mie scattering" and is the most complicated of the scattering phenomena. Experimental evidence on this type of scattering indicates a dependence of scattered intensity on wavelength of $\lambda^{-1.3}$ to $\lambda^{-0.7}$. The discrepancies are undoubtedly due to variations in the scattering atmospheres which were studied. When the particles are much larger than a wavelength, no dependence of scattered intensity on wavelength is observed so that the scattered light is white as observed on clouds illuminated by the sun.

A great deal of work has been done on atmospheric absorption in the visible and infrared portions of the spectrum but studies with high resolution were made only recently. The constituents of the atmosphere which cause absorption in the visible and near infrared include oxygen, water vapor, and carbon dioxide. The absorption is generally due to molecular resonance lines many of which are observable only under high resolution because they are quite narrow.

Before an operating wavelength is selected, it is necessary to examine atmospheric absorption in the region immediately surrounding the wavelength of
interest for absorption lines. The He-Ne line at 6328Å is in a favorable region with no significant absorption lines in its vicinity; thus, it will suffer no measurable absorption. However, the wavelength 1.152μ lies in the vicinity of five water vapor lines, all of which contribute to absorption at atmospheric pressure. Because reduced pressure narrows the lines, only two of those absorption lines contribute to absorption at high altitudes. The ruby wavelength is in a region of a number of lines of both oxygen and water vapor so that heating it, thus causing a change in wavelength, subjects it to a variety of absorption conditions. Further into the infrared region, where many laser wavelengths lie, the number of absorption lines increases and, in addition, molecular band structure becomes important so that only a few good "windows" exist. The 3.5 and 3.99μ lines of helium-xenon are infrared lines which exhibit very low atmospheric attenuations.

Losses, or perturbations, caused by refractive differences in an active atmosphere constitute the other troublesome factor affecting optical communications. The atmosphere is characterized by localized variations in its index of refraction caused by temperature gradients. These variations, or refractive "cells", are caused by turbulence in the air and are frequently associated with regions of high wind velocity and/or wind shear such as that found in the vicinity of a jet stream.

At any instant of time, the effect of these refractive cells is to produce bending and some break-up of a beam traversing them. This beam "dancing", or scintillation, causes amplitude variations at the receiver.

Several investigations were recently made of refraction effects over horizontal paths. Unfortunately, these studies are not very useful for a vertical propagation path because the air motions are so different. These studies will have some limited application for propagation angles near the horizon.

Vertical propagation studies have been made by observing stars or lights on aircraft as sources; however, no known studies have been made to date employing coherent light over vertical paths. The studies which have been made indicate that the major scintillation effects originate in a layer at an altitude of 40,000 to 50,000 feet. Good correlation was obtained between the altitude of the scintillating layer and wind speeds aloft. The amount of beam deflection, or scintillation, for vertical paths amounts to 0.5 second of arc for good seeing conditions to about 2 seconds of arc for poor conditions. The spectrum of the noise induced by scintillation appears to have an upper limit of 500 to 1000 cps with a general decrease in amplitude from 1 to 500 cps. The frequency generally increases as the angle from zenith increases. There is some evidence that signal fluctuations caused by the atmosphere scintillations decrease as the observing aperture increases, thus indicating an averaging effect over a distance of a foot or two.

In contrast, the recent work done on horizontal paths indicates beam deviations as high as 5 seconds of arc with a frequency spectrum generally decreasing from 1 to 100 cps but peaking at approximately 20 cps.

One other atmospheric effect which should be mentioned for the sake of completeness is the various phenomena which can be grouped under the term atmospheric emission; this includes air glow, aurora, and thermal emission. These
effects, however, are quite weak in intensity and are of no importance when a narrow band spectral filter is used on the receiver.

System Configurations

The following discussion concerns the equipment needed to perform the precision tracking and acquisition tasks treated in the preceding paragraphs. For convenience, the discussion is divided according to the following basic equipment components: beam deflector, modulator, optical system, and detector.

Beam Deflectors

Both the acquisition and tracking modes of operation depend on beam steering or deflection. Certain acquisition schemes need deflection rates up to 1 Mc, while requirements for both acquisition and tracking call for a high degree of precision. Certainly, the beam deflector must be capable of pointing the beam to a required angle to within one half of the beamwidth or less. High precision deflection can be obtained by purely mechanical means such as a moving mirror but high deflection rates require accelerations too high for this arrangement.

Another possible arrangement, which could be more satisfactory if successfully implemented, would be a beam deflection system which is electronically controlled by the application of electrical energy. In order to obtain beam deflection which is dependent upon electrical power, and not on mechanical displacement, it is necessary to find a means to alter the phase front of the light beam. One method might be to introduce a variable index of refraction gradient in a plane perpendicular to the direction of propagation of energy. The electro-optic effect in crystals, the elasto-optic effect in crystals or plastics, the Kerr effect in certain liquids, or the Cotton-Mouton magneto-optic effect are all possible means to accomplish beam deflection by altering the index of refraction.

Beam deflection has been accomplished using both the electro-optic and elasto-optic effects. Of the two, the electro-optic effect in potassium dihydrogen phosphate (KDP) has shown the greatest promise. Beam deflection through an angle of one half degree or so has been demonstrated with rates in the kilocycle region. Neither the maximum possible angles nor rates are represented by these figures. The state of the art in these devices is still so new that many questions are still unanswered. For example, little is yet known about deflection precision, temperature effects, or effects of crystal anisotropies. It will be some time before a sufficiently complete evaluation can be made of this class of device to determine suitability for the acquisition and tracking tasks in an optical communications system.

Optical System

The optical system for optical communications must serve the dual function of collimating the transmitter beam to the desired size and to efficiently collect energy for the receiver from the desired field of view. It is possible, therefore, to have two separate optical systems, one to transmit and one to receive, or to combine the two functions into a single optical system.
The coherent nature of laser light makes it possible to employ optics for transmitting which approach the diffraction limited value in size. The necessary diameter of optics under these conditions is given by the following relation

\[ d = \frac{1.22\lambda}{\theta}, \]

where
- \( d \) = aperture diameter in centimeters,
- \( \lambda \) = wavelength in centimeters,
- \( \theta \) = beamwidth in radians.

A one-second beamwidth, then, requires an aperture diameter of 17 cm. The sizes of the receiving optics, on the other hand, are not selected on the basis of diffraction limiting but rather on the maximum light gathering power for allowable size and weight. Optical telescopes of large aperture are usually of the reflecting, rather than refracting, type since weight and distortion are less. Even reflecting telescopes become large as the aperture is increased because of the longer focal lengths necessary and will have a practical limitation for use in space vehicles.

The extreme accuracy requirements of the optical system calls for a very rigid system. For example, the maximum allowable deflection of the focal point will be of the order of \( 4 \times 10^{-4} \) inch or less. A way to meet this requirement as well as to decrease size, and perhaps weight, is to shorten the optical system by folding. The folded optical configuration which has proven most satisfactory through the years is the Cassegrain system.

An optical receiver employing Cassegrain optics is shown in Figure 4. The primary mirror is the collecting aperture and has a parabolic surface. The secondary mirror is placed in front of the primary mirror at such a distance that aperture blockage caused by it is acceptable. The secondary mirror has a reflecting surface facing the primary mirror which is a hyperboloid of revolution. One focal point of the hyperbola is coincident with the focal point of the primary mirror while the other focal point lies within the system as shown. Following the focal point is a lens of short focal length, such as an eyepiece lens for a telescope, which has its focal point coincident with that of the hyperboloid. The function of this lens is to re-collimate the received signal before it is passed into the beam deflector. Between the lens and the beam deflector is a convenient point to place a narrow band interference filter to reject all noise but that near the desired wavelength. The beam deflector is then followed by a detector which will be a photomultiplier if the radiation is in the visible or near infrared portion of the spectrum.

Operation of this receiver is as follows. Incoming light energy from a wide field of view is collected by the primary mirror. This mirror, in conjunction with the secondary mirror, focuses that energy on the focal plane. The focal plane lies perpendicular to the axis of the optics and is located at the position of the indicated focal point. The beam deflector then acts as a variable position stop and selects energy from only a tiny area to be transmitted to the detector. The beam deflector, therefore, imparts to the system the capability of looking at only a small field of view at a time and of changing that field at will.
Should it be desirable to change the size of the field of view, as in the variable field system, the focal point of the lens need only be moved so that it is non-coincident with that of the secondary mirror.

Size and weight reduction, as well as the need for two identical beam deflectors if separate optics are used for transmitting and receiving, makes the possibility of combining the two functions in a single optical system attractive. The difficulty encountered with this combined system is that half the transmitted and received signal must be lost in the beam splitter and isolation between transmitter and receiver will be almost impossible to obtain. The latter problem cannot be solved by time sharing because tracking requirements will necessitate a constantly transmitted signal.

There is one scheme, however, which may avoid both of these problems; that is, to make use of the fact that lasers are available which operate at a number of different wavelengths. If the transmitter and receiver were to operate with a common optics system but at different frequencies, good isolation could be obtained through spectral filtering in the receiver. If this were done, the other difficulty, that of power loss in the beam splitter, could also be overcome by using a dichroic beam splitter. A dichroic mirror or beam splitter is one that is made to transmit at one wavelength and reflect at the other. Thus, it is possible, through a two color scheme, to eliminate both major difficulties encountered in using common optics for transmitting and receiving. A new problem which may arise, however,
is one of dispersion. If anything in the path of the beam, such as atmospheric refraction cells, has a different index of refraction for the two wavelengths used, the possibility exists that they will follow different paths. If the path directions for the two wavelengths should deviate by more than one half the beamwidth, the system could be rendered inoperable.

Detectors

The choice of the optical detector will depend upon the wavelengths, convenience, and bandwidth requirements of the particular system under study. In the visible and near infrared, the detector choice will be a photomultiplier while operation further into the infrared will necessitate employment of one of the various available solid-state detectors.

Superheterodyne detection will probably not be employed for this type of communication system because of Doppler shift. For example, if the relative velocity between the two ends of the communication path is 1000 miles/hour (a somewhat conservative value) the output frequency of the superheterodyne detector due to Doppler shift is 700 Mc. Therefore, although a superheterodyne optical system could be valuable for extracting Doppler information, it would be a hindrance for a communications system whose needs are better served by a video detector.

Conclusions

Long-range communication systems based on the laser as the source of radiated power will probably prove feasible for broadband operation. It is unlikely, however, that optical systems will successfully compete with systems operating at microwave or lower frequencies when narrow bandwidths are used.

The problems of acquisition and tracking can be solved assuming the availability of good coarse position information, although better components must be developed. The needed components are precision high-speed beam deflectors, wide-band modulators and light, compact optical systems capable of withstanding launch and space environments without losing alignment. High-power CW lasers are also needed, together with the means of paralleling several lasers for increased radiated power. All of these components are currently the subject of intensive study in laboratories throughout the country and all appear to be technically feasible.