A LASER LINK OPERATING AT ONE GIGABIT/SEC.

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Summary This paper describes the design of a 1 Gbps digital telemetry/ communication system achieving a probability of bit error of 10^{-6}. The system is based on the use of near future (approximately 2 years) components and is suitable for use in satellite- satellite, ground-satellite, and aircraft-satellite links. Both the advantages and problems associated with the use of laser links are cited, and the techniques used in this system that make use of the advantages and overcome the problems are identified. Small packages and apertures are used to achieve high ERP (116 dBW), narrow beams with small apertures permit use of low prime power (170 watts total for laser), enormously greater link privacy and reduced susceptibility to counter measures is obtained, direct detection eliminates doppler search and tracking, and the small package size gives satellite systems multiple package possibilities. To obtain these advantages very narrow (5 p radian) operational beams must be acquired and tracked, point-ahead offset for relative terminal motions must be implemented, effects of atmospheric disturbances must be minimized if the atmosphere is in the link, and any repeater configurations must demodulate/remodulate because of lack of any laser system capability for frequency translation and amplification. The following unique features of laser systems as opposed to microwave cussed: requirements for acquisition and tracking point-ahead requirements, unique modulation types hand circular polarization, unique types of noise and background shot noise, elimination of doppler direct detection, ability of the receiving system on its receiving aperture, unique atmospheric propagation disturbances, and possibility of signal coding to remove the signal spectrum from the vicinity of the noise spectrum.

Summary of Capabilities and Configuration of the Laser Link This paper describes a 1 Gbps digital laser telemetry/communication system based on components that will be available within the next 18 months to 2 years. The system is adaptable for use on the following six types of links:

1) Synchronous satellite-to-synchronous satellite
2) Earth orbiter-to-synchronous satellite

3) Ground station-to-synchronous satellite
4) Synchronous satellite-to-ground station
5) Aircraft-to-synchronous satellite
6) Synchronous satellite-to-aircraft

Although these links may differ in some details according to their special problems, they all have the following traits in common. Each link has two terminals, both terminals capable of continuously transmitting and simultaneously receiving. One terminal has a 1.06 micron Nd: YAG 1.0 watt high data rate transmitter, and the other a 0.53 micron doubled Nd: YAG 100 milliwatt low data rate beacon for use in acquisition and tracking. The link can be acquired from initial pointing uncertainties as large as ±0.5° to operational beamwidths as small as 5 microradians, (a reduction factor of 3,000 in lessthan 20 seconds. The high data rate transmitter and beacon receiver can be packaged together weighing approximately 100 pounds, and the combination beacon transmitter and high data rate receiver package would weigh 125 pounds.

Advantages, Disadvantages and Unique Features of Laser Links Much higher data rates become possible with the use of laser, rather than microwave links. Microwave links appear to be limited to bandwidths of 300 to 500 MHz. In contrast, because of the very narrow high ERP laser beams achievable with small apertures, laser links with bandwidths from 1 to 10 GHz become practicable. For example, with a 1.0 watt transmitter, a 1-foot diameter diffraction-limited telescope, and a wavelength of 1 micron, an ERP of 120 dBW is attainable. To reach even one-tenth of 1% of this ERP, or 90 dBW, would require a 100 watt transmitter and an antenna 17 feet in diameter at a frequency of 60 GHz. Laser systems easily afford huge ERP’s with small antennas and modest powers that microwave systems can only provide with monstrously large powers and antennas.

Being able to achieve huge ERP’s with small packages has many advantages for satellite use. Low drag profiles for aircraft and low altitude satellites become possible for high data rate systems. Satellite launches are simplified because of the small antenna size. Smaller packages afford multiple package, and therefore, multiple link possibilities to satellites. Also, the narrow beams offer the potential for greater precision in position determination.

Laser systems greatly enhance electronic countermeasures capability. The very narrow beamwidths and the sidelobes, which are so low as to be non-measurable, afford link privacy and reduced susceptibility to countermeasures. The ground footprint of the transmitted beam when a satellite is involved in the link is very much smaller for laser links than for microwave links.

When direct detection laser systems are used, doppler problems in acquisition and tracking are eliminated. Direct detection systems simply count photons arriving over a specific range of wavelengths. Huge ranges of frequency can be accommodated even when the wavelength is restricted to a very narrow range.

Finally, communications at optical frequencies is free of the spectrum congestion at microwave frequencies.

The very narrow beams that provide laser links with such high ERP's also provide these links with some severe problems. Acquisition and tracking of the extremely narrow beams requires the design of a very accurate and flexible acquisition and tracking system. For example, the laser beam should be tracked to an accuracy of a fraction of its beamwidth to keep the pointing error losses low. Tracking to 1/10 of the beamwidth, or 0.5 microradian, accuracy in the presence of spacecraft vibration and line-of-sight rotations as high as 1500 microradians per second is not a trivial task. Point ahead compensation must be made for relative motion between the transmit and receive terminals. During the time required for the light signal to travel from the transmitter to the receiving terminal, the receiving terminal moves a small distance. Because laser beams are so very narrow, the receiver may very well travel outside the beam during this time, particularly if one or both link terminals is a satellite. The transmitter must then be pointed ahead of the apparent receiver direction in order to intercept the receiver with the transmitting beam. The apparent receiver direction is tracked with the aid of a beacon on the receiver platform.

At present, laser system design is further complicated by the state of flux of component development and the lack of knowledge of the kind and degree of some physical processes which tend to disrupt laser propagation. Laser, modulator, and detector technology is changing rapidly. Designing around components not as yet entirely developed, as must be the case for a 1 Gbps system, requires that the system be designed with a large tolerance for components development. Further tolerance must be allowed for atmospheric links because the atmosphere causes many propagation disturbances, the magnitude and variability of many of them as yet being unknown.

Repeater configurations must use demodulate/remodulate systems because there is no available frequency translating and amplifying system. Laser repeaters are, therefore, sometimes more complicated than microwave repeaters.

There are a number of unique features of laser telemetry as compared to microwave telemetry. The types of noise and the noise variability with signal level are different from microwave interference. The statistics of the emission times of electrons from the detector cathode are Poisson for both signal and background. This means that there is signal shot noise increasing with signal level whether any type of interfering source is present or not. The signal-to-signal shot noise ratio increases linearly with received signal power. Background shot noise arises because of optical radiation arriving at the receiver from such spurious sources as sun, moon, stars, and man-made sources. Since the photodetectors have a small dark current output in the absence of any input radiation, dark current shot noise also interferes with the signal. Photomultiplier tubes are commonly used as laser detectors. These tubes typically have such high gains that the usual dominating type of interference in microwave systems, namely thermal noise, is rendered negligible compared to shot noise. Laser system noise is then primarily shot noise, which increases as signal level increases and arises from uncertainties in photoelectron emission time, spurious background sources, and detection dark current.

The greatest amount of background and dark current shot noise is concentrated at DC. Therefore, any signal waveform design which puts the signal spectrum away from DC enhances the signal compared to the background and dark current shot noise. This feature can be useful if strong backgrounds are present and must be rejected.

Unique types of modulation can be employed in laser telemetry. Polarization modulation, such as left and right hand circular, can be used to construct a CW digital signal. Doppler tracking and acquisition problems present in microwave systems can be obviated by direct detection of laser signals. Another unique feature is that receiver orientation for signal energy collection does not depend solely on the diffraction beamwidth λ/D: the photodetection surface can be made large enough to collect all energy impinging on the receiving aperture. Laser systems also encounter the unique problems previously mentioned of accurate acquisition and tracking requirements, point-ahead compensation, and atmospheric propagation disturbances generally worse than for microwave systems. Also, there is no optical frequency translating and amplifying technique available for relay terminals.

Operational Requirements on a 1 Gbps System Obtaining a 1 Gbps, or higher, data rate with a low probability of bit error is possible if the telemetry system is designed to meet some rather stringent requirements. The system described in this paper achieves 1 Gbps with a bit error probability of 10^{-6}. The power, weight and size must be compatible with the terminal platform - space, aircraft, or ground. The modulation chosen must maintain acceptable performance on the link channel, channels in the atmosphere presenting the greatest problem. Timely acquisition to operational beamwidths must take place. For example, the system in this paper acquires a 5 microradian beamwidth in a $\pm 0.5^\circ$ pointing uncertainty region in less than 20 seconds. Narrow beams must be tracked at the required rates. For instance, a low earth orbiter using earth-pointing attitude control and communicating with a synchronous satellite, requires a 1500 microradian per second tracking rate. Also when one or more of the terminals is on a satellite, point-ahead must be implemented. The entire system must be reliable and maintainable, perhaps for as long a time as 5 to 7 years in a space environment.

A Laser Link Designed to Operate at 1 Gbps The high data rate transmitter/beacon receiver block diagram is shown in Figure 1. The transmitter is a Nd:YAG 1.0 watt output laser operating at a wavelength of 1.06 microns. A lithium niobate crystal intracavity modulator imposes left and right hand circular polarization modulation on the signal at the 1 Gbps data rate.

To transmit the 5 microradian operational beamwidth and receive the beacon signal, a one foot diameter telescope is used. A dichroic beam divider composed of material that reflects radiation at $\lambda = 0.53$ micron and is transparent to radiation at $\lambda = 1.06$ micron reflects any of the incoming radiation outside a central hole to the coarse acquisition image dissector. Once the coarse acquisition sensor is tracking the beacon, it positions the received signal within the beam divider hole by using the transfer lens servo system. The beacon signal then passes through the hole to the neutral density beam divider, where it is split between the communication detector and the fine tracking image dissector in a ratio of 10 to 1. The dichroic beam divider at the front of the receiver is transparent to radiation at $\lambda = 1.06\mu$ so that the aperture f or the transmitted beam will be large enough for formation of the 5 microradian beam. A beam spoiler is provided so that the beam may be widened during acquisition. Risley prisms are used to accomplish transmit beam pointing ahead of the direction of beam reception.

The beacon signal detector is composed of two photomultiplier tubes with quantum efficiencies of 0.3 at a wavelength of 0.53 micron. A noise rejection filter 2.Å wide rejects interfering background signals. Both coarse and fine acquisition and tracking sensors are image dissector tubes. These tubes permit rapid scan of a small instantaneous field of view over a large dynamic field of view, limiting the background observed to the smaller field of view.

The beacon transmitter/high data rate receiver block diagram is shown in Figure 2. Operating at a wavelength of 0.53 micron, the doubled Nd:YAG laser has an output power of 100 milliwatts and is externally circular polarization modulated by a lithium tantalate crystal at rates as large as 10^6 bits per second. The optics are very similar to the high data rate transmitter/beacon receiver optics, the telescope being larger (2 feet in diameter rather than 1 foot), and beam splatters again being used to divide the beam between the acquisition sensor and the data receiver. Because the high data rate tracker requires so much signal during acquisition, the beam is split half and half between it and the communication detector. No point ahead is required of thp beacon because its beam is wide enough to encompass the point ahead angle. Likewise, one tracker is sufficient to acquire the opposite terminal to the accuracy required for pointing the wide transmitted beam.

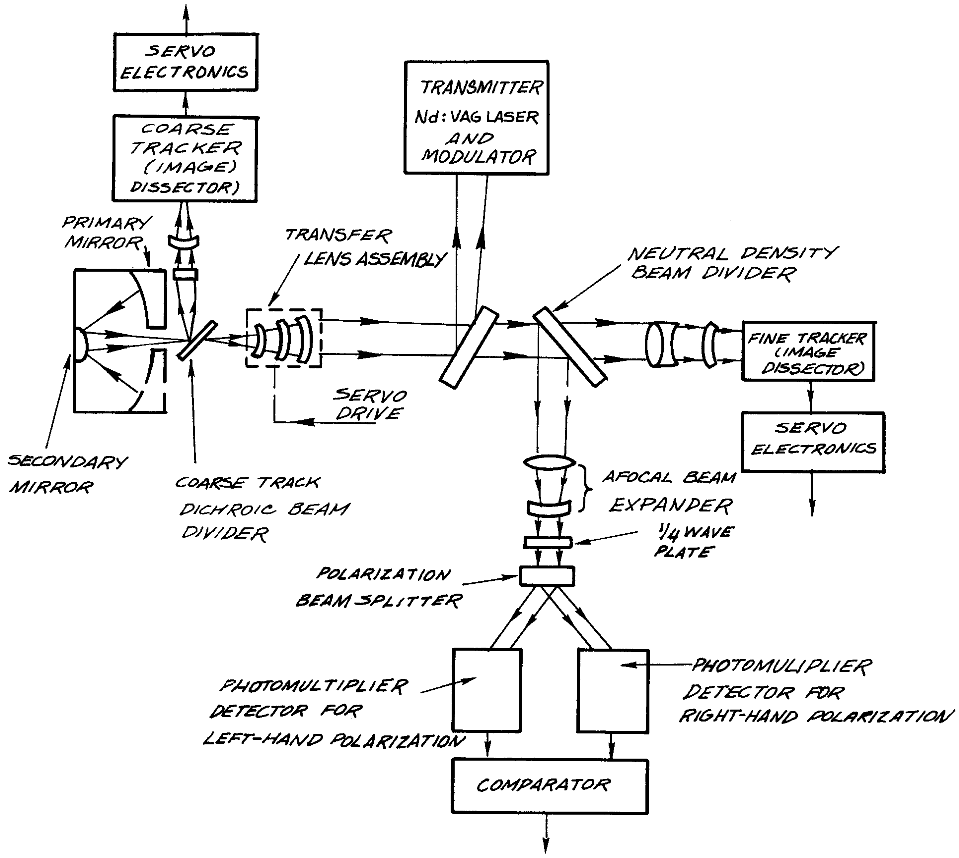

Figure 1. High Data Rate Transmitter/Beacon Receiver

The high data rate signal detector is composed of two static crossed field photomultiplier tubes with quantum efficiencies of 0.02 at a wavelength of 1.06 micron. Again, a 2.0 Å wide filter is used to reject background noise. In the receiver the acquisition and tracking sensor is a quadrant detector. Even though the background from the entire detector surface can interfere with the signal on a quadrant detector, it is used instead of an image dissector because image dissectors at a wavelength of 1.06 micron have very low quantum efficiencies. The quadrant detector locates the signal in a particular quadrant and moves it to the center of the detector.

The high data rate link is operated in the following way in order to meet the requirements on it. The YAG laser is modulated at I G/bps using a lithium niobate crystal inside the laser cavity. Right-hand circular polarization represents a “one” and left-hand a “zero” bit in the data stream. Radiation inside the cavity is of one circular polarization, and application of a modulating voltage to the crystal changes the polarization to circular of the opposite sense. The result is a data bit stream of I nanosecond pulses, some left-hand circularly polarized, some right-hand circularly polarized. Because the laser is operated in a CW mode, it makes efficient use of its power. A second point in favor of polarization modulation is that it is thought to be very insensitive to atmospheric disturbances, although data to support this is imcomplete.

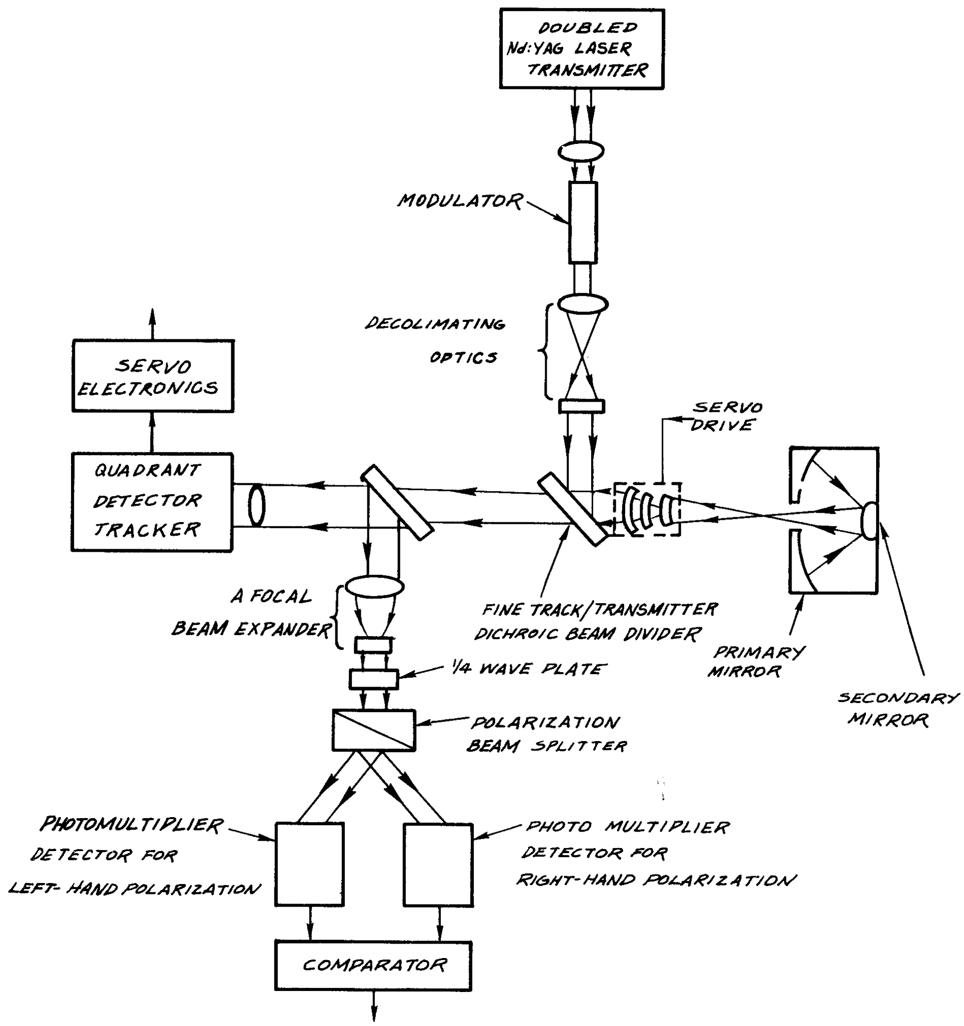

Figure 2. Beacon Transmitter/High Data Rate Receiver

After it is modulated, the laser beam passes through the beam spoiling and pointing offset assemblies. The beam spoiler widens the beam for initial acquisition only, and the Risley prism is used for offsetting the transmitter pointing direction from the tracked receiver direction. The beam then is reflected from the dichroic beam divider and is transmitted through the Cassegrain telescope, which is used in common by the high data rate transmitter and the low data rate receiver.

At the high data rate receiver the laser beam is split half and half between the fine tracker and the signal detector. The detector is comprised of a polarization separator and two photomultiplier tubes, one for each polarization. Bit detection is accomplished by comparing the outputs of the two detectors: if the right-hand polarization detector output is larger than the left-hand, a “one” is adjudged to have been sent, and vice versa. Such reception requires only comparison and no difficult threshold setting depending on background level, but does require balancing of the gains of the two channels. To meet the high data rate requirements, the tubes must respond to 1. nanosecond pulses and have sufficiently high gain so that the signal level is far above the thermal noise. The electronics following the tubes must demodulate and handle data at a gigabit rate.

The half of the high data rate laser beam energy not used for signal detection is received by a quadrant detector used as a tracker. This quadrant detector generates an angular error signal which is used to control the gimbals for the whole laser communication package for coarse positioning.

The beacon link is used to aid acquisition and tracking and can also be used for command and ranging data. Operation of the doubled Nd: YAG beacon link is much the same as for the high data rate link, except that the ERP can be lower for the lower rate link. Therefore, a less powerful laser is needed and a broader transmit beam can be used. In fact, the beam can be widened to 300 P radians while permitting reception of 20 kbps command data, thus obviating the implementation of transmitter point ahead, which reaches a maximum of 75 microradians over the range of likely satellite-to-satellite orbit configurations. Circular polarization modulation is again imposed on the transmitted beam, this time externally to the laser cavity using a lithium tantalate crystal.

Beacon reception is very similar to high data rate reception, and is done while splitting the received beam between a fine tracker and a signal detector consisting of a polarization separator and two photomultiplier tubes. The fine tracker is an image dissector whose output servos a transfer lens in order to fine position the received radiation and moves the gimbals for the entire communication package for coarse positioning.

Before data transmission can be begun, the link must be acquired. Acquisition is begun with a transmitter in a broad beam mode and a receiver searching a wide field of view. Acquisiton is started with the terminal receiving that receives at the largest signal-to-noise ratio, considering transmitter power, pointing uncertainty, background radiation, etc. In the case of the low earth orbiting-to-synchronous satellite link, the low earth orbiter must receive first, facing away from the bright earth background. When the receiving terminal acquires the signal, it begins to transmit on a narrow beam. Both terminals then successively narrow their transmit beams and receiver fields of view until operational acquisition takes place.

In order to obtain the angular accuracy to point the narrow high data rate beam, acquisition must be accomplished in two stages, one coarse and one fine. During coarse acquisition a dichroic mirror with a small hole in it reflects most of the incident energy to the coarse acquisition sensor. As the coarse sensor acquires the signal, it begins to track it and position the signal beam in the center of the dichroic mirror where the hole is. Energy passing through this hole is then picked up by the fine sensor for final acquisition. The system described in this paper acquires an operational beamwidth of 5 microradians with an initial pointing uncertainty of ±0.5° in less than 20 seconds. Beacon coding is used to reject falsely acquired signals.

During communication, the tracking system must sense and measure the antenna pointing error in two axes, where pointing error is the angular difference between the nominal receive antenna boresight and the direction of arrival of the radiation from the other end of the link. The system must then drive the receive boresight positioning system and control the receive antenna position. Sufficient bandwidth must be provided to track through all angular motions of the receive line-of-sight with respect to the platform. This includes orbital motions and spacecraft attitude changes caused by normal spacecraft attitude control and also by structural vibrations. To keep the pointing error loss low, the tracking accuracy should be a fraction of the total beamwidth. The system described here is designed to track to 1/10 beamwidth, or 0.5 microradian, accuracy. Tracking rates as large as .078°/sec can be encountered with an earth-oriented low orbit satellite-to-synchronous satellite link and may be required over 180° of gimbal angle. For accuracies and rates such as these, spacecraft vibrations, which can be in the 1/2 to 50 Hz region with amplitudes as high as 50 microradians, present a difficult problem in tracking.

A requirement for pointing offset of the transmitter and receiver arises because of the relative acceleration of the two terminals. (see Figure 3.) During the time for transit of the two-way transmit beams, one terminal may well move outside the other's beamwidth. With a low earth orbiter-to-synchronous satellite link, there could be a requirement for as much as 75 microradians point-ahead. Risley prisms are used to point the transmit beam ahead of the tracking receiver direction. A table of point-ahead values can be stored on board the satellite, and interpolation is used in conjunction with the table. This is an open loop method of generating point-ahead, and a problem exists with the open loop technique in determining whether or not point-ahead has been accomplished. A loop closed between the transmitter and receiver can be used with conical scanning of the point-ahead beam and feedback of the con-scan error signal from the receiver terminal. Point-ahead is made further difficult in ground-tospace links because of atmospheric beam tilting. Some times this problem can be solved by using a wider beam and a very powerful transmitter on the ground.

Laser Detection Processes In addition to standard considerations, such qs high transmitter power and gain, there are some unique aspects to achieving good laser signal-to-noise ratios. First of all, there is signaldependent noise even in the absence of any other background interference. This noise results from the statistical nature of the times of emission of photoelectrons from the detector cathode. The statistics on the number of photoelectrons per time interval are Poisson. Let β_s be the average number of signal photoelectrons emitted per second. Then th signal power increases as β_s^2 while the signal

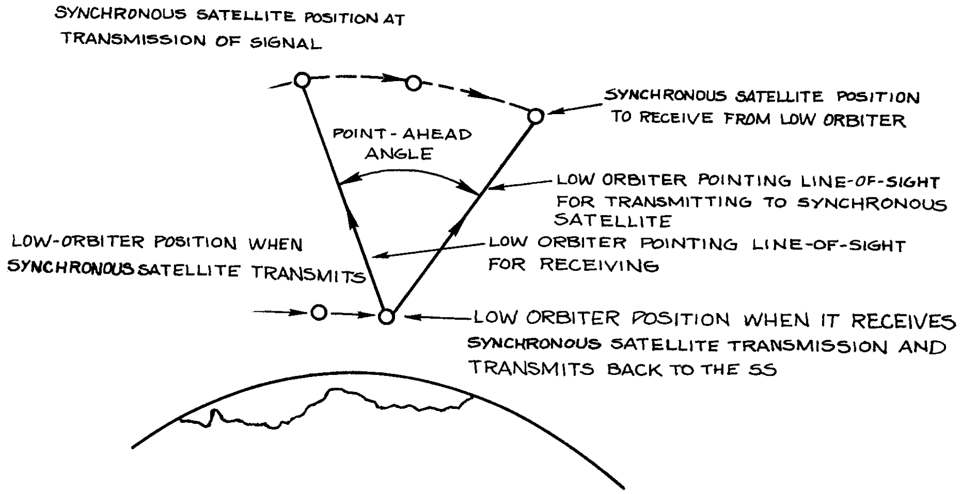

Figure 3. Point-Ahead Geometry

shot noise increases as β_s. Therefore, increased signal level improves the signal-to-noise ratio linearly in the absence of external interference. (See Figure 4 for spectral density at output of detector cathode. This figure shows a total DC value resulting from signal, background, and dark current and shot noise density from these three sources also.)

Background interference arises from spurious light sources. To reduce background noise, a narrow band optical filter and a receiver with a narrow field of view can be used. During acquisition an image dissector is especially useful in reducing noise from this source because the dissector scans a small instantaneous field of view over a large angular search area. It looks at background in the small instantaneous field of view only. The contribution of background to the average signal level at DC and to the shot noise density is also shown in Figure 4.

Dark current is the current flowing in the photodetector in the absence of any input signal and is another noise source. With an image dissector, only the dark current generated within the instantaneous field of view contributes to shot noise interference with the signal. The dark current contributions to the DC level and shot noise density are also shown in Figure 4.

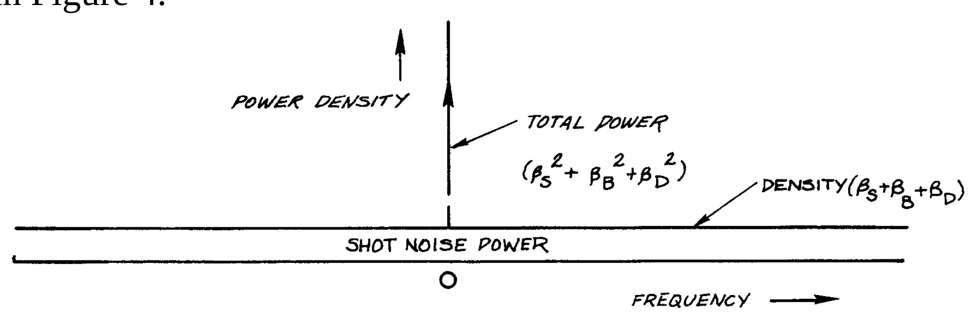

Figure 4. Power Spectral Density at Detector Cathode Output

Two more noise sources of significance are thermal and residual modulation noise. The gain of the photomultiplier tube detector is usually designed to be so large as to overpower thermal noise, the usual dominant noise source in communications. A source of noise present in polarization modulation systems is residual modulation of the wrong polarization. The residual modulation appears in the output of the detector for the undesired polarization and renders the decision as to which modulation was transmitted more difficult.

The dominant noise sources for this system are, then, signal, background, and dark current shot noise and residual undesired modulation. This is a very different set of types of noise and noise statistics than encountered in microwave telemetry.

Direct detection of photoelectrons, which is possible at visible wavelengths, avoids all problems in doppler shift and other frequency uncertainties during acquisition and tracking. In this system, both the acquisition and tracking sensors and the communication receivers use direct detection. Direct detection operates as follows. A photon strikes the detector cathode surface. With a finite probability an electron is then emitted from the surface and causes a detector output pulse on its arrival at the anode. A counter adds these pulses over the detection interval so that the resulting output is a direct detection of the number of incident photons. Using such direct detection, or counting, all signal frequency uncertainty problems are obviated. For instance, doppler shifts of signals do not impose a requirement for a large frequency search during acquisition. Also, neither doppler nor source frequency drifts impose any frequency tracking requirements.

For acquisition and tracking, two types of detectors - image dissector and quadrant detector - are in common use. Each has its own set of advantages and disadvantages.

Using an image dissector as a photodetector, a large total dynamic field of view can be scanned with a small instantaneous field of view. (See Figure 5.) At a qiven instant the image dissector output current originates only from the small θ_1 x θ_1 instantaneous field of view. This means that not only can a target be seen at a given instant only if it is inside θ_1 x θ_1, but also that only background radiation and dark current inside the small FOV can be seen. Therefore, while a large field of view is being rapidly searched during acquisition, the background can be limited to a small FOV. The scan speed can be varied, stopped, and started at will and can be very fast. In the tracking mode, the instantaneous field of view can be dithered about the signal spot, aiding the generation of an error signal derived by tracking the center of the spot. Use of an image dissector also offers the possibility of simultaneous acquisition and tracking of multiple signals.

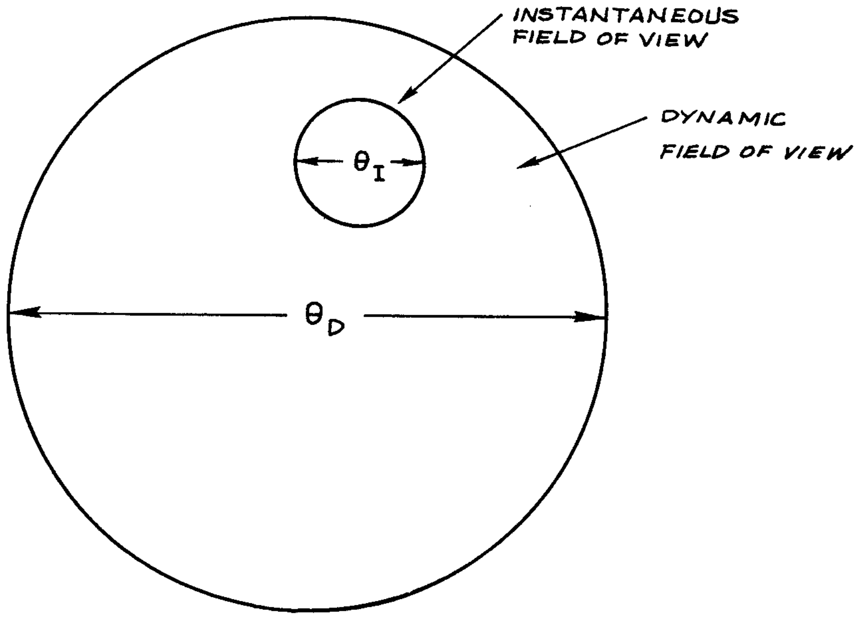

Figure 5. Image Dissector Field of View

A second type of tracking detector is a quadrant detector. When a quadrant detector is used, the receiver is not scanned, but the focussed image is moved to the center of the detector and is maintained there within some limit cycle. (See Figure 6.) For the quadrant detector, there is no instantaneous field of view gating of the background: the total tube background is present with the signal at all times,,and the signal is within the active FOV during all of acquisition. Since image dissectors with efficiencies greater than 0.1% to 0.2% are not available for the 1.06 micron wavelength, quadrant detectors must be used for acquisition and tracking at this wavelength.

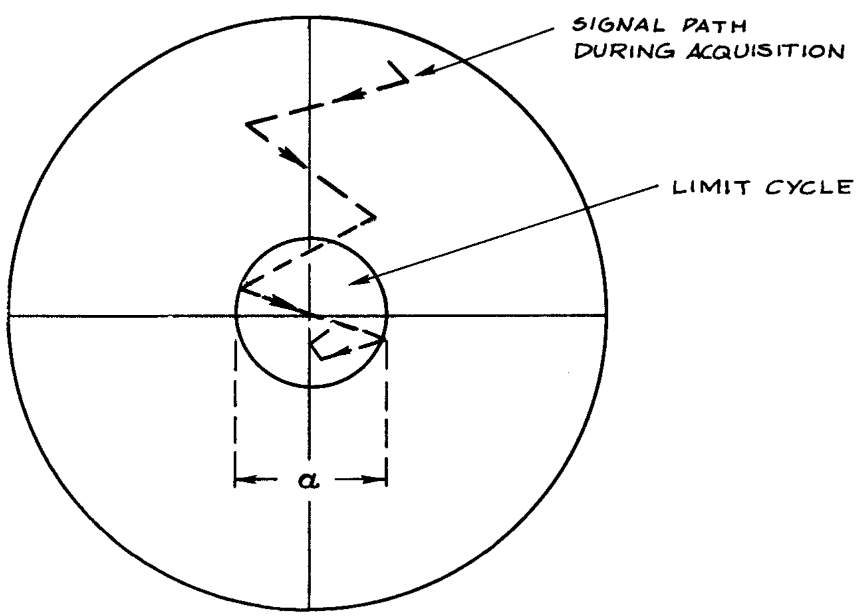

Figure 6. Signal Path on Quadrant Detector During Acquisition

Modulation Choice The choice of modulation format has a major impact on the communication system complexity, size, weight, power, and hardware reliability. High information transfer efficiency is desired to minimize the average signal power required at the detector, thereby minimizing the transmitter prime power and antenna aperture requirements. The laser may be operated in one of two ways: It may be pulsed in a very high peak power low duty cycle mode, or it may be modulated in some way in a CW mode, operation at high peak powers being more difficult than CW operation. Of the modulations of the CW mode, those which avoid amplitude modulation are most efficient. These reasons influenced the choice of CW polarization modulation for this system.

In the case of atmospheric propagation, a modulation relatively insensitive to atmospheric disturbances is needed - another factor favoring polarization modulation. Still another factor in the choice is receiver design. Some modulations require a dual channel receiver, some a single channel. The single channel receiver uses less equipment, but its threshold depends on both signal and background levels and may be difficult to set, and the dual channel receiver requires matching the gains of the two channels. Polarization modulation uses a dual channel receiver - one channel for each polarization, thus avoiding threshold setting. AGC is used to control the gains of the two channels to equality and to provide a capability for operating in the appropriate portion of the tube dynamic range. Yet another consideration in the choice is attainable completeness of modulation. For example, there is leakage in the “off” position of intensity modulation, residual polarization of the wrong sense in left and right hand polarization, and leading and trailing pulse tails in pulse position modulation.

Implementation ease and feasibility in modulating and demodulating also influence the modulation choice, especially at 1 Gbps data rates. Some pulsed modulations allow time gating elimination of much of the background interference but CW modulations do not. The I Gbps link described here achieves 10^{-6} bit error rate performance without such gating, but the gating may be desirable for some systems at higher data rates, lower error rates, or higher background levels.

Summary of 1 Gbps Link Achievements The laser link described here is designed to make use of the advantages afforded by lasers and overcome the problems associated with them. With 213 watts prime power and a 100 pound package, a 1 Gbps system with a 10^{-6} bit error rate appears to be feasible. This package, which includes a 12-inch telescope, achieves an ERP of 116 dBW. (At microwave frequencies of 60 GHz, a really imaginative combination of transmitter power and antenna diameter, such as a 32-foot dish and a 10 KW transmitter, are required to achieve 116 dBW.) The small telescope required for this system has a much lower drag profile when used as a satellite or aircraft antenna than an antenna achieving similar performance at microwave frequencies. The small package also simplifies satellite launches and affords the possibility of multiple telemetry packages.

The laser system has advantages in reducing vulnerability to jamming. Since the laser beams have non-measurable sidelobes and leave small footprints on the earth, they have greatly increased privacy and reduced susceptibility to ECM.

The direct detection of photoelectrons used in this system eliminates lengthly frequency searches in acquisition and eliminates frequency tracking during telemetry transmission. To see how advantageous this is, consider the doppler shift between two satellite terminals whose relative velocity is known very well - to ±10 fps for example. At λ = 1.06 micron, the resultant doppler shift is ± 6 MHz. To search this with a 100 Hz acquisition bandwidth would require searching 120,000 frequency slots for every angular cell.

The techniques used to overcome the problems associated with the use of laser links are as follows. Both a coarse and a fine acquisition sensor are used sequentially to accomplish the transition from an initial angular uncertainty of ±0.5° to an operational beamwidth of 5 microradians, a factor of 3.5 x 10^3. The fine acquisition sensor is also used for tracking and can achieve a tracking accuracy of ±0.5 microradian. Fine receiver optics pointing is achieved with a transfer lens and coarse pointing with gimballing of the telescope and communications package. A beacon is used at the link terminal containing the high data rate receiver to aid in acquisition and tracking and possibly as a command link. Point-ahead is accomplished by rotating Risley prisms by an amount obtained from an on-board stored table. The modulation used is polarization modulation, which is largely insensitive to atmospheric disturbances. Finally, high data rate electronics has been designed and breadboarded, providing the demodulate/ remodulate capability needed if a repeater configuration is desired.

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