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Intersatellite Optical Heterodyne Communication Systems

High-capacity intersatellite communication crosslinks will allow more efficient and reliable operation of military and commercial satellite systems. High-speed optical crosslinks can serve as a key building element of an interconnected space-based communication system for military applications. A network such as this would provide immediate communication among satellites, eliminating the need for ground-based relay stations and expensive worldwide ground tracking networks, which would greatly improve the efficacy and reduce the vulnerability of existing satellite systems. Crosslinks can also provide connectivity for commercial global satellite communication systems and for deep-space applications. Optical heterodyne communication systems using semiconductor lasers offer small-aperture, modest-weight, low-power, point-to-point crosslink packages, characteristics that are suitable for the envisioned applications. System research and development performed at Lincoln Laboratory permits the implementation of an efficient optical crosslink based on readily available, state-of-the-art devices and technology.

High-capacity intersatellite communication crosslinks will permit more efficient and more reliable operation of future satellite systems. Crosslinks can achieve connectivity between terminals on opposite sides of the earth without expensive intermediate ground relay stations. Operating between a communication relay satellite and an observation satellite (weather satellite, earth resource satellite, or the space shuttle), intersatellite crosslinks also eliminate the need for expensive worldwide ground tracking networks. Figure 1 illustrates examples of possible intersatellite links.

Both microwave, *eg,* 60-GHz, and optical communication technologies are legitimate candidates for future satellite crosslink systems. Microwave links with capacities larger than approximately 10 Mbps require antenna apertures and transmitter powers large enough that it becomes increasingly difficult to integrate such systems on host spacecraft. Future intersatellite links to be used for satellite data acquisition networks or long-distance communication trunking systems may require capacities as great as several Gbps. Optical crosslinks offer the potential of operation at these high data rates because optical frequencies allow the use of very narrow transmit beams (10 μrad or 2 seconds of arc), which achieve high received signal levels with comparatively small antenna (telescope) packages.

Recent developments in optical communication technology are very encouraging for the potential operation of optical satellite crosslinks [1]. Most notable among these developments are the availability of coherent semiconductor lasers and the successful demonstration of an optical heterodyne system in the laboratory.

Figure 2 compares the antenna sizes required for 60 GHz and for optical crosslinks. These data are not the results of a mere antenna scaling exercise but correspond to system designs based on state-of-the-art transmitter and receiver technologies [2]. It is evident that as the data rate becomes high, an optical system will be the logical choice. The differences in terminal weight required for 60-GHz systems and for optical systems are somewhat smaller and less significant, as shown in Fig. 3.

Heterodyne optical systems further boost the advantage held by optical systems at high data rates because a heterodyne system requires

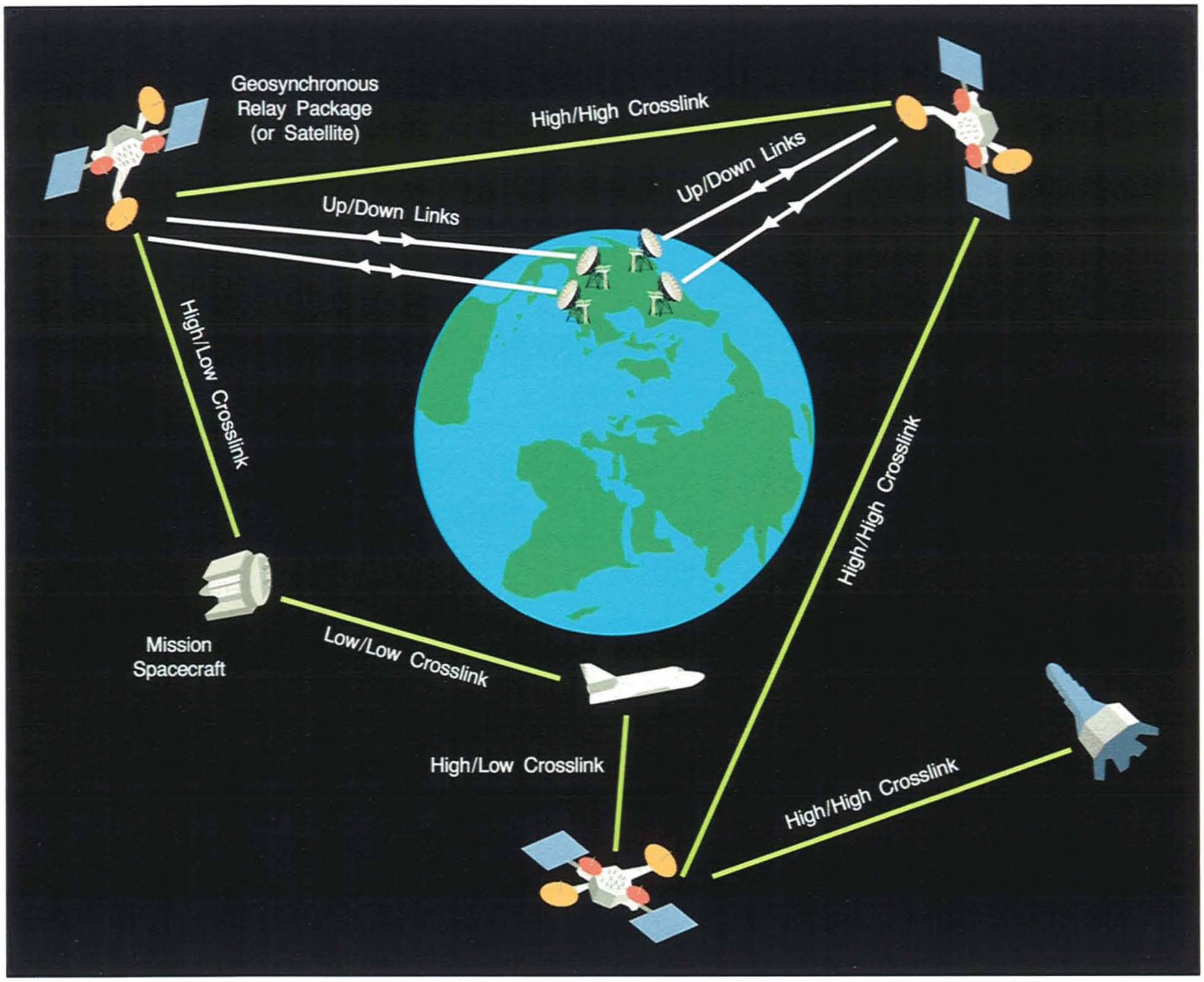

Fig. 1 — This crosslink can allow any of the spacecraft to communicate with another one without using unwieldy ground relay stations.

even smaller aperture sizes than direct detection systems (Fig. 2). This small aperture size is permitted by the nearly quantum-limited performance available from heterodyne detection systems. Direct detection systems, on the other hand, are usually limited by avalanche photodetector excess noise, background noise, and amplifier thermal noise. Compactness, high power conversion efficiency (prime-to-optical-output-power conversion efficiency ~20%), and single-frequency operation make the GaAlAs laser a good candidate for the laser source in a heterodyne system. At the GaAlAs wavelength region (0.8 μm), the sensitivity of a heterodyne system can be higher than a direct detection system by 15 dB.

Another advantage of a heterodyne optical system over a direct detection optical system is that it allows narrowband (~1 GHz) spectral filtering to be performed at the heterodyne receiver's intermediate frequency. Direct detection systems, on the other hand, have to rely entirely on optical filters for background light rejection. These filters are typically several angstroms (~100-to-500 GHz) wide, and the direct detection receiver's sensitivity is further

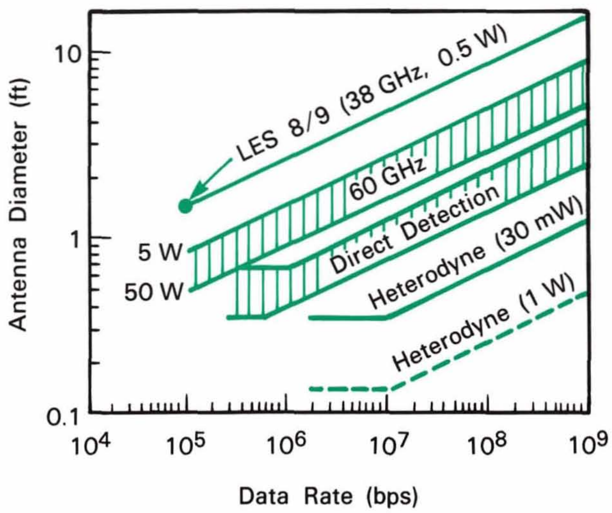

Fig. 2 — Aperture diameter required for a variety of proposed crosslink technologies. The superiority of optical systems at high data rates is evident.

degraded when looking directly at a strong source of background light such as the sun or man-made interference.

One of the earliest examples of a satellite crosslink was a 38-GHz link between the geosynchronous Lincoln Experimental Satellites 8 and 9 (LES 8/9), which were launched in 1976. No experimental or operational laser communication systems have yet been flown in space. However, optical technology has evolved to the point where it is now feasible to consider such systems for space applications.

This paper describes the critical technology and system issues facing the realization of a space heterodyne optical communication system. A system that can be built in the near future, based on state-of-the-art devices available today and on technology and system devel-

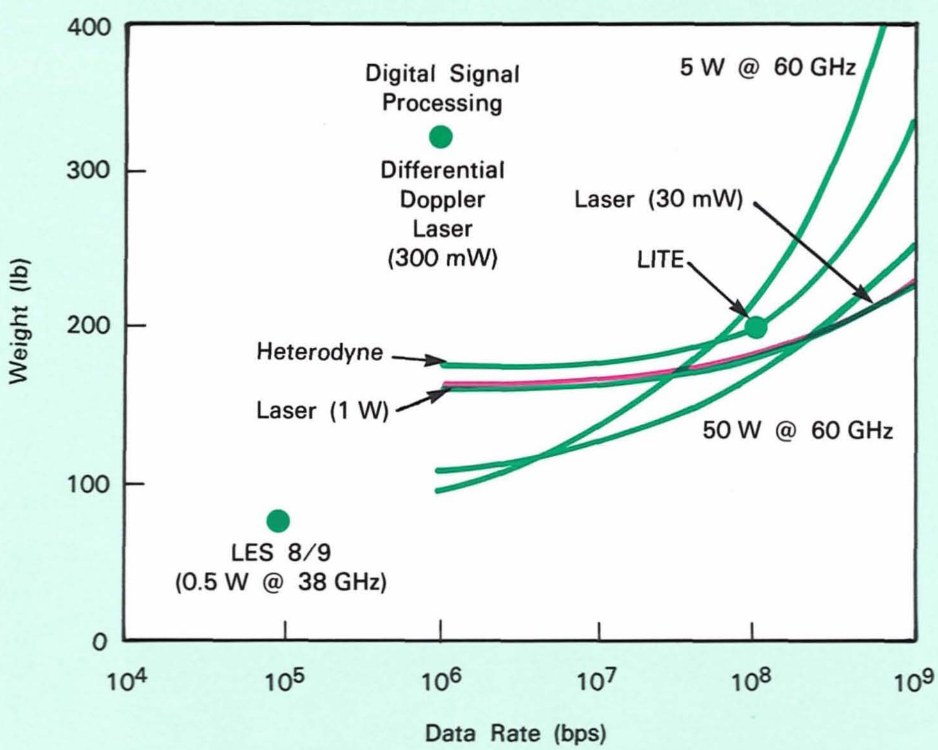

Fig. 3 — A comparison of crosslink package weights. At data rates greater than about 10^8 bps, an optical system provides the lightest package.

opment performed at Lincoln Laboratory over the last few years, is presented.

General Mission Requirements and Constraints

Space-based communication channels include the satellite-to-satellite channel, the ground/aircraft-to-satellite channel, satellite-to-ground/aircraft channel, and the satellite-to-underwater-receiver channel. The data rate requirements of an optical channel span a wide range, typically from 1 bps to 1 Gbps. Commercial data-rate requirements typically fall into the higher end of this range, from 1 Mbps to 1 Gbps.

The most important of these channels is the satellite-to-satellite channel. Link distance, relative velocity, point-ahead angle, angular tracking rate, Doppler shift, background radiation, and satellite platform stability are all issues that will affect the detailed design of any satellite communication system. Antenna size is a key parameter for consideration in the design of satellite communication systems; it will directly impinge upon the choice of technology for the transmitters and receivers. Antennae for use with heterodyne optical systems are smaller than those used with direct detection systems. Small antenna size is a particularly valuable feature when the application calls for many transmitters and receivers to be colocated on the same space platform. More conventional microwave links would require larger antennae at high data rates.

Since many communication packages are merely secondary payloads in satellites, the weight and power requirements of the crosslink must also be minimized. A good target weight is 100 to 200 lb, and power consumption should be held to somewhere in the range of 100 to 200 W. Heterodyne optical communication systems can meet these criteria.

In addition to the system-level issues, the design of a satellite communication system must address broader issues. To amortize the development and manufacturing costs over a wide range of applications, the technologies and

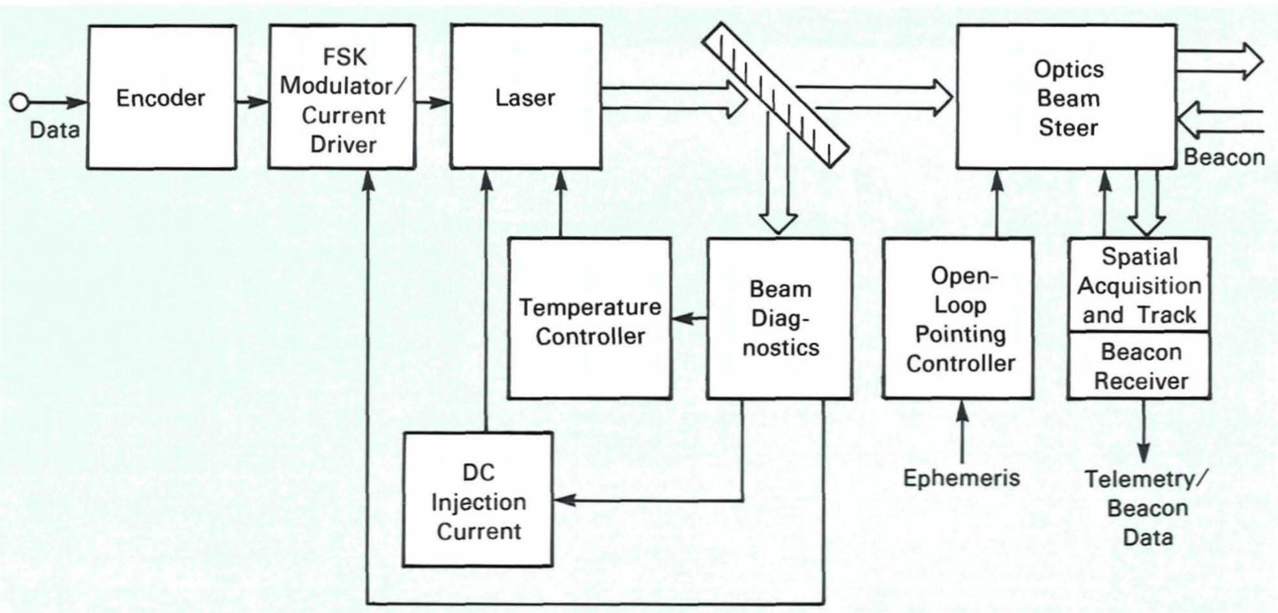

Fig. 4 — Block diagram of an optical heterodyne transmitter. Note the feedback from the beam diagnostics package to the FSK modulator, to the dc injection-current source, and then to the temperature controller that stabilizes the laser's cavity length.

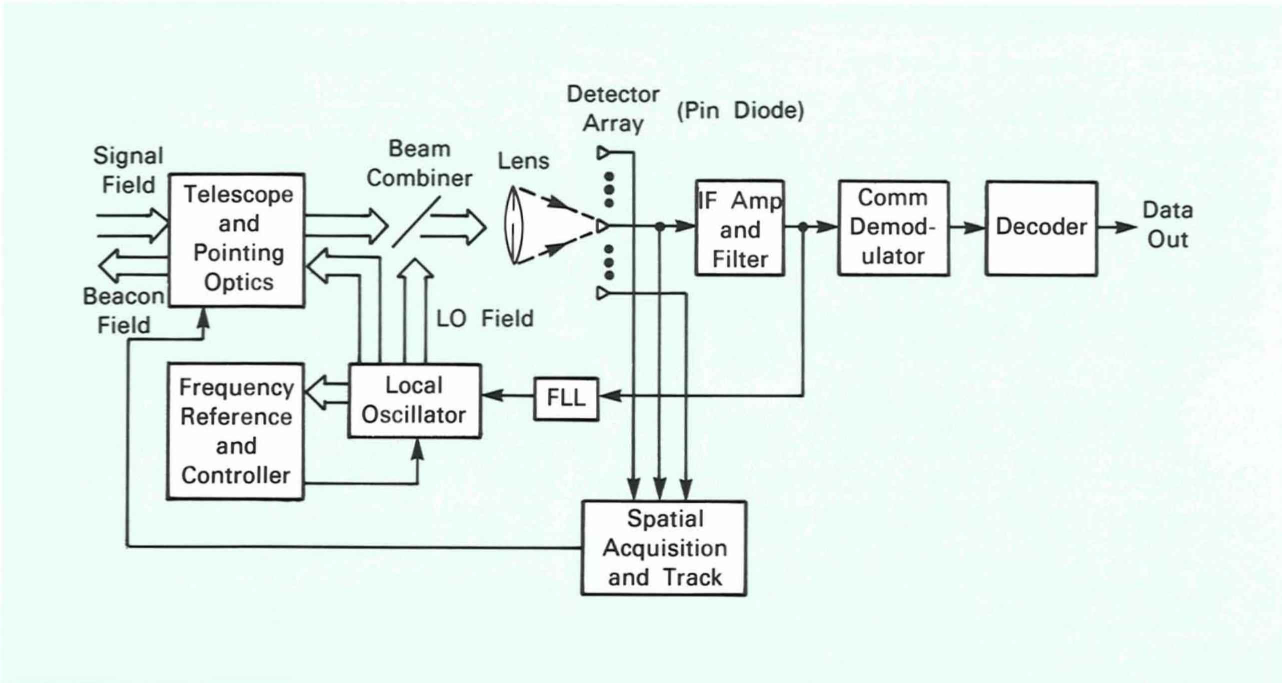

Fig. 5 — The optical receiver includes the spatial acquisition and tracking electronics, which provide feedback from the detector array to the telescope and pointing optics.

the system-level requirements of a crosslink system must be compatible with a wide range of data rates. Heterodyne systems using semiconductor lasers can operate over a very wide range of data rates. Thus only one technology has to be developed, improving the prospect of system interoperability in the future.

Some crosslinks must operate continuously, sometimes with the sun in the field of view (FOV). This is no easy task. The sun generates enormous amounts of power in the optical range. Heterodyne systems can operate with very narrow intermediate frequency (IF) filters, which reduce greatly the intensity of the sun's power and permit operation with the sun in the FOV with no degradation.

All the key components of a crosslink system must have good reliability, reliable supplies, and relatively low cost. The components described in this paper for the strawman crosslink system are mature, reliable, and readily available commercially. This fact further reduces the technical and financial risks of putting such crosslinks in space.

Technology and System Issues

Laser Technology

The essential features of a space-to-space heterodyne optical communication system using GaAlAs lasers are illustrated in the block diagrams of a transmitter and receiver of Figs. 4 and 5. A heterodyne optical communication system operates much like a conventional radio system. The transmitter uses the signal with the information to be transmitted to modulate a transmitter-laser; at the receiver, the incoming signal is mixed with a local oscillator (LO) laser. The resultant IF signal is processed to recover the original signal much as a radio frequency (RF) signal is recovered. Mixing the very weak signal and the strong LO at the receiver raises the signal level well above the noise level of subsequent electronics. The heterodyning can be effective enough that quantum effects are the only limiting factors of the receiver sensitivity. The channel can be modeled as a classical additive white-Gaussian-noise channel, allowing well-known modulation and demodulation techniques to be applied. Near theoretical-optimum receiver sensitivity can be realized with this system, with sufficient frequency selectivity, to permit operation even when the sun is directly in the receiver FOV.

As might be expected, a heterodyne optical system imposes demanding technology constraints on system components. Single-frequency laser operation is absolutely essential for the transmitter and LO lasers in a heterodyne system. The transmitter frequency and the receiver LO frequency must be tracked to recover the information in the signal. Single-frequency semiconductor lasers have only been available in quantity for a few years. Until recently semiconductor lasers lased at several frequencies, preventing heterodyne operation.

An example of one of these new lasers is a 30-mW Fabry-Perot GaAlAs laser that operates nominally at 0.83 μm (Fig. 6.). It is a single spatial-mode laser with electrical-to-optical power conversion efficiency of about 20% when operating in the continuous wave mode, at its maximum rated power of 30 mW, and biased at twice the threshold current. Figure 7 shows the power spectrum of the laser. This laser operates essentially in a single longitudinal (spectral) mode; the main-to-side mode ratio exceeds 25 dB (typically 27 dB, and a maximum of 35 dB). The mode spacing of 3 Å (130 GHz) simply reflects the Fabry-Perot cavity length (300 μm) of the laser. That is, the longitudinal-mode spacing is determined by the cavity length; an integral multiple of half wavelengths must fit within the cavity.

The cavity length also determines the laser's frequency. Modulation of the cavity length is directly reflected in a modulation of the laser frequency, an effect that is used to tune the laser. The tuning is required, among other things, to accommodate the shift in frequency due to the relative motion of the satellites. The maximum Doppler shift encountered in most crosslink applications is about ±10 GHz, or about ±0.6 Å of tuning range required of the lasers. Most single-frequency GaAlAs lasers today can be tuned far in excess of this amount by temperature-tuning the effective laser-diode-cavity length (Fig. 8). Thermal tuning of the cavity is brought about by expansion and contraction of the physical cavity (-2.2 GHz/K) and by changes in the refractive index related to the temperature dependence of the band-edge absorption within the cavity (-27.7 GHz/K). The total tuning index is 30 GHz/K (or 0.66 Å/K).

The laser frequency tunes with bias current in a similar fashion as with temperature. The low-frequency current tuning index is about 3 GHz/mA and is largely due to thermal tuning of the optical length of the Fabry-Perot cavity.

Because of these high tuning sensitivities, the transmitter and LO lasers must be kept at relatively stable temperatures (~0.01K) and bias currents (~10 μA). A frequency -tracking system at the receiver will finish the task of locking the LO laser to the transmitter laser.

In addition to temperature and bias-current effects, the frequency noise characteristics and the linewidth of the lasers are of concern. Proper design of the frequency-tracking and communication systems requires good characterization of the noise process. The spectrum of the laser frequency noise has a significant $1/f$ component at low frequencies and it is essentially white between 100 kHz and several GHz. At around 8 GHz a relaxation oscillation resonance takes over and the spectrum decays at 20 dB/decade thereafter (Fig. 9). The white-noise component produces spectral broadening of the laser line and accounts for the predominantly Lorentzian line-shape (Fig. 10). In particular, if the spectrum height of the white frequency noise is S_0 (Hz^2/Hz, single-sided), the resultant Lorentzian full-width half-maximum linewidth is: $\Delta\nu_L = S_0$. The linewidth varies approximately as the reciprocal of the laser output power and, for lasers operating at 30 mW, typical linewidth values are 3 to 8 MHz. The $1/f$ frequency noise induces random center-frequency wander of the Lorentzian spectrum, broadening the apparent linewidth by approximately 1 MHz. This part of the noise spectrum is particularly detrimental to a heterodyne system; unattended, the IF signal will eventually stray outside the detector's response-bandwidth. Thus, this component of the

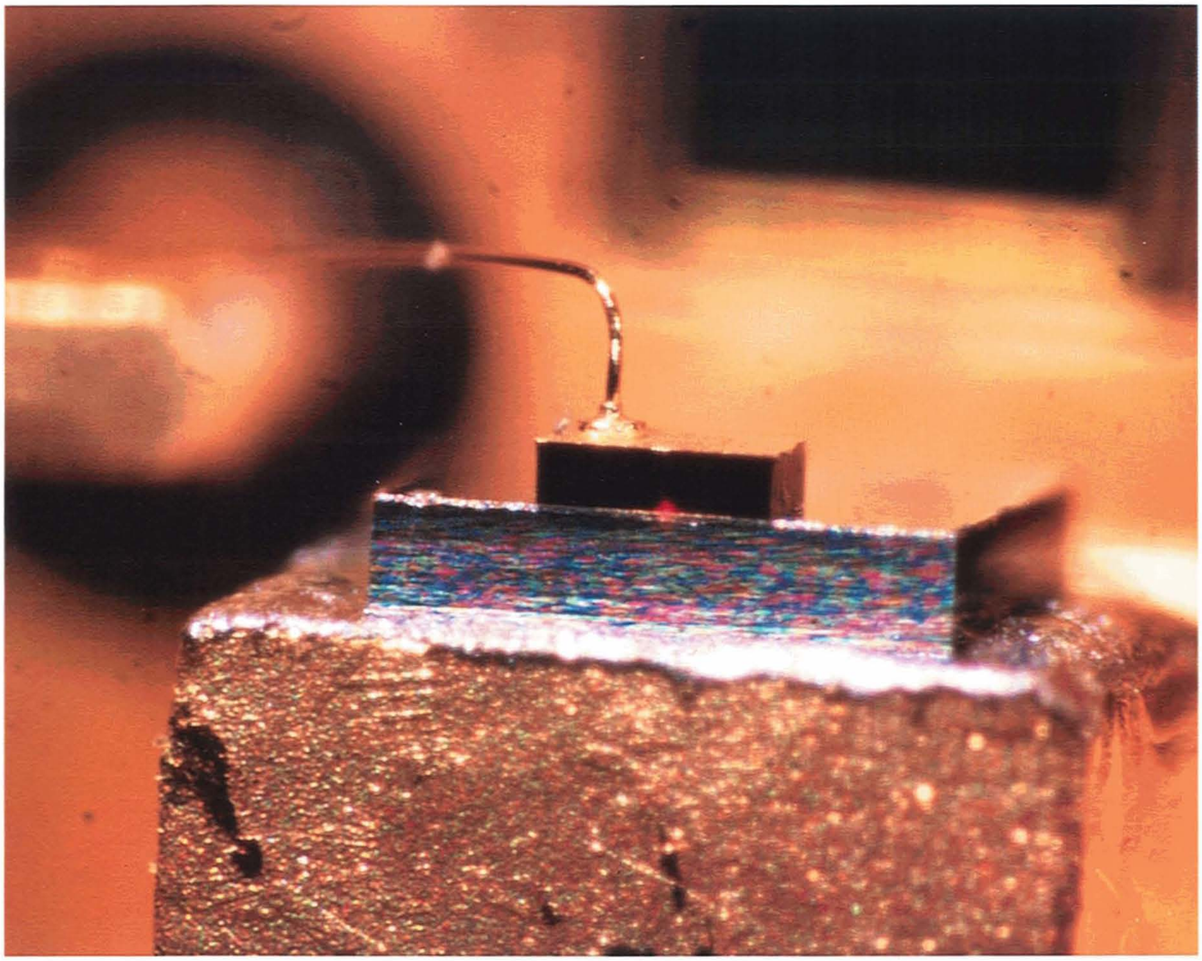

Fig. 6 — This GaAlAs laser is a single spatial-mode laser. It provides the single-frequency operation necessary for heterodyne communication.

frequency noise must be tracked and compensated for by the receiver's frequency-locking system.

Transmitter Technology

Development of efficient modulation and demodulation techniques is an important step in realizing the promised performance gains of optical heterodyne communication systems. To a first approximation, the optical heterodyne channel can be modeled as a classical additive white-Gaussian-noise channel. Phase-shift keying (PSK) and frequency-shift keying (FSK) are two modulation schemes commonly used with classical white-Gaussian-noise channels. It would seem that either modulation scheme may be suitable for use with optical heterodyne channels, but the presence of device imperfections, such as nonzero-linewidth lasers at the transmitter and receiver, significantly complicate the analysis and choice of a modulation scheme.

Modulation schemes requiring coherent demodulation, such as PSK, require tracking of the laser phase-noise. For example, for a laser linewidth of 5 MHz (IF linewidth of 10 MHz), 10^{10} to 10^{11} photons/s must be detected at the receiver

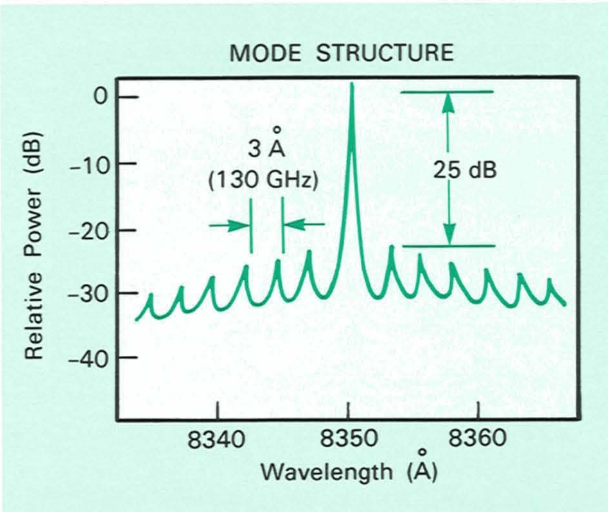

Fig. 7 — Power spectrum of a GaAlAs laser.

to phase-lock [3]. Typical optical channels that operate at several hundred Mbps and at a communication efficiency of 10 photons/bit do not offer this required power (10^9 photons/s vs the required $10^{10\text{-}11}$). This lack of power rules out the possibility of phase locking, unless further laser developments reduce laser linewidths significantly. Laser linewidths can be reduced by using external cavity lasers, which, however, increase the mechanical complexity of the system, thus increasing the cost and decreasing the reliability of the system.

When phase tracking at the receiver is not

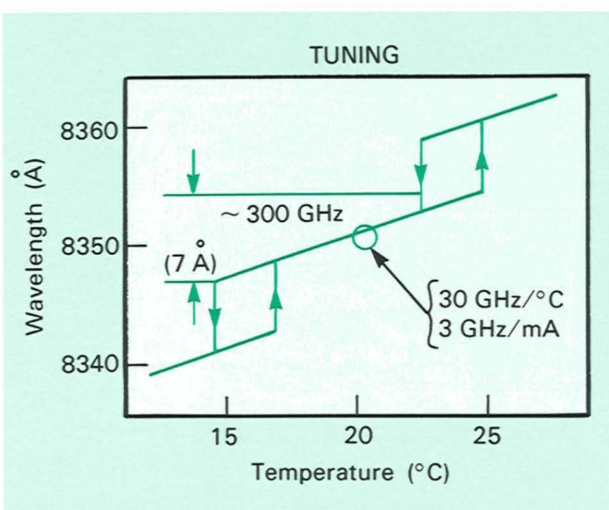

Fig. 8 — Wavelength vs temperature of a GaAlAs laser.

feasible, one of the most efficient modulation schemes possible is FSK signaling paired with noncoherent demodulation. M-ary FSK signaling (signaling with one of M possible tones) can be conveniently accomplished by direct-current modulation of the semiconductor laser. Nonco-

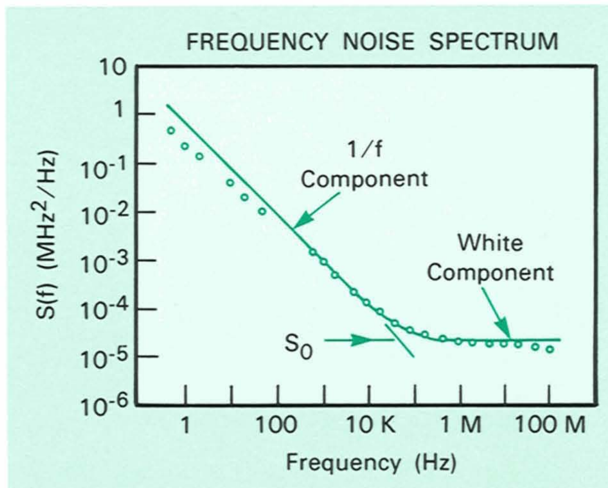

Fig. 9 — Frequency noise spectrum of GaAlAs laser.

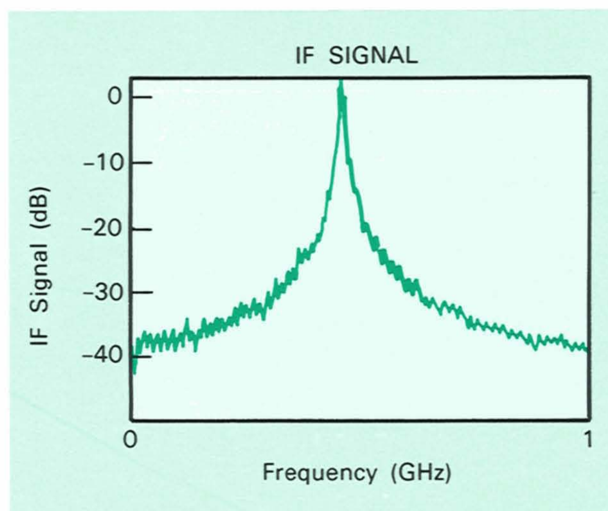

Fig. 10 — Lineshape of GaAlAs laser.

herent demodulation of FSK only requires frequency tracking, which has been demonstrated to stabilize center-frequency drift of the laser caused by the $1/f$ component of the FM noise spectrum to a few MHz rms error [3,4]. Operational use of such a system has been shown to cause negligible performance degradation [5].

A GaAlAs laser can be frequency-modulated through direct injection-current modulation [6,7], thereby providing both a frequency-modulated transmitter laser and a frequency-agile LO. If an FSK transmitter is to be realized by direct injection-current modulation of a semiconductor diode laser, its modulation characteristics throughout the spectrum of the modulation waveform must be uniform. In particular, for an FSK injection-current modulator, operating in the 100-Mbps region, the laser must exhibit a flat frequency modulation (FM) transfer function from dc to a few hundred MHz. Most GaAlAs lasers do not exhibit flat FM transfer functions; thermally enhanced FM characteristics cause excessive tuning of the diode-laser output frequency at low frequencies. Consequently, the FSK tones often drift — the amount of drift depending upon the bit pattern being transmitted and the duration of a tone. Uncompensated, this thermal frequency drift can severely degrade communication-system performance by spreading tone energy over a wide bandwidth, thus increasing cross talk between frequency slots and creating data-pattern-dependent errors. A passive equalization network that significantly reduces the effects of low-frequency thermal FM is simple to implement and requires neither active electronic nor optical components [8].

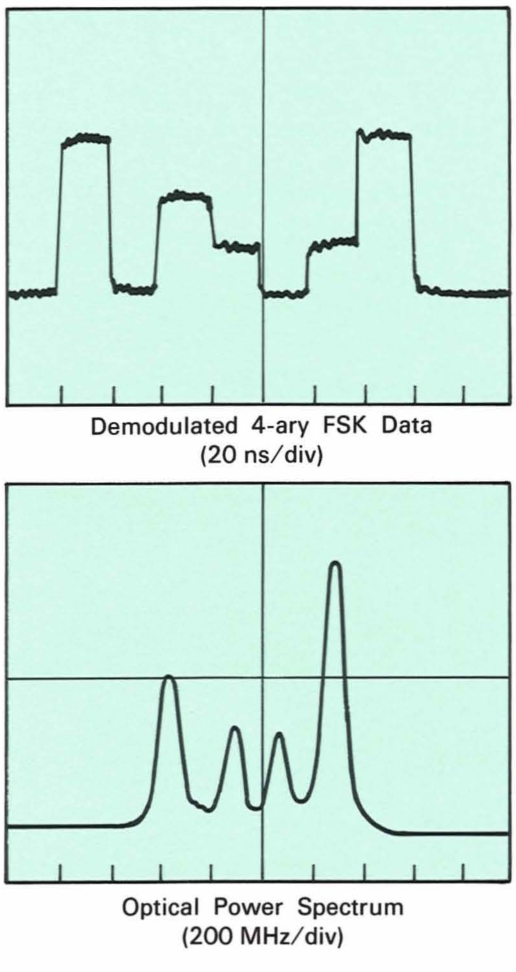

Fig. 11 — Recovered FSK laser output (upper trace; time-scale 20 ns/div) and the time-averaged optical power spectrum of the FSK laser output (lower trace; 200 MHz/div).

Binary and 4-ary FSK modulators have been developed at Lincoln Laboratory. The 4-ary modulator consists of a 0-to-200-mA variable constant-current source used to bias the laser diode. This biasing determines the frequency of tone zero. Incremental injection currents are switched in to the bias network via a series of high-speed GaAs field-effect transistors. These currents are summed in the bias network to provide the modulation injection currents that determine the frequencies of tones one, two, and three. Figure 11 shows 4-ary FSK data recovered at the receiver. The modulator can be run at a 110-MHz symbol rate with two bits per symbol (4-ary FSK), yielding 220 Mbps. The tone transition time for this system is 1 ns (~10% of a symbol duration) [9].

Optical Heterodyne Receiver

The key subsystems of a heterodyne receiver are the front-end, the frequency-tracking system, and the demodulator. The front-end is mainly composed of the detectors (PIN photodiodes) and the LO. The frequency-tracking system consists of a feedback loop from the IF output of the front-end back to the LO. Frequency tracking ensures that the LO laser follows any drift between the transmitter and LO lasers. The demodulator can be a matched filter,

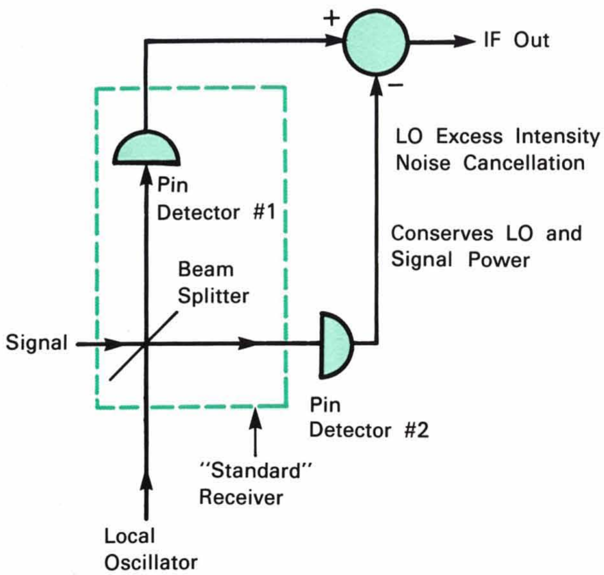

Fig. 12 — The dual-detector heterodyne receiver provides nearly quantum-noise-limited reception.

or delay-line discriminator receiver.

With a sufficiently strong LO, the dominant receiver noise is, ideally, the quantum-detection noise [10]. In fact, the statistical model of a heterodyne receiver can be described by a linear electric-field amplifier with quantum noise added to the output. At the electrical output of the optical detector, this noise can be modeled as additive white Gaussian noise with spectral height (single-sided) $N_0 = h\nu/\eta$, where h is Planck's Constant, ν is the frequency of the optical field, and η is the quantum efficiency of the photodetector. The receiver front-end sets the signal-to-noise ratio (SNR) of the detection process and directly affects the end-to-end performance of the communication system. Introduction of this level of quantum-detection noise is unavoidable, given that conventional lasers are used at both the transmitter and the receiver. Lower quantum noise can be effected in certain circumstances utilizing the novel properties of a newly found optical field called a "squeezed state" [11]. The squeezed state, due in part to the rapid diminution of its novel properties as optical power is lost, has yet to yield a practical alternative to conventional lasers in this application.

At the receiver, the LO provides gain, and its power is set high enough to overcome the effects of thermal noise introduced by subsequent processing electronics. Since the mixing process provides gain via the LO, a unity-gain photodiode can be used as the detector. The advantage of using a unity-gain photodetector is that noisy amplifying detectors (*eg*, avalanche photodiodes) generally degrade the SNR of the signal. For heterodyne receivers at the 0.8-μm wavelength region with a bandwidth of over 1 GHz, the photocurrent generated by the LO should be at least 1 mA to insure near quantum-limit receiver performance. This requirement implies the need for a few milliwatts of LO power along with detectors that provide better than 50% quantum efficiency. Such detectors — silicon PIN photodiodes — are now commercially available in quantity.

Another challenge at the receiver is to reduce the excess noise density generated by the LO

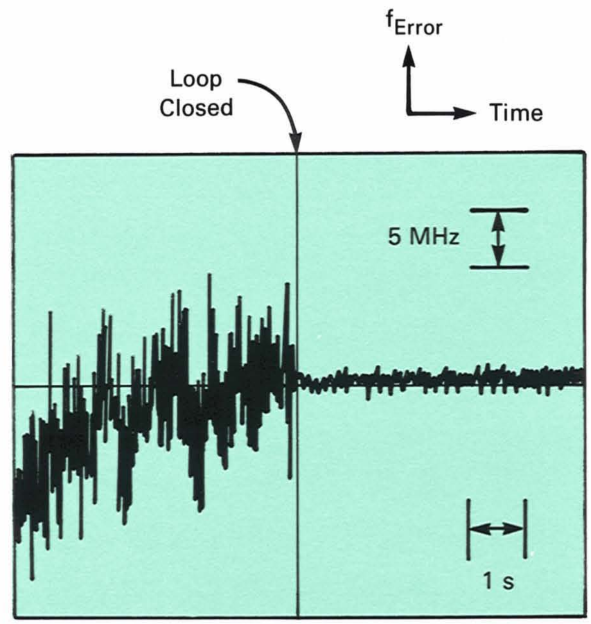

Fig. 13 — Effect of frequency tracking on the IF center-frequency stability. With the tracking system in effect (right side of photo), the IF frequency doesn't drift more than 1 MHz rms.

intensity fluctuations to a level less than that of the quantum-detection noise in order for the receiver sensitivity to be quantum-limited. Figure 12 shows a dual-detector intensity-noise-canceling receiver first proposed by Oliver [12]. The receiver was developed to combat the excess intensity-noise of the laser [10,13–16]. The excess noise currents from the two detectors are in phase with one another, while the signal components are 180° out of phase. Thus, subtracting the two detector outputs cancels the excess noise and completely recovers the desired signal. Receiver sensitivities within 0.5 dB of the quantum-noise limit have been obtained over a 1-GHz bandwidth using this technique [15].

An additional impediment to quantum-noise-limited receiver sensitivity is poor spatial-mode matching between the incoming signal and the local oscillator. Both the phase and amplitude profiles must match accurately to obtain efficient mixing from the receiver. High-efficiency mode matching (phase and amplitude) with less than 1/2-dB loss has been demonstrated at visible wavelengths and, more recently, at 0.8 μm [17].

Another noise component, the $1/f$ frequency noise that corresponds to the center-frequency jitter of the laser, can be reduced by frequency tracking. Tracking requires that the IF center

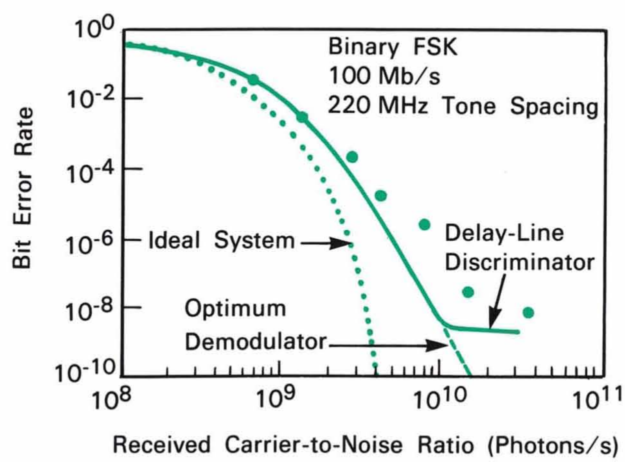

Fig. 14 — End-to-end system bit-error-rate performance. The effect of the finite-width laser dominates at high received signal levels, causing a leveling of the bit-error rate at about 10^{10} photons/s.

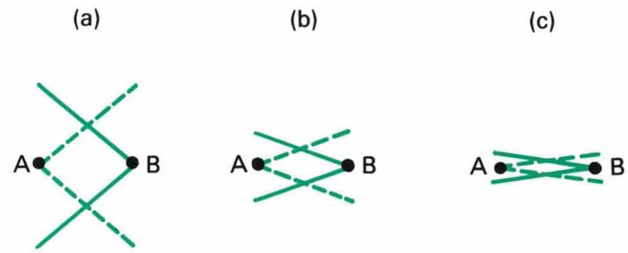

Fig. 15 — Beam acquisition sequence for a satellite crosslink.

frequency be sensed by the receiver and that the LO then be tuned to maintain the IF at a fixed value. Tuning of the LO can be accomplished through temperature and injection-current modulation.

An experimental system that utilizes the above techniques has been successfully demonstrated at Lincoln Laboratory [3]. The tracking system is designed to operate in a system that receives signals of 10 to 100 pW; it tracks the $1/f$ noise out to about 100 kHz. The effect of frequency tracking on the IF center frequency stability is shown in Fig. 13. Before the loop is closed there is considerable IF drift. After the loop is closed the IF frequency is maintained to better than 1 MHz RMS. This measurement was performed at a received signal level of 10^8 photons/s, 10 dB below the expected signal level.

The results of an end-to-end system performance measurement are shown in Fig. 14. These measurements were obtained from a system transmitting binary FSK data at 100 Mbps [4]. The system utilized all the techniques, equalization, noise cancellation, and frequency tracking alluded to earlier. The demodulator in this case was a delay-line discriminator. The curve labeled "ideal system" refers to a system based on a zero-linewidth laser. The effect of a non-zero IF linewidth (~15 MHz) is to level out the performance to a "floor" at high received signal levels. At 10^{-5} error rates, the receiver sensitivity is about 35 received photons per bit of information that is transmitted.

System Issues

Spatial acquisition and tracking present some of the most significant design and implementation challenges for optical intersatellite systems. Because of the very narrow optical beamwidths (roughly a few μrad), satellite terminals must acquire and track the beams with great angular accuracy. Spatial acquisition is complicated by uncertainties in beam pointing that arise from a number of sources. Although the most significant source of error in acquisition is spacecraft-attitude control error, other error sources, such as ephemeris error (spacecraft location-prediction errors due to inaccuracies in timing, in the orbital model of the spacecraft, and in approximations to this model) and limitations in the accuracy of optical pointing mechanisms, contribute significantly to the beam-pointing uncertainties. Attitude control accuracy is limited to about one mrad by attitude sensor uncertainties, attitude control-loop errors, and various mechanical alignment uncertainties. Star trackers are capable of providing much greater accuracy, but their added expense and complexity weigh against their use in a typical crosslink package, and their added accuracy are not usually required.

To overcome acquisition and tracking uncertainties, each terminal must provide a beacon to aid in beam acquisition by the other terminals. The beacon function can be served by the information-carrying signal beam. The acquiring terminals can employ search strategies such as parallel search, zooming, or serial search [18]. Parallel search leads to the most rapid acquisition. Charge-coupled devices (CCD) or charge-injection devices (CID) are well suited to the role of acquisition detectors for use in parallel-search beam acquisition. Low-noise devices with as many as 1000×1000 pixels have been developed and can provide an acquisition FOV large enough (1 mrad × 1 mrad or more) to satisfy acquisition system requirements easily. Note that since the acquisition field of view may be 1 mrad × 1 mrad, it occupies 10^6 times the size of the transmit beacon. Figure 15 depicts a typical acquisition scenario, which begins with each terminal broadening its transmit beamwidth to illuminate the entire uncertainty region. Although the received power densities over a geosynchronous link distance will be low (on the order of 10^{-12} W/cm^2 for a 30-mW laser and a 1-mrad beamwidth), integration times in the CCD/CID can be chosen to build up a SNR that is more than adequate for signal acquisition. Current systems are capable of beam acquisition in as little as a few seconds.

Once the beam is acquired, the spatial tracker must track out local angular disturbances on board the host spacecraft along with any relative translational motion of the other terminal. Tracking error generally cannot exceed 0.1 beamwidths, otherwise the SNR and, consequently, the data demodulation performance at the receiver will be seriously degraded. Tracking-system design requires a careful assessment of the dynamic environment of the spacecraft. Satellites can produce significant angular disturbances, varying widely in amplitude and frequency, due to the motion of solar arrays, other payloads sharing the platform, and attitude control systems. Disturbances on the order of 100 μrad or more can be expected at around 1 to 10 Hz, but they decrease to a few μrad at 100 Hz and above. Even though the perturbations decline markedly at frequencies greater than 100 Hz, closed-loop tracking bandwidths of 1 kHz or more may be required for sufficient disturbance rejection. High-bandwidth mirror technology provides the required closed-loop tracking bandwidth. Also, because of relative platform motions and the finite transit time of light, an open-loop point-ahead angle correction, which may amount to as much as 50 μrad, must be included.

Either direct detection or heterodyne tracking receivers can be employed as a spatial error sensor. The heterodyne spatial tracker, like the heterodyne data receiver, has the advantage of greater sensitivity to signal and better immunity to background noise, including the significant contribution from the sun, when tracking with the sun in the FOV.

The optical subsystem design must limit throughput losses to less than 3 to 4 dB. The optical subsystem must also present a wavefront that varies in phase less than 0.1λ, and maintain pointing and alignment to within 0.1 beamwidth. This performance must be maintained in an environment of mechanical disturbance inputs from the spacecraft and

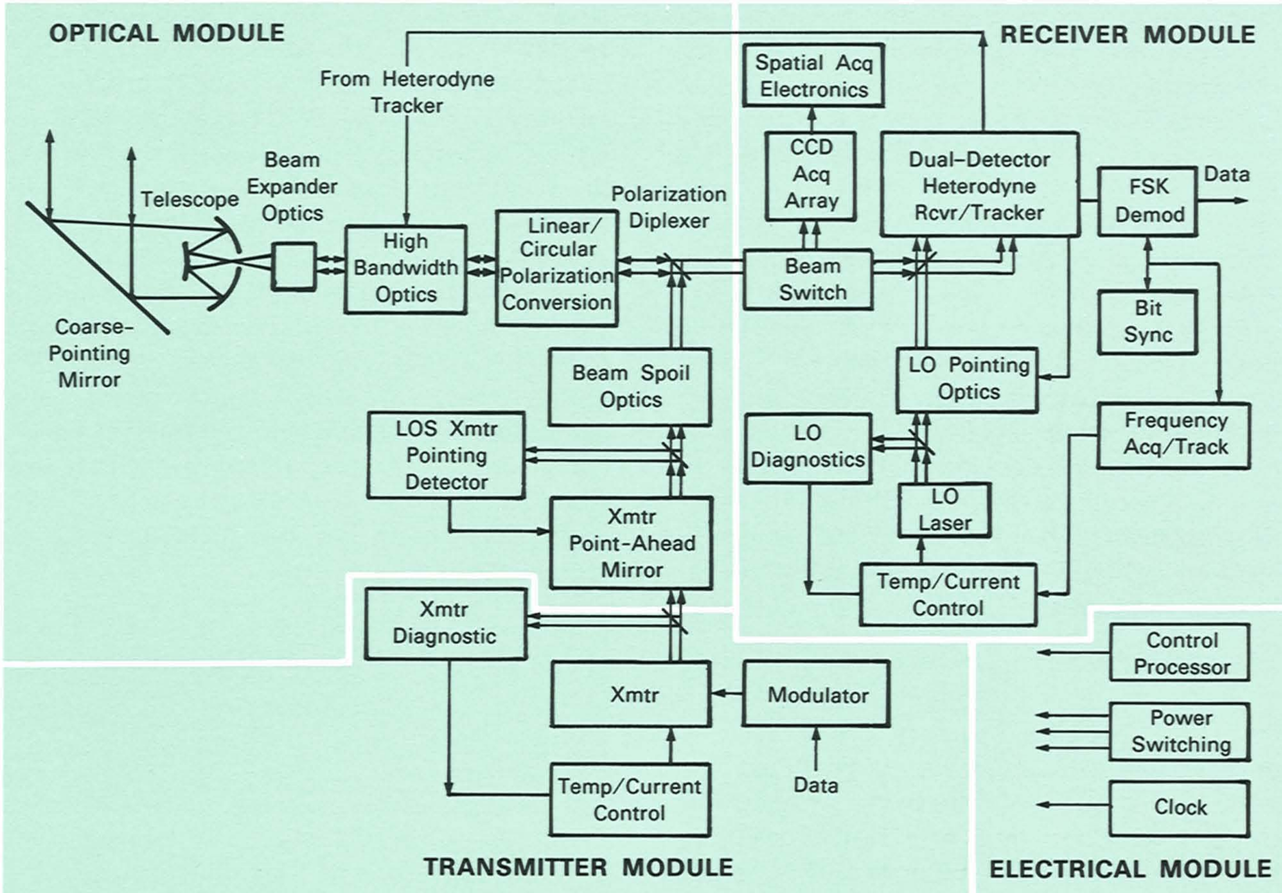

Fig. 16 — Design of a laser communications crosslink package.

time-varying thermal conditions.

The mechanical design must first ensure physical survival of the package through launch. Furthermore, the design must provide a high degree of structural stiffness and stability so that critical optical alignments can be maintained and pointing accuracy is not degraded in the spacecraft's normal operating environment. Where possible, isolation from on-board satellite disturbances should be provided.

The package can be subject to varying thermal scenarios, including full illumination by the sun, darkness, and transitions between the two extremes, and varying conditions of heat generation from on-board electronics. The thermal design of the package must insure a stable internal thermal environment; temperature gradients must therefore be minimized or stabilized to avoid compromising the performance of precision optics.

Strawman System

A block diagram of a strawman crosslink package is shown in Fig. 16. Four major subsystems are indicated: optical, electrical, transmitter, and receiver. The optical module contains the telescope, coarse-pointing mirror, and other optical components needed for beam pointing and transmission. The electrical module provides conditioned electrical power and control processors. The receiver consists of a CCD acquisition system, spatial tracking detectors and electronics, the data receiver front-end, including LO laser, and demodulation electronics. Finally, the transmitter module contains the laser transmitter, its modulator, precision temperature and current controllers, and an autonomous diagnostics package that monitors laser power, wavelength, and modulation characteristics. Table 1 summarizes the gross characteristics of a 220-Mbps system for a 1x synchronous-orbit (~22,000 mi) intersatellite link distance. A sample link budget is given in Table 2.

The information on the strawman system is based on a space-flight experimental design performed at Lincoln Laboratory. The numbers and characteristics set forth here are the result of a substantial development effort and are substantiated by test data or estimates based on detailed designs. We feel it is feasible to build a system with the described characteristics for launch in the early 1990s.

Conclusion

We believe there is a need for high-speed crosslinks between space platforms for both commercial and military applications. The added sensitivities of heterodyne systems over direct detection systems offer 15-dB higher efficiency in the use of signal power. This permits high rate links (200 Mbps) to be realized with a single semiconductor transmitter laser of modest power (30 mW) and small apertures (20 cm).

Our research and development program at Lincoln Laboratory has adequately addressed critical technology and system issues toward the realization of such an optical communication system. It is now possible to assemble a system using current technologies. The characteristics of such a system will be extremely competitive with 60-GHz crosslink technology, especially in the high-data-rate region. Ultimately, cost will also be a major consideration.This system is based upon commercially available devices, which, coupled with the ongoing development of these devices, should make this system cost-competitive as well as technologically attractive.

TABLE 1
Heterodyne Laser Crosslinks System Characteristics

	Data Rates *100 Mbps*
Source	30 mW
Aperture diameter	20 cm
Modulation	4-ary FSK
Weight	205 lb
Power	225 W

TABLE 2
100-Mbps Heterodyne Laser Link Budget

Transmit laser (30 mW)	-15.2 dBW
Transmit optical loss	-4.0 dB
Transmit aperture gain (20 cm)	117.6
Space loss (40,000 km)	-295.6
Receiver aperture gain (20 cm)	117.6
Spatial tracking loss	-1.0
Receiver optical loss	-2.5
Photodetector Q.E. = 0.8	-1.0
Spatial-mode match loss	-1.0
Detected power	-85.1 dBW
Detected photons/s	101.1 dB-Hz
Receiver front-end noise	-1.0 dB
Implementation loss	-2.1
Receiver sensitivity (photons/bit at 10^{-5} BER)	-12.0
Data rate (100 Mbps)	-80.0
Margin	6.0 dB

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