SPACE LASER COMMUNICATIONS COMPETITION FOR MICROWAVES

Raymond W. Svorec
Member of Technical Staff
Electronic and Optics Division
The Aerospace Corporation
El Segundo, California

Francis R. Gerardi
Systems Director
Defense Dissemination Program Directorate
The Aerospace Corporation
El Segundo, California

When the military and civilian space systems of the future are launched from earth, they will probably talk to us–and each other–over laser beams. Why lasers? A laser communications (lasercom) system presents many challenges to the dominance of microwave communications. First, there is capacity. Lasercom systems have already demonstrated gigabit-per-second transmission rates in both laboratory and aircraft-to-ground tests. And even higher data throughput rates, rates unmatchable by microwave systems, appear feasible for carrying the huge amounts of data generated by space systems.

Then there is security. Because of their tightly focused communications beam, lasercom systems provide inherent protection against jamming and eavesdropping. This highly collimated beam makes possible a third advantage–communication over vast distances. For example, lasers appear ideal for handling communications with deep-space probes.

Furthermore, the physical parameters of lasercom systems add another advantage. Because laser light consists of shorter wavelengths than microwaves, a tightly focused beam can be produced by a transmitting telescope, a unit a full order of magnitude smaller than the microwave antenna needed for an RF system with comparable performance. To the people integrating a communication system into a satellite, this means a significantly simpler job. And with weight and cargo space always at a premium in spacecraft, lasercom systems get even more points over their microwave competition.

For space-based laser communications to become viable, some tough challenges.in electrooptical technology must be met. Major issues include pointing accuracy, component lifetime, system simplicity and system costs.

“Pinpoint aiming accuracy” is no exaggeration for a system that must deliver a tightly focused laser beam to a receiver tens of thousands of kilometers away. Specifically, this pointing accuracy must be on the order of microradians, a level only achievable by a cooperative, closed-looped pointing and tracking technique. Thus, acquisition of the receiving satellite and establishment of closed-loop fine tracking are technologies that are critical to lasercom systems.

The lifetime of the components comprising the system is also crucial, since the lasercom system may have to operate unattended for five years or more. The extensive development of long-lived electro-optical components and the use of redundancy to eliminate single-point failure areas are just two of the ways planned to extend the life of lasercom systems. Advanced technology is also being used to reduce the size, weight and power burdens of lasercom systems to further increase their attractiveness in space. For example, if semiconductor lasers can be used instead of optically pumped lasers, such as neodymium:YAG, system burden will be reduced.

The cost of system development and deployment, while not directly a technology issue, is still of supreme importance to potential users of space laser communications systems. It will naturally be high for the first operational systems, but can be expected to decrease for subsequent systems and should eventually be comparable to microwave communication links.

THE BUILDING BLOCKS: LASERS

The major elements of a lasercom system include the laser, telescope, optical system, detector subassembly and signal processing electronics.

Various lasers have been considered for such systems, but most of them present problems. Flashlamp-pumped Nd:YAG lasers, for example, fall short because of the insufficient lifetime of existing flashlamps. Another candidate, the sun-pumped Nd:YAG laser, boasts long-lifetime and free pumping energy but will have to overcome several burdens: a large solar concentrating mirror, stringent gimbal requirements to keep the sun on the mirror, and the need to maintain the satellite within the view of the sun.

Another option is use of a semiconductor laser array using coherent or incoherent beam combining techniques. This, however, would require higher power and better beam quality than current laser diodes can deliver.

Actually, the solution to the laser problem may lie in a combination of lasers - the semi-conductor-laser-pumped Nd:YAG lasers such as the one now under development at McDonnell Douglas Astronautics. This approach promises high reliability, comparatively low weight and power requirements, and the potentially excellent beam quality of the Nd:YAG laser. A Nd:YAG laser pumped by an array of gallium-arsenide lasers would experience a "graceful" drop in performance over its lifetime as individual laser diodes failed but the rest of the array kept operating. In contrast, failure of the flashlamp in a flashlamp-pumped system would result in catastrophic failure.

A variety of equipment would be used in conjunction with a laser-diode-pumped Nd:YAG lasercom system. To ensure overlap of the laser diode emission wavelength and the wavelength of the Nd:YAG absorption peak, the temperature of the array would need to be maintained within a few degrees. Also, an intracavity element would be included to make possible frequency doubling, cavity dumping or modelocking. One possible configuration would have three arrays, each with a heat sink, arranged radially around the Nd:YAG laser rod, which also has a heat sink.

A modelocked laser produces a train of laser pulses about 0.2nsec in duration at a repetition rate between a few hundred million pulses per second and one billion pulses per second. Switching to a cavity-dumped laser may produce more powerful laser pulses of 25nsec duration at several thousand pulses per second. Since modulation schemes permit transmission of two to six bits per laser pulse, modelocking can be used for data rates on the order of gigabits per second, while cavity dumping is limited to megabits per second.

Engineers at The Aerospace Corporation have been pursuing the design of a diode-pumped Nd:YAG laser for communications, concentrating on several key areas. These include the wavefront quality of the output laser beam, output power improvement to the level needed for intersatellite communication and the wavelength stability of the diode array.

TELESCOPE AND OPTICAL ASSEMBLY

The optical assembly consists of a series of lenses and mirrors to conduct the beam between the laser and detector subassemblies and the telescope. With dozens of elements involved, each piece in the assembly must have an optical quality of 0.01 to 0.02 wave for the telescope to be able to generate a diffraction-limited beam. Also, beam steering mirror reflectivities should be better than 99 percent and transmission loss for any optical element should be less than one percent.

After passing through the optical assembly, a beam would be expanded and collimated for transmission by a Cassegrain telescope with a paraboloidal mirror and a smaller convex secondary mirror. This same telescope could collect and concentrate the incoming laser beam for reception by detectors. To produce diffraction-limited performance, it must yield an exit beam with a wavefront quality of better than 0.1 wave rms. At wavefront values substantially in excess of this value, excessive beam divergence with a reduction in the far-field pattern on-axis power occurs, and sidelobes may be generated. These factors may preclude successful transmission due to insufficient laser power at the receiver or difficulties in the closed-loop pointing and tracking.

Further elaboration on the optical assembly depends on the choice between a dual-wavelength and a single-wavelength system. To isolate the transmission and reception channels if both use the same wavelength, right-hand and left-hand circular polarizations can be used for the incoming and outgoing beams, respectively. Since the isolation between the two beams must be greater than 10^6, any mixing of polarizations (i.e., conversion of the left-hand to right-hand polarization) due to the multiple-layer dielectric coatings in the optical train must be avoided.

In anticipation of this problem, the Optical Systems Department at The Aerospace Corporation performed an analysis on the effects of contamination and layer thickness errors in multilayer dielectric stacks. Our results showed that a one-percent random error in layer thickness will create an approximately two-degree differential phase retardation between the s (perpendicular) and p (parallel) waves. Thus, dielectric coatings with the few-degree-or-less differential phase retardation required by common-wavelength lasercom systems must use state-of-art fabrication techniques.

CODING INFO FOR COMMUNICATIONS

In laser communications, pulse position modulation (PPM) is a popular signaling scheme for transmission of digital data. As with any digital link, performance evaluation of the system is based on the bit error probability. In some systems, error correction coding may be used to improve performance. As the encoding methods used with PPM become more complex, the corresponding error probability relations likewise become more difficult to evaluate.

In standard PPM, binary data is sent in blocks of $\log_2 M$ bits by transmitting a laser pulse in one of M time slots. The M slots constitute a modulation frame, and a data symbol is defined by the position of the signal pulse within the frame. It is assumed that the signal slot has average signal-plus-noise photon count ($K_s + K_n$), and all other slots produce an equivalent noise photon count of K_n. The probability that an incorrect signal slot produces a count K_n that exceeds the signalling slot count is the probability of an incorrect decision. A symbol error corresponds to deciding on an incorrect frame slot. Since each slot corresponds to a binary word of $\log_2 M$ bits, the probability of a bit error can be determined from the symbol error probability, which depends on K_s and K_n.

The Reed-Solomon block codes are convenient error-correcting codes for use on PPM links. These are nonbinary codes that use a 2^m member alphabet. When used on PPM links, the Reed-Solomon alphabet size and the number of slots in the PPM frame is equivalent to a Reed-Solomon code symbol. The code word length for a Reed-Solomon code is equal to one less than the alphabet size; that is, $n = 2^m - 1 = M-1$. Out of the n symbols in the code word, some number k will be information and the rest (n-k) will be coding overhead. The number of symbol errors that the code can correct is proportional to the code overhead and is given by $E=(n-k)/2$.

For coded PPM links using a Reed-Solomon code, the data is arranged in k symbol blocks and then encoded into n symbol code words. Each word is then transmitted as successive PPM frames.

The code can correct patterns of up to E symbol or frame errors (an incorrect decision as to where the signal pulse occurs in each PPM frame) within the n-frame code word. If hard decisions are made for each PPM frame, the code word error probability is only a function of the number of frame errors that are made. This is known as hard decision decoding.

In soft decision decoding of coded PPM, the entire n-frame word is processed before any decisions are made. The decoder integrates the energy over each allowable code symbol sequence and compares for maximum. The correct sequence has signal energy from each pulse slot in the path sequence. The most common errors will result from decisions between the correct sequence and those that differ from the correct sequence in the minimum number of symbols.

POINTING AND TRACKING

For pointing and tracking, a pyramid with reflective faces divides the received beam into four separate beams, all of which land on a quadrant avalanche photodiode detector. As is commonly done in quadrant detection, the outputs from the different quadrants are compared to generate an error signal from which pointing error can be determined. Accurate pointing and tracking can be maintained by driving the difference of the outputs from the different quadrants to a null–i.e., by fine tuning the laser pointing.

Beam pointing itself is accomplished with mirrors rotated by piezoelectric transducers or motor servomechanisms (torque motor beam steerers). The pointing error can be kept to several microradians with a laser beam divergence of approximately ten microradians. This corresponds to an error of 300 meters at a range of 80,000 kilometers for the position of the centroid of the Gaussian beam. Adding the output from the quadrant photodiodes yields the received communications signal. Thus, this subassembly can combine the functions of pointing and tracking with those of the receiver.

Lasercom subsystems should also be capable of autonomous reacquisition if the pointing lock-on is lost. They should be able to conduct totally autonomous acquisition of lasercom satellites in alternate constellations and also to reestablish contact after a major orbit maneuver of either the transmitting or receiving satellite. A computer simulation developed at The Aerospace Corporation has shown that the proposed acquisition pointing and tracking sequence meets satisfactory performance and sensitivity levels. However, some issues in autonomous reacquisition remain to be scrutinized.

THE SURVIVABILITY QUESTION

Given the harsh environment and remoteness of space, survivability is a critical issue for a lasercom system. The optical system must be sturdy enough to withstand the shock and vibration of a Space Shuttle launch. Once in orbit, thruster products and outgassing from lubricants and gaskets all can contaminate the optical system. This problem may be alleviated by using a sealed optical system and a gimballed telescope with a solar rejection window that also acts as a barrier against contaminants. In this case, contamination is limited to deposition on the outside window.

The long-term space radiation environment existing beyond the Van Allen belts must also be dealt with. Use of lenses made of cerium-doped glass or fused silica, shielding of critical components, and rad-hardened electronics all help to counter this threat. Also, the high off-axis rejection of the receiving telescope provides projection against aircraft and ground-based jamming threats. To maximize reliability, component redundancy may be engineered for all components except the structure and primary optical system.

The lasercom crosslinks soon to be realized in hardware are more than just an alternate method to communicate between satellites. Next-generation lasercom systems now at the developmental stage may provide an unprecedented capability for inherently secure, survivable, jam-proof space communication at gigabit-per-second or higher data rates, all of this in systems with reduced weight burden and power requirements. Alternative applications of this technology will include satellite-to-submerged-submarine communication and communication between two aircraft–for example, between a tanker and fighter plane being refueled.