ENGINEERING PLANETARY LASERS FOR INTERSTELLAR COMMUNICATION

N93-14010

Brent Sherwood[1] and Michael J. Mumma

Planetary Systems Branch
Laboratory for Extraterrestrial Physics
Greenbelt MD 20771

Bruce K. Donaldson

Department of Aerospace Engineering
University of Maryland
College Park MD 20742

Spacefaring skills evolved in the twenty-first century will enable missions of unprecedented complexity. One such elaborate project might be to develop tools for efficient interstellar data transfer. Informational links to other star systems would facilitate eventual human expansion beyond our solar system, as well as intercourse with potential extraterrestrial intelligence. This paper reports the major findings of a 600-page, 3-year, NASA-funded study examining in quantitative detail the requirements, some seemingly feasible methods, and implications of achieving reliable extrasolar communications.

INTRODUCTION

Current attention on advanced space projects focuses on exploring and settling available planetary bodies, particularly the Moon and Mars. If the next centuries unfold even remotely as contemporary vision projects, a time will come when humans will seek projects beyond the ones we know, to stretch their capacities in ways we can barely predict. Outside our solar system, the universe will always beckon. Completely new kinds of projects to explore it will continue to arise from humanity's growing skills and knowledge—projects that will consume and guide the creative energies of our descendants just as surely as they would mystify and frighten us. Glimpsing some of that future, even through the murky filter of our present skills and knowledge, helps us to know where we might be heading, and why. This paper attempts to outline a novel problem that may occupy our descendants, sketches the kind of space technology they might use to solve it, and pursues the ramifications of their having solved it.

EXTRASOLAR LIFE

For decades people tried to predict the prevalence of extrasolar intelligence using the Drake equation, a product of astronomical, biological, and social probabilities. Depending on assumptions made, the equation posits between 1 and 10^9 advanced civilizations in the Milky Way (*Hart*, 1980), rendering its result academic. Recently, even its underpinning—that life must evolve independently in different stellar systems—has been invalidated theoretically (*Papagiannis*, 1980).

Many schemes have been proposed for interstellar travel (*Dyson*, 1982), opening the possibility of stellar colonization. Using star systems as staging bases, a cultural lineage expanding outward at even the modest rate of one light year per century could sweep the entire galaxy in fewer than 10^7 years, a span only 0.1% of the galactic age (*Papagiannis*, 1980). Diversity of cultural intentions would preclude stopping such a settlement wave, once started (*Hart*, 1980), until it had occupied practically every useful star system in the galaxy (*Turner*, 1985). The absence of verifiable evidence of local colonization suggests that this sudden perfusion of life throughout our galaxy might not have occurred yet. Our own rapid technical progress then makes tenable the possibility that humans might take part in it or even initiate it.

Substantial galactic intercourse among an eventual network of human progeny cultures, or between human and alien cultures (if they exist) would require an ability to communicate across interstellar space at high data transfer rates. Laser beams are particularly suitable for point-to-point links (*Townes*, 1983) and can carry large amounts of data. Interstellar signals generated by infrared (IR) lasers in particular could be detected with useful signal-to-noise ratio (SNR) using contemporary techniques for quantum-limited heterodyne astronomy (*Glenar*, 1981). The work reported here (*Sherwood*, 1988) investigates some options for using IR lasers to establish communication links among neighborhood stars; its goal is to define quantitatively the magnitude and difficulty of the problem of achieving substantive interstellar communication.

THE LINK

A sphere of radius 25 pc (82 ly) centered on the sun encloses 773 approximately solar-type stars (luminosity class V, of spectral types F, G, or K) (*Seeger and Wolfe*, 1985), many more eligible communication targets than any given transmitter could service practically. Yet even at that distance, the far-field spot size required of a point-to-point beam is dominated by the target

dimension desired (Fig. 1), rather than by overall pointing error (given space telescope accuracy) or stellar proper motion uncertainty (known with the forthcoming Astrometric Telescope Facility). Specifying target spots closely concentric with stars, similar in size to the orbits of the terrestrial planets of our solar system, allows high far-field beam brightness. This in turn allows high intercepted signal power for a distant receiver. Infrared extinction by interstellar and circumstellar dust is not a general problem for the target sample.

We presume a pulse-code-modulated binary bit stream, and specify a bit error probability no greater than the 10^{-9} high standard for optical links (*Gowan*, 1984). We presume also a small heterodyne detector with contemporary performance, at the focus of a space-based, 1-km diameter, segmented reflective collector. This receiver is assumed to be stationed in the inner part of the target stellar system, within the central Airy spot of the signal's far-field diffraction pattern. To find and track the signal's Doppler excursions while maintaining high SNR, the receiver must have many reconfigurable, adjacent narrowband channels (extreme examples, depending on the laser transmitter and receiver used, range from 10^4 adjacent 300-kHz channels to ~10^9 adjacent 3-Hz channels). With these conditions and reasonable assumptions of system efficiencies, a variety of laser types might achieve information transfer to any of our 773 candidate neighbor stars at rates as high as roughly 100 kb/sec. A transfer rate of 100 Mb/sec, approachable if higher bit error probability is allowed, is required for real-time color video transmission.

Achieving such link quality requires a laser signal of high specific brightness, determined by the transmitter design. Configurable reflective transmitter optics can keep the IR signal bright by focusing it closely around the target stars. Subject to photon shot-noise constraints, link quality then becomes a function of the source laser's specific power (W/Hz), a measure of its spectral efficiency. Two extreme options for increasing specific power are either to make a high-power laser, or to operate a moderately
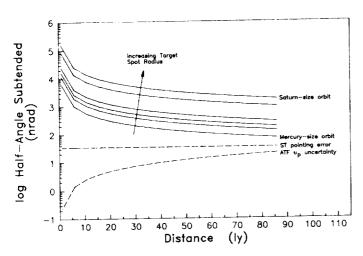
powerful laser with unusually narrow emission linewidth. Either approach might yield a laser signal detectable at great distances with sufficient SNR.

The first method (high power) fits schemes already published for many types of space-based lasers (*Williams and Conway*, 1982), and (as will become clear later) may indeed represent the least cumbersome approach to interstellar communication. A laser practical for this use might be several hundred meters long, be pumped either by nuclear energy, or direct or indirect sunlight (if stationed near Mercury's orbit), and put out about 50 MW. Although power levels orders of magnitude higher than this have been proposed as feasible, serious engineering problems remain unsolved for large space lasers. Notably, cooling the gain medium enough to sustain lasing, cooling the beam optics (passively, to avoid vibration and hence pointing disturbance), and fabricating large IR-transmissive cavity envelopes all represent substantial challenges. Once possible, however, high-power source lasers would have the advantage that many could be emplaced as dedicated transmission stations about any star, linking it effectively and continuously with as many neighboring star systems as desired.

The work reported here, however, investigates in great detail the second method (moderate power), which limits the spectral linewidth of laser emission (*Sherwood*, 1988). This approach would make use of an intriguing resource coincidentally available in our own solar system. Natural CO_2 laser gain has recently been observed (*Deming et al.*, 1983) and modeled (*Deming and Mumma*, 1983) in the mesospheres of Mars and Venus. Its discoverers have suggested that engineered planetary lasers could yield beams of high specific power, useful for deep-space communication (*Deming and Mumma*, 1983).

PLANETARY LASERS

The terrestrial planets of our solar system having atmospheres compositionally dominated by CO_2 (Mars and Venus) support natural stimulated emission in the 10.6 μm and 9.4 μm rovibrational bands of the molecule. Collisional excitation and direct solar pumping appear to maintain quantum population inversions in thin mesospheric shells over the daysides of both planets. Although the gain per unit length is small, planetary atmospheres are vast, so that the single pass gain along a tangential path through the subsolar point at the proper altitude of either planet is nominally about 7%, which is comparable to single pass gain through laboratory laser gain media (*Deming and Mumma*, 1983). Inducing laser oscillation to yield a usable output beam by configuring an optical resonator around such a planet then constitutes a novel problem in advanced space system design.

The available peak single-pass gain shrinks with a cosine dependence as the path's tangent point moves around the planetary sphere away from the subsolar point, and vanishes on the darkside (*Deming and Mumma*, 1983). Since the line of sight defined by any pair of orbiting satellites cannot be stationary with respect to the subsolar point, resulting gaps in system gain could be filled in by establishing multiple reflectors as a ring resonator around the planet. Continuous oscillation might then occur. The net gain would increase as more satellites were added, with a smoother first-order envelope for odd-sided polygonal resonators (Fig. 2). A pentagon provides both these benefits while still limiting both system size and low-altitude gravitational and drag perturbations on the resonator satellites. The continuously available effective single-circuit steady-state gain then amounts to at least 10% for either Mars or Venus.
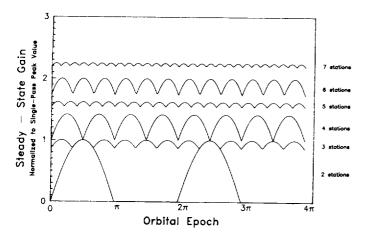

Fig. 1. The beam divergence required to cover distant target orbits exceeds by orders of magnitude the reference angular uncertainties of both pointing ability and star location.

Fig. 2. The single-circuit steady-state gain available from a lossless planetary laser resonator is better for odd-sided, higher-order polygon geometries.

However, Mars and Venus provide strikingly different environments for operating an orbital laser resonator. Mars's orbital eccentricity (0.0934) causes a 39% annual variation in insolation and hence in available laser gain. A sun-synchronous resonator orbit, enforced by Mars's oblateness to pass over the subsolar region at all times throughout the martian year, is the only orbit that does not compound the annual gain variation with further seasonal cycles. However, such an orbit also overflies the entire martian surface, the spectacular geography of which produces the bumpiest gravity field known among planets (*Balmino et al.,* 1982). The altitude variations alone experienced by satellites in a pentagonal resonator formation might be as large as 50 km over a timescale of only 20 min. Since the inversion layer through which the laser line of sight must pass is only about 10 km thick (*Deming and Mumma,* 1983), operating a planetary laser continuously at Mars would pose a serious dynamical problem.

By contrast, Venus is extremely spherical, smooth, and benign. With a slow rotation rate (its day exceeds its year) and large mass, it is the most spherical planet known. Fully 60% of its mapped surface lies within 500 m of its modal radius (*Pettengill et al.,* 1980) and because its topography is largely isostatically compensated (*Masursky et al.,* 1980), gravitational bumpiness is limited mainly to continental margins. Satellites at the pentagonal altitude for Venus would experience radial departures of less than 2.2 km and tangential departures of less than 700 m from their nominal Keplerian orbit, allowing them to sustain continuously a cavity beam as large as 5 km in diameter. Venus's obliquity is only 3°, so an essentially equatorial orbit plane always contains the subsolar point. And the planet's orbital eccentricity is only 0.0067, so the available gain varies by less than 3% annually. Finally, Venus space is much more likely to remain unpeopled—and uncontaminated—than Mars space. For all these reasons, Venus is the better site for positing planetary laser operation.

Extracting a useful output beam from a large orbiting planetary resonator would be facilitated if the cavity were not strictly a ring laser. The laser topology considered here is instead that of a more conventional linear oscillator wrapped around the planet so that its "ends" are adjacent, but separate, at one vertex of the pentagon. The tangent points for maximum mesospheric gain are

130 km above Venus, so the pentagonal resonator orbit altitude is 1589 km (Fig. 3). For lasing to occur, the coherence length of an intracavity electromagnetic field must exceed the double-pass cavity length, which in this case is 90,000 km, several orders of magnitude greater than any laser coherence length yet demonstrated. Since the inverse of the field's coherence time is its oscillation linewidth, achieving oscillation in a planetary-sized resonator would dictate extremely narrow spectral emission (less than 3.3 Hz for the venusian pentagon) (*Sherwood,* 1988).

While such extreme spectral purity would yield the high specific power needed for substantive interstellar communication, sustaining laser oscillation over planetary dimensions constitutes a technological challenge of unprecedented scale. The toughest technical problem involved (autonomous, simultaneous, precise, optomechanical control distributed and coordinated around a planet) would completely drive any planetary laser design. However, virtually all the component problems that this challenge combines must be solved anyway in the separate contexts of other large space projects already envisioned for the next century. Applying rigorous spacecraft systems synthesis to a set of emerging and demonstrated advanced technologies is the only means available to explore the ultimate feasibility of engineered planetary lasers.

A REFERENCE DESIGN

To pursue the details of engineered planetary lasers, and expose quantitatively the critical technology advances required to make one work, we now outline one possible type of venusian laser transmitter for interstellar signaling at rates up to 1 kb/sec. This reference system consists of 13 spacecraft distributed throughout Venus space; linked by dedicated laser telemetry, they act cooperatively as one device. The craft are divided functionally into three teams: six make up a split-ring pentagonal resonator with a 1-km diameter laser cavity; three others work as a switch to focus and steer the emergent beam, and two teams of two craft each alternate in impressing the beam with a program signal and aiming it toward target stars. All use a common subsystem vocabulary, all are assembled in Venus space, and all are serviced robotically.

Figure 4 shows the labeled resonator configuration. The optical surfaces defining the cavity must "ride" the beam in phase at all times, with drift rates less than 2 μm/sec, if the laser is to oscillate coherently. The cavity path length cannot change except by multiples of the lasing wavelength (called cavity mode hopping). To ensure this, each reflector must be positionable with 60 nm relative accuracy. The reference planes describing the ideal positions and angles of all six cavity reflectors change continuously, as especially thermal and gravitational perturbations vary with orbital anomaly. The immense challenge of operating the planetary laser is, at core, one of updating those reference planes and matching them with real hardware at all times. All spacecraft systems in the fleet resonator exist only to support that function.

Huygens' principle allows fragmenting the problem of kilometer-scale diffraction-limited optical apertures, thereby shifting most of the technical difficulty from materials to control. The reflector surfaces of the 95,000-MT Basic Vertex Stations 2, 3, 4, and 5 (Fig. 5) are elliptical, segmented arrays of 230,000 3-m hexagonal, honeycombed beryllium (*Paquin et al.,* 1984) gold-faced mirrors. Each is isolated from and positioned relative to the spacecraft bus with a resolution of nanometers by three electromagnetic translators (EMTs) (*Sielman and Balsarowicz,* 1984), allowing three-DOF mirror pointing control. The bus
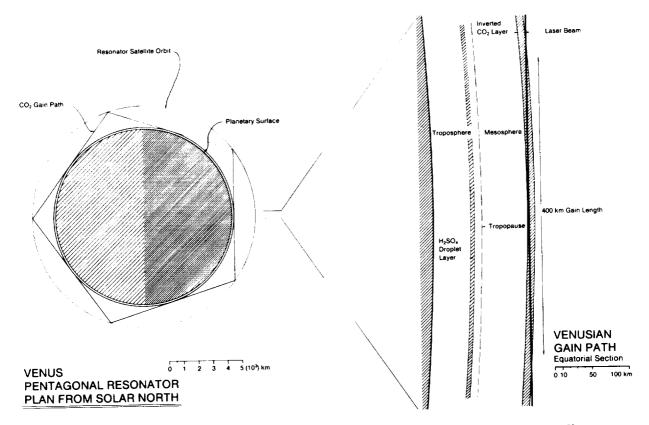
Fig. 3. The pentagonal-resonator orbit altitude and active gain length are determined by inversion conditions at Venus.
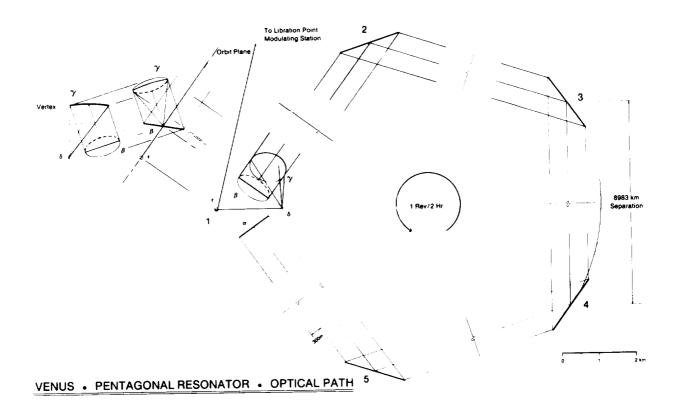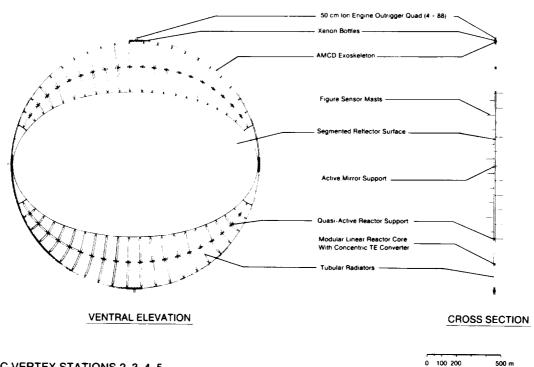

VENUS • PENTAGONAL RESONATOR • OPTICAL PATH

Fig. 4. The split-ring resonator configuration maintains the oscillating field and couples out a controllable laser beam.

VENTRAL ELEVATION

CROSS SECTION

BASIC VERTEX STATIONS 2, 3, 4, 5

0   100 200   500 m

Fig. 5. The basic vertex stations are large, actively flat mirror satellites.

SECTION/ELEVATION OF VERTEX STATION SYSTEMS
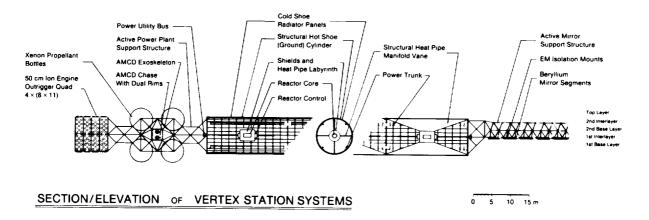
0   5   10   15 m

Fig. 6. The spacecraft systems are selected for energy-efficient, long-life, vibrationless, redundant performance.

structure itself (Fig. 6) is built up of active truss members, C/Mg composite (*Remondiere et al.,* 1985) tubes whose extension, bending, and vibration behavior are monitored with nanometer resolution by embedded fiberoptic strain and temperature sensors (*DePaula et al.,* 1987), and actively controlled with submicrometer resolution by fast piezoelectric (PZ) surface films (*Studer et al.,* 1986) and slow thermal actuators (*Haftka and Adelman,* 1985). This backup structure provides a responsively stiff reaction ground for mirror segment actuation.

An overlapping hierarchy of short-range optical sensors provides intersegment alignment data across the expanse of each reflector surface, and differential interferometry (*Hewitt,* 1984) provides

phase data about the stations' relative positions. Dedicated laser-telemetry links the resonator craft, providing each with state data on the others at the 6-Hz interactive rate constrained by lightspeed delay around the pentagonal ring. Coordinating all these data to generate the actuator commands necessary for sustaining laser oscillation poses the ultimate problem of the fleet system, on which hinges the feasibility of operating a planetary laser (*Sherwood,* 1988).

No contemporary, artificial computational technology can come close to the required performance. The fleet controller must process on the order of 10^9 widely distributed signals simultaneously within milliseconds, despite component failures, a changing

perturbation environment, and the inescapable 6-Hz verification limit. Hence it must compensate predictively, based on an adaptive capacity to learn in detail the repetitive disturbances of its orbit and its own past performance, refining its commands over time (*Sherwood,* 1988).

An ancient precedent for processing complexity far beyond even these needs is vertebrate neurophysiology (*Kent,* 1981). Artificial intelligence (AI) progress in modeling and duplicating neuronal interaction, albeit nascent, is sufficiently successful and accelerating (*NASA,* 1988) to warrant positing its eventual application to problems of this type. The fleet controller can then be projected to be a massively parallel, adaptive, optical (*Fisher,* 1983) neural net (*NASA,* 1986) distributed throughout all the fleet systems to monitor and govern precisely their mechanical behavior.

The housekeeping systems (Fig. 6) are selected for their smooth, vibration-free operation as well as economical logistics. Overall spacecraft attitude is trimmed by annular momentum control devices (AMCDs), which are dual, magnetically suspended, thin Kevlar rims circumscribing the entire spacecraft. Counter-rotating at high speed, they effect three-axis control maneuvers by slight differential tipping and speed changes (*Anderson and Groom,* 1975). The debris-shielded AMCD chases are maintained circular by an active exoskeleton truss, their control hardware positioned within micrometer tolerances by PZ mountings. Overall station-keeping propulsion and momentum desaturation occur via ganged xenon-ion engines. Each craft is tanked with a replaceable 10-year propellant supply (about 17,000 MT for the entire fleet), based on disturbance forces including

solar pressure and gravity, and exospheric drag. Modular thermoelectric (TE) fission power plants (*El-Genk and Hoover,* 1985) supply about 400 MW to run the control, propulsive, structural, and nervous systems of each station.

The two cavity "end" reflectors, 1α and 1β, are much the same as Stations 2, 3, 4, and 5, but somewhat smaller due to their unique incidence angles (Fig. 4). Not being principal-axis planet oriented, and therefore subject to large, constant gravity-gradient torques, these two reflector craft are braced against each other structurally. The gold mirror surfaces of 1β are etched as a blazed diffraction grating with 11.68-μm ruling, and 1β itself is oriented in the Littrow configuration. This simultaneously limits cavity oscillation to the lowest-threshold (P12) line of CO_2 (wavelength 10.513 μm), and diffracts 2% (180 kW) of the circulating s-plane polarized laser light out of the orbit plane to reflector 1γ, which focuses the output beam back up into the orbit plane onto 1δ, which, in turn, undoes most of the beam's convergence and relays it up to 1ϵ tethered above (Fig. 7). Then 1ϵ uses two pivoting mirrors to send the 10-m diameter intermediate beam alternately to one of the twin final stations. Concentrating the intermediate beam (at 2300 W/m² almost as strong as venusian sunlight) allows 1δ, 1ϵ, and all subsequent craft in the fleet to mass less than a thousandth as much as the vertex stations, and to consume about a thousandth as much power.

The final stations are fixed in Venus space at the planet's collinear Lagrange libration points, L1 and L2. From the near-equatorial resonator orbit, 1ϵ can always see one or the other of these stations, allowing an essentially continuous transmission duty cycle to any star. The reference transducers (Fig. 8) monitor
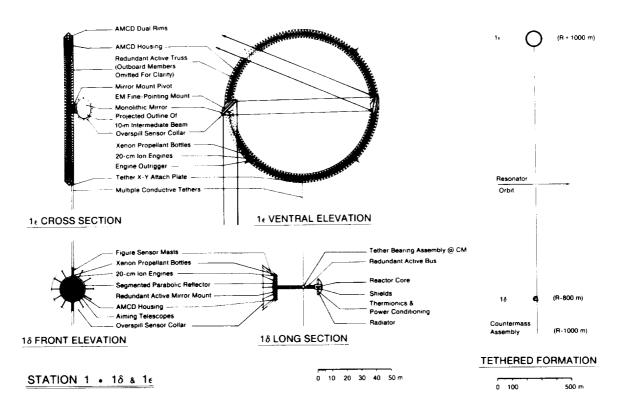

Fig. 7. The switching satellites control focus and direction as the laser beam leaves the resonator orbit.
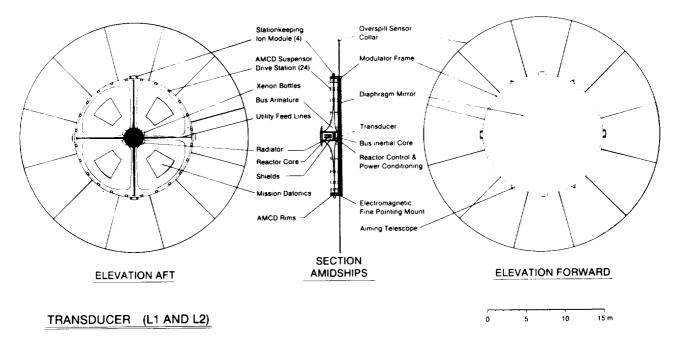
Fig. 8. Three-axis-stabilized transducer satellites modulate and target the interstellar laser beam.

the 21% of the diffracted intermediate beams they receive from Venus, apply corrective pointing and focusing biases, and modulate it electromechanically with deformable membrane mirrors. More advanced transducers using microwaveguide modulation (*Liu*, 1986) might accommodate mission signals at rates much faster than 100 kb/sec, up to the 100 Gb/sec contemporary signal processing limit. Aiming at targets in the celestial hemisphere behind either transducer requires a final reflection, provided by its associated ring (Fig. 9).

The reference planetary laser just outlined represents the first attempt to bring current understanding of imminent technologies to bear in a rigorous, integrated way on the advanced problem of substantive interstellar communication. We intend the outline not as a polished "solution," but rather as the seed of a problem worth solving. Even if the technical difficulties become tractable, emplacing and operating any system for such transmission would prove a formidable undertaking. Application of current costing methods to the project, though, is a misleading exercise. Rather, asking for what kind of society the project would consume only 1% of the gross economic product, reveals its proper context. That would be a mature interplanetary culture already competent at sophisticated spacecraft control, interorbital transport, resource mining from lodes distributed throughout the inner solar system, and microgravity and vacuum industries. Our own society will be heading toward those capabilities in the next century.

THE LIMIT

Augmenting the planetary laser reference design (increasing the cavity beam diameter to 5 km, collecting more of the diffracted beam at the Lagrange point stations, and bringing receiver

degradation closer to theoretical limits) would make its spectrally narrow signal even more useful by increasing received power. Other advances [in high-power nonplanetary space lasers, optical processing, and modulation techniques (*Manneberg et al.*, 1987)] might improve transfer rates for communication systems well beyond the 10-Gb/sec limit of current data processing speeds. The result could be an interstellar link capable, with practically arbitrary bit reliability, of supporting data transfer rates as high as the IR carrier frequency could ever allow (*Sherwood*, 1988), on the order of the Tb/sec (Fig. 10).

If large lasers can establish substantive communication channels among neighboring stars, cultures operating them would have available an unprecedented bridge across the astronomical distances of interstellar space. Should our own society ever achieve the necessary spacefaring skills and economy, we would by that time probably have other technologies that we are already developing, such as molecular engineering, well in hand. To identify what kind of future such tools might forge, we outline the possibly inevitable consequences of combining these advanced capabilities. Having seen fire, could we predict rocket engines? Having split the atom, did we predict nuclear arms negotiations? Where, then, might interstellar communication lasers lead?

If interstellar information transfer at rates as high as the 10^{20} b/yr just discussed is possible, complex instructions could be sent reliably to distant receivers configured upon arrival by small, human-launched, photonically propelled (*Forward*, 1984) interstellar probes. If nanotechnological assembly, computation, recording, and biostasis (*Drexler*, 1986) become available, such probes could then process local material resources according to those transmitted instructions. A civilization possessing these tools might use them to transmit complex datasets directing remote
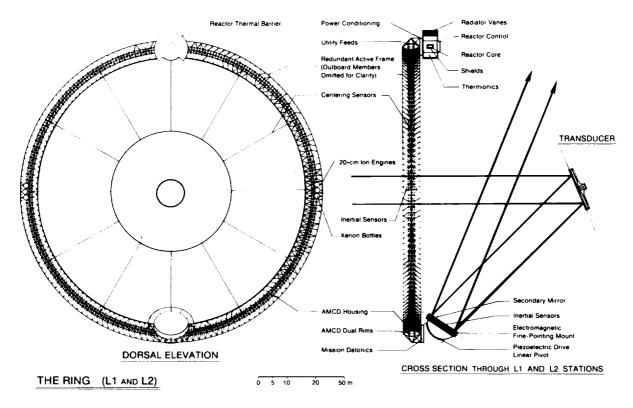
Fig. 9. A final reflection allows targeting the entire celestial sphere.

nanoassembly of the unique molecular structure of their bodies and brains (*Sherwood*, 1988). This ability would amount to interstellar transportation through cloning. Adding efficient deep-space communication by high-power lasers to nanotechnology could then lead to a future of direct interstellar travel, thus reducing greatly the time required for human progeny to colonize the galaxy.
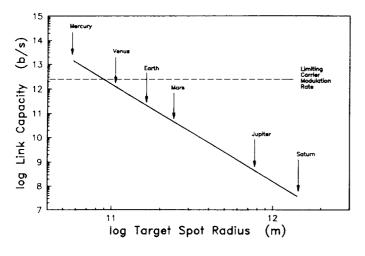
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Fig. 10. Given advanced modulation techniques, nonplanetary high-power lasers could allow extremely high-rate communication between stellar targets.

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