Chapter 5
Microspacecraft

Microspacecraft would be satellites or deep-space probes weighing no more than about 10 kilograms (22 pounds).[1] Tens or hundreds could be usedto measure magnetism, gravity, or solar wind at widely separated points simultaneously. A swarm of different microspacecraft could obtain detailed radio images of galaxies, while others could be used for communications, gamma-ray astronomy, or planetary photoreconnaissance.

They would not *require* development of new launch systems; they could be launched like buckshot on existing small launch vehicles. However, if there were a demand for launching thousands per year, it might be cheaper to launch them on laser-powered rockets (see figure 5-1), if these prove feasible.

Extremely rugged microspacecraft, constructed like the Lightweight Exe-Atmospheric Projectile (LEAP) being developed for the Strategic Defense Initiative,[2] could be launched to orbit by an electromagnetic launcher (railgun or coilgun) or a ram cannon. An electromagnetic launcher in orbit could launch them toward outer planets at muzzle velocities that would allow them to reach their destinations and return data to Earth within a few years. This might allow a graduate student to design a mission and then receive mission data in time to use it in a Ph.D. dissertation.

SPACECRAFT CONCEPTS

Several concepts for microspacecraft have been proposed. One example is the Mars Observer Camera (MOC) microspacecraft proposed by the Jet Propulsion Laboratory at the California Institute of Technology (CalTech). It would be a generic imaging microspacecraft; dozens could be launched on each of several missions-to the Moon, the planets, their moons, comets, and asteroids. A MOC microspacecraft would be shaped like an oversized hockey puck, about 15 centimeters (cm) in diameter and 4 cm thick (see figure 5-2). It would weigh about 800 grams (g). A version could be designed to withstand the accelerations to which electromagnetic launch would subject them.

Placed in different orbits or trajectories, they could trade off field of view for resolution, or vice versa. For example, one MOC microspacecraft in a polar orbit about Mars could serve as a Martian weather satellite, providing two-color images with a resolution of 5 to 10 kilometers (km)-sufficient to resolve Martian clouds. A similar MOC microspacecraft in a lower orbit could serve as a mapper, providing two-color images of a smaller field of view with better resolution—100 meters (m). In time it could map the entire planet. A similar MOC microspacecraft in an even lower orbit about the Moon could provide a two-color global map of the Moon with 10 m resolution. Existing global maps of the Moon currently show no features smaller than several hundred meters.

LAUNCH SYSTEM OPTIONS

New, specialized launch systems need not be developed to launch microspacecraft, because they could be launched on existing launch vehicles—by the dozens, if appropriate. However, some proposed unconventional launch systems might prove to be better or cheaper than conventional launch vehicles for launching microspacecraft.

One example of such a system is a laser-powered rocket that would use a laser beam, instead of combustion, to heat the propellant, which could be inert (i.e., nonreactive). If feasibility is proven, a 10-megawatt (MW) laser may be able to launch a l-kg payload of one or more microspacecraft; a gigawatt laser might launch a l-tonne (t) payload consisting of several microspacecraft or a larger spacecraft.

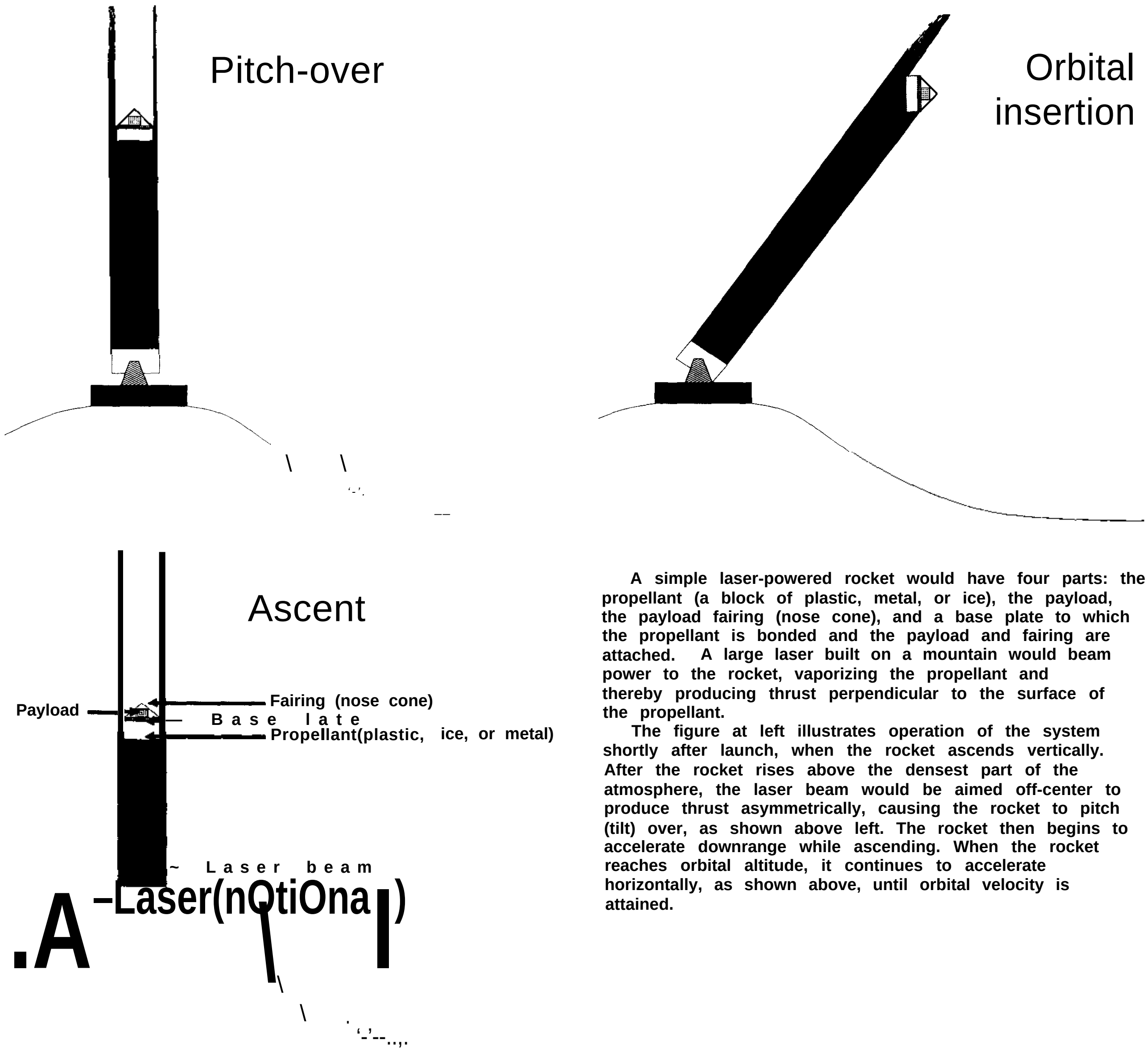
The smallness of microspacecraft has another potential advantage: some microspacecraft could be built to withstand high accelerations comparable to those endured by cannon-launched guided projectiles such as Copperhead.[3] Such "g-hardened"

[1] See Ross M. Jones, "Coffee-can-sized spacecraft," *Aerospace America,* October 1988, pp. 36-38, and "Think small-in large numbers, " *Aerospace America,*October 1989, pp. 14-17.

[2] See U.S. Congress, Office of Technology Assessment, *SDI: Technology, Survivability, and Software,* OTA-ISC-353 (Washington, DC: U.S. Government Printing Office, May 1988), pp. 120-121.

[3] The U.S. Army's M712 Copperhead cannon-launched guided projectile is an artillery shell fired from a 155mm howitzer. It has a sensor and electronics for detecting a spot of laser light on a target illuminated by a low-power, pulse-coded, target-designating laser aimed by a soldier or pilot. When Copperhead detects such a spot, it steers toward it using fins deployed after launch. Copperhead rounds cost about $35,000 each.

Figure 5-1—Laser-Powered Rockets



A simple laser-powered rocket would have four parts: the propellant (a block of plastic, metal, or ice), the payload, the payload fairing (nose cone), and a base plate to which the propellant is bonded and the payload and fairing are attached. A large laser built on a mountain would beam power to the rocket, vaporizing the propellant and thereby producing thrust perpendicular to the surface of the propellant.

The figure at left illustrates operation of the system shortly after launch, when the rocket ascends vertically. After the rocket rises above the densest part of the atmosphere, the laser beam would be aimed off-center to produce thrust asymmetrically, causing the rocket to pitch (tilt) over, as shown above left. The rocket then begins to accelerate downrange while ascending. When the rocket reaches orbital altitude, it continues to accelerate horizontally, as shown above, until orbital velocity is attained.

SOURCE: Office of Technology Assessment, 1989.

microspacecraft could be launched by “direct launch” systems[4] such as railguns,[5] coilguns,[6] and ram cannons.[7] In the near term, microspacecraft could be launched by chemical rockets, such as

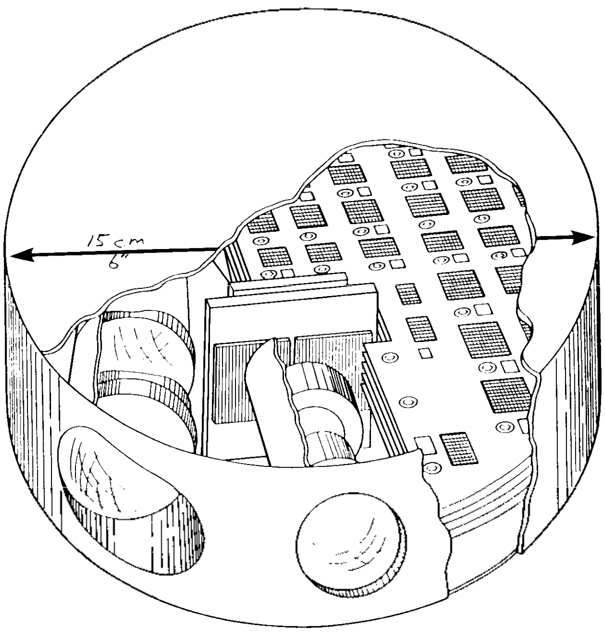
[4]So called because the projectiles, which would enclose and protect the microspacecraft (or a mission payload), would require no further propulsion after they leave the muzzle of the launch system, if launched into solar orbit or an interplanetary trajectory. A projectile would require a small rocket motor or some other kind of motor to enter Earth orbit.

[5]Miles R. Palmer and Ali E. Dabiri, “Electromagnetic Space Launch: A Re-Evaluation in Light of Current Technology and Launch Needs and Feasibility of a Near-Term Demonstration,” *IEEE Transactions on Magnetics*, vol. MAG-25, No. 1, January 1989, p. 393ff.

[6]Henry Kolm and Peter Mongeau, “Basic Principles of Coaxial Launch Technology,’ *IEEE* Transactions *on Magnetics*, vol. MAG-20, No. 2, March 1984, pp. 227-230.

[7]A.P. Bruckner and A. Hertzberg, “A Ram Accelerator System fo, Direct Launch of Space Cargo,” Paper No. IAF-87-211, presented at the 38th Congress of the International Astronautical Federation, Brighton, England, Oct. 10-17, 1987.

Figure 5-2-Mars Observer Camera microspacecraft Design Cutaway View-Actual Size



SOURCE: Jet Propulsion Laboratory, 1988

Scout and Pegasus, that are designed to launch payloads of a few hundred kilograms for a fraction of the cost of launching them on larger launch vehicles.

In the remainder of this section we focus on unconventional launch technologies. A surprisingly large number of them have been proposed; one recent review[8] lists 60 propulsion technologies—in addition to conventional chemical rocket technology—that are potentially applicable to space transportation. About half are applicable to Earth-to-orbit transportation; most are applicable to in-space transportation (e.g., orbital transfer or escape), which demands less thrust and power than does Earth-to-orbit transportation. For brevity, we discuss only two unconventional launch technologies here: railguns and two-pulse laser-supported-detonation (LSD) thrusters, which are the simplest of several proposed laser-powered rockets. We discuss only their application to Earth-to-orbit transportation here, although both are also applicable to in-space transportation.[9] In fact, orbital transferor reboost of low-altitude satellites could be done with much smaller lasers than would be required for launching projectiles from Earth to orbit.[10]

Direct launch systems would subject payloads to high accelerations. For a specified muzzle velocity, the barrel length of any type of direct-launch system must grow as the reciprocal of acceleration. To achieve a muzzle velocity of 8 kilometers per second with an acceleration of 1,000 gs,[11] a direct-launch system must have a barrel more than 3 km long. It would be impractical for a launcher to be much longer, or to subject a payload to correspondingly lower acceleration.

To launch a projectile vertically at an acceleration of 1,000 gs, the projectile must be subjected to a force 1,001 times its weight.[12] Hence exotic design, fabrication, and testing processes are required—especially for electronic and optical components—and there are constraints on the shape of the projectile, and, in practice, limits on its size. Proposed projectiles have weights ranging from a few kilograms to a tonne. They could carry payloads such as fuel, food, water, structural components for space assembly, and specially designed electronic and optical systems such as those used in the Army's Copperhead cannon-launched guided projectile and SADARM cannon-launched sensor-fuzed weapon, and the Lightweight Exe-Atmospheric Projectile being developed for the SDI.

[8] Dani Eder, "Technological Progress and Space Development," draft, Apr. 30, 1989.

[9] See, e.g., Ross M. Jones, ''Electromagnetically Launched Micro Spacecraft for Space Science Missions,' AIAApaper 88-0068, Jan. 11, 1988, and Arthur Kantrowitz, ''Laser Propulsion to Earth Orbit: Has Its Time Come?' J.T. Kare (cd.), *Proceedings SDIO/DARPA Workshop on Laser Propulsion*, CONF-860778 (Livermore, CA: Lawrence Livermore National Laboratory, July 7-18, 1986), vol. 2, pp. 1-12.

[10] Kantrowitz, op. cit., foomote 9, and P.K. Chapman, ''Strategic Defense Applications of Ground-Based Laser Propulsion, ' J.T. Kare (cd.), op. cit., footnote 9.

[11] The g (not to be confused with the gram, which is also abbreviated as ''g") is a unit of acceleration. At an acceleration of 1 g, an object's velocity increases by 9.8 m (32 ft) per second per second.

[12] If a projectile near the ground were dropped, i.e., subjected to no force, it would accelerate downward; its downward velocity would increase by 9.8 m per second each second. If sitting on the ground, it would be subjected to a force equal to its weight; this keeps it from falling into the ground-it accelerates at zero gs. If subjected to a force twice its weight, it would accelerate upward at 9.8 m per second per second, If subjected to a force thrice its weight, it would accelerate upward at 19.6 m per second per second, and so on.

In a previous report, OTA described two proposed direct launch systems: ram cannons and coilguns.[13] Coilguns could have important advantages over railguns, which are simpler and more familiar electromagnetic launchers (EMLs). For example, coilguns can be designed so that the projectile does not contact the barrel, avoiding barrel erosion, and they can be scaled to launch large masses efficiently at high velocities. Until recently, railguns were expected to be very inefficient at launching multi-kilogram projectiles at the muzzle velocities (more than eight kilometers per second) required to reach orbit with minimal assistance from rockets. Low efficiency would cause barrel heating and melting, as well as a high electric bill. However, in recent tests, railguns demonstrated unexpectedly high efficiencies in accelerating small projectiles to muzzle velocities of 3 to 4 km per second,[14] raising hopes that they might be able to accelerate half-tonne projectiles to more than 8 km per second.

Another cause for increased interest in railguns for direct launch is the realization that ordinary automobile batteries could be used for energy storage and would cost much less than alternatives previously considered. Automobile batteries could also power coilguns.

The Air Force recently decided to demonstrate suborbital launching of a microspacecraft using a railgun at Eglin Air Force Base, Florida, after augmenting its battery power system and adding a barrel with a 30-cm bore, similar to one used recently at Maxwell Laboratories. According to one estimate, the upgraded gun could launch 5 to 10 kg at 4 km per second three years from program start for only about $10 million. A l-kg projectile launched at 3 km per second with a l-kg sabot is expected to reach an altitude of 200 km if the projectile's nosetip is allowed to ablate, or 400 km if the nosetip is cooled by transpiration. *S

Proponents predict that a prototype operational EML capable of launching 500-kg projectiles each carrying about 250 kg of payload could be developed in about six more years for an additional $900 million to $6 billion, including $50 million to $5 billion for development of vehicles and tracking technology.[16 17]

If produced and launched at a rate of 10,000 per year, projectiles (less payloads) would cost as little as $1,000 per kg according to one estimate, but over 60 times this, according to another estimate. An EML projectile would require (besides its mission payload) guidance, navigation, and control systems, as well as a rocket kick motor to inject it into Earth orbit.[18] Just as allowing a payload of specified function to be larger allows it to be cheaper, miniaturizing it makes it more costly, and g-gardening it would make it still more costly. On the other hand, if a mission required many projectiles, high-rate production and learning effects could reduce unit costs. Other launch costs might be as low as $50 per kg at this rate.

If batteries are used, the limit would be about 10,000 launches (2,500 t) per year.[19] Because of the brief launch windows for rendezvous, very little of this tonnage could go to a space station,[20] but most or all could be used for other applications, e.g., distributed low-altitude networks of tiny satellites for communications, space surveillance, ballistic-missile defense, or space defense.

If the payload were reduced and the projectiles' chemical rockets enlarged, the projectile would have more cross-range capability; the launch windows for rendezvous with a space station would be longer, and more payload could be delivered to a space station per year. However, the launch cost per pound would increase. Chemical rockets could also be used to reduce the muzzle velocity required, so that a

13U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide,* OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988), p. 50.

14Miles R. Palmer, "Electromagnetic Space Launch, ' SA88091 (McLean, VA: Science Applications International Corp., May 6, 1988).

15Ibid.

16Ibid.

17Miles R. Palmer, personal communication, Oct. 12, 1989.

18A space probe bound for solar orbit or a fly-by of another planet would not require this.

19A greater launch rate could be achieved at greater cost if batteries are not used.

20Palmer and Dabiri, op. cit., footnote 5.

smaller[21] or more conventiona1[22] direct-launch system could be used.

Laser propulsion would have important advantages over direct launch. Acceleration would be much lower—about 6 or 7 gs on typical trajectories to low orbit—so payloads would not have to be designed to withstand gun-like stresses. Moreover, no expensive device to store and quickly discharge gigajoules of energy would be required, as it would be for a railgun or coilgun, because power would be beamed to a rocket continuously during ascent. Perhaps the most important advantage of laser propulsion is that a simple laser-powered rocket, unlike an EML projectile, would not require guidance, navigation, and control systems, or a separate kick motor for injection into orbit.

But laser propulsion would require a powerful, expensive laser and a large, expensive adaptive mirror. For efficient utilization and low average cost per launch, both must operate reliably without maintenance for longer periods than do existing lasers. And laser launch operations would be halted by overcast that would not impede direct launch. Moreover, laser propulsion technology is less developed than EML technology and is predicated on unproven theories of thermal blooming suppression and thruster plasmadynamics. Validation of these theories may require construction of a full-scale launch system.

An SDIO official has estimated that a 20-MW carbon-dioxide laser with a 10m-diameter beam director telescope could launch rockets carrying 20 kg of payload for an incremental cost of about $120 per lb, assuming the laser efficiency is 15 percent, the rocket efficiency is 40 percent, electricity can be generated for four cents per kilowatt-hour, and the structure and propellant each cost about as much as the electricity. According to the SDIO, the 2m-diameter rocket structure would weigh only a few kg and would require only about 120 to 150 kg of inert propellant such as ice or polyformaldehyde plastic; launching would require 30 to 40 megawatt-hours (MW-h) of electric power.[23]

If the system could operate continuously without downtime for maintenance or overcast, the launch rate could be almost 60,000 per year. In practice, occasional overcast would make full utilization unachievable, and approaching it would probably require at least two lasers and mirrors, so that one pair could operate while the other is being serviced. Even this would not assure operation most of the time, unless the duty cycle of the lasers (i.e., the fraction of time they are lasing) is much greater than the duty cycles demonstrated by industrial and other high-power lasers (see box 5-A). However, if a launch rate of 100 per day could be maintained, over 1,600,000 pounds of payload could be launched into orbit each year. This would be almost twice the estimated combined capability of current U.S. space launch systems,[24] almost three times the annual tonnage launched in 1984 and 1985, and about four times the annual tonnage launched from 1980 to 1985.[25]

The SDIO postulates that, in practice, 100 payloads could be launched per day, on the average, and the average cost could be as low as about $200 per pound, if capital cost (table 5-1) were depreciated over 5 years and if annual operating cost (excluding rocket cost) were comparable to the annualized capital cost of $90 million. The SDIO estimates that launching only one or two payloads a day (500 per year) would be sufficient to reduce average cost to about $4,500 per pound and make laser-powered rockets competitive with conventional rockets for small payloads. Some users might be willing to pay a premium for the speed with which a laser-powered rocket could be prepared to launch a payload.

The SDIO estimates that a first launch to orbit could be attempted about 5 or 6 years after program start and expects to demonstrate a rocket efficiency of 20 percent or more in experiments now being planned. However, the highest efficiency demon-

21 Palmer and Dabiri, op. cit., footnote 5, and Henry Kolm and Peter Mongeau, "An Alternative Launching Medium," *IEEE Spectrum, vol. 19, No.* 4, April 1982, pp. 30-36.

22 Large cannons have been ~@ to launch suborbital projectiles and sounding rockets to altitudes of 400,000 feet; see C.H. Murphy and G.V. Bull, "A Review of Project HARP," *Annals of the New York Academy of Science,* vol. 140, No. 1, 1966, pp. 337-357, and R.G.V. Bull and Charles Murphy, *Paris Cannonen—The Paris Guns and Project HARP* (Springer-Verlag, November 1988).

23 Jordin T. Kare, "Pulsed Laser Propulsion for Low Cost, High Volume Launch to Orbit," preprint UCRL-101139, Lawrence Livermore National Laboratory, Livermore, CA, June 2, 1989. A different launch simulation program (Kantrowitz, op. cit., footnote 9.) predicts each launch would require about nine minutes (hence about 20 MW-h of electric power) and about 200 kg of propellant.

24 OTA, *Launch Options for the Future: A Buyer's Guide,* op. cit., footnote 13, p. 20.

25 Ibid., p. 5.

Box 5-A—Lasers for Rocket Propulsion: The State of the Art

A laser-powered rocket would use a laser beam, instead of combustion, to heat the propellant, which could be inert (i.e., noncombustible). The beam could come from a ground-based laser; the rocket could be extremely simple and weigh only 10 times its payload. For comparison, the Scout launch vehicle weighs 1,300 times its payload.

Studies of Earth-to-orbit laser propulsion postulate the use of infrared lasers, which could be carbon-dioxide or deuterium-fluoride electric-discharge lasers or free-electron lasers. The most mature of these is the carbon-dioxide electric-discharge laser, but free-electron lasers are more efficient. If a carbon-dioxide laser or a free-electron laser operating at the same wavelength (0.01 mm) were used, the economical laser power would be about 1 megawatt (MW: 1 million watts) per kilogram (kg) of payload, if the laser-powered rockets can achieve the 40-percent energy-conversion efficiency once predicted by laser-propulsion proponents. To date, only 10-percent efficiency has been achieved. Laser-propulsion experts now predict that at least 20-percent efficiency can been achieved. At this efficiency, a laser power of about 25 MW might be required to launch a 20-kg payload. If, pessimistically, no more than 10-percent efficiency is achieved, about 50 MW might be required to launch a 20-kg payload.

It appears to be feasible to build such a laser; the U.S. has built a gigawatt (billion-watt) free-electron maser and electric-discharge lasers of much greater peak power, but none that could produce even 10 MW average power for ten minutes, the boost duration required to reach low orbit. Almost a decade ago, the Antares carbon-dioxide electric-discharge laser at the Los Alamos National Laboratory produced brief pulses with a peak power of 40 terawatts (40 trillion watts). But a very different design, similar to that of industrial lasers used for welding, would be required for prolonged operation at high average power. Free-electron lasers have, to date, produced less peak power. A free-electron laser developed by Los Alamos and Boeing has produced pulses of ten megawatts peak power, but only six kilowatts average power, at a wavelength of 0.01 mm. In early experiments, the partially completed Paladin free-electron laser at the Lawrence Livermore National Laboratory amplified five-megawatt pulses from a carbon-dioxide laser 500-fold, presumably producing pulses of about 2.5 gigawatts peak power. The carbon-dioxide laser power is being increased to a gigawatt, and the free-electron laser has now been extended. If its electron accelerator operates at the average power for which it was designed (at least 25 megawatts), and if 40 percent of the electron-beam power is converted to laser beam power (comparable to the efficiency demonstrated by a similar free-electron laser at a wavelength of 8.8 mm), the Paladin free-electron laser would produce a laser beam of at least 10 megawatts average power.

Neither carbon-dioxide lasers nor free-electron lasers have demonstrated the duty cycle (the fraction of time a device operates) that would be required for an operational launch system. The duty cycle of a free-electron laser designed for a high duty cycle would be limited primarily by the lifetime of the cathode used by the electron accelerator. Loosely speaking, the cathode is like the filament of a light bulb, and more closely resembles the cathode of a cathode-ray tube such as a TV picture tube. Several cathodes designed for long life are being tested. Alternatively, an electron storage ring (an arrangement of magnets) could be used to recirculate the electron beam, as was done in the first free-electron laser and others.

Focusing a multimegawatt laser beam on a small rocket hundreds of kilometers away is another serious technological problem; in particular, control of beam-degrading nonlinear optical effects, such as thermal blooming, has not yet been demonstrated at any average power and beam diameter of interest. Some research sponsored by the Strategic Defense Initiative Organization (SDIO) is aimed at demonstrating high-power beam control for ballistic missile defense; the beam control required for propulsion would be more difficult in some respects.

Nevertheless, participants at a 1986 workshop on laser propulsion sponsored by SDIO and the Defense Advanced Research Projects Agency expressed optimism that a free-electron laser and beam director then planned for other purposes "should be capable of launching test payloads to low [Earth] orbit in the early 1990s." SDIO subsequently established a laser propulsion program and considered using a free-electron laser and a beam director to be developed for the SDI Free-Electron Laser Technology Integration Experiment (FEL TIE) to experiment with laser propulsion, even though the FEL TIE laser would be designed to operate at a wavelength shorter than optimal for laser propulsion.

Subsequent budget cutbacks postponed by at least two or three years the date by which the FEL TIE laser and beam director could be operating. More recently, SDIO decided the FEL TIE laser should use a radio-frequency linear accelerator (RF linac) similar to the one developed for the Los Alamos-Boeing free-electron laser instead of an induction linac similar to the one used in the Paladin free-electron laser. The Los Alamos-Boeing RF linac produced an electron beam of higher quality than that produced by the induction linac used by the Paladin laser; however, use of an RF linac may cause the FEL-TIE laser to produce laser pulses with a waveform that is far from optimal for laser propulsion. This, together with the nonoptimality of the FEL TIE wavelength, may lead SDIO to abandon hope of using the FEL TIE laser for laser propulsion experiments and force SDIO, perhaps teamed with other sponsors, to develop a laser and beam director specifically for laser propulsion experiments.

Table 5-l-Estimated Cost of a 20-Megawatt Laser for Powering Rockets

Development	$ 75 million
Laser	$185 million[a]
Telescope	$lO0 million
Adaptive optics	$ 15 million
Tracking	$ 50 million
Power plant	$ 50 million
Structure	$ 50 million
Total capital cost	$450 million
Total nonrecurring cost	$525 million

[a] estimated as $25 miliion +$8 per watt.

SOURCE: Strategic Defense Initiative Organization.

strated to date is about 10 percent. If only 10 or 20 percent efficiency could be attained, an 80- or 40-megawatt laser would be needed, and average cost per pound would be greater than indicated above. If the cost of the power plant increases in proportion to its power, average cost would be about $490 or *$275* per pound for 10 or 20 percent rocket efficiency, respectively, at a launch rate of 100 per day.[26]

Because of the brief launch windows for rendezvous only 2 payloads per day could be launched directly to a rendezvous with the space station. Payloads launched at other times would take longer and require more fuel to rendezvous.[27] The SDIO considers 8 payloads per day to be a conservative estimate of the number of payloads that could be launched to rendezvous with the space station each day. With additional investment, the laser and rockets could be given more crossrange capability. This could be done by making the beam director and rockets larger or by adding a conventional chemical rocket to the laser-powered rocket.

ISSUES

What could microspacecraft do that conventional spacecraft couldn't? The consensus of the NASA/SDIO microspacecraft for Space Science Workshop Panel[28] was that:

> There is a class of science and exploration missions that can be enabled by microspacecraft (i.e., infeasible with larger spacecraft). This class of missions requires many simultaneous measurements displaced imposition .. .. Examples . . . include: 1) a global network of surface or atmospheric sensors on planets such as Mars. . ., 2) measuring the spatial and temporal structure of magnetospheres about the Earth, Sun, or other regions of space, and 3) using microspacecraftas distributed arrays for either radio or optical signals.

They would have another advantage: they could be launched *from Earth orbit* toward outer planets by *space-based* electromagnetic launchers (railguns or coilguns) at muzzle velocities that would allow them to reach their destinations and return data to Earth years earlier than could spacecraft launched by conventional rockets. This would accelerate the cycle of acquiring knowledge.

What is the market for such services? How much is now spent on conventional spacecraft for space science which microspacecraft could do? The 1988 NASA budget was about $9 billion, of which about $1.6 billion was for "space science and applications."[29 30] Much of this is for NASA's "great observatories,' such as the Hubble Space Telescope and the Advanced X-ray Astrophysics Facility, and for planetary probes such as Galileo. The consensus of the NASA/SDIO microspacecraft for Space Science Workshop Panel was that:

> microspacecraft cannot achieve the science objectives of the great observatory missions such as the Hubble Space Telescope or the Advanced X-ray Astrophysics Facility. Also, intensive, multi-faceted science investigations such as those of Galileo at Jupiter cannot be supported by the microspacecraft concept. . . . many space science missions will have to continue to use established technology. Microspacecraft, if they are to be used in deep-space missions, must establish a new inheritance chain, for example by being used in near-Earth scientific or non-scientific missions.

[26] Calculated by OTA using the launch simulation program of Kantrowitz, oP. cit., footnote 9. The launch simulation program used by Kare, ''Trajectory Simulation for Laser Launching,' Kare, op. cit. (footnote 10), pp. 61-77, predicts a 50 to 100 percent longer ascent than does Kantrowitz's program (for the case of 40 percent thruster efficiency) and hence 50 to 100 percent higher electric power usage and incremental cost.

[27] See P.K. Chapman, op. cit., footnote 10.

[28] NASA/OAST & SDIO/IST, *Microspacecraft for* Space Science *Workshop—Report of the Workshop Panel*, California Institute of Technology Jet Propulsion Laboratory, Oct. 6, 1988.

[29] U.S. Congress, Congressional Budget Office, The *NASA Program* in *the 1990's* aria' *Beyond* (Washington, DC: Congressional Budget Office, May 1988); figure 1; see also figure 4 and box 3.

[30] The Department of Defense space program also includes some focused space science projects.

An EML, ram cannon, or laser (to power rockets) may permit microspacecraft to be launched from Earth to orbit at low average cost, but only if utilized efficiently. Maximum efficiency would require launching on the order of 10,000 microspacecraft per year. How much would these microspacecraft cost? Could space science budgets pay for so many microspacecraft? If not, what other types of microspacecraft might be launched by such a system to maintain an efficient launch rate?

Possibilities include:[31]

- low-altitude comsat networks (civil or military);
- "Brilliant Eyes," "Brilliant Pebbles,' or "Small Dumb Boosters" for a strategic defense system;[32]
- logistics for a space station or other space operations. Payloads could include structural components, fuel, armor, etc.; and
- intercontinental artillery.

The utility of these applications has not been established. All require further analysis before they can be used to justify developing a direct-launch system or a laser and laser-powered rockets. Some proposed logistics schemes appear more promising than others. For example, it is probably feasible to launch Small Dumb Boosters (orbital transfer stages) with which Brilliant Pebbles could rendezvous and mate. Some have proposed launching projectiles loaded with water, liquid oxygen, and liquid hydrogen toward the Space Station Freedom, but the costs of collecting and decanting them have not yet been estimated.

The risk of satellite collisions would increase greatly if tens of thousands of microspacecraft were placed in orbit, unless a means of collision warning and avoidance is developed. Existing space surveillance systems may be inadequate for tracking tens of thousands of microspacecraft, although Brilliant Eyes or Brilliant Pebbles could help with this. Ground-based lasers could be used to change the orbits of satellites equipped with slabs of inert propellant, whether launched by laser or not.[33] However, this may not be adequate for collision avoidance, because such satellites may pass over propulsion lasers only infrequently, so advanced warning of a collision hazard would be required, but might be costly and subject to false alarms.

Brilliant Pebbles would not require advanced warning of a collision; they could be programmed to avert collisions by dodging approaching spacecraft. They could also be commanded to ram a nonmaneuverable satellite (e.g., a failed Brilliant Pebble) that posed a threat to more valuable U.S. and foreign satellites. But a successful intercept might generate debris and increase the long-term risk to spacecraft. Collision avoidance schemes based on other technologies developed for antisatellite or ballistic missile defense applications have been proposed; some would not generate debris.[34]

31 Miles R. Palmer, op. cit. footnote 14.

32 These were described above in the section on lightsats. Brilliant Pebbles would weigh tens of kilograms-more than the lightest microspacecraft, and more than some lightsats, but still light enough to be launched by laser-powered rocket.

33 A laser could be used to maneuver satellites much heavier than those it could launch into orbit.

34 OTA has just begun an assessment of technologies for controlling space debris and protecting satellites from it. The assessment was requested by the Senate Committee on Commerce, Science, and Transportation, its Subcommittee on Science, Technology, and Space, and the House Committee on Science, Space, and Technology.

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List of Publications.--Catalogs by subject area all of OTA's published reports with instructions on how to order them.

Assessment Activities.—Contains brief descriptions of recent publications and assessments under way, with estimated dates of completion.

Press Releases.—Announces publication of reports, staff appointments, and other newsworthy activities.

OTA Annual Report.--Details of OTA's activities and summarizes reports published during the preceding year.

OTA Brochure.—"What OTA Is, What OTA Does, How OTA Works."