Affordable Spacecraft: Design and Launch Alternatives

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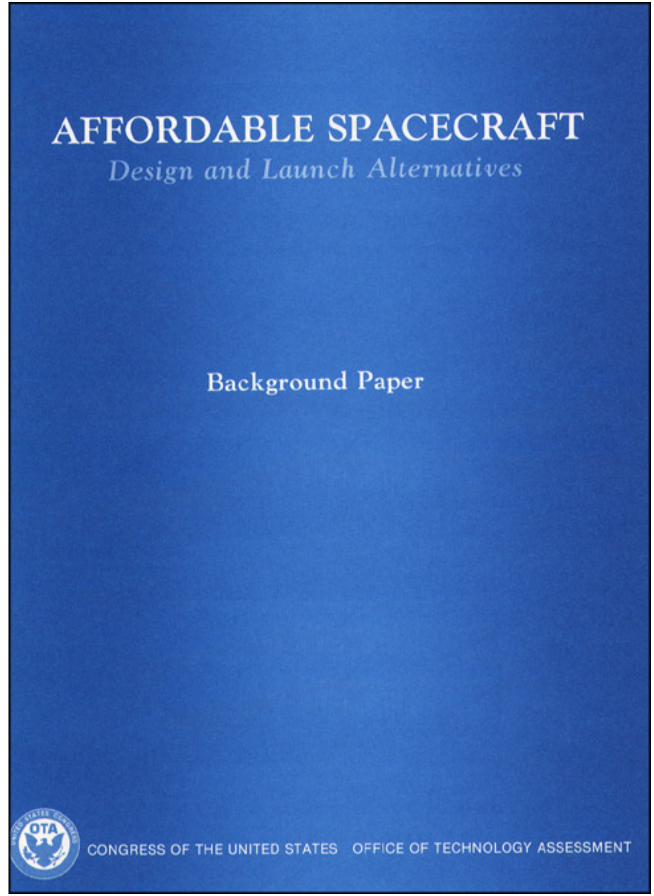

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Foreword

Several major DOD and NASA programs are seeking ways to reduce the costs of launching spacecraft. However, it typically costs much, much more to build a spacecraft than to launch it into a low orbit. Therefore, unless the costs of building spacecraft are reduced, even dramatic reductions in costs of launching to low orbit would reduce total spacecraft program costs by only a few percent.

This background paper examines several proposals for reducing the costs of spacecraft and other payloads and describes launch systems for implementing them. It is one of a series of products of a broad assessment of space transportation technologies undertaken by OTA at the request of the Senate Committee on Commerce, Science, and Transportation, and the House Committee on Science, Space, and Technology. In 1988, OTA published the special report *Launch Options for the Future: A Buyer's Guide* and the technical memorandum *Reducing Launch Operations Costs: New Technologies and Practices.* In 1989, OTA published the background paper *Big, Dumb Boosters: A Low-Cost Space Transportation Option?* and the special report *Round Trip to Orbit: Human Spaceflight Alternatives.* A summary report on space transportation, entitled *Access to Space* to be published in the spring of 1990, will be the final report in the space transportation series.

In undertaking this effort, OTA sought the contributions of a wide spectrum of knowledgeable individuals and organizations. Some provided information; others reviewed drafts. OTA gratefully acknowledges their contributions of time and intellectual effort. OTA also appreciates the cooperation and assistance of the Air Force and NASA. However, OTA is solely responsible for the content of this background paper and the other OTA publications.

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Summary

Several major efforts are aimed at finding ways to reduce the cost of launching spacecraft. However, it typically costs much, much more to build a spacecraft than to launch it to low Earth orbit (LEO). Unless spacecraft costs are reduced, even dramatic reductions in launch costs will have only a small effect on total spacecraft program costs.

This Background Paper reviews four possible approaches to spacecraft design that have been proposed to reduce total spacecraft program costs. Adopting them could change the launch rates, payload capacity, and reliability demanded of conventional launch vehicles, or create a demand for exotic launch systems to launch very small spacecraft cheaply. Conversely, developing new, economical launch systems would strengthen incentives to adopt these new approaches to spacecraft design.

This is one of several publications documenting OTA's broad assessment of space transportation technologies requested by the House Committee on Science, Space, and Technology, and the Senate Committee on Commerce, Science, and Transportation. Previous publications in this assessment examined a variety of future launch options,[1] ways to reduce the costs of launch operations,[2] low-cost, low-technology ("big, dumb") boosters,[3] and options for transporting humans to and from orbit.[4] A final report will be published in 1990.

THE HIGH COST OF SPACECRAFT

Because of the high cost of spacecraft, a dramatic reduction in launch cost alone will not substantially lower spacecraft program costs. Although launching a pound of payload to LEO currently costs about $3,000, procuring that pound of payload typically costs much more. For example, representative U.S. spacecraft busses[5] of types first launched between 1963 and 1978 cost between $130,000 and **$520,000** per pound dry,[6] including amortized program overhead costs. Procurement of the mission payloads carried on those busses cost about 50 percent more—about $200,000 to $800,000 per pound.[7] Reducing launch costs from $3,000 to $300 per pound of payload, a goal of the Advanced Launch System program,[8] would reduce the total cost of procuring and launching a dry spacecraft (half bus, half mission payload) by less than 2 percent.

A spacecraft bound for a high orbit or another planet requires an upper stage, which when fueled is typically more than twice as heavy as the spacecraft but costs less. Even so, a payload consisting of a Centaur upper stage (about $2,250 per pound) and a spacecraft weighing a third as much (half bus, half mission payload) might cost from $40,000 to $160,000 per pound. Reducing launch costs to $300 per pound would

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[1] U.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)*.

[2] U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988).

[3] U.S. Congress, Office of Technology Assessment, Big, *Dumb* Boosters: *A Low-Cost Space Transportation Option?* (Washington, DC: U.S. Congress, Office of Technology Assessment, International Security and Commerce program, February 1989).

[4] U.S. Congress, Office of Technology Assessment, *Round Trip to Orbit: Human Spaceflight Alternatives*, OTA-ISC-419 (Washington, DC: U.S. Government Printing Office, August 1989).

[5] The "bus" of a spacecraft consists of the structure, power sources, and other subsystems required to support the mission payloads it carries.

[6] Unfueled.

[7] *Space Systems and Operations Cost Reduction and Cost Credibility Workshop, Executive Summary* (Washington, DC: National Security Industrial Association, 1987), p. 3-10, fig. 3.7.3. These estimates were derived by amortizing nonrecurring costs (e.g., for development) over four satellites; some programs procure more than four while others procure only one. OTA inflated the estimated costs, which were in 1982 dollars, to 1987 dollars using the GNP inflator from table B-3 of *the Economic Report of the President*, January 1989, and then to 1989 dollars by assuming 4.2 percent annual inflation in 1987 and 1988.

[8] 101 Stat. 1067.

reduce the total cost of procuring and launching such a payload by only 2 to 6 percent.

APPROACHES TO REDUCING PAYLOAD COSTS

To reduce payload costs, and for other reasons, novel approaches to payload design and fabrication have been proposed:

- Design payloads to fit launch vehicles leaving size and weight margins of about 15 percent
- Allow payloads to be larger and heavier: Fatsats
- Allow satellites to be simpler, and make them lighter: Lightsats
- Design Microspacecraft to be launched like artillery shells

Each type of spacecraft—fatsat, lightsat, or microspacecraft-would impose unique launch demands. New, large launch vehicles would be needed to launch the heaviest satellites. Lightsats could be launched on existing launch vehicles, but new, smaller launch vehicles might launch them more economically. In wartime, small launch vehicles could be transported or launched by trucks or aircraft to provide a survivable means of space launch. Microspacecraft could be launched on existing launch vehicles, but they might instead be launched by more exotic means such as a ram cannon, railgun, coilgun, or laser-powered rocket. Some of these might be proven feasible in the next decade.

Weight margin: Designing payloads to fit launch vehicles while reserving ample size and weight margins can reduce the risk of incurring delay and expense after assembly has begun.

It is often the case that satellites grow substantially heavier than expected as they proceed from design to construction. For example, dry weights of military spacecraft have been about **25** percent greater, on the average, than initially predicted. Growth in estimated weight may be caused by underestimating the weight of a spacecraft (especially one designed to use the most advanced technology) or by changing mission requirements during development (requiring hardware to be added). If a payload grows so heavy during assembly that it threatens to "gross out" its assigned launch vehicle (i.e., cause its weight to equal or exceed the maximum allowable gross lift-off weight), the payload must be redesigned to cut its weight. This causes delay and increases cost.

To reduce the risk of exceeding vehicle payload capacity, program managers could require designers to design each payload to fit its assigned launch vehicle with room to spare and to weigh substantially less than the maximum weight the vehicle can launch to orbit. However, this design philosophy would lead to more stringent size and weight constraints than would otherwise be imposed. If a mission simply could not be performed by payloads predicted to be small enough to fit the largest launch vehicles with adequate size and weight margins, new, larger launch vehicles would have to be developed to provide the desired margin. In many cases, however, sufficient margin could be provided by clever design, e.g., by designing several smaller single-mission payloads instead of a single multimission payload, or developing and using an electric-powered or space-based orbital transfer vehicle (OTV) instead of a conventional OTV.[9]

Fatsats: If payloads were allowed to be heavier for the same capability, some could cost substantially less. For example, OTA estimates that Titan-class payloads that cost several hundred million dollars might cost about $130 million less if allowed to be five times as heavy.

[9]To place a satellite in a high orbit, a launch vehicle must carry both the satellite and either an upper stage to take the satellite directly to the high orbit, or an OTV to take the satellite from a low-altitude parking orbit to the high orbit. A conventional OTV weighs two or three times as much as the satellite it carries. An electric-powered OTV could weigh less than a conventional OTV of comparable capability, creating more weight margin. A space-based OTV could be launched separately from its payload, allowing the payload to weigh as much as its launch vehicle could carry while reserving the desired weight margin. However, operation of space-based OTVs would be complex and require costly infrastructure.

If payloads were allowed to be much heavier, a manufacturer could forego expensive processes for removing nonessential structural material, as well as expensive analyses and tests for assuring the adequacy of the remaining structure. Standardized subsystems, which could be produced economically in quantity, could be used instead of customized subsystems designed to weigh less.

The savings that might be realized are uncertain. In principle, they could be estimated by comparing the costs of a heavy payload and a light payload that perform the same functions with the same capability. However, the United States has never designed and built two payloads, one heavy and the other light, that perform the same functions equally well, in order to compare actual costs. A few estimates have been derived by comparing the cost and weight of an actual spacecraft with the estimated cost and weight of hypothetical heavier spacecraft of comparable capability. Designers have also compared the estimated costs and weights of hypothetical spacecraft of comparable capability and different weights. All such studies predict payloads could cost less if allowed to weigh more, but the estimates of savings differ.

An accurate estimate of potential savings requires a detailed trade-off analysis for each payload. Achieving these savings will probably require giving spacecraft program managers, and those who establish mission and spacecraft requirements, incentives crafted specifically for the purpose, and may require developing new launch or orbital-transfer vehicles to carry the spacecraft.

Lightsats: If allowed to be less capable, reliable, or long-lived, payloads could be both lighter and less expensive. Useful functions such as communications and weather surveillance could be performed by payloads small enough to be launched on small rockets from airborne or transportable launchers.

Small, simple, and relatively inexpensive civil and military satellites have been, and still are, launched at relatively low cost on small launch vehicles or at even lower cost, sometimes for free, as "piggyback" payloads on larger launch vehicles.

The Department of Defense is considering whether the increased survivability and responsiveness such spacecraft could provide would compensate for possibly decreased capability. Some missions might be accomplished as well by a swarm of several small satellites as by a single large one. If so, a swarm would be less expensive in many cases, because smaller satellites typically cost much less per pound than do large ones. Even if the satellites were launched individually, which would increase total launch cost, total mission cost might be lower.

Microspacecraft: Spacecraft weighing only a few pounds could perform useful space science missions and might be uniquely economical for experiments requiring simultaneous measurements (e.g., of solar wind) at many widely separated points about the Earth, another planet, or the Sun.

These could be launched on existing launch vehicles. Eventually, it may be possible to launch them on laser-powered rockets or, if they are as rugged as a cannon-launched guided projectile,[10] with a ram cannon or an electromagnetic launcher. Within the next decade, experiments now being planned may establish the feasibility of some of these launch systems. Their costs cannot be estimated confidently until feasibility is proven, but at high launch rates they might be more economical than conventional rockets. An electromagnetic launcher could also be constructed in orbit to launch microspaceprobes to outer planets; they would arrive years earlier than if they were propelled by conventional rockets.

[10] A cannon-launched guided projectile is an artillery shell equipped with a system (e.g. TV camera and computer) for recognizing a target and movable fins or other means for steering the projectile toward a target. The Army's M712 Copperhead is an example.

OPTIONS FOR CONGRESS

What can Congress do to promote spacecraft cost reduction and, thereby, reduce the cost of space programs? Some options deal directly with spacecraft design; others would promote the development of launch systems that could launch small, inexpensive spacecraft at low cost or heavy spacecraft with generous weight margins.

Options for Influencing Spacecraft Design

Option 1:

Congress could order a comprehensive study of how much the Nation could save on space programs by:

- *designing payloads to reserve more weight and volume margin on a launch vehicle;*
- *allowing payloads to be heavier, less capable, shorter-lived, or less reliable;*
- *designing standard subsystems and buses for use in a variety of spacecraft;*
- *designing spacecraft to perform single rather than multiple missions; and*
- *using several inexpensive satellites instead of a single expensive* one.

Lockheed completed such a study in 1972;[11] anew one should consider current mission needs and technology. It would complement the Space Transportation Architecture Study (STAS) and more recent and ongoing studies[12] that compare space transportation options but not payload design options.

As noted above, to estimate potential savings accurately, a detailed trade-off analysis must be done for each payload, or more generally, for each mission. So, for greater credibility:

Option 2:

Congress could require selected spacecraft programs--for example, those that might require a new launch vehicle to be developed--to award two design contracts, one to a contractor who would consider the unconventional approaches mentioned above.

Option 3:

Congress could require both the Department of Defense and NASA to refrain from developing a spacecraft if the expected weight or size of the spacecraft, together with its propellants, upper stage, and support equipment, would exceed some fraction of the maximum weight or size that its intended launch vehicle can accommodate. Public Law 100-456 required the Department of Defense to require at least 15 percent weight margin in fiscal year 1989.[13] New legislation could extend this restriction to NASA and could require size margins in future years.

Options for Promoting the Development of Launch Systems

Option 4:

Congress could fund the development of the Shuttle-C cargo launch vehicle, the Advanced Launch System, liquid-fueled rocket boosters for the Shuttle, or a larger Titan launch vehicle.[14] Any of these vehicles could launch payloads larger and thus less expensive (for comparable performance) than payloads designed to fly on Shuttles or Titan IVs. Alternatively, if payload size and weight are not increased, these proposed launch vehicles could provide greater size and weight margins, thereby reducing the risk of needing costly weight-reduction efforts. However, their greater payload capacity would also enable payload pro-

[11] Lockheed Missiles and Space CO., *Impact of Low-Cost Refurbishable and Standard Spacecraft Upon Future NASA Space Programs*, NTIS N72-27913, Apr. 30, 1972.

[12] E.g., the Air Force's Air *Force-Focused STAS*, NASA's *Next Manned Space Transportation System* study, the Defense Science Board's *National Space Launch Strategy* study, and the *Space Transportation Comparison* study for the National Aero-Space Plane Program.

[13] See S. Rept. 100-326, p. 36, and H. Rept. 100-989, p. 282.

[14] The costs and benefits of these launch systems would differ; see U.S. Congress, op. cit., footnote 1, and the forthcoming final report of this assessment.

gram managers to forego these potential savings and instead pursue greater payload performance by increasing payload size or weight. If they do so and weight overrun occurs, it would probably cost more to trim the weight of a larger payload than it would to reduce the weight of a lighter payload by the same percentage. Requiring weight margins, as described above, would reduce this risk.

Option 5:

Congress could continue to fund the development of the Standard Small Launch Vehicle (SSLV[15]) and the Sea Launch and Recovery (SEALAR) system[16] to provide survivable means of launching military lightsats. The Department of Defense probably will not allow operational lightsats to be designed for such launch vehicles until the vehicles are operational. Hybrid rockets, which can use liquid oxygen to burn nonexplosive solid propellant similar to tire rubber, could also be designed to launch lightsats from transportable launchers. Such hybrids would have some safety advantages and might be allowed where conventional solid- or liquid-fuel rockets are not. Later—perhaps by 2005-NASP-derived vehicles might be able to launch 20,000-pound payloads in wartime.[17] With continued funding, the National Aero-Space Plane Program would continue to develop technology for NASP-derived vehicles.

Option 6:

Congress could fired the development of a laser or a direct-launch system (e.g., a railgun, coilgun, or ram cannon) for launching microspacecraft at high rates economically. Many uses have been proposed, but to date only the Strategic Defense Initiative Organization (SDIO) has identified a plausible demand for high-rate launches of microspacecraft. However, demand for launches of scientific, commercial, and other microspacecraft could increase, perhaps dramatically, if launch costs could be reduced to a few hundred dollars per pound and payloads were inexpensive. The SDIO estimates development and construction of a laser for launching 44-pound payloads would require about $550 million over 5 or 6 years. The SDIO estimates it could launch up to 100 payloads per day (more than 20 Shuttle loads per year) for about $200 per pound.

Railgun proponents predict a prototype railgun capable of launching 1,100-pound projectiles carrying 550 pounds of payload could be developed in about 9 years for between $900 million and $6 billion, including $50 million to $5 billion for development of projectiles and tracking technology. If produced and launched at a rate of 10,000 per year, the projectiles (less payload) would cost between $500 and $30,000 per pound (estimates differ). The cost of launching them might be as low as $20 per pound—i.e., $40 per pound of payload.

15The SSLV is being developed by the Defense Advanced Research Projects Agency (DARPA).

16SEALAR is being developed by the U.S. Naval Research Laboratory.

ITS. U.S. Congress, op. cit., footnote 4, pp. 67 and 74.

Chapter 2
Weight and Volume Margins

As payloads progress from the drawing board (or computer-aided design workstation) to the launch pad, their volumes tend to expand to fill the payload fairings of their betrothed launch vehicles, and their weights tend to grow to the maximum that the launch vehicles can launch. Dry weights of representative U.S. military satellites have been about 25 percent greater, on the average, than the estimates of dry weight made when they were proposed.[1] On occasion, satellites grow so heavy that their assigned launch vehicles would be unable to place them in the desired orbits. When this happens, drastic and expensive efforts are undertaken to reduce the weight of the satellite—and sometimes of the launch vehicle as well. A TRW executive has said, “We have to spend numbers like $150,000 a pound trying to get the last few pounds out of a spacecraft. ”[2]

A contract for spacecraft development and production typically specifies that the spacecraft perform certain functions and not weigh more than a specified maximum weight. Usually this maximum weight is chosen to be less than the maximum weight a particular launch vehicle can place in the desired orbit. The difference between these two values provides a margin that allows for contingencies such as less-than-expected launch vehicle thrust.

The spacecraft designer initially tries to design the spacecraft to perform the specified functions and not weigh more than the specified maximum weight, *minus*

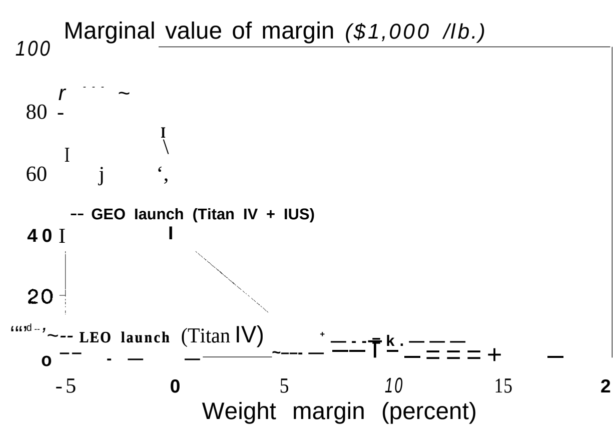
1. a *“contingency”* amount by which the estimated weight of the spacecraft is *expected* to grow as the design matures, and
2. a *“weight margin”* representing greater-than-expected growth in the estimated weight as the design matures.

Based on its experience producing high-tech government spacecraft and spacecraft subsystems, TRW expects weight to grow ultimately 15 percent larger than initial estimates and hence budgets a contingency of 15 percent initially. As the design matures and the estimated weight increases as expected, the contingency budget is decreased.

TRW may also allow a margin of 15 percent or more for greater-than-expected weight growth, initially. TRW estimates that the value of weight margin increases with decreasing margin, from zero at 15 percent margin, to $5,000 to $10,000 per pound at 5 to 10 percent margin, to $40,000 per pound at O percent margin, to as much as $100,000 per pound at negative margin, depending on the time remaining before launch (figure 2-l). Margins are seldom negative at an early design stage; if margin becomes negative shortly before the spacecraft is to be launched, expensive redesign may be required to reduce the spacecraft weight below the maximum weight specified in the contract, and TRW estimates that it maybe worth up to about $100,000 per pound to avoid this. This is much greater than the cost of transporting a typical spacecraft to its operational orbit: about $15,000 to $30,000 per pound to geosynchronous orbit, as estimated by TRW.[3]

TRW notes that spacecraft designed to incorporate advanced-technology subsystems can consume weight margins with unusual rapidity, leading to redesign (which may require 3 or 4 months), increased risk, and possibly additional redesign, as well as downward revision of ‘requirements. Two

Figure 2-I—Value of Weight Margin



SOURCE: TRW (*plotted* by OTA).

[1] P. Hillebrandt et *al., space Division Unmanned Space Vehicle Cost Model, Sixth Edition,* SD TR-88-97 (Los Angeles AFB, CA: Headquarters, Space Systems Division, U.S. Air Force Systems Command, November 1988), p. VIII-6; distribution limited to U.S. Government agencies only.

[2] G.W. Elverum, Jr., “Reliability Up/Coats Down Through Simplicity,” *Space Systems Productivity and Manufacturing Conference IV* (El Segundo, CA: Aerospace Corp., 1987), pp. 175-1%.

[3] Clark Kirby, TRW, personal communication, Nov. 16, 1988.

redesign cycles totaling 6 to 8 months could lead to a 10 to 25 percent cost growth. TRW also notes that volume constraints are also costly.

How much margin should be reserved? Reserving too little increases the risk of delay and cost overrun, should redesign become necessary, because weight growth exceeds expectations late in a development program. Yet reserving too much margin imposes an opportunity cost: one either foregoes the opportunity to add extra fuel or equipment, and hence capability, to the payload, or one foregoes the opportunity to make the payload less expensive by allowing it to be heavier. In the latter case, the opportunity cost is tangible and can be estimated.[4] The optimal margin will be that at which the marginal opportunity cost of not making the payload a pound heavier equals the marginal value that the additional margin would provide by reducing risk of cost overrun and schedule slippage.

If the marginal value of weight margin is as estimated by TRW (see figure 2-1), then a margin of 11 to 12 percent would be optimal for a Titan IV payload.[5] This is comparable to the margin (15 percent) that Public Law 100-456 required the Department of Defense to reserve for satellites DoD approves for development in fiscal year 1989. In reporting on the National Defense Authorization Act for fiscal year 1989, the Senate Committee on Armed Services proposed requiring that

> *. . . the Under Secretary of Defense for Acquisition shall not approve for development a new satellite if the proposed payload weight exceeds 85 percent of the lift capacity of the launch vehicle(s) identified with the proposed satellite, and shall not approve for development a block change if the proposed payload weight exceeds the weight of the existing payload.*[6]

This language was endorsed in conference and signed into law.[8]

The expectation that increasing weight margins would reduce cost risk does not imply that it would save money to build a new launch vehicle large enough to launch the heaviest payloads with increased weight margins. Predicting whether it would save money would require comparing the cost of developing the vehicle with the total benefits it would provide—including the reduction in cost risk that increased weight margins would provide. Ironically, building larger launch vehicles could increase this risk: Without discipline, payloads might still be designed to allow little margin, and margins could still be tight or negative, but with greater consequence. To eliminate a l-percent negative margin, one would have to trim 2,000 pounds from a 200,000-pound payload, compared to only 390 pounds in the case of a 39,000-pound payload. In some cases this could be done by carrying less fuel than planned and accepting reduced payload performance. If not, reducing the dry weight of a 200,000-pound payload by 1 percent would cost $240 million more than reducing the dry weight of a 39,000-pound payload by 1 percent, if weight reduction costs $150,000 per pound. This illustrates why allowing margin for, and controlling, weight growth will be much more important for large payloads (such as proposed heavy-lift launch vehicles could carry) than for smaller ones.

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[4] See "A Parametric Analysis" in ch. 3.

[5] Viz. a payload that would cost between $100 million and $5 billion if built to weigh 39,000 pounds—i.e., to reserve no margin.

[6] S. Rept. 100-326, p. 36.

[7] H. Rept. 100-989, p. 282.

[8] S. Rept. 100-326 did not specify whether the [estimate of] proposed satellite weight should include expected weight growth in addition to the nominal weight estimated from the design for the satellite. If so, Public Law 100-456 would require at least a 15 percent weight margin in addition to whatever weight growth is expected. If the payload consisted solely of an unfueled satellite, 25 percent weight growth would be expected [P. Hillebrandt et al., op. cit., footnote 1, pp. VIII-6], so Public Law 100-456 would require a 40 percent weight margin in addition to the nominal weight estimated from the design for the satellite.

Chapter 3
Fatsats

Many experts find it plausible that a payload could be designed to perform a function at lower cost if it were allowed to be heavier. However, there have been few attempts to estimate just how much cheaper payloads could be, if allowed to be heavier, or how much they should weigh in order to minimize the total cost of producing and launching a payload.

The first section of this chapter discusses one of several ways in which payloads could be made less expensive if allowed to be heavier: standard subsystems could be used in lieu of customized subsystems designed to minimize weight. The next section describes how a high-altitude satellite could be allowed to be heavier (and hence less expensive) without using a larger launch vehicle: by using an orbital transfer vehicle with electric engines (e.g., arcjets). The third section discusses estimation of cost versus weight trade-offs, with subsections describing parametric and bottom-up methods and comparing parametric with bottom-up estimates. The final section discusses some organizational obstacles to reducing cost by allowing payload weight growth.

STANDARDIZING SUBSYSTEMS

One of several ways to trade off cost for weight is to use standard spacecraft subsystems or busses.[2] The use of a standard or previously developed subsystem may result in a heavier spacecraft but allow a satellite program to avoid paying part or all of the substantial nonrecurring costs of developing a custom subsystem. In addition, because of learning and production-rate effects, it helps reduce the recurring cost of producing the standard subsystem.

Using a standard subsystem could reduce subsystem cost by a factor roughly equal to 1 plus the ratio (expressed as a Ii-action) of nonrecurring to recurring cost. For example, the ratio of nonrecurring cost to recurring cost is typically 2/1 for a spacecraft bus (see table 3-l), so the nonrecurring cost of developing a spacecraft bus is about twice the recurring cost of producing a bus. If a mission requires one spacecraft, the cost of developing and producing a custom bus would be about three times the cost of producing a suitable previously developed bus. By using a previously developed bus, one could therefore save about two-thirds of the cost of a customized bus.[3] The cost would be reduced by a factor of 3, i.e., by 1 plus the ratio of nonrecurring cost to recurring cost (2/1).

More could be saved on subsystems with higher ratios. For example, the cost of structure, which has ratios ranging from 5/1 to 8/1, could be reduced by a factor of at least 6, and possibly 9.

The amount saved could be a small percentage of total spacecraft program costs, which also include the costs of mission-peculiar payloads and program overhead, etc. A 1972 Lockheed study[4] concluded that development and use of standard subsystems could save only about 4 percent of the cost of 91 payload programs, when used in addition to low-cost design methods and payload refurbishment. The savings attributable to standardization would be about 6 percent of the program costs already reduced by low-cost design and refurbishment.[5]

Manufacturers have estimated that 95 percent learning might be achieved, i.e., every time the cumulative number of units produced is doubled, the incremental unit cost would decrease 5 percent.[6] The Air Force has assumed 95 percent learning in estimating first-unit production costs from lot sizes

[1] See, e.g., Lockheed Missiles and Space Co., *Impact of Low-Cost Refurbishable and Standard Spacecraft Upon Future NASA Space Programs*, NTIS N72-27913, Apr. 30, 1972.

[2] A spacecraft "bus" consists of those spacecraft subsystems—e.g. structure, thermal control, telemetry, attitude control, power, and propulsion—that are not peculiar to a particular mission, as cameras or radio relays would be.

[3] The cost of integrating an off-the-shelf subsystem into a spacecraft is small. The Boeing Company's Parametric Cost Model predicts that the cost of integrating an off-the-shelf subsystem into a spacecraft would be about 3 percent of the cost of designing anew subsystem for the spacecraft. [Boeing Aerospace Co., May 1989]

[4] Lockheed Missiles and Space Co., op. cit., footnote 1.

[5] In this study, Lockheed assumed a "mission model" now recognized as highly inflated; this probably led to overestimation of the potential savings from standardization. On the other hand, the percentage savings attributable to standardization might have been greater if refurbishment had not been assumed.

[6] F.K. Fong et al., *Unmanned Spacecraft Cost Model*, 5th ed., SD-TR-81-45 (Los Angeles AFB, CA: Headquarters, Space Systems Division, U.S. Air Force Systems Command, June 1981); NTIS accession number AD-B060 824L; distribution limited to U.S. Government agencies only.

Table 3-l-Ratios of Nonrecurring to Recurring Cost of Spacecraft Subsystems

If a previously developed subsystem can be used in a new spacecraft in lieu of a custom-designed subsystem, subsystem cost could be reduced by a factor roughly equal to one plus the ratio of nonrecurring to recurring cost-e.g., threefold for a spacecraft bus (a spacecraft without its mission payload).

Subsystem	Ranges of ratios nonrecurring Cost/ recurring cost
Structure	5/1 to 8/1
Propulsion (apogee kick)	2/1 to 6/1
Thermal control	4/1 to 40/1
Attitude control	1/1 to 2/1
Electrical power	1/1 to 2/1
Telemetry, tracking, & command	2/1 to 3/1
Spacecraft (less mission payload)	about 2/1
Communications mission payload	2/1 to 3/1

SOURCE: U.S. Air Force Systems Command, Space Systems Division.

and prices,[7] but there have been too few buys of each type of U.S. spacecraft to demonstrate learning conclusively.

UPPER STAGES AND ORBITAL-TRANSFER VEHICLES

Often a payload has an upper stage or an orbital-transfer vehicle (OTV) in addition to a spacecraft. Some analysts have considered options for reducing the costs of upper stages by allowing them to be heavier.[8] Others are considering the opposite approach: making OTVs smaller-and perhaps more expensive--in order to save money by using a smaller launch vehicle, allowing the spacecraft to be larger, or providing more margin for spacecraft weight growth. Space-based OTVs have also been proposed;[9] they could be reused and would not be launched together with the spacecraft, which could therefore be larger. However, refueling and maintaining them could be complicated and might require the development and maintenance of costly space- or ground-based infrastructure.

Electric propulsion could be used to make OTVs smaller and lighter while at the same time increasing the mass they could deliver to a high orbit. They could use photovoltaic ("solar") cells to generate electricity[10] to power an electrostatic ion thruster, an arcjet thruster, or an electric engine of some other type (many are possible) that has an exhaust velocity much greater than that of a chemical rocket. This would reduce the mass of fuel required for orbital transfer, increasing the payload that could be transferred. The "dry weight" of an electric OTV (EOTV) could also be smaller than that of a chemical OTV of comparable total impulse, further increasing the payload that could be transferred.

There would be drawbacks. An EOTV would produce little thrust, so transfer of a payload from a low-altitude parking orbit to geostationary orbit might take 3 to 6 months. Before reaching its destination orbit, the payload would age a few months and, more important, might degrade because of its longer transit through the Van Allen radiation belts. An EOTV would be designed to tolerate such a transit, but some satellites might not be. A near-term solution would be to shield sensitive satellites against the radiation, but this would reduce the maximum satellite mass that could be carried.

The longer transfer time could also be detrimental to security. A military satellite on an EOTV would remain longer at low altitude and within range of low-altitude anti-satellite weapons than if it rode a conventional OTV to its destination orbit. If a critical satellite fails or is damaged, an EOTV might not be able to replace it without a serious lapse in mission performance.[11] These drawbacks could be mitigated by launching military satellites on schedule rather than on demand. That is, near the end of its projected useful life, each satellite would be deactivated, maintained as a spare, and replaced by a new satellite, which could have been launched months earlier.

The Air Force Systems Command Space Systems Division estimates that EOTVs would be more economical than conventional OTVs for selected

7p. Hillebrandt et al., *Space Division Unmanned Space Vehicle Cost Model, Sixth Edition,* SD TR-88-97 (Los Angeles AFB, CA: Headquarters, Space Systems Division, U.S. Air Force Systems Command, November 1988); distribution limited to U.S. Government agencies only.

8Dani Eder, "Why Spacecraft Should Get Less Expensive If Launch Costs Decrease," unpublished, undated, marked "D582-1(X)03-1." Boeing presented results of this analysis at the ALS Phase 1 System Requirements Review, and to OTA in a briefing, "ALS program Development." See also Hughes Aircraft Co., Space and Communications Group, *Design Guide for ALS Payloads,* October 1988.

9E.g., see Lockheed Missiles and Space Co., *Final Report---payload Effects Analysis Study,* LMSC-A990556 (Sunnyvale, CA: June 1971), NTIS accession number N71-3749630; and J.M. Sponable and J.P. Penn, "Electric Propulsion for Orbit Transfer: A Case Study," *Journal of Propulsion and Power, vol.* 5, No. 4, July-August 1989, pp. 445451,

10Nuclear power was once considered more promising; see Lockheed Missiles and Space Co., Op. Cit., footnote 9.

11However, in some scenarios, neither could a conventional OTV.

missions. For example, a 5,250-pound spacecraft could be launched to geostationary orbit either on a Titan IV launch vehicle with an Inertial Upper Stage for about $250 million or on a Delta II launch vehicle with a solar-electric OTV for about $124 million,[12] saving about $126 million. A Titan IV with an EOTV could launch a 30,000-pound spacecraft to geostationary orbit for an estimated cost of $269 million. The Space Systems Division is planning to demonstrate an expendable solar-powered EOTV, probably with an experimental payload, sometime between 1993 and 1995.

ESTIMATING POTENTIAL COST REDUCTION

There have been few attempts to estimate how much cheaper spacecraft could be, if allowed to be heavier, or optimal weights for minimal production and launch costs. Analyses of historical data show that heavier spacecraft are typically costlier than lighter spacecraft;[13] usually, however, heavier spacecraft are also more capable than lighter spacecraft. They perform more functions, more difficult functions, or similar functions better.[14] So these analyses do not answer the important questions:

1. How heavy should a payload[15] be in order to minimize the combined costs of payload production and launch on a currently operational launch vehicle? Are payload weights actually optimized for current launch vehicles?
2. How heavy should a payload be in order to minimize 'combined production and launch cost, if the launch cost per pound of payload were reduced, or the maximum payload weight that could be launched were increased, by some factor? By what factor would total payload production and launch cost be reduced?

Answering these questions requires comparing the costs of heavy payloads and light payloads that perform the same function equally well. Unfortunately, such data do not exist; there are no two payloads, one large and the other small, designed at the same time (and hence with comparable technology available) to perform the same set of functions equally well. The few analyses that have estimated how much cheaper a payload could be if allowed to be heavier have been hypothetical. They are based on both "bottom-up" and parametric estimates.

Bottom-up estimates are obtained by designing two or more versions of a payload to perform the same functions at minimum cost without exceeding weight or size limits, which differ from version to version. For example, two versions of a communications satellite could be designed: one to be launched on a Scout launch vehicle, the other on an Atlas-Centaur. Each version would be designed to minimize production and launch cost. Comparing the costs of the two different versions would indicate how much less expensive the larger version would be.

Bottom-up estimates are time-consuming and expensive to derive, and there may be no basis for assuming the cost-versus-weight trade-offs derived would apply to versions larger or smaller than those designed or to payloads that must perform different functions. For example, there is no rationale for expecting that bottom-up estimates of costs and weights of communications satellites of comparable capability could be used to illustrate cost-versus-weight trade-offs for remote-sensing satellites of comparable capability.

Parametric estimates are obtained by assuming that if the weight of a payload were allowed to increase, the minimum cost at which it could be built would vary in some qualitative way-e. g., approach a limit, or decrease exponentially. The parameters of the relationship-e.g., the minimum costs for particular weight limits—are chosen to make the hypothetical relationship fit historical cost and weight data, bottom-up cost and weight estimates, or both, as well as possible.

The fit will not be exact, however;[16] it may be a good fit on the average, with some payloads costing

[12] Including $3 million for RDT&E.

[13] P. Hillebrandt et al., op. cit., footnote 7, and figure 4-1 of Lockheed Missiles and Space Co., Op. cit., footnote 9.

[14] See Lockheed Missiles and Space Co., op. cit., footnote 9.

[15] The *payload* of a launch vehicl, may be a spacecraft (e.g., a satellite or planetary probe) together with an upper stage (to propel it to a transfer orbit or escape trajectory) and support equipment for attaching them to and releasing them from the launch vehicle, Some launch vehicles (e.g., the Space Shuttle and sounding rockets) sometimes carry payloads (e.g., scientific instruments) that remain attached to the launch vehicle.

[16] Unless there are so many parameters (i.e., statistical degrees of freedom) in the model that the available data are too few to estimate them with statistical significance.

more, and others less, than predicted by the relationship (the "model"). The fact that the model represents only average costs and cost-versus-weight trends may be an advantage in studies, such as this one, which focus on such averages and trends. However, it would be a limitation if accurate cost-versus-weight trade-offs for a specific mission were required. If the functions to be performed by the payload were specified in detail, and if resources permitted detailed engineering design of several alternative versions of different weights or sizes, then bottom-up estimation could be used and should provide greater accuracy.

Thus bottom-up estimation and parametric estimation are complementary approaches to cost estimation.[17] Neither approach by itself would be of general value: a bottom-up estimate is applicable only to a specific payload, and parametric estimates are abstract and hence useless unless fitted to bottom-up estimates of cost and weight.[18]

The bottom-up and parametric approaches are exemplified by two analyses produced almost two decades ago: a parametric model developed by Carl Builder at the Rand Corp.,[19] and a bottom-up analysis by Lockheed Missiles and Space Co.[20] Both were cited in congressional debate on the merits of the Space Shuttle.[21]

A Parametric Analysis

Builder did not estimate cost reductions for particular payloads; he described a procedure for doing so using data or assumptions about payload cost and launch cost. He assumed average launch cost would vary as the payload capability of the launch vehicle raised to some power A (this is called a "power-law" relationship) and payload cost would vary as the payload weight raised to some power B. To use Builder's model, one must specify the exponent A and the initial cost and weight of a payload designed to minimize payload plus current launch cost. *One need not specify what the payload does;* in theory, it should make no difference. If launch costs are reduced by some factor,[22] the optimum weight and the cost of a functionally equivalent payload designed to minimize payload plus reduced launch cost may be calculated using formulas derived by Builder. The difference between the old and new minimum total costs is the savings obtainable if launch costs are reduced by the specified factor, assuming payloads are reoptimized to take advantage of the new launch costs.[23]

OTA derived an estimate of the exponent A used in Builder's model by fitting a straight line to points on a log-log plot of the payload capabilities[24] and average launch costs[25] of Delta, Titan, and the Space Shuttle. Figure 3-1 shows the three points and the line obtained as a least-squares fit to the points. The slope of the line corresponds to a value of 0.74 for the exponent A, implying that average launch cost would increase by two-thirds if the payload weight were doubled.

Figure 3-1 also shows a point representing the predicted payload capability of the Pegasus air-launched vehicle (see figure 4-6) and the price charged by its operator, Orbital Sciences Corp. (OSC), for the launches and launch options purchased by the Defense Advanced Research Projects Agency. The line fitted to Delta, Titan, and Shuttle costs and payload capabilities accurately predicted the cost (to the government) of a Pegasus launch.

If launch cost is assumed to vary with payload weight in the way described above,[26] Builder's model predicts that a payload that would cost $1 billion if designed to weigh 39,000 pounds could be

17 U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices,* OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988), app. A.

18 As noted above, there is seldom more than one historical "data point" for the cost and weight of fictionally identical spacecraft.

19 Carl H. Builder, *Are Launch Vehicle Costs a Bottleneck to Economical Space Operations?* Rand working document D-19482-PR, December 1969.

20 Lockheed Missiles and Space Co., op. cit., footnote 9.

21 See the remarks of Senator Mondale in the *Congressional Record—Senate,* May 26, 1971, pp. 17100-17106, and the remarks of Senator Anderson in the *Congressional Record-Senate,* Apr. 20, 1972, pp. 13786-13790.

22 By the same factor, regardless of payload weight.

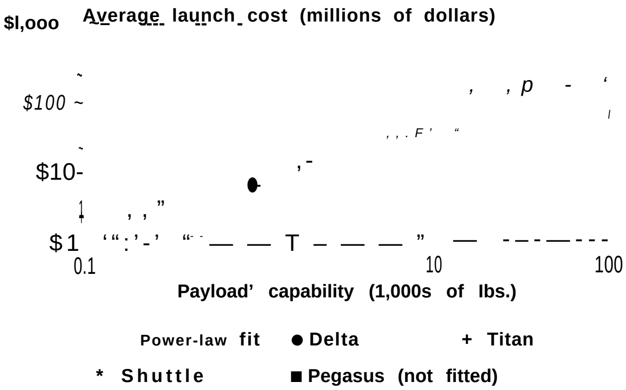
23 More precisely, "assuming payloads are optimally sized for minimum total cost in both cases." Builder, op. cit., footnote 19.

24 To a 100 n.mi.-high orbit inclined 28.5 degrees. U.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), table 2-1.

25 Including amortized fixed annual launch cost. OTA assumed launch at the maximum rate estimated in table A-1 of ibid. and used the nominal cost-estimating relationships in that table.

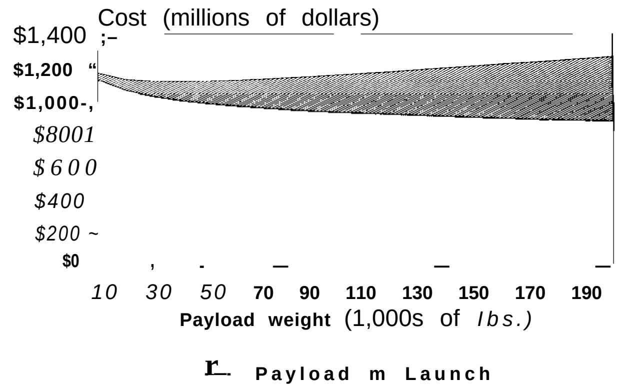
26 I.e., in proportion to the payload capability of the launch vehicle raised to the Power 0.74.

Figure 3-l—Average Launch Cost v. Payload Capability



SOURCE: Office of Technology Assessment and Orbital Sciences Corp., 1988.

Figure 3-2-Cost for Hypothetical Mission With Current Launch Cost Trend



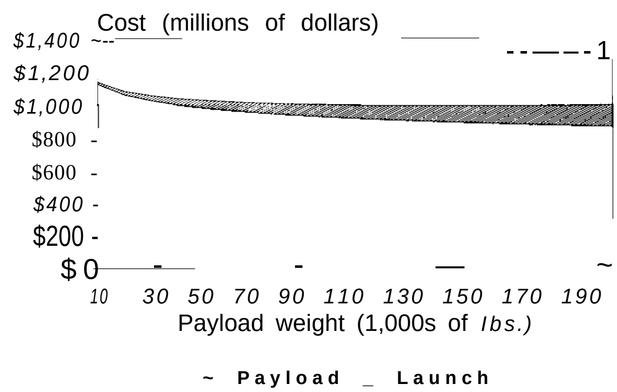
SOURCE: Office of Technology Assessment, 1990.

made for 5.8 percent less if it were allowed to be twice as heavy. More generally, if allowed to be heavier or designed to be lighter, the cost of such a payload would be proportional to its weight raised to the power –0.086 (the exponent B in Builder's model). Figure 3-2 shows how the payload cost and the launch cost would vary with the payload weight. Designing the payload to weigh 39,000 pounds would minimize the total cost.

Figure 3-3 shows how the payload cost and the launch cost would vary with the payload weight if launch cost were reduced by a factor of 3—i.e., by 67 percent. It illustrates that total cost is insensitive to weight for weights between 80,000 pounds and (at least) 200,000 pounds. The optimal weight would be about 150,000 pounds. Reducing the launch cost by 67 percent would reduce the total cost by only 11 percent. *It should be emphasized that this is the estimated cost reduction achievable by allowing payload weight to grow without changing payload performance. It assumes that the baseline payload was designed to minimize total cost.* If a baseline payload was not designed to minimize total cost, redesigning it (possibly to weigh more) could save money even if launch costs are not reduced. If launch costs are reduced, additional savings could be obtained by allowing weight growth; these additional savings are the savings estimated by Builder's model.

Figure 3-4 shows these results in a different form along with results of similar analyses of other hypothetical payloads initially weighing 39,000 pounds but costing $2 billion, $3 billion, and $4

Figure 3-3-Cost for Hypothetical Mission if Launch Costs Are Reduced 67 Percent

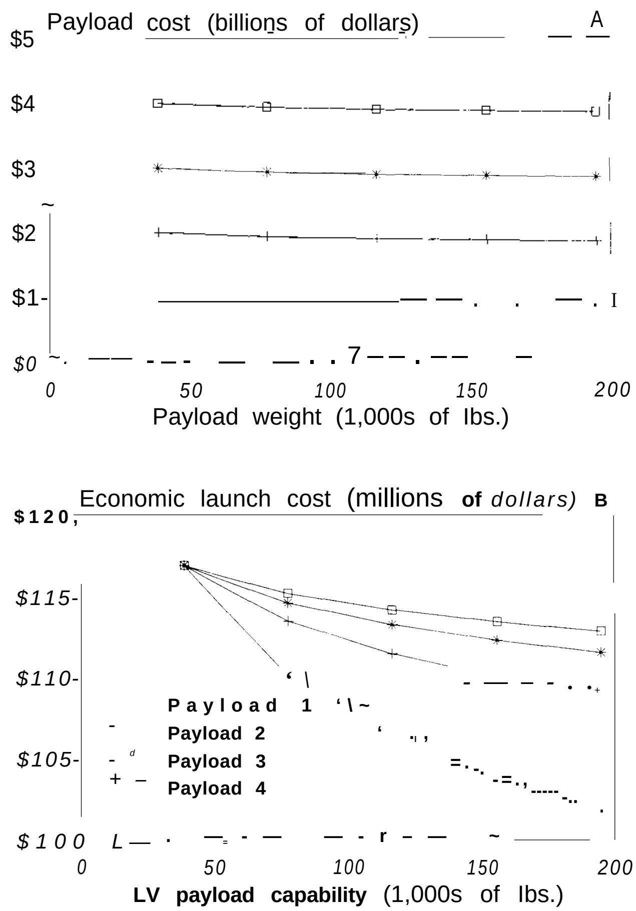


SOURCE: Office of Technology Assessment, 1990.

billion. Figure 3-4a shows how these costs could be reduced, according to Builder's model, if the weights were allowed to grow. For each weight, figure 3-4b shows the ("economic' launch cost at which that weight would be optimal. These estimates predict that allowing the weight of a Titan-IV-class payload to increase by 400 percent (for example) would reduce payload cost by an amount that is nearly the same for a $1-billion payload as for a $4-billion payload. The estimates also predict that the lower the initial cost of a payload, the more the cost per launch must be reduced to justify increasing its weight by a large factor.

Builder's assumption about the relationship between payload weight and launch cost would lose

Figure 34-Payload Cost v. Weight Trade-offs and Economic Launch Costs



SOURCE: Office of Technology Assessment, 1990.

validity if extrapolated to extremely heavy payloads.[27] It would imply that the average cost of launching a pound of payload could be made as low as desired--even lower than the cost of the fuel required to launch a pound of payload—by building a launch vehicle of sufficiently large payload capability. But his assumption fits the estimates of Pegasus, Delta, Titan, and Shuttle launch costs in figure 3-1 very well. The cost-versus-payload curve fitted to Delta, Titan, and Shuttle launch costs predicted the cost of Pegasus accurately, even though the payload capability of Pegasus is eightfold smaller than that of the smallest vehicle (Delta) on which the curve is based. The curve could probably be extrapolated with comparable validity to a payload capability of 200,000 pounds.

Similarly, Builder's assumption about the relationship between payload weight and payload cost would also lose validity if extrapolated to extremely heavy payloads.[28] It would imply that they could be built at a lower cost per pound than that of the bulk structural material (e.g., aluminum) from which they are made. However, this is not a problem for the ranges of payload weights and costs-shown in figure 3-4.

Bottom-Up Analyses

Lockheed used bottom-up analysis to estimate how much the cost of building, launching, and operating selected payloads could be reduced by making them larger[29] and by other measures.[30] Lockheed considered three payloads, selected to span a range of costs, that had been built and launched and for which design and cost data were available. The least expensive was the Lockheed P-1 1 subsatellite, which could be modified for use as a Small Research Satellite (SRS). The most expensive was the Orbiting Astronomical Observatory, the redesigned version of which was designated OAO-B. The other was the Lunar Orbiter, which could be modified for use as a Synchronous Equatorial Orbiter (SEO), four of which could perform Earth resources observation.

Lockheed estimated how much the costs[31] of the OAO-B and SEO payload programs could be reduced if the payloads were redesigned to be launched on unmanned expendable launch vehicles or to be launched on a (then) proposed version of the Space Shuttle.[32] The savings estimated for the first

27If A is less than one.

28If B is less than one.

29Lockheed used parametric methods t. estimate cost-versus-weight trade-offs for payload subsystems. Lockheed assumed the cost-versus-weight trade-off curve for each subsystem was a hyperbola which, for an extremely heavy subsystem, approached a minimum cost per pound and, at the other extreme, approached the minimum weight achievable.

30E.g., repairing or refinishing them in orbit or retrieving them to be repaired or refurbished on Earth.

31Including costs of research, development, testing, and evaluation (RDT&E), production, launch, operation, and replacement (or, if the Shuttle were used, refurbishment) of satellites.

32Lockheed considered two versions.

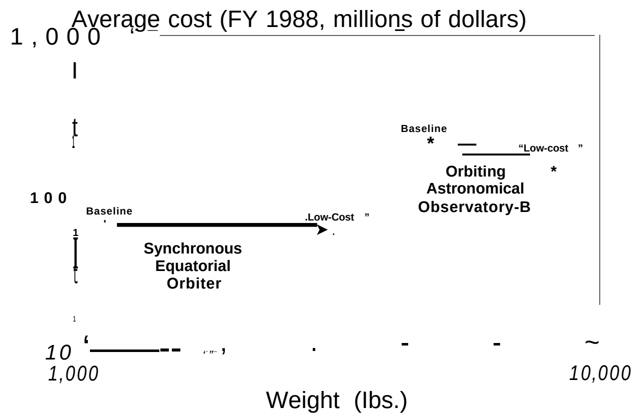
case were attributed to payload growth.[33] However, Lockheed did not redesign the baseline versions of OAO-B and SEO to minimize cost without exceeding the baseline weight, hence Lockheed attributed to weight growth some cost reduction that should have been attributed to improved design. The amount of cost reduction misattributed to weight growth cannot be determined from Lockheed's report, so the cost reductions Lockheed attributed to weight growth should be considered upper bounds on cost reductions achievable by allowing weight growth.

Figure 3-5 compares Lockheed's estimates of the weights and the average unit costs[34] of the baseline OAO-B and SEO with Lockheed's estimates of the weights and costs of "low-cost" versions designed to be launched on expendable launch vehicles. The potential savings in fiscal year 1988 dollars would be $10.1 million (21.3 percent) and $43 million (15.2 percent) for SEO and OAO-B, respectively. The estimated weight growth required to achieve such savings would be 170 percent and 69 percent, respectively.

A more recent bottom-up analysis by Boeing Aerospace Co. estimated the cost of a "typical" payload could be reduced by a large percentage if weight growth by a modest percentage were allowed, and that it would save money to allow such weight growth if launch cost per pound were reduced.[35] For example, Boeing estimated the cost could be halved if the weight were allowed to grow 30 percent (see figure 3-6).[36]

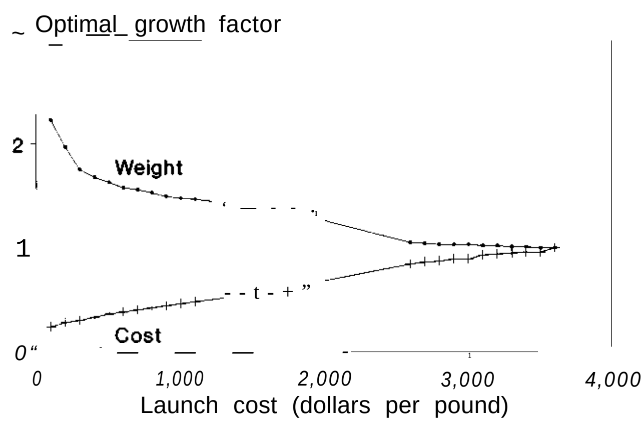
Boeing actually considered a payload consisting of an upper stage and a hypothetical spacecraft using specific subsystem technologies and with subsystem weights in an assumed ratio.[37] Boeing claimed the hypothetical spacecraft was typical, implying that similar cost reductions could be expected for other types of spacecraft. However, some of the subsystem technologies Boeing assumed for the spacecraft were atypical. For example, the analysis estimated

Figure 3-5-if a Satellite Were Allowed To Be Heavier, It Could Cost Less



SOURCE: Estimates from Lockheed Missiles and Space Co., 1971, plotted by Office of Technology Assessment, 1990.

Figure 3-6-The Effect of Reducing Launch Cost on the Optimal Weight and Cost of a Payload



Boeing Aerospace Co. estimated that, if average launch cost per pound were reduced from $3,600 per pound, it would be economical to redesign a hypothetical payload to allow it to be heavier by the weight-growth factor indicated and less costly by the cost-reduction factor indicated. Boeing assumed that the original design minimized the sum of payload and launch costs at a launch cost of $3,600 per pound, and that the average launch cost per pound does not depend on the payload weight.

SOURCE: Boeing Aerospace Co., 1988.

33 Only part of the savings estimated for the second case was attributed to payload growth; the rest was attributed to reduced launch cost and to services that only a reusable vehicle such as the Shuttle could provide: intact abort capability, on-orbit checkout, repair, and refurbishment. Additional savings in both cases were attributed to use of improved technology.

34 Total program costs, excluding launch costs, divided by the number of satellites launched (6 OAO-B, 20 SEO), inflated to fiscal year 1988 dollars by OTA.

35 Eder, *op.* cit., footnote 8.

36 Advanced Launch System (ALS) program officials have misquoted this result, saying a 50-percent cost reduction would require 70 percent weight growth. See, e.g., Thomas M. Irby, "Status of the ALS Program," *Space Systems Productivity and Manufacturing Conference-V* (El Segundo, CA: The Aerospace Corp., 1988), p. 30.

37 The ratio was allowed to change when the payload was redesigned with relaxed weight constraints.

the cost and weight of the satellite's electric power subsystem by assuming it consisted entirely of solar cells (which typically dominate the *cost* of a satellite's power subsystem), with no batteries (which typically dominate the *weight* of a satellite's power subsystem).

Some of the proposed cost-reducing and weight-increasing substitutions Boeing proposed--e. g., substitution of commercial-grade solar cells for spacecraft-grade (S-class) solar cells—would decrease payload reliability and expected lifetime to an extent not estimated by Boeing. Thus Boeing did not estimate weight-versus-cost trade-offs for equal reliability; some of the savings Boeing attributed to weight growth should have been attributed to reduced reliability .38 Therefore, the savings Boeing attributed to weight growth may be upper bounds for spacecraft of the type Boeing considered.

Another recent bottom-up analysis estimated cost-versus-weight trade-offs for some subsystems but not for complete payloads.[39] Like earlier studies by Lockheed[40] and the Aerospace Corp.,[41] it identified payload "cost drivers"—i.e., costly payload components or testing-and recommended changes in payload design, components, testing, or operations that might reduce space program cost. Many of these changes would require increasing the weight of the payload (the "fatsat" approach discussed here) or specifying a simpler or easier mission, or fewer missions (the "lightsat" approach discussed in chapter 4).

A Comparison of Parametric and Bottom-Up Analyses

Estimates differ on how much cheaper payloads could be if they were allowed to grow to a specified weight, and how much they should grow if cost per launch were reduced to a specified amount. One parametric estimate by OTA predicts that a hypothetical expensive payload as heavy as a Titan IV could launch could cost about $130 million less if allowed to be five times as heavy. It would be economical to design the payload to be so heavy if it could be launched for less than about $100 million.[42] Less would be saved if the baseline payload cost were comparable to or less than the average Titan IV launch cost, estimated hereas$117 million. The only bottom-up estimate that could be compared to these is one by Boeing, which predicts much greater savings (at least 76 percent, or $760 million for a billion-dollar payload) but is based on a conceptual design for a payload that is atypical in important respects; moreover, the redesigned payload was allowed to use less reliable components, and launch cost per pound was assumed to be independent of payload weight.

OTA also derived parametric estimates to compare to detailed bottom-up estimates by Lockheed for two spacecraft. Lockheed estimated 66 percent greater savings for one spacecraft (SEO), and 360 percent greater savings for the other (OAO-B), but attributed to weight growth some savings that should have been attributed to optimization of the baseline designs. However, these discrepancies are comparable to the unexplained statistical variations often encountered in spacecraft cost estimation. The less detailed Boeing estimate, if applicable, would predict much greater savings than predicted by OTA: 530 percent more for OAO-B, and at least 630 percent more for SEO, at the weight growth factor proposed by Lockheed.[43]

ACHIEVING POTENTIAL COST REDUCTION

Realizing most of the potential savings predicted by these estimates will probably require creation of incentives to dissuade satellite program managers and designers from adding capability, and thereby weight, until launch vehicle lift margin, engine-out

[38] Lockheed did so and estimated how man, satellites would be required to provide comparable mission performance for 10 years. Lockheed concluded that use of S-class components, which would maximize expected satellite life and minimize the number of replacements required, would be most cost-effective.

[39] Hughes Aircraft Co., op. cit., footnote 8.

[40] Lockheed Missiles and Space Co., op. cit., footnote 9.

[41] *Spacecraft Cost* Drivers *Study—Final Report: Phase 1* (El Segundo, CA: The Aerospace Corp., October 1983).

[42] The Advanced Launch System is intended to launch such payloads for much less.

[43] However, Boeing estimated that it would not be economical to seek the extreme cost reduction predicted for SEO unless launch cost per pound were reduced by a factor of 36.

Box 3-A—Fatsats: The Good and Ugly, and the Bad

HEAO—During a budget crunch, NASA took steps to repackage its High-Energy Astronomical Observatory instruments, designed for two Titan payloads, into three Atlas-Centaur payloads. This reduced launch costs by about 2 x $125K -3 x $60K = $70K in today's dollars, by TRW's calculation. It also created extra weight margin. This allowed designers to design the spacecraft with high safety factors (strength margin etc.), so that they could dispense with the costly construction and testing of model and qualification spacecraft.[1]

Phobos 1 & 2-In July 1989, two science spacecraft, Phobos 1 and Phobos 2, were launched from the Soviet Union toward Phobos, the larger of the two moons of Mars. Their busses were designed and built in the Soviet Union, as were some of their instruments; other instruments were designed in Austria, France, Sweden, Switzerland, West Germany, and several East European nations participating in Project Phobos. Some of the Soviet instruments were designed with generous weight margins. Jochen Kissel, a West German member of the project's scientific council, said, "We could use standard printed circuit boards rather than ultraminiaturized parts . . . It made everything cheaper and simpler.

Nevertheless, because of greater-than-expected weight growth, some instruments were removed from one or the other spacecraft. The two spacecraft were originally intended to carry identical suites of instruments, so that Phobos 2 could perform all functions of Phobos 1 in case Phobos 1 failed, or vice versa.

As it happened, Phobos 1 did fail. More accurately, contact with Phobos 1 was lost late in 1988, because an erroneous command was transmitted to Phobos 1 from the ground. To compensate for the loss, mission directors planned to command Phobos 2 to rendezvous with Phobos rather than proceeding to the smaller Martian moon, Deimos, as it would have had Phobos 1 succeeded. Phobos 2 lacks the radar mapper, neutron spectrometer, and solar x-ray and ultraviolet telescopes of Phobos 1, but carries an infrared spectrometer and a hopping lander which Phobos 1 lacks.[3]

Ironically, contact with Phobos 2 was also lost on March 27, 1989, about two weeks before the planned encounter with Phobos was to occur (on April 9-10).[4] Nevertheless, Phobos 2 gathered a significant amount of data before this failure. This anecdote illustrates the value of generous weight margins on some instruments, the cost of negative weight margins on other instruments and on the spacecraft as a whole, the value of redundant spacecraft, and the risks of human errors and compound failures.

Milstar-Milstar is an advanced communications satellite being built for the Department of Defense. A few will be built—fewer than originally planned—allowing nonrecurring program costs to be amortized over a few satellites. Aside from this economy, Milstar appears to exemplify the antithesis of the fatsat philosophy: it is designed to be large in order to cram it with capability, not to reduce its cost. It has had to be redesigned at least once to reduce its estimated weight and add margin. Costly edge-of-the-art technologies have been adopted to reduce weight, and some are so risky that additional greater-than-expected cost and weight growth could occur.

Milstar was made fatter to be better, not cheaper, and its gross weight kept growing. A subsystem designer quipped, "Milstar is going to gross everybody out. "

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1 TRW, briefing, Nov. 16, 1989. See also *Science, vol.* 199, Feb. 24, 1978, p. 869, and *Astrophysical/Journal, vol.* 230, June 1, 1979, P. 540.

2 Eric J. Lerner, "Mission to Phobos,'' *Aerospace America*, September 1988, pp. 34-39.

3 Ibid., and ''Phobos 1 Loss to Change Mars Mission,'' *Aviation Week and Space Technology*, Oct. *3, 1988,* p. 29.

4 ''Soviets Lose Contact With Phobos 2 Spacecraft," *Aviation Week and Space Technology*, Apr. 3, 1989, p. 22.

capability, and reliability are reduced, requiring expensive weight reduction programs for redress. The managers of satellite programs funded by line-item appropriations have little incentive to spend less than the amount appropriated. When funding allows, spacecraft purchasers, with rare exceptions, opt to increase performance rather than reduce cost.

Chapter 4
Lightsats

Lightsats are satellites that are light enough to be launched by small launch vehicles such as a Scout or Pegasus, or others now in development. Military lightsats could be designed for wartime deployment or replenishment from survivable transportable launchers to support theater commanders. Civil lightsats, and some military ones, would not require transportable launchers; they could be launched by a wider variety of launch vehicles, including larger ones.

The first Soviet and U.S. satellites were lightsats, according to this definition. Explorer I, the first U.S. satellite, weighed only 31 lb but collected data that led to the discovery of the Van Allen radiation belt. But in another sense, the first satellites were fat—as heavy as early launch vehicles could launch. As larger launch vehicles were developed, larger, more capable satellites were developed to ride them. Nevertheless, small satellites continue to be launched for civil and military applications that require only simple functions.

Interest in lightsats has grown recently,[1] partly in anticipation of new rockets designed to launch them at low cost, and, in the case of military lightsats, because of a desire for a survivable means of launching satellites-e.g., transportable launch vehicles too small to launch large satellites.[2]

A few years ago the Defense Advanced Research Projects Agency (DARPA) began to examine lightsats, initially to demonstrate the ability of simple and inexpensive satellites to perform simple but useful tasks, and, more recently, to demonstrate the utility of satellites small enough to be launched from transportable launchers to support theater commanders during a war. DARPA is considering concepts for several types of lightsats--for communica-ions, navigation, radar mapping, and targeting. The Army, Navy, or Air Force may choose to procure similar lightsats for operational use. They would be designed to be affordable as well as small, because many might be needed for replenishment after attrition. “With lightsat, we can undoubtedly put up satellites for less money than it will cost the Soviets to shoot them down,’ said Dr. John Mansfield, while Director of DARPA’s Aerospace and Strategic Technology Office.[3]

SPACECRAFT CONCEPTS

The first lightsat developed by DARPA’s Advanced Satellite Technology Program was a communications satellite, the Global Low-Orbit Message Relay (GLOMR; see figure 4-l). Weighing only 150 lb, GLOMR was launched by the Space Shuttle on October 31, 1985, into a 200-mile-high orbit inclined 57 by degrees.

DARPA has ordered nine more UHF communication satellites from Defense Systems, Inc., the contractor that built the GLOMR. Seven of these, called Microsats, will weigh approximately 50 lb each. These satellites will be launched together into a polar orbit 400 nautical miles high by the Pegasus launch vehicle. Once deployed, they will spread out around the orbit. They will carry ‘‘bent-pipe’ radio repeaters—i.e., the messages they receive will be retransmitted instantaneously to ground stations. The other two satellites will be larger “store/foreward" satellites called MACSATs (forMultiple-Access Communication Satellite). They will weigh about 150 lb each and will be launched together on a Scout launch vehicle. They will store messages received from ground stations and forward (or “dump”) them when within range of the ground stations to which the messages are addressed. The bent-pipe satellites and the first store/foreward satellites will cost DARPA about $8 million excluding launch costs.

Amateur (“ham”) radio operators have built a series of small satellites carrying radio beacons or repeaters, the first of which, OSCAR I, was launched in 1961. Since 1969, the nonprofit Radio Amateur Satellite Corp. (AMSAT) and its sister organizations worldwide[4] have built or designed several of these for scientific, educational, humanitarian, and recreational use by hams. AMSAT, which has only one paid employee, is now building four 22-pound

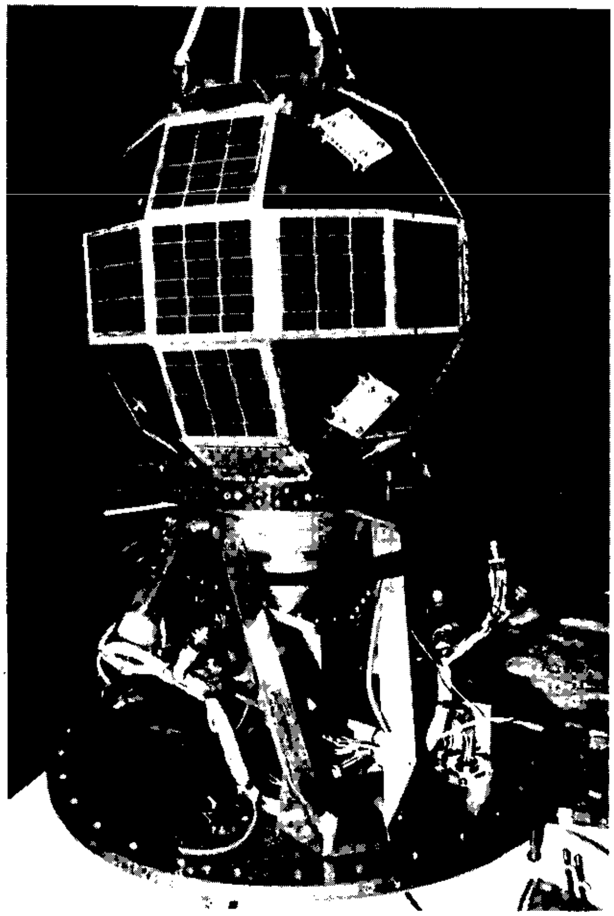
[1]See, e.g., A.E. Fuhs and M.R. Mosier, ‘‘A Niche for Lightweight Satellites,’ *Aerospace America,* April 1988, pp. 14-16., and Theresa M. Foley, “U.S. Will Increase Lightsat Launch Rate to Demonstrate Military, Scientific Uses, ’ *Aviation Week and Space Technology,* Sept. 26, 1988, pp. 19-20.

[2]There is no consensus on whether this is the best approach to assuring continued mission performance in wartime.

[3]Quoted by James W. Rawles, “LIGHTSAT: All Systems Are Go,” *Defense Electronics,* vol. 20, No. 5, May 1988, p. 64 ff.

[4]AMSAT-North America has sister organizations i n Argentina, Australia, Brazil, Britain, @-many, Italy, Japan, Mexico, and the Netherlands. The Soviet Union has also launched satellites for amateur radio operators.

Figure 4-l-The Global Low-Orbit Message Relay (GLOMR) Satellite



SOURCE: Department of Defense.

(l0-kilogram) communications satellites called Microsats[5] (figure 4-2). (These Microsats are unrelated to the above-mentioned Microsats developed for DARPA and to the "microspacecraft" discussed in the next part of this report.) All four satellites are designed to receive, store, and forward digital messages using a technique called packet communications. All four use a standard bus, the Microsat bus. One of the satellites, called PACSAT, is being built for AMSAT. An almost identical satellite called LUSAT is being built for a sister organization, AMSAT-LU, in Argentina. A third satellite, nicknamed Webersat, will carry, in addition to its packet radio repeater, a low-resolution color TV camera designed at the Center for Aerospace Technology at Weber State College in Logan, UT. The fourth satellite, Digital Orbiting Voice Encoder (DOVE), was built for BRAMSAT (AMSAT-Brazil). It will carry a digital voice synthesizer to generate voice messages that can be received by students using inexpensive "scanner' radios.[6]

AMSAT contracted with Arianespace to launch these four satellites together for $100,000. The Ariane 4 launch vehicle will also deploy the UoSAT-D and UoSAT-E amateur-radio satellites built at the University of Surrey in England in addition to the four Microsats and its primary payload, the SPOT 2 photomapping satellite.[7] The launch, originally scheduled for June 1989, has been postponed until January 1990, at the earliest.

Microsats are among the smallest communications satellites ever built. They are lightsats, because they are designed to perform relatively simple functions. But they are also fatsats, because they are heavier and larger than they would be if built by methods usually used for more conventional (and more expensive) satellites. Assembly of some Microsat subsystems is literally a cottage industry. Although some printed circuits are being built for Microsats by a contractor using high-tech methods, others are being built in the homes of Amateur radio operators all over the country. When they volunteer to assemble printed circuits, AMSAT sends them the instructions.

CONCEPTS FOR PHASED ARRAYS OF SPACECRAFT

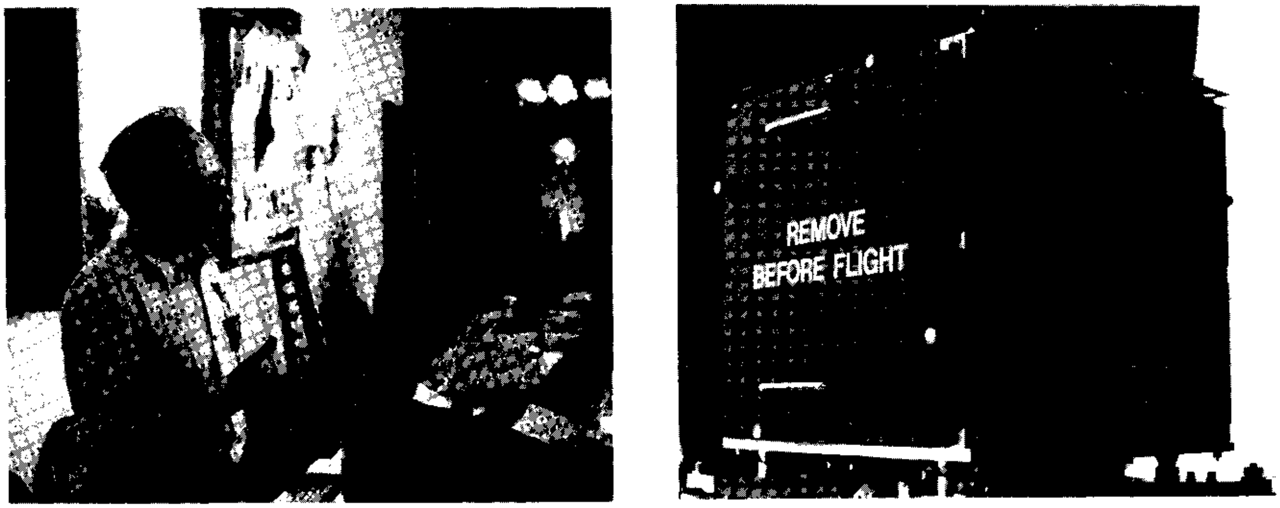
Groups of small satellites could collectively provide communications or radar capabilities that could otherwise be provided only by a large satellite. To do so they would have to operate coherently as elements of a phased array: all satellites must relay the signals they receive to a satellite or ground station that can combine them in a way that depends on the relative positions of the satellites, which must be measured extremely accurately. When transmitting, the satellites must all transmit the same signal,

[5] See Courtney Duncan, "The AMSAT-NA Microsats,'' 73 *Amateur Radio,* May 1989, pp. 83-84, and Doug Loughmiller and Bob McGwier, "Microsat: The Next Generation of OSCAR Satellites—Part l," *QST*, May 1989, pp. 37-40.

[6] The digital voice synthesizer is similar to the DIGITALKER developed at the University of Surrey in England for use on the UoSAT-OSCAR-9 and UoSAT- OSCAR-11 amateur-radio satellites built there.

[7] Jeff W. Ward, "Experimental OSCARS," *QST, May* 1989, p. 62 ff.

Figure 4-2--Microsat: A 22-lb Communications Sa e e o Amateu Ham Rad o Ope ato s



(1) Flight model beside Leonid Labutin, UA3CR.
(r) Close-up view. (Copyright Radio Amateur Satellite Corp.)
Photos: Andrew C. MacAllister, WA5ZIB.

but each satellite must delay its transmission by a period that depends on its relative position.

The Air Force has considered "placing large phased arrays in space with major components of the arrays not rigidly connected to each other" (see figure 4-3), because "If we can achieve coherence among these components, phased arrays can be spread out over very large volumes in space, giving them an unprecedented degree of survivability. It therefore may be possible to create a phased-array device (e.g., a space-based radar) that we can place into space and enhance simply by adding more relatively inexpensive elements whenever the threat increases and budget pressures permit."[8] If small enough, each element could be launched by a small launch vehicle.

If a large radar or communications satellite were divided into several modules, "crosslink" equipment for communications among the modules would have to be provided, which would add some weight and cost. Aside from this, historical cost data indicate that a communications mission payload might cost less if divided into several smaller payloads of equal aggregate weight and power.[9] The same might be true of radar equipment. Each module would need its own bus, but the cost data also indicate that several small busses would probably cost less, or no more, than a single bus of equal aggregate weight.[10] Learning and production-rate effects could make the small modules and busses even less expensive. Economies of scale in launching might make it economical to launch as many as possible on a large launch vehicle, but they could be launched individually on small launch vehicles if desired-e. g., in wartime, if peacetime launch facilities have been damaged.

Coherent operation of several satellites requires relative positions to be measured with errors no greater than a fraction of a wavelength of the radiation to be sensed or transmitted. The accuracy required for coherent operation of several satellites as a microwave radar or radiotelescope has already been demonstrated.[11] Coherent operation of several

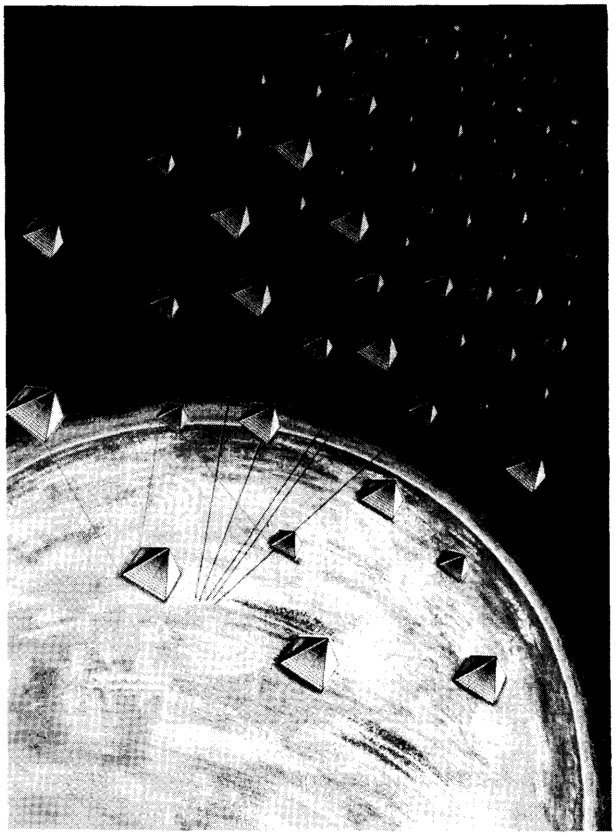
[8] Headquarters, Air Force Systems Command, *Project Forecast II Executive Summary* (Andrews Air Force Base, MD: Headquarters, Air Force Systems Command, undated). This concept is described in greater detail in the classified final report. AFSC-TR-86-008; see pp. PS-30.01 to PS-30.19 of Annex D of vol. IV, which authorized readers may request from the Defense Technical Information Center (accession number AD-C039 642).

[9] P. Hillebrandt et al., *Space Division Unmanned Space Vehicle Cost Model Sixth Edition*, SD TR-88-97 (Los Angeles AFB, CA: Headquarters, Space Systems Division, U.S. Air Force Systems Command, November 1988); distribution limited to U.S. Government agencies only.

[10] Ibid.

[11] M.A. Dornhein, "TDRS, Ground Antennas Link for Radio Astronomy Observations," *Aviation Week and Space Technology*, Dec. 1, 1986, pp. 32-33.

Figure 4-3—Sparse Array of Satellites Could Provide Detailed Radar Maps (Artist's Concept)



SOURCE: U.S. Air Force.

satellites as a ladar or optical telescope is beyond the state of the art. However, someday it may be feasible to launch several telescope modules, each smaller than the Hubble Space Telescope, and assemble them in space (or allow them to assemble themselves) into a rigidly connected phased array[12] that would operate as an optical telescope with better light-collecting capability and resolution than the Hubble Space Telescope. If technology advances further, two or more such arrays, not rigidly connected to one another, could operate coherently to further increase light-collecting capability and, especially, resolution.[13]

A scientist at the Jet Propulsion Laboratory (JPL) of the California Institute of Technology (CalTech) has proposed a less ambitious phased-may radiotelescope that could be begun today: an Orbiting Low-Frequency Array of 6 or 7 satellites in a formation 200 km across (see figure 4-4). It could map astronomical sources of radio signals with wavelengths longer than 15 meters; such signals cannot penetrate the Earth's ionosphere to reach ground-based radiotelescopes. The angular resolution of the proposed array could be comparable to that of a dish antenna 200 km across. JPL estimates that each satellite would cost about $1.5 million and weigh less than 90 kg (200 lb) if cylindrical, or 45 kg (100 lb) if spherical[14] They must be launched to a circular orbit at least 10,000 km high, so the equivalent weight to low orbit would be about 170 lb for the spherical satellite.

LAUNCH REQUIREMENTS

Operational launchers for military lightsats must meet several requirements, the most distinctive being survivability in high-intensity (if not nuclear) conflict. Such survivability is required of U.S. strategic and theater missile launchers, and operational lightsat launchers might adopt some of their features. Like the rail-mobile launcher for the Soviet SS-24 intercontinental ballistic missile (ICBM), the similar launcher being developed for U.S. Peacekeeper (M-X) ICBMs, and the Hard Mobile Launcher being developed for the Small ICBM ("Midgetman"), lightsat launchers could pursue survivability through mobility. They could also employ concealment, as do the Pershing 2 launcher and submarines (e.g. Trident) that launch ballistic missiles.

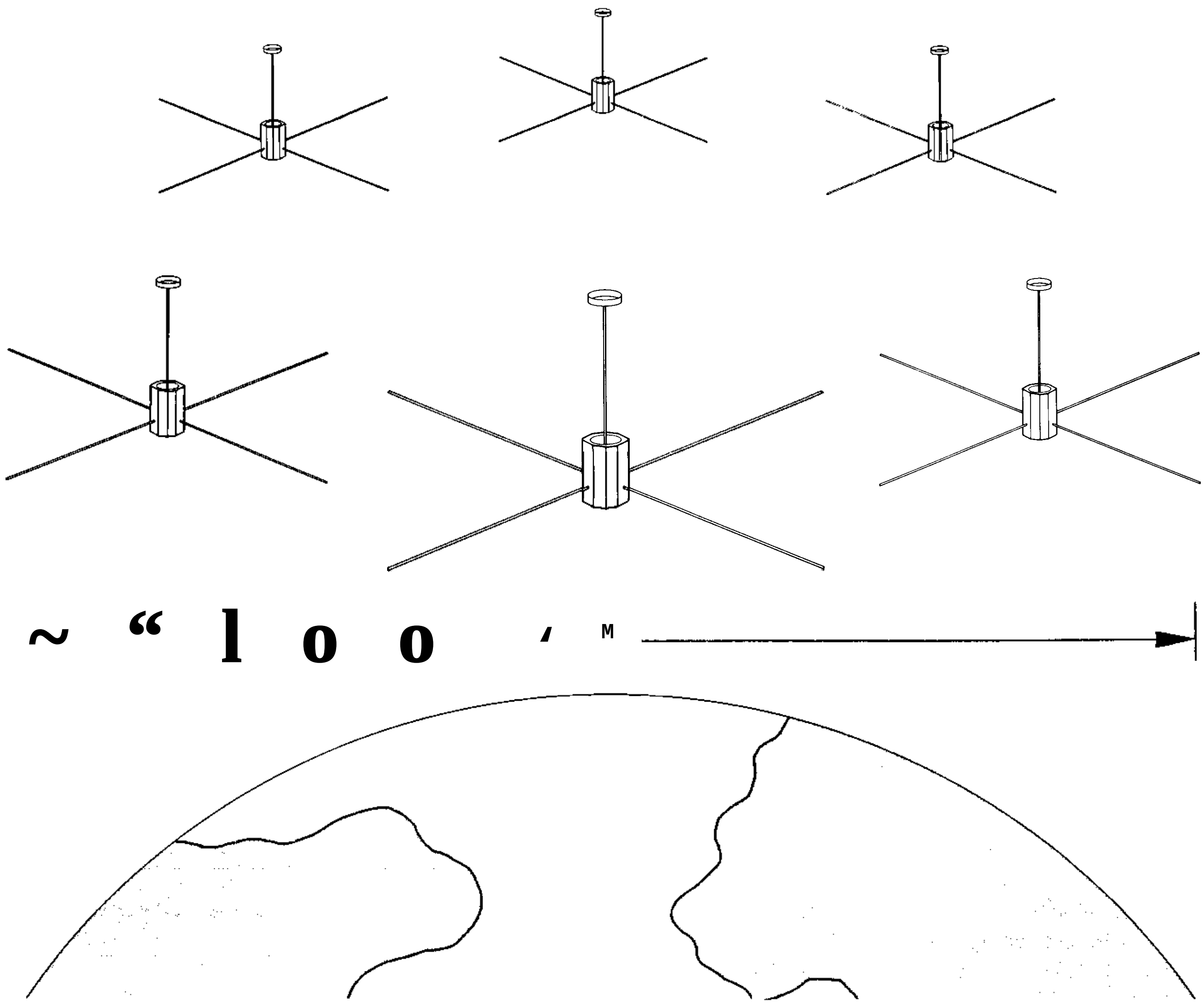
Operational military lightsat launchers would probably be required to launch on short notice and to sustain higher launch rates than typical space launch facilities do. On the other hand, lightsat launch vehicles would be useful with less lift capability than most launch vehicles have, although DARPA has said the Scout launch vehicle lifts too little to be useful as an interim launch vehicle for launching developmental lightsats, and the Scout does not have the survivability and launch rate desired for wartime use. The Pegasus launch vehicle may provide an innovative means of improving launch flexibility and survivability.

[12] Such as the proposed Coherent System of Modular Imaging Collectors (COSMIC) described by the National Research Council in Space *Technology to Meet Future Needs* (Washington, DC: National Academy Press, 1987), p. 39.

[13] Ibid.

[14] Tom Kuiper, "Sub-millimeter Waves, " in NASA/OAST & SDIO/IST, *Micro Spacecraft for Space Science Workshop-Presentations*, California Institute of Technology Jet Propulsion Laboratory, July 6-7, 1988; pp. 136-142.

Figure 4-4-Orbiting Low-Frequency Array of Radioastronomy Satellites (Artist's Concept)



SOURCE: California Institute of Technology, Jet Propulsion Laboratory.

Civil lightsats and developmental military lightsats would not require transportable launchers.

LAUNCH SYSTEM OPTIONS

Existing Launch Vehicles

Civil lightsats, or developmental military lightsats, could be launched-alone or co-manifested with other payloads-on currently operational launch vehicles larger than the Scout. If they are small enough, they could be launched by the Scout.

Air-Launched Vehicles

The communications satellites now being developed by DARPA are very light; several can be launched on the Pegasus air-launched vehicle (ALV). The Pegasus ALV is being developed by Orbital Sciences Corp. (OSC) and Hercules Aerospace Corp. as a $50 million privately funded joint

Figure 4-5-Pegasus Launch

The Pegasus air-launched vehicle is released from a modified B-52 aircraft operated by NASA's Dryden Flight Research Facility (artist's concept).

SOURCE: Orbital Sciences Corp.

venture. DARPA will pay OSC $6.3 million to provide the launch vehicle for a government demonstration launch. This price includes neither the cost of using NASA's B-52 as an ALV carrier (see figure 4-5) nor the cost of safety support from the Air Force's Western Test Range. Pegasus is expected to be able to launch a 335-kg (738-lb) payload into an orbit 500 km (270 nmi) high and inclined 25 degrees, or a 244-kg (537-lb) payload into a polar orbit 500 km high (see figure 4-6).

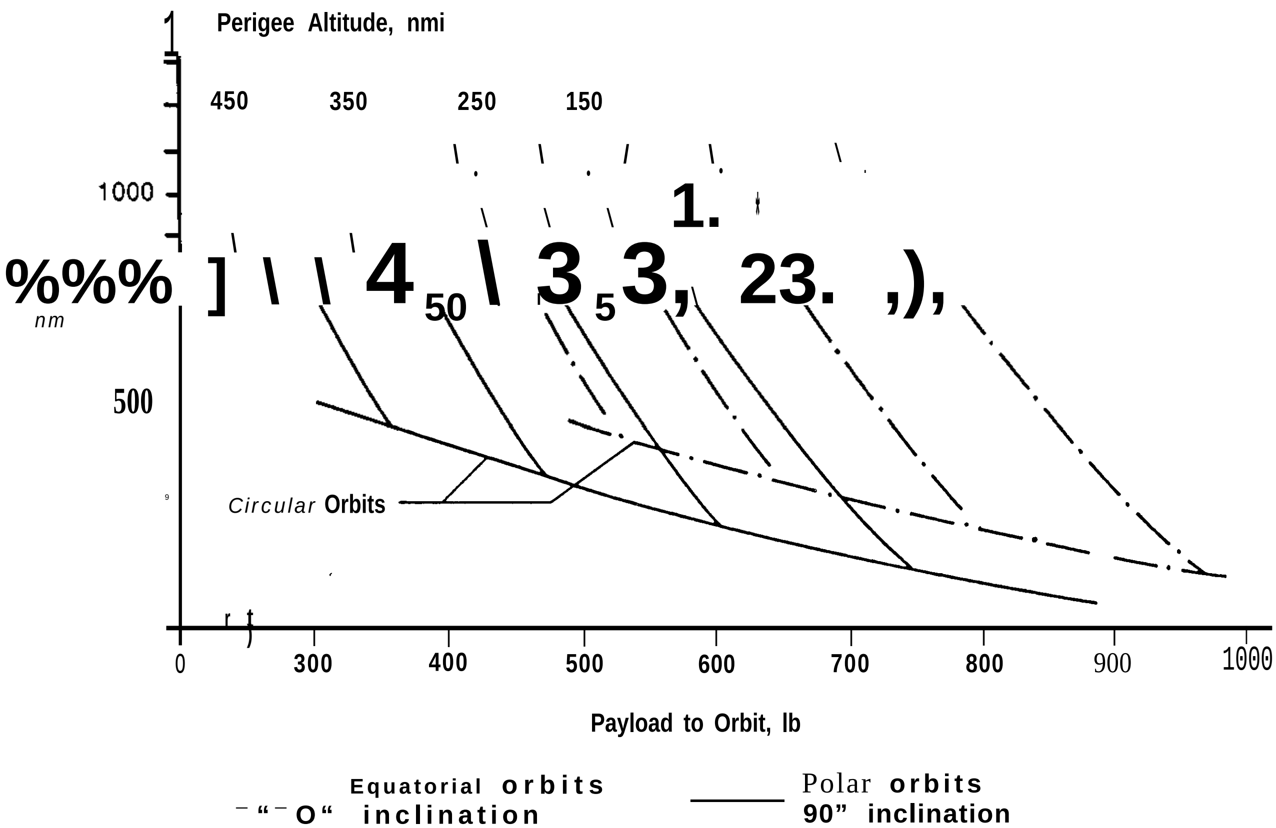
DARPA originally intended to launch the Microsats on the first Pegasus launch, but has decided to launch them on the second launch, perhaps late in 1989. On its first flight, now scheduled for January 1990, Pegasus will carry:

1. a 150-lb Navy communication satellite,
2. a NASA scientific experiment payload, and
3. instrumentation to evaluate the performance of the ALV.

DARPA's contract has four launch options remaining, and OSC has offered to add six additional launch options to the contract.

OSC and Hercules also expect Pegasus can launch lightsats into geostationary orbit; they recently signed an agreement with Ball Aerospace to launch two BGS-1OO Ball geostationary satellites in late 1990 or early 1991. OSC estimates each launch will cost between $6 million and $8 million, and that each of the satellites, which will weigh about 400 lb and carry a 400-watt single-channel transponder, will cost between $5 million and $8 million. OSC estimates each mission (satellite, launch, and support) will cost about $20 million. The satellite design

Figure 4-6-Projected Performance of Pegasus: Payload v. Orbital Altitude and Inclination



SOURCE: Orbital Sciences Corp.

is modular; Ball is developing larger versions with more transponders or more power per transponder.[15]

Standard Small Launch Vehicle

Last year, DARPA issued a Request for Proposals to develop a transportable ground-launched Standard Small Launch Vehicle (SSLV) capable of launching 1,000 lb of payload to a polar orbit 400 nmi high. DARPA recently awarded a contract to Space Data Corp. (a subsidiary of OSC) for development, one launch (from Vandenberg Air Force Base in the fall of 1991), and options for four more. The first stage of the vehicle proposed by Space Data Corp. will use a solid rocket motor developed for the Peacekeeper ICBM by Morton Thiokol. The second, third, and fourth stages will be the first, second, and third stages of Pegasus, without the wings. OSC is also developing a commercial version of the SSLV, called Taurus.

Other small launch vehicles have been developed or proposed by companies that performed Phase 1 SSLV studies for DARPA. Space Services, Inc. (SSI) developed a launch vehicle called Conestoga, which uses clustered Castor solid rocket motors. The first Conestoga was successful on a sub-orbital flight, but the second failed shortly after launch on November 15, 1989. LTV Aerospace, which produces the Scout, could produce an upgraded version. Lockheed Missiles and Space Co. proposed a launch vehicle that would use the first- and second-stage motors from Poseidon C3 fleet ballistic missiles and Morton Thiokol Star 48 motors for the third stage. Lockheed estimated that the vehicle could be available in two years and could launch a 770-lb

[15] "Pegasus, Ball to Launch Communication Satellites Into Geosynchronous Orbit," *Aviation Week and Space Technology*, June 12, 1989, p. 64, and *Military Space*, June 19, 1989, p. 8.

payload from a land-based launcher to a 250-mile high orbit inclined 28 degrees.[16]

Other Options

The U.S. Naval Research Laboratory (NRL) is developing a concept for a sea-launch system to launch a partially submerged launch vehicle from a platform towed out to sea.[17] This system, called SEALAR (SEA Launch And Recovery) might provide the survivability required by lightsats. Sea-launch systems have been tested, to different degrees, by the U.S. Navy (Project Hydra), Truax Engineering[18] (SEA DRAGON, SUBCALIBER), and StarStruck (now American Rocket Co.). DARPA is not known to be considering a sea-launch system for its Advanced Satellite Technology Program, but such a system might prove attractive to the Navy in the future.

Storage, shipment, and mobile basing of small launch vehicles could be made safer by using hybrid rocket motors—rocket motors that use liquid oxygen to burn solid fuel, which can be inert (nonexplosive). American Rocket Co. (AMROC) of Camarillo, CA, has developed a throttleable, restartable, 70,000-lb thrust hybrid rocket motor, the H-500. On its first launch attempt (October 5, 1989), the motor failed and the prototype sounding rocket it was to power collapsed and burned at Vandenberg Air Force Base, CA. It is noteworthy that it did not explode, and did very little damage to the pad.

The sounding rocket, a prototype of AMROC'S planned Industrial Research Rocket, carried a payload designed by AMROC for a Strategic Defense Initiative experiment and a prototype reentry vehicle developed by the Massachusetts Institute of Technology (MIT) Space Systems Laboratory. The reentry vehicle was to deploy an umbrella-like structure made of space-suit material and decelerate to a soft landing in the Pacific Ocean, where it was to be recovered.

AMROC is developing a larger sounding rocket and an even larger Industrial Launch Vehicle, the largest version of which is being designed to launch a 4,000-lb payload into low Earth orbit. AMROC is not specifically designing the launch vehicle for survivable basing (although this is not precluded) and has not entered DARPA's SSLV competition. Before the sounding rocket failure, AMROC expected a frost launch late in 1990.

AMROC is also developing a larger hybrid motor for a larger launch vehicle, as well as a smaller hybrid motor for various applications, possibly including use on projectiles launched from electromagnetic launchers (discussed below).

General Technology Systems (GTS) is developing a small launch vehicle called LittLEO to launch lightsats. It is expected to be able to launch almost a tonne (2,200 lb) of payload into a polar orbit 300 kilometers (162 nautical miles) high. First launch is planned for 1992, probably from Andoya, Norway. GTS quotes a price of nine million pounds sterling per launch, which is equivalent to roughly $6,400 per pound to LE0.[19]

E'Prime Aerospace Corp. (EPAC) is developing a series of launch vehicles for launching payloads weighing from 1,000 to 20,000 lb into LEO and up to 8,000 lb into geostationary Earth orbit (GEO). EPAC quotes a prices of $12 million per launch for the smallest launch vehicle and $80 million for the largest.[20] EPAC plans to launch from Cape Canaveral Air Force Station, FL, and from Vandenberg Air Force Base, CA. A first launch is planned for 1992.

The Soviet Union is developing a launch vehicle called "Start" for launching lightsats. Start would use guidance and propulsion systems developed for the SS-20 ballistic missile and could be launched from a mobile launcher, carrying 300-lb payloads to orbits 500 km high. Space Commerce Corp., in Houston, is seeking customers for Technopribor, which is developing Start, and quoting a price of about $5 million to $6 million per launch. Technopribor estimates a test launch could be conducted in 1991.

Lightsats can also be launched as "piggyback" payloads on launch vehicles carrying larger primary payloads. Many U.S. and foreign launch vehicles have done this for years. Arianespace has developed

16"Lockheed Will Develop Small Military Booster Using Poseidon C3 Hardware," *Aviation Week and Space Technology,* Sept. 26, 1988, p. 18.

17NRL, Naval Center for Space Technology, briefing for OTA staff, Feb. 17, 1989.

18Capt. Robert C. Truax, USN (ret.), "Commercial View on Launch Vehicles," *Space Systems Productivity and Manufacturing Conference [V* (El Segundo, CA: Aerospace Corp., Aug. 11-12, 1987); pp. 55-69.

19Ian Parker, "Getting There Cheaply," *Space,* vol. *5, No. 4,* July-August 1989, pp. 45-48.

20Ibid.

procedures to do so routinely with the Ariane 4 launch vehicle, which, as noted above, is scheduled to launch six amateur-radio satellites in addition to the SPOT 2 photomapping satellite on January 19, 1990. General Dynamics is planning to offer a similar service using its commercial Atlas launch vehicle, which could launch, in addition to a primary payload, one 3,000-lb satellite or several smaller lightsats to LEO, or a 2,000-lb payload to geostationary transfer orbit.[21] This service could be offered in late 1991 for about $6,000 per pound to LEO; the primary payload owner may reserve the right to approve the price offered.[22]

Someday, small lightsats might be launched on laser-powered rockets (discussed below). Lightsats could also be launched on vehicles proposed for launching larger payloads or crews--e.g., the Advanced Launch System, the Advanced Manned Launch System, and NASP-derived vehicles.[23] Of these, only National Aero-Space Plane (NASP)-derived vehicles (NDVs) are intended to provide a survivable capability for wartime launch.

ISSUES

Are lightsats the most economical answer to the problem of satellite vulnerability? Replenishing satellites in wartime is only one of several partial solutions; others include hardening satellites and stockpiling spare satellites in orbit during peacetime,[24] as well as arms control, actively defending satellites, and reducing reliance on satellites for support of military operations.[25]

What military requirements could lightsats satisfy? An Air Force officer responsible for space system planning said, "The challenge to the small satellite community has been to get out of the mold of a solution looking for a problem; that is, what missions will a small satellite support."[26] According to the previous Secretary of the Air Force, "The decision on whether a system is 'small' depends on such things as orbit, mission, requirements, and technology capabilities. When these factors properly converge, we have built Smallsats . . . . What we want are a realistic set of requirements and concepts for smaller systems."[27] Several concepts have already been proposed, the most grandiose of which are being considered by the Strategic Defense Initiative Organization: ''BrilliantPebbles" or larger space-based missile interceptors, "Brilliant Eyes" (space-based space-surveillance satellites that would demonstrate Brilliant Pebbles technology—see box 4-A), decoys for Brilliant Pebbles, and "Small Dumb Boosters" (orbital transfer stages with which Brilliant Pebbles could rendezvous and mate).

Could lightsat technology and launch vehicles benefit civil applications? They already have. For example, for two decades amateur radio operators have built and used lightsats for recreational, educational, and public-service communications. Conceivably, networks of tens or hundreds of lightsats could provide continuous global communications or navigation services commercially. There is some commercial interest in concepts that would require only a few lightsats.[28][29]

Since Sputnik I and Explorer I, science has benefitted from lightsats and will continue to benefit-more so if launch costs are reduced. Medium-sized multi-mission remote-sensing satellites have used some instruments, such as the Scanning Multichannel Microwave Radiometer on Seasat-1,[30] that are light enough to be mated to a

21 To reach geostationary orbit (GEO) from geostationary transfer orbit (GTO), the payload must have an orbital transfer stage.

22 Ian pinker, op. cit., footnote 19.

23 See U.S. Congress, Office of Technology Assessment, *Round Trip to Orbit: Human Spaceflight Alternatives*, OTA-ISC-419 (Washington, DC: U.S. Government Printing Office, August 1989).

24 See, for example, the speech that the Honorable Edward C. AMridge, Jr., Secretary of the Air Force, prepared for a luncheon at the Aviation Club, Crystal City, VA, Sept. 15,1988, and Col. Charles Heimach, USAF, Speech to Second Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, September 1988.

25 See U.S. Congress, Office of Technology Assessment, *Antisatellite Weapons, Countermeasures, and Arms Control*, OTA-ISC-281 (Washington, DC: U.S. Government Printing Office, September 1985); reprinted in Office of Technology Assessment, *Strategic Defenses* (Princeton, NJ: Princeton University Press, 1986).

26 Col. Charles Heimach, USAF, op. cit., footnote 24.

27 Hon. Edward C. Aldridge, Jr., op. cit., footnote 24.

28 Fuhs and Mosier, op. cit., footnote 1.

29 The Center for Innovative Technology of the Commonwealth of Virginia has commissioned economists at George Mason University to assess potential markets for small satellites. This study is nearing completion.

30 A.R. Hibbs and W.S. Wilson, "Satellites Map the Oceans, " *IEEE Spectrum,* October 1983, pp. 46-53.

Box 4-A—Brilliant Eyes?

Lawrence Livermore National Laboratory (LLNL) is developing a new class of electronic high-resolution wide-angle TV cameras that, from an altitude of 1,000 km (610 mi), could image a land area the size of the state of Virginia and show individual buildings. The first prototype camera, completed in 1987, has optics that are about 1 ft in diameter and 16 in long, excluding electronics. With improved electro-optical components, its resolution would be comparable to or slightly better than that of the French SPOT satellite (about 10 m) from a comparable altitude (832 km). At a lower altitude it could show greater detail but would have a smaller field of view. On Earth, it could be used as a telescopic TV camera to record the tracks of meteors and low-altitude satellites against the night-time sky.

LLNL has also developed a preliminary design for a miniature version of this camera compact enough for use as a satellite navigation system. The system is designed to get periodic position updates by viewing many stars at the same time. The total mass of the system is expected to be less than 250 grams (about half a pound). LLNL expects that "this [wide-field-of-view] system, with its combination of high resolution and high light collection capability, will also find applications in robot vision and smart munitions.

SPOT Imagery of the Pentagon and the White House
Lightsats Could Produce Comparable Imagery

SOURCE: U.S. Geodetic Survey.

[1] *LLNL, Energy and Technology Review,* July-August 1988, pp. 88-89.

lightsat bus to become a lightsat for meteorology and oceanography. Arrays of lightsats could someday use interferometric (phased-array) and aperture-synthesis techniques to provide high-resolution radar or microwave imagery for Earth-resources mapping or "mediasat" applications.[31] This might be more economical than using a large, monolithic satellite; predicting an arrays' relative economy would require comparing cost estimates based on detailed designs.

[31] See U.S. Congress, Office of Technology Assessment, *Commercial Newsgathering From Space,* OTA-TM-ISC-40 (Springfield, VA: National Technical Information Service, May 1987).

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.

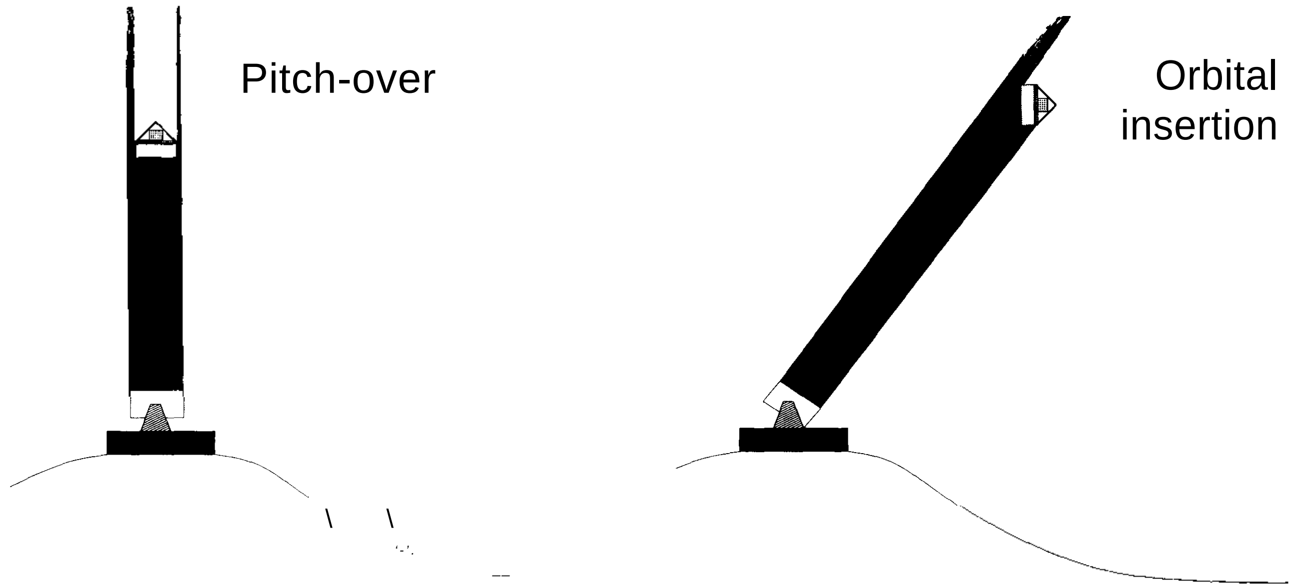
The smallness of microspacecraft has another potential advantage: some microspacecraft could be built to withstand high accelerations comparable to those endured by cannon-launched guided projectiles such as Copperhead.[3] Such "g-hardened"

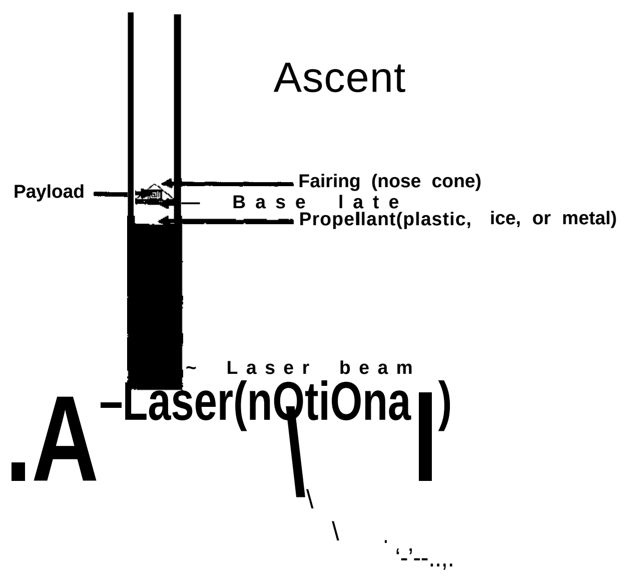
[1] See Ross M. Jones, "Coffee-can-sized spacecraft," *Aerospace America,* October 1988, pp. 36-38, and "Think small-in large numbers, " *Aerospace America*, October 1989, pp. 14-17.

[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

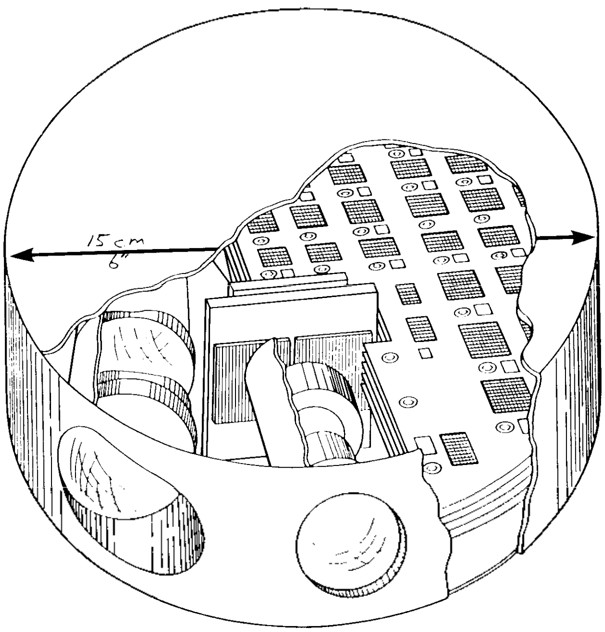
[4] So called because the projectiles, which would enclose and protect the microspacecraft (or a mission payload), would require no further propulsion after they leave the muzzle of the launch system, if launched into solar orbit or an interplanetary trajectory. A projectile would require a small rocket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

[13]U.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.

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

[15]Ibid.

[16]Ibid.

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

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

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

[20]Palmer 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	$100 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 million +$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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