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LIGHTSATS AND CHEAPSATS: THE ENGINEERING CHALLENGE OF THE SMALL SATELLITE

Military interest in survivability and restoration of assets and the dearth of flight opportunities for scientific missions have rekindled interest in small satellites. APL has played a leading role in small-satellite development since the space age began. This article examines the technology areas and management concepts that enable small satellites to perform useful missions.

INTRODUCTION

America has produced the most sophisticated space projects in the world, as exemplified by the shuttle, the Space Telescope, and the Voyager spacecraft. Many of our goals in space can be met only with large, complex, and, therefore, costly spacecraft. But somewhere along the way this nation seems to have forgotten the important role played by smaller low-cost systems. Neglect of this resource has contributed to the erosion of our space-technology base, the inefficient use of resources, and a disturbing reduction in launch opportunities. It has also left our military vulnerable to the loss of a few key satellites. Realizing this, DoD, NASA, and the commercial sector have recently begun new initiatives to better use the potentialities of small low-cost satellites. (A "small" satellite is taken here to mean less than about 500 lb. "Low cost" is usually, but not always, correlated with small size and is generally taken to mean less than about $10 to 20 million. The terms lightsat, cheapsat, and small satellite will be used interchangeably here.)

APL has specialized in small cost-effective satellites since 1959. The 51 satellites we have designed, fabricated, and launched have ranged from 112 to 1450 lb, averaging 255 lb.[1] To perform significant missions with such compact satellites, we have had to learn how to put high performance into small packages and how to make trade-offs among low cost, high reliability, and quick reaction. The renewed attention on small satellites is, therefore, of great interest to APL.

THE USE OF SMALL SATELLITES

Small satellites have application to scientific, civil, military, and commercial programs. Historically, low-cost spacecraft have allowed for timely and frequent access to space for a wide range of scientific researchers to perform advanced, and sometimes high-risk, experiments. But more recently, concentration on large, complex missions has led to increased costs and reduced launch opportunities. These missions must then impose a conservative and lengthy selection process that may limit a space scientist to participation in only two complete programs in the course of a career. More junior scientists may be excluded altogether, and they may move on to other fields. NASA has begun to address this problem with such programs as the recently announced Small-Class Explorer.

Small satellites also have served an engineering role in the development and verification of new space technology, without putting major programs at risk. Several studies (e.g., Ref. 2) have warned of America's eroding space technology base. By ignoring technology development as a legitimate mission, we have been living off our past, while other countries catch up and surpass us. A prime reason has been the limited access to space for testing new technology at low cost and reasonable risk. Using small satellites to "build a little, test a little, learn a lot" allows new technologies to be introduced incrementally and at low cost. At the same time, small satellite programs yield training opportunities for young engineers, thus broadening the nation's base of technically competent personnel.

Between the shuttle stand-down and the wait for the Space Station, America's introduction of new industrial space applications has virtually come to a halt. Here again, small satellites (including some with small reentry vehicles) could reduce the amount of capital at risk and cut the time required for a positive return on investment.

Many military space missions demand sophisticated satellites, which are necessarily costly, few in number, and tempting high-value targets in wartime. Small, less sophisticated satellites could, in time of conflict, provide survivability by proliferation. They could rapidly restore minimum military operations or perhaps launch new operations held in reserve for warfare. A constellation of lightsats operating in conjunction with a few larger geosynchronous satellites makes a particularly robust combination. A high-level DoD committee[3] has concluded that "the Soviets, far more than we, have designed their space systems in support of military operations in wartime." The Soviets understand the value of replenishment and apply it to their military space program (or, as Lenin said, "Quantity has a quality all its own.").

Military applications for small satellites include store-and-dump communications, medium-range communications, remote imaging, bistatic and distributed radar, location and targeting of ground-based signals, intelligence gathering, data relay for oceanographic and weather buoys, nodes for C^3 (command, control, and communication) networks, and activation or deactivation of munitions in the field. Lightsats can serve as valuable reconnaissance assets for Third World allies involved in lower intensity conflicts. Small satellites are easy to store and would be easier to protect on orbit with either decoys or stealth techniques. They could be launched from mobile, survivable launchers (or from aircraft) and could become operational almost instantly after launch. The DoD has begun an active effort, led by the Defense Advanced Research Projects Agency, to examine the potential military uses of lightsats.[4]

PATHS TO THE SMALL SATELLITE SYSTEM

To take full advantage of small satellite systems, four areas must be addressed: (1) suitable launch vehicles, (2) the satellites and their payloads, (3) appropriate ground-support systems, and (4) a reexamination of traditional aerospace management thinking.

Lightsat Launchers

Typically, about one-half of a new space system's cost is transportation-related. Today's high launcher costs dictate longer satellite life, higher reliability, redundant subsystems, more and stricter test programs, lengthy schedules, and so on up the cost spiral. The development of one or more new, low-cost expendable launch vehicles (ELVs) for small satellites is, therefore, essential. The ideal ELV would lift 500 to 1000 lb to low earth orbit for less than about $8 to 10 million, with insertion errors small enough that satellites would not have to carry extra propulsion. This is about twice the performance level of the current Scout ELV. The Defense Advanced Research Projects Agency has begun to develop such an ELV through its Standard Small Launch Vehicle Program.

Another source of low-cost ELVs is the reconfiguration of obsolete strategic missiles, an option that U.S. negotiators should preserve in future force reduction treaties. Conversion of 14 of the 55 available Titan-2s is already underway; each could launch several lightsats at once. Submarine-launched ballistic missiles could likewise be modified into attractive ELVs for military use.

Delta-class ELVs could launch multiple satellites simultaneously, using an appropriate dispenser. The United States has launched as many as 10 at once in the distant past, and APL-designed Navy Navigation Satellites are currently launched in pairs (one active, one on-orbit spare) on a Scout. Government or private agencies could "broker" multiple launches by assembling manifests of users who can share a common orbit, analogous to the way the Air Force Space Test Program manifests unrelated experiments onto a single spacecraft. The shuttle could also carry 24 or more lightsats into orbit concurrently on a special cradle.[5] Low-cost solid propulsion elements could then disperse the satellites from their common orbit. Of course, shuttle options must take into account extra design costs associated with man-rated safety requirements.

Piggybacking satellites with major payloads is another option, if the cost burden owing to increased reliability and quality requirements is kept reasonable. Shuttle secondary payloads such as Getaway Specials, the Hitchhiker pallet, and the free-flying Spartan present other opportunities. Two small satellites have already been launched from Getaway Special canisters, and others are being developed (see Fig. 1).

Small Satellite Design

The path to lightsat begins with mission design. For a satellite to be small and low in cost, it must have a focused mission objective, perhaps even a single purpose. The payload may consist of only a single instrument or a small number of related instruments. Some loss of flexibility must be tolerated.

Mission design may exploit "low-cost orbits." Low altitudes can reduce launch costs, allow more weight, increase resolution, reduce RF power, and decrease antenna sizes. Polar orbits or the highly elliptical orbits used by Soviet Molniya satellites can often meet coverage requirements without resorting to expensive geostationary satellites. Many lightsat concepts involve constellations of several or even hundreds of satellites. Constellations can improve coverage from low altitude and can yield survivability by proliferation. They degrade gracefully, and multiple launching improves the "exchange ratio" (that is, it becomes more expensive to destroy a satellite than to launch one). Multiple builds also amortize the design cost and permit volume purchasing and true mass-production techniques.

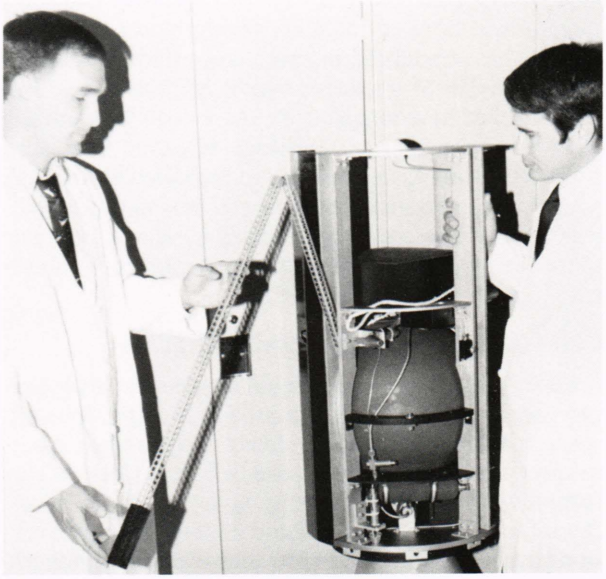

Figure 1–A mock-up of the ORION free-flying satellite being developed by the U.S. Naval Postgraduate School for launch from inside a Shuttle Getaway Special canister. [Official Navy photograph courtesy of the U.S. Naval Postgraduate School]

System engineering for lightsats must recognize simplification and cost reduction as major system goals. The lightest, lowest-cost, most reliable components of a satellite are those that are not there (to paraphrase a well-known computer industry rule). Intensive optimization must be avoided and "enhancements" resisted. Designs may include larger-than-normal margins and safety factors, so that test models and extensive analysis can be eliminated and testing itself reduced. Tolerances are relaxed as much as possible. Mechanisms are eliminated or simplified, structural elements are limited to repetitions of simple shapes, and volumes are kept ample to accommodate low-cost electronic-packaging techniques. Design engineers, who typically pursue high performance and efficiency, must learn to accept suboptimal weight, power, or volume.

The choice of attitude-control method is a critical early decision driving much of the remaining system design. Certain methods are especially suited to lightsats. For a low-altitude, earth-pointing satellite, where control to only a few degrees is needed, gravity-gradient stabilization is still attractive. A momentum wheel can give yaw control, and modern damping techniques reduce the time and cost for initial attitude acquisition. Spin stabilization can be simple and cost-effective, although a spinner's body-mounted solar cells suffer a π:1 disadvantage in watts generated per dollar or per pound of array. APL's Active Magnetospheric Particle Tracer Explorers/Charge Composition Explorer (AMPTE/CCE)[6] solved this problem by deploying small arrays facing the sun, normal to the spin axis, as shown in Fig. 2. APL is also developing an autonomous, active magnetic control system for low-altitude lightsats, and we have even considered passive magnetic control for some missions.

Figure 3 shows the cost breakdown for a typical satellite of moderate cost (not a lightsat). Among the support systems, communications and tracking stands out as a cost driver, followed by power, and integration and test. Communication costs are driven by reliability requirements, extensive redundancy, mass data storage, and lengthy checkout of complex interfaces. Advances in ultrathin solar cells offer hope of reducing solar array costs as well as weight. Integration and test is a labor-intensive operation, expanding directly with satellite complexity. Structure and mechanical costs, primarily associated with design and analysis, increase with the number and complexity of shapes and as the design operates closer to structural limits. Material costs are negligible.

The very name lightsat implies a direct correlation between weight and cost (see Fig. 4, curve A). This perception arises when performance enhancements, secondary missions, and redundant subsystems are added, making the satellite both heavier and more costly. But if the mission objective (including the reliability requirement) is held fixed, then increased weight can be used to *reduce* satellite costs by, for example, using heavier but lower-cost structural techniques or low-cost electronic packaging such as wirewrap (Fig. 4, curve B). These techniques can save time and money in initial fabrication, in debugging, and in accommodating changes.

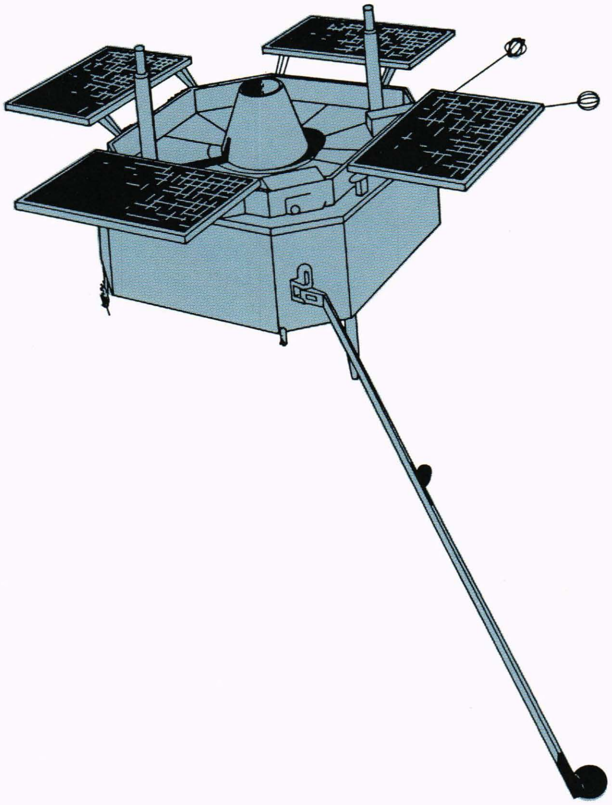

Figure 2— APL's Active Magnetospheric Particle Tracer Explorers/Charge Composition Explorer (AMPTE/CCE) spacecraft combines the simplicity of spin stabilization with the cost-effectiveness of a fully illuminated solar array.

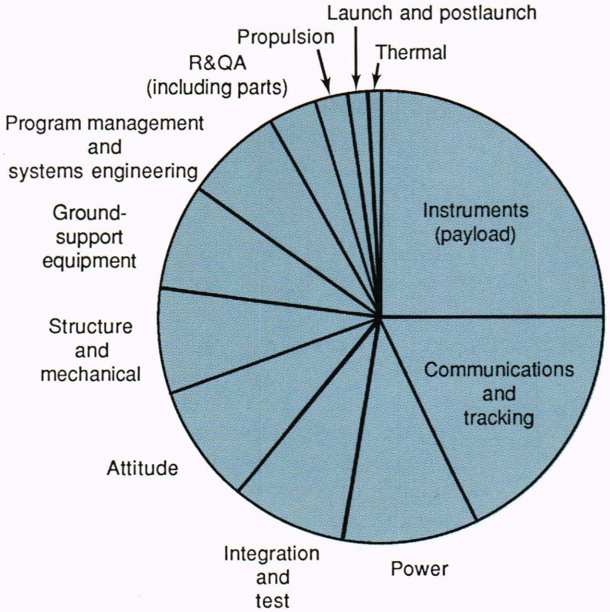

Figure 3— Where does the money go? Cost breakdown for APL's Geosat-A, a typical medium-size satellite of conventional (not lightsat) design.

Most programs fall between these extremes (e.g., Fig. 4, curve C), so that, for any particular satellite mission,

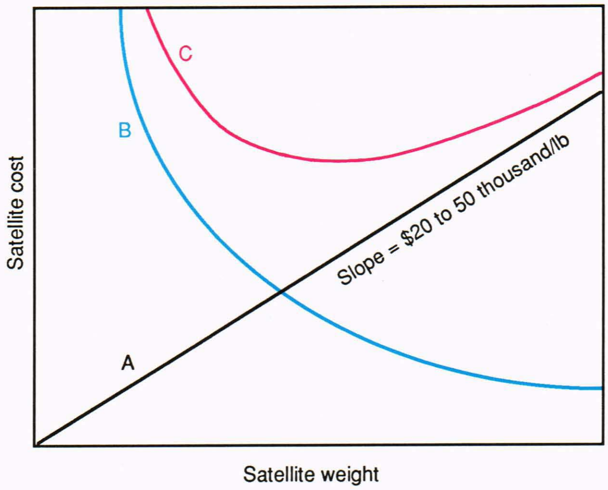

Figure 4— Relationships between satellite weight and cost.

there is an optimum spacecraft weight that minimizes total system cost. The lightsat system engineer must constantly steer the design team toward that point, being always alert for opportunities to trade weight for dollars. In practice, since launch vehicle payload weights come in definite weight increments, this often means adjusting the mission requirements to minimize the cost for a fixed weight. These optimum points change with time, and the constantly improving performance/weight ratio is, in fact, a key reason for the renewed interest in small satellites.

Advances in electronics, more than in any other area, have made it possible to accomplish nontrivial missions with small, partially redundant satellites. Advances in standard integrated-circuit technology have reduced size, parts counts, and number of interconnects, leading directly to improved reliability. Application-specific integrated circuits (e.g., gate arrays, programmed logic devices, standard cells) compound the benefits. Monolithic microwave integrated circuits are bringing these same advantages to radio-frequency circuitry; electronically steerable antennas based on these circuits can make it easier to track low-altitude satellites and can simplify the attitude control requirements. Quick reaction integrated-circuit technologies, such as in-house personalization of gate arrays, can make application-specific circuits available on short schedules. New mass-storage technologies can replace heavy, expensive mechanical tape recorders. The low altitude and the moderate mission design life of typical lightsats enable some state-of-the-art parts to be flown that might otherwise be excluded because of radiation susceptibility (although single-event upsets can still present problems).

Modularization and standardization are two more ways to cut subsystem costs. Modularization borrows from the personal computer the idea of tailoring performance by adding expansion modules to a central core design—for example, a command system that expands by adding blocks of commands, a telemetry system customized with blocks of channels, or a solar panel that can add standard segments. A suitably innovative solar panel design can be adapted to spinning satellites as well as to deployed panel satellites. APL's series of Small Astronomy Satellites demonstrated 15 years ago modularization at the satellite level—a standard "generic bus" onto which various experiment sections were bolted.

Standardization cuts costs by eliminating custom tailoring of interfaces and design of special interface conversion circuitry. Although some *de facto* interface standards have evolved (e.g., the +28-V power bus and the NASA standard convolutional code), they are the exception, not the rule. Realizing this, the American Institute of Aeronautics and Astronautics has recently proposed a satellite standards initiative that will keep lightsat requirements in mind. For example, it may be desirable to have a second, lower standard bus voltage for the lowest-cost satellites. A standard lightsat payload/vehicle mechanical interface would also be useful. General-purpose programmable devices allow for standard hardware, with customization limited to the software. Standardization of these software modules presents another opportunity for cost savings.

The need for small, low-cost satellites, coupled with the improved reliability of modern electronic components, is forcing a healthy rethinking of reliability engineering. Although the definitive study is yet to be done, there is general agreement that it does not pay to skimp on parts quality for lightsats. But neither is it necessary to impose the rigid and expensive parts programs that might be required for ultra-long-life or man-rated missions.

In particular, new ways of trading off parts quality and subsystem redundancy can improve mission cost-effectiveness. Redundancy was maintained in the past at the piece-part level. Later, parallel subsystem redundancy became the accepted technique. With constellations of lightsats, where the survival of any single satellite is not absolutely required for the survival of the entire constellation, we can begin to consider maintaining redundancy at the level of the satellites themselves. The lowest-cost satellites may also be designed to have a single subsystem serve multiple purposes, challenging traditional concepts of fault isolation and redundancy. Consider, for example, a satellite to collect data from buoys and retransmit the data to the ground. For highest reliability and immunity to any single failure, the reliability block diagram of the communications system might look like Fig. 5a. Command and telemetry systems are fully redundant; a separate, fully redundant system alerts the buoys and receives their data. A more typical conventional design would mix redundant and single-string subsystems, as shown in Fig. 5b.

In the lightsat version (Fig. 5c) the system has been redesigned so that a single receiver accepts satellite commands as well as the buoy data, and a single transmitter issues the alert signal and transmits telemetry. Forcing a subsystem to do two tasks like this will cost the lightsat some flexibility and performance and may slightly increase the parts counts in the individual subsystems. But by combining functions and eliminating entire subsystems, the lightsat version is only slightly less reliable

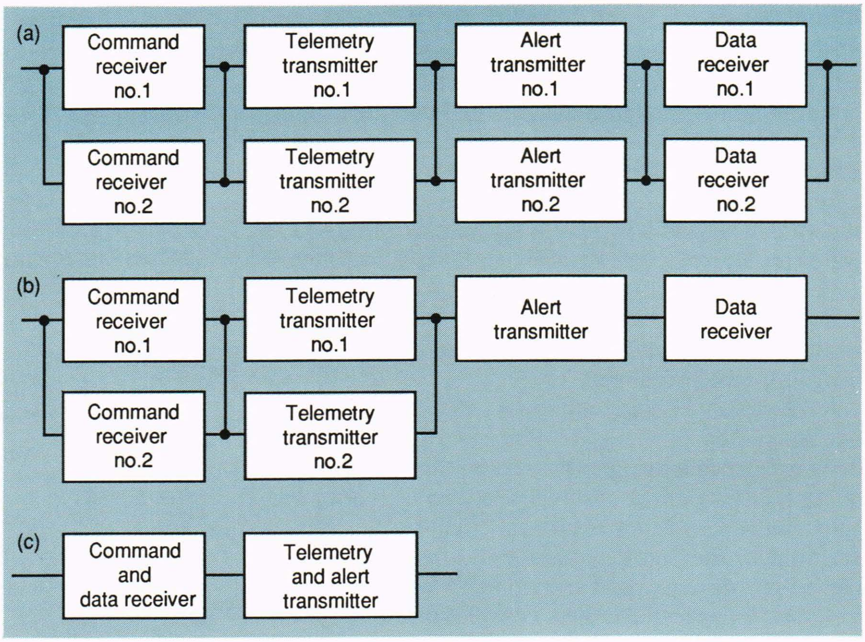

Figure 5— Reliability block diagrams of (a) fully redundant radio-frequency system, (b) partially redundant system, and (c) nonredundant lightsat version, using each subsystem for multiple purposes.

than the conventional version, as shown in Fig. 6. The fully redundant system is, of course, the most reliable and flexible, but at a cost of four times the lightsat's hardware, plus extra checkout time. Compared with the conventional partially redundant design, the lightsat's reduced complexity has nearly compensated for the loss of redundancy. A constellation of such lightsats would afford sufficient units to realize this "average" performance, thus making it cost-effective for short missions.

Significant gains can be made in the areas of ground-support equipment and integration and test. Advanced personal computers allow for the use of computer-based ground-support equipment for lightsats, with negligible hardware costs. The software for such equipment can be modularized like the flight hardware and software. In fact, some of the biggest payoffs of modularization and standardization are realized in the ground-support equipment and checkout time, not in the flight hardware. For mass-produced lightsats, contractors will need to reexamine the cost-effectiveness of standard industry tests and also consider the optimum level of integration (board, subsystem, spacecraft) to perform those tests.

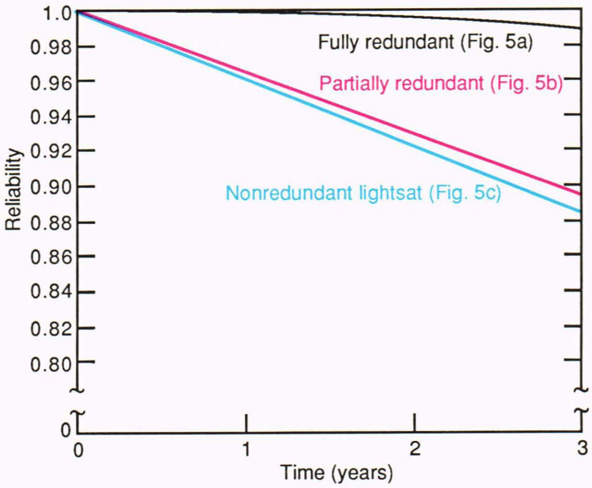

Figure 6— Reliability versus time for the three system arrangements shown in Fig. 5. A failure rate of 2.0×10^{-6}/h is used for each block in Fig. 5, except for 2.2×10^{-6} for the lightsat version.

Ground Support for Small Satellites

Much of the economy of cheapsats can be lost if the ground terminals are made expensive to compensate for satellite simplicity. Fortunately, ground stations for most small satellites need not be as elaborate as those for current NASA and DoD programs. One new approach, proposed by NASA for its Small-Class Explorer Program, is to field self-contained, transportable ground stations at principal investigator sites, from which the spacecraft can be fully controlled in orbit. Modern computer connectivity techniques now permit a control station to be dispersed in this way. These stations would operate semi-autonomously with perhaps a single pass per day, using small antennas and low-power transmitters. The Swedish Viking satellite used a related approach, in which investigators gathered for a few weeks at the ground station and ran a continuous data-taking campaign and scientific seminar.[7]

Lightsats should be given first choice of the lower (S-band and below) communication frequencies to simplify both satellite and ground radio-frequency equipment. It might even be worth restoring frequency allocations in the VHF/UHF bands, at least for the command links. Ground control can exploit the same advances in high-performance personal computers that were so beneficial to ground-support equipment, preferably using much of the same hardware and software. And artificial-intelligence software is showing potential in reducing operational and training costs.

Management of Small Satellite Projects

Small-satellite design is best accomplished by small, centralized teams in which, ideally, each member is proficient in more than one area. A circuit designer, for example, may also have a working knowledge of electronics packaging and thermal control. The designer of the ground-support-equipment hardware may also write its software. The goal is to reduce the number of interfaces and keep control localized. This, in turn, allows the use of less formal configuration management procedures, and documentation can be held to the essential minimum. Schedules should be kept tight, and micromanagement must be prohibited.

Reliability and quality assurance (R&QA) support cannot be ignored for lightsats. Particularly where system designs are single-string to save costs, skimping on parts quality, inspection, or test will prove to be a poor bargain. But R&QA resources for the small-satellite project are limited; they must focus totally on areas with the highest payoff (e.g., parts selection and test, process control, inspection, and design consultation and review) rather than on paper pushing or legalistic wrangling over arbitrary boilerplate requirements.

Streamlined government oversight is essential. Sponsors must learn to select proven, reliable contractors, and then give them freedom to make the tough R&QA tradeoffs. If a sponsor cannot bring himself to relinquish that much control, he should at least place an individual at the contractor site with authority to instantly approve design changes. Some of the cherished concepts of past R&QA, such as 100% parts traceability and sponsor approval of parts and design changes, may prove to be incompatible with lightsats.

Using students, amateurs, and other nonprofessionals is often touted as a cost-saving device, especially for the very lowest cost cheapsats. The 60% failure rate experienced by Getaway Special experiments[8] supports APL's view that lightsats require every bit as much professionalism, discipline, and experience as their larger counterparts. This is especially true where a design is to be replicated in quantity for a constellation.

For the largest constellations of lightsats, true mass-production techniques must be considered. These include design of the satellite for computer-integrated manufacturing, automated insertion of electronic parts, automated bonding of solar cells, wave and reflow soldering of circuit boards, and statistical acceptance-testing methods. None of these techniques is common in today's handcrafted satellites.

CONCLUSION

Small satellites once formed the backbone of the U.S. space program. They are now being rediscovered for useful and critical missions, for the demonstration of new technology, and for the training of engineers and scientists. APL assumed a leadership role in small satellites when the technology was far less advanced than it is today. Modern advances in electronics, automated design and fabrication equipment, and many other fields have expanded the scope of missions that lightsats can currently perform. Small-satellite systems promise important benefits for scientific, military, and commercial users, and will continue to be an exciting area for APL.

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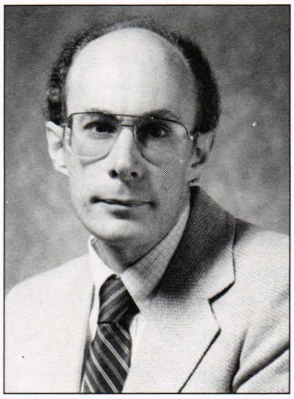

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