Bitsy: A Minimum Cost Spacecraft for Nanosatellite Missions

Rick Fleeter

Aeroastro, Herndon, VA

Abstract. Reducing spacecraft cost and size has two key aspects, one of which is usually ignored. The first and more common is a focus on engineering and management advances to reduce the size, mass and price of spacecraft. Steps include learning to work in small teams, using commercial, off the shelf parts, allowing use of more modern, more highly integrated components and miniaturization of on board instruments. These approaches have yielded remarkable reductions in size (and hence launch cost) coupled with dramatic capability increases in microspacecraft over the past ten years. AeroAstro, under IR&D and US Air Force support, has under development a 1 kg, 1 litre autonomous, 3 axis stabilized spacecraft suitable for operation both in LEO and in higher energy orbits. This spacecraft, Bitsy, can be built with a recurring cost under $100,000. The second and often overlooked aspect of miniaturization is finding applications well suited to microspace technologies. Just as the personal computer gained acceptance leveraging WordStar, Visicalc and eventually the Internet, microspace applications still await their suite of "killer apps.". The desire to obtain simultaneous measurements across very large distances, including geomagnetic mapping, might motivate missions tailored to highly miniaturized spacecraft. The paper will describe key elements of the design approach taken to realize a radically miniaturized and low cost spacecraft suitable for deployment by the hundreds. The mission profiles such a spacecraft can accommodate will be discussed with focus on simultaneous mapping of the earth's magnetic field. A more general description of the capability envelope typical for this class of microspacecraft and a range of potential missions is also provided.

1. Introduction

Disruptive technologies , those that establish new paradigms in existing technologies and markets, follow a development path that is widely misunderstood in at least two respects. First is their characteristic time for introduction. Our experience as consumers is that new products are hurried to the market at ever increasing speed with innovations obsoleting products, sometimes even before they even reach the market. In fact, new ideas percolate through the stages of research and eventual application and product development with deliberate slowness.

Microspacecraft did not pop out of nowhere - first came the development of semiconductors, orbital rockets, efficient forms of data communication and solar and battery electric energy technology advances. Our industry to a large extent merely integrates and leverages technologies to build something new. Only systems engineering innovation is specific to microspacecraft.

Second, looking at mature products can give the impression that next generation products supersede the capabilities of their ancestors. This is usually false. For example, aircraft, especially in their early stages of development, are far less comfortable than trains, they were at first much less safe, and their schedules were unreliable. Air travel is more costly than rail, and at first aircraft were not much faster than trains. What aircraft did provide was an alternative means of transportation which happened to suit new niches (e.g. flying mail across the Andes) not served by trains, and gradually over 50 years some (but not all) of their detriments were addressed.

Personal computers disrupted the technology of main and mini-main frames. They were significantly handicapped compared with their predecessors in almost every respect - speed, memory, I/O capacity, program size, programming language, which led the then President of DEC (a manufacturer of mini-main frames) to state that there was no reason anyone would want to own such a [handicapped] machine for the home. The niches PCs would fill - including telecommuting, web-surfing, game-playing, emailing and music production, to name a few, were all yet to be considered at the birth of the Altair and the original Apple.

So it is with microspacecraft. They produce much less electric power, downlink much less data, cost more per kg, point less accurately and in general do nothing as well as larger spacecraft. Their popularity owes to only a few factors: many of us can't afford any more expensive spacecraft; they can be developed and launched in a year or two rather than a decade or two; and we are finding new niches suitable for very small, but not for very large, spacecraft.

AeroAstro was formed out of my belief that these factors would expand the utility and constituency of space, and out of a frustration for the lack of appreciation of their significance at the large aerospace organizations I worked at. While economics have forced an industry-wide rethinking, there is still a tendency to compare cost per bit or kg, or "sophistication" of missions between large and small spacecraft, and a need to somehow postulate that a $1M spacecraft can approach the capability of much larger ones.

The ALEXIS, HETE and TERRIERS spacecraft built by AeroAstro have been a blend of philosophies - each pressed the performance envelope to try to approach larger mission capability, but each was grounded in budget realities. ALEXIS was one of the first of the contemporary microsatellites (Figure 1). The 105 kg spacecraft was launched in April, 1993 to provide all sky imaging in the soft X-ray and to perform research on electromagnetic pulses, particularly from lightning. ALEXIS provides about 65W of continuous power, 0.05 degree attitude information and a 750 kb/s downlink for its payload of six telescopes and processors plus a fast digitizing wideband radio. ALEXIS is fully operational at its fifth anniversary on orbit - 4.5 years beyond its design lifetime. ALEXIS' bus and ground station were built for $3.5M, TERRIERS' for about $2.5M, and HETE for about $4.5M. The spacecraft provided relatively large amounts of power to their payloads - typically 25 to 75 watts, and significant data handling and computing power, HETE employing eight 56001 DSPs and four transputer parallel processors. They provide typically 1 Gbit of daily data flux to the ground, and pointing knowledge at the 0.1 degree level.

Magnetospheric mapping is one of a class of missions that will become the "killer applications" for microspacecraft. They require minimal spacecraft capability, but also minimal mass (important in order to fly many in a single launch and impart to them large velocity increments) and minimum cost (to afford to fly them in highly populous constellations.

2. Serving the Magnetospheric Mapping Mission

Rather than try to build the next Hubble fit into a Walkman chassis,

Science Closure and Enabling Technologies for Constellation Class Missions, edited by V. Angelopoulos and P. V. Panetta, pp. 103-106 , UC Berkeley, Calif., 1998.

AeroAstro has focused on the one feature that has driven the acceptance of both the PC and the microsatellite - low cost. But the techniques we and others had used to cut scientific spacecraft bus cost by one to two orders of magnitude have now already been exploited achieving the cost reductions that enabled HETE, ALEXIS and TERRIERS. These included: reducing complexity so as to enable a team size of under 15 people to work on a spacecraft (thus minimizing interface and documentation overhead); exploiting low parts count and the very high reliability of modern commercial integrated electronics to allow use of cheaper, more capable components; introduction of plastic encapsulated, surface mount and commercial grade parts to space application; finding piggyback and shared launch accommodations; highly autonomous operations using low cost ground stations colocated with and staffed by the science team; and employment of a highly motivated, diverse and hard working team.

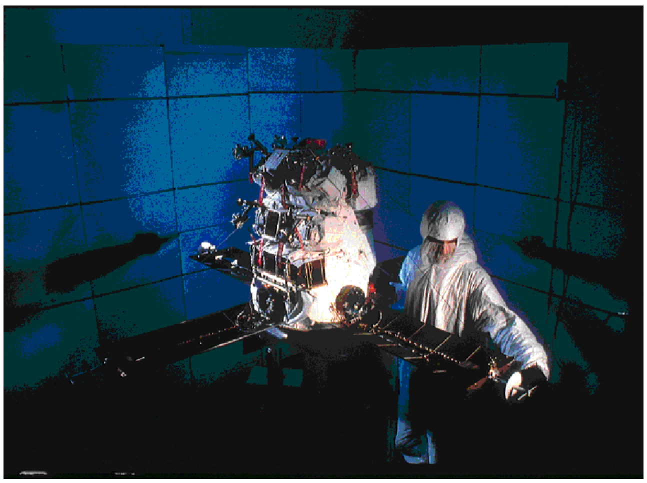

Figure 1. Aeroastro engineer working on ALEXIS spacecraft.

The additional leverage we could find to further lower cost has formed the basis of the Bitsy spacecraft conceptual design (Figure 2). Engineering, assembly and test labor and the overhead associated with it account for two thirds the cost of a delivered spacecraft. Typical small spacecraft are comprised of numerous circuit boards housed in several chassis and connected by complex wiring harnesses. Because spacecraft engineers do not build tens or hundreds of thousands of such circuit boards, they have to painstakingly inspect and troubleshoot newly manufactured boards in a process that is exceedingly expensive. Typically, an engineering month per circuit board is budgeted for manufacture and checkout, not including the original design and normal fabrication costs. Similarly, skilled technicians must cut individual wires to length, solder them to connectors and thus slowly build up complex cabling and harnesses.

These activities, unlike the development of software, itself a major cost element, must be repeated for each spacecraft of a constellation, if traditional practices are to be implemented. Our experience in builds of one, three and seven identical spacecraft is that the "learning curve" for these skilled, labor intensive activities is hardly overrated. Mass production in the sense we expect from automobiles, video cameras and pagers, is quite different from these small numbers of units. Even 60 simultaneously built spacecraft may require as much as 30 times the effort of the construction of the first one. This is because the errors discovered in a sample of even 60 circuit boards perceived identical are rather diverse, while their number is not large enough to justify robotic assembly, automated testing and the large capital investment to create custom tools and fixtures as are typically found in consumer product assembly systems producing tens of thousands of units per

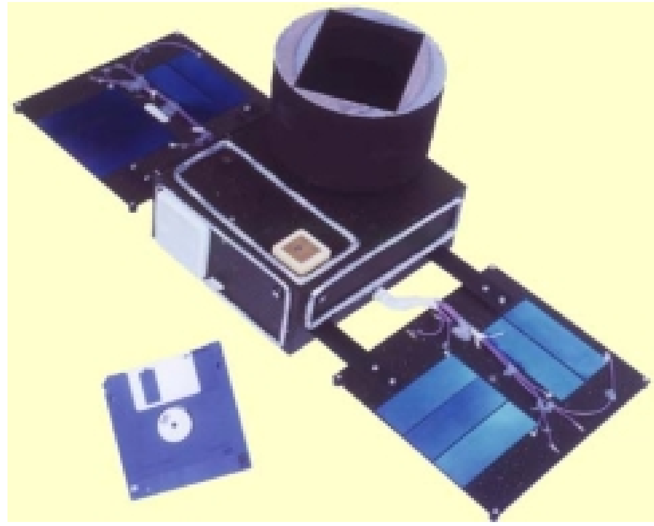

Figure 2. The Bitsy Spacecraft. This model includes two deployable solar panels to provide power for support to an on-board camera and star tracker

month for many years. These costs are only multiplied as we seek workmanship and component flaws in burn-in, vibration and thermal vacuum testing. Similar inefficiencies exist in construction of the mechanical housings for these electronics. Often hogged out of aluminum ingots, the structures require meticulous finishing and handwork to carefully install the circuit boards using board holding brackets, lots of tiny screws that are easily dropped into the housing, sometimes necessitating de- and re-assembly, and installation of connectors and other small but vital components including grounding posts, thermal conductors and tie downs.

To bring about an order of magnitude reduction in cost, two factors were necessary. To cut software costs per unit, an order of magnitude more units must be built - 10 to 100 instead of 1 to 10. And to cut hardware costs we need to reduce the number of boards, the number of boxes and the number of wires and connectors among them by about the same factor of ten. The analogy with personal computers is strong. So long as a PC requires a hard disc drive, a large color monitor, CD-ROM drive, floppy drive, keyboard, amplified speakers and modem, plus an AC power supply and a large metal and plastic box to put it all in, the cost floor is hard to make much lower. But a computer like the Psion, Newton or Palm Pilot has either no keyboard or a very simple one, a small monitor, no moving parts (floppy, hard drive or CD-ROM), a DC battery supply and only a single tiny speaker. Their costs are about a factor 10 less than full functioned computers.

Bitsy is built upon a single circuit board, sectioned into RF, Power, IO and processor/memory quarters. While the board complexity is quite high, increasing troubleshooting investment per board, the anticipated error rates are reduced compared with turning on four or possibly ten times as many boards. (Our "conventional" radios are built typically onto three or more separate boards for receiver, transmitter and amplifier sections. Computers often have outboard memory cards. Thus the four Bitsy segments replace many more than four boards.) Even the batteries are mounted directly on the circuit board. The only outboard devices are thus only the payload and possibly some attitude control sensors or actuators.

To address as broad a class of missions as possible Bitsy employs "bang-bang" attitude control, instead of magnetic torque coils typical of small satellites which are mostly employed at LEO. Thus Bitsy is not reliant on the earth's magnetic field for actuation, and does not require on-board momentum storage, spinning, or a boom for stabilization. It can thus be flown at LEO, GEO or highly elliptical orbits, or even on missions beyond earth orbit. Of course a trade-off exists between control precision and lifetime, but with coarse control (+ 10 degree) punctuated by brief periods of tighter control (+0.1 to 1 degree), lifetimes of two years are practical. By using a low vapor pressure vaporizing liquid propellant, the mechanical structure doubles as the propellant tank, and propellant lines are eliminated.

Note that Bitsy's development proceeded with one overriding optimization - low cost. But can the resulting spacecraft fulfill any useful missions? Typical of disruptive technologies, the initial answer for many, including about half the engineers at AeroAstro, was "no" because the only missions many conceived of were based on conventional and micro- spacecraft missions. The specifications of Bitsy are tabulated below.

Bitsy is the spacecraft analogy of an embedded computer in several respects. It has no "payload capacity" because Bitsy is the payload - it mounts atop or within the science instruments. In its native form it has very limited capability - for instance only a few watts of steady state electric power. But Bitsy includes interfaces to add on additional sensors, actuators and "apertures" including additional solar arrays or directional antennas. This is the reason there are now in circulation at least three different images of Bitsy - how it looks depends in part on what it does. But the basic suite of capability - to compute, communicate, housekeep and interface, and the software which runs on the platform, are present in al the incarnations.

The Bitsy specifications common to all its incarnations are: 1) It has a 1 kg total mass for a fully functional three-axis stabilized spacecraft bus. 2) It costs less than $1M to produce a turnkey system and has a recurring cost of less than $100K for the basic system. 3) It can be built on a fast schedule, with flight readiness of 9 months after receipt of order for most mission. 4) It has an extensible design: It can fly as is, or become the core of a more capable spacecraft. The supported enhancements include electric power, altitude control upgrades, propulsion, high speed data links and high gain antennas. Technical specifications of Bitsy presented in Table 1 are intended as guidelines for preliminary mission design. Some are easily enhanced at low-cost but improving others may require substantial development.

Physical Characteristics
1.0 kg total mass Integrated electronics unit with Integrated solar panel
Dimensions 15cm x 15cm x 5cm
Payload volume / mass & propulsion module: no limitations
Thermal Control
Active control can be implemented within payload power
Lifetime
3 months to 3 years (propulsion dependent)
Basic Power
Unregulated 8V power bus
4Wh rechargeable lithium-ion battery
Payload Power
No limitation
Data Storage
Minimum 0.5 Gbit, extensible to 24 Gbit
Payload Raw Data Rate Output
5 Mbps (maximum, over standard parallel interface)
Data Processing
32-bit RISC microprocessor
ANSI C language support
Three-Axis Attitude Control
Attitude determination using star camera: 0.5 mrad, 2 sigma
Attitude control with cold-gas thrusters: 50 mrad, 2 sigma
Attitude stability 1 mrad/sec (target, orbit dependent)
Spinning and other configurations available
Communications
UHF, S-Band or X-Band
Uplink & low-speed downlink: 2 kbps
Optional high-speed downlink: 10-100 kbps

Table 1. Technical specifications of Bitsy.

3. Applications and status

Several factors combine to make Bitsy a good fit for the geomagnetic mapping mission. Its mass is about 1 kg, it can be fitted with sufficient electric power to operate the mission instrument suite, it is highly robust, it can be used on any launch vehicle, and it is very low cost. In quantities greater than about 10, depending on the complexity of its application (and hence the required instrument compliment) recurring cost can be as low as $50,000. Even flying 100 Bitsies, the spacecraft cost will be a small fraction of the mission cost. Major cost elements will be transportation to the desired orbit or trajectory, itself made smaller by the spacecraft's low mass and mechanical strength, and the science operations of the constellation.

Bitsy's development has been funded by AeroAstro R&D and by the US Air Force Phillips Laboratory. Its Lithium-Ion rechargeable batteries and charger system, radio transmitter and receiver and propulsion system have been prototyped. Sufficiently capable small processing units suitable for Bitsy have already been developed. Much of its software has been produced under other programs. The vaporizing liquid propulsion system has been built and operated in a vacuum chamber.

During 1998 AeroAstro has been applying the Bitsy design to another remote sensing application - inspection. Bitsy's low cost and maneuverability (due to its low mass) makes it practical to use to roam around spacecraft like Shuttle and Space Station reducing astronaut EVAs. This application has already been demonstrated by larger spacecraft but their size and cost reduce their desirability for all but the most critical missions.

4. The Future of Bitsy

Bitsy with the above specifications is available now. And an important aspect of disruptive technologies is that after gaining acceptance in one or two narrow applications niches, new technologies will help to migrate the product into more complex applications, sometimes displacing the previous generation technology. For example, several organizations are developing highly miniaturized momentum wheels and star cameras. These could combine to provide high resolution pointing and tracking, combined with high slew rates and longer lifetime. Improvements in GPS, stable clocks and laser cross-synchronization may enable coherent operation of radio or even optical detectors on widely spaced microsatellite platforms. The realization of big LEO communications Constellations like Globalstar and Iridium will for many LEO missions eliminate the need for a dedicated ground station, enabling the researcher to simply dial up the spacecraft regardless of its orbital location and exchange data, probably using common internet protocols. The predicted significant rise in launch rates driven by these LEO systems and by Space Station should increase the opportunities for piggyback launch accommodations of Bitsy-like microspacecraft. Ten years ago the struggle for resources to build and launch astrophysics small satellites like ALEXIS and HETE was nearly lost because of doubt significant science could be accomplished with a 100 kg class spacecraft. Ten years from now, 1 kg class spacecraft, deployed individually and in coordinated or randomized constellations may be as commonly accepted as are today's SMEX and UNEX class missions.

Rick Fleeter, CEO, AeroAstro, 520 W Huntmar Park, Herndon, VA 20170 (e-mail: rick@aeroastro.com)