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LOW-COST SMALL SATELLITES FOR ASTROPHYSICAL MISSIONS

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1. Introduction: What is a Miniature Satellite?

A miniature satellite is a low-cost platform to support a small space experiment. Space astrophysics has been hindered by decades-long delays in important experiments. With miniature satellites, one hopes to reduce both experiment cost and lead time to an affordable level.

Miniature satellites are not a new idea. The first scientific satellites, including Explorer I, were small and developed on a timescale of months. Important science was done by these pioneer missions. Though the easy discoveries have been made, important missions in exploration and follow-up can still be carried out from small platforms.

Successful small satellite programs continue to this day. These include the OSCAR amateur radio satellite program, in which 17 small satellites, built by amateurs, have been flown over 25 years with no satellite failures (Fleeter, 1988). Two small free-flyers, GLOMAR and NUSAT, were ejected from the Shuttle in 1985. GLOMAR, a radio-relay experiment, was built in less than a year for under \$1 million, and operated over a year in orbit. Small satellite projects continue to this day. Approaching launch are the Air Force STACKSAT array of 3 small satellites (P87-2), a number of other small satellites under Department of Defense auspices. The Air Force Space Test Program is developing a standard small experiment platform called STEP (Space Test Experiment Platform). NASA has started a small explorer program, beginning with SAMPEX, a solar and magnetospheric particle explorer, FAST, a fast auroral snapshot experiment, and SWAS, a sub-millimeter astronomy experiment.

The definition of a miniature satellite is subjective. In my opinion, miniature satellites to date fall within the following approximate bounds.

Table I: Miniature Satellite Parameters

Power	≤ 50 Watts
Payload Mass	≤ 50 kg
Design Lifetime	≤ 1 year
Project Lifetime	≤ 3 years
Spacecraft Cost	$\leq \$1$ -4 million

The modest experiment scope allow an expedited project organization; the modest investment allows a certain amount of risk. Larger projects can in principle be run as miniature satellites, but risk budget and schedule runaway in overmanagement, quality control, and documentation.

2. Commercial Miniature Satellites

Now is a good time to buy a miniature satellite: competition is intense, and satellite buyers are eagerly sought. In the case of ALLEXIS, Los Alamos National Laboratory issued a request for

quotation in November 1988. Nine companies responded. In the final round, we received four strong proposals. The final selection was made on the basis of cost and technical merit.

The ALEXIS spacecraft discussed below could be upgraded at modest cost. The spacecraft could point in 3 axes with the addition of a momentum wheel and, possibly, a small star tracker. More data storage could be added by replacing the present 256K SRAM array with expected 1M components. The extended ALEXIS bus could thus accept and store approximately 100 kilobits/second of telemetry (time averaged), and point to celestial targets to within $\sim 0.1^\circ$.

Ball Aerospace Systems Division, under their TECHSTARS program, is developing a miniature satellite capability. A bus massing less than 120 lbm could provide > 50 Watts to a payload, with 5 MIPS of processor power, data storage of 1 Gbit, and 3-axis attitude control to 0.2° and knowledge to 0.1° . Such a bus would cost $\sim \$4$ M for the first vehicle, and $\sim \$2$ M for copies (T. Higbee, private communication).

Fairchild Space Company is also active in the small satellite field, and presently building SPINSAT for the Office of Naval Research. Fairchild, also, find that small satellites with significant capabilities can be built for a few million dollars. Their smallest "Class 1" design study would support a payload of < 100 lbm with a platform of < 100 lbm, providing < 15 Watts to the payload for a recurring platform cost less than \$1 million. At a slightly larger scale, their "Class 2" design study would support a payload of < 750 lbm with a platform of < 250 lbm, providing < 100 Watts to the payload for a recurring platform cost less than \$3 million (Bartlett 1989).

Other potential vendors include Globesat, Inc., of Logan, Utah, Intraspace of Salt Lake City, Space Data Corporation of Tempe, Arizona, and Defense Systems, Inc. of McLean, Virginia. With such intense competition, several companies are offering attractively-priced high performance spacecraft.

3. The ALEXIS Project

ALEXIS is an example of a miniature satellite for astrophysics. ALEXIS (Array of Low-Energy X-Ray Imaging Sensors) is an ultrasoft X-ray monitor experiment that consists of six compact normal-incidence telescopes operating in narrow bands centered on 66, 72, and 93 eV. The Air Force Space Test Program is scheduled to launch ALEXIS via a Pegasus air-launched vehicle into a 400 nm polar orbit in April 1991. The ALEXIS satellite and experiment are funded by DOE, and are being built by a collaboration of Los Alamos and Sandia National Laboratories, and Space Sciences Laboratory/UC Berkeley. The technological objectives of ALEXIS are to 1) demonstrate the feasibility of a wide field-of-view, normal incidence ultrasoft X-ray telescope system and 2) to determine ultrasoft X-ray backgrounds in the space environment. In addition, ALEXIS will pursue a number of scientific objectives including: mapping the diffuse background in three emission line bands with the highest angular resolution to date, performing a narrow-band survey of point sources, searching for transient phenomena in the ultrasoft X-ray band, and providing synoptic monitoring of variable ultrasoft X-ray sources such as cataclysmic variables and flare stars.

Each ALEXIS telescope consists of a layered synthetic microstructure (LSM) spherical mirror, a prime-focus curved microchannel plate detector with a wedge and strip readout, background-rejecting filters and magnets, and image processing readout electronics. Figure 1 shows a cutaway of one ALEXIS telescope. The multilayer optics are discussed in more detail in Smith, Bloch, and Roussel-Dupré (1989, 1990). The ALEXIS telescopes are aligned in pairs, each pair covering a 33° field-of-view. The geometric area of each telescope will be about 25 cm^2 , with spherical aberration limited resolution of about $1/2^\circ$. The 5σ survey sensitivity is estimated to be several $\times 10^{-3}$ photons $\text{cm}^{-2} \text{ s}^{-1}$ for line emission at the center of the bandpass. Other aspects of the experiment are discussed in Priedhorsky et al. 1989. ALEXIS, with its wide fields-of-view and

well-defined wavelength bands, will complement the upcoming NASA Extreme Ultraviolet Explorer and ROSAT EUV Wide Field Camera, which are sensitive broad-band survey experiments. Unlike these experiments, ALEXIS is tuned to emission in the $\sim 70\text{eV}$ Fe IX-XII complex, can observe transient emission over half the sky, and monitors variable sources continuously for 6 months of each year.

Figure 1. Cutaway view of one of the six ALEXIS ultrasoft X-ray telescopes.

Position and time of arrival are recorded for each detected photon. The ALEXIS telescopes are aligned to sweep over the entire anti-Sun hemisphere each 30-second spin; the whole sky is therefore mapped out in one year. ALEXIS will always be in a survey-monitor mode, with no individual source pointings. Because it sweeps the entire anti-Sun hemisphere, it is well-suited for simultaneous observations with ground-based observers who prefer to observe sources at opposition. Coordinated observations need not be arranged before the fact, because all sources in the anti-Sun hemisphere will be observed and archived.

ALEXIS and a piggyback experiment mass 125 lbm, draw 45 Watts, and produce 10 kilobits/second of data. The supporting spacecraft, described in the next section, has less mass (100 lbm) and draws less power (13 W) than the experiments.

4. The ALEXIS Spacecraft

The ALEXIS spacecraft is a spinning vehicle which provides power, telemetry, data storage, attitude control and determination, and other services to ALEXIS and its piggyback experiment. The spacecraft is being built by Aero-Astro, Inc., of Reston, Virginia, (formerly Astronautics)

under contract to Los Alamos National Laboratory. The contract price for the ALEXIS spacecraft is less than \$2 million.

The complete ALEXIS satellite masses 225 lbm at launch. The satellite consists of the Aero-Astro spacecraft and the Sandia-Los Alamos-Berkeley payload. In its stowed configuration, the satellite is 24 inches in diameter by 30 inches high, exclusive of antennae, with a spacecraft section 9 inches high. The payload is on the anti-Sun side of the spacecraft. Figure 2 shows the spacecraft.

Figure 2. ALEXIS spacecraft with subsystems

The spacecraft spins about its longitudinal axis, which is pointed to within 2° of the Sun at all times. Attitude control is by means of magnetic torque coils in 3 axes. Spin axis determination is by a fine sun sensor. Spin phase angle is from an infrared horizon crossing indicator and a 3-axis magnetometer. Ground algorithms are used to reconstruct attitude to $\pm 0.25^\circ$ (3 sigma worst case). Upon insertion into orbit, the magnetic torquers damp out tumble rates of up to 10 rpm, using magnetometer data, then spin up the spacecraft to a nominal 2 rpm. Using coarse Sun sensor data, the spin axis is precessed towards to Sun. The solar panels are then deployed; once deployed, the moments of inertia are such that the spacecraft is stable for spin about its longitudinal axis. For the rest of the mission, the satellite spins at 2 rpm and keeps station on the Sun.

Spacecraft power originates in a silicon solar cell array, provided by Israeli Aircraft Industries, which supplies 114 Watts at the beginning of mission. During orbital nighttime, power is supplied by 4 redundant strings of commercial nickel-cadmium cells. Exclusive of spacecraft systems power, the power system provides to the payload a minimum of 56 W of unregulated 28 V power at beginning of life, declining to 51 W after 1 year on orbit.

Experiment data are stored continuously and transmitted during passes over a Los Alamos ground station. The data storage and telemetry system is sized to accept experiment data at a mean rate of

10 kilobits/second. Due to the polar orbit, the satellite is visible from Los Alamos during one or two passes every 12 hours. ALEXIS thus carries 448 Mbits of static RAM mass memory, net of error detection and correction. The radio frequency downlink carries 750 kilobits/second at 2260 MHz, with an estimated error rate less than 2×10^{-9} /bit. Command data are uplinked at up to 5 Megabits/day, with a calculated error rate less than 1.2×10^{-9} /bit.

The ground station is based on a 1.8-meter steerable dish installed on a roof at Los Alamos. The ground RF circuitry is custom built. Immediate control of the data flow is via a Macintosh II computer, with archiving and first pass processing on a Sun workstation. Data will be archived on an optical disk, and transmitted to collaborators at Berkeley on VCR-type magnetic tapes.

Given the schedule and budget of ALEXIS, it is impractical to require S-level electronic parts. We ensure reliability with a mixture of military (883-B) and industrial-grade parts, selected based on budget and reliability considerations. Parts will receive a dose of ~5 krad if the mission lasts 3 years. We have therefore chosen and tested parts for radiation tolerance. Again, schedule and budget prohibit the use of explicitly radiation-hard parts. Typical parts are, for the mass memory, Dense Pak memory modules built from Hitachi 256K SRAM chips, and for logic circuitry, Texas Instruments HCMOS.

To be cost-effective, ALEXIS must be built as quickly as we can, while meeting project technical and quality requirements. The ALEXIS team in place represents a fixed cost per month; to first order, the project cost is proportional to the time elapsed between program start and launch. We are therefore building ALEXIS to the following schedule:

Table 2: ALEXIS Schedule

• January 1988	Start
• May 1988	Apply to Space Test Program for Launch
• August 1988	System Design Review
• April 1989	Preliminary Design Review
• May 1989	Memorandum of Agreement for Launch
• October 1989	Critical Design Review
• April 1990	Prototype Integration
• November 1990	Payload/Spacecraft Integration
• April 1991	Launch

5. Conclusion

Though ALEXIS is hardly complete, we have learned a lot about miniature satellites already. The following advice is proffered to those contemplating similar projects:

A miniature satellite should carry one experiment. Multiple experiments lead to increased spacecraft requirements and more costly integration. The ALEXIS spacecraft, which carries a main experiment and a piggyback, is more complicated than it would have been for the ALEXIS experiment alone.

A miniature satellite project must accept risk. Ultimate reliability is not consistent with a foreshortened schedule and modest budget. In the case of ALEXIS, we accept risk in the use of some industrial parts and a substantially single-string design.

Minimize paper deliverables. The ALEXIS project is built around a zero-based paperwork requirement; a proposed document is rejected unless absolutely necessary. We have found that preliminary and critical design reviews, interface control documents, software specifications, and test plans cannot be done without.

Minimize weight and volume. Even for a miniature satellite, each additional payload pound adds complexity and support requirements. Kilograms cost dollars.

Move fast. Time costs dollars.

Fit-test interfaces early. Interfacing systems should be brought together and tested at the earliest possible phase of the project. The goal is not a successful fit, but identification of problems.

Thoroughly test at the satellite level. Ultimately, our confidence in the ALEXIS system will derive from vibration, functional, and thermal vacuum tests of the integrated satellite. Some subsystems are thermally cycled and vibration tested at the box level.

Scrounge vigorously. Miniature satellites and their components are a buyer's market. Some suppliers will provide components below cost to enter the market.

Keep the project team tightly integrated. Two half-timers do not make the equivalent of one full-timer for project progress.

Control the satellite from a local ground station. Ground station hardware and software is now cheaper than interfacing to a system such as TDRSS.

Be flexible about launch opportunities. In the case of ALEXIS, we began to design the satellite before we knew the launch vehicle. The design was compatible with both Scout and Pegasus boosters. Because we had an ongoing program, it was relatively easy to obtain a launch.

The ALEXIS mission, including launch, vehicle integration, and flight operations, but excluding the piggyback experiment, represents an investment of approximately \$15 million. It is therefore a very cost-effective approach to a scientific goal, as modern scientific satellites typically cost \$100 million and up. However, ALEXIS is not a particular bargain on a per-pound basis (\$150K/payload pound). Astrophysics missions for miniature satellites should be those that yield significant science in a small package. Particular missions that might be suitable include 1) small X-ray, ultraviolet, and solar telescopes. These can provide a continuous observational capability between major missions, provide additional observing time beyond that provided by major missions, and support multiwavelength observational campaigns; 2) transient monitors, sensitive to X-ray stars, gamma-ray bursts, etc.; 3) transient response, dedicated to continuous monitoring of identified transients such as X-ray transients and supernovae, and 4) technology development. Other missions will not doubt arise from the ingenuity of the astrophysical community.

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