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Satellite Miniaturization Techniques for Space Sensor Networks

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I. Introduction

THERE is a growing trend toward distributed missions for scientific and remote sensing applications in which large numbers of satellites are required. Analogous to proliferating terrestrial wireless sensor networks, *space sensor networks* could provide an unprecedented capability to investigate widespread phenomena. For example, several important space weather missions have yet to be realized, due to the present inability to take simultaneous measurements of a phenomenon over a large volume. Space economics and environmental concerns dictate a cost-effective mass-producible low-mass satellite for such massively distributed missions in low Earth orbit (LEO).

An investigation of very small (subkilogram) satellite miniaturization techniques has been undertaken, focusing on enabling technologies targeted at space sensor network applications. Existing and emerging very-small-satellite technologies have been assessed and compared, with power generation and payload volume being the key performance metrics. Two novel design methodologies have been developed, simulated, and verified through functional and environmental testing of hardware prototypes. SpaceChip, inspired by the satellite-on-a-chip vision, is a monolithic heterogeneous system-on-a-chip (SOC) integration approach [1,2]. PCBSat is a proposed miniaturization approach, which is based on printed circuit board (PCB) substrates [3]. PCBSat is focused on deriving the smallest practical satellite within the context of space sensor network and constrained to the use of commercial off-the-shelf (COTS) components, processes, and deployment systems.

This Note is intended to summarize the existing research effort [1] and to update the interested reader with the most recent developments on very-small-satellite miniaturization techniques [2]. An example case study is considered in which a space sensor network could demystify ionospheric plasma depletions, which are thought to cause problematic navigation and communication signal *scintillation* (i.e., communication outages).

The Note is organized as follows: Sec. II highlights an example space sensor network mission enabled by very small satellites; Secs. III and IV summarize results of the SpaceChip and PCBSat investigations, respectively; and Sec. V concludes the Note by presenting the mission suitability and cost effectiveness of all technologies considered in this research.

II. Space Sensor Networks

Space sensor network concepts are emerging to satisfy a growing number of distributed missions that require a cost-effective approach to multipoint sensing. Formation flying is one of the earliest envisioned applications of a space sensor network that enables synthetic apertures [4]. More recently, spacecraft fractionation has shown promise to deliver improved system redundancy and on-orbit upgradeability [5]. One near-term application of space sensor networks is space weather studies.

Plasma bubbles in the ionosphere are known to cause communication and navigation satellite signal outages by scintillating the radio frequency (RF) signal between space and ground segments. Testimonials of disruptions to commercial, government, and military operations have made forecasting scintillation a top priority. For example, the $100 million (estimated) single-satellite Communication and Navigation Outage Forecasting System launched April 2008 is the first satellite mission primarily dedicated to studying and forecasting plasma bubbles [6].

Currently, there is a three-order-of-magnitude (1000:1) disparity between terrestrial weather and space weather sensors. With only a dozen or so space-based sensors in existence, any mission that could even double the amount of sensors in a single deployment would be of significant scientific value. Terrestrial weather forecasting requires sampling of the atmospheric temperature, pressure, and winds. Similarly, space weather requires measurement of the plasma temperature and density, along with neutral winds.

A few simple quantifiable objectives are proposed for a case study mission. Distributed simultaneous in situ measurements are required of the plasma density and temperature up to once per second. Distributions of a few meters to tens of kilometers will provide a range of data sets. A midlatitude circular orbit ($\sim$30–35 deg inclination and $\sim$350–500 km altitude) is suggested, as it allows sensors to enter and exit the region of interest to establish baseline and disturbed measurements. Orbit control is not required or desired, as the natural perturbations will serve to alter the distribution and lower the altitude over time without adding the complexity of a propulsion subsystem. This will allow spatial variations in the measurements and will address orbital debris concerns of space sensor networks, as the mission will be sufficiently short-lived.

Using a COTS deployment system [7], up to a dozen very small satellites, depending on their size, can be ejected from a single deployer. Typical intersatellite separation springs, which produce relative velocities of up to 2 m/s, are replaced by an atypical approach of using monofilament line to bundle the satellites, allowing the constellation to gently and naturally disperse after ultraviolet radiation quickly dissolves the line. This approach is essential to keep the satellites within wireless network range, which is assessed to be 100 km, based on available technology. A coorbiting master relay satellite of a similar size stores and forwards collected data over the

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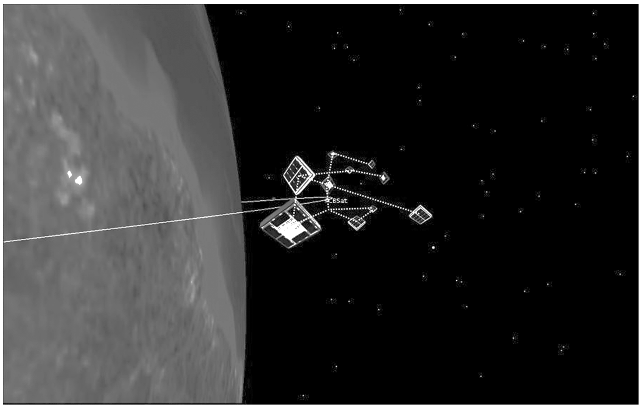

Fig. 1 Notional case study mission architecture.

network to the ground. The notional mission architecture is depicted in Fig. 1 [2].

Three-dimensional spacecraft separation is achieved by leveraging natural LEO disturbances. Assuming identical spacecraft mass properties, intentional aerodynamic drag differences up to 1% between satellites can provide intersatellite spacing. High-precision simulations show that this approach yields a 6 m in-plane separation after 24 h, which will ultimately keep the satellites within range of each other up to four months, depending on the solar cycle calendar. To achieve out-of-plane separation, solar radiation pressure, acting on small intentional reflectance variations, can produce a small inclination change after a period of days.

III. Satellite on a Chip

SpaceChip is a proposed term that describes the effort to define, assess, and develop the elusive design methodology of a satellite on a chip, which, in its purest form, aims to literally integrate complete satellite functionality on a single chip. The advantage of this approach is its inherent ability to support mass production of hundreds to thousands of ultra-low-cost satellites, akin to a “smart” version of Project West Ford [8]. SpaceChip is a heterogeneous self-powered monolithic SOC architecture targeting commercially available complementary metal-oxide-semiconductor (CMOS) processes, which is a sharp contrast to other competing very-small-satellite miniaturization approaches, which largely employ multiple-tier fabrication processes [9–11].

Remarkably, the personal electronics industry has responded to consumer demands by developing very-low-power SOC solutions for sensor, power management, data handling, radio transceiver, global positioning system (GPS), and numerous other applications, all which are, conveniently, the basic building blocks for a satellite on a chip. Even more encouraging is the niche development of SOC power generation [12], environmental tolerance [13], attitude control [14], and even propulsion [15] for particular endeavors. Despite this enabling research and development, the SpaceChip feasibility study reveals that the maximum physical constraint of $20 \times 20 \times 3$ mm, imposed by semiconductor processing limitations [16], greatly impacts its ability to generate power through integrated solar cells, in addition to low efficiencies achieved in CMOS ($\sim$3%) [12]. Derived power budgets on the order of 1 mW have a ripple effect through all the requisite subsystems, such as a short communication range of 1 km at 512 bits/s [2]. However, this concept has proven more applicable to less demanding wireless sensor network applications in a range of hostile environments [12]. Numerous on-chip sensors are now available from emerging technologies [17], although physical size constraints prevent the integration of an electrostatic analyzer to measure the plasma for the case study mission. Continued research and development of novel approaches for integrated solar cells [18], or possibly an alternate power generation technology, is absolutely essential to achieving the literal realization of satellite on a chip.

IV. Satellite-on-a-Printed Circuit Board

PCBSat is inspired by the first smart picosatellites launched in 2000, but unlike these earlier prototype missions, the focus is on commoditization of very small satellites for space sensor networks. A specific configuration geared toward the case study mission is summarized based on the Miniaturized Electrostatic Analyzer (MESA) plasma sensor payload [19]; however, the concept is intended for a range of applications.

The driving system configuration requirement is compatibility with COTS deployment systems [3]. This fixes the length and width to 10×10 cm, leaving the height as a variable, but tied to the mass by a 1-kg/10-cm guideline. For this particular mission and corresponding configuration, a minimum height of 2.5 cm is attained at a mass of 310 g. The exploded and assembled views are shown in Fig. 2. The top and bottom faces are for solar cell, sun sensor, temperature sensor, and separation switch mounting, using FR4 PCB substrates. Two Delrin® structural spacers thermally isolate the solar panels from a similarly sized core PCB, in addition to serving as the low-friction physical contact with the deployer on the corners.

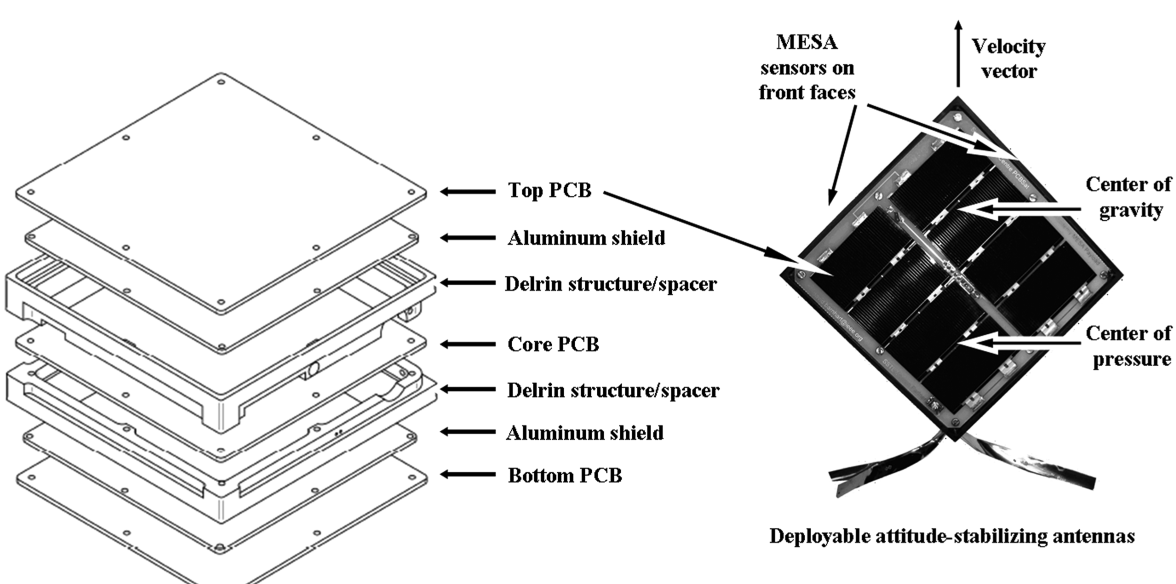

Fig. 2 Exploded and assembled views of PCBSat.

Between the core PCB and the solar panels, thin aluminum plates are used to passively control the core temperature, provide a radiation shield to reduce total ionizing dose effects, and provide an RF ground plane [2].

The core is a two-sided, four-layer PCB, for which the top side contains full-featured subsystems. The electrical power subsystem includes peak-power trackers, battery charge regulators, lithium-ion battery, and voltage regulator to provide a 3.3 V bus with 880 mW sunlit average power. A flash-programmable 8-bit microcontroller serves as the heart of system, processing nearly 4 million instructions per second. Single-event upset and latchup are mitigated by hardware redundancy and high-current sensors. Intersatellite communications are provided by a 500 mW RF, 115.2 kbps, 900 MHz COTS data radio with embedded mesh networking. Passive attitude control is established by the placement of the center of gravity slightly ahead of the center of pressure (created by the LEO drag environment and deployable antennas), emulating a shuttlecock. A postage-stamp-sized GPS module with miniature PCB-mount helical antenna provide time and position stamping capability, although COTS modules require firmware modification before spaceflight. The entire bottom side of the core PCB is devoted to the payload components. A subsystemless architecture emerges, in which all components and ground planes are strategically located to reduce electromagnetic interference [2].

V. Cost-Effectiveness

An initial-cost model is developed for all technologies investigated in this research: CubeSat [10], microengineered aerospace systems [9–11], PCBSat, and SpaceChip. MCMSat is introduced as a hybrid concept between PCBSat and SpaceChip based on multichip module technology. Actual vendor data is used in the model. These technologies are also compared with more established nano- and microsatellite busses of the small-satellite industry. Unit costs, cost per watt, and cost per payload volume are the chosen metrics for comparison of the technologies that are applicable to the case study plasma-bubble mission. A baseline constellation size of 10 sensor satellites, 1 data relay satellite, and 1 ground station is discussed here. Launch costs are included, but nonrecurring engineering and testing costs are not.

A summary of initial-cost-model results is shown in Table 1 [2]. The CubeSat platform satisfies the case study requirements for a mission cost of $900,000. CubeSat is more expensive than PCBSat and MCMSat in terms of unit costs ($75,000) and cost per watt ($31,000/W), but is the clear leader for the payload volume metric, for which it is the least expensive ($292/cm^3$). Microengineered aerospace systems cannot be fairly included in the cost comparison, as this advanced technology is primarily focused on the structural and propulsion subsystems in addition to multifunctional structures. SpaceChip clearly has the lowest mission ($174,000, includes a CubeSat relay for adequate downlink and 1667 satellite constellations due to deployer mass margin) and unit costs ($2700), yet is cost-prohibitive in terms of the chosen metrics, not to mention the lack of a viable payload for the case study mission. PCBSat comes in second in mission ($264,000) and unit ($12,000) costs, has a clear advantage in terms of cost per watt ($13,000/W), but loses out to CubeSat in terms of payload volume ($943/cm^3$). Finally, the hybrid concept of MCMSat ranks just below PCBSat in all cases ($352,000, $20,500, $23,000/W, and $1600/cm^3$). Data for constellation sizes of 100 to 10,000 are illustrated in Fig. 3 [2].

Table 1 Cost-effectiveness comparison for a constellation of ten satellites

System	Unit cost	Power	Payload	Mission cost
CubeSat	$75,000	$31,000/W	$0.292/cm^3$	$900,000
SpaceChip	$2700	$551,000/W	$22,000/cm^3$	$174,000
PCBSat	$12,000	$13,000/W	$0.943/cm^3$	$264,000
MCMSat	$20,500	$23,000/W	$1.6/cm^3$	$352,000

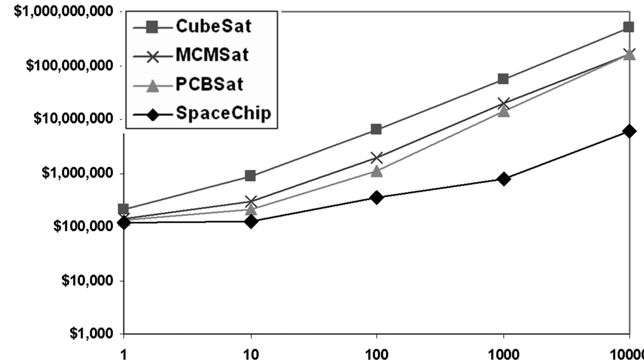

Fig. 3 Entire space-segment costs (log scale) vs constellation size.

Finally, all technologies are compared at the single unit cost level with established small-satellite buses. An interesting result is that all subkilogram technologies considered in this research are at least an order of magnitude less expensive in terms of unit cost and cost per watt. However, cost of payload volume is within the same order.

VI. Conclusions

This research has advanced the state of the art of very small satellites by providing new demonstrated cost-effective miniaturization approaches enabling sensor network architectures. The initial cost model suggests that CubeSat may not be the most cost-effective approach for massively distributed missions, depending on mission and payload requirements. Ultraminiaturization, such as suggested in SpaceChip, is currently cost-prohibitive. Integrated approaches that leverage commercial mass production infrastructures, such as PCBSat or MCMSat, may be more favorable at high volumes. Further investment in spacecraft miniaturization, such as the pioneering efforts of microengineered aerospace systems, is essential to increase the capabilities of miniaturized systems. However, significant advances in miniaturized payload and power generation technologies are the true enablers of this emerging space system architecture.

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