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The Next Little Thing: Femtosatellites

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ABSTRACT

The CubeSat revolution changed the way we think about small satellite missions. The original CubeSat vision was to enable simple, meaningful missions that universities could undertake within their limited budget and resource base. CubeSats were later adopted by industry and various government agencies with a focus on component miniaturization to squeeze more capability out of smaller configurations to lower mission costs. Ironically, this trend has triggered supplier and launch service price increases that are now a strain on universities and small research groups. The community focus on miniaturization has been costly in our endeavor to do more with less. Femtosatellites, defined as having a mass less than 100 grams, turn this scenario on its head by forcing a do less with more mentality; individual spacecraft will be less capable, but coordinated operation of massively distributed femtosatellites can achieve the required overall mission capability. We believe that femtosatellites are the next “little thing” in the small satellite community that can restore research affordability, encourage revolutionary advances, and provide transformational mission capabilities.

1. INTRODUCTION

CubeSats have comprehensively changed the way we think about small satellite missions.[1] The original goal was to provide a low-cost entry point into space for universities and small programs. Standardizing the launch vehicle interface, through containerization, was a key enabler to the CubeSat concept.[2] Government organizations throughout the world, in a declining budget environment, have looked to the CubeSat standard as a cost-saving measure for space missions. The US Government has gone so far as to develop a standardized 3U CubeSat bus as a part of the Colony program, with a bus cost goal of $250,000.[3]

As is the case for any successful technology concept, CubeSats have become a victim of their own success. The demand for CubeSat components and launches, in addition to US Government participation, has dramatically increased the entry point for a CubeSat mission. US export laws, namely ITAR, have prevented some of the US CubeSat technology from being available worldwide. This has created foreign markets, which are particularly strong in Europe, that now offer indigenous CubeSat technologies to the whole planet. While the overall proliferation of CubeSats is beneficial, basic market-driven economics has made it more difficult for highly cost-constrained organizations. Furthermore, payload development for CubeSat missions is almost universally focused on miniaturization. The authors have been personally engaged in US Government sponsored payload developments for CubeSat missions, some with budgets that are in the millions of dollars. Unfortunately, many of these efforts are not successful. The widespread occurrence of this miniaturization approach begs the argument if the 3U CubeSat standard is the optimal small satellite form factor for technology demonstration. The basis by which the elemental CubeSat unit (1U) was chosen was not the result of a detailed trade study. However, this argument is not within the scope of this paper.

Femtosatellites may be an affordable solution in this unforeseen new CubeSat-dominated environment if one divorces the thought of miniaturization from the process of developing a femtosatellite mission. The idea is to *do less with more*, adopting the idea that a new space mission may leverage massive distribution, enabled by adequately capable, low-cost femtosatellites. We discuss several game-changing missions in this paper, along with related issues such as new orbital mechanics that enable low-cost constellations, and the impact on space debris policy.

2. BACKGROUND

Femtosatellites

Femtosatellites are not a novel idea. The first femtosatellites were launched in May 1963 as part of the West Ford Experiment.[4] In reality, they were only tiny dipole needles massively distributed in space to serve as an artificial radio frequency (RF) relay "layer." Arguably, these were not real satellites, but set the stage for massively distributed satellite concepts of the future, which will be discussed later in this paper.

The next appearance of a femtosatellite concept is "satellite-on-a-chip," first published thirty years later in 1994.[5] Many femtosatellite concepts have been proposed since then, with increasing popularity and feasibility as commercial parts and processes can now cost-effectively support femtosatellite concepts. For example, in 2002, the Co-Orbiting Satellite Assistant (COSA), a 100-gram femtosatellite, was proposed as an ejectable satellite inspector for a weeklong mission.[6]

In 2005, a comprehensive study on the feasibility of satellite-on-a-chip was undertaken.[7] The work ultimately concluded in 2008 that very small satellites (those under 1 kg), are greatly disadvantaged by physical size limitations for payload accommodation and power generation.[8] However, after a detailed trade study including cost, a proposed "right size" very small satellite is 10 x 10 x 2.5 cm in size (for P-POD compatibility) with a mass of approximately 300 grams, based on a stacked printed circuit board (PCB) fabrication approach shown in Figure 1.[9] This simple current-technology PCB approach is more cost-effective and capable when compared to satellite-on-a-chip, CubeSats, and multi-chip module (MCM) architectures. A price point of less than $10,000 proves to be highly effective at enabling multiple massively distributed mission concepts, discussed in the Mission Section of this paper. The cost drops dramatically when mass produced.

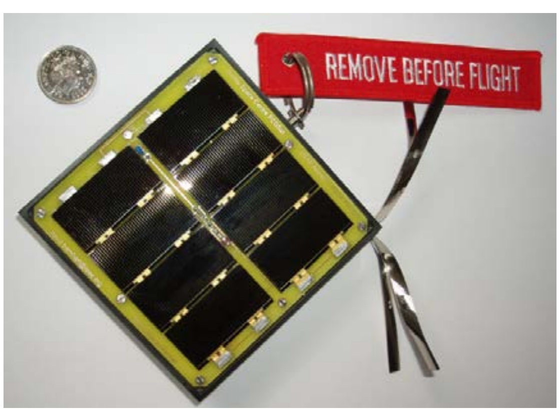

Figure 1: Photograph of PCBSat8

In 2008, the N-Prize effort further stimulated the very small satellite community. They offered a £10,000 prize (approximately $20,000 that year) to anyone who could put a functioning 20-gram satellite into orbit. The competition is now closed and must complete by September 2013.[10] WikiSat, inspired by the N-Prize challenge, is a 20-gram femtosatellite designed for the competition.[11] Although it does not perform a useful mission in the traditional sense, a supporting low-cost Wiki-launch system was also proposed.

PocketQub was developed with similar motivations. By taking a 1U CubeSat and dividing it into eight "PocketQubs," universities and low-budget research groups can get back into the game as the unit launch costs are one-eighth less in theory.[12] The mass of a PocketQub, depending on the design, could qualify as a femtosatellite. The first PocketQubs are slated to fly on a Dnepr launch in 2013, to be deployed from UNISAT-5, with a mass of approximately 400 grams each.

PhoneSat is another potential femtosatellite approach. NASA Ames has developed a concept that has been shared by many; i.e. the idea of flying a mobile phone in space. On April 21, 2013, three PhoneSats were put in space. Obviously, a COTS mobile phone cannot work as-is in space, but with some modifications, such as the transceiver and power supply, a mobile phone can provide a lot of common satellite bus functions.[13]

Other research groups have been inspired by a variety of very small satellite concepts and supporting technology, including femtosatellites. For example, Brown hosted a "ChipSat" workshop in 2010.[14] The University of Michigan has seriously explored the idea of using an electro-dynamic tether to provide propulsion for a satellite-on-a-chip mission.[15] KickSat is a Cornell University CubeSat/femtosatellite effort funded by crowd-sourcing.[16] $30,000 US was the original funding goal to support development, fabrication and testing of a CubeSat that will deploy hundreds of ~5-cm square "Sprites." Sprites are basically single-board femtosatellites that have solar cells, a transceiver, a microcontroller with memory, and sensors. Broadcasts are limited to an identification name or number, and a few bits of data. With a pledge of $1,000 US or more, you can get your own Sprite and development kit to program the transmissions.

Dozens of other femtosatellite, satellite-on-a-chip, and very small satellite concepts have emerged since the mid-2000s. The common theme has been focused on a low-cost solution for space experimentation and potentially real missions. The efforts that have been focused on minimal miniaturization to achieve the mission objectives.

Distributed vs. Fractionated Mission Architectures

The focus of this paper regarding mission architectures is massive distribution of identical spacecraft mission concepts enabled by massive distribution are discussed later in this paper. This architecture is distinctly different than fractionation, made popular by the Defense Advanced Research Project Agencies' (DARPA's) prior F6 effort.[17] Fractionation is where the functions of a monolithic satellite are broken up into a local cluster of different spacecraft that collectively perform the same function.

Massive distribution is not a new concept either. The Global Positioning System (GPS) was the first "massively" distributed constellation, with a nominal constellation size of 24. Up until this time, constellations rarely approached a dozen spacecraft. The largest distributed constellation to date is the IRIDIUM global mobile phone network, with a nominal spacecraft count of 66.[18] Other large constellations were envisioned in the 1990s for mobile internet and telecom, but were never realized due to the unforeseen rapid expansion of terrestrial networks.

Mass Production vs. Miniaturization

The legacy distributed constellations just discussed have relatively expensive single-satellite costs. IRIDIUM is the only space system acquisition that approached "mass production" by employing an assembly line approach. In stark contrast, femtosatellites can be readily mass-produced using largely commercial processes and components. This paper focuses on massive constellations of mass produced femtosatellites, with homogeneous and heterogeneous options possible.

When projects become primarily focused on miniaturizing a payload, they typically fail for two reasons: either the costs become too high or the miniaturization objective cannot be reached. The laws of physics will always dictate a minimum solar power collection area or a minimum aperture size for the payload. Femtosatellites should be designed within the constraints of existing technology.

Femtosatellite Flight History

A number of passive femtosatellites, and of course millions of West Ford wires, have flown. The smallest *functioning*, free-flying satellites to date are the Aerospace PicoSat 1A/1B tethered experiment, deployed from the Orbiting Picosatellite Automated Launcher (OPAL).[19] Launched in 2000, they were each 250 grams in mass and 10 x 7.5 x 2.5-cm in size. Two more were ejected from MightySat 2.1 a year later, a satellite flown by the Air Force Research Laboratory.

About the same time, among the same circle of engineers, the CubeSat concept was being developed. The smallest envisioned satellite configuration at the time was 1 kg, conforming to a volume of 10x10x10 cm, referred to as 1U.1 A standard containerized deployment system, the P-POD, was developed to launch three 1U CubeSats at the same time.2 The CubeSat pedigree and lineage have been reported in multiple publications, so is not reported here, but total multiple dozens of missions to date

3. FEMTOSATELLITE-ENABLED MISSIONS

Femtosatellites are an enabling technology primarily due to their low cost when miniaturization is not the objective. Very low-cost satellites, less than $10,000 each, open up new mission concepts and enable massive distribution to satisfy mission objectives. The major drawback of massively-distributed femtosatellites is potential space debris which will be addressed later.

The following missions are just a subset of potential missions enabled by the massive distribution of femtosatellites:

- Smart West Ford (RF signal relay)
- In-situ space weather monitoring
- Upper atmosphere modeling
- One-way satellite inspector
- Terrestrial gamma ray flash monitoring

Smart West Ford

As noted previously, the West Ford Experiment was a massive distribution of millions of tiny needles to create an artificial ionosphere that would reflect 8-GHz radio waves. In May 1963, 480 million tiny dipole needles, about 1.8 cm long, 18 µm in diameter, and only 41 µg in mass, were deployed in a 3700-km altitude orbit.[20] The purpose of the experiment was to demonstrate a launch on demand, i.e. tactical relay in orbit, with broad global coverage. The downside of this approach was that it required powerful ground stations in the kilowatt range. Also, the ideal frequency was relatively fixed due to the needle length.

A modern approach to West Ford would be to use a dramatically smaller number of satellites, perhaps in the 100s-to-1000s range, each with active and intelligent capability. This would allow for detection and retransmission of RF signals, either immediately or in a store-and-forward configuration. Also, the incoming signal could be up- or down-converted, depending on mission requirements. Knowledge of where the individual femtosatellite locations would not be important. Rather, knowing the approximate orbit would be all that is required. The ground station would hold the antenna fixed and wait for femtosatellites to pass through. With a few thousand femtosatellites distributed in a low orbit directly overhead, users simply tune to the appropriate transmit and receive frequencies to establish communication. This gives a robust, beyond line of sight capability, potentially worldwide. Unlike West Ford, these satellites would only respond to uplinks with appropriate identifier codes. Coupled with a small launch system, a tactical communication capability becomes feasible, perhaps even launched on demand from the field. This unconventional approach would provide reliable communications in a contested environment.

In-Situ Space Weather

Space weather was once a niche area of study by the scientific community. As the world now depends on space-enabled technologies, even small interruptions in space-based systems due to space weather have a large impact on many people. Being able to predict space weather and its likely effects on space systems is now a top priority for civil, commercial, and governmental sectors alike.

Terrestrial weather monitoring has been made nearly ubiquitous with movements such as WeatherBug in the United States. Over eight thousand weather stations are networked together to dramatically increase the sampling density within populated areas. This is in addition to the already existing radio and television weather forecasting stations, all loosely coordinated by the National Weather Service.

Currently, there are very few space weather sampling systems such as the Solar and Heliospheric Observatory (SOHO) satellite system that monitor solar activity and provide warning of solar flares. Femtosatellites are impractical for this type of monitoring, due to payload hosting limitations and required RF communication links. Nor are they appropriate for space weather buoys spread throughout the solar system. However, they are ideal for massive distribution in low Earth orbit (LEO).

A complete space weather sensor network concept was presented previously in 2008, with a focus on the space segment and femtosatellite design.[8,9] The concept was updated in 2012, which focused on the ionospheric plasma science and two key orbital scenarios.[21] The enabling space weather sensor that can be hosted on a femtosatellite is the Micro Electrostatic Analyzer (MESA).[22]

Figure 2 presents results from two different in-situ femtosatellite employment scenarios.[21] The profiles correspond to 0400 UCT on day 74 of 2010 and to 161.25 degrees longitude and 10 degrees latitude. The two constellations considered are composed of ten femtosatellites evenly spaced in a string of pearls configuration in a 90 degree inclination circular orbit at the noted altitudes. The presented data is from a full physics-based global data assimilation model. GPS represents data collected from appropriate GPS ground stations that can deliver total electron count (TEC). Note that a lower altitude constellation delivers results closer to the Truth model.

The research is aimed at predicting the formation and characteristics of plasma bubbles in the ionosphere that can deflect signals between a satellite and a user on the ground. This frequent issue is a problem for both commercial and military users.

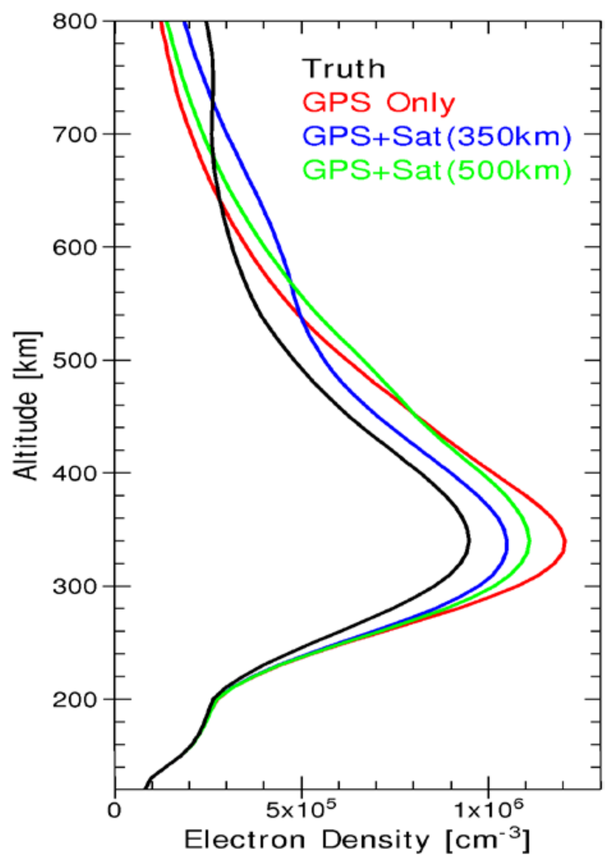

Figure 2: Electron Density vs. Altitude[21]

Upper Atmospheric Density Monitoring

In low-Earth orbit, aerodynamic drag in the upper atmosphere is difficult to predict due to the highly dynamic nature of atmospheric density. This variability effects space situational awareness (SSA) of satellites, especially at altitudes below 400-km. One of the authors experienced this first-hand during flight operations of the PicoSatellite Solar Cell Testbed-2.[23] The ground station antenna had a ~5^{o} angular beamwidth, and communications with the satellite were unavailable several times during its 4.5-month orbital lifetime. Communications loss was caused by solar activity that temporarily increased upper atmospheric density. Orbital elements that were 1-day old did not include the increased drag, and the instantaneous spacecraft position, predicted by the previous elements, was off by more than 5 degrees over the next few days.

Massively distributed femtosatellites in LEO would be a cost-effective way of sampling the drag environment. The University of Colorado's Drag and Atmospheric Neutral Density Explorer (DANDE) is a 50 kg spherical microsatellite designed to sample density, wind and composition in the thermosphere (basically LEO). Spherical femtosatellites could potentially provide a distributed set of real-time density measurements based on drag measurements. A cluster of femtosatellites would fly at a ~500-km altitude in a low-drag mode to provide on-demand deployment over a period of years. Once activated, individual femtosatellites would inflate one or more balloons to generate a high-drag spherical spacecraft with a roughly one-month orbital lifetime. Spheres do not require attitude control and make drag calculations simpler. These spacecraft will include a tracking beacon to find and identify individual femtosatellites, and potentially download GPS position and velocity data. While atmospheric density data could be generated by models that incorporate drag estimates based on orbit tracking data, multiple GPS fixes per orbit would provide significantly better drag determination accuracy.

One-Way Satellite Inspector

Satellite inspectors are micro-, nano-, pico-, or femtosatellites that could be ejected from a host spacecraft to resolve on-orbit anomalies such as improper array deployment, improper antenna deployment, micrometeoroid damage, surface damage due to impact with materials from the upper stage, and decreased solar cell output due to surface contamination. Ideally, a small spacecraft is ejected from the host spacecraft that subsequently co-orbits the host in order to provide controlled mobile imaging for high-resolution inspection of external surfaces over a period of hours, days, or weeks. Three-axis stabilization, orbit-adjust propulsion, an optical imaging system, and a communications system are required.

Satellite inspectors have been feasible for more than a decade, but the perceived risk of collision between a co-orbiting inspector and the host spacecraft has limited their implementation to a handful of demonstrations such as the 72-kg mass Inspektor (December 1997), the 16-kg mass AerCam Sprint (December 1997), the 6.5-kg mass SNAP-1 (February 2000), the 1.4-kg mass MEPSI (December 2006) and the ~0.5-kg mass DCAM-1/2 platforms (June 2010).[24-28] Inspektor lost attitude control and the host (Mir space station) had to maneuver to prevent a collision, AerCam successfully flew around the Shuttle bay under astronaut control, SNAP-1 ran out of propellant before it could rendezvous with a target microsatellite, MEPSI was purposefully limited in propellant to prevent re-contact its host (US Space Shuttle Discovery), and the 6-cm diameter, 6-cm long, DCAM-1/2 platforms avoided the whole collision issue by being ejected from JAXA's IKAROS solar sail on one-way escape trajectories.

Figure 3 shows a plot of steadily-declining satellite inspector mass over the last two decades. The straight line in Fig. 1 is a fit to the U.S., U.K., and Japanese flights that predicts a femtosatellite version starting in 2014. Satellite inspector mass has been steadily declining due to advancements in micro/ nanoelectronics and microelectromechanical systems, and due to the elimination of proximity propulsion and positional awareness sensors by using one-way escape trajectories. With lower-mass satellite inspectors, more can be carried on any given spacecraft, thus justifying use of short-lived disposable inspectors. Without the possibility of re-contact with the much more expensive host vehicle, satellite inspectors may become more viable. This application "does less with more".

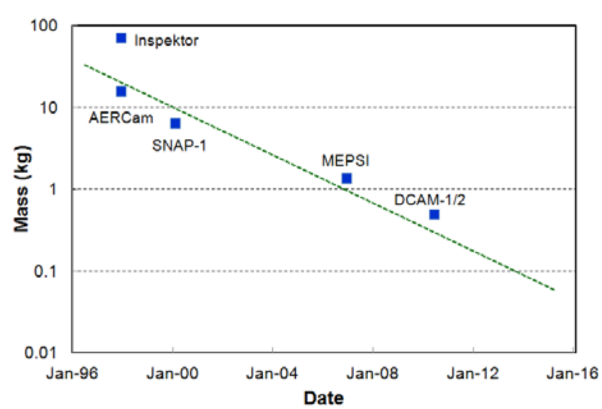

Figure 3. Satellite Inspector Mass As a Function of Flight Date

Based on analyses done by one of the co-authors, the linear fit in Fig. 3 is actually conservative; a 40-gram mass disposable satellite inspector can be fabricated today. The inspector camera can be a miniscule 3-mm scale, commercially-available, system-on-chip camera typically used in cell phones and tablet computers.

Figure 4 shows a photograph of the OmniVision OVM7690 "CameraCube" on a U.S. dime that contains a 640 x 480 pixel color image sensor, an embedded processor, and wafer-level optics.[29] This sensor costs about $8 US in single-unit quantities.

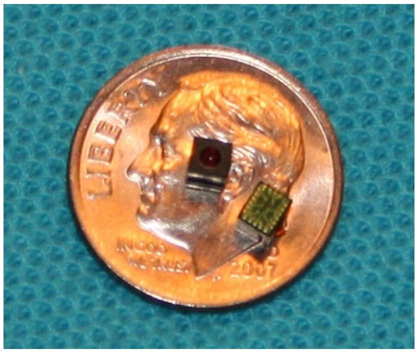

Figure 4. Photograph of the OmniVision OVM7690 with Integrated F/3, 67^o Field-of-view lens

A femtosatellite transceiver will be significantly larger than the imager. The Aerospace Corporation has successfully used vendor-modified FreeWave MM2-T data transceivers on their AeroCubes. Vendor modifications included increasing the bandwidth of the intermediate frequency filter to allow for Doppler shift, and increasing the timeout limit for handshaking between transceivers to 8 milliseconds. The 14-gram mass MM2-T transceivers are 5.1 x 3.6 x 1.0-cm in size and operate at 915 MHz with data rates up to 153 kbps using Gaussian frequency shift-keyed (GFSK) modulation with a maximum power output of 1 W.[30] Power consumption for 1-W output is ~3 W.

A lower-power, even smaller option is the HopeRF RFM22B module with 1.6 x 1.6 x 0.49-cm dimensions, a mass of ~1-gram, and a power output of 100 mW at 915 MHz.[31] Power consumption is 56 mW in receive mode and 260 mW in transmit mode at 100-mW RF output. This transceiver operates at 433, 868, or 915 MHz and has data rates ranging from 0.123 to 256 kilobits/second (kbps) with frequency shift-keyed (FSK), GFSK, or on/off (OOK) modulation. This transceiver is adequate for 125-kbps satellite-to-host links between identical transceivers with 0-dB gain antennas at up to 20-km range, or satellite to ground links with a 5-meter diameter ground station antenna at up to 1200-km range at 125-kbps data rates. These radios, like most commercial units, still need modifications to account for Doppler shifts and round-trip time-of-flight delays up to 8 ms for space-to-ground links.

How long will a femtosatellite inspector remain within 20 km of the host spacecraft for low-power cross links using omidirectional antennas? Figure 5 shows a representative trajectory, not including differential drag effects, in the host satellite frame between a host satellite in a 360-km altitude circular Earth orbit and a one-way inspector ejected at 0.5 m/s at a 10^o angle from the nadir direction. The data points are 1 minute apart. The inspector has an initial in-flight (or V-bar) velocity component and the trajectory plot is in the orbit plane and centered on the host vehicle. Figure 5 shows that the inspector returns to the host satellite orbit 55 minutes later, about 2 km behind the host (neglecting differential air drag). Maximum inspector to host range is about 2.5 km over an orbit period (92 minutes).

Doubling the ejection speed doubles the range as a function of time, and the minimum miss distance on return (about 3 km). In the 0.5-m/s ejection case, the inspector is within 50 meters of the host vehicle for 100 s, thus establishing photo inspection time. With a 0.5-s interval between images, 200 photos can be taken with host spatial resolutions ranging from 0.7 mm at 1 s to 7 cm at 100 s. Total data storage ranges from 184 Mbytes (uncompressed) to ~18 Mbytes (10x JPEG compression). At 125-kbps data rates, data download times vary between 2.5 and 25 minutes. Maximum host to inspector ranges during data download are less than 3 km. Download to a single ground station would require between 1 and 5 passes at the same data rate.

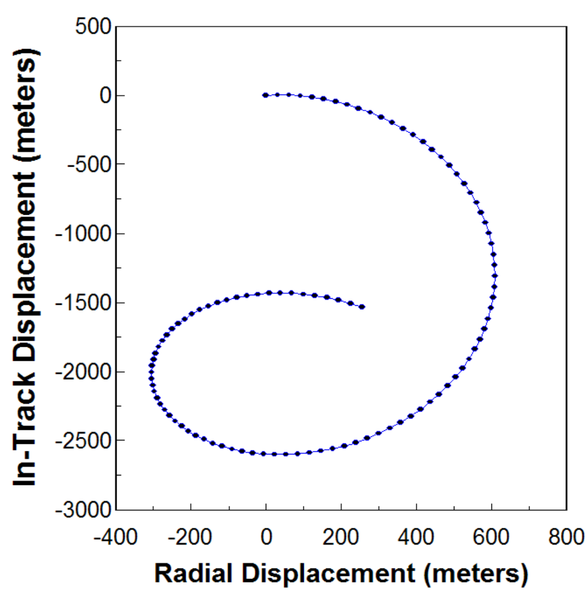

Figure 5. Trajectory and Range Plots for a One-way Satellite Inspector Ejected at a 10^o angle from the Nadir Direction at 0.5 m/s.

How much power and energy storage is required for this mission? The camera plus JPEG compression requires about 300 mW, and the transmitter requires 260 mW. With 100 s of image taking and JPEG compression followed by 2.5 minutes of transmitting, the minimum energy requirement is only 70 W-s; about 20 mW-hr. The LP30-FR lithium-polymer cell, developed for radio-controlled "Microlight" model airplanes, has 1.1 x 1.7 x 0.36-cm dimensions, a 1.16-gram mass, a 100-mW-hr storage capacity, and a 2-W maximum output.[32] The energy storage and power output are more than adequate for this disposable femtosatellite mission.

The Aerospace Corporation used three 2.5-gram mass, 6-mm diameter by 25-mm long, Faulhaber 0620 motors with a 100,000-rpm maximum speed as reaction wheel motors in their AeroCube-4 series spacecraft. Rotor diameters are 1.2 cm, and the entire triad has a mass of 60 grams. These motors and rotors were tested in a vacuum bell jar under an accelerated life test of 3,600 on/off cycles (30 s on, 30 s off) with thermal cycling between -15 ^{o}C to +50 ^{o}C without failure.

The Faulhaber 0308 series BLDC motor is another promising candidate for femtosatellite reaction wheels. These 0.31-gram motors are 3 mm in diameter by 10.4-mm long, including the shaft, and operate at 3V with a maximum per-phase power of 0.1 A and a maximum speed of 84,000 rpm. With a 3-mm diameter by 4-mm thick external stainless steel rotor, these motors can rotate a 50-gram mass, 5 x 5 x 2-cm femtosatellite at up to 6^{o}/s rates. Unlike their larger siblings, these motors use jewel bearings instead of ball bearings, and do not have integrated Hall sensors for feedback control. Optical sensing of rotor position can be used as Hall sensor surrogates. Our current driver circuit requires ~5 square centimeters of PCB area per motor. By limiting coil currents to 25-mA, the motor coils could be directly connected to a 3-V microcontroller output pins to significantly reduce required PCB board space.

The Aerospace Corporation PicoSat group has also designed and fabricated magnetic coils and driver circuits for detumbling picosatellites and nanosatellites. For femtosatellites, we would use 1.8-cm long, 40-AWG (80-micron diameter) copper coils wound on 2-mm diameter mumetal cores. These 2.5-gram coils would require 60 mW of power to rotate a 50-gram femtosatellite in LEO by 90^{o} within 15 seconds. These 3V coils can be directly driven by microcontroller outputs since they require only 20 mA of current.

Terrestrial Gamma Ray Flash Monitoring

Visible light photons have energies ranging from 2 (red light) to 3 (blue light) electron volts (eV). X-rays are highly-energetic photons with energies between 100 eV and 100 keV, and gamma rays are even more energetic with energies in excess of 100 keV. Gamma rays are typically associated with radioactive materials and energetic cosmic events like supernovae and gamma ray bursts. "Gamma ray bursts (GRBs) are the most extreme explosive events in the universe. The initial (prompt) phase lasts typically less than 100 s and has an energy content of ~10^{51} ergs, giving a luminosity that is a million times larger than the peak electromagnetic luminosity of the bright emission from an exploding-star supernova."[33] Gamma ray bursts occur about once a day, and are believed to signal the creation of a black hole or other exotic compact object. While one would think that GRB detection and celestial location would be relatively easy even for a small satellite, gamma rays cannot be readily focused and large areas are required to separate the burst signal (~1/cm^2-s) from background (~2/cm^2-s) over 10-to-100-s burst lengths.

NASA's 1450-kg mass SWIFT spacecraft, for example, has a burst alert telescope (BAT) composed of a 2.7-m^2 coded aperture mask 1-meter above a 1.2 x 0.6-m array of 32,768 CdZnTe semiconductor radiation detectors to sense 15-to-150-keV photons.[34] The photon flight path between the aperture mask and detector array is surrounded by a radiation shield to reduce background radiation levels. Individual detectors are 4 x 4 x 2-mm in size, the instrument has a 1.2-steradian field-of-view, and the total background count rate is ~17,000 per second. Integrating the number of counts over a fixed time period for each pixel generates a two-dimensional image that is a combination of diffuse background counts plus a shadow of the aperture mask. Image analysis yields the direction of the source, relative to the viewing direction, within 4-arcminutes.

A 2-mm thick, 20-cm^2 CdZnTe detector array with 50% photon detection efficiency that could fit on a femtosatellite would detect roughly 10 GRB photons and 20 background photons each second. Each detector pulse has an amplitude proportional to particle or photon energy, so an energy spectrum can be measured if enough particles (10 or more) are detected.

Since CdZnTe has a density of 6.4-grams/cc, this detector would a mass of 26-grams, excluding signal conditioning and processing electronics. Positive GRB detection with 5-sigma deviation from background would require integration over at least 5 seconds; a reasonable integration time. Determination of angular position of the GRB using a shadow mask, however, would require significantly more detector area, and hence mass, to provide statistically-significant data. A femtosatellite could therefore detect GRBs, but not be able to locate them.

A better gamma ray detection mission for femtosatellites is to monitor terrestrial gamma ray flashes (TGFs). TGFs occur at altitudes between 10 and 20-km during a lightning strike.[35] About a thousand TGFs have been observed by satellites with X-ray and gamma-ray detectors. Energies range from 0.1-to-100 MeV with a total radiated energy per flash of 20-to-40-kJ. These flashes occur at least once per 10,000 lightning discharges, and the directed gamma ray burst can generate high-energy electrons at higher altitudes (~35-km), through pair-production and other processes, that escape into space.[36] Pair production turns a gamma ray into an electron-positron pair, so TGFs also generate positrons that enter low Earth orbit. The remaining gamma-rays travel upwards with a full-width half-max cone angle of 20^o-to-80^o. At 500-km altitude, the gamma ray footprint is hundreds of kilometers in diameter. Electrons and positrons travel along magnetic field lines, generating a footprint at 500-km altitude that is only tens-of-kilometers in size.

While not as powerful as GRBs, typical bright TGFs are much closer and yield integrated fluencies of ~0.7 photons/cm^2 at ~565-km altitude over a 2-ms time period.[37] This short flash duration provides a temporary count rate that is two orders-of-magnitude larger than the background rate. If the 20-cm^2 detector array is aimed at the Earth and three or more events above 100-keV energy are observed within 2 ms of each other, one can assume a TGF has occurred within a few hundred kilometers of the subsatellite point.

Data to be logged include time of the TGF, number of detected pulses within 2 ms, and pulse amplitudes. A temporal accuracy of a second is acceptable since the positional error at orbital velocity is much less than the diameter of either the photon or electron/positron volumes. A high-precision time base such as a GPS receiver, is not required. Location over the Earth within tens-of-kilometers can be determined using time and orbital elements. Even with 1000 detections of 4 coincident pulses per day, only 10 kilobytes of memory storage are required per day of operation. Downloads to ground stations at a 1200-baud rate should occur once every four days.

This mission is another "do less with more" mission. The spacecraft can be relatively light weight and inexpensive, thus allowing tens or hundreds to be deployed. The larger numbers of spatially-separated detectors would improve the overall odds of detecting TGFs, improve our scientific understanding of how many occur per day and where, and provide additional information on energy and flux distributions.

4. FEMTOSATELLITE ORBITAL MECHANICS

Many femtosatellite missions require constellations with multiple orbital planes. Due to their small mass and secondary or tertiary payload status on launch vehicles, it is unreasonable to consider individual launches to each orbital plane. Femtosatellite constellations must be created using one or possibly two launches and some form of orbit control to populate other orbital planes. This enables the "Constellation in a CubeSat" approach using femtosatellites stored inside and deployed by a CubeSat. Constellations of roughly 8 through 24, 100-gram mass, femtosatellites could be created using 1U through 3U CubeSats.

Constellations usually require multiple orbital planes, each with a different instantaneous right ascension of the ascending node (RAAN). The right ascension of the ascending node is the right ascension angle where the orbit crosses the equator on the ascending node, thus indicating orbit orientation in inertial space, and the nodal regression rate is the angular rate at which the RAAN changes. Orbital planes rotate about the Earth in an inertial frame at the nodal regression rate. This rate is a function of both altitude and orbit inclination. Figure 6 shows nodal regression rates as a function of orbit inclination for circular orbit altitudes of 450, 525, and 600 km.

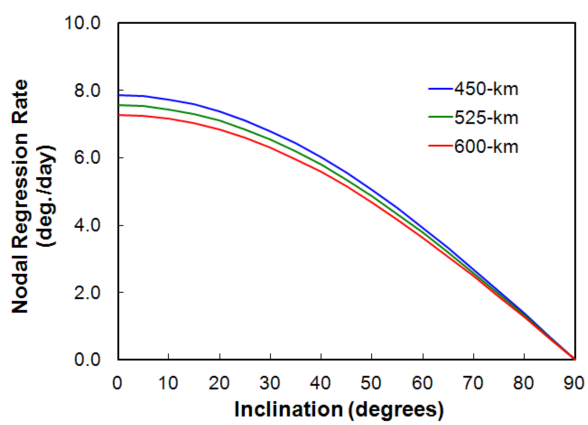

Figure 6. Nodal Regression Rates as a Function of Orbit Inclination for Circular Orbits with 450, 525, and 600 km Altitudes.

Changing RAAN typically involves changing orbit altitude, waiting in this orbit long enough to generate the required difference in RAAN between the original and new orbit, and then returning to the original orbit altitude. While these maneuvers are typically done using on-board propulsion, they can also be accomplished using variable drag control if the initial orbit altitude is higher than the required altitude, and one has sufficient patience. Removing on-board propulsion simplifies both the femtosatellites and launch vehicle integration issues. Ballistic coefficient *B*, is given in this work by:

$$B = C_D A / m \qquad (1)$$

where C_D is a drag coefficient (~2), *A* is spacecraft area normal to the flight direction, and m is spacecraft mass, is much larger for femtosatellites than for typical spacecraft. A 50-kg mass microsatellite with a 30 x 30-cm area perpendicular to the flight direction will have a ballistic coefficient of 36 cm^2/kg while a 0.1-kg femtosatellite with a 10 x 10-cm perpendicular area will have a ballistic coefficient of 2000 cm^2/kg. Femtosatellites are more susceptible to air drag and will deorbit much faster than larger satellites for a given starting altitude.

Figure 7 shows apogee and perigee height for two 100-gram mass femtosatellites with 1 x 10 x 10-cm dimensions starting in a 600-km altitude circular orbit on January 1, 2015. The upper chart shows orbit evolution for the lowest drag case (10-cm^2 projected area) while the lower chart shows orbit evolution for the highest drag case (100-cm^2 projected area). The red curve is the apogee, the blue curve is the perigee, and these curves were calculated using the LIFETIME high-fidelity orbit propagation program developed at The Aerospace Corporation. Atmospheric density was based on the NASA Marshall 50th percentile atmosphere. Note that the low drag case has an orbit lifetime of just over 25 years while the high-drag case has an orbit lifetime of only 4.3 years.

With positive attitude control, femtosatellites can not only modify their orbit lifetime, but also their mean anomaly or orbit phase angle. Orbit rephasing using variable drag was demonstrated using the Aerospace Corporation AeroCube-4A, -B, and -C 1U CubeSats over a period of several months.[38] These 1.3-kg mass spacecraft were delivered to a roughly 480 x 780 km altitude orbit with a 65° inclination, and have deployable wings that can be used to vary ballistic coefficient between ~170 cm^2/kg and 600 cm^2/kg. Femtosatellites with a 10:1 range of ballistic coefficient dispersed in a single orbit at altitudes below 600 km should be able to perform large-angle (>90°) coordinated rephasing maneuvers with month-long timescales. These maneuvers would be used to concentrate or disperse femtosatellites along an orbit.

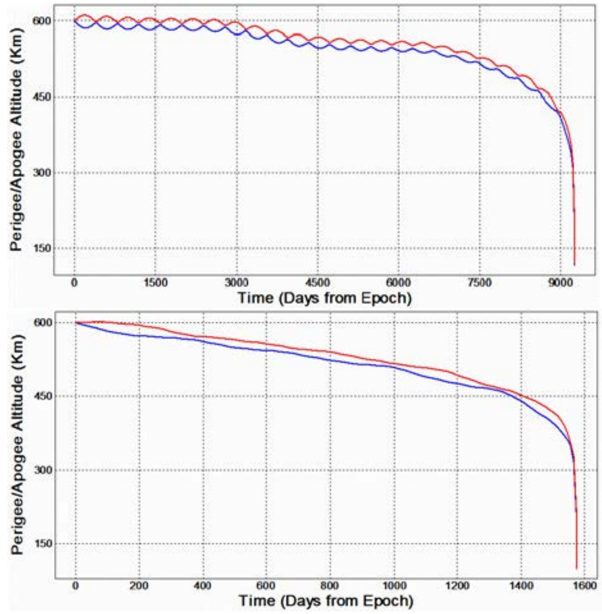

Figure 7. Orbit Perigee and Apogee as a Function of Time for a spacecraft with a ballistic coefficient of 200 cm^2/kg, (top) and 2000 cm^2/kg, (bottom).

Orbit phase control enables an important function for any spacecraft: collision avoidance. One of the authors has experienced responding to a phone call from the Joint Space Operations Center (JSpOC) informing him of a potential collision between his spacecraft and some other space object. Being able to slightly modify your spacecraft orbit when required, especially to avoid a potential collision, benefits all space users. Collision avoidance can be performed by changing your expected position, several days in the future, by more than a kilometer. Analyses performed using The Aerospace Corporation's Satellite Orbital Analysis Program (SOAP) have shown that changing the ballistic coefficient from 200 cm^2/kg to 2000 cm^2/kg will change instantaneous orbit position 72 hours later by more than 3 km at altitudes below 800 km for circular orbits. Figure 8 shows a plot of position change, after 3 days, vs. altitude for a Jacchia-Roberts 1991 model atmosphere. Femtosatellite ballistic coefficient modification using attitude control can be a powerful tool for avoiding orbital collisions.

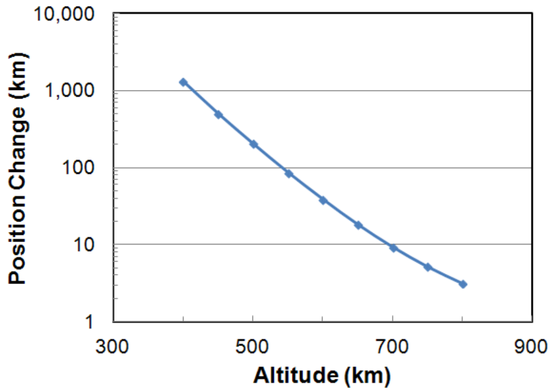

Figure 8. Position Change, 72 hours After Changing Ballistic Coefficient from 200 cm^2/kg to 2000 cm^2/kg, as a Function of Circular Orbit Height.

Much longer time scales are required for RAAN modification. As an example, start with a cluster of 0.1-kg mass, 1 x 10 x 10-cm femtosatellites initially deployed at 600-km altitude from a CubeSat or other dispenser. These femtosatellites can be stored at altitudes greater than 580 km for 4 years by putting all spacecraft into a minimum drag mode (see Fig. 7 top). Putting a fraction of these femtosatellites into high drag mode for 2-years will place these femtosatellites into a ~525-km altitude orbit (see Fig. 7 bottom). The high-altitude group will be called group 1 while the lower altitude group will be called group 2.

For a TGF constellation that covers Earth's tropical regions where most lightning occurs, one would use an orbit inclination of 30^o. At this inclination, the difference in nodal regression rates between 600 km and 525-km circular orbits is 0.24^o/day, and the average difference between groups 1 and 2 during the 2-year altitude-lowering period is 0.12^o/day. After the two year period to put group 2 at 525-km altitude, the RAAN difference between groups 1 and 2 will be ~90^o. At this point, the group 2 spacecraft can be put into low-drag mode while the group 1 spacecraft can be put into high-drag mode. After 2 more years, groups 1 and 2 will be at ~500-km altitude with a RAAN difference of ~180^o. This is the maximum RAAN change required to generate equally-spaced orbit planes around the Earth. It takes ~4 years to establish a full constellation, and this constellation has a ~4 year remaining lifetime if all spacecraft fly in minimum-drag mode. Eight equally-spaced 30^o inclination planes can be created by starting the high-drag mode for an individual femtosatellite from group 1 every 3-months. Figure 9 shows a rendering of the resulting 8-plane constellation where each plane contains a single femtosatellite, and all femtosatellites have the same phase angle. This would result from a propulsion-less "Constellation in a CubeSat" using a 1-U CubeSat that deploys 8 femtosatellies.

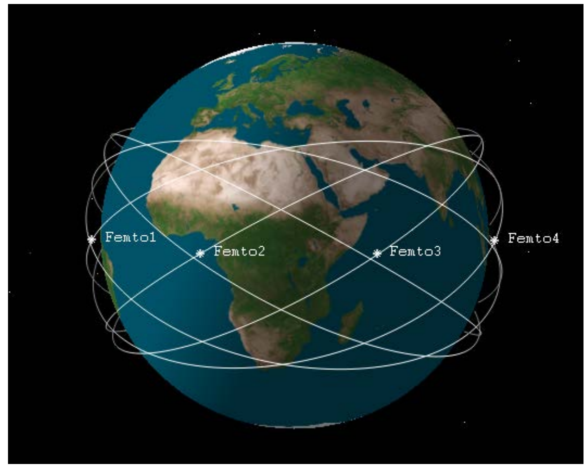

Figure 9. Rendering of an 8 Plane 30^o Inclination Constellation with One Femtosatellite Per Plane.

5. ENABLING COMPONENT TECHNOLOGIES

Femtosatellites obviously require cm-scale systems and subsystems. We have already discussed cm-scale transceivers, magnetic torque coils, imagers, and reaction wheels, but still need command and control, attitude sensing, and potentially position sensing. Modern commercial, off-the-shelf (COTS) electronics provides capable flight processors and memory storage on circuit boards a few centimeters on a side with a mass under 10 grams and power requirements in the tens-of-milliwatt range. A major advancement that has occurred over the past decade is the development of commercial Flash memory with unprecedented storage capacity. A micro SD memory card with 64 GB of storage is now readily available at ~$50, with 128 GB on the horizon. A 1.5 x 1.1 x 0.1 cm, 64-GB card has a mass of ~0.25 grams, and with a 125-kbit/s downlink and 2 passes per day of ~10-minute duration, it would take over 10 years to download this amount of data. Data storage is not a problem for femtosatellites.

Downloading data at rates in excess of 100 kbps will require medium-gain antennas on the spacecraft, and attitude control to aim those antennas at a suitable ground station. Attitude control is also required to aim cameras and other sensors. To point at a target such as a ground station, the spacecraft needs to know its position and time, or alternatively, have a pointing angle table based on the satellite's orbital elements, and an accurate clock. In either case, a GPS receiver can provide accurate time, or through distributed position measurements, an accurate set of orbital elements.

The GPS receiver board shown in Figure 10 was developed at the Aerospace Corporation and has flown in their AeroCubes. It has a mass of 30 grams, requires 1.5 W for operation, has dimensions of 55 x 55 mm, and provides a positional accuracy of ~20 meters. The Radio Aurora Explorer (RAX) CubeSats flew modified NovAtel OEMV-1-L1 GPS receivers with a lower mass of 21.5 grams, a 46 x 71 x 10.3-mm size, and 1-W power consumption.[39] Researchers modified the firmware to remove altitude and velocity restrictions, remove the tropospheric model, and extend the Doppler range. An even better match to femtosatellite weight and power constraints is the NovAtel OEMStar receiver with similar dimensions, smaller mass (18-grams), and lower power operation (~450-mW).[40]

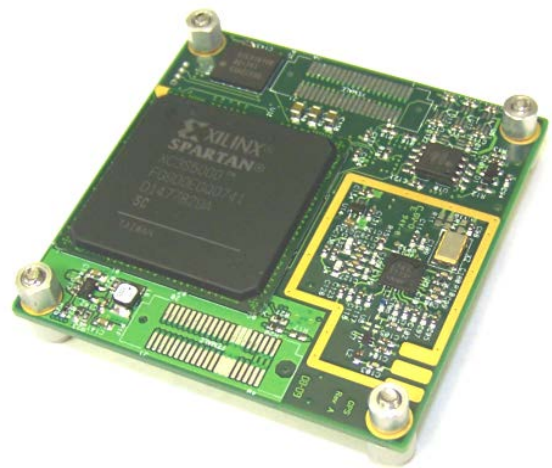

Figure 10. Photograph of the Aerospace Corp. GPS Receiver Board. (30 grams)

Once orbital position or time is known, spacecraft orientation or attitude must also be known and controlled to aim at a ground station or other target. The Aerospace Corporation has developed sun and Earth sensors with cm-scale dimensions that could be used in femtosatellites. Sun sensors are readily fabricated using quad photodiodes and aperture plates. An alternative approach is to use miniaturized imagers like those shown in Fig. 4, coupled with an image-processing circuit. The straight-forward sun sensor shown if Figure 11 is based on a 1-cm diameter, 3.3-mm high quad photocell. An aperture plate with a 1.5-mm square opening is bonded to the top of the detector, and a 6-mm high optical baffle provides Earthshine rejection for incidence angles greater than 34 degrees off-normal. The assembly, with aperture and baffle plate, has a mass of 4-grams.

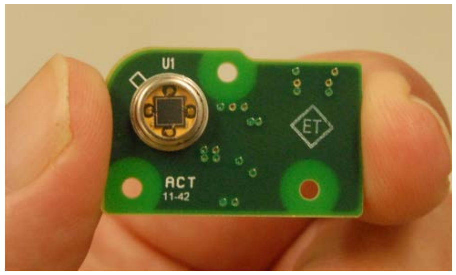

Figure 11. Photograph of a 2-axis Sun Sensor Flown on the AeroCube-4 spacecraft. The Aperture Plate and Optical Baffle are Missing in this Photograph.

An Earth nadir sensor shown in Fig. 12, has dimensions of 25 x 25 x 14 mm, a mass of 12 grams, and a demonstrated Earth nadir accuracy of about 1^o. This sensor is based on nine Melexis MLX90614 infrared optical thermometers that see the Earth, and Earth plus space, in four cardinal directions. For femtosatellites, one could use four Melexis MLX90620 optical thermometers pointing in different directions. These 1.1 x 0.9-cm diameter, 2-gram mass sensors have a 4 x 16 array of thermopile detectors that can be used to find the Earth's horizon within 1^o when part of the array sees warm Earth and the other part sees cold space. Four of these sensors can replace the sensor shown in Fig. 11 while two provide the required attitude accuracy to minimize or maximize femtosatellite drag. In combination with a magnetometer and/or sun sensor, they can provide full three-axis pointing information in inertial or Earth-centered reference frames.

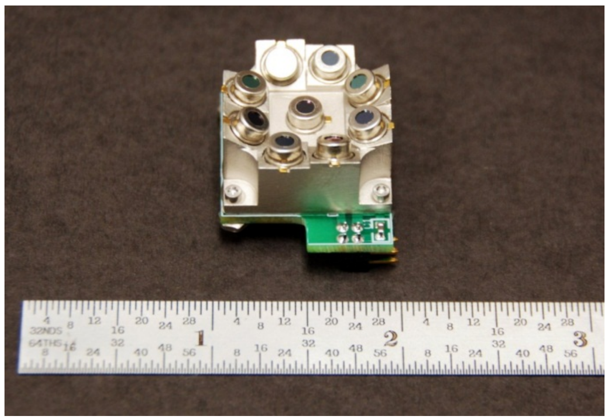

Figure 12. Photograph of the Earth Nadir Sensor Used on the Aerospace Corporation AeroCube-4 Spacecraft.

Magnetic field sensors are relatively low mass and easy to integrate into femtosatellites. The Honeywell HMC5883L is a 3-axis magnetometer in a 3 x 3 x 0.9-mm surface-mount package.[41] It can provide ~1^o magnetic field direction accuracy while consuming only 0.3-mW of power.

6. FEMTOSAT ACCEPTANCE CHALLENGES

Femtosatellites, if built from COTS components with a payload that is not purposely miniaturized, are a low-cost proposition for startup research and academic groups with limited resources. However, there are two main challenges for widespread femtosatellite acceptance: the orbital debris perception and the communication network architecture.

Impact to Orbital Debris Policy

Some femtosatellites, due to their very small size, may be difficult to reliably track by space sensor networks. Adding active beacons, and if possible a GPS receiver, should significantly improve tracking success. "Massively distributed" concepts will require at least active beacons to identify individual spacecraft.

It is widely accepted that satellites in LEO comply with a 25-year re-entry plan and this should not be an issue for femtosatellites as long as the starting altitude is below 700-km. Assuming that femtosatellites are deployed in a non-threatening orbit to the International Space Station (ISS) and other operational systems, their lifetime in LEO will be sufficiently low. The PCBSat concept discussed earlier suggests a low ballistic coefficient, due to its relatively small mass within a 10x10 cm area. Simple lifetime predictions are well below a year. This would ensure quick disposal of any femtosatellite in LEO.

It is also now common practice to reduce or eliminate space debris during the launch, separation, and disposal phases of a space mission. What about spacecraft being perceived as debris while they are in the operational phase of a mission? Currently, there are no real guidelines for a massively distributed femtosatellite concept, and some guidelines are sorely needed. One good starting point for any mission with hundreds to thousands of femtosatellites would be to require variable drag control. This can be as simple as deploying a drag enhancement device when needed. A deployable/retractable drag enhancement device, like attitude control on a highly non-spherical spacecraft, would be ideal.

Communication Architecture

There are two femtosatellite communications architectures that have been presented in the example mission section. For extremely small femtosatellites, such as the 40 gram satellite inspector, direct communication with the host spacecraft may be the only option possible due to the very low power available on the femtosatellite inspector. This is due to the relatively high data rate required for the mission, depending on the number of images taken.

Most other missions require a traditional direct downlink to one or more ground stations. The unlicensed (in the US) Instrumentation, Science, and Medicine (ISM) band at 915 MHz is the suggested frequency for our missions, due to the modest gain available using 2-to-5-meter class ground stations. However, this band is not unlicensed worldwide, potentially conflicting with mobile phone frequencies, such as is the case in Europe.

Antenna size and data rates are also an issue with femtosatellite design. At 915 MHz, $\lambda/4$ antenna segments are 8.33 cm. However, small deployable wire antennas can be effectively used. Additionally, all the data rates in the proposed missions are in the low kbps range. This allows the spacecraft transmit power to be low while leveraging a reasonable gain of the ground station antenna.

7. VERY SMALL SATELLITE COST MODELING

The Small Satellite Cost Model (SSCM), developed by the Aerospace Corporation, has been in development since 1989.[42] However, it is recognized that this model is not currently scalable to CubeSats through femtosatellite mass classes. Consequently, the development of the Aerospace Picosatellite Cost Model (A-PICOMO) effort was initiated.[43] A-PICOMO is focused on satellites with a mass under ten kilograms, which is an important step in cost modeling, but does not yet include mass-production considerations.

For femtosatellite missions, the mass-production of satellites becomes the driving factor in determining cost. Figure 13 illustrates the cost comparison of four very small satellite technologies for the space weather mission discussed previously.[8] Cost data at larger quantities was derived from actual vendor component costs. The CubeSat is a minimum-capability 1U system that is capable of meeting the mission requirements. The other three approaches are femtosatellite-class systems based on different fabrication approaches.

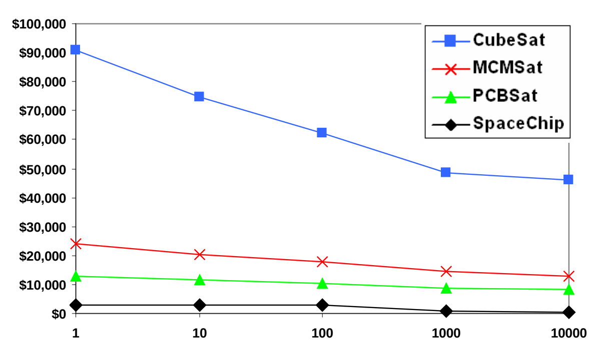

Figure 13: Unit Satellite Cost When Mass-Produced[8]

It is important to note that for this data the SpaceChip results are based on a theoretical space weather sensor design for a literal satellite-on-a-chip design, but actual cost data for the appropriate satellite die is used. In contrast, the other three approaches are based on actual existing component and sensor technologies packaged in three different ways: traditional CubeSat, MCM, and PCB. The conclusion of this preliminary cost-modeling effort for massively distributed femtosatellite constellations is that PCB-based manufacturing is likely the most cost-effective.

Much more work is required on these cost models. The high level of integration of mobile phone technology, as studied by the PhoneSat effort, is in the same class of integration required by a mass-produced femtosatellite. The next step is to work with industry to develop a cost estimate for a highly-integrated femtosatellite.

8. SUMMARY AND CONCLUSIONS

Femtosatellites offer a cost-effective route to space for universities, small organizations, and even individuals. One femtosatellite project has even used the relatively recent crowd-sourcing phenomenon to fund key development efforts. We have briefly discussed possible femtosatellite missions such as Smart West Ford, in-situ space weather monitoring, upper atmospheric density monitoring, one-way satellite inspectors, and terrestrial gamma ray flash monitoring. These are but a small subset of potential femtosatellite missions. Commercial, off-the-shelf technologies already exist to support these missions, limited only by the designer's imagination. In the longer term, relatively inexpensive femtosatellites could enable massively-distributed space systems. To make these compatible with other space systems in LEO, we should consider adding orbit control schemes such as variable drag control.

Acknowledgments

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References

1. H. Heidt, J. Puig-Suari, A. S. Moore, S. Nakasuka, and R. J. Twiggs, "CubeSat: A New Generation of Picosatellite for Education and Industry Low-Cost Space Experimentation," in Proc. 15th AIAA/USU Conf. on Small Satellites, Logan, UT, 2000, Paper SSC00-V-5.
2. I. Nason, J. Puig-Suari, and R. J. Twiggs, "Development of a Family of Picosatellite Deployers Based on the CubeSat Standard," in Proc. 2002 IEEE Aerospace Conf., Big Sky, MT, vol. 1, 2000, pp. 457–464.
3. B. Carlson, "NRO's Historical, Current, and Future Use of Small Satellites," National Reconnaissance Office, VA, [Online]. Available: http://www.nro.gov/news/speeches/2011/2011-01.pdf, 2011.
4. W. E. Morrow and T. F. Rogers, "The West Ford Experiment," Proceedings of the IEEE, vol. 52, no. 5, 1964, pp. 461–468.
5. J. Keller, "Startup to Develop Satellite-On-A-Chip," Military & Aerospace Electronics, vol. 5, no. 2, Feb. 1994, p. 1.
6. A. Huang, W. W. Hansen, S. W. Janson, and H. Helvajian, "Development of a 100 gm Class Inspector Satellite Using Photostructurable Glass/Ceramic Materials," Proc. of SPIE, vol. 4637, 2002, pp. 297–304.
7. D. J. Barnhart, T. Vladimirova, and M. N. Sweeting, "Satellite-on-a-Chip: A Feasibility Study," in Proc. Fifth Round Table on Micro/Nano Technologies for Space Workshop, Nordwijk, The Netherlands, 2005, ESA WPP-255, pp. 728–735.
8. D. J. Barnhart, "Very Small Satellites Design for Space Sensor Networks," Ph.D. Thesis, Univ. of Surrey, Guildford, England, U.K., June 2008, http://handle.dtic.mil/100.2/ADA486188
9. D. J. Barnhart, T. Vladimirova, and M. N. Sweeting, "Very Small Satellite Design for Space Sensor Networks," AIAA Journal of Spacecraft and Rockets, vol. 46, no. 2, Mar.-Apr. 2009, pp. 469-472.
10. P. Dear, "N-Prize," The N-Prize, UK, [Online]. Available: http://www.n-prize.com, 2013.
11. J. Tristancho, "Implementation of a femto-satellite and a mini-launcher," M.S. Thesis, Polytechnic University of Catalunya, Spain, 2010.
12. R. Twiggs, "PocketQub," [Online]. Available: http://pocketqub.org, 2013.
13. National Aeronautics and Space Administration, "PhoneSat: NASA's Smartphone Nanosatellite," [Online]. Available: http://www.phonesat.org, 2013.
14. D. J. Barnhart, "Very Small Satellite Design for Space Sensor Networks," in Proc. Brown University ChipSat Workshop, 2010.

15. I. Bell, B. Gilchrist, J. McTernan, S. Bilen, N. Voronka, R. Hoyt, M. Peck, "Enabling Ultra-small Sensor Spacecraft for the Space Environment using Small-Scale Electrodynamic Tethers," in Proc. AIAA Space 2011 Conference & Exposition, 2011.

16. Z. Manchester, "KickSat – Your Personal Spacecraft in Space!" Kickstarter, [Online]. Available: http://www.kickstarter.com/projects/zacinaction/kicksat-your-personal-spacecraft-in-space, 2013.

17. O. Brown and P. Eremenko, "Fractionated Space Architectures: A Vision for Responsive Space," in Proc. 4th Responsive Space Conf., Los Angeles, CA, 2006, Paper RS4-2006-1002.

18. T. P. Garrison, M. Ince, J. Pizzicaroli, and P. A. Swan, "Systems Engineering Trades for the IRIDIUM® Constellation," Journal of Spacecraft and Rockets, vol. 34, no. 5, Sep.–Oct. 1997, pp. 675–680.

19. J. Cutler, G. Hutchins, and R. J. Twiggs, "OPAL: Smaller, Simpler, and Just Plain Luckier," in Proc. 14th AIAA/USU Conf. on Small Satellites, Logan, UT, 2000, Paper SSC00-VII-4.

20. C. F. J. Overhage and W. H. Radford, "The Lincoln Laboratory West Ford program – An Historical Perspective," Proceedings of the IEEE, 52 (5), pp.564-570, May 1964.

21. R. Balthazor, D. Barnhart, et. al., "Sensitivity of Ionospheric Specifications to In Situ Plasma Density Observations Obtained From Electrostatic Analyzers Onboard of a Constellation of Small Satellites," in Proc. 26th AIAA/USU Conf. on Small Satellites, Logan, UT, 2012, Paper SSC12-IV-1.

22. C. L. Enloe, L. H. Krause, and R. K. Haaland, "Miniaturized Electrostatic Analyzer Manufactured Using Photolithographic Etching," Review of Scientific Instruments, vol. 74, no. 3, 2003, pp. 1192–1195.

23. S. W. Janson, B. S. Hardy, A. Y. Chin, D. L. Rumsey, D. A. Ehrlich, and D. A. Hinkley, "Attitude Control on the Pico Satellite Solar Cell Testbed – 2," paper SSC12-II-1, 26th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 2012.

24. Brian Harvey, *Russia in Space; The Failed Frontier?*, p.59, Praxis Publishing, Chichester, United Kingdom, 2001.

25. Steven Fredrickson, "Mini AERCam: The Miniature Autonomous Extravehicular Robotic Camera," *Small Satellites: Past, Present, and Future*, pp. 487-523, AIAA and The Aerospace Press, 2009.

26. C. Underwood, "The UK's First Nanosatellite – SNAP-1," *Small Satellites: Past, Present, and Future*, pp. 297-325, AIAA and The Aerospace Press, 2009.

27. D. Hinkley, "Picosatellites at The Aerospace Corporation," *Small Satellites: Past, Present, and Future*, pp. 635-674, AIAA and The Aerospace Press, 2009.

28. Japan Aerospace Exploration Agency, IKAROS press release, [Online]. Available: http://www.jaxa.jp/press/2010/06/20100628_ikaros_e.html , June 28, 2010.

29. OmniVision, OVM7690 web page, Omivision, Santa Clara, CA, [Online]. Available: http://www.ovt.com/uploads/parts/OVM7690_PB%281.0%29_web.pdf, 2012.

30. FreeWave, MM2-T Series Datasheet, FreeWave Techologies Inc., Boulder, CO, [Online]. Available: https://www.freewave.com/Portals/0/Documents/Data%20Sheets/MM2/LDS0001MMT%20Rev%20A%20MM2-TTL.pdf, 2013.

31. Hope Microelectronics, RFM22B/23B data sheet, Hope Microelectronics Company LTD., Shenzhen, China, [Online]. Available: http://www.hoperf.com/upload/rf/RFM22B_23B.pdf , 2013.

32. Plantraco, "LP30-FR Bahoma Cell with 5-mm Bahoma," Plantraco Ltd, Saskatoon, SK, Canada, [Online]. Available: http://www.microflight.com/LP30-FR-Bahoma-Cell-with-5mm-Bahoma, 2013.

33. Neil Gehrels and Peter Meszaros, "Gamma Ray Bursts," Science, 337, pp. 932-936, August 24, 2012.

34. Neil Gehrels et al., "The *SWIFT* Gamma-Ray Burst Mission," The Astrophysical Journal, **611**, pp. 1105-1020, August 20, 2004.

35. M. Tavani et al., "Terrestrial Gamma-Ray Flashes as Powerful Particle Accelerators," Physical Review Letters, 106, 018501, January 2011.

36. B. E. Carlson, T. Gjesteland, and N. Ostgaard, "Terrestrial Gamma-Ray Flash Electron Beam Geometry, Fluence, and Detection Frequency, Journal of Geophysical Research, 116, A11217, 2011.

37. M. S. Briggs et al., “First Results on Terrestrial Gamma Ray Flashes from the Fermi Gamma-Ray Burst Monitor,” Journal of Geophysical Research, 115, A07323, 2010.

38. J. Gangestad, B. Hardy, and D. Hinkley, “Operations, Orbit Determination, and Formation Control of the AeroCube-4 CubeSats,” paper SSC13-X-4, AIAA/USU Small Satellite Conference, Logan, Utah, August 10-15, 2013.

39. S. C. Spangler, M. W. Bennett, D. C. Meinzer, A. T. Klesh, J. A. Arlas, and J. W. Cutler, “Design and Implementation of the GPS Subsystem for the Radio Aurora Explorer,” Acta Astronautica, 87, pp.127-138, June-July 2013.

40. NovAtel, OEMStar web page, [Online]. Available: http://www.novatel.com/products/gnss-receivers/oem-receiver-boards/oemstar/ , 2013.

41. Honeywell, HMC5883L web page, Honeywell, Plymouth, MN, [Online]. Available: http://www51.honeywell.com/aero/common/documents/myaerospacecatalog-documents/Defense_Brochures-documents/HMC5883L_3-Axis_Digital_Compass_IC.pdf , 2013.

42. “Small Satellite Cost Model,” The Aerospace Corporation, CA, [Online]. Available: http://www.aerospace.org/expertise/technical-resources/small-satellite-cost-model/sscm-overview/, 2013.

43. M. Boghosian, “Cost Estimating Methodology for Very Small Satellites,” 1st Interplanetary CubeSat Workshop, Cambridge, MA. May 29-30, 2012.