THE SMALL SATELLITE DILEMMA

David FINKLEMAN

Center for Space Standards and Innovation
Colorado Springs, Colorado, USA

ABSTRACT

Small satellites are wonderful opportunities and a potential serious space safety dilemma. Their size and mass could reduce launch costs greatly. Their limited kinematic capabilities and small cross sections could also complicate orbital safety. Several missions require many small satellites, increasing the overall risk to themselves and others. As efficient, miniaturized components and propulsion techniques develop, small satellites can operate on orbit longer and in higher orbits, posing enduring risks in higher orbits. This paper considers small satellite operational concepts and capabilities that should minimize risk

Reference 1 estimates potentially hundreds of small satellites by some definition shortly to be in low Earth orbit.

The definition of smallness is controversial. We propose not to distinguish by physical size or mass but rather by functional characteristics important for mitigating debris and moderating orbit traffic. These include the ability to observe the spacecraft for the purpose of orbit determination, the ability of the spacecraft to maneuver, and the ability to communicate with and control the satellite.

NASA recently solicited concepts for debris mitigation from Cubesats, so the world is taking these spacecraft seriously and their potentially unfavorable impact on the space enterprise even more seriously. Each nation has a different perspective on small satellites. Recently during ISO deliberations in Brazil, Russian representatives stated that Russia is very much against very small satellites. China is ambivalent but tending towards the same opinion. Nations that only build or only operate satellites are much more favorably inclined. Developing nations are enthusiastic, and the UN Office of Outer Space Affairs is promoting that interest with conferences and workshops.

without compromising technical or economic potential. We propose satellite classifications on orbit based on functionality rather than size or mass. Some large satellites with limited capability can present even worse risks than small satellites.

1 INTRODUCTION

There is a revolution in small satellites that are relatively inexpensive to develop and launch. Approximately 90% of small satellites reside or are intended to operate in low Earth orbit; however, an increasing number join the crowd already in Sun Synchronous Orbit[1].

Figure 1. Typical cubesat configurations. (Courtesy of ISIS Cubesat Solutions)

There are more than 50 Cubesats currently in long lived orbits.[2] This is the outcome of their being deployed where the primary payload of the launch was deposited. The US Air Force recently demonstrated the ability to deploy small satellites enroute to the launcher's ultimate destination in orbits with confident decay within required time limits.[3] We will demonstrate that that there are operationally safe orbit regimes for small satellites that still satisfy most mission needs. We will also report studies of orbit selection for maximum and most frequent observability and describe techniques for achieving sufficient observability, maneuverability, and communication without great impact on the valuable payload mass.

2 CHARACTERISTICS FOR SAFE OPERATION

There are opportunities to develop safe operational techniques for small satellites. Our colleagues participate in the QB50[4] project

Proc. '6th European Conference on Space Debris'
Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013)

which will launch from Russia 50 identical, two unit Cubesats to characterize the upper atmosphere. These satellites will be designed and built with diverse instruments by universities all over the world.

It is very important to the debris mitigation community that small satellites should not be distinguished from large ones for debris purposes. No IADC guidelines should be compromised or special dispensation granted to small satellites. Our task is to exploit these exciting prospects within practical constraints.

2.1 OPERATIONAL DISCRIMINANTS

There are several different small satellite definitions. We adopt that that seems most common as presented in the IAA study of Earth Observation Satellites:mini satellites < 1000 kg. micro satellites < 100 kg, nano satellites < 10 kg, pico satellites < 1 kg

However, these are not sufficient to characterize satellite orbital risks or architectures. A mass discriminant belies size, orientation, maneuverability, observables, and many important matters.

The choice of orbital architectures for small satellites by any definition must consider these other characteristics.

2.2 OBSERVABILITY

If an object in orbit cannot maneuver, knowing where it is or might be is critical. The first consideration is that the object be discernible either passively by virtue of its own emissions or reflections of background radiation or through active illumination. The degree to which the object's state of motion can be determined or its future state estimated depends on the distribution of observation opportunities and the density of observations acquired during each observation interval.

Observability should be among principal considerations for the design of the vehicle and choice of orbit architecture. As an example, consider a single small satellite for which there are sufficient optical observables. Assume that mission requirements allow any reasonable altitude or inclination. The task is to find an orbit during which there is the cumulative time of observation is greatest given a small set of ground based sensors. Figure 1 depicts such a situation with instruments in Hawaii, Diego Garcia, and Kwajalein specified.

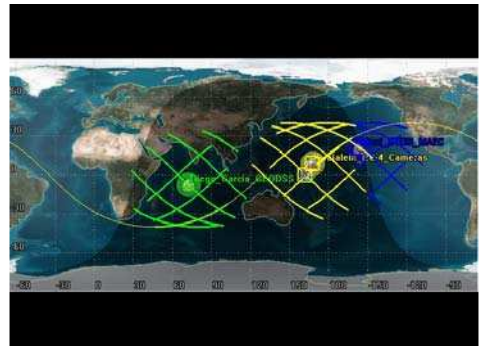

Figure 2. Small satellite orbit designed for greatest observability from designated observation locations.

Safe operation generally requires some compromise in mission capability. For our single satellite to see most of the Earth over time, the inclination and apogee should be as high as possible. For example if one wishes to monitor synoptic energy balance. There would be only rare and brief opportunities for the designated sensors to gather data for orbit estimation. In this case, the optimal parameters for longest cumulative observation over the course of a day are: inclination=32 deg, eccentricity=0. 1, apogee altitude= 8490 km. The observation passes over the course of the day chosen for analyses are bold lines in the figure.

There is a significant opportunity to observe small satellites almost ubiquitously with radio telescopes. Almost all satellites have significant radio frequency signatures from instrumentation and internal electronics, not to mention communication devices. Very precise orbit observations are feasible, and the observations can also reveal anomalies in electrical devices onboard.

2.3 MANEUVERABILITY

The ability of a small satellite to maneuver mitigates one having to deal with an uncontrolled object in orbit. A small satellite may exploit aerodynamics even in the sparse atmosphere in low Earth orbit. The degree of maneuver depends on the architecture of control surfaces exposed to the environment and the physical characteristics of the environment. A comprehensive review of satellite aerodynamics is in the Wiley Aerospace Engineering Encyclopedia[5]. Aerodynamic attitude or orbit control is efficient but environmentally unreliable, particularly for collision avoidance. Avoidance maneuvers cannot be developed more than a few tens of hours in advance with high probability because satellite trajectories cannot be estimated with actionable precision more than a few tens of hours in advance, particularly in drag dominated low Earth orbits.

Figure 3. Nanosatellite propulsion and attitude control module (Courtesy of ISIS Cubesat Solutions)

Aerodynamic forces may not be sufficient to achieve a safe end state in the time available. As Ref 4 reports, aerodynamic forces in the extremely rarefied low Earth orbit regime are extremely difficult to estimate. Momentum transfer depends on the physical characteristics of satellite surfaces, which change as the satellite is exposed to the environment. There have been notable successes such as the descent of Curiosity to Mars and notable failures such as the Beagle Mars mission. Passive aerodynamics that expend no mass are more suitable for attitude adjustment than maneuver in the author's opinion. Control surfaces also consume part of the sensitive satellite mass budget and affect mass properties, for example, increasing inertia.

Propulsive maneuver is more suitable. Propulsion requires stored energy and mass. CubeSat architecture and missions do not allow much mass to be allocated to stored propellants. Chemical propulsion (perforce solid because of the overhead of conditioning stored liquid propellants) is not the best approach. Electromagnetic propulsion, whose high specific impulse can be achieved using electrical energy that can be replenished, seems best. However, these are low thrust devices, and augmenting satellite energy to the extent maneuvers require may take a long time at long, continuous thrust. Stored high pressure gas or fluids that can be catalyzed to a high pressured gaseous state with adequate safety and control are also propulsion alternatives.

All of these possibilities are practical for long term, modest orbit or attitude adjustment, but they seem unsuitable or unreliable for relatively short notice collision avoidance. Small satellites in conjunction with other small satellites have no avoidance alternatives. Since desirable missions all favor the same orbit regimes, collisions among small satellites should not be discounted. Conjunction management between small satellites and larger satellites that can maneuver enough to avoid catastrophe becomes the sole responsibility of the larger satellite, which requires more energy to adjust its orbit than the small satellite would.

Having optimized orbit architecture, one must assure that the probability of encountering other satellites during the mission is acceptable. Our hypothetical small satellite experiences close approach within 20 km of a Thor Agena D rocket body. As shown in Figure 4, the geometry is very consequential; nearly perpendicular to our satellite's velocity vector. Depending on the duration of our mission, we should watch this object closely as well as check regularly for other close approaches. Several satellites approached within 50 km at the time the analysis was conducted.

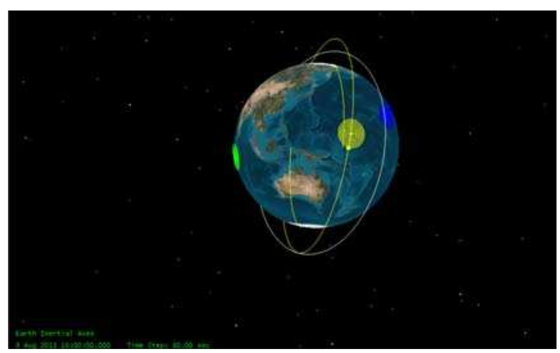

Figure 4. Conjunction geometry between hypothetical nanosat and Thor-Agena Rocket Body, SSN-04607

2.4 COMMUNICATION AND CONTROLLABILITY

A small fraction of satellites intentionally has no communication ability. These are, for example, small satellites whose ballistic coefficients are known precisely and whose surfaces are appropriately faceted and reflective to assure strong returns from passive or active illumination. They are most used to calibrate space surveillance sensors or to characterize atmospheric dynamics, since drag may dominate changes in their trajectories and those changes can be attributed to changes in density.

All other small satellites must be able at least to downlink data, if not respond to commands from the ground. These communication links enable ranging at least and perhaps angular resolution sufficient for reasonable orbit determination. However, observations of this nature are gathered over extremely short arcs and are often conducted with small antennas with poor angular resolution. Gathering and processing sufficient information to determine orbits may require several passes, and there are gaps between observations that are long enough for orbits to change materially due to environmental variability during the intervals when the satellite cannot be observed.

Figure 5. Nanosatellite communication module and antenna (Courtesy of ISIS Cubesat Solutions)

This raises other issues. If the satellite trajectory cannot be controlled or even known very well, how well can observations of other bodies in space or of areas on the Earth are registered in any reference frame?

3 THE ABILITY OF SMALL SATELLITES TO OPERATE SAFELY AND CONDUCT PRODUCTIVE MISSIONS

The insightful publication, "The Future of Small Satellites[6]," provides a basis for assessing the ability of small satellites to achieve characteristics that are desirable for safe operation. An important contribution to that volume estimates attainable capabilities based on size.[7] Current and reasonably advanced communication, propulsion, energy storage, power conditioning, and maneuver technologies were considered and applied to the spectrum of small satellite classifications. The authors' research leads them to use a spacecraft density of one gram per cubic centime of internal volume.

Electrical Power: Area per unit volume is greatest for spheres and increases inversely with object size. Therefore, solar energized small satellites have higher power to mass ratios than large satellites. However, the power attainable is still rather small. The authors' estimate the potential for no more than 10 watts for body mounted cells on a nanosat in representative low Earth orbit, including eclipse periods, and not accounting for battery power during eclipse. This might be doubled is extensible panels are used. However, extensible panels consume mass and increase complexity and failure modes. Current standards and political constraints preclude nuclear energy sources in Earth orbit; particularly in low Earth orbit.

Energy Storage: Considering allowable charge and discharge rates, nanosats could sustain one watt of continuous power for only a few months and as much as ten watts for a few days.

Figure 6. Nanosatellite power and energy storage module (Courtesy of ISIS Cubesat Solutions)

Ground Surveillance and Communication Characteristics: Physics dictates that the amount of electromagnetic energy that can be captured by an aperture and the resolution attainable depend on aperture size. Large aperture resolution can be achieved with multiple, phase matched small apertures at the expense of the extent of the spatial frequency content of the scene and the amount of energy that can be captured (signal to noise for each aperture). A single nanosat could achieve hardly more than a few meter ground separation distance resolution in the visible spectrum.

Communication antennas have comparable constraints. The tradeoff between antenna gain and effective isotropic radiated power is important. The Reference aggregates these in assessment of data rates that could be supported. Using the nominal 10 watt continuous power level estimate, a nanosat in low Earth orbit could support hardly more than one megabit per second or a few kilobits per second from GEO.

Stabilization and Pointing: These two aspects of small satellite operation are not independent, but they impose different technical demands.

Large satellites have high inertia, requiring larger torques to initiate motion and sustain acceleration. This can be mitigated by applying torques to the least massive elements of the system thread involved in redirecting boresights dynamically. Pointing components can take advantage of stable platforms whose stability is assured by the mass and inertia of the platform.

Small satellites do not enjoy that advantage. Pointing and stabilization are very closely coupled. Stabilization is the most important element, since the satellite cannot be allowed to tumble. The low inertia allows high angular acceleration, which must be damped. Rawadesh at the University of Kentucky characterizes the stabilization and pointing task as well as most references.[8]

Active techniques which expend energy either propulsively or electromagnetically employ actuators such as momentum storage devices. Active techniques may be beyond the pale for mission oriented nanosatellites. Achieving sufficient control authority and margin is a challenge.

Passive methods include passive magnetic stabilization, aerostabilization, and gravity gradient stabilization. As stated in the reference, passive techniques often achieve stability on only two of three rotation axes. “Rotation around the magnet axis in magnetic stabilization is uncontrolled, as well as roll in aerodynamic stability and rotations about the gravity gradient boom axis.” Janson estimates the capabilities of passive techniques in small spacecraft platforms. Passive techniques so far can achieve no better than stabilization precision of a few degrees. Active techniques at this scale can achieve boresight stabilization on the order of milliradians[9]. Large satellites can do much better.

Maneuverability: Small satellites can take advantage of the rocket equation, which reveals that the delta V that can be achieved depends on how much propellant is available but on how much of the initial mass of the satellite is propellant. Electromagnetic thrusters have specific impulses of thousands of seconds, but these artr not widely employed. For a specific impulse of a hundred seconds, if 90% of nanosatellite mass were propellant, total delta V could be about one km/sec, still a small fraction of LEO orbit velocity. An inclination change of one degree would require a few hundred meters per second. If only 10% of nanosat mass were propellant, only a few modest maneuvers would consume the entire capability. Independent of overhead mass and power requirements of maneuverability, one cannot expect much collision avoidance maneuverability from a nanosat.

4 REGULATORY, LEGAL, AND ETHICAL CONSTRAINTS

One can only conjecture how the evolution of the small satellite enterprise will affect the sustainability of space activity. Several commentators opine that small satellites almost by definition cannot meet even current regulatory constraints.[10] The US National Oceanic and Atmospheric Administration served notice on the smallsat community that Earth observation satellites for which a United States entity is responsible require licenses.[11] The Federal Aviation Administration is diligent about launch and reentry requirements. The Federal Communications Commission requires licenses for all U.S. satellite transmissions.[12] Virtually none have sought or been granted such licenses. Licenses require competent launch and disposal information as well as plans for the areas to be observed, the resolution of the products, and intended dissemination. There are many considerations, such as whether such conservative requirements will lead the smallsat focus to other nations or whether if concessions are granted, the entire regulatory regime would be diluted.

There are several ethical and technical guidelines for satellites. None discriminate small satellites from large ones. No nanosatellite project could exist if all were applied fully and dogmatically. Launch providers and associated liability partners bear much of this burden. At least they might become more discriminating of the smallsats they agree to deploy and the missions of the satellites. Oltrogge offered at a recent smallsat conference that the community must pay greater attention to operational and design best practices. ISO has begun to develop such non-normative operational practices. All are invited to participate.

5 CONCLUSION:

Small satellites are revolutionary opportunities for organizations and nations with limited financing and other resources. The capability should be encouraged and exploited for mutual benefit. This paper cites the risks of unfettered exploitation and bounds the ability of smallsats, nanosats and smaller in particular, to meet the constraints imposed on larger satellites and, in principle, on all satellites. None of these constraints is normative or broadly legally enforceable. Space mission and commerce stakeholders should consider this small satellite dilemma and arrive at acceptable compromises before compromise ceases to matter.

6 REFERENCES

[1] The Bright Future of Small Satellite Technology, August 1, 2011 | Via Satellite | Giovanni Verlini

[2] Oltrogge, D.L. and Leveque, K., An Evaluation of Cubesat Orbital Decay, SSC11-VII-2, AIAA/Utah State University, Small Satellite Conference, August 2011.

[3] Setting the example: minimizing and remediating space debris, AGI Blogs, 29 Feb 2012, by Astrodamus

[4] QB50, https://www.QB50.eu/

5 Finkleman, D, Atmospheric Interactions with Spacecraft, Wiley Encyclopedia of Aerospace Engineering, 2010

[6]Small Satellites: Past, Present, and Future, Henry Helvajian and Siegfried W. Janson, editors, ISBN 978-1-884989-22-3. 2009

7 Janson, S.W., Satellite Scaling Issues, pg 771, Small Satellites: Past Present, and Future, H Helvajia and S.W. Janson, Eds, Aerospace Corporation Press, 2009

[8] PASSIVE ATTITUDE STABILIZATION FOR SMALL SATELLITES, Samir Ahmed Rawashdeh, unpublished thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering in the College of Engineering at the University of Kentucky, 2009.

[9]Janson, S.W., Satellite Scaling Issues, pg 796, Small Satellites: Past Present, and Future, H Helvajia and S.W. Janson, Eds, Aerospace Corporation Press, 2009

[10] Kleiman, M, The Laws of Spaceflight, A Guidebook for New Space Lawyers, American Bar Association, 2012

[11] Glenn Tallia, NOAA's Licensing of CubeSats as Private Remote Sensing Space Systems under the National and Commercial Space Policy Act, NOAA General Counsel, January 20, 2012

[12] 47 CFR Part 25, 47 CFR Part 5, and 47 CFR Part 97.