

The Challenges of Developing an Operational Nanosatellite

David Homan
 Lockheed Martin Space Systems Company
 12257 S. Wadsworth Blvd, MS S4310, Littleton, CO 80125; (303) 971-9430
david.r.homan@lmco.com

Quinn Young
 Space dynamics Laboratory
 Utah State University Research Foundation
 1695 North Research Park Way, North Logan, UT 84341; (435) 797-4120
quinn.young@sdl.usu.edu

ABSTRACT

Recent nanosatellite programs and studies of nanosatellites for operational missions have highlighted challenges that are unique to this spacecraft category. While each small satellite class has peculiar design challenges, nanosatellite development challenges are compounded by the unique niche that nanosatellites occupy and the current perception of hardware maturity levels available to support nanosatellite spacecraft. Recent experimental successes with microsatellite systems are allowing such spacecraft to rapidly move toward operational systems. This has produced a false perception that the same small, high TRL operational components and subsystems used in microsatellites will transition easily into the smaller nanosatellite designs. At the same time advances in the sophistication of CubeSat missions and academic programs have increased the expectation of the mission utility that should be possible with nanosatellites. This paper focuses on the unique design challenges of high mission utility nanosatellite programs and the current state of component and subsystem hardware available to meet the unique nanosatellite design constraints. Addressing these challenges in coming years will enable this class of spacecraft to become a viable and healthy part of the aerospace industry, and as a secondary payload improve the launch options and reduced cost commensurate with operationally responsive space (ORS) solutions.

INTRODUCTION

This paper presents the lessons learned and the design challenges experienced in the transition of a “nanosatellite” design from an experimental demonstration mission to an operational mission. The insights and lessons learned are based on the firsthand experiences of the authors with nanosatellite design, research and development efforts, and operational programs. We present this paper with a three-fold purpose. First, we hope to spread our enthusiasm for a segment of the satellite market that has vast potential for real, high value operational missions, particularly in space situational awareness, an area of high mission value. Second, to provide insight into the greatest design challenge facing this class of spacecraft: the lack of available flight-qualified hardware of the quality and reliability necessary for an operational mission. Third, we hope to motivate government, industry and academia to mutually coalesce and work to fill this gap in space qualified hardware.

The paper starts with an explanation of definitions and assumptions, to provide clarification of the perspective with which the authors approach the subject. An

overview of the design challenges follows on a subsystem-by-subsystem basis. Lastly, the challenges for unique nanosatellite launch configurations and the associated constraints for the spacecraft design are presented. The paper concludes with a summary of the insights, challenges, and a recommended path forward.

BRIEF DEFINITIONS AND ASSUMPTIONS

The following key definitions and assumptions used by the authors are intended to clarify how “nanosatellite,” “operational” and “high mission utility” are perceived and used by the authors in this paper. Also presented here are the interpretation and assumptions of hardware technology readiness level (TRL) necessary for operational nanosatellite design.

What defines a nanosatellite

The order of magnitude boundaries commonly used to define nanosatellites, using a 1 to 10 kg mass, are an oversimplification based on mathematical convenience. The authors use a more functional definition for “nanosatellite” where mission needs and design life exceed commercial part capabilities and functional

capabilities of picosatellites (< 5Kg) but require innovative approaches to design and integration and redundancy from the standard means used for larger satellites (> 50 Kg). In between these 5-50 kg limits is a class of satellites that can be divided into subsystems, uses more space-qualified parts, and provides sufficient performance for substantial mission utility. Nanosatellites within this definition typically require unique design, assembly and integration to maintain a mass below 50 kg.

What defines operational or high mission utility

In the context of this paper, an operational satellite is one that is intended to fulfill a critical official government or commercial mission with a substantial operational life typically three years or greater, rather than demonstrate technologies or concepts in preparation for a mission. High mission utility refers to the level of sophistication and capability of the mission. Many nanosatellites are developed as technology demonstrations or educationally focused missions with very short mission life and lower levels of mission criticality. Developing an official mission within the mass constraints of a nanosatellite, with a high level of performance, reliability, and confidence in mission success is a significant challenge.

Small Sat paradigm of high TRL, flight heritage, off-the-shelf components to reduce cost and schedule

Highly capable microsatellites have been used as low-risk, low-cost means mission options. The use of high TRL, off-the-shelf components with flight heritage provides a high level of mission reliability at a relatively low cost. In this context a TRL level of 6 or higher is desired, requiring at least a prototype level test in a relevant environment; to acceptably mitigate risk for operational customers. It is desirable to use this successful paradigm for nanosatellite development. Currently the continued miniaturization of components necessary to move into the nanosatellite regime is hampered by the maturity and availability of components in a number of critical technology areas. Without mature components the costs, schedule, and risks of a comparable nanosatellite is much greater because of the necessary development of these technologies. The authors are optimistic that current technology development programs and customer interest in nanosatellites will allow a healthy market to develop for nanosatellite-class components.

DESIGN CHALLENGES

A low-cost, single-string, demonstration mission, by far the largest class of nanosatellite missions, conflicts with the reliability requirements of an operational nanosatellite. Meeting high mission utility in an

operational nanosatellite currently requires significant new development in preparation for tomorrow's operational mission opportunities. The authors have been involved in a nanosatellite development program and know that limited nanosatellite applicable hardware is currently available, while in other cases the technology exists but the flight heritage hardware has yet to be developed. The key challenges are outlined below.

Command and Data Handling

The command and data handling (C&DH) subsystem has a number of available options for either high-reliability, highly-capable systems or low-power, low-mass systems. The reliable and capable systems require more mass and power resources than can be spared for a nanosatellite system, while those that meet the mass and power constraints do not provide the level of reliability or capability required for an operational mission. The challenge, therefore, is finding components that fit between these two categories.

The capability of an operational mission C&DH system is greater than that common to current nanosatellites. The processing power must be sufficient for the increased software functions typical of operational systems, such as data compression, data processing, failure detection and response, flight safety watchdogs and redundant processing of critical processes (e.g. triple modular redundancy). Data transfer rate and data storage requirements can be higher, both to collect sufficient state of health telemetry and for more sophisticated payloads that can be assumed for an operational mission. Similarly, input and output (I/O) capabilities can be greater for operational missions because of the additional safety, switching, and monitoring hardware. Both volatile and non-volatile memory requirements can be greater for software, data and redundancy. These types of needs are difficult to provide for within the mass and power budgets available.

GN&C

With the exception of star trackers and earth sensors, component size is not the primary driver for the Guidance, Navigation, and Control (GN&C) subsystem. Reaction wheels and torque rods are relatively easily scaled. IMU technology is available in ever smaller packages, due in part to improvements in MEMS gyros. Sun sensors are readily available in very small packages, and earth sensors are taking advantage of advances in sensor technology, allowing even smaller sizes. For this technology area the availability of reliable, space qualified components is the greatest challenge.

An example of this challenge is illustrated with reaction wheels. An industry survey in February 2008 identified 27 potential reaction wheels from eight different manufacturers. Of the 27 reaction wheel options, only 12 had space flight heritage, two others had been through environmental qualification testing, four had been discontinued and nine were new designs in development.

Having 12 reaction wheels to choose from did not sound too bad until we looked at the details. Of the 12 wheels, only six were below a 5 kg system mass impact (see next paragraph for explanation) and none were below 2 kg. These were significant mass impacts for a single component on a 50 kg or less nanosatellite, disappointing the originally optimistic feeling that a good variety of hardware was available. Given the results of the survey, it is understandable that there is an emergence of new suppliers taking the opportunity to fill the size gap^{1,2}.

A quick explanation of our term “system mass impact” is provided. We used a system mass impact metric instead of just the reaction wheel unit mass in order to uniformly compare the hardware. The system mass impact thus included additional control electronics, radiation shielding, and any additional brackets required (e.g. mounting three single wheels to compare to an integrated 3-axis reaction wheel assembly).

For reaction wheels at least, the existing choices for high reliability, space flight heritage hardware for an operational nanosatellite are very limited. The upside is that eight of the nine new reaction wheel designs have a system impact mass < 5 kg and six of the nine designs under development are < 1 kg, so within a few years, there could be a good selection of reaction wheels for any size nanosatellite between 5 and 50 kg.

Star trackers and earth sensors both have an additional limitation in the physics of the optical system, which result in decreased sensitivity and accuracy as the optical system is scaled down. These optical instruments also usually incorporate some means of sunshade which is an additional volume and mass that is not always accounted for in the instrument specifications. Advances in focal plane technology are allowing some limited reduction in optical size without performance decreases, providing some relief to nanosatellite constraints. Using visible sensors to perform multiple functions can provide a functional redundancy, but no fixed focal length sensor was identified to satisfy all requirements.

Communications

Two challenges drive the design of the communications subsystem: size and power. The miniaturization of antennas needed to fit within a nanosatellite volume reduces antenna gain, thereby reducing signal strength. Other communications hardware can be similarly challenging. Diplexer and switch sizes are driven by the requirements of the communications capability, not the size of the spacecraft. Transmitters and receivers have been reduced in size, providing reasonable performance and reliability in a small package, but are still proportionally a larger portion of the nanosatellite mass – a problem that is made even more difficult with the addition of encryption capability that is needed for an operational satellite.

The second issue is the level of consumption and dissipation of power. The decrease in antenna gain can be offset by an increase in RF power; however, power is an even scarcer resource on nanosatellites than it is on larger satellites. The higher data rates desired for an operational spacecraft result in a disproportionately large increase in the percent of power dedicated to the communications subsystem.

System level trades are vital to balance communication subsystem size, weight and power (SWAP) with C&DH SWAP based on unique mission requirements.

Electrical Power

The electrical power subsystem (EPS) may be the most scalable of the subsystems. Solar cells, batteries, power converters, diodes, shunts, and grounding systems are all easily or fairly scalable. Three challenges have been found: solar array drive mechanisms, temperature dependency and battery maturity. Solar array drive mechanisms to rotate the solar array to the sun may not be necessary for most small satellites, but for those programs that require them, the availability and maturity of miniaturized units results in significant challenges (new development efforts may be required). Temperature variations affect the efficiency of solar arrays and batteries. The prevalence of body mounted solar arrays and the low structure thermal mass that increases the temperature variations of the spacecraft can decrease the available power generated and stored. Extreme temperature cycling has an adverse effect on battery life, which drives more complicated thermal control requirements.

The final EPS challenge, battery maturity, is driven by size constraints. Few space qualified batteries, including Li-ion, are available with power densities that are optimum for nanosatellites. The decreased mass requirements could be satisfied by newer, higher power

density battery technologies, but the maturity of such technology is an issue.

Thermal Control

The design approach needed to miniaturize the spacecraft requires a higher level of integration leading to additional challenges to the thermal subsystem. Thermal zones can be highly coupled. Potential “cross-talk” between heater zones can be a serious control problem. In addition, the low mass of the spacecraft means low thermal capacitance, and faster thermal response. The small size can also result with higher power densities (power per unit volume), particularly with a high mission utility operational spacecraft (the implication being that higher capabilities will require higher power levels, which is generally true).

Another challenge is that heaters, sensors, MLI, and thermal control coatings become proportionally larger as the spacecraft size decreases. MLI and thermal control coatings (and heaters as well) are proportional to surface area, but the thickness does not change. The overlap necessary to close-out MLI blankets also becomes proportionally large. Although temperature sensors have become increasingly smaller over the years, the same sensors are needed for a small spacecraft as a large spacecraft, resulting in another proportional increase. For a nanosatellite, the percentage of mass devoted to thermal control can increase, but fortunately the total mass still remains small, and is likely to remain in the 2-5% of dry mass range³ typical of spacecraft. And lastly is the challenge of finding sufficient area for placement of heaters, temperature sensors, and blanket fasteners.

Structures/Mechanisms

Structures have both advantages and disadvantages as the spacecraft size decreases. The stiffness of the structure can increase significantly as size diminishes, allowing reductions in the structure mass as well as fastener sizes; however, the proportion of the structure mass devoted to fasteners and associated hardware increases. The minimum material required around threads, the minimum number of engaged threads, and other similar design considerations are only marginally affected by the decrease in spacecraft size. What is likely to occur is that margins will increase as the design is driven more by the necessities of building and assembling the spacecraft and less by the strength of materials. In fact, the structure can be driven as much by the amount of material needed for thermal heat transfer as by the need for strength and stiffness.

One specific challenge as the mass of the satellite decreases is the high quasi-static loads that can be transferred through the separation system during

launch. The low mass of nanosatellites results in higher design loads. On the other hand, the small size has little acoustic excitation.

Different design approaches, such as advanced materials or alternate methods for fastening, can be used to find a more optimal combination of thermal, structural, and mounting characteristics. These approaches have significant potential for improving nanosatellite performance, but are more expensive and less mature, increasing programmatic risk. Similar design challenges affect the separation system, deployment mechanisms, the solar array substrate, and other mechanical systems.

Harness

The harness for an operational nanosatellite can be more challenging than one would expect. The decreased size of the spacecraft shortens the harness length but increases the challenge of routing and mounting in very small areas. A task made even more difficult in the case of separating power and data harnesses. This is especially challenging if mission critical functions require true physical separation between critical harnesses. In addition, the size of wires, insulation, shielding, connectors, and back shells do not decrease proportionally. As harness lengths decrease, the fractional mass of the connectors and back shells increases.

Lightweight custom harnesses, using smaller connectors and ribbon cable or flexible flat cable, can be used with discretion to decrease the mass of the harness, but only to the extent that the power and data integrity requirements of the individual components are not compromised. Such harnesses come with higher initial cost and development risk as reworkability is minimal, but for an operational system this reduces recurring labor and increases reliability over traditional “hand laid” wire harnesses.

Typically smaller connectors require reduced wire gauge, which reduces the harness mass, but smaller wire gauge requires more conductors for the equivalent power, thus negating most gains from smaller connectors. Since small connectors are almost a requirement “by definition” on a nanosatellite, this emphasizes the importance of scaling the size, weight, and power of individual components to fit the nanosatellite design and highlights another area where using microsatellite qualified hardware on a nanosatellite could cause unforeseen challenges.

Propulsion

An operational nanosatellite propulsion system could be required to perform both primary and/or secondary

attitude control, provide orbit boost/adjust, provide station keeping, and perform disposal maneuvers. The performance requirements for these functions cover a large spectrum from very low impulse bits for attitude control to high thrust engines for orbit boost, orbit adjust and possibly satellite disposal. Additionally, extended mission life greater than 12 months and the potential for on-orbit servicing or SSA missions where “the target satellite remains in constant motion”⁴ could drive delta-V requirements.

Initial trades for operational nanosatellite propulsion systems showed that a warm gas monopropellant propulsion system could achieve the delta-V requirements considered applicable to a long duration, responsive mission, as well as the small impulse thrusters for S/C attitude control. Other propulsion system architectures were either too massive, used too much power, or were not responsive to timely SSA objectives for a nanosatellite.

Designing propulsion systems that meet these requirements for microsatellites has been successfully demonstrated. It has been previously proposed that transitioning that same propulsion capability to a <50 kg spacecraft should be possible using “miniature ‘conventional’ components” with “conventional integration still possible” though higher levels of integration between components/subsystems are “desirable.”⁵

The authors found this miniaturization of conventional components approach to be fundamentally true and achievable, however most components from the propellant tank to the thrusters, pressure transducers, filters, and service valves are not currently optimized for a nanosatellite and require some level of redesign and requalification to scale from a microsatellite to a nanosatellite. Directly using non-optimized microsatellite components that could be transitioned directly to a nanosatellite, such as filters, pressure transducers and service valves, can cause a domino effect throughout the electrical power, structure, and GN&C subsystems.

The roadmap to a mature, space qualified, miniaturized responsive nanosatellite propulsion system is not technically insurmountable; obviously propellant tanks need to be scaled, nozzles need to be redesigned, filters scaled accordingly, pressure transducers reduced in physical size and qualified for very low operating pressures, and service valves need to be physically smaller. The current challenge is the proverbial “chicken and the egg” syndrome as customer’s require high reliability, space qualified hardware for operational systems, but the investment in development

time, money and on-orbit operations required to produce such hardware has not occurred.

Flight Software

Flight software is a function of the complexity of the spacecraft and mission. Nanosatellites may of necessity be simplified as much as possible, but an operational spacecraft with high mission utility can be expected to have significant flight software requirements. These requirements influence the design through hardware requirements, such as requiring a more powerful processor or greater memory, which result in increases to the mass and power of the spacecraft and the cost of the program. For a highly capable nanosatellite, the software may also require customization to run on simplified or less capable C&DH systems that are chosen because of mass or power constraints. The limited size and mass of a nanosatellite can thereby result in an increase in cost.

LAUNCH CONSIDERATIONS

The small size of nanosatellites is well adapted to secondary launch opportunities. Such opportunities present a design challenge in that the spacecraft could be launched in any orientation. Mechanical stress, propellant, and contamination analyses and related designs can be complicated by this flexibility.

An additional challenge is that the nanosatellite must comply fully with the same range safety issues as large satellites. Propulsion, communications, and separation system designs are all affected by this requirement. The paradigm followed by many small satellite programs, accepting greater risk and shorter mission lifetimes in exchange for reduced mass, does not apply if range safety is jeopardized. While reductions in redundancy are acceptable for systems used only for the mission, the need for safety during launch is higher, if anything, when a high-value primary payload cannot be jeopardized by a lower cost secondary.

ADDITIONAL SYSTEM DESIGN CHALLENGE

An additional system design challenge spans multiple subsystems. One of the most significant technological challenges occurs when higher radiation tolerant components are needed for MEO and GEO orbits. There are far fewer miniaturized components in the 50 to 100 Krad(Si) total ionizing dose range than the LEO range of 20 Krad(Si). Small LEO technology demonstration missions and university sponsored LEO missions appear to have supported the development and sustainment of miniaturized LEO components, but there has not been a similar market for the higher earth orbits, perhaps due in large part to the difficulty and cost of reaching higher orbits.

PRIORITIZED ROADMAP TO ACHIEVE VIABLE OPERATIONAL NANOSATELLITES

There are four existing areas that could be used to develop and feed nanosatellite-scaled, space-flight heritage hardware into future operational nanosatellite programs. The four areas, shown in Figure 1, are large operational “host” satellites, operational (and demonstration) microsattellites, University-Class satellites⁶ and demonstration nanosatellites. This is unquestionably quite a broad spectrum, in fact one might argue that we could have just said “everyone” can help develop nanosatellite hardware, but each one of these four areas, or test platforms if you will, has a very specific role that can be utilized to start to fill the flight heritage hardware for spacecraft between 5 kg and 50 kg.



Figure 1: Key elements of operational nanosatellite mission development.

Large operational satellites provide an excellent test platform for individual component space validation in higher MEO and GEO regimes that are not readily accessible with smaller launch vehicle platforms. The rarity of GEO launches could be leveraged by testing multiple nanosatellite-scale hardware components on a single large host. The large host spacecraft could relay test data over long durations and in severe space environments; for example, test multiple C&DH assemblies or sensors simultaneously looking for performance degradation. Using the large satellite as a test platform leverages the existing “infrastructure” to power, command, perform and downlink test data.

Microsatellites also provide a potential test platform whose infrastructure can be leveraged for test purposes, but at a smaller scale. Single components or small subsystems could be accommodated on an operational microsatellite. The orbit regime would most likely be LEO, with occasional opportunities for HEO and GEO. If conceived and implemented as such, a demonstration microsatellite mission could be tailored as a test specific platform for a larger quantity of nanosatellite scaled hardware. The benefits from this class of

spacecraft platform are that they are less expensive and more frequently launched than the large satellites, industry has standard microsatellite busses to choose from and the space environment is different and more dynamic than that experienced by large satellite platforms.

University-Class satellites could also play an important role as test platforms for nanosatellite hardware components. These spacecraft have the advantage of relatively low cost to orbit, albeit with launch schedule risk, provide very dynamic space environment test beds in LEO, vitally need component suppliers and have significant history with nanosatellite design (39 of the 63 University satellite launches between 1981 and 2006 met our criteria for a nanosatellite between 5 kg and 50 kg⁶).

Lastly, hardware from the three component and subsystem test platforms would feed into demonstration nanosatellites. These are needed to validate specific system design, integration, mission planning and mission operation issues, as applicable only to nanosatellite scaled spacecraft, that can only be done on a complete spacecraft. These demonstration missions would continue as they do today to validate GN&C, C&DH, flight software, propulsion, power, and thermal subsystems, but some risk would be reduced by using known components with flight heritage. Many times the individual components, subsystems, spacecraft and mission operations all have some new aspect to them. This roadmap ensures that the emphasis of the demonstration nanosatellite program is on the system integration and mission operation, not developing individual components.

Obviously none of this will just happen without a collaborative effort between government, industry, and academia. Each member of this collaborative group provides unique capabilities and resources that can forge a strong, dynamic team to bring this critical mission capability into fruition.

CONCLUSION

This is an exciting time for 5-50 kg “nanosatellite” development. This class of spacecraft is in a very good position to move forward into demonstration missions and potentially filling a segment of operationally responsive spacecraft. Our detailed design experience has shown that nanosatellites, with all the mission utility and functionality of microsattellites (or larger) are very achievable in the near future, either in a highly integrated architecture or a scaled-down version of a more traditional spacecraft.

While this paper has presented some of the challenges facing operational nanosatellite development, it is our hope that by identifying these challenges and a potential roadmap to overcome the challenges, that the government, industry, and academia will come together in a win-win-win scenario to further advance high mission utility, operational nanosatellite development.

While the primary function of our proposed roadmap is speeding the development of flight heritage hardware for operational nanosatellites, there are many secondary benefits to implementing the roadmap. These include: 1) Flight proven hardware with reduced SWAP for all classes of satellites, thus increasing mission utility potential for all spacecraft, 2) Increased mission utility for University-Class satellites, 3) Renewed motivation for students and schools to participate in the University Nanosat Program, 4) Renewed motivation for industry to collaborate with universities and 5) Motivation for University-Class satellite programs to integrate rigorous system level design and testing⁶ and focus less on individual component development. These benefits make this a “WIN” for government, industry, and academia.

ACKNOWLEDGEMENTS

The authors especially thank Andrew Grimes from Lockheed Martin Space Systems Company for the use of his Reaction Wheel Trade Study results from February 2008.

¹ Doug Sinclair, C. Cordell Grant, and Robert E. Zee, “Enabling Reaction Wheel Technology for High Performance Nanosatellite Attitude Control”, SSC07-X-3, 21st Annual AIAA/USU Conference on Small Satellites, Logan, UT, 13-16 August, 2007.

² “IMI-101 Miniature 3-Axis Reaction Wheel Product Specification” IntelliTech Microsystems, Inc., Bowie, MD, 2007.

³ James Wertz, and Wiley Larson, ed. “Space Mission Analysis and Design, Third Edition”, Microcosm Press, El Segundo, California, 1999.

⁴ S. Z. Barley and Dr. P. L. Palmer, “Characterization of a Monopropellant Microthruster Catalytic Bed”, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA 2005-4544, July 2005.

⁵ Roberto Cocomazzi, Alessandro Avanzi, Dario Modenini, Paolo Tortora, “System Design and Performance of Cold Gas Microthruster for Microsatellite Attitude Control”, 42nd

AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA 2006-4629, July 2006.

⁶ Michael Swartwout, “Twenty (plus) Years of University-Class Spacecraft: a review of what was, an Understanding of What Is, and a Look at What Should Be Next”, 20th Annual AIAA/USU Conference on Small Satellites, SSC06-I-3, Revised 8/21/2006.