Achieving Small Satellite "Smart Space"

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ABSTRACT

There is an increasing proliferation of small satellite based solutions for diverse applications. There is an expectation to deliver mission success to match the steady upward trajectory of system performance. The present challenge facing the developer community is how to provide a balanced design approach that meets both the operational needs and practical imperatives of a small satellite solution, which can scale to constellation-level numbers, within commensurate programmatic constraints. Though functionally distinct, the drivers for government programs seeking complementary solutions to more traditional exquisite system acquisitions and "New Space" players desiring rapid ways to dependably build-out their space layer, all motivate the need to consider a hybrid approach to produce the desired end state: "Smart Space." This approach represents a strategy that includes consideration of determining appropriate mission assurance standards, design standards, part sourcing strategy, expansion of the supply-chain, performing qualification and acceptance testing, reporting on anomalies and implementing corrective and preventive actions. SSL has a flexible, highly tailorable approach to project execution and mission assurance. This approach draws upon observable metrics for satellite fabrication, assembly, integration, and test, along with empirically measured flight performance of GEO and LEO satellites. In this paper we discuss the methods that SSL is employing for its "Smart Space" approach, across satellite production activities for both government and commercial customers, as well as recommendations for how the community should continue to evolve their methods for production engineering and verification.

ABOUT SSL

SSL (a Maxar Technologies Company) is a global leader in delivering advanced systems for communications, exploration, data gathering and next-generation services. Based in the U.S., the company designs and manufactures innovative spacecraft and space-related systems with an advanced product line that includes high-power geostationary satellites, state-of-the-art small satellites and sophisticated robotics and automation solutions for remote operations.

SSL is best known as a provider of large geostationary communications spacecraft (GEO-Comm) for services such as direct-to-home television, video content distribution, broadband internet, and mobile communications. As of the end of 2017, SSL has built 139 three axis GEO-Comm satellites and has the largest fleet currently in service. These satellites are built to the highest quality and reliability standards and use robust systems engineering; qualification testing; space grade (grade 1) parts; full redundancy and other techniques to ensure mission success. SSL is currently implementing several highly sophisticated in-orbit servicing spacecraft and subsystems for government and commercial satellites following this same methodology.

Less well known is that SSL also provides smaller spacecraft systems in primarily non-geosynchronous orbits. SSL non-GEO experience includes more than one hundred satellites ranging from the initial communications experiments and sub-synchronous constellations, the first Globalstar constellation, the Planet / Skysat Earth Observation Satellite constellation, built under contract, and under development, various multi-spacecraft constellations such as World View Legion for Digital Globe, and single-spacecraft demonstration vehicles. SSL product lines are described in Figure 1 and a small satellite example is shown in Fig. 2.

Product	Power	Dry Mass	Life
SSL-1300	5-20+ KW	1300-4200 Kg	15 years
SSL-500	Up to 1.6 kW	500-700 Kg	Up to 10 years
SSL-100	Up to 400 W	Up to 250 Kg	Up to 5 years

Figure 1: SSL Product Lines

Modern design and manufacturing methods are emphasized in a “Smart Space” approach used for the smaller satellites. This allows us to service a wide range of payloads for customers with a wide range of risk tolerance.

Figure 2: SSL Small Satellite Example

WHAT IS “SMART SPACE?”

Smart Space is an effort to move beyond what has become routine in the traditional GEO-Comm space model. Our Smart Space effort has focused on reexamination of the applicability and effectiveness of heritage practices to develop a clean, but adaptable, baseline of processes with which to move forward. Our objective is to have a balanced design approach that meets both the operational needs and the practical imperatives of a small satellite solution that can scale, when needed, to the constellation level. Retention of the most effective practices is desirable, even in a constrained project, while optimizations can be implemented for better efficiency as projects scale.

An example is “Highly Accelerated Life Test” (HALT) testing, which defines real capabilities and margins for equipment. After establishment of good design margins, subsequent testing can be scaled back to performance and workmanship verification and, with sufficient data, to functionality. HALT testing is expensive for GEO equipment, but it is much less so for equipment of lower cost.

We have factored modern manufacturing processes, which we are also introducing into our GEO-Comm model, into Smart Space projects as well. Some key initiatives and practices are discussed in subsequent sections.

MISSION RISK TAILORING

The traditional risk management approach developed for SSL’s Flagship 1300 Class Programs is based on a rigorous design, manufacturing, and validation process in which all levels of risk are identified and mitigated as part of a comprehensive risk mitigation strategy. Focused on reducing risks to the maximum extent possible at each lifecycle state for every SSL built satellite, this approach has proven effective, and ensures the very high level of reliability that our customers have come to expect.

Using this knowledge SSL has been able to tailor our mission assurance activities to meet the specific mission, system, or program requirements without increasing risk in an unacceptable way.

Each pursuit is evaluated against a prototypical mission risk class based on mission requirements, risk tolerance of the mission and the customer’s business goals. The tailoring of mission assurance activities is patterned after the Mission Assurance Improvement Workshop (Ref. 1).

MISSION RISK CLASS PROFILES

Class A and B (Critical Operational Systems) projects are implemented according to the standards and practices used for the SSL Geosynchronous standard, with little customization. This leverages an inventory of flight-proven, high reliability components that are in continuous manufacture. Hardware capability brackets that required for most earth orbits and many deep space missions. Class B is relatively similar to Class A, with minor relaxations such as Grade 2 parts in place of Grade 1, as defined in Ref.2.

Class C (Moderately Critical Operational Systems) projects are customized based on customer needs. Often, increased performance requirements dictate the use of modern components and devices available on the commercial markets that must be evaluated and adapted for use in space. This increased risk pays off in the form of capabilities that exceed those of a traditional Class A or B project without the years spent bringing technologies to the traditional space levels.

Class D (Non-Critical Operational Systems) projects take the opportunity of low-cost launch and manufacture to demonstrate capabilities or perform experiments that are important, but are of shorter term and are not critical to the business or security of the customer. We have seen such programs be multiply sourced as a method of risk-reduction, with vendors competing to provide their own variations of short-schedule demonstration missions.

Using this framework, SSL is producing its own Mission Assurance requirements for LEO - small sat missions incorporating our lessons learned incorporating the highest value-added activities to optimize the likelihood of mission success, regardless of whether a program is Class A/B or Class C/D.

The mission risk class helps establish the implementation risk baseline and a mitigation strategy by addressing:

• Test Philosophy: Design and Workmanship Validation

• Hardware Management: Unit/Part Quality, Qualification, and Test/Screening Levels

• Supplier Management: Supplier Evaluation, Selection, and Monitoring

• Configuration Management: Part, Unit Traceability and Reporting

• Document Management: Documentation Levels, Documentation and Data Deliverables

• Customer Involvement Matrix: NCR and Engineering Change Reporting, Management, and Approval Levels

The value of the risk classification framework is that it provides a common language that enables communication of the risk associated with a given program from a very early proposal stage. It promotes conversation with our customers regarding the risk posture of a proposal and provides a clearer picture of which risks are assumed, managed, and of the strategies to mitigate them. On the execution side, establishing a common understanding of what is allowed on the various mission types in terms of process, parts, and procedures is of significant importance.

PRODUCT ASSURANCE BEGINS DURING THE DESIGN PHASE

Small, agile, empowered co-located teams representing all subsystems and phases of manufacturing are critical to the design phase of the program. These teams ensure that each design trade is evaluated not just for performance, but as part of the overall system which includes source of supply evaluations, manufacturing constraints, and test approach. Mockups and additive manufacturing are routinely used to aid in manufacturability assessments throughout the design phase. This approach reduces costly design iteration and simplifies manufacturing operations.

Additionally, SSL is investigating concepts from high volume production settings for use in Small Satellite production. One example is Advanced Product Quality Planning (APQP), which was developed by the automotive industry to achieve their goal of zero defects by focusing on quality early in the design process. The aerospace industry has tailored APQP (see AS9145) to achieve the goal of 100% mission success. The APQP approach has not only improved quality but also has driven down production costs in the automotive industry and if implemented correctly should do the same for aerospace.

PERFORMANCE VERIFICATION – DID WE BUILD THE RIGHT THING?

Every system design begins with understanding the customer requirements and their mission goals. Once all of the mission parameters are clearly defined, the program's risk mitigation strategy is created according to risk tolerance. This provides SSL and its customers with a clear picture of the risks. The risks are managed to a plan specifying how and when they will be retired, within the program schedule and cost targets.

The performance and environmental requirements may be verified on a proto-qualification spacecraft. The test campaign serves to demonstrate that all design parameters have been met and that the spacecraft design is suitable for its intended mission. For constellations, the proto-qualification spacecraft serves as the first article used to certify the manufacturing processes.

RELIABILITY ANALYSIS– WILL IT PERFORM OVER TIME?

Reliability analysis ensures reliable performance of the spacecraft or constellation of spacecraft over the required mission life. Traditional methods assess reliability at the individual satellite level, but in constellations SSL has furthermore adapted its approach to consider the constellation as a whole when assessing the ability to meet performance requirements. The design guidelines for each mission are derived through quantitative reliability assessments encompassing constellation and spacecraft level evaluations of redundancy, cross-strapping, and single-thread items. This approach has enabled us to simplify system architectures without introducing unacceptable risks by deploying redundancy approaches that take the entire constellation into account.

FUNCTIONAL VERIFICATION – DID WE BUILD IT RIGHT?

Test programs are tailored based on mission risk classification which leverage data compiled from SSL's extensive flight history. We determine the highest activities using a data driven approach that is commensurate with the defined risk tolerance. All critical parameters are tested to demonstrate proper integration of the system on the proto-qualification vehicle with a subset of those tested on each follow-on satellite. Testing is further streamlined once the manufacturing processes are deemed stable and repeatable. This approach is applied to lower levels of integration as well. Our goal is to ensure that risk is retired as early as possible. SSL is streamlining testing between levels of integration so that all tests are performed at the point in the manufacturing cycle where they provide the maximum benefit.

QUALITY ASSURANCE FOCUSED ON CRITICAL TASKS

Each task or operation is evaluated by level of criticality from routine tasks, work order/phase completion, to critical operations to ensure the proper level of oversight is provided throughout the design and manufacturing process. SSL's quality strategy divides this activity into two levels within the quality function:

1) Quality Engineering is accountable for all aspects of Quality, they define the quality requirements that are to be followed by all levels of the organization. These requirements such as critical operations, inspection plans, non-conformance disposition and correction, change control, improvement activities and metric monitoring and analysis are all tailored to ensure requirements are achieved and risk tolerance is met.

2) Quality Control is responsible to ensure the requirements as defined by Quality Engineering are executed and met during the entire production cycle. They provide signature authority to close out a manufacturing stage and verify all work required for that stage has been performed correctly before moving on to the next phase.

NON-CONFORMANCE REPORTING (NCR) PRIORITIZED BASED ON RISK

The SSL Non-Conformance Reporting (NCR) System follows an industry accepted CAPA (Corrective Action / Preventive Action) system, whereby problems are categorized and prioritized based on overall risk. The risk is determined by assessing the probability of re-occurrence and severity. This includes an analysis of the impact on cost and schedule, the ability to detect the issue, and impact to mission should the risk be realized (see Figure 3). This allows for management to focus resources on the issues with the highest risk so that they can more effectively determine root cause and corrective / preventive action. Lower risk problems require direct causes to be corrected and contained.

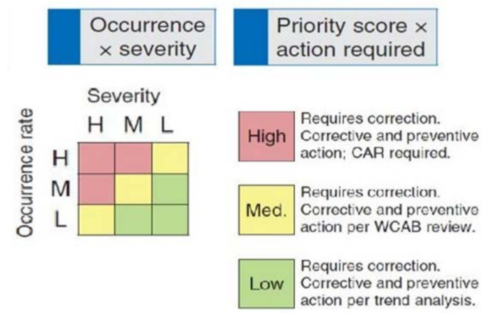

Figure 3. NCR Priority and Severity Risk Evaluation Criteria

NCR data are regularly reported to ensure the maximum level of transparency to our customers. All NCRs are prioritized based on the overall risk as described above and dispositioned in accordance with the mission risk classification of the program. All dispositions require a minimum of two signatures and typically include the subject matter expert and a representative from quality assurance. Closure of NCRs are also defined according to the mission risk classification and are reviewed with the customer when there is a system level out of specification or test anomaly that has a direct impact on contractually specified performance parameters prior to the closure of a major NCR.

MATERIALS REVIEW BOARD PROCESSES THAT SUPPORT VOLUME PRODUCTION

The incorporation of the CAPA process aligns well with constellation manufacturing which allows for all items exhibiting anomalous behavior during satellite integration activities to be removed from the manufacturing line and replaced with the next unit in the production run. The unit displaying anomalous behavior is placed in a station where further investigation of the item is performed off-line with minimal interruption to the spacecraft build and to the factory. All corrective actions implemented are evaluated against established process controls to ensure accurate metrics are maintained and any negative trends are quickly identified to ensure that the appropriate corrective and preventative actions are properly implemented.

PARTS – WHAT DO WE BUILD IT WITH?

Level 1 parts are still the standard, but level 2 are becoming more common at both SSL and in its supply chain. Part levels are defined in Ref. 2. COTS parts are still being evaluated, but thus far have only been used on mission risk class A and B programs when no class 1 or

2 part exists and only after extensive screening to establish level 1 equivalency. On mission risk class C and D missions, COTS parts are procured in bulk and whenever possible from a single date lot code. This approach reduces the amount of lot level testing and screening and improves part traceability.

RADIATION

Traditionally SSL has designed to radiation models AE8 (electrons) and AP8 (proton) models with 20% margin. Newer programs are performing evaluations to the latest version of the trapped radiation environment for protons and electrons, which are given by models AE9 and AP9 for electrons and protons, respectively. These newer models provide selectable levels of confidence (e.g. 90%), which is not an option in the older models.

In general, certain electronic parts (or materials) may exceed parametric limits or fail to function at all after exposure to a total ionizing dose (TID) of radiation. The radiation comes from protons and electrons trapped in the earth's radiation belts, as well as solar flares. The exposure of any part depends on the spacecraft orbit and mission duration, the solar cycle, spacecraft structure and the parts package. For parts that exhibit parametric drift that exceeds the parametric limits, the post radiation drift values are statistically evaluated to determine if they exceed the end-of-life (EOL) worst case design limits of the circuit in which they are used. Data obtained from SSL evaluation tests, data obtained from tests performed by parts manufacturers or published literature are all used for radiation acceptability evaluations. Some parts may be susceptible to low dose rate effects, and these are tested at low dose rate radiation levels.

Parts that do not meet the minimum TID are reviewed for use in each application circuit. For low cost missions using COTS hardware, radiation testing may be performed on sacrificial circuit cards or units, rather than at part level. Acceptability depends on a determination of whether or not the shielding provided by the spacecraft structure is sufficient to limit the accumulated dose at end-of-life to a level less than that required to cause circuit malfunction. If the shielding provided by the spacecraft structure is not sufficient, then additional shielding necessary to meet the end of life requirement is added. If shielding cannot provide adequate protection, then use of a radiation sensitive part may limit the mission life. These determinations require knowledge of the total accumulated dose and the worst case parametric design requirements for the circuits using the parts.

Single event effects have various sources, namely Galactic Cosmic Rays, trapped protons and solar flare protons. In selecting a part for use in space, all of the Single Event Effects (SEE) need to be considered. Modern electronic part types, both digital and analog, may be sensitive to Single Event Upset (SEU), Multiple Bit Upsets (MBU), Single Event Functional Interrupts (SEFI), Single Event Burnout (SEB), Single Event Gate Rupture (SEGR), Single Event Dielectric Rupture (SEDR), and Single Event Latch-Up (SEL). Use of part types or circuits susceptible to these effects can interrupt a mission, or end it prematurely, unless there is an internal unit self-detection and correction of the failures caused by the occurrence of these effects. The rates or likelihood of the effects can be determined from single event effects testing. From test results (cross-section of interaction) that are representative of the application, and a knowledge of the environment, an upset rate, or failure rate, is estimated. It is an exercise for the mission planner, based on risk profile, to accept the risk or add mitigation where critical.

CONCLUSIONS

Compared to our experience in GEO-Comm space projects, we are early in our Smart Space learning process. Still we have learned, or re-learned, several important concepts.

First, Smart Space for a company like ours need not be an effort in isolation. We have expertise and capabilities within our infrastructure to draw upon that we can take advantage of, even from a walled-off project, and it is a mistake not to do so.

We have learned that we cannot just abandon our established processes to implement modern production. We implemented a scaled-down version of our GEO-Comm nonconformance workflow system on small sat projects. We have learned that structure and planning is important for even the smallest and quickest of projects.

We rediscovered that supplier selection requires diligence. The lowest price supplier is not always the lowest cost path. The financial state of each supplier is as key a variable as is the heritage of their product, its performance and price. Continuity of expertise is more important at small-scale suppliers than at larger companies that have detailed documentation and larger numbers of experienced staff.

Equipment that is newly designed needs extra up-front attention. Production planning in-house and at suppliers should start early. Schedules, parts procurement, test equipment, facilities should be considered prior to contract award.

Software development has proven challenging. This is especially so when interaction is required between software components. Early discussion and agreement on interfaces and requirements is essential.

Mission Assurance should be involved during program development and implementation. Waiting for traditional gates is not a good practice when performing non-traditional development. This applies to customer oversight and involvement as well. Teamwork is the best approach to achieve a common goal.

Appropriate tradeoffs between adaptability and standardization; cost and certainty; performance and heritage determine the effectiveness of each program and of each product.

We need to be smart about "Smart Space", and we are learning much along the way.

References

1. Aerospace Report NO. TOR-2011(8591)-21: Mission Assurance Guidelines for A-D Mission Risk Classes published in June 3, 2011.
2. NASA EEE-INST-002 Instructions for EEE Parts Selection, Screening, Qualification, and Derating