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Key Technology, Programmatic Drivers, and Lessons Learned for Production of Proliferated Small Satellite Constellations

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ABSTRACT

Proliferated small satellites are a critical element of achieving a more capable and resilient space enterprise vision. Current game-changing initiatives across the U.S. government seek to achieve robust, agile capabilities inherent with large-scale constellations and to leverage the significant investments being made in the commercial sector. Production scale and pace are critical elements for affordability. A measured balance between modularity, autonomy, rightsized verification concepts, and rigorous supply chain management permits rapid, cost effective mission deployments. Maxar (formerly Space Systems Loral), has gained unique insights to key production methods and lessons learned to enable these capabilities from several active programs, including delivery of nearly 20 SkySat-C spacecraft to Planet, development of Maxar's WorldView Legion imaging constellation for launch in 2021, and preliminary efforts on Telesat's LEO 200+ satellite communications constellation. In this paper, we will provide metrics from these programs along with discussion about derived insights, as well as recommendations for how the community should continue to evolve to meet the stringent performance and affordability thresholds required to achieve a resilient proliferated LEO vision.

INTRODUCTION

Market forces, user demand, and the readiness of technology are all driving a renewed push for creating large scale, proliferated space architectures to serve both Government and commercial equities. In many cases, the requirements and associated solutions are highly intertwined. Behind this momentum, driving this next phase of the industrial revolution, commonly referred to as Industry 4.0, are critical enablers predicated upon interconnectivity, automation, machine learning and real-time data. There are four design principles in Industry 4.0 which support companies in identifying and implementing applicable scenarios [1]:

1. Interconnection: The ability of machines, devices, sensors, and people to connect and communicate with each other in real time or across heretofore disparate interfaces.
2. Information transparency: The collection of immense amounts of data and information from all points in the manufacturing process, thus creating a highly observable operating state that permits cognizance and identification of key areas that can benefit from innovation and improvement.
3. Technical assistance: The integration of assistance systems to support humans by aggregating and visualizing information comprehensively for making informed decisions and solving urgent problems on short notice. Additionally, the use of cyber-physical systems to physically support humans by conducting a range of tasks that are unpleasant, too exhausting or unsafe for their human co-workers.
4. Decentralized decisions: The use of cyber-physical systems to make decisions on their own and to perform their tasks as autonomously as possible.

But Industry 4.0 is not enough alone to fully execute production development and delivery of quality, affordable satellite systems at the scale of planned mega constellations like Amazon's Project Kuiper, SpaceX Starlink, Telesat LEO, OneWeb, and others. Modern design and manufacturing methods that are rooted in proven procedures and tailored for mission risk posture must also be utilized.

Maxar is a trusted partner and commercial innovator in space infrastructure and Earth intelligence. Based in the U.S., Maxar delivers global communications services and designs and manufactures innovative spacecraft to explore and advance the use of space. Maxar's advanced product line includes high-power geostationary satellites, state-of-the-art small satellites and sophisticated robotics and automation solutions for remote operations.

In the context of proliferated LEO constellations, Maxar's experience includes delivery of more than one hundred satellites ranging from the initial communications experiments and sub-synchronous constellations, the first Globalstar constellation, Planet's SkySat Earth observation constellation, and various multi-spacecraft constellations including Maxar's next-generation high resolution Earth imaging constellation, WorldView Legion.

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 standard practices to develop a clean and adaptable baseline of processes with which to move forward. Our balanced design approach 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. In this paper we will discuss some considerations for an Industry 4.0 smart space layer, then Maxar's approach to modern manufacturing processes that have been successfully validated across multiple flight programs.

CONSIDERATIONS FOR A SMART SPACE LAYER

In order to get beyond line of sight access, reduce bandwidth demands, and to provide real time observation, more processing is being deployed on satellites. Providing this capability, in short timelines and an ability to refresh rapidly, is driving a reliance on FPGAs, GPU processors, and ARM processors on small satellites. Although the cost points for these technologies are being achieved by high volume mass production markets, these technologies are not being developed specifically for space. 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 parts with the lowest upsets tend to be parts with lower processing capacity or I/O throughput which when used drive the mass and power beyond acceptable limits for small satellites. 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 constellation planner, based on risk profile, to accept the risk and trade localized and constellation level mitigation where critical.

As discussed by Loman et al [2], parts that do not meet thresholds for minimum total ionizing dosage (TID) are reviewed for use in each application circuit. For low cost missions using commercial-off-the-shelf hardware, radiation testing can 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. In LEO orbital regimes the annual dose rate is highly dependent on altitude and inclination. Cost driven systems choose orbits at lower altitude to use less robust circuits. Not all applications allow for the preferred radiation environment. Shielding helps with total does but the benefit of shielding has diminishing returns above 300 mils. Since the added mass changes the cost effectiveness of the launch vehicle the cost savings of using less robust parts must be traded against the total cost of getting a constellation of satellites to orbit.

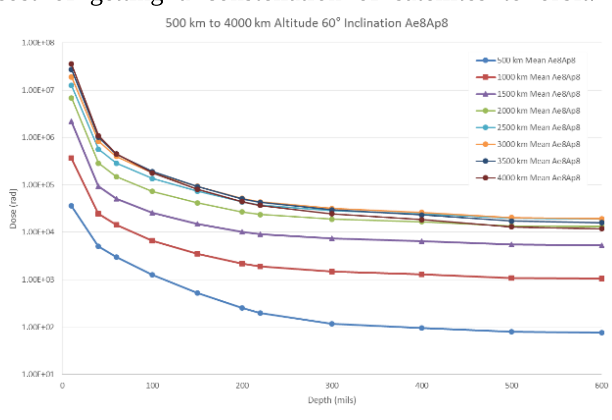

Figure 1: Radiation effects on critical components, including those that enable smart space layer functionality must be considered during the design process.

Consideration of the part requirements for space use and careful supply chain management is essential for creating an integrated solution that will work. To achieve the economies of scale and just-in-time responsive timelines demanded for production scale, careful coordination with vendors and even their lower-level sub-suppliers is required. For constellations which require vendors to supply larger than historical volume of space flight equipment, Maxar implements Supplier Development Teams (SDT) to support the industrialization development at critical equipment vendors. Each SDT is a multi-discipline group of Maxar specialists tasked with aligning each vendor's industrialization methodology and delivered product with Maxar's cost, schedule, reliability, and performance metrics.

Use of long-term purchase agreements and other contracting mechanisms that ensure a mutually incentivized, transparent relationship are essential. As shown in Figure 2, there can be significant savings as quantities are increased, where the provided results compare average unit cost savings between orders of six vs. 300 based on supplier bids, not actual production costs.

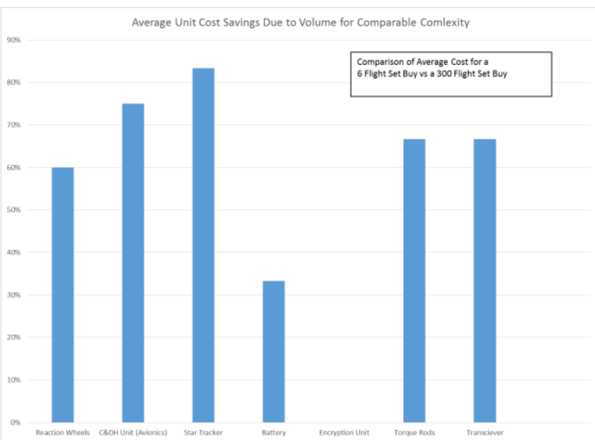

Figure 2: Significant economies of scale at the subsystem level can been realized through coordinated volume supplier agreements.

CONDUCTING VOLUME PRODUCTION

Maxar's Volume Production System (VPS) is designed to minimize schedule and maximize cost efficiency while maintaining industry standard reliability for high mix, medium volume production activities ranging from advanced Space Vehicle modules (propulsion, avionics, etc.) through top level Space Vehicle I&T. The ability to find efficiencies while providing volume flexibility is a major pillar of the VPS. Because new technologies, architectural approaches, and constellation management techniques are proven before committing to the full constellation, programs take a crawl, walk, then run market introduction approach. Typically a small number of protoflight units to support a proof-of-concept phase is conducted before commissioning a larger number of units in a second program phase. This is sometimes followed by a third program phase producing an even larger amount of units required for the system to fully achieve mission goals. This flexible process is designed for continual evolution—an imperative characteristic necessary to maintain parity with the evolution of the proliferated LEO concept. The practical implementation of MVPS focuses on the metrics of per unit cost, time-to-market, minimal CAPEX (capital expenditure), and legacy Product Assurance concepts for the initial low volume phase. Concurrently, the VPS requires the program team to create a Space Vehicle design that enables a minimized recurring I&T cost--based on the program's predicted throughput demand and budget allocation—by leveraging volume opportunities and Industry 4.0 elements that are most pertinent to achieving the program goals.

The foundation of Maxar space vehicle products is the Bill of Process (BOP). Similar in concept to a Bill of Materials (BOM) which draws upon a library of qualified parts, the BOP is a program specific register of qualified processes, procedures, scripts, facilities, ground support equipment, and a number of other secondary elements such as available consumable equipment, ergonomics accommodation, non-flight equipment plan, etc. The BOP manifests as a set of production requirements that ensure the Space Vehicle design is compatible with the overall production capability. This is a significant departure from traditional space products, where design and production development are serial activities. Espousing the concept of 'manage the exception, not the rule,' perhaps the most important artifact of the BOP is rapid identification of incompatibly between the design and production, as those incompatibilities are the foundation for most anomalies encountered during legacy Space Vehicle production. This early identification allows the program team to create an informed engineering solution—such as redesigning the product, enhancing production capability, or often a hybrid of both—during a program phase where a change corresponds to significantly lower cost, schedule, and risk impact.

From day one of a program, IPTs are implemented to enable concurrent and collaborative engineering, which maximizes the efficiency and output of development activity. IPTs identify and dedicate key personnel to a program to maintain continuity and increase the speed of decision making, and ultimately results in a more robust, higher performing product. Because the cost of manufacturing accounts for an exponentially increasing portion of overall cost and schedule as production volume increases, the production team members of the IPT are tasked with championing manufacturing and production requirements—known as the Voice of

Manufacturing—to significantly greater levels of importance than traditional single-spacecraft programs.

Modular spacecraft design, governed by Maxar's next generation Scalable Modular Product Architecture (SMPA), ensures that a space vehicle is efficiently modularized. By focusing on building testable spacecraft elements, or modules, we can pull forward and parallelize many of the operations traditionally performed during system level AIT.

Volume production enables cost reductions in our processes and throughout the supply chain as the result of applying the learning curve, reduced test protocols, amortization of non-recurring costs, and the ability to manage quality through process control in ways typically not practical for low volume space products. In our production of units and even full spacecraft within a constellation, we have proven the reality of these capabilities and can rely on this reduction to provide the best possible price for our customers while still maintaining maximum performance and quality.

Pulse-line production facilities follow Industry 4.0 concepts that have been proven by other volume manufacturing industries. The pulse line is made up of multiple work stations designed to efficiently isolate AIT operations by discipline and total duration. Once in full production mode, the period of operations at each work station are equivalent--or 'balanced'--allowing the entire production line to 'pulse' all of the flight hardware simultaneously to the next work station.

PRODUCTION SCHEDULE

Volume Correlated Verification (VCV), a pillar of the VPS) outlines a tiered approach which focuses priority on designing for cost and efficiency of production in addition to the traditional focus on designing for performance. The VCV architecture, shown in Table 1, defines discreet phases of production to efficiently maximize quality and consistency of each space vehicle as a program progresses from early units into volume production. Because SSL's customer base has widely varying mission needs, the VCV is extremely volume flexible and can be tailored to align throughput and risk tolerance for both low-volume constellations and multi-hundred unit constellations,

As is typical with volume production in most industries, early units are subject to a significant scope of verification activities to qualify the product and ensure that risk from design anomalies is sufficiently mitigated. For a constellation this manifests as a traditional protoflight I&T campaign for the first unit. As a program moves into low rate production of the Pilot phase, the VCV shifts from design verification and standardization of the product into design verification of the production line. After the pilot phase, the program moves into the high volume production phase where the focus is on workmanship verification of the product and managing production line performance through statistical process control.

Key elements of the additional I&T objectives discussed in Table 1, are 1) the concept of "takt" time, which is the average time between the start of production of one unit and the start of production of the next unit, when these production starts are set to match the rate of customer demand, and 2) the concept of "Experience curve" which is an logarithmic prediction of decreasing effort (in the form of time, cost, etc.) for subsequent units in a production run

Table 1: Maxar Volume Correlated Test Philosophy

	ProtoFlight (PFM)	**Pilot**	**Production (Recurring FM)**
Unit Quantity	1	1-4	Practical SSL Volume = Tens to Hundreds
Primary Objective	Space Vehicle Design Verification Ensure system level compliance to performance and quality parameters	Production Verification Validate that processes, procedures, and production line concepts (GSE, scope per station, etc.) are compatible with high rate production	Volume Execution Maintain production line performance metrics Quality escapes Workmanship verification results Time parameters
Space Vehicle Testing Objective	Design & Workmanship Verification Full PFM test plan All applicable performance metrics verified All quality metrics/limits verified Some operations may not occur on volume production line	Workmanship & Reduced Design Verification Design verification only for critical elements (single point failures, etc.) + additional design verification identified during PFM build Reduction of environmental testing	Workmanship Verification Functional checks for most elements Performance checks only for critical spacecraft elements Reduced environmental testing from PFM and Pilot I&T plans

		All operations performed on volume production line	
Additional I&T Objectives	Validate GSE concepts Create manufacturing product structure Generally legacy approach to spacecraft I&T	Focus on quality & consistency of: Operator training Shop floor systems & documentation Production control Baseline production line performance Sets/validates initial takt time Identifies cycle times & bottlenecks Validates station layout/concept VSM & line balancing opportunities	Focus on production line performance Quality escapes Consistent & improving time parameters (Cycle, takt, set-up, downtime) NVA elimination Station/line balance Kanban efficiency Significant emphasis on process control Break points & technology insertion Consistent execution Statistical verification
Quality Approach	Anomalies may be design or workmanship: Stop work until resolved	Anomalies are typically line related with some residual design & workmanship: Stop work until resolved	Minimal workmanship and line related anomalies: Move hardware to off-line hospital station for resolution

ENABLERS FOR RESPONSIVE SV I&T

The following items are used (or in some cases where noted, can be used) to enable rapid throughput during volume production.

Single Mechanical Fixture Stand throughout I&T: To minimize time spent handling the SV, CAPEX spend on handling equipment, and risk associated with handling events, the primary space vehicle support stand is a singular item compatible with all production line operations. Ideally, this stand will also be used in the shipping container.

Built-in Self Test (BIST): In order to achieve rapid I&T schedules, it is imperative that the SVs utilize self diagnostics. This minimizes the cost of developing and purchasing electrical GSE and the associated documentation. It further eliminates the recurring effort required to connect, operate, and disconnect the EGSE for each unit, and also eliminates the need to allocate production facility space and resources for the EGSE.

Standard Program Test Scripts: A corollary concept to the BIST is the notion of standard program test scripts. This means that a subset of test used during the software simulator phase, which focuses on interoperability of modules, is the same script used during system level I&T operations. This eliminates the recurring effort of developing different test scripts for different program phases and, as importantly, minimizes the inevitable effort required to debug new scripts.

Flatsat Activities: The initial stages of spacecraft development include advanced simulated verification activity, which is an early validation of test scripts, electro-mechanical interfaces and interconnects, and other major elements of the system level integration plan. This activity is an integral enabler to successful production, as it significantly reduces the number of anomalies that are traditionally experienced as a program progresses through the I&T plan by pulling anomaly discovery forward from what is historically first-use during expensive and schedule critical initial I&T phases. Accomplishing flatsat development requires replicating space vehicle equipment and functions through an evolving hybrid mix of hardware and software, where the initial flatsat activity will rely heavily on software simulators and then transition to mostly hardware has the brassboards or engineering units become available.

Strategic Inventory: For higher volume constellations a major element to production risk reduction is the concept of strategic inventory. In the event an anomaly is identified on any element of the SV that cannot be immediately resolved, the SV is moved off the production line and into a hospital work station for future investigation. If required, the anomalous element is removed from the SV with a return-to-supplier action being taken if the issue cannot resolve the anomaly within the SV production facility, and the next available unit is installed in its place.

Scalability for Needed Production Line Expansion: Because the SV production line is developed using the VPS and VCV, expansion of the production line can be a straightforward and cost-effective exercise. Additional stations can easily be added to increase capacity, up to and including duplication of the entire production line.

CASE STUDY: PRODUCTION OF SKYSATS

In 2014 Skybox awarded Maxar a contract to deliver the first 13 satellites of its planned operational constellation [5]. This award was made upon the successful demonstration of its internally developed pathfinder. The effort, which eventually grew to a production run of 18 total flight units, comprised ESPA-class space vehicles of approximately 60 x 60 x 95 centimeters in size and a wet mass of 120 kilograms that included an SSC/ECAPS green propulsion system. An electro-optical payload supplied by L3 was integrated as customer furnished equipment to support the mission of globally capturing sub-meter color imagery and up to 90-second clips of HD video at 30 frames per second.

Figure 3: Maxar utilized numerous development and production methods to efficiently deliver 18 Skysats for Planet (formerly Skybox).

Maxar collaborated closely with Skybox to review the design baseline and make select modifications for improved volume manufacturability. Over the course of the program, two additional configuration and lot resets were performed to match evolving requirements, supply chain sourcing, and other technical/programmatic items. Figure 3 shows the produced satellites from lot 2. Over the course of the entire effort, Maxar was able to empirically validate multiple metrics associated with volume economics and efficiencies, to include those at both the subsystem level (e.g., Avionics, Figure 4) and system-level (Figure 5) in which 87% and 76% experience learning curves were demonstrated, respectively.

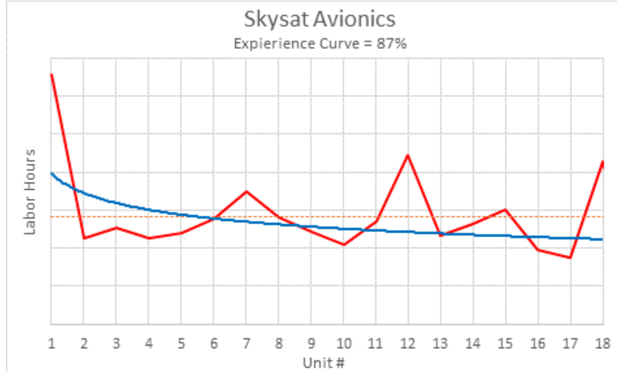

Figure 4: A Significant Learning Curve was Empirically Validated at the Subsystem-level (Avionics) Across the Production of 18 Skysats to Include Periodic Technology Updates.

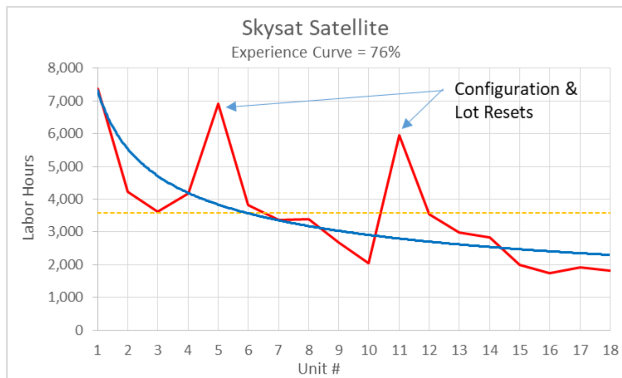

Figure 5: A Significant Learning Curve was Empirically Validated at the System-level Across the Production of 18 Skysats to Include Two Configuration & Lot Resets.

SUMMARY AND NEXT STEPS

As we have discussed, Maxar's Volume Production System (VPS) is designed to minimize schedule and maximize cost efficiency while maintaining industry standard reliability for high mix, medium volume production activities ranging from advanced Space Vehicle modules (propulsion, avionics, etc.) through top level Space Vehicle I&T. The five major elements of the MVPS are 1) the Bill of Process (BOP), 2) Integrated Program Teams (IPTs), 3) Modular Spacecraft Design, 4) Volume correlated verification (VCV), and 5) Pulse-Line Production facilities.

Through Maxar's validated approach to responsive space vehicle production, we have been able to achieve timely, reliable, and affordable delivery of many satellites at scale. We are continuing to apply these methods and lessons learned to a host of current flight programs and initiatives, like the WorldView Legion constellation that will launch its initial operational capability in early CY2021, as well as the Telesat LEO constellation that Maxar is currently in competition to build as part of an envisioned 200+ satellite system.

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