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Quantity and Quality: Scaling Small Business for Large Constellations

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ABSTRACT

In 2018, Sinclair Interplanetary accepted an order constituting 40 star trackers and 80 reaction wheels, an order three times larger than had been received previously. Moreover, the delivery cadence was three times faster (12 units per month) than any previous large order. Faced with these obligations and an internal requirement to maintain quality, the company took stock of itself. Since drastically scaling its staff complement of seven people to meet the demand would have risked negatively impacting quality, Sinclair Interplanetary set out to meet its obligations by adjusting the way it manufactures its products. A combination of outsourcing, process changes, equipment upgrades, descoping, and other techniques were ultimately used to improve efficiency and meet production needs. As a result of these changes, both quality and consistency have been improved. Relevant to any small space company looking to scale its production capacity, this paper details the obstacles encountered, successes, failures and lessons learned during this exercise of production enhancement. Further, it uses this experience to predict the limits of the processes that are now in place, and what further steps would be required to exceed those limits.

INTRODUCTION

Operating since 2001, Sinclair Interplanetary is a supplier of spacecraft hardware based in Toronto, Canada. Its primary products are reaction wheels[1] and star trackers[2]. In January 2018, when the company accepted an order for 20 satellites-worth of star trackers and wheels (hereafter referred to as 'the project'), it employed seven individuals.

Based on actuals from the previous calendar year, recent upgrades to test support equipment, and a short run of high-cadence wheel production in 2017, the company was confident that it could meet the obligations of the project by working smarter rather than harder and without drastically scaling its workforce.

PRODUCTION PLANNING

The project required the first four flight sets to be delivered approximately nine months after kickoff. Thereafter, the contractual delivery cadence was one flight set (four wheels and two star trackers) every two weeks. This project offered the company its first true opportunity to apply a recurring batch production philosophy over an extended period.

Ground test equipment (Figure 1) recently put in place allowed testing of up to six wheels or six star trackers at a time (a batch). Therefore, a production cadence of two weeks for wheels and four weeks for star trackers would produce units at the required rate, with 50% margin. This margin acted as insurance against sub-100% yield, other orders needing to be serviced in the same time frame, and future production delays.

Figure 1: Ground Test Pod populated with five star trackers

Using actuals from previous orders it was determined that a batch of reaction wheels takes approximately 10 weeks to progress from having parts and subassemblies in-house to having completed wheels. For star trackers, the time was 12 weeks. Therefore, at the specified cadence, up to five batches of reaction wheels and three batches of star trackers would be at various stages of production at any given time (see star tracker example in Figure 2).

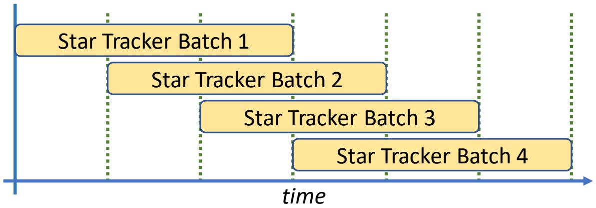

Figure 2: Typical batch overlap

Each 10 or 12-week production run was broken down into approximately 25 subtasks and distributed as seemed reasonable on a weekly basis. Lining up the overlapping (but offset) batches allowed a week-by-week assessment of resource utilization. After some leveling, a distribution was obtained that required approximately 67% of available staff resources in any given week.

PRODUCTION ENHANCEMENTS

Beyond the introduction of a batch-based process, several other enhancements were made to company operations for the project.

Upgrades

Although a 67% staff utilization was considered workable, the company preferred to aim for 50%. This was achieved during the project by making two new hires.

Key equipment utilization was also examined. At 75% utilization the thermal chamber was deemed oversubscribed and a single point of failure in the production line. A second chamber was purchased and brought online. Existing thermal test equipment (e.g. Figure 1) was duplicated to ensure parallel thermal tests could be run as needed.

Outsourcing

Sinclair Interplanetary has traditionally manufactured electronics boards (Figure 3) in-house using a combination of hand soldering and reflow technology, though trial production runs had been done with outsourcing electronics assembly. By the time this project started the company was very comfortable outsourcing the assembly of both reaction wheel and star tracker circuit board assemblies.

It would have been impossible to complete the project on schedule without outsourcing this process. More details on the outcomes of this process can be found in the 'Lessons Learned' and 'Limits to Growth' sections.

Figure 3: Reaction wheel electronics assembly

Due to the quantities involved, Sinclair Interplanetary also outsourced some mechanical tasks for the first time. Specifically, 3D-printed parts in the reaction wheel that must be reamed and/or tapped (threaded) were provided to a trusted machine shop for this operation and the subsequent cleaning. These tasks had previously been performed in-house by hand due primarily to the fragility of one of the parts (Figure 4).

Figure 4: Thin-shell 3D-printed reaction wheel magnet retaining ring

In total 2800 holes were reamed and 400 of those holes were also tapped. Outsourcing this work likely saved at least two person-weeks of effort and an incalculable amount of wrist strain. The subsequent installation of threaded inserts was performed in-house because a suitable external provider for this service could not be found in the time available. This is an area that Sinclair is still interested in outsourcing.

Descoping

Because maintaining heritage against previously delivered hardware was important to the customer, very little descoping was performed. Two opportunities to simplify production without increasing risk or jeopardizing yield were identified.

First was the omission of eight threaded inserts in the reaction wheels that were identified as being unused by the customer. Although this may seem trivial, when multiplied by the 100 structural sets that were manufactured to build 80 wheels, approximately one person-week of effort was saved.

Secondly, validating the performance of star trackers after vibration acceptance testing was removed from standard production. A survey of 60 previous star trackers revealed no change in measurement uncertainty after this stage of environmental testing. Risk exposure in removing this step was minimal as each unit still undergoes a performance validation after thermal acceptance testing. This descoping saved at least two person-days of effort per batch of star trackers in the production timeline. Over the duration of the project, this amounted to almost three person-weeks of effort.

PROCESS CHANGES

Star Tracker Focusing

Prior to the start of the project, star tracker focusing had been identified as providing a large opportunity for process and speed enhancements. The established process for star tracker focusing required the use of the Space Avionics and Instrumentation Laboratory (SAIL) optical calibration facility at Ryerson University[3]. This system utilizes a 3-axis gimbal to orient the unit-under-test relative to a fixed simulated star. As equipped, each batch (6) of star trackers required half a week to focus. Much of this effort was manual labour—reviewing results, adjusting the lens position, and shimming the focal plane—but a path to automation was identified.

The SAIL facility is equipped to perform a 300-position survey for star tracker calibration and post-environmental test validation measurements. This process demands arcsecond precision and repeatability of the 3-axis positioning stage. However, when focusing a star tracker, the accuracy and repeatability requirements are orders of magnitude less stringent, so the opportunity existed to replace this system with a simplified and dedicated focusing apparatus. Having a focusing system at Sinclair saved time on frequent transit to and from the SAIL facilities and alleviated bottlenecks that would occur at the SAIL facility when different batches of star trackers overlapped, or other customers occupied their facilities.

The primary requirement of any star tracker focusing system is the ability to sweep a simulated star throughout the field of view of the unit. Typically, this is accomplished by rotating the unit under test relative to a stationary simulated star. To achieve full autonomy, the new focusing system additionally required the ability to adjust the bulk focus of the star tracker. In the ST-16RT2 star tracker, this is accomplished with a rotation of the lens relative to the chassis. Due to complications in rotating both the star tracker and a motorized stage to turn the lens, the new focusing systems was designed with a stationary star tracker and a moveable star. Referring to Figure 5, the relative angle of the star to the star tracker is controlled using a motorized two-axis tip-tilt relay mirror. Meanwhile the star tracker is held stationary and the lens secured within a rotational stage, allowing for hands-off measurement and focus manipulation.

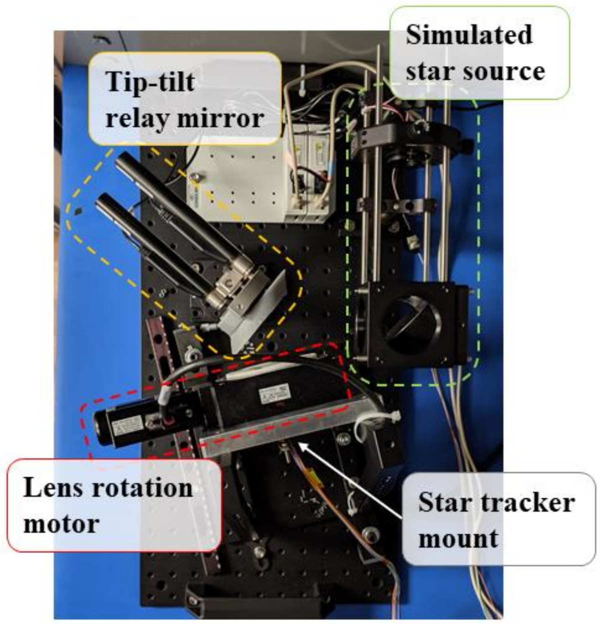

Figure 5: Automatic focusing system

The automation of the focusing process begins after the operator verifies the torque level on the threaded lens in the chassis and loads the unit into the quick-release receptacle. A MATLAB interface then performs the complete focal survey, following these steps:

1. Search process to calibrate the two-axis tip-tilt relay mirror and center the simulated star on the star tracker detector
2. Bulk focus sweep in 14 micron increments (as measured from lens to detector) with the star held in the center of the detector
3. Focal plane surveys over an 8 degree by 6 degree swath of the detector at 7 micron lens-detector increments, centered around the optimal bulk focus position
4. Calculation of the full-field optimal focus position

Prior to this project, parts (2) and (4) were fully manual and part (3) required frequent operator intervention to proceed. Although some autonomy was implemented, 100% operator supervision was required to keep the process moving. With the new system, a process that had previously required four to six hours of effort per star tracker, now required 20 minutes. Half of star trackers require shimming to adjust the position of the focal plane and therefore a repeat of this focus survey procedure (at least once), so an estimated two person-months were saved by this innovation.

Reaction Wheels

Motor Performance Characterization

Reaction wheels are subject to several qualitative tests during assembly. Operators assess mechanical vibrations, audible characteristics, and bearing wind-up. For large scale production, these operator-sensitive evaluations introduce opportunity for inconsistency and schedule dependency on specific personnel.

To satisfy customer requirements over the entirety of the project, key performance characteristics were measured for every wheel. This testing was always carried out after completion of environmental acceptance testing. Static friction, frequency response, and torque performance are assessed for each unit. Results are compared with customer-defined limits and units meeting or exceeding these requirements can be reliably added into their attitude control system.

As a new procedure, non-recurring development and recurring production effort were added to the reaction wheel schedule. While far from ideal in a tight schedule, the testing, analysis, and reporting process was completely automated, and batches of reaction wheels could be put through characterization testing within an hour. For this project, an hour of recurring effort has proven valuable, with outcomes including improved build consistency across batches and the identification of non-conforming wheels.

Outlier identification is critical as each wheel has several unique dynamic characteristics. Some are set by external suppliers (e.g. rotor balance), while others are driven by in-house build variations. Within this project, one in-house aspect that suffered from inconsistencies in assembly was stator winding.

A performance deviation was identified in a subset of reaction wheels from the torque box results of the characterization procedure. When accelerating towards maximum angular momentum, the wheels are expected to maintain constant torque. However, some wheels showed a loss of acceleration authority prior to reaching the target speed. Detection of this issue is illustrated in Figure 6, where opposite corners of the torque box are cut off.

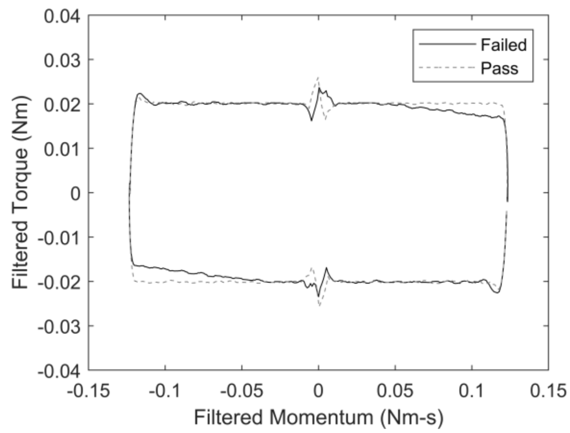

Figure 6: Torque box comparison

All serialized components and subassemblies made at Sinclair have digital build logs, so the history of each problematic wheel was evaluated for trends. It was in this review that stator winding was identified as the common factor. Although the electrical characteristics of the stators were within expected limits, these reaction wheels clearly failed to meet the performance requirements.

Visual inspection revealed that the problematic stators were consistently wound more tightly than the acceptable population. Leveraging the modular internal design of the reaction wheels, these wheels could be dismantled, have their stators de-mated and replaced, and reassembled in minimal time. These reworked reaction wheels could then join the next batch to repeat environmental testing. To mitigate against this build inconsistency causing further delays, a torque box test was performed after first assembly of every reaction wheel and prior to the lengthy environmental testing.

Bearing Preload

All Sinclair reaction wheels are shimmed to ensure that the preload applied to the bearings falls within acceptable bounds. Prior to the project, measurement of preload had been a sensory process. An operator would place a wheel on a scale while attempting to feel when two structural parts contacted each other. The reading on the scale when this contact happened was the preload that would be applied to the bearings when those parts were subsequently bolted together. This process was difficult to train and highly subject to operator bias.

For the project, a new set of equipment was designed and commissioned that measured the applied load and the deflection simultaneously (Figure 7).

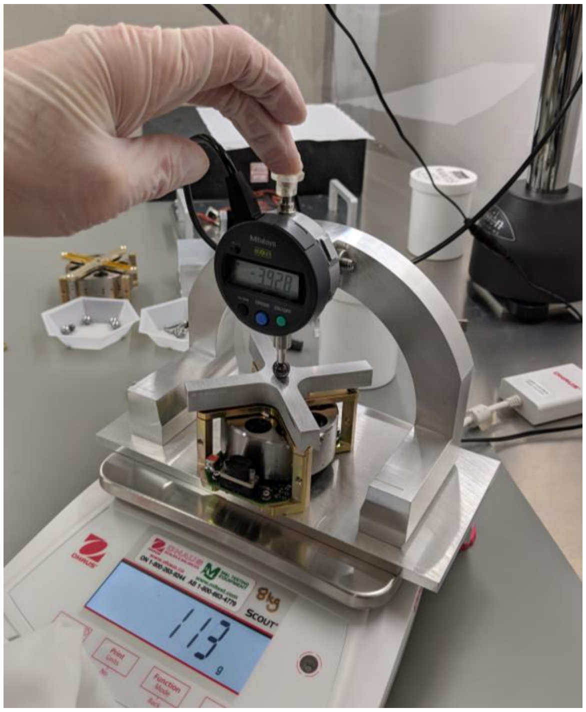

Figure 7: Wheel shimming equipment

By plotting these two data sets against each other (Figure 8), the point at which the two structural components came into contact is obvious due to the sudden change in stiffness of the system. The preload is the force applied at the knee of the ascending curve.

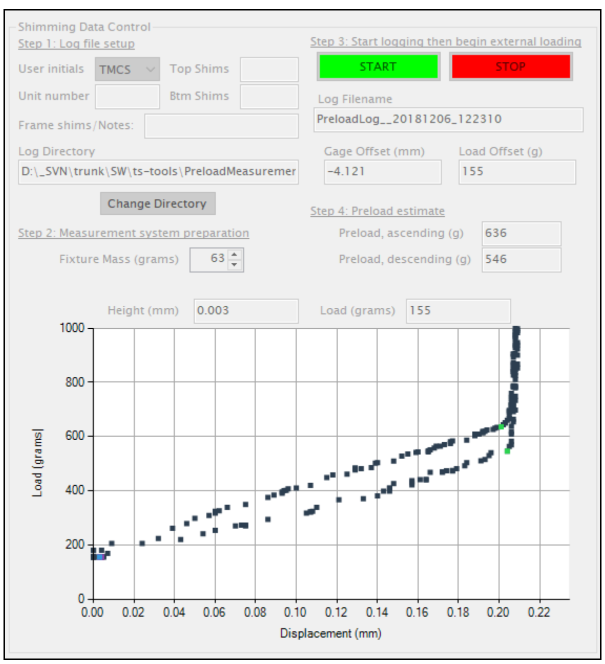

Figure 8: Wheel shimming output

Though the introduction of this GSE likely did not save significant time or effort, it did make the shimming process far more repeatable and consistent. Moreover, it made the process accessible to all staff members thereby ensuring that when shimming was on the critical path, trained resources were more readily available.

LESSONS LEARNED

Batch vs. Lot

At the outset of the project an examination of production processes was undertaken to determine which processes should be performed on the entire lot of parts and which should be performed in smaller batches.

On the one hand, activities performed as a lot are more efficient and consistent. This approach also enables yield issues to be identified early so they can be remedied off the critical path. Conversely, in a resource limited environment, lot-based activities ensure nothing can be completed until everything is completed. This has no impact on schedule if the part or subassembly in question is not on the critical path, nor are the resources undertaking the lot-based activity being pulled away from critical path activities. As soon as either of these is not true, lot-based approaches negatively impact schedule by delaying the first delivery, which is often the most critical. Clearly, a lot-based approach across the board is ill advised.

On the other hand, and again in a resource-limited scenario, batch-based approaches are less efficient from a total labour perspective since they involve more context switching and setup time. A batch-based approach will also inevitably result in more variability across the population. However, batches are clearly advantageous for scheduling purposes, resulting in a shorter time to first delivery and better alignment between unit deliveries and the spacecraft production schedule.

Some lot vs. batch choices are obvious. It makes no sense to have a high-capacity machine shop produce a fraction of the total order on a biweekly or monthly basis when they could instead deliver the entire lot in only a few days more time. The wheel structures were machined, coated, installed with threaded inserts, cleaned, and installed with bearings before the first batch of electronics was ready. Since there was no overlap in the resources needed for these tasks, they did not impact the critical path at all, saving effort, schedule, and cost.

Similarly, it makes no sense to perform environmental acceptance testing on a lot basis. Thermal chambers are only so large, and the effort associated with building large amounts of ground support equipment (e.g. harnesses) would easily outweigh efficiencies that might result from testing more units at a time.

Ultimately, the choice between lot vs. batch processing tended to fall on disciplinary lines. That is, mechanical parts and tasks (machining, 3D printing, coating, insert installation, cleaning, etc.) were processed on a lot basis while optical and electrical parts were managed on a batch basis. The primary exception was the main circuit boards, which were populated on a lot basis by an external high-throughput line before being inspected and tested on a batch basis at Sinclair facilities.

Generally speaking, the more activities can be done off the critical path on a lot-basis, particularly by subcontractors, the less is left to do in the final stages of unit assembly, integration, and testing and the higher the cadence at which the company can complete product.

Beware of Supplier Sensitivity to Quantity

Prior to 2018 Sinclair Interplanetary had never ordered more than 40 of any custom-machined components. To produce 80 reaction wheels an order of approximately 100 pieces was submitted across the board. While the difference between 40 and 100 may not seem terribly large, it was enough that suppliers who had traditionally manufactured in one way, transitioned to new methods or machines. This resulted in unexpected yield issues on parts that had been unchanged and unproblematic for almost a decade. Those yield issues ultimately reduced schedule margin and increased costs.

The lesson is that even changes in quantity that are perceived as small can result in large changes of quality. When faced with increasing order sizes, even if your company's process do not change, it is important to come to an early understanding with suppliers about how increased quantity impacts their internal processes.

Avoid Rework

Sinclair Interplanetary has traditionally maintained a build-to-order approach where the components and subassemblies of units are maintained in inventory but completed units rarely are. As such, when the company would receive an order, the required number of units would be constructed and tested. When issues arose during integration or testing, the natural response was to stop, diagnose the issue and resolve it.

But in a program that is continuously producing units, where replacement units are always coming up behind, and where there is margin baked in, there is very little incentive to rework units. Rather, it is more efficient to proceed with the units you have and set the faulty unit aside for a rainy day than to put the rework on the critical path.

This philosophy also applies at the subassembly level. To produce a batch of six units a set of seven subassemblies were typically processed. This ensured that even if there were a problem with a subassembly, the full batch of units could still be built with no loss of schedule. When all subassemblies in a batch were acceptable, the excess parts were accumulated until they constituted a batch of their own and could be shoehorned into the production schedule, further increasing schedule margin.

Intermediate-Scale Electronics Production Cannot Be Completely Process-Controlled

With the volumes associated with the project, Sinclair Interplanetary effectively scaled out of the boutique electronics manufacturing range, for which it makes sense to assemble boards in-house. That said, with 25 to 75 boards in a given production run, the company is not presently able to take advantage of mass production efficiencies offered by external suppliers since there is not enough margin to provide the feedback needed to completely stamp out process bugs.

Industrial-scale assembly setup requires extensive testing and validation with corresponding adjustments. Typical production consists of temperature profiling of blank boards, building boards, and stencil adjustments. These steps might be alternated for multiple cycles until the assembly shop converges on a satisfactory result. A liberal estimate for the units consumed in this iterative process is 100-200 boards. This estimate applies to an intended build of 1000 boards that are to be completely process-controlled. Since the project's build quantity fell well short of this range, there was no opportunity to realize the benefit of the full scope of possible stencil and thermal profile modifications. These inadequacies are believed to have contributed to a higher defect rate per board, most notably with respect to solder balls.

Optimizing board design for manufacturability, ease of inspection, and rework capability should be performed prior to production. It becomes especially important for intermediate-scale electronics production, since it cannot be completely process-controlled. Optimizing the design for any one aspect can conflict with optimizing the others, thus it is helpful to always keep in mind the highest-priority items to get right across all three areas.

In the case of Sinclair products, the main processor ball grid array integrated circuit on the star tracker board is notoriously difficult to rework. The detector can be reworked, but at high risk to the functionality of the main processor. Therefore, the entire build is optimized for those two parts, in that order of priority. It is more economical to identify and rework defects on other parts caused by lack of optimization to their soldering than to risk scrapping entire boards due to defects in the main processor or detector.

Beyond ensuring acceptability of key components, designing for visual and manual accessibility is very important. For example, the prevalence of solder balls under parts puts an imperative on minimizing blocking of side profile views. In some cases, it is necessary to withhold machine placement of certain components that would otherwise obscure inspection.

Certain parts could not be machine-soldered on Sinclair circuit boards without major reorganization of component layout or qualifying new processes that fall outside of company experience and heritage. Therefore designing the board with enough space to allow for hand-soldering after the machine build is also key.

Despite the challenges involved in transitioning to machine assembly, Sinclair was well-prepared for this project. The company expanded upon experience with incremental optimizations of board design for machine-soldered builds to include enhancements for mixed hand- and machine-soldered builds. At the same time, there remain inefficiencies that seem to be inherent to the current scale of production that incentivize further scaling up with a combination of more orders, more technological solutions, and more staff.

The Value of Quantitative Process Monitoring

The primary difficulty in assessing the quality and efficiency of engineering and production processes is that obtaining specific feedback with low latency is very rare. In recent months, Sinclair Interplanetary has taken steps to understand process outcomes with greater refinement to control them more effectively.

Because performing manual visual inspections of printed circuit board assemblies has been an entrenched feature of in-house electronics quality assurance—as well as a very time-consuming and repetitive one—how much value the process contributes was explored. This involved applying descriptive and inferential statistics, as well as Monte Carlo analysis, to answer questions such as: How internally and externally consistent are inspectors? How many defects might any given board be expected to contain? What is each inspector's defect detection rate? How does this rate change with the number of inspections performed? Through this analysis, it was confirmed that the equivalent of two inspections per board are needed to maintain quality standards; more would be superfluous, fewer would be insufficient.

One important lesson about analyzing inspection processes quantitatively is that the resulting data can reveal weaknesses in the process used to produce the item being inspected; high incidence rates of a particular anomaly, or persistence of an anomaly over time, can point to aspects of the production process that can be improved. Deliberately stepping back from individual unit inspections and surveying overall trends on a regular basis has become an important step in quality control as production volume has increased.

THE LIMITS TO GROWTH

Figure 9 shows the number of units that Sinclair Interplanetary has shipped for the last eight years. The impact of the measures described in this paper are evident in 2018 and 2019.

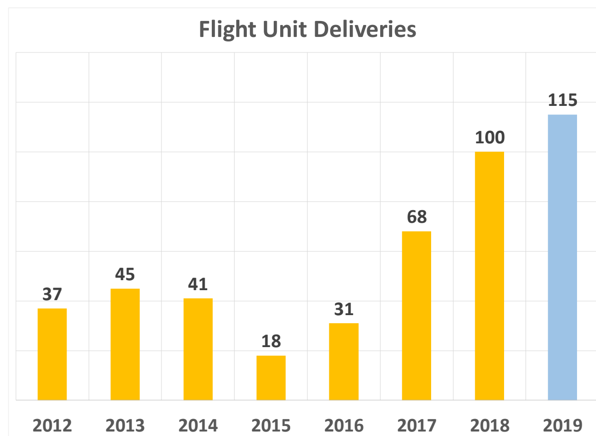

Figure 9: Flight Unit Deliveries by Year (2019 projected using confirmed orders only)

It is important to note that Figure 9 shows units shipped, not units produced. That is, the numbers are capped by demand, not by supply. With the now demonstrated ability to sustain a production of 18 units every 4 weeks Sinclair Interplanetary is currently able to supply approximately 200 units/year.

With constellations becoming both more commonplace and larger and with the company routinely fielding requests for proposals for very large quantities of product, how can production meet the increased demand just through marginal staffing increases, incremental expansion of facilities, and by finding additional efficiencies (i.e. without changing the fundamental way the company has operated since its inception)? The following sections examine the current bottlenecks in the production process.

Solder Dipping

Tin whisker mitigation is of major concern to space tolerant electronics production. For quality and consistency, parts should be ordered with tin-lead coating directly from the factory, but these are difficult to obtain. Hence, historically and for this project, most of the circuit board components have been tin lead hot solder dipped by hand. For various reasons, the dipping process has not been tightly controlled which has propagated inefficiencies in both the dipping itself, and the rest of assembly and inspection.

However, the greatest inefficiency in the dipping process is the sheer amount of labour required. With roughly 130 parts per board to be dipped, and an average dipping rate of 125 parts/hour, more than one person-week is required for a production load of 200 electronic assemblies. This figure does not include the additional effort to inspect dipping or to re-dip because of low initial yields which can, combined, double the effort involved. It is also worth noting that although dipping is skilled work, it is one of the least rewarding deployments of the company's limited labour supply.

For these reasons, Sinclair has recently started exploring options for moving this work out-of-house. The most promising technology appears to be robotic hot solder dipping, which performs essentially the same task as hand-dipping, but with much greater control over process parameters. It is estimated that switching to this process would save at least 20% of a full time equivalent. Deploying that labour elsewhere in the production process would increase production capacity by approximately 8% (~16 units per year).

Electronics Inspection

Manual visual inspection of printed circuit board assemblies is a time-consuming and repetitive process, which, on the surface, is ripe for automation. Boutique-scale production has allowed for two 100% inspections on each board without staffing and schedule discomfort. This changed with the January 2018 order. With roughly seven boards to double-inspect each week, the inspection load consumed a high volume of staffing resources. While a short-term solution was found in making two new hires and acquiring additional inspection space, the long-term viability of that solution is questionable and further scaling of that solution is not ideal.

In addition to taking on a new supplier to perform half of the inspections, Sinclair has been exploring the two most popular automated inspection methods: optical (AOI) and X-ray (AXI). Again, at a borderline scale of production, machine technologies can be expensive; AOI and AXI machines must be programmed and then the programming must be qualified. This requires dozens of training boards—a large fraction of what is produced in a given run.

The scale issue extends even to which suppliers are available for outsourcing; most companies that perform AOI and AXI will only provide the service to customers who are not only using them for the build, but who are producing industrial-scale runs of boards. The small pool of AXI suppliers, combined with this extra factor, have prevented a trial of that technology so far. Moving AXI in-house is also not an option as the machine is simply too heavy for the Sinclair facilities.

Having completed the electronics inspections for the project and evaluated the consequences of continuing with the double-100% inspection process for builds of comparable sizes, Sinclair Interplanetary has invested in in-house AOI capability with the purchase of a multiple-angled camera desktop AOI machine. Though there will be a learning curve to operating the machine, its ability to store libraries of information about particular parts and board designs will eventually eliminate 50% of the company's inspection load. At current production capacity this would save up to 50% of a full time equivalent. Deploying that labour elsewhere in the production process would increase overall capacity by approximately 20% (~40 units per year).

Supplier Bottlenecks

Most Sinclair Interplanetary suppliers are either large enough that they can handle an increase in production or can scale their processes easily. Lead times can be long which does not impact the rate of production but does impact the time to first unit. For large orders, Sinclair currently baselines a time to first unit of 6-8 months. The only way this can be reduced is to hold inventory, which can be impractical on a large scale.

Currently the only external process that does not have a demonstrated ability to scale its production rate is the coating supplier for star tracker baffles where a rate of greater than 100 units per year has not yet been demonstrated. Since star trackers represent only 20%-30% of total unit production, this has not yet been a rate limiting step, but it could be in a scenario in which a large order of star trackers is received with no corresponding order of reaction wheels.

CONCLUSIONS

Through incremental changes to the way it builds product, Sinclair Interplanetary has demonstrated an ability to produce more than 100 units per year, triple the average production rate of 2012-2016. The processes that have been developed will enable the company to produce at least 200 unit/year. Critically, quality and consistency of products have each been improved as a result of these process changes. It is predicted that by addressing remaining bottlenecks in the production process, capacity could be increased to approximately 300 units per year by 2020/2021, representing an 8x improvement in under five years.

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