Smallsat Manufacturing, The Spire "Constant NPI" Model.

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ABSTRACT

Producing 100 of anything in 1 year is not considered high volume in most businesses, but in the satellite manufacturing world it is, even if those satellites are 3U cubesats. The additional complications of a variable launch schedule and the need to launch the latest hardware drives a need for a robust but agile process. As with everything at Spire we are addressing this problem with an iterative approach to the 4 main requirements. These are not serially dependant steps, but a group of parallel iterations.

1 - Define & improve the manufacturing model.

An early realisation was that a contract manufacturing model for assembly, integration and testing (AIT) did not meet our requirements, it was slow and expensive. Neither did a strict "build to launch" model work, launches move and Launch Service Providers (LSPs) have differing requirements. Using Monte Carlo predictive models for part procurement resulted in unnecessary material buy triggers. At the moment we build satellites to a specification that is fit for any launch with a minimal safety stock policy.

2 - Develop the manufacturing team.

To facilitate a smooth transition of new hardware and processes into manufacturing we created a Manufacturing Engineering team (MFG ENG). MFG ENG focus on engineering solutions for process issue resolution and improvement. Through this constant de-skilling and automation of the assembly, integration and test process we have been able to transition the composition of the satellite assembly personnel from senior engineers to technicians. The interactive team structure and flow of information from Engineering through MFG ENG to Manufacturing is critical to continuous improvement throughout the system.

3 - Design, Install & maintain the right manufacturing facility.

The use of external test houses for environmental testing is expensive and inflexible. Vertical integration in this area has resulted in massive cycle time gains with the quality and cost bonus that comes with reduced handling of the satellites.

4 - Enhance the integrated design and manufacture process.

Development of an internal material and manufacturing control system has greatly simplified planning, in addition to automating the collection and recording of performance and quality data.

Automation of test software is hugely beneficial, which is not always so with test fixturing as the development and hardware lead time means test fixtures are not always cost effective.

The result of the above is that we have a "Constant New Product Introduction (NPI)" model where we never move to a volume environment but have integrated the NPI process to produce flight ready hardware. Arriving at, and utilising this model has resulted in a conversion cost reduction of >70%, build cycle time reduction of >40% and most importantly increased on-orbit performance and reliability.

OVERVIEW

As we enter into this narrative type description of how Spire has arrived at its current manufacturing model it should be noted that all development is undertaken with a baseline Kaizen philosophy in all aspects of the Platform business. This expands to the teams, and size of teams, required to create the satellite platform.

DEFINE AND IMPROVE THE MANUFACTURING MODEL

Deciding on what model to use

The original question posed was, how do we build a lot of satellites (100/year) with the constraint that we must launch the latest hardware available?. This precipitated a lot of questions around quality requirements, change management and resourcing, all of which are relevant to any model.

Recognised manufacturing regimes driven by volume and product mix were all assessed with respect to meeting the above requirements, all high volume options, though great for efficiency through automation and effective use of Statistical Process Control data, are no good for Spire satellite manufacturing, 100/year is low volume.. Low volume high mix models with focus on efficient changeovers between models is also not applicable as rapid changeover is mainly driven by cost.

We need a model that support us following a standard process with constantly changing product hardware and system software.

Build to Launch

The decision was made to build batches of satellites with the same hardware & software aligned to our launch schedule, a "build to launch" model. This served us well for the initial launches but when there was significant movement in the launch schedule, which as a secondary payload we have no control over, we were left exposed against the 2nd requirement, launch the latest hardware. This resulted in satellite rework, rebuild and retest, all of which is additional handling adding the associated quality risks. There was also the additional self imposed constraint that when we built hardware to a specific Launch Service Providers (LSP) specification we did not have the flexibility to transfer to another launch with differing specifications without additional processing. So some success but not an efficient method of operation.

Build to Stock

To address the variation of LSP requirements we adapted to test all satellites to an internally derived "Spire Specificaton" that encompassed all known LSP requirements. This allowed us to transition to a "build to stock" model. This model was utilised for a few quarters and was effective when satellites were not on the shelf for more than a month. The engineers are continually improving the satellite performance based on ground testing and telemetry from in orbit assets. During the early days the improvements were frequent and significant to the level that it would be remiss not to upgrade the satellites in stock. SW upgrades are simple and can be performed post launch. Hardware improvements meant the disassembly of flight ready satellites and a repeat Assembly Integrated Test (AIT) process. This, again, was a costly process in terms of resource and quality risk. We needed to delay build start until we were close to the predicted launch date so avoiding wasted effort and maximising the satellites performance.

Build to Monte Carlo Prediction

To deliver the latest design at the right time we need to place orders for parts in a "just in time" fashion. Tricky when some bespoke parts are long lead (up to 24 weeks), so we need to be planning a year in advance. To minimise the risk in this process we needed a way to accurately predict the notoriously volatile launch timing. We had a significant amount of data on the various LSP's by this point so built that into a Monte Carlo prediction model and used that for part ordering based on the models predicted launch dates. What we found with this model was that the Monte Carlo predictions, like the human predictions, were optimistic. In addition the engineers were delivering design improvements within the part lead times. The result of this was a delay in planned build start and a lot of obsolete parts. Again, not very efficient.

Hybrid Model

The long lead parts were generally bespoke space specific hardware like solar arrays (SA), battery, electrical power systems (EPS) and antennas. Another issue associated with these parts was the cost and time taken to implement design changes. These delays were restrictive to Spires rapid iteration mode of operation. The solution was to take ownership and vertically integrate this hardware. The initial investment in developing Spire designed hardware was not insignificant but the long term cost savings are dramatic, as is the impact of owning the embedded firmware and the flexibility in the supply chain. The below table has examples of hardware that has been brought in house and the relative cost savings achieved as compared to the supplied parts.

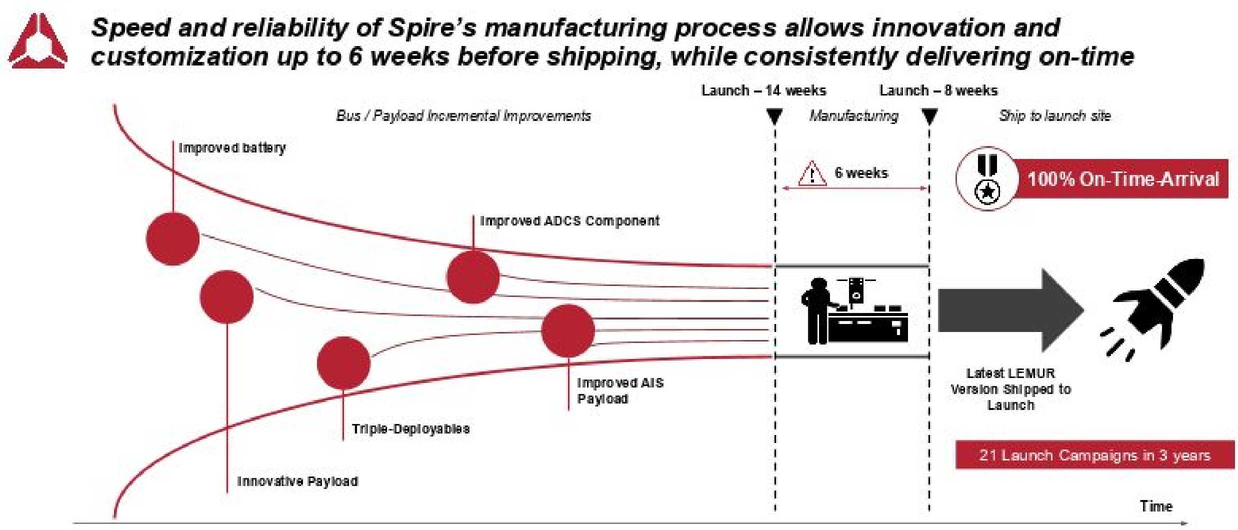
Hardware Vertical Integration - Supplier v Spire Cost Savings

Hardware Description	**GBP Saving**
Attitude Determination and Control System	43%
Deployable Solar Arrays	38%
Electrical Power System	57%
Battery	63%
UHF/VHF deployable antennas	72%

In parallel with bringing designs in house the ongoing development of other systems meant we now had a more stable satellite platform so improvements, though many were less impactful and could be applied between batch builds.

Coming out of these learnings and implementations is a hybrid manufacturing model where we build batches aligned to launches but with a level of safety stock included. The build is scheduled to start as late as possible to ensure all engineering changes are implemented (Figure 1). This has served us well and enabled 100% on time delivery of satellites for launch campaigns, we can also mitigate any risk of a generic hardware design failure by having a mix of flight qualified and ground qualified satellite build standards within a single launch.

Figure 1 : Just in Time Manufacturing scheduling



The evolution of build models described above spans 36 months and is still evolving as the Spire business model evolves to include a hosted payload offering.

DEVELOP THE MANUFACTURING TEAM

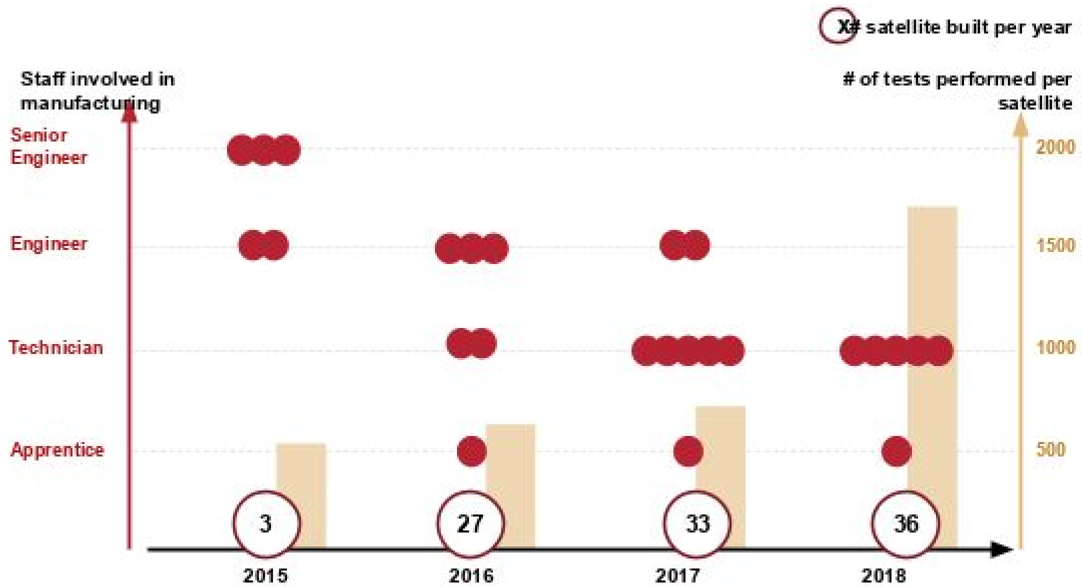
Spire is committed to growing our people under a system where "Autonomy" of work management and "Mastery" of the necessary skills are recognised and rewarded.

Initially satellite manufacturing was performed by Spire senior design engineers with the support of contract staff. We were experimenting with the option to outsource satellite manufacturing but that was short lived for similar reasons to the need to vertically integrate the long lead parts. When using contract manufacturers their need for detailed internal documentation, training and qualification was found to be restrictive, we could not iterate the build process rapidly. Over the "Build to Launch" and "Build to Stock" periods we moved away from any contract manufacturing support and hired a Manufacturing (MFG) team that embraced the Spire rapid iteration model.

From a satellite manufacturing perspective Spire is its own customer, our external customers see data, our internal customers are satellite operations. This means that the Platform Engineering team owns the design, and the Platform Manufacturing teams owns all associated build process tools and documentation, subsequently we define the necessary training and qualifications for our teams, more vertical integration, this time of people with a Spire defined skillset that align perfectly to our model. This is done with the understanding that we must have quality built into the process in order to produce a robust product that the operations team can manage and that will reliably generate the quantity and quality of data that the sales teams and our external customers need.

As the MFG team were exposed to more of the AIT activities we saw a natural progression of personnel that had extensive satellite build knowledge move towards suggesting and implementing change that enhanced the build process. The old adage of the people that execute the process know best how to improves it holds here. Empowering these people to act on their instinct resulted in the natural evolution of the Manufacturing Engineering team (MFG ENG) with the remit of providing engineering solutions for process issue resolution and improvement. This ongoing process of de-skilling and automation of the assembly, integration and test (AIT) process allowed the build team to focus on what they do best, building satellites, not data collection or documentation, that increasingly happens in the background, the resulting satellite build team is a very lean outfit.. MFG ENG has been very successful, they now number the same as the satellite manufacturing team. Figure 2: "Deskilling of Satellite AIT" below shows the transition in staff assigned to satellite AIT and also note that testing has tripled but the overall yield has been maintained at around 94%.

Figure 2 : Deskilling of Satellite AIT



The other task of the MFG ENG team is to provide a link to the Design Engineering team (ENG). In a business where there is a clear transition from the design to the volume production environments the standard process would be to perform at least 4 builds with gradually increasing maturity and quantity. (Engineering Build - Prototype Build - Pilot Build - Production). The transition from Engineering through Prototype, Pilot and into Production would be the realm of the New Product Introduction team. At Spire we do not have that, we tried it, and it was obvious that it was not suited to rapid iteration. We do have a stringent qualification process, which is focussed and fast. For any change, from a major revision of the satellite bus to a re-spin of a sub-system, the below process is utilised.

ENG provide qualified designs, the MFG engineering team are involved in the productionisation and development of system firmware and process software to ensure compatibility. There will be a qualification build of any new hardware, the extent of qualification testing (regression, system, Environmental ALT) required is defined by the ENG team and approved by system owners. Post qualification we will go into production of the design. We accept that this strategy has risk, but Spire accepts that risk in order to constantly upgrade our constellation. The hybrid manufacturing model protects us to a high degree, however, anything thought to elevate that risk is subject to a business review with senior staff where the benefit analysis.

The result of the above is that we have a "**Constant New Product Introduction**" process where we never move to a volume environment but have integrated the NPI process to produce flight ready hardware. The close links between ENG, MFG ENG and MFG enable this.

DESIGN, INSTALL & MAINTAIN THE RIGHT MANUFACTURING FACILITY

Initially Spire had to use rented cleanroom, RF test, Vibration test and Thermal Vacuum test facilities. The impact of that was significant in terms of cost, cycle time and quality. The quality impact was both physical due to additional transport & handling, and in the quality of the data collected and available for further investigation. The logistics of transporting the satellites, equipment and people to perform testing was prohibitive, the facilities had to be pre-booked and were often inflexible in access hours. To resolve these issues in July 2016 Spire took possession of a 6,000 sq/ft facility, in the same location as their current offices, and fitted it out to be a bespoke 3U cubesat manufacture and test facility. A 900 sq/ft class 8 cleanroom with sun simulator room and dual thermal chambers, anechoic RF chamber, thermal vacuum chamber and Vibration test capabilities were installed. This enables end to end build test and integration into the LSP deployers all in one place. The first satellites were shipped from the facility in December 2016.

ENHANCE THE INTEGRATED DESIGN AND MANUFACTURE PROCESS

The cubesat design standard means that Spire can, and does, have standard mechanical fixtures for use in the AIT process. The constant NPI process, along with the relatively low volume means that extensive automation of assembly would be cost prohibitive. By the time an automated solution was developed and in place it would have been superseded by the satellite hardware resulting is a significant waste of resources, going against our Kaizen philosophy.

Automation of the control and test systems is a very different situation. There is huge value in this. We do not want people manually creating documents, entering data or generating reports, everything should be done in the background. To enable this Spire has developed an in house software tool that has elements of the following;

- Manufacturing Requirements Planning (MRP),
- Warehouse Management System (WMS)
- Product Lifecycle Management (PLM)
- Document Management System (DMS)
- Factory Control Systems (FCS)
- Quality Systems, Issue Ticketing and resolution tracking.
- Finance Systems built in.

We call it Spire Requirements Planning (SRP). The decision to develop this system in house and not purchase an off the shelf solution was driven by 2 factors.

1. We wanted a system that did what we needed it to do and not a system where we are paying for functionality that we will never use.
2. A single location for all our data means there is no need to develop interfaces or API's, no divergence of data between systems, an accurate end to end system that delivers full traceability and closed loop quality from part sourcing to in orbit performance.

Automation of test was initially a stand alone activity but has now been integrated with SRP so that all functional and parametric test data is logged into SRP. For any test failure SRP will auto generate an issue ticket and populate that ticket with all available information making escalation communication from MFG to MFG ENG fast and accurate.

Specific functionality within the SRP system are;

Designs

- Design Creation - All designs created in SRP are under revision control
- Design Qualification control - SRP stores qualification documentation and approvals.

- BoM management - Create, edit and manage BoM status
- Change Management (ECN) - All designs & BoMs once qualified are under ECN control

Inventory

- Warehouse location - Global location list
- Serialized part control - all inventory for satellite build is a serialized instance of a design
- Part request & return - automated request and approval

Purchasing

- Item master - created for all parts purchased, Bom, non- Bom or asset.
- Vendor management - lists suppliers and history of their deliveries and performance
- Purchase Requisition Approval - auto directs approval requests
- Purchase Order Creation - Creates and tracks PO status

Manufacturing

- Demand Planning - Work Orders and forecast demand for part order management
- Work Order creation - details a work package for MFG
- Workflow creation & change management - Design specific work process
- Work Planning - extended list of all open work tasks
- Rework control - tracking of rework required to bring a design to spec (based on PO)
- Test Suite Integration - details of test suites for all automated testing

Finance

- GL Code & Class management - supports GAAP
- Fixed asset tracking - for amortization
- Project spend tracking - tracks spend against a preset budget and flags overspend

Quality

- Quality Manual - Spire lean quality manual
- Yield tracking - Supplier and manufacturing test yield reporting
- Ticketing system - integrated issue resolution tracking system
- Certificate of Conformance - alerts Ops to any items that may affect Checkout & Commissioning

Deployed Asset

- Ground Station Status - Live status reporting and alerting
- Satellite Status - In orbit satellite status.

THE END RESULT

The result of all the above efforts are bom and conversion cost reduction, reduced build cycle time and most importantly increased on-orbit performance from the satellites. This means an easier to manage constellation for our internal customers and more, better & faster data to our external customers.

Overall Manufacturing Process improvements

	Jan 2016 - May 2019 change
BOM Cost (with additional features added over time)	-30%
Conversion Cost (-overheads)	-75%
Cycle Time	-45%

CONCLUSION

Finding the right manufacturing system for Spire has been a journey, what we have now gives us great competitive advantage and is the engine behind our innovation. The journey continues, what is fit for purpose now may not be in the future as the product offering from Spire expands. In the spirit of everything is an iteration” we will continue to evolve and embrace new technologies to further improve.