ABSTRACT
“Space is hard” often gets translated to “Space technology is hard”. This mindset disregards some of the critical aspects of developing, deploying and operating a Cubesat constellation. Throughout this paper, we walk through what Spire has undertaken to get a commercial satellite constellation up and running. To enable both scale and rapid technology iteration, the design processes and systems have evolved to be lean but reliable. An iterative systems engineering approach ensures the necessary control, speed and reliability as features are added to the constellation. Solid process control and an experienced manufacturing team ensure reliable, repeatable and rapid satellite Assembly, Integration and Testing (AIT). A global groundstation network provides full control in accessing the satellite data. Complex software systems are in place to orchestrate the space and ground assets, to extract maximum customer value and provide the mission flexibility that’s needed in rapidly changing market environments. An efficient satellite operations team monitors and responds to the changing behaviors of the constellation. All of these factors together comprise a system that can be leveraged to enable other businesses to be successful as well without having to build and maintain all this infrastructure, as the importance of the space-as-a-service concept grows.

INTRODUCTION
Spire Global is the world’s only fully integrated, multipurpose nanosatellite constellation integrator and operator for the purpose of earth observation and communication. Since its founding in 2012, Spire internally developed the capability to perform end-to-end space missions for the purpose of providing data applications and services. In particular, Spire has developed complementary technologies, facilities, and processes that enable rapid iteration and on-orbit validation.

While initially operating as just a payload provider and operator, it quickly became clear that the existing cubesat supply chain in 2012 was not mature enough to provide the backbone for a commercial cubesat constellation. This led the company down the path of vertical integration for most of the constellation value chain. Throughout this journey, we’ve developed systems, processes, facilities and teams to design, build, test, and deploy spacecraft and groundstations, written software to automate and run one of the largest, most flexible, and heterogeneous satellite constellations ever launched, and navigated the legal and regulatory environments in that the space industry is inherently bound to.

The purpose of this paper is to shed some light on these often-overlooked elements of building a space data business and leaving the reader with a good sense of the systems, processes and practices required to be successful.

SPIRE CONSTELLATION
Spire’s current constellation consists of 3U LEMUR-2 Cubesats. At the time of writing 57 LEMUR2 platforms are in orbit, with a total of 81 launched (a few still awaiting deployment on ISS) across 14 launch campaigns. Nine LEMUR2s have naturally deorbited, and ten were lost in a launch failure in November 2017. Some additional LEMUR2s have been shipped to various launch providers and are awaiting launch or completing build and testing now. The first LEMUR2 satellites were launched in September 2015 and the most recent ones at the time of writing were deployed in February 2018. Eight more launches are currently in the pipeline for the next 12 months. Spire’s launch history is noted in Table 1:

<table>
<thead>
<tr>
<th>Date</th>
<th>Vehicle</th>
<th>Launch</th>
<th>Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>03/08/2013</td>
<td>H-IIB</td>
<td>HTV-4</td>
<td>ISS</td>
</tr>
<tr>
<td>09/01/2014</td>
<td>Antares</td>
<td>CRS-1</td>
<td>ISS</td>
</tr>
<tr>
<td>19/06/2014</td>
<td>Dnepr</td>
<td>Deimos2</td>
<td>SSO</td>
</tr>
<tr>
<td>28/09/2015</td>
<td>PSLV</td>
<td>AstroSat</td>
<td>Equatorial</td>
</tr>
<tr>
<td>22/03/2016</td>
<td>Atlas-5</td>
<td>OA-6</td>
<td>ISS</td>
</tr>
<tr>
<td>17/10/2016</td>
<td>Antares</td>
<td>OA-5</td>
<td>ISS</td>
</tr>
<tr>
<td>09/12/2016</td>
<td>HIT-B</td>
<td>HTV6</td>
<td>ISS</td>
</tr>
<tr>
<td>14/02/2017</td>
<td>PSLV</td>
<td>Cartosat-2D</td>
<td>SSO</td>
</tr>
</tbody>
</table>
The satellites are spread over a variety of LEO orbits, between 400-600km in altitude, and between equatorial and SSO inclinations, to form a nearly global coverage pattern with high revisit times and low latencies (typical coverage shown in Figure 1).

Spire currently operates in 4 market segments: advanced maritime domain awareness, critical weather data, air traffic data, and space-as-a-service. The first three are directly related to the data that the Spire constellation collects, whereas the last one leverages all the elements of the value chain Spire has built over the years.

In general, Spire is interested in markets where we can collect data when no one else can, where the numbers of sensors matters more than the size of the sensor, and where the sensors are reprogrammable in orbit, applying Moore’s law to space and providing ever-increasing customer value.

Each LEMUR2 satellite can host multiple applications, allowing for exponential improvement in data quality as new satellites are deployed. With multiple payloads per platform, the constellation can also be flexibly tasked based on customer demand.

**SPACE VALUE CHAIN**

![Space Data Value Chain](image1)

The space data analytics value chain (illustrated in Figure 2) consists of satellite design, satellite build and AIT, satellite launch, operations, data sales and analytics. Spire has chosen to own all of the elements of this value chain, with select external partnerships for satellite launch. Doing so enables more speed, reliability and control. Since all engineering is done in house and all necessary facilities are in house, we can achieve a rapid iteration cycle, increasing the amount of value provided to our customers with every loop. Between satellites batches or software updates, we’ve seen performance improvements of up to 10-100x. As an added benefit, system cost generally decreases as well. This is our way of providing the highest quality data with the lowest amount of risk possible.

As an example, in 2017, we delivered 47 satellites for 9 different launch campaigns, with 4 major satellite versions represented on these launches.

**SATELLITE ENGINEERING AND MANUFACTURING: IDEAS GO IN, SATELLITES COME OUT**

**Satellite design & systems engineering**

Spire borrows heavily from agile software methodologies in the ways it thinks about satellite iterations and engineering. We are not afraid to try something new, and we keep a process only as long as it helps us achieve our goals. If something’s working, it stays. If it’s not working, or not moving us forward, we mustn’t be afraid to cut it out - to not hold on to something just because we’ve been doing it a certain way. There is nothing sacred about the process itself, only what the process lets us accomplish.

As an example, on Figure 3 the Spire satellite iteration model is illustrated, using major versions for backwards incompatible changes, minor versions for simple features and fixes, and branching to enable development of multiple features in parallel. It enables us to build multiple types of satellites with different capabilities and different risk levels at the same time, which in turn allows us to react quickly to changing market environments and improve satellite performance with every single iteration.
As new feature ideas enter the satellite pipeline following a customer request or need, or following engineering-driven improvements, a standard scope of work is prepared and the systems engineering process is kicked off for the new version of satellite.

At the mission level the inputs to the process are the mission requirements and objectives. High-level trade-offs are done to determine mission feasibility and overall scope of change to the LEMUR satellite platform. This includes verifying the design budgets (i.e. mass & volume budget, RF budgets, power budget, data budget), any necessary constellation analysis or simulation, high level subsystem trade-offs, and cost and timeline trade-off evaluation. Based on the output of these trade-offs, a high-level feature list is compiled for the satellite system level. If any requirements need to be placed on any of the ground systems (e.g. operations, ground stations), those are identified at this stage as well.

Once the mission requirements are translated into the system level in the form of a high-level satellite feature list and a set of budgets, the satellite deep-dive review is held with the satellite design team. The output of this review is a detailed requirements list for all satellite subsystems and a list of actions for the system level design. The satellite qualification plan is put together at this stage, as well as the subsystem qualification plans.

Based on the detailed design requirements, the necessary subsystems are (re)designed and go through thorough design reviews. The subsystems all have individual qualification plans that are defined based on the overall satellite qualification plan and the subsystem requirements. Subsystem prototype hardware is acquired and put through the qualification plan.

Then, based on the qualification test report, a go/no-go decision is made to either make alterations to the subsystem design or proceed to acquire flight hardware for the design. In the subsystem qualification stage all the documentation and test hardware and software needed to hand off the designs to the satellite manufacturing team is completed.

Once all subsystem qualification tests have passed and the necessary prototype hardware is in house, a qualification model (QM) is built. The QM is a full equivalent of what will later be the flight model (FM). The qualification model serves two purposes: it will be used for integrated testing against the satellite qualification plan, and after passing the satellite qualification review the QM will remain on the ground as the representative ground test platform for that satellite revision. At that point the QM is handed over to the satellite operations team.

After the qualification tests have passed, the designs are handed off to the manufacturing team and flight hardware can then be acquired by the supply chain team as necessary for the satellite builds. Each satellite goes through functional and environmental acceptance testing before delivery. At the end of the test campaign a Certificate of Compliance (CoC) is produced that is signed off by the satellite design team, the manufacturing team, and the satellite operations mission director.

Based on the CoC, a mission readiness review is held before deployment to ensure the satellite operations team is ready to put the satellite into production. The output is a list of action items to prepare the ground systems and satellite operations teams. After initial checkout and commissioning, satellite operations produces a post-deployment checkout report, which indicates the performance of the satellite in orbit and describes any issues found against the checkout procedures.

As indicated on Figure 4, this process is not entirely linear, as a lot of iteration and back and forth happens throughout the design stages. For example, it’s possible to get to the detailed subsystem design stages, and make changes to the systems design based on some new findings.
In the end, the output of the satellite engineering team is documentation, a brilliant idea is not useful if it can’t be communicated. A novel design doesn’t improve the satellite if it can’t be built by the manufacturing team. Teams doing the actual work are organized as matrixed teams and their work product is considered the documentation they produce, later to be used by supply chain and manufacturing teams to enable quality satellites to be built (see Figure 5).

Figure 5: Design outputs

**Design management and supply chain**

To keep track of all the design flows described in the previous section, Spire has developed a comprehensive software package that allows us to not only track all designs and processes but also to ensure all documentation needed to produce satellites is present.

The “Spire Requirement Planning” (SRP) tool (screenshot shown in Figure 6) provides us with features commonly found in PLM, ERP and MRP systems, allowing us to effectively bring all design data, supply chain and finance data, and manufacturing data together in the same place.

Design data is kept in the system for all items that are present on the satellite’s Bill of Materials (BOM). Detailed design information is made available for the different types of designs (e.g. schematics, mechanical drawings). When new designs are entered in the system, all information for the design items is gradually populated throughout the design cycle, until everything is present, at which point we’re ready to hand over to supply chain to order components, and to manufacture satellites. Once hardware is built, it is also tracked in this system, along with all performance and test data, such that later when satellites are in orbit, there is complete traceability to the subsystem and component level. This is data often used in debugging on-orbit issues or anomalies.

Figure 6: Spire SRP system

In addition to design data and hardware tracking, the system includes features like manufacturing demand planning, work and purchase orders, integration with finance systems, etc. Again, this is a system that supports our rapid iteration cycles and allows us to be lean and flexible in our engineering processes, while at the same time ensuring quality and reliability.

**Satellite AIT**

Spire has its own satellite Assembly, Integration and Testing (AIT) team and associated systems and facilities (e.g. Spire cleanroom in Figure 7). This is another aspect that enables a faster iteration cycle, and increases our satellite build capacity.

Figure 7: Spire Clean Area

Once subsystems and other components are received in inventory, they undergo incoming inspection and a go through a round of acceptance testing, which usually tests basic functionality in a stand-alone fashion. A large amount of this testing is automated, using customized equipment, such that technicians can focus
on the test results rather than following lengthy manual procedures. All procedures are also captured on the SRP system, such that a subsystem’s progress can be tracked. If a subsystem passes tests and is approved for flight stock, it’s returned to inventory.

When the time comes to build satellites, as informed by our launch schedule, tested subsystems are pulled from the shelf and satellite build kits are put together. Satellites are then assembled using standard work instructions (again – through SRP), and integrated functional testing is performed. At this point, satellites will start getting built up to flight spec and start going through the environmental test campaign.

Whereas previously Spire used external test houses to perform its environmental testing (thermal cycling, thermal vacuum, vibration, EMI etc.), more recently these test capabilities have been brought in house, dramatically reducing the time it takes to test a satellite and increasing schedule and build flexibility (e.g. Satellite in Spire EMI chamber in Figure 8). For example, per-satellite TVAC test times have been reduced by 50%, vibration test times by 75% and EMI/RF test times by 60% (while increasing test coverage by 25%). Fixed in-house test setups also allow for more custom and automated tests, which further reduces test time.

For a constellation operator, it’s paramount to have access to every opportunity for a groundstation contact, regardless of whether you end up using it or not. For us, having the flexibility to schedule (or not) a ground station to optimize our constellation contact time is important, and would be much harder if we only had limited windows of opportunity at certain stations, or if we had to schedule windows well in advance. As a side benefit, it also results in a lower cost given that we only need to guarantee compatibility with our own constellation.

Starting with a single groundstation site in San Francisco in 2012, our network has expanded to 30 sites across the world, with hardware deployed to all 7 continents (current and future coverage illustrated in Figure 10). The network consists of a combination of UHF and S-band groundstations (see Figure 9). Starting later in 2018, we will start adding X-band capabilities to the network, as we roll out those capabilities to the constellation.

GROUNDSTATIONS

Since its founding, Spire has also owned the groundstation element of the space data chain. To fully enable flexibility in acquiring data and operating the constellation, control of the groundstation network was necessary from day one.

In addition to increasing manufacturing speed, having test facilities in house has also enabled our engineering teams to do faster and more thorough root cause investigations, new feature qualifications, subsystem qualification etc.

In addition to the Spire-run groundstations, we also use surge-support ground stations from partner groundstation networks if needed for our data requirements.

**Figure 8: a LEMUR in Spire EMI chamber**

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**GROUNDSTATIONS**

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**Figure 9: Spire groundstation**

The groundstations operate in bent-pipe mode, which means that no data is ever left un-encrypted on a groundstation. The groundstations are deployed, maintained and monitored by our own field team. A similar iterative approach to groundstation design as utilized by the spacecraft team is used by the groundstations team.

In addition to the Spire-run groundstations, we also use surge-support ground stations from partner groundstation networks if needed for our data requirements.
Operating a large cubesat constellation comes with a few challenges:

- The iterative design approach yields a heterogeneous constellation, where every launched batch might at best have slight hardware differences and at most completely different payloads.
- As satellite software is often updated, various satellites will run different versions of software, even within a single launch batch.
- Each satellite usually develops its own “personality”, given the specific hardware it has on board.
- Operational priorities can shift based on customer demand.

Additionally, all of the above issues are also present for groundstations.

So to be able to operate efficiently a number of backend systems are required.

**Per-satellite configuration**

As indicated above, each satellite usually ends up having a unique personality, resulting in the need for a per-satellite configuration database. This database keeps track of things like satellite frequency configuration and licensing jurisdiction, status of subsystems, status of watchdogs, timestamps of the last time maintenance procedures were executed, software interface version, ADCS control mode, telemetry alerting limits etc. Whenever missions are scheduled and executed, the satellite configuration database is used to determine how to interact with a specific satellite and what software interfaces to use.

In addition, the database also contains groundstation characteristics, so the scheduler (see below) knows which satellites are compatible with which groundstations.

**Scheduling, automation and data management**

Managing a few satellites can be done by hand by a team of operators. Managing 20 satellites can be done with a little bit of scripting and simple automation. Managing more than 50 satellites requires a completely different level of automation. We can no longer think of the satellites as individual assets, but we have to consider the constellation as a whole. How do we best continuously (re)optimize our assets to provide maximum customer value?

Two major software systems support this. In space, satellites run a suite of automation software. This software knows for each task that the satellite has to perform the actions it has to take on-board to complete this task and present the resulting data over the next groundstation contract. On the ground, a central heuristics-based scheduler optimizes the schedule for satellite/groundstation contacts as well as for payload operation windows. As the schedule gets synchronized to the constellation, satellites capture the data they’re instructed to collect and downlink it as they pass over groundstations (either self-initiated or initiated by uplink commands). As time progresses, based on feedback from the constellation on how captures are being executed, the schedules can be adapted to optimize for customer value. If no major issues arise, no human interaction is required for this system to run and deliver data to our APIs.

After the data is downlinked, it’s pushed to a downstream processing or analytics system based on the data type, after which it’s made available in a customer facing APIs.

**Incident management**

Given the level of automation present, the main job of the satellite operations team is not to directly command or task the satellites, but rather to monitor the constellation for any anomalies that might occur, and manage those appropriately. To be able to do this effectively, an incident management system is required, that can link back to operational data, on-ground test results, and any other information that can help resolve the issues at hand. The satellite operations team can then feed this information back to the satellite engineering team as new satellite versions are being developed.
SPACE-AS-A-SERVICE

All of the capabilities explained in this paper have taken significant resources to build and have been iterated upon as Spire has grown. Deploying and running a commercial constellation in production has shown us that these are essential to provide optimal customer value. The systems have now reached a maturity level where we can leverage them to help other businesses be successful. Companies that are being founded today find themselves in a completely different market and ecosystem than they would have in 2012 when Spire started, with more satellite hardware and software, groundstation, and operations software providers present than ever before. Investors and other stakeholders in these companies are less interested in building up the complete technology stack from scratch but rather urge these new companies to use existing capabilities as much as possible. Therefore, Spire is now offering its services as designer, integrator and operator to businesses that want to get their payloads in space, and just want to get the data back on the other end, without the investments and complexities associated with operating all of the necessary systems and processes.

CONCLUSION

Mastering space technology is hard but turning this technology into a commercially viable production system is equally tough and the amount of effort involved is usually underestimated. This paper discusses how Spire has approached some of these lesser-known aspects, what we have learned, and now that these systems are maturing, how we can help other businesses achieve success using the capabilities and value chain we’ve developed.