Smallsat Manufacturing, The Spire “Constant NPI” Model

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Spire Today

- **Nanosatellite constellation based data and data analytics provider**
- 170+ people across six offices (San Francisco, Boulder, DC, Glasgow, Luxembourg, and Singapore)
- ~80 LEO 3U CubeSats (10x10x30 cm) in orbit with passive sensing payloads, >100 launched, 30+ global ground stations
- Complete global coverage, observing each point on Earth 100s times per day, every day
- Deploying new applications within 6-12 month timeframes
- World’s largest ship tracking constellation
- World’s largest weather/space weather data constellation
- Commercial global weather forecasting engine
- $130M+ raised with top institutional investors, including
  - Bessemer Venture Partners, RRE Ventures, Qualcomm Ventures, Airbus, Luxembourg Future Fund, Seraphim Capital
Satellite capabilities

● Advanced 3U Cubesat bus
● >95% Spire internal IP
● Multi-functional spacecraft
  ○ AIS
  ○ ADS-B
  ○ GNSS-RO
  ○ Other (hosted payload, experimental payloads etc.)
● Key payload capabilities:
  ○ 0.1 - 10 GHz
  ○ Software-Defined Radios
  ○ OTA upgradable
  ○ Low-Noise, High EMC integrity
Manufacturing problem statement

The goal
- Launch ever 6 weeks
- Build spacecraft at “volume”
- Reliably and deterministically
- Quickly
- Affordably
- Never miss a launch
- Always build the latest and greatest design

The challenges
- Highly variable launch schedule, across half a dozen of vehicles
- “High” volume in spacecraft = Low volume for the rest of the world
- Continuous hardware improvement makes automation and standardization hard
Manufacturing model

We experimented with a number of models ...

- Outsourcing model
  - Find external partners that handle AIT
  - External partners never as invested in success as your own team
  - No proven track record
  - Couldn’t keep up with speed and volume of changes
  - Restrictive need for extensive documentation that would change all the time
  - Costly

- Didn’t work well, moved to building with our own team
Manufacturing model

We experimented with a number of models ...

- Build-to-order (=Build-to-launch)
  - Launch pipeline informs build schedule
  - Launches moving throw a wrench in build schedule
  - Overstock of old designs while new hardware already available
  - Satellite can’t be easily moved around between launches
  - Frequent rebuild and re-testing (e.g. vibe) cause quality issues
We experimented with a number of models ...

- **Build-to-stock**
  - Adapt an internal specification enveloping all launch vehicle requirements
  - Effective when satellites are on the shelf less than a few months
  - Same risk as build-to-launch that we accumulate outdated hardware
  - Ended up delaying build start dates closer and closer to launch dates
Manufacturing model

We experimented with a number of models ... 

- **Build-to-prediction**
  - Developed a Monte-Carlo model of launch pipeline, to determine build schedule and procurement needs
  - Launch schedule was still too unpredictable
  - Ended up over-ordering and having too much stock, OR having to scramble and build faster than anticipated

![Graph A](image1.png)

![Graph B](image2.png)
Result - “Constant NPI” model

Hybrid Model

- Manufacturing batches *loosely* associated with launch schedule
- Envelope launch vehicle requirements in qualification/acceptance process
- Short-lived safety stock
- Design focused on allowing late changes without intrusive rework
- Vertical integration enables speed and control

Results

- Cycle time reduction
- Cost reduction
- Increase in yield, quality and test coverage
- Perfect track record of on-time delivery to our launch partners

<table>
<thead>
<tr>
<th>Jan 2016 - May 2019 change</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOM Cost</td>
</tr>
<tr>
<td>Conversion Cost</td>
</tr>
<tr>
<td>Cycle Time</td>
</tr>
</tbody>
</table>
Spire’s ownership of design through delivery coupled with select external partnerships for satellite launch enables speed, reliability and control.
Iterative engineering processes

**Production**
- Automation is key to producing at Spire scale
- “Follow-the-Sun” schedule ensures global coverage in case issues arise

**Innovation**
- Satellites are a limited resource; each iteration solves a customer need
- Innovations are evaluated with a customer focus, and driven by business need

**Checkout & Commissioning**
- Post-launch deployment sequence deploys antennas and solar arrays while initiating a self-health assessment
- Satellite Ops team prepares the satellite for production, uploading the latest software and conducting data quality evaluation

**Design**
- Innovations are then rigorously stress-tested
- Power / thermal / data requirements are assessed to gauge demand on systems

**Manufacturing**
- Every satellite goes through an automated, fully traceable manufacturing process
- Each step is documented so as to “de-skill” as much as possible the process, leaving no room for error

**Systems Engineering**
- We deconstruct systems until we reach the individual task level, breaking each idea into distinct project plans
- Company-wide engineering visibility ensures design is coherent with project timeline and customer requirements
Satellite production cadence

Spire’s fully-integrated Glasgow facilities boast installed capacity for one satellite/week and proven 2-day burst capacity

Average satellite build time (days)

- **One-week manufacturing cycle**
  - 2015: 8 days
  - 2016: 8.4 days
  - 2017: 7.5 days
  - 2018: 5.6 days

- **“Burst” capacity**
  - 2018: 2.0 days

“Burst” capacity is our fastest demonstrated manufacturing cycle at current facility size.
Scale = higher quality, lower cost

Reducing costs per satellite is a core component of our business model.

Component costs per satellite (% vs. first version)

<table>
<thead>
<tr>
<th>Version</th>
<th>Component Cost %</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEMUR2 1.0–1.1</td>
<td>100%</td>
</tr>
<tr>
<td>LEMUR2 2.1</td>
<td>75.5%</td>
</tr>
<tr>
<td>LEMUR2 2.2</td>
<td>75%</td>
</tr>
<tr>
<td>LEMUR2 2.3–2.6</td>
<td>73%</td>
</tr>
<tr>
<td>LEMUR2 2.8</td>
<td>72%</td>
</tr>
<tr>
<td>LEMUR2 3.0</td>
<td>71%</td>
</tr>
<tr>
<td>LEMUR2 3.1–3.2</td>
<td>59%</td>
</tr>
<tr>
<td>LEMUR2 3.3</td>
<td>46%</td>
</tr>
</tbody>
</table>
Extensive test-driven development

Spire performs all testing in-house, accelerating our manufacturing cycle, maintaining quality control, and reducing costs
Vertically integrated facilities

Glasgow facility possesses all required testing equipment, expediting component evaluation and eliminating time loss.

- Assembly
- Integrated Test
- Thermal Chamber
- Vibration Testing
- Thermal Vacuum
- Environmental Stress
- Final Functional Test
- RF Chamber
- Sun Simulator

Satellite Build & Functional Test
Driven by automated testing

Design for Manufacturability (DFM) and Test Automation decreases minimum required skill level of team

- Laser focus on automated engineering solutions apparent in build and test staff
- 2x testing/satellite from 2017-2018 with flat yield rate at around 94%

Staff involved in manufacturing

<table>
<thead>
<tr>
<th>Year</th>
<th>Apprentice</th>
<th>Technician</th>
<th>Engineer</th>
<th>Senior Engineer</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>23</td>
</tr>
<tr>
<td>2016</td>
<td>27</td>
<td>15</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>2017</td>
<td>33</td>
<td>16</td>
<td>13</td>
<td>21</td>
</tr>
<tr>
<td>2018</td>
<td>36</td>
<td>17</td>
<td>12</td>
<td>15</td>
</tr>
</tbody>
</table>

# of tests performed per satellite

- 2015: 500 tests
- 2016: 1000 tests
- 2017: 1500 tests
- 2018: 2000 tests
Built on traceability and quality control

Testing processes are comprehensively tracked to minimize manufacturing risks and quickly identify defaults

### Spire Resource Planning (SRP) - Tasks

<table>
<thead>
<tr>
<th>Step</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Subsystem Thermal Cycle v1</td>
</tr>
<tr>
<td>2</td>
<td>Incoming Inspection v1</td>
</tr>
<tr>
<td>3</td>
<td>WI-021 LEMPDU v2</td>
</tr>
<tr>
<td>4</td>
<td>Conformal Coating v1</td>
</tr>
<tr>
<td>5</td>
<td>Conformal Coating Inspection v1</td>
</tr>
<tr>
<td>6</td>
<td>WI-021 LEMPDU v2</td>
</tr>
<tr>
<td>7</td>
<td>FTDi Programming v3</td>
</tr>
<tr>
<td>8</td>
<td>LEMPDU Board Registration and Flash v1</td>
</tr>
<tr>
<td>9</td>
<td>Power Switch &amp; Voltage Test v3</td>
</tr>
<tr>
<td>10</td>
<td>Entire State Machine Test v2</td>
</tr>
<tr>
<td>11</td>
<td>Power Bus Overcurrent Protection test v2</td>
</tr>
</tbody>
</table>

- **Part Testing**
  - 12+ hours baking process at +50 Celsius
  - All our PCBs are inspected to IPC-A-610 Class 2 and anyone inspecting PCB is required to be IPC-A-610 certified. Recertification occurs every 2 years.
  - Conformal Coating is a spray that forms in the state of a thin plastic coating. This coating not only prevents damage but it may also prevent foreign objects moving and shorting the circuitry.

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<thead>
<tr>
<th>Step</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Work Order 10658 for 4 LEMUR2</td>
</tr>
<tr>
<td>2</td>
<td>Created by Daniel Bryce on 05 Sep 2018</td>
</tr>
</tbody>
</table>

- **Satellite Build**
  - A Work Order is created for each satellite batch, with an SRP entry for each of the satellites to be created.
  - Each of the satellites undergoes the testing process (> 100 items) individually before being sent to the launch platform.
Enabling experimentation and variants
Shoutout to the team!
Thank you!
Thank you!

Questions?

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