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Commissioning the World's Largest Satellite Constellation

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ABSTRACT

Planet's Flock 3p is a constellation of 88 Dove Earth observation nanosatellites launched on a single Indian Polar Satellite Launch Vehicle (PSLV). Commissioning this fleet of satellites is a unique and challenging task that requires significant planning, automation, and operations. At Planet, a small team of operators is charged with shepherding the flock of satellites from initial deployment through full sensor and radiometric calibration.

This paper will discuss the challenges, innovations, and results of Flock 3p commissioning with a focus on on-orbit results, lessons learned, and implementation of an agile aerospace approach to the operation of large constellations.

BACKGROUND

Founded in 2010 by a team of ex-NASA scientists, Planet is driven by a mission to image the entire Earth every day, and make global change visible, accessible, and actionable. Over the past four years, Planet has launched and operated over 200 "Dove" Earth imaging satellites.

On February 14, 2017, as part of the ISRO PSLV-C37 mission, Planet launched 88 satellites onboard a single rocket. After a successful launch and deployment, the Mission Operations team was tasked with commissioning this new flock with a short three month turnaround.

Much like Planet's iterative and agile approach to designing spacecraft hardware, the commissioning process has grown over time based on experience with previous Dove flocks. The team was able to complete on-orbit calibration, checkouts, and upgrades in the allotted timeframe by embracing automation and a culture of moving forward in concert with anomalies and unknowns.

AGILE AEROSPACE

How Planet Builds and Tests

The Dove satellite is a highly capable Earth imaging platform in a 3U form factor, which is developed and manufactured in-house in San Francisco. Planet pioneered agile aerospace methodology, which has at its core a rapid, capabilities-focused, test-driven design lifecycle that is coupled with a low-cost design and aggressive launch procurement strategy. In contrast to traditional aerospace approaches, this allows Planet to leverage R&D investments of consumer electronics by flying the latest commercial off-the-shelf (COTS) components, as well as to quickly recover and learn from failures. Each new build of Dove satellites contains improvements learned from operational experience of the previous build as well as a suite of untested "tech demo" technologies that have the potential to improve future builds. Even Flock 3p, intended to fulfill Planet's goal of global Earth coverage every day, contained a set of tech demos for higher gain radio antennas, better battery charge estimation, enhanced thermal control of the optics, and higher efficiency solar arrays.

For each launch, Planet builds a "flock" of Doves with a mix of proven technologies from previous launches and higher risk candidate technologies for future builds. In addition, a subset of the flock is allocated for these experimental technologies as well as to provide redundancy for the expected rate of on-orbit failure.

The speed at which commissioning occurs is critical both for the business and for informing future builds. Being able to get on-orbit test results from new technologies before the next launch is often a challenge, but it is also a critical part of the way Planet iterates and improves on the capabilities of the Dove flocks of satellites.

Planet also takes an agile approach to software and firmware development. The software teams rely heavily on modern techniques like continuous integration (CI), continuous deployment (CD), and automated integration tests. New ground and control software are released to production several times per week. Onboard firmware and software updates happen several times per month. On-orbit Doves that have been designated as "staging" satellites serve as an on-orbit testbed for tests that would be more expensive to do on the ground, for example, validating attitude control algorithms.

How Planet Launches

Planet's ideal imaging orbit is morning sun-synchronous (like most other remote sensing missions). However, Planet's strategy is to aggressively procure regular launches even if they are not to an ideal orbit. Variability in orbits, such as in power and thermal budgets, is managed through operations and extensive software automation. For this reason, Planet has historically utilized commercial launch services through Nanoracks to provide convenient access to space through the International Space Station (ISS). Flocks are launched as cargo to the ISS and deployed through the JEM Small Satellite Orbital Deployer (J-SSOD) in groups of two. Because the Dove satellites do not have active propulsion, these satellites have an orbit very similar to that of the ISS.

Planet has also done several direct launches with Doves as a secondary payload to sun-synchronous orbits, which provide the benefit of a consistent sun angle.

Table 1: ISS vs SSO Orbits

	ISS Orbit	SSO Orbit
Sun Angle	Varies over time	Consistent based on LTAN/LTDN Can drift over several years
Thermal Environment	Solar beta angle maxima require special handling	Minor variation over the year
Orbital Altitude	390km - 450km at deployment	About 500km
Inclination	52 degrees	~98 degrees
Orbit Lifetime	12-18 months (depending on solar activity and drag profile)	4-5 years
Coverage	Missing northern Canada and Russia, Antarctica, southern tip of South America	Full Earth with some seasonal polar gaps

Planet strives for diversity in its launch manifest for a number of reasons. Vehicle family diversity is important because launch failures will usually delay the manifest of that vehicle family by a year or more while an accident investigation is underway. Geopolitical diversity has also proven to be very important to accommodate unpredictable changes in regulations and the global political environment. The table below shows Planet's full historical launch manifest, including RapidEye and SkySat launches.

The number of Doves manifested on each launch depends heavily on the situation and capacity available, but in general Planet has the goal of maintaining the on-orbit capacity necessary to collect all of the Earth's land mass every day.

Table 2: Historical Planet Launches

Name	Launch Vehicle	Launch Date	Orbit	# of Sats	Status
RapidEye	Dnepr	8/29/08	SSO	5	Operational
Dove 2	Soyuz 2.1b	4/19/13	Other	1	Retired
Dove 1	Antares	4/21/13	Other	1	Reentered
Dove 3	Dnepr	11/21/13	SSO	1	Retired
Dove 4	Dnepr	11/21/13	SSO	1	Failed Deployment
SkySat 1	Dnepr	11/21/13	SSO	1	Operational
Flock 1	Antares	1/9/14	ISS	28	Reentered
Flock 1c	Dnepr	6/19/14	SSO	11	Retired
SkySat 2	Soyuz 2.1b	7/8/14	SSO	1	Operational
Flock 1b	Antares	7/13/14	ISS	28	Reentered
Flock 1d	Antares	10/28/14	ISS	26	Failed Launch
Flock 1d'	Falcon 9	1/10/15	ISS	2	Reentered
Flock 1e	Falcon 9	4/13/15	ISS	14	Reentered
Flock 1f	Falcon 9	6/28/15	ISS	8	Failed Launch
Flock 2b	H-IIB	8/19/15	ISS	14	Reentered
Flock 2e	Atlas V	12/6/15	ISS	12	Operational
Flock 2e'	Atlas V	3/23/16	ISS	20	Operational
Flock 2p	PSLV	6/22/16	SSO	12	Operational
SkySat 3	PSLV	6/22/16	SSO	1	Operational
Skysat 5-7	Vega	9/16/16	SSO	4	Operational
Flock 3p	PSLV	2/15/17	SSO	88	Operational

How Planet Operates

From the beginning, Dove Satellite Operations at Planet have strived for no real-time or 24/7 operations. Fundamentally, the satellites have a simple ConOps: when over land, point nadir and image. When a downlink session is scheduled, the Dove turns on the X-band transmitter and tracks the ground station as it passes under the satellite [1]. Whenever the satellites are not doing the above, they charge their batteries in a commanded background drag profile optimized for spacing out the constellation over time [2].

Planet's Mission Operations team heavily focuses on automation to manage nominal operations of the fleet of satellites. Rather than building manual/human processes and then trying to replace them with automation, Planet builds automation first and then iteratively improves it. The space and ground segments are managed through a homebuilt, scalable, microservices-based "Mission Control" interface that scales to hundreds of satellites and a large network of geographically diverse antenna sites. This interface is used for nominal operations, debugging operations, custom activities, commissioning, and experiments. Software upgrades are reviewed on a weekly basis and after verification on the ground, are tested in space on "staging sats" before deploying to the entire fleet. This agile approach is possible due to tightly coupled software, hardware, and operations teams.

COMMISSIONING SCOPE

The scope of Dove commissioning has grown over the years with the maturity of the Dove and the resulting image products. The operations team has taken an agile, iterative approach and has built upon lessons learned from previous flocks.

The goal of commissioning is to take a flock of Doves from the deployment state to the nominal imaging state where the satellites are regularly providing calibrated imagery within product specifications as part of the automated operations and planning system. This includes:

1. Making first contact and performing basic health checks
2. Providing ephemeris information from active ranging data for initial orbit determination
3. Detumbling using the attitude determination and control system (ADCS) and deploying solar arrays
4. Performing on-orbit subsystem calibration
5. Software updates

COMMISSIONING HISTORY

Dove 1 and 2

Dove 1 and Dove 2 were early technology demonstrators with a 3U form factor. Both were launched in April 2013 for short duration missions that required operators to actively monitor and send commands during each ground station pass.

Dove 3

Dove 3 was a technology demonstrator launched in November 2013. Commissioning activities were limited to solar panel deployment and attitude determination control system (ADCS) checkouts. These steps were completed manually by a team of operators, but with the assistance of some basic automation scripts.

Flock 1

Flock 1 consisted of 28 Dove satellites. These satellites were deployed from the International Space Station in February of 2014. One of the goals of Flock 1 was to develop a system for automated operations and commissioning. The team of operators for this flock was small (1-2 people without overnight or weekend support). Flock 1 commissioning consisted of several steps as outlined in Table 3.

Table 3: Flock 1 Commissioning Steps

Task	Description
First Contact	Make contact and retrieve a set of health data
Disable Flap Burn	The antenna flap was programmed to deploy autonomously on a repeating timer. This step disabled the deploy circuit once contact had been made.
Detumble	Enable ADCS and reduce tumble rates using the magnetorquers.
ADCS Checkout	Validate the reaction wheel performance by commanding a sun point of the solar arrays.
Deploy Solar Panels	Point the spacecraft at the sun and deploy the solar arrays. For Flock 1 this was only executed in sunlight with ground station coverage.
Firmware Updates	Update the radio and microcontroller firmware using the satellite communication channels.
CPU Checkout	Boot the onboard computer and test communication with it.

Software Upgrades	Upload and install new software on the onboard computer (CPU).

Flock 1c

Flock 1c was a flock of 11 Doves that were launched on a Dnepr rocket into a sun synchronous orbit in June of 2014. For Flock 1c, additional steps were added to the commissioning scope as shown in Table 4.

Table 4: Additional Commissioning Steps

Task	Description
ADCS Magnetometer Calibration	For Flock 1, the onboard magnetometers were calibrated on the ground before launch. This put a large burden on the manufacturing team and was moved to an on-orbit activity for Flock 1b and 1c.
ADCS Sun Sensor Calibration	This was done manually on Flock 1c as the ADCS team refined their control algorithms for fine pointing accuracy.

Several activities that were performed for Flock 1 were found to provide low value and were dropped in Flock 1c commissioning. For example, the CPU checkout was deemed unnecessary and dropped from the sequence.

Flock 1b, 1d, 1e, 2b, 2e

Flock 1b was launched as cargo to the International Space Station and originally was intended to deploy before Flock 1c's launch. Due to a variety of delays, this flock was deployed in two groups, one year apart. Flock 1d, 1d', 1e, 2b, and 2e were also launched and deployed through the International Space Station.

As the customer facing product developed and the team gained experience with nominal operations of the Dove constellation, the scope of commissioning grew to include several steps which are outlined in Table 5.

Table 5: Expanded Commissioning Scope

Task	Description
Scheduled Panel Deploys	Solar panel deployments were scheduled from the ground and validated using telemetry on a subsequent pass instead of watching them in real-time.
Thermal Control	Enable battery heaters and active thermal control for other subsystems
ADCS Calibration Maneuver 1	A sequence of maneuvers that collect data for the sun sensors and magnetometers as well as a set of ground software to perform the calibration autonomously.
ADCS Calibration Maneuver 2	Calibration of the star camera (a hardware addition in later builds) and its alignment with the main camera.
Dark Fields	Dark field images taken at night over the ocean to calibrate the camera sensor.
Moonshots	Images of the moon used for relative radiometric calibration.

Flock 2p

Flock 2p was the first sun-synchronous launch for Planet since Flock 1c. The Doves of Flock 2p were intended to validate the on-orbit performance of the design for Flock 3p. This flock was shipped with a pre-release version of the onboard commissioning software used to perform initial checkouts without ground interaction.

Table 6 lists the last 5 flocks that were commissioned prior to Flock 3p and how long it took on average to downlink the first images taken in-orbit from the satellite, this is also referred to as first light. Although Flock 2e/2e' commissioned faster than Flock 2p, Flock 2e/2e' put significantly less stress on the operations team and ground network due to their deployment schedule and more limited commissioning scope. These 32 satellites were deployed from the ISS over three separate events, each one a month apart. In addition, the satellites came out two at a time, separated by a minimum of 3 hours, resulting in better pass allocation and more manageable workloads for manual processes like the attitude determination and control system (ADCS) calibrations. On Flock 2p, although there were fewer satellites overall, there was much more added complexity due to their initial clustering. This was also the first time Planet tested the onboard commissioning software on newly deployed satellites.

Table 6: Commissioning Completion Time

Flock	Orbit	# of Satellites	# of days until first light
1b, 1d'	**ISS**	**12**	**77**
1e	**ISS**	**14**	**28**
2b	**ISS**	**12**	**21**
2e, 2e'	**ISS**	**32**	**12**
2p	**SSO**	**12**	**18**

CHALLENGES

Ground Station and Pass Limitations

Early availability and coverage analysis resulted in a requirement for additional ground station sites to support the 88 new Doves. Even with the added antenna capacity, the competition between satellites for ground station access during early orbit phasing limited the ability to schedule onboard activities. Before the initial testing on Flock 2p, all stages of commissioning required ground commanding prior to moving onto the next stage. This reliance on ground passes was most apparent during Flock 2e and 2e' when 16 satellites were deployed over the course of 3 days. The high demand in the first two weeks for communication passes stressed system capacity, limited health packet reception frequency and the ability to command the satellites to the next stage in commissioning. This decreased the effectiveness of operating the fleet at nominal cadence.

Operator-to-Spacecraft Ratio

The team of satellite operators at Planet are responsible for commissioning new satellites, detecting and responding to on-orbit issues, maintaining the health of the production fleet, running on-orbit experiments, rolling out software and firmware upgrades, increasing operational efficiency by developing better alerting tools, automation scripts, and improved process, and collaborating with other teams for future operational and design improvements. This is done with a core team of three satellite operators in San Francisco, and more recently, with the addition of a team in Berlin who are also responsible for RapidEye operations.

From the beginning, Mission Operations at Planet has developed under the expectation that hundreds of satellites will be operational at any given time. Because of this, many of the tools used are already designed for batch updates and fleet wide tracking. However, a unique set of tasks are always needed for commissioning satellites in addition to the unknown problems that may accompany new hardware. As the number of satellites scale up, so do the problems. In order to manage this, the level of Dove operations conducted by the Berlin team was increased and the daily check-in process was streamlined for monitoring and detecting new issues.

On-Orbit Calibration Maneuvers

Historically during commissioning, the bottleneck due to both lack of ground accesses and operator time has been during ADCS calibration. Previously, operators would wait until the necessary software upgrades were onboard before scheduling calibration maneuvers. Operators would then need to check to make sure that the maneuvers were scheduled onboard ahead of their execution time, and that there were sufficient passes after the maneuver to get the calibration data down. If the data failed any of the ADCS calibration integrity criteria, it would have to be rescheduled and checked on again. This process was very manual and would have been nearly impossible to manage with the current operator-to-spacecraft ratio.

INNOVATIONS

Onboard Commissioning

For Flocks 1a through 2p, bus commissioning was automated using ground-based software. This required a ground station contact between each step in the commissioning process. Because of competition for ground station access on Flock 3p and the lag time between passes for an individual satellite (often 2-3 days), this approach was not considered scalable.

An onboard software package was developed to run on the satellite's CPU that could execute bus commissioning with minimal ground interaction. This software included fault protection to detect anomalies with the power system, ADCS, and deployment mechanisms and hand control back to the operations team.

The number of ground contacts was reduced to two: one to initiate bus commissioning and one to check the result. The first pass is used to upload the satellite's orbital parameters (TLE) and synchronize the satellite's clock which may have drifted by several minutes while in storage.

The Dove's primary payload and ADCS computer is an x86 CPU running Ubuntu Linux. This allows the team to take advantage of mature open-source projects where custom development would be prohibitive. For example, the ADCS team uses the IGRF 2010 and 2015 [3] models to fit on-orbit data to the predictive model. The team was able to quickly port this routine to use the SciPy and numpy Python libraries [4], allowing it to run onboard the spacecraft. Because the spacecraft uses common software infrastructure with the ground station, the team was able to reuse ground software libraries directly on the satellite CPU.

When a fault was detected by the onboard commissioning software, the software would abort and leave the satellite in a safe state.

Several potential fault triggers were covered by the onboard commissioning software:

- Spin up
- Batteries low
- Batteries imbalanced
- Invalid software configuration

Ground Software Bundles

The command and control software, known internally as the "Ops Scripts" are deployed to the ground network as a Debian package bundle. A change to the Ops Scripts generally affects all satellites on-orbit, however a capability was developed to allow deployment of different versions of Ops Scripts to run on a per-satellite basis. For Flock 3p commissioning, this allowed the team to branch off a stable, tested version of the Ops Scripts that would run on Flock 3p.

Changes to the Ops Scripts for other satellites were made on the master branch and could be deployed independently at a normal cadence (typically one or more times per week). Quick fixes and changes to the commissioning scripts could also be deployed without affecting previous flocks and potentially interrupting the imagery pipeline. As changes became infrequent later in the process, the ops team decided to merge the Flock 3p branch back into master and reunite all Flocks under the same ground software package.

Megahealth

The operations and spacecraft design teams agreed that obtaining a basic set of health telemetry from each satellite should be done at least every 24 hours. This was intended to provide adequate lead time to respond to anomalies as well as track the health and performance of the flock early on, before high volume recorded telemetry was available.

Shortly after launch, the Doves were still densely bunched within the beam width of a single UHF ground station, meaning simultaneous UHF passes would result in unacceptable RF interference. A tool called "Megahealth" was developed that would round-robin through all satellites in view to collect health telemetry. As a result, the team was able to meet a requirement to gather health data for each satellite at least once per 24 hours in almost all cases. This had the benefit of not requiring any manual effort on behalf of the operations team to ensure background health data across the full fleet.

The Megahealth task was able to contact 71 satellites on the first available ground station pass about 30 minutes after launch. By the end of the second ground station pass, all 88 satellites were contacted and accounted for.

Later in the commissioning process the Orbit Determination team requested that short burst of ranging pings be added to the Megahealth task to augment dedicated ranging passes. Because Flock 3p was using a separate ground software bundle, this change was rolled out quickly and provided valuable data for orbit fitting.

Sequencer

In order to address the need to automate ADCS commissioning, a service developed by members of the ADCS and Missions Software team was created called "Sequencer". The main objective of Sequencer was to reduce operator workload through automation of data processing and calibration scripts. It minimized the overall time required for calibration by automating the scheduling of calibration activities.

Previously, ADCS calibration involved either a SatOps or ADCS operator to "hand-hold" the process for multiple steps. These steps included waiting for a specific onboard state before requesting the maneuver to be scheduled, then checking the status of the onboard schedule and re-requesting if necessary, checking if the maneuver was successful, verifying logs came down from the maneuver, and then following up on any failed calibration calculations. Sequencer automated the process to only require human intervention if the calibration fails at the very last step due to an unknown reason. This is done by tracking the satellite's process through a configuration key that is updated at various stages. Every two hours, Sequencer runs as part of an automated task and checks the last known state of that satellite. Depending on a pre-programmed set of criteria, Sequencer will either go back to the previous state and reattempt or move on to the next state.

Process

Many approaches to commissioning 88 satellites were considered, including commissioning serially (one Dove at a time), all 88 in parallel, or a hybrid. Trade studies were done to consider where the limitations were and which approaches mitigated those the best. In the end, the team decided to first commission three satellites end-to-end, then kick off the remaining satellites in groups every week.

Canaries

Three Doves were identified ahead of time to be the "Canaries" of the flock. While the remaining 85 satellites tumbled in the background, the canaries would go through the entire commissioning process to identify any unexpected bugs or hotfixes that needed to be made. This not only helped manage the workload, but it also gave operators a chance to validated all of the commissioning process and Sequencer software. This end-to-end verification included onboard commissioning (including detumble and panel deployment), completion of CPU upgrades, automated scheduling of C1 maneuver, download of logs, calibration and posting of C1 parameters, automated scheduling of C2 maneuver, download of logs, calibration, and posting of C2 parameters to the configuration management service, and enabling of imaging on the satellites.

Batches

From the various trade studies that were done in preparation for F3P Commissioning, it was determined that the limiting factor for the rate of commissioning is the availability of non-overlapping imaging swaths and non-conflicting ground station passes as the Doves spread out. This inherent rate limiter, along with a desire to manage operator workload, led to the strategy of releasing Doves into the commissioning flow in batches of 10 per week. The satellites in each batch were determined by choosing the maximum spacing between the satellites in each grouping, to maximize non-conflicting pass opportunities.

Handling Anomalies

Planet's approach allows for a certain fraction of launched satellites to be in an anomalous state, and strategies were developed to manage this in real time. "Off-nominal commissioning" refers to situations where satellites are deployed with a condition that affects calibration workflow and therefore impacts their timeline to imaging and downlinking. A framework is suggested below to allow quick decision-making when these situations are encountered.

Specifically, an "off-nominal" satellite is one that:

- Cannot complete commissioning through the automated workflow without special handling; AND
- Has an issue that only affects the individual satellite; AND
- Solving the issue would take more than one hour of engineering effort.

These cases are expected to be rare, and typically to be related to hardware. In past deployments, off-nominal satellites were commissioned with the same priority as nominal satellites and issues were handled in the order they were encountered. However, this was only possible because of relatively small flocks and would have been difficult to maintain with Flock 3p. Progress would be throttled not only due to operator/engineering availability, but also ground station access limitations.

In order to create balanced workloads and priorities, the framework for triaging issues is given below.

For F3P, the plan for an "off-nominal" satellite was to:

1. Lower the satellite's priority in the scheduling system, and label as "off-nominal"
2. Expect that the satellite will not complete commissioning at the monthly cadence expected and communicate accordingly
3. Triage the priority of the satellite with the subsystem team based on effort expected to get the satellite to normal operations.

Satellites that met these criteria were removed from the nominal queue and triaged based on the time it would take to return them to imaging operations, rather than in the order in which they are encountered. This allows the setting of expectations about which satellites will be debugged first. For example, a satellite that is suffering from star camera issues, which is used for high accuracy imaging and downlink, will take priority over a satellite that has malfunctioning coarse sun-sensing photodiodes, which only affects non-imaging activities such as differential drag operations.

RESULTS

First Contact

Planet has a 100% record of contacting satellites that have been successfully deployed on-orbit. Flock 3p was no different, and health packets were received from all 88 satellites within the first two orbits after launch using the previously described Megahealth tool. This was the largest and quickest initial contact ever made with Dove satellites following deployment.

Canaries and Batching

The purpose of the three canaries was to test the entire automated commissioning process first in order to focus on in-orbit or process anomalies. This decision proved to be very valuable as it caught a lot of small bugs or optimizations that could have affected the rest of the flock, which would have increased the workload on the small number of satellite operators. Examples of issues that were caught and fixed with the canaries include:

- Missing X-band radio and payload settings on the ground side
- Failed calibrations due to missing files or logs

- False positives reporting successful coarse sensor calibration
- Tweaks to the scripts that run during commissioning to increase the number of background health and ranging obtained from the non-commissioning satellites
- Fixes to alerting and messaging to operators for commissioning state changes and tracking

Once these issues were addressed and the canaries had completed commissioning, the first batch of 10 was kicked off for commissioning. Between the third and fourth batch, operators were advised by the Electrical Engineering team to accelerate panel deployment on all remaining satellites due to an issue discovered in the power system. The team believed that deploying the solar panels would help guard against this issue. With this recommendation, the next batch was delayed while all remaining satellites were kicked off to complete the onboard commissioning portion. Once all satellites were operating with their panels deployed, the batching for the remainder of the commissioning process resumed.

Power Issues

The Dove satellites in Flock 2k and Flock 3p both contained a change that removed a solar panel. Power analysis indicated that under most conditions, this change would have a negligible impact on power margin. However, at high spin rates and under certain illumination conditions the Dove could actually be slightly power negative in its deployment state.

Several Flock 3p satellites were deployed in this unfavorable configuration and started to trigger alerts for low battery state-of-charge. Battery capacity on the Dove is fairly large (designed for lifetime and high-power operations). This allowed the team 2-3 days to react before the battery charge would reach a critical level.

The team responded by enabling the onboard commissioning sequence early for satellites that showed a declining state-of-charge on the batteries. This would trigger a detumble that would pull the satellite out of its unfavorable sun condition and deploy the solar panels to recharge. The onboard commissioning software was designed with the assumption that tumbling was power positive. The team therefore had to override several health check parameters in the software designed to assure that the battery state-of-charge was high enough to continue. The onboard commissioning software was designed with configurable safety and duration parameters which made implementing the overrides straightforward.

Several more satellites eventually drifted into a power-negative spin configuration during the commissioning process. The team created a process whereby the on-call team member could check an alarm page and take definitive action if any satellite reported a low state-of-charge. This allowed sufficient time margin for the team to react without requiring 24-hour on-call support from the operations team.

Onboard Commissioning Software

Autonomous bus commissioning was attempted using the onboard software for 86 out of the 88 Flock 3p satellites. One of the primary goals of onboard commissioning software was to reduce the need for operator intervention. While a majority of Flock 3p satellites completed this sequence without any operator overhead, there were several instances that required an operator to restart the software, sometimes with new parameters.

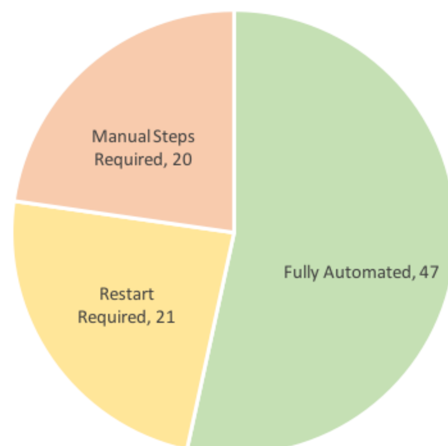

Figure 1: Onboard Commissioning Automation Success

The top reasons for requiring a manual restart or operator intervention were:

1. USB communication issues that were fixed in a later software release. This could cause the commissioning software to abort early when it had trouble communicating with onboard sensors.

2. Intermittent sensor issues due to known vulnerabilities in the software version shipped with Flock 3p.

3. Corrupt or old ACS recorded telemetry – a large portion of Flock 3p inadvertently shipped with some sensor logs from the ground. This caused onboard calibration to fail on the first attempt but was easy to work around by clearing the logs and retrying.

4. Power system anomaly response – several satellites had their health and safety limits adjusted to allow onboard commissioning to run as an anomaly response to a low battery condition.

In addition about 20 satellites required manual steps to complete the bus commissioning process. The top reasons for aborting or skipping the onboard commissioning software were:

1. USB software issues that were more persistent on certain Doves in Flock 3p due to their hardware configuration. These satellites completed commissioning successfully but required manual confirmation.

2. "Tech Demo" satellites that had limited or partial software support for new hardware. Running onboard commissioning on these satellites was considered "best-effort".

3. Hardware issues that needed workarounds.

While several satellites did require manual steps to proceed past bus commissioning, operator interaction was reduced by at least a factor of four over previous flocks.

Commissioning Rate

Flock 3p complements the Flock 2p satellites to complete what Planet calls the "Mission 1" constellation promising of daily revisits of anywhere on the planet. Efforts were made to align sales strategy and customer expectations with the actual ramp of capacity. The main objective was to have a substantial capacity online before the start of the growing season. Success for commissioning was defined as meeting or exceeding a minimum required commissioning rate of 5 satellites added to product imagery per week. In Figure 2, the blue line indicates that minimum requirement and the red line indicates the number of satellites that had begun commissioning at that moment. The green line is the actual number of satellites that were producing customer-quality imagery each week. Except for a slight deviation during the second half of March 2017 due to delaying batch 4 for power mitigations, yield expectations were exceeded.

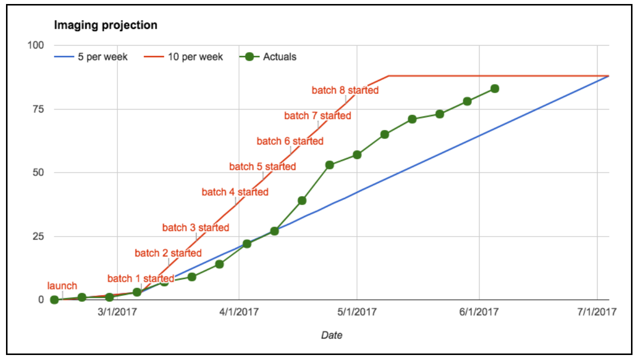

Figure 2: Flock 3p Theoretical and Actual Commissioning Rates

Sequencer: The Real MVP

The commissioning of Flock 3p was the first time a fully automated calibration process was deployed, allowing an average calibration rate of approximately one satellite per day.

The main objective of the Sequencer was to decrease the number of operator hours required to do ADCS calibration. The following tables and pie charts show the proportion of calibrations that Sequencer handled automatically versus those that needed some sort of operator intervention.

Table 7 and Figure 3 breaks down the automation into calibration maneuver 1 or calibration maneuver 2. Satellites listed as "auto" downlinked the data, passed data integrity checks, ran the calibration script, passed the output sanity checks, and proceeded to the next stage automatically. Satellites listed as "manual" downlinked the data but required operator intervention to check one of the subsequent stages. Satellites listed as "auto (check)" downlinked the data and would have successfully calibrated automatically but were affected by some spacecraft specific issues. Activities that ran but were not used in the calibration are not included in this table.

Table 7. Automation breakdown by calibration activity

	Calibration Maneuver #1	**Calibration Maneuver #2**	**Operational Summary**
Auto	56	54	**110**
Auto (check)	11	1	**12**
Manual	8	20	**28**
Total	75[1]	75	**150**

[1] These numbers were compiled after all nominal performing satellites had completed commissioning. The 75 excludes the 3 canaries, 2 retired satellites, and 8 "off-nominal" satellites that required additional debugging.

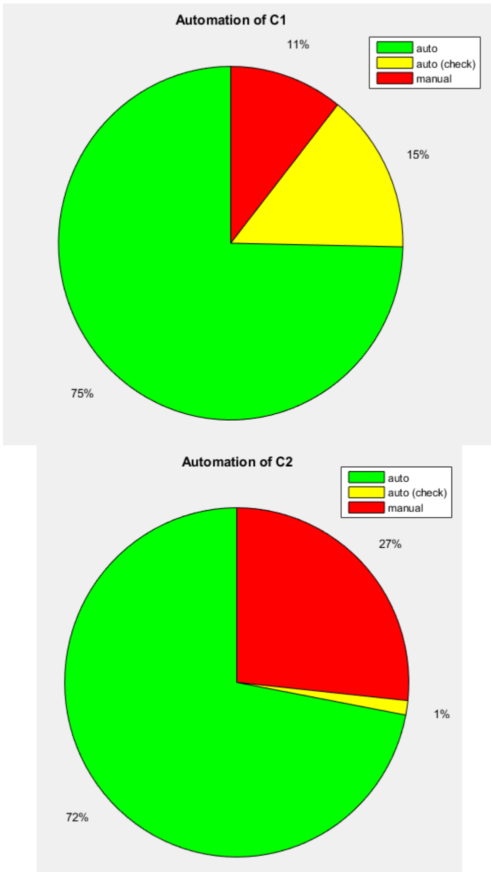

Figure 3: ADCS Calibration Automation Results

Calibration maneuver 2 experienced a greater percentage of automation failures than calibration maneuver 1; this was expected because the maneuver used for Flock 3p was new and being used in commissioning for the first time. Many of the limits and operational parameters used were chosen based on historical settings determined through experimentation with a few Flock 2p satellites.

CONCLUSION

Since its founding, Planet has defined and embraced agile aerospace. Planet's culture encourages iterative development based on experimentation. The operations team has grown and refined the commissioning process through experience on eight different launches.

Spacecraft operations at Planet also demands a focus on automation. By rejecting the idea that satellites require large teams to operate, the team has built one-of-a-kind automated systems for commissioning and operating large fleets of satellites. Operators focus on improvements and anomalies, not day-to-day operations.

With 88 satellites deployed from a single rocket, Flock 3p is the largest launch in history. Despite requiring an extensive list of calibration and checkout activities, Planet's small spacecraft operations team was able to meet its deadlines and have Flock 3p producing imagery for customers in just over three months.

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