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Dove High Speed Downlink System

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ABSTRACT

Planet's mission is to monitor global change by imaging the entire Earth every day. To achieve this objective, Planet has launched over 250 satellites and built the mission control and ground station infrastructure to autonomously monitor and control the satellites and download their data. Historically, CubeSat radios have been downlink limited because of size, weight, and power (SWaP) constraints. Planet has overcome the downlink data rate limitation by optimizing every part of the radio communication system to achieve over 220 Mbps peak and 160 Mbps average data throughput.

This paper presents an overview of the latest generation compact, low-mass, and low-power High Speed Downlink (HSD) radio that was built and deployed on over 100 3U form-factor *Dove* satellites that form Planet's Mission 1 constellation. The HSD operates at X-band and is built using commercial-off-the-shelf (COTS) parts with a high-gain spacecraft antenna and reasonably sized ground station antennas (4.5m - 7.6m diameter reflector). Planet's X-band ground station network includes 22 active dishes across 8 sites located around the world. Commercial standards, such as the DVB-S2 modulation and coding suite, have been used where appropriate. The latest generation HSD system is capable of providing downlink volumes of 12-15 GB during a single ground station pass, which has a duration of 7 to 10 minutes. Some lessons learned along the way are presented as Planet transitioned from building and operating a few prototypes to a production constellation of over 100 satellites and 22 active ground stations.

INTRODUCTION

Planet is a space and data analytics company that designs, builds, and operates a constellation of Earth observation satellites called *Doves* (3U CubeSat class) in order to meet its Mission 1: *Image the whole earth every day and make global change visible, accessible, and actionable.* By providing up-to-date medium-resolution imagery of the Earth, Planet hopes to democratize access to geospatial data and provide information vital to making well-informed decisions on Earth.

Planet has successfully launched 267 Doves, including 88 that were launched in February 2017 on the Indian Polar Satellite Launch Vehicle (PSLV). There are currently over 100 active imaging satellites. The satellites are nadir-pointing and always on and imaging when they are over land with reasonable solar illumination. The satellites were designed to have sufficient imaging swath width such that 100 evenly-spaced nadir-pointing satellites on a single orbital-plane at $\sim$ 500 km sun synchronous orbit (SSO) can image the entire Earth every day at 3-5 m ground resolution. This orbital configuration also allows for the optimal use of a very limited number of high latitude ground stations. The number of satellites on orbit, images collected per satellite, and the total capacity of ground stations informed the planning for the custom X-band high speed downlink (HSD) radio. In parallel with the HSD development effort, Planet embarked on a system-wide optimization which included bringing up and operating a worldwide network of ground stations, building a sophisticated data pipeline infrastructure, developing robust automatic scheduling and control systems, and building effective performance analytics tools. This tightly coupled system-wide development effort has enabled Planet to download several terabytes of imagery data every day from the constellation of Dove CubeSats.

Planet's latest generation HSD radio uses DVB-S2 modulation and coding protocol, custom X-band transmitter, and a high-gain helical antenna to interface with ground station antennas (4.5m - 7.6m diameter reflectors) equipped with commercial off-the-shelf (COTS) downconverters and receivers. Planet has demonstrated 220 Mbps peak data rates, and is currently working to resolve onboard data transfer limitations to further increase the space-to-earth data rate to 320 Mbps.

Radio Development History

In order to meet Mission 1 data volume objectives, Planet built a custom high-speed X-band radio using COTS components that is tightly integrated with the rest of the cubsat bus. Several radio architecture decisions were made in order to meet the size, weight, and power (SWaP) constraints of the CubeSat platform while also improving the overall system efficiency. For example, the final stage RF power amplifier was integrated adjacent to the antenna to improve the total system power efficiency. This allowed the use of antenna solutions with 10-12 dBi gain, but still achieve data rates comparable to much larger class satellites that typically have very high gain antennas. The custom development solution also allowed for rapid prototyping and repeated iterations that led to continuous improvements to the radio subsystem. Planet's first satellite launch hosted the sixth iteration (Build 6) of the spacecraft that transmitted 2 W of RF power through a 3 dBi gain patch antenna. A 6.1 m dish at the Chilbolton Observatory in the UK served as the ground station antenna. On April 25, 2013, Planet achieved its first successful X-band downlink at 4 Mbps data rate, which set a new data rate record for CubeSat class satellites [5].

The success of the early launches and tech demos proved that Planet could meet its Mission 1 goals by following the "agile aerospace" philosophy of rapid prototyping, repeated iterations, and continuous improvements. Less than three years after the first launch, the thirteenth iteration (Build 13) of the satellites was launched on the Indian Polar Satellite Launch Vehicle (PSLV) in June 2016. This constellation code named *Flock 2P* or *F2P* included twelve "Build 13" satellites. Further improvements were made to this build and *Flock 3P* or *F3P* consisting of 88 satellites was launched in February 2017. With the F3P launch, Planet set a record for the most number of operational satellites (100 Build 13 satellites and several B10, and B12 satellites). Planet has demonstrated 220 Mbps peak data rates with the Flock 3P constellation and average data rates of approximately 160 Mbps. Cumulatively, these satellites generate several terabytes of imagery data daily that is downlinked to eight geographically diverse ground station sites. The active imaging satellites and the ground stations are shown in Figure 1.

Improvements to the spacecraft HSD system have followed Planet's iterative design approach. Higher gain antennas have been added and improved, RF circuit impairments have been addressed, amplifier settings have been optimized, and the radio firmware and software has undergone constant development. Table 1 provides a summary of key HSD development milestones.

HIGH-SPEED DOWNLINK (HSD) DESIGN

The HSD radio operates at X-band with a center frequency of 8150 MHz and 70 Mbaud symbol rate. This frequency is within the 8025-8400 MHz (X-band) range where Earth Exploration Satellite Service (EESS) has a primary spectrum allocation [1].

Waveform Selection

Many modulation and framing formats, also know as waveforms, have been proposed for both satellite and terrestrial communication links. Like many other aspects of the Dove satellite design, the high-speed downlink waveform was selected primarily based on availability of commercial solutions. Key selection criteria included performance of the waveform relative to the Shannon limit as well as the power and computation complexity of an implementation.

The Digital Video Broadcast - Satellite - Second Generation (DVB-S2) waveform standard has been widely adopted in the satellite communication industry [2]. This standard specifies the physical signaling mechanisms, near-optimal forward error correction, and framing mechanisms for arbitrary user data (in addition to video, its primary use case). The DVB-S2 standard provides 28 modulation and coding (MODCOD) options which include robust QPSK up through performant 32APSK modes. In total, the available MODCODs span nearly 20 dB of carrier-to-noise ratio requirements, which are essential for the adaptive modulation and coding scheme (discussed later). Most importantly, these codes are all within roughly 1 dB of the Shannon limit.

The wide array of commercially available components needed to realize a DVB-S2 communication link made DVB-S2 a very pragmatic solution for the Dove's downlink system. While waveforms exist that have been specifically tuned for satellite use cases and honed for performance (e.g., some CCSDS standards), these solutions are far from practical due to the lack of ready-made modulator and demodulator solutions.

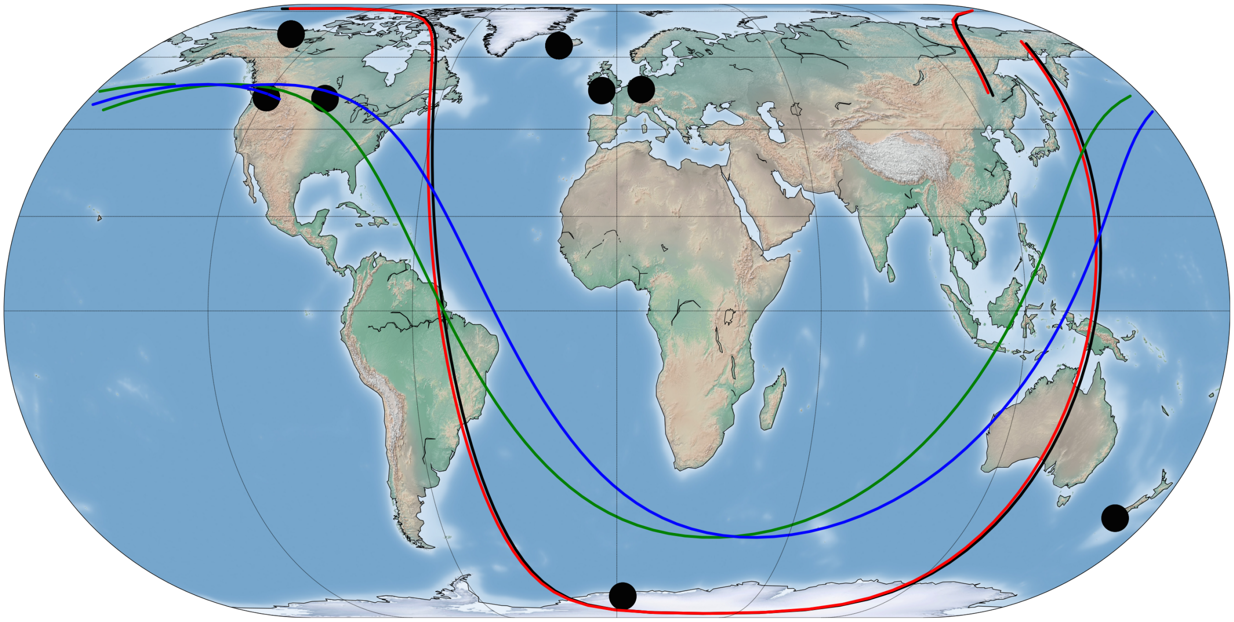

Figure 1: Location of X-band ground station antennas (black circles) and ground tracks of representative Dove satellites per flock (Flock 2P = Black, Flock 3P = Red, Flock 2E = Blue, Green).

Table 1: Summary of key HSD development milestones.

Date	**Milestone**	**Build#, HSD#**	**Improvements**
4/21/2013	Dove 1	B6, HSD1	HSD1 with operational X-Band system with patch antenna (3dBic), achieved 4Mbps using QPSK modulation scheme at 1/2 FEC rate.
11/21/2013	Dove 3	B8, HSD1	Upgraded system with ACM (Adaptive Coding and Modulation), high gain helical antenna (10dBic), achieved 25Mbps using 8PSK modulation at 8/9 FEC rate.
6/19/2014	Flock 1c (11 satellites)	B9, HSD1	Increase symbol rate from 10 Mbaud to 20 Mbaud and achieved 34Mbps using QPSK modulation at 8/9 FEC rate
6/1/2016	Flock 2e (12 satellites)	B12, HSD1	Increased symbol rate to 24 Mbaud, improved helical antenna (12dBic), optimized and linearized the X-Band transmitter chain and achieved 100 Mbps using 32APSK modulation and 8/9 FEC rate
6/21/2016, 2/14/2017	Flock 2p (12 satellites), Flock 3p (88 satellites)	B13, HSD2	HSD2 with new hardware, firmware, and software improvements on satellite and ground station, symbol rate increased from 24 Mbaud to 70 Mbaud, achieved 220Mbps using 16APSK modulation and 3/4 FEC rate (Raw RF link rate achieved 283 Mbps)

Transmitter Design

The high-speed downlink transmitter, shown in figure 2, consists of a conventional x86 CPU, an FPGA housing a DVB-S2 modulation core, and a chain of analog RF components. The vast majority of the modulation complexity is contained within the commercial DVB-S2 modulator core. Planet's proprietary packet format is encapsulated within raw DVB-S2 baseband frames. The modulated digital data from the FPGA is converted to baseband using a high speed digital to analog converter (DAC) and a superheterodyne transmitter is used to convert the baseband signal to X-band. The final stage power amplifier produces 2 W RF power which is transmitted to the ground stations using a high gain right hand circular polarized helical antenna with 12 dBi gain.

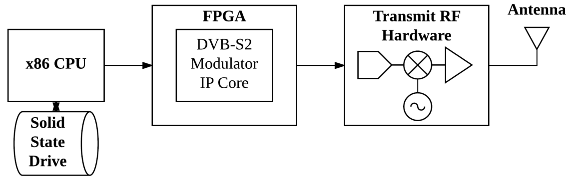

Figure 2: Satellite high-speed downlink transmitter functional blocks.

Significant effort has been invested in making the transmitter design as flexible as possible. Parameters such as center frequency, symbol rate (i.e., bandwidth), amplifier bias, and numerous other RF hardware parameters can be adjusted in real time. This versatility has proven useful for optimizing on orbit link performance on some satellites even after launch.

The HSD2 transmitter currently on-orbit in the Build 13 satellites is an evolution of the original design. A major redesign effort was completed between 2015 and 2016 to increase the maximum modulation bandwidth of the design and to improve some characteristics of the modulator including phase noise and transmitter error vector magnitude. These improvements have allowed better utilization of the spectrum allocation and to favor more power-efficient MODCODs within the DVB-S2 suite. These satellites currently operate at 70 Mbaud symbol rate, which corresponds to a peak downlink rate of 320 Mbps, but the downlink is currently capped at 220 Mbps due to other data handling limitations. (Work is in progress to remove these limitations.)

Receiver Design

Receiver design is arguably a much more difficult undertaking than building a transmitter. Fortunately, the market is saturated with DVB-S2 receiver products ranging from low-cost TV tuner cards to higher performance rack-mounted solutions. Most of these products are intended for use with conventional geosynchronous communication satellites and typically expect L-band RF input. A X-band to L-band downconverter at the antenna feedpoint is used at the ground stations to adapt these receivers to Planet's specific spectrum allocation.

In addition to providing decoded baseband frames, the receiver also provides a variety of statistics about reception conditions including the Signal to Noise Ratio (SNR) and link margin. The ground stations run a proprietary adaptive coding and modulation (ACM) algorithm that is used to maintain adequate link margin between the satellite and the ground station (figure 3. At roughly 1 second intervals, this algorithm assesses link margin and sends a message on the high-speed uplink (HSU) to the satellite to adjust up or down in rate depending on the link conditions.

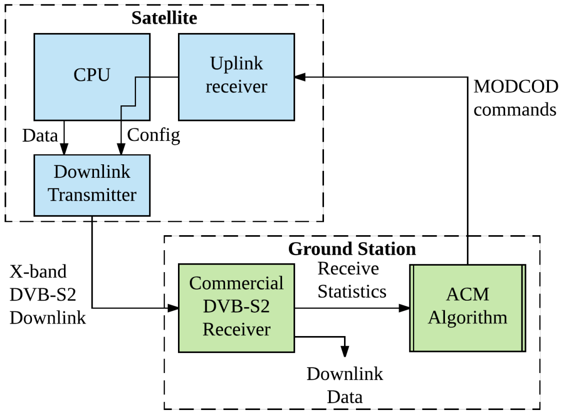

Figure 3: Adaptive coding and modulation control loop.

Ideally, the ACM algorithm would only have to compensate for slant range dynamics during a pass, however in practice it is also useful to make the system robust to other variables. Antenna pointing, especially on the ground side where beamwidths are a fraction of a degree, is one such area. Satellite-to-satellite manufacturing variations are another area where ACM has proven useful. Regardless of the source of the link impairment, ACM ensures that link operates as fast a possible for a given link condition. The ability to maintain a very low data rate link even with extremely large impairments is valuable for solving both satellite and ground station problems.

While traditional link-budget-driven design practices are still an important part of realizing a communication link, Planet's approach was to include hooks in the design that make the system robust to errors in the link budget. The 20 dB range of MODCODs provided by the DVB-S2 standard form the basis for this aspect of the design. The ACM mechanism is reliant on having a concurrent uplink solution. Figure 4 shows the link metrics (Pilot SNR, user data rate and link margin) for a pass taken with a Flock 3P satellite at the Keflavik ground station on June 13, 2017. The ACM dynamically adjusts the MODCOD to maintain a 3-5 dB link margin.

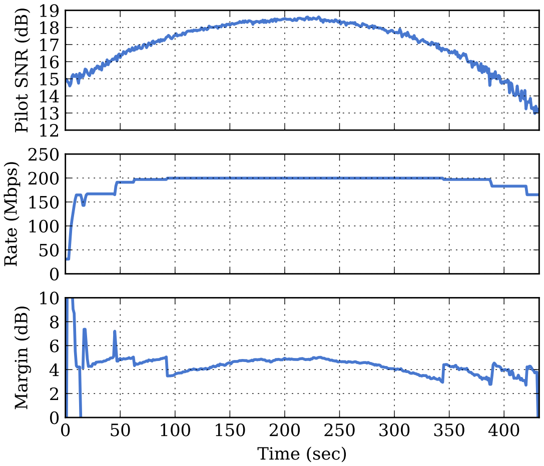

Figure 4: Link metrics for a Flock 3P satellite pass recorded on June 13, 2017 at the Keflavik ground station.

Protocols and Framing

A proprietary framing scheme encapsulates Planet-proprietary packets into DVB-S2 baseband frames. There are typically many Planet packets within a DVB-S2 baseband frame, and these packets are allowed to span two baseband frames if necessary. Planet packets are completely agnostic to the DVB-S2 physical layer (e.g., ACM) and are simply sent in a first-in-first-out order. A cyclic redundancy check (CRC) is used to ensure integrity of Planet packets over this link, however, because of the properties of the DVB-S2 forward error correction scheme it is rare to see bit/byte corruption in baseband frames. Baseband frames either decode or not, and the receiver is generally very good about not releasing baseband frames that fail to decode.

A variety of protocols are multiplexed over the high-speed downlink and its high-speed uplink counterpart. A CPU software feature known as SXNET (S-band, X-band network) allows us to tunnel IPv4 traffic over the link. Having IP connectivity to the satellite CPU — which allows for connection with standard tools, is hugely beneficial for debugging onboard software issues. In addition, differential file transfer tools can be leveraged for delivering software updates to the satellite. Round trip ICMP (Internet Control Message Protocol) ping times over SXNET are rarely greater than 100 ms, so the user experience is reasonably favorable. SXNET, however, is not without its limitations.

One distinguishing characteristic of the SXNET link from a typical terrestrial link is extreme asymmetry in data rates. The uplink rate is 250 kbps while the downlink rate can exceed 200 Mbps. Because of this asymmetry, traditional transport protocols like TCP (Transmission Control Protocol) are inefficient for bulk data transfer. A proprietary protocol was developed to overcome some of these limitations.

GROUND STATIONS

Planet operates its own ground station network to best meet the data volume needs of the large on-orbit constellation. The ground stations use COTS components where possible to reduce complexity and cost. In total, Planet operates equipment at 15 sites using a combination of rented equipment, co-located antenna systems, and fully independent sites. The diversity in assets allows the ground network to better scale to meet the demands of the on-orbit constellation. Relatively rapid flexibility in downlink capacity is especially important in an industry where a constellation can be built, launched, and deployed in the time needed to obtain licensing for a ground site.

Nearly all Planet ground station sites include UHF radios for telemetry, tracking, and control (TT&C). These systems are used for scheduling, basic health, and ranging for orbit determination. Eight of the ground station sites also include X-Band (HSD) capabilities. These eight geographically diverse sites contain a total of twenty-two dishes of varying diameters, from 4.5 meter to 7.6 meter. All dishes are designed for at least 29 dB/K G/T (gain to noise temperature) to optimize both the satellite downlink data rates and ground system cost.

The payload data is downlinked from space at X-Band, down-converted to L-band using a low noise block downconverter (LNB), and demodulated using a COTS DVB-S2 receiver. Typical ground stations passes average at 160 Mbps and peak at 220 Mbps data rates with data volumes of 12-15 GB downloaded per 7-10 minute ground station pass. The receiver deframes DVB-S2 packets, and sends raw IP frames to the ground station server via gigabit ethernet interface. The ground station server monitors the link status (SNR, link margin, received RF power level, bit error rate), reassembles the picture files, and uploads the pictures and metrics to the cloud. Additionally, many Planet ground antenna systems have a built-in feedback loop for basic open-loop power-tracking using link statistics provided by the DVB-S2 receiver. The power tracking introduces random offsets and tests and checks the feedback look for a positive or negative response. Planet's Dove ground network is nominally autonomous and remotely monitored to enable scalability and improve operational efficiency [3, 4]. Figure 5 shows the internals of Planet's S-band/X-band ground station system, and Figure 6 shows a picture of a 4.5 m diameter dish at Keflavik, Iceland.

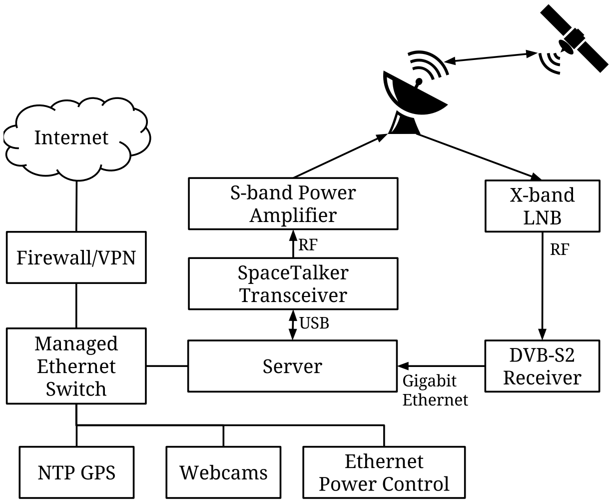

Figure 5: Ground station system functional blocks.

Figure 6: A 4.5 m diameter ground station antenna at Keflavik, Iceland.

IMAGE PIPELINE

During downlink, images are temporarily buffered locally on a server co-located with the receive antenna and added to an internet upload queue. The imagery gets uploaded to cloud storage over secured internet connections, which kicks off a per-image processing pipeline. The local storage decouples imagery downlink from network interruptions or congestion and allows sizing the leased line for average bandwidth (as opposed to peak bandwidth or latency). The imagery is also kept stored on the satellite until the next pass so that it can be confirmed as having successfully entered the processing pipeline before being deleted.

Upon ingestion, images are individually de-mosaiced (de-bayered), color-corrected, flat-fielded, and ortho-rectified. Orthorectification aligns the image to within 10m (RMSE) horizontally and maps the data to a fine digital elevation model. Further analysis generates a cloud cover mask and ensures that images released to customers satisfy a series of quality metrics. During the month of May 2017, the 90th percentile of the imagery that rectified and passed quality metrics was published within 5.5hrs of being downlinked by a ground station.

Successfully rectified images are available to customers as soon as processing has completed. To satisfy the multiple use cases of different customers, imagery is available in a variety of forms:

- Orthorectified images ("scenes", which consist of one full-frame capture) are available via REST HTTP API for customers.
- "Tiles" are produced, similar to the OSM "slippy map" architecture, on a grid that is fixed for all

Planet products by rectifying and stacking the RGB and NIR bands of scenes from a single strip of imagery.

- All of the rectified imagery that meets minimum quality conditions is made available on a web-based application open to all for browsing and new imagery alerting based on user-defined areas of interest.

DATA ANALYSIS AND METRICS

Planet's mission control infrastructure monitors and controls the satellites and the ground network handles over 650 HSD passes per day. Due to the large number of passes and the limited engineer time available, it is impossible to assess each pass manually. Therefore, Planet has created an automated metrics gathering and failure detection system to monitor constellation-wide high speed downlink performance.

The automated metrics system has been built using open source tools, shown in Figure 7 and runs at regular intervals. Pass relevant information, that includes information from the satellite, the ground station, and physical characteristics (orbit-related), is first consolidated. An automated pass classifier assesses the quality of the pass and identifies a possible reason for failure. The combined pass information, along with the failure diagnosis, is written to a database. A dashboard aggregates information from the passes and creates interactive visualizations. The interactive visualizations allow easy access to pass performance information to any engineer without the need to code new tools.

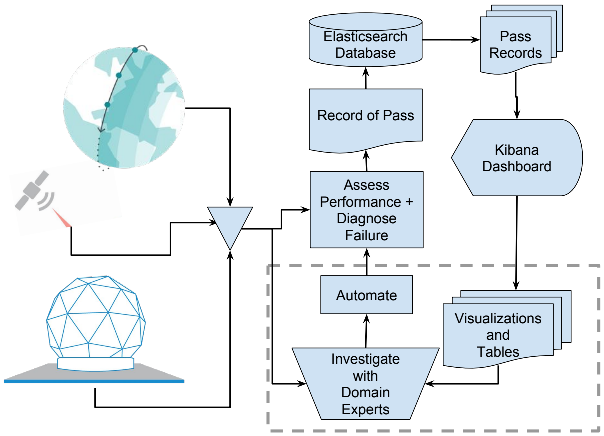

Figure 7: Internals of the metrics generation and reporting system.

The pass classifier automates the decision making process of domain experts in order to automatically diagnose possible failure modes for sub-optimal passes. An HSD pass is considered to be a failure if the amount of image data downloaded is less than 80% of the total downlinked data volume predicted using a link budget model. The prediction uses a formula that depends on the transmitter and receiver characteristics, slant range, and orbital geometries during the pass to compute the RF link margin. Once a pass is judged to be a failed pass (which only implies sub-optimality and not an outright failure due to the conservative assumptions in the data rate predictions) the automatic classification begins.

An automated classified has been developed to classify failures. Every week, domain experts from RF and Communication Systems, Orbit Operations, Satellite Operations, System Integrations, and Ground Station Operations teams discuss, classify, and debug failed passes. After manually classifying the passes, the diagnosis is automated by creating a hierarchical tree of failures. The hierarchy of the failure mode is primarily based on the certainty with which that failure mode can be identified.

This automated approach has allowed for the classification of thousands of passes into discrete buckets with well defined problem statements. The total number of failures and the severity of the failure modes provides the direction for problem solving. Using this approach, the HSD performance was improved by $\sim$ 50% from 110 Mbps average to 160 Mbps average over a few month period and pass-to-pass variance was reduced.

SUMMARY

Using the "agile aerospace" philosophy, Planet has rapidly prototyped and iteratively developed an end-to-end high speed satellite communication solution that not only included the development of the spacecraft and ground station hardware and software, but also the automated monitoring, scheduling, and control systems, and data metrics and analytics solutions. These co-optimized systems are tightly coupled and work together to achieve record downlink speeds of 220 Mbps and data volumes of over 4 terabytes per day. Figure 8 shows monthly aggregated historical downlink data rates and Figure 9 shows constellation wide daily downlink data volume along with the number of active satellites.

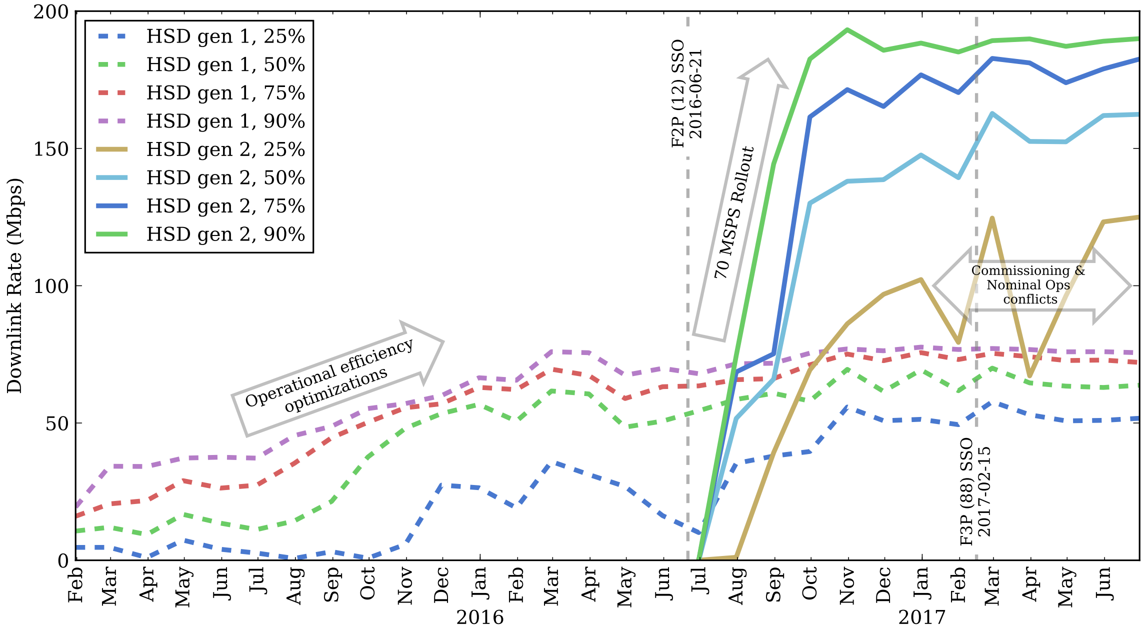

Figure 8: Data rate quantiles for HSD1 and HSD2 annotated with key milestones, aggregated monthly.

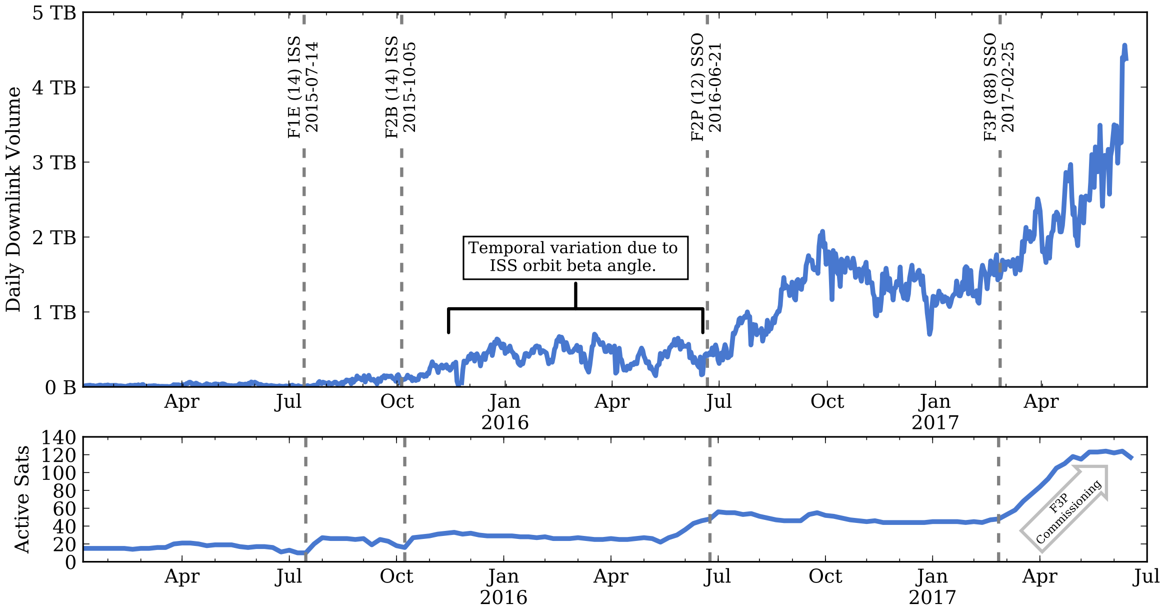

Figure 9: (Top) Constellation-wide daily downlink data volume with key launch dates. (Bottom) Number of active satellites.

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