SSC19–VI–01

Planet High Speed Radio: Crossing Gbps from a 3U Cubesat

Kiruthika Devaraj†, Matt Ligon, Eric Blossom, Joseph Breu,
Bryan Klofas, Kyle Colton, Ryan Kingsbury
Planet Labs Inc.
645 Harrison Street, 4th Floor, San Francisco, CA 94107
† kiruthika.devaraj@planet.com

ABSTRACT

Planet is a vertically integrated aerospace and data analytics company that operates the world's largest commercial fleet of remote sensing satellites. Our mission is to image the whole world everyday, and make change visible, accessible, and actionable. We have launched over 350 satellites and built up an automated mission control and ground station infrastructure to monitor and control the satellites, and download the imagery data. Historically, small satellite radios have been downlink limited because of tight size, weight, and power (SWaP) constraints. Rapid prototyping, iteration, and adaptation of the latest commercial-off-the-shelf (COTS) technology has allowed for continuous improvements in data throughput on our high speed radio from a very low-cost cubesat platform. In this talk, we will report on our latest X-band radio and antenna solution which has achieved a data rate over 1.6 Gbps from a 3U CubeSat on-orbit.

Planet's High Speed Downlink 2 (HSD2) is the latest generation compact, low-mass, and low-power radio that was built and deployed on 3U form-factor imaging CubeSats in December 2018. This system operates at X-band and is built using COTS parts with a dual polarization antenna. The two physical channels represent the two polarization modes, right hand circular polarization (RHCP) and left hand circular polarization (LHCP) and each physical channel utilizes 300 MHz of total bandwidth. Within each physical channel, there are three logical channels spaced 100 MHz apart center-to-center frequency. The individual channel symbol rate is 76.8 Msps. Each physical channel has 1 W RF output power and 15 dBi antenna gain. The total DC power consumption of the radio including the processor and the FPGA is 50 W and the total volume occupied by the radio and antenna, including the mechanical deployment structure for the antenna is 0.25U. The commercial digital television broadcasting standard DVB-S2 is used for modulation and coding. An adaptive coding and modulation (ACM) scheme is used to dynamically change the modulation and coding for each channel individually based on the available link margin. Our ground station network includes 15 dishes (29 dB/K gain-to-noise-temperature) across 5 sites located around the world. The HSD2 is capable of providing downlink volume of over 80 GB during a single ground station pass.

INTRODUCTION

Historically, one of the factors limiting the utility and wider adoption of small satellites in scientific, commercial, and government applications has been slow, bulky, and expensive radio frequency (RF) communication systems. Missions were architected around these low speed radios and had to resort to selective downlinking or aggressive compression of data, resulting in poor data quality and high latency. The options for commercial X-band satellite radios capable of hundreds of Mbps or higher are limited.

Most CubeSat-class radios operate at UHF or S-band, and a few operate at X-band. The higher speed X-band commercial radios are able to provide about 50-100 Mbps [1-3]. Larger form factor satellites have demonstrated higher speeds on-orbit at X-band, such as Planet's Skysat satellites with 480 Mbps downlink and the Japanese satellite Hodoshi 4, which has demonstrated 505 Mbps link speed [4]. Digital Globe's WorldView-2 and Worldview-3 satellites operate at 800 Mbps and 800/1200 Mbps [5] respectively, but they are much larger form-factor satellites and weigh over 2500 kg. Ka-band has many times the available bandwidth compared to X-band, and NASA has been migrating to Ka-band to improve radio communication speeds. Ka-band, however, has higher attenuation through the atmosphere and clouds, as well as high rain fade. Ka-band also suffers from limited availability of COTS components, such as amplifiers, filters, and mixers, as compared to X-band. JPL's ISARA mission flew with a 33 dBi gain reflectarray antenna and a Ka-band radio and demonstrated a link margin that could support a 100 Mbps link [6]. The highest performance commercial Ka-band radio with flight heritage has only demonstrated 320 Mbps data rate today on a 6U CubeSat [7].

Optical communications seems like an attractive option for small satellites because of the availability of practically unlimited bandwidth, tremendous speed, and the lack of regulations around lasers compared to FCC and ITU-regulated RF spectrum [8]. There are multiple government and commercial efforts underway to build low SWaP laser communication satellite and ground terminals. NASA's Optical Communications and Sensors Demonstration (OCSD) system has demonstrated about 100-200 Mbps from a 1.5U CubeSat at 450 km [9-10]. Mynaric, a commercial laser-communications company, has demonstrated a 1 Gbps link between two high altitude balloons and is currently working on Gbps optical communication satellite terminals and ground stations [11].

Optical communication terminals however can be expensive, with individual satellite optical terminals and ground stations costing close to $1M each. In addition, optical communication availability is heavily dependant on cloud coverage. Given that about 70% of the Earth is blanketed by clouds on a daily basis [12], multiple optical ground terminals are needed to ensure timely downlink of data. While RF spectrum licensing can be a slow process, and is often cited as a reason to move to optical, we have found that the experimental license application process takes less than 6 months while a commercial spectrum license takes about 9-12 months from submission to approval.

By presenting the remarkable progress that Planet has made on its X-band High Speed Downlink version 2 (HSD2) radio development using the "agile aerospace" approach of rapid prototyping, iterative development, and streamlined manufacturing, we make the case that the small satellite community is far from being capability-limited on RF communication technology even at X-band.

Planet has been making evolutionary and revolutionary changes to our high speed downlink (HSD) radio with challenging Size, Weight, Power, and Cost (SWaP-C) constraints [13]. Rapid prototyping, iteration, and adaptation of the COTS technology has allowed for continuous improvements in data throughput from a very-low-cost small satellite platform. Figure 1 shows the agile and iterative improvements that Planet has made overtime across Dove spacecraft hardware variants. More specifically, over the last two years, Planet improved downlink data rates on the Dove CubeSats by 7.5X and has built, launched, and demonstrated this capability from space. Planet's HSD2 is the latest generation of compact, low-mass, and low-power radios. The HSD2 radio and dual polarization antenna were operationally tested and deployed on CubeSats in December 2018 and as of June 2019, there are 22 operational 3U CubeSats with HSD2 radio. The HSD2 radio achieved a data rate of over 1.6 Gbps to a 4.5 meter diameter ground station and is capable of providing a downlink volume of over 80 GB during a single ground station pass from LEO.

HSD2 OVERVIEW

The new generation HSD2 is built on the success of the previous generation HSD Dove radio that operates at 220 Mbps throughput [13]. The key features of HSD2 include:

- X-band operation in the Earth Earth Exploration-Satellite Service (EESS) band (8025-8400 MHz)
- Dual circular polarization antenna that allows for instantaneous doubling of bandwidth
- Compact volume of 0.25U including the radio, antenna, and the antenna deployment mechanism
- DVB-S2 modulation scheme with adaptive modulation (QPSK to 32APSK) and coding rates (1/4 FEC to 9/10 FEC)
- 50W total DC power consumption including the processor and FPGA during downlink

Satellite Transmitter

The HSD2 satellite transmitter shown in Figure 2 consists of a processor (CPU) and solid state drive (SSD) linked to an FPGA which drives the analog and RF transmitter chains. The FPGA multiplexes the incoming data to six DVB-S2 cores that modulate and provide forward error correction (FEC). Planet's data packets are encapsulated within the DVB-S2 baseband frames. Each DVB-S2 core runs at 76.8 Msps baud rate. The six logical channels are frequency offset and combined into two physical channels and converted to analog baseband using a high-speed digital to analog converter (DAC). Two independent superheterodyne transmitters are used to convert the baseband signals to X-band signals, which are then fed to final stage power amplifiers and right and left hand circular polarized (RHCP/LHCP)

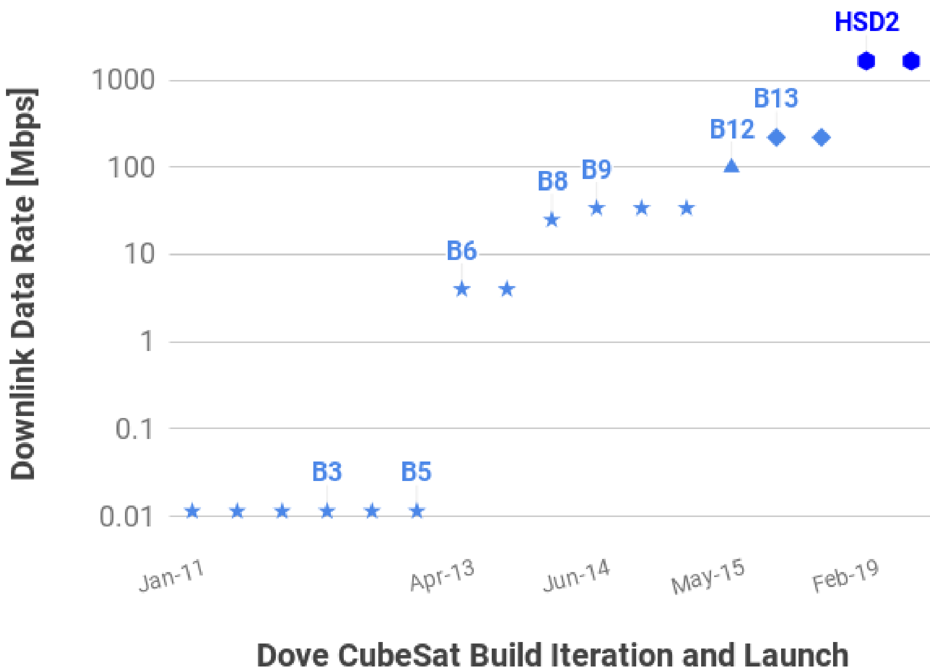

Figure 1: HSD data rate improvements for various Dove build iterations are shown as blue points on the scatter plot. Triangle represents 100 Mbps radio launched on B12 in May 2015, diamond represents the 220 Mbps radio launched on B13 in May 2016, and hexagon represents the 1.6 Gbps HSD2 radio launched in December 2018 and March 2019.

antennas for transmission. Table 1 summarizes some of the transmitter parameters.

Ground Stations and Receiver

Planet operates its own ground network to efficiently meet the data volume needs of our large constellation and for flexibility and agility in the deployment of new technologies. Rapid flexibility is especially important when a new constellation can be built and launched in the same time needed to obtain a license and construct or lease a new ground station. In total, Planet operates 15 owned S/X-band antennas at 5 sites. Figure 3 shows the Keflavik ground station at Keflavik, Iceland and Figure 4 shows the Canadian ground station at Inuvik, Canada. Planet operates telemetry, tracking, and command (TTC) antennas at UHF band from all the S/X-band sites as well as 5 additional sites. Planet's TTC Low Speed Transceiver is based on OpenLST [14] and is also used for time-of-flight ranging [15]. This diversity in assets and locations allows the ground network to scale to meet the demands of both HSD1 and HSD2 radio systems.

Planet ground stations use COTS components where possible to reduce cost and complexity. All Planet ground systems can support both HSD1 and HSD2 downlinks. Planet's ground station network was originally designed for operating with the single channel HSD1 [13, 16]. With the addition of multiple channels and dual polarization, the receiver chain has gone through significant hardware and software upgrades. A left-hand polarized feed and low noise block downconverter (LNB) were added to each dish to support the second polarization. The intermediate frequencies were chosen such that the LHCP is combined onto the same coax cable as the RHCP, with appropriate guard bands. Five demodulators were added to the one existing demodulator in each system to interface with the six-channel HSD2 transmitter. Some key HSD2 receiver and ground station parameters are provided in Table 2.

The demodulators output digital data on a separate 1 Gbps ethernet interface. A COTS network switch bonds these individual channels onto a single 10 Gbps fiber optical link that is fed into the ground station server. This approach of maintaining the individual channels on a separate network and multiplexing in the network switch provides the flexibility to

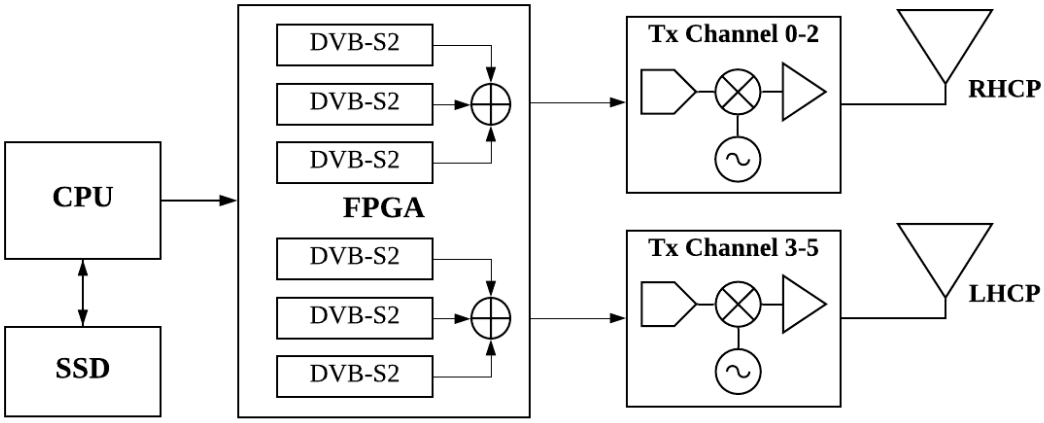

Figure 2: Block diagram of the six channel HSD2 satellite transmitter.

Table 1: HSD2 transmitter parameters

Parameter	Value
Channel Symbol Rate	76.8 Msps
Channel Spacing	100 MHz
Channel Bandwidth	96 MHz
RF Output Power	1 W per polarization
Antenna Polarizations	Ch 0, 1, 2: RHCP Ch 3, 4, 5: LHCP
Antenna Gain	15 dBi per polarization
Radio and Antenna Volume	0.25U (2.5 cm X 2.5 cm X 10 cm)
DC Power Consumption	50 W
Modulation	QPSK, 8PSK, 16APSK, 32APSK
Coding	1/4 to 9/10 FEC
Channel Data Rates	Variable from 37 Mbps to 336 Mbps
Maximum data rate achieved on orbit	1674 Mbps (at the time of publication)

Figure 3: 4.5 m diameter S/X dish in Keflavik, Iceland.

Figure 4: Canadian Satellite Ground Station Inuvik (CSGSI), Inuvik, NWT, Canada.

Table 2: HSD2 ground station parameters

Parameter	Value
Ground dish size	4.5 m-5 m diameter
Number of dishes	15
Gain at X-band	49 dBi
Beamwidth (half power)	0.55 deg
G/T (gain over noise temperature)	29 dB/K
Cross polarization	25 dB
Max data downlinked per pass	82.91 GB (at the time of publication)

change the number of channels or add more channels in the future without significantly altering the existing hardware infrastructure. A block diagram of the HSD2 receiver is shown in Figure 5. If the S/X data throughput exceeds the local network capacity, the ground station will store and then forward the data to Planet's imagery pipeline. Planet's scheduling software takes into account expected data downlinked and limits passes if needed to avoid a backlog of imagery uploads from building up on the local server.

Channel count and polarization states are stored as configuration variables for both satellites and ground stations, allowing different configurations throughout the network. This makes the network robust as the failure of one or two channel will not impact the remaining channels. Scheduled contacts bring up as many channels that are operational on both the ground station and the satellite. With dynamic per-pass configuration of channels, single-channel contacts (HSD1) become simply a special case of six-channel contacts (HSD2).

Table 3 provides a simplified link budgets calculation for a single polarization on 3 channels.

HSD2 Software

The HSD2 software that runs on the satellite and the ground station ensures that the transmitter and receiver work in tandem to optimize data throughput. The low-level software stack makes the six DVB-S2 channels appear to higher level software as single bonded channel. Because of the low error rate of the communication link, the nature of the data being transmitted (mostly images), and the highly asymmetric uplink (S-band uplink speed of 256 kbps), a negative acknowledgement (NAK) based protocol is used to transfer files from the satellite to the ground station.

The Adaptive Coding and Modulation (ACM) feature of DVB-S2 [17] allows for the selection of the appropriate modulation and forward error correction code (MODCOD) from a set of 28 choices that span QPSK through 32APSK modes and 1/4 FEC to 9/10 FEC. The MODCODs can vary on a per channel and per frame basis. Ground receiver and deframer statistics are closely monitored for link margin. The link margin metric in combination with the currently selected MODCOD and an appropriate safety margin are used to choose the MODCOD for the next epoch. This evaluation is performed on a per channel basis.

ON-ORBIT RESULTS

On November 28, 2018, Planet launched 4 prototype next generation Dove satellites, followed by 2 more prototypes on December 3, 2018. After the initial commissioning steps, the HSD2 demonstrated 1.15 Gbps peak data rate on December 12, 2018 and downloaded about 46 GB of data shown in Figures 6 and 7.

Planet launched an additional 20 next generation satellites - *Flock 4A (F4A)* on March 31, 2019 [18]. After the F4A satellites were commissioned, these satellites in space were used as a testbed to further improve the HSD2 performance. An aggressive ACM algorithm was implemented to allow for near-error-free operation with very little excess link margin. The transmitter settings were tweaked to optimize for maximum signal power while minimizing signal distortion. With these additional changes, the HSD2 is currently achieving peak data rates over 1.6 Gbps and can downlink over 80 GB of data in a single ground station contact. Figures 8 to 13 shows an example of ground station pass taken on May 28, 2019 with the Keflavik ground station and satellite 2227.

Contrasting HSD2's dynamically adaptive system is a static system that is used on, for example, Digital Globe's Worldview (WV) satellites. WV satellites utilize fixed downlink speeds of 800 Mbps (WV1, 2) or 800/1200 Mbps (WV3) [5] and the radios are designed to maintain a sufficient margin to close the link at that fixed speed at all possible slant ranges. Planet's dynamically adaptive approach, while ensuring that the communication system still meets a specific downlink volume on a constellation-wide ba-

Table 3: Simplified Link Budgets for HSD2 radio

Parameter	**Ch: 0, 3**	**Ch: 1, 4**	**Ch: 2, 5**	**Units**
Orbit Altitude	500	500	500	km
Elevation Angle	15	15	15	deg
Slant range	1408	1408	1408	km
Satellite Transmitter				
Frequency	8.09	8.19	8.29	GHz
Symbol rate	76.8	76.8	76.8	Msps
Bandwidth	96.0	96.0	96.0	MHz
PA Output Power	0.33	0.33	0.33	W
Circuit Loss	2	2	2	dB
Antenna Peak Gain	15	15	15	dBi
EIRP of Spacecraft	8.2	8.2	8.2	dBW
Ground Station				
Free Space Loss	173.5	173.6	173.7	dB
Losses (pointing, polarization, radome, atmosphere)	1.8	1.8	1.8	dB
Ground antenna gain	49	49	49	dBi
Ground System G/T (at 15 deg)	29	29	29	dB/K
Received C/N0	90.5	90.4	90.2	dB-Hz
Demodulator				
Modulation	16APSK	16APSK	16APSK	
Symbol rate	76.8	76.8	76.8	Msps
Composite Code rate	0.75	0.75	0.75	
Uncoded data rate	228	228	228	Mbps
Implementation loss	0.5	0.5	0.5	dB
Required Es/N0 at target BER	10.7	10.7	10.7	dB
Link Margin	**0.9**	**0.8**	**0.7**	**dB**

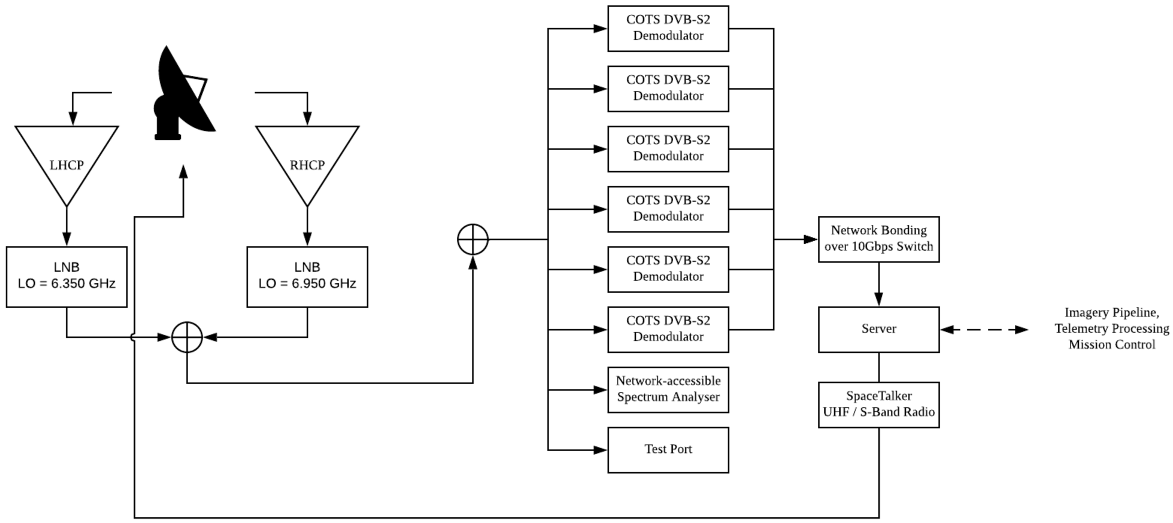

Figure 5: Block diagram of the six channel HSD2-capable ground station.

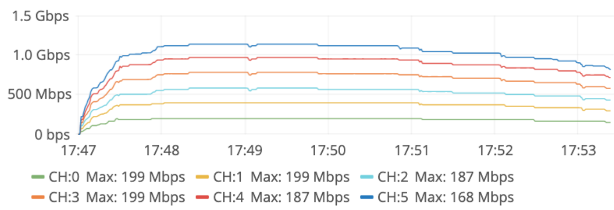

Figure 6: Six channel HS2 system achieved peak rates of 1.15 Gbps on December 12, 2018.

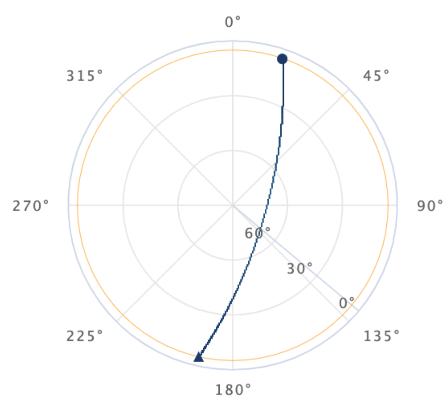

Figure 8: Azimuth and elevation angles of the satellite 2227 pass over the Keflavik ground station on May 28, 2019.

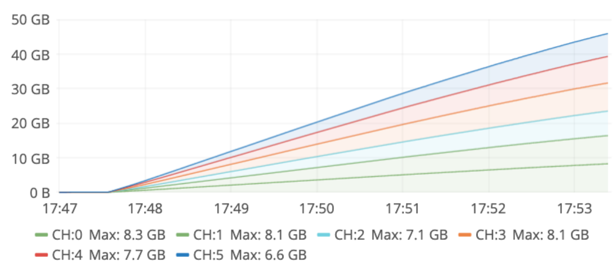

Figure 7: Six channel HS2 system downloaded 46 GB of data December 12, 2018.

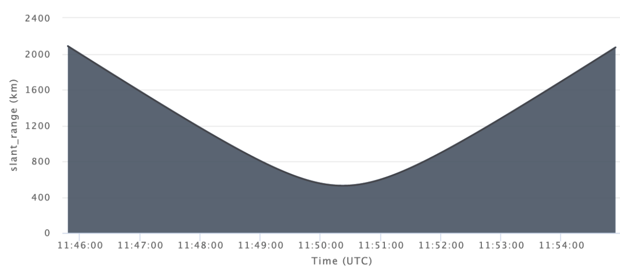

Figure 9: The slant range to the satellite as a function of the UTC time during the pass. The distance between the ground station and the satellite changes from over 2000 km at 5 deg. elevation to 530 km at 71 deg. elevation.

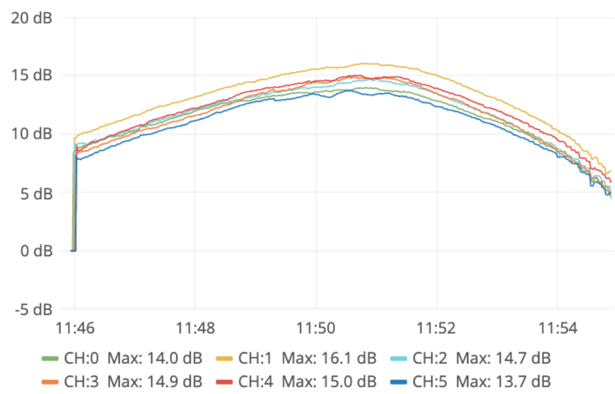

Figure 10: The demodulator recorded signal to noise ratio (SNR) is shown for the six channels at the ground station.

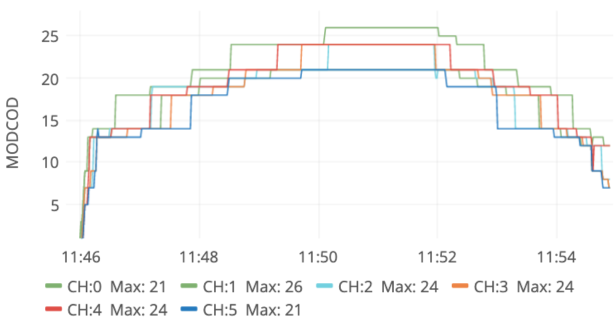

Figure 11: MODCOD is adaptively incremented or decremented based on link availability by the ACM algorithm on an individual channel basis. The modulation changes from QPSK at the start of the pass to 16/32APSK at the middle of the pass for various channels.

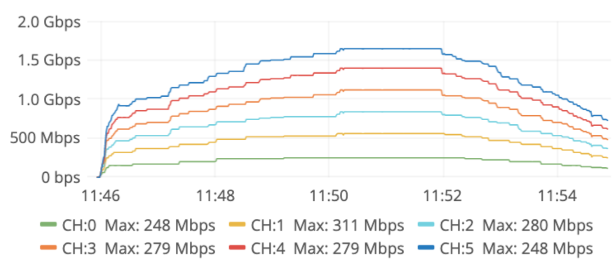

Figure 12: The data rate recorded by the demodulator shows max data rates between 248 Mbps to 311 Mbps for the six channels.

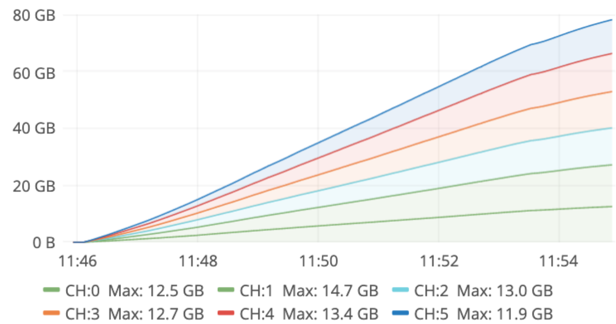

Figure 13: The cumulative data downloaded from the satellite is about 80 GB.

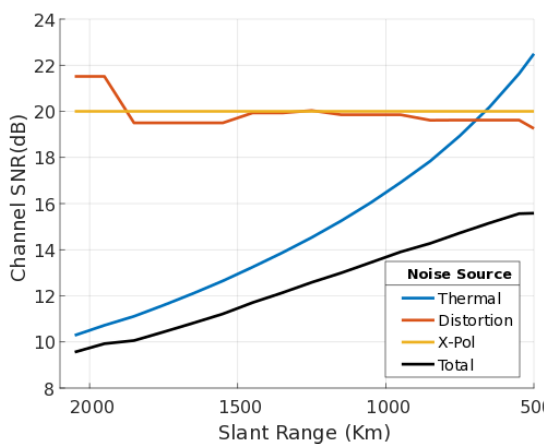

Figure 14: Black curve shows the total simulated SNR at different slant ranges. Contributions from various sources are shown with thermal noise in blue, signal distortion in red and cross polarization in yellow.

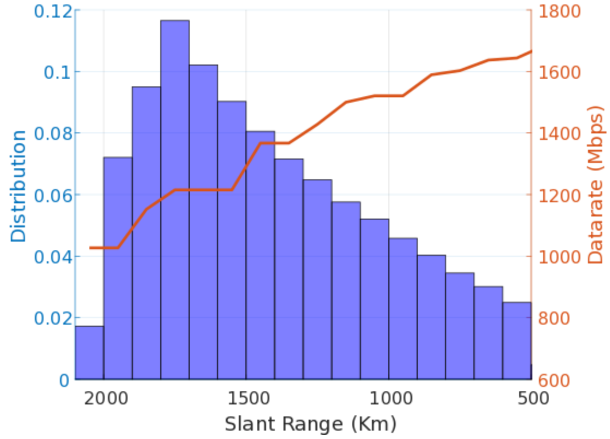

Figure 15: The histogram of slant ranges from a Dove satellite in a 500 km SSO orbit is shown in blue and the predicted data rate as a function of slant range from the HSD2 channel simulator is shown in red.

sis, allows for flexibility on the communication parameters as long as the software is able to make adjustments to maximize the overall throughput. This approach allows a more efficient utilization of the ground resources, reduces satellite power consumption, and adds operational flexibility. This is an example of Planet's "capabilities driven" approach vs. a traditional "requirements driven" approach.

Figure 14 and 15 show the results of an extensive HSD2 communication system modeling effort. A channel simulator was built that includes the effects of transmitter distortion and antenna cross polarization in addition to the orbital geometry effects. About 20 different parameters, including the power amplifier distortion, inter-channel separation, channel filter roll-off, and antenna cross-polarization etc., were optimized to find the system configuration that would allow for the maximum throughput from HSD2 as a function of slant range. The channel simulator outputs the slant range dependent SNR and data rate and predicted a peak data rate of 1.7 Gbps and an average data rate of 1.3 Gbps.

Analysis of on orbit performance from the *F4A* satellites validates the accuracy of the channel simulator. Figure 16 shows the on-orbit measured data rate from *F4A* satellites 2227 and 222B over a three week period from May 20 to June 11, 2019 at the Keflavik ground station.

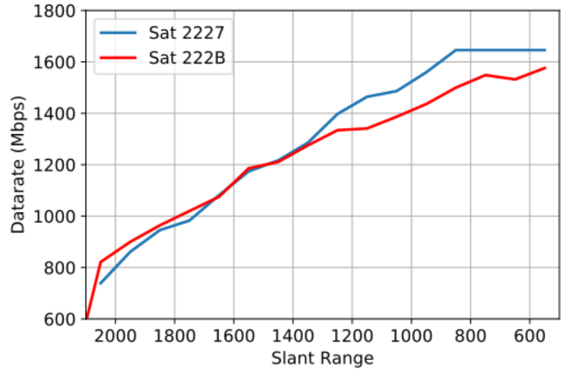

Figure 16: Data rate measured at the Keflavik ground station from the *F4A* satellites 2227 (blue) and 222B (red) over a three week period from May 20 to June 11, 2019.

SUMMARY

While Planet is still bringing our next generation constellation up to full capacity, HSD2 is already showing great results in the production environment. Typical ground stations passes average 400 seconds in duration, and at peak data rates over 1.6 Gbps the ground terminal can collect over 80 GB of data per pass.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contributions of former Planeteers Kwabena Agyeman and Jeremy Webb for their contributions to the HSD2 system.

REFERENCES

[1] https://www.jpl.nasa.gov/cubesat/pdf/Brochure_IrisV2.1_201611-URS_Approved_CL16-5469.pdf

[2] http://www.tethers.com/SWIFT.html

[3] https://sst-soa.arc.nasa.gov/09-communications

[4] Saito et al. "High Bit-rate Communication in X Band for Small Earth Observation Satellites - Result of 505 Mbps demonstration and plan for 2 Gbps link." Proceedings of the 30th Annual AIAA/USU Conference on Small Satellites, August 2016.

[5] https://www.mathworks.com/company/user_stories/digitalglobe-simulates-complete-satellite-to-ground-communications-systems.html

[6] Hodges et al., "The ISARA Mission – Flight Demonstration of a High Gain Ka-Band Antenna for 100Mbps Telecom", Proceedings of the 32nd Annual AIAA/USU Conference on Small Satellites, August 2018.

[7] Leveque et al., "Unlocking the Next Generation of Nano-Satellite Missions with 320 Mbps Ka-Band Downlink: On-Orbit Results", to be presented at the 33rd Annual AIAA/USU Conference on Small Satellites, August 2019.

[8] Carrasco-Casado et al., "Optical communication on CubeSats — Enabling the next era in space science", IEEE International Conference on Space Optical Systems and Applications (ICSOS), 2017.

[9] https://www.nasa.gov/sites/default/files/atoms/files/ocsd_fact_sheet_21oct2015.pdf

[10] Rose et al., "Optical communications downlink from a 1.5U cubesat: OCSD program", Proceedings of SPIE 10910, Free-Space Laser Communications XXXI, 109100T, 2019.

[11] https://mynaric.com/wp-content/uploads/2018/03/20180110_Mynaric_GBC_research_ENG.pdf

[12] https://earthobservatory.nasa.gov/images/85843/cloudy-earth

[13] Devaraj et al., "Dove High Speed Downlink System", Proceedings of the 31th Annual AIAA/USU Conference on Small Satellites, August 2017.

[14] https://www.planet.com/pulse/planet-openlst-radio-solution-for-cubesats/

[15] Foster et al., "Orbit Determination and Differential-Drag Control of Planet Labs CubeSat Constellations." http://arxiv.org/abs/1509.03270v1. AAS 15-524.

[16] Colton K., Klofas B. "Supporting the Flock: Building a Ground Station Network for Autonomy and Reliability." In Proceedings of the 30th Annual AIAA/USU Conference on Small Satellites. SSC16–IX–05. Logan, Utah. August 2016.

[17] ETSI EN 302 307 V1.2.1, 2009-08 Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications (DVB-S2).

[18] https://www.planet.com/pulse/first-up-for-2019-pslv-launch-of-20-next-generation-doves/