SSC19-VI-05

Unlocking the next generation of nano-satellite missions with 320 Mbps Ka-band downlink: on-orbit results

Kyle Leveque, Louis Carleton, Jan King
Astro Digital, Inc.
3171 Jay St. Santa Clara CA, 95054; (408) 638-0591
kyle@astrodigital.com

Zach Cuseo
Advanced Solutions, Inc.
7815 Shaffer Pkwy Littleton, CO, 80127; (303) 979-2417
zcuseo@go-asi.com

Russell Babb
Utah State University
4130 Old Main Hill, Logan Utah, 84322; (385) 269-2347
Russell.babb@aggiemail.usu.edu

ABSTRACT

Relatively low downlink data rates have historically limited the scientific and commercial return from CubeSats and SmallSats. As the capability of payloads for these satellites continues to increase, high-speed downlink capability is required to realize the increasing potential from these systems. In this paper we present the on-orbit results of our high-speed Ka-band transmitter operating aboard the twin Corvus-BC3 and Corvus-BC4 6U CubeSats. The 1-U form factor Ka-band system enables the unprecedented data return from a multi-spectral imager in this class of spacecraft. We highlight the spacecraft design and operational challenges that have been overcome on these missions that will enable high-speed downlink on any CubeSat or SmallSat. While the pointing requirements for this Ka-band downlink are readily achievable by today's small satellites, we discuss some of the hidden complexities on both the attitude determination and control system (ADCS) as well as on the ground segment. Currently in-place ground infrastructure, including a 2.8 m dish at a downlink station in Svalbard, Norway, has enabled rapid commissioning and on-demand downlink several times a day for these sun-synchronous spacecraft. This paper includes flight data from early commission to routine operation at high-data rates. We believe the lessons learned on these missions will be valuable for other CubeSat developers that plan on moving away from UHF, S-band, and X-band and into the realm of millimeter microwave frequencies (such as 27 GHz).

SPACECRAFT OVERVIEW

The Corvus-BC spacecraft was developed for collection of multi-spectral Earth imagery at a resolution of 22 meters. The platform utilizes a star tracker, magnetometers, sun sensors, an inertial measurement unit (IMU), reaction wheels, and magnetic torque coils for precision 3-axis pointing. A dual-band GPS receiver and on-board orbit propagator provide accurate positional knowledge at all times. Telemetry and command are accomplished with a UHF half-duplex radio and a backup S/L band radio. Electrical power is generated using both body-mounted and deployable solar arrays. Power is distributed with a custom Electrical Power System (EPS) which includes 48 Watt-hours of lithium-ion battery energy storage capacity.

Figure 1: Corvus-BC Spacecraft

Data and Power Module (DPM)

The Corvus-BC Data and Power Module (DPM) combines many of the control and housekeeping functions of the spacecraft into an easily accessible single integrated unit. The DPM consists of the following "cards": Battery Board, Power Board, Charging Board, Flight Computer, GPS, and UHF TT&C radio. The Battery Board contains 4x 18650 Lithium Ion cells, that offer a total 48 Whrs of energy storage. The Power Board offers regulated power switched voltages to the spacecraft subsystems including 5V, 8V, and 12V switches. All solar panel inputs are run into the Charging Board, which offers Peak Power Tracking (PPT) for battery charging. The Flight Computer contains a Cortex-A8 ARM processor running at 720 MHz with 512 MB of RAM. The Flight Computer runs a standard Linux kernel that has been customized for our application, with almost all spacecraft specific code running as user space applications. A MEMS IMU is located on the Flight Computer board and serves as the primary rate gyro. A Novatel OEM-615 is used as the GPS receiver. Finally, an AstroDev Lithium is used as the primary TT&C radio.

Figure 2: Assembled DPM Subsystem

Attitude Control Module (ACM)

The Attitude Control Module (ACM) consists of three Sinclair Interplanetary 30 millinewton-meter-second reaction wheels and a single 2 Hz sample-rate Sinclair Interplanetary star tracker. This hardware allows for low jitter 3-axis attitude control with a pointing knowledge of better than 92 arcseconds in all axes (including system level jitter and propagation errors). The reaction wheels provide a nominal torque of 2 millinewton-meters, which enables full 180 degree maneuvers in less than 30 seconds. These enable a pointing accuracy of better than 195 arcseconds in all axes, which translates to ~0.5 km of ground error from a 600 km orbit. All Sinclair products are put through rigorous environmental and functional tests to qualify them for launch and operations.

All three reaction wheels are controlled with a single UART RS-485 port. They consume 1.8 watts each at 5 volts when generating maximum torque, dropping down to 0.1 Watts at steady state low speed rotation. The Star Tracker is controlled with an RS-422 port, and consumes 0.4 Watts of power at 12 Volts while active. Quaternions are provided at a maximum rate of 2 solutions per second, allowing for spacecraft attitude control with only a simple MEMS inertial measurement unit.

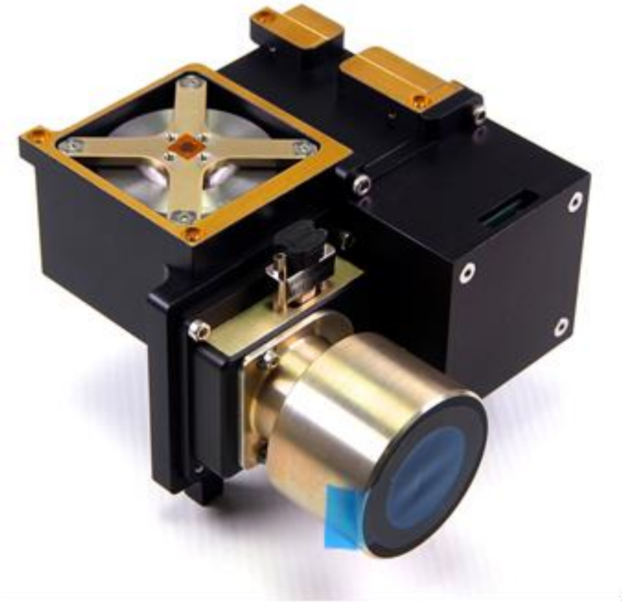


Figure 3: ACM Subsystem

Smart Solar Panels

The Astro Digital Smart Solar Panels serve as attitude control sensors and actuators and can be fitted with any solar cells that use the standard 26.62 cm^2 Spectrolab form factor. The +X and –X panels (defined as the panels on the UHF Antenna and Star Tracker faces respectively) each have 4 cells. The body-mounted Y axis panels have 18 cells each, and the deployed Y panels have 20 cells each. The –Z panel, which is the face opposite of the cameras, has 3 cells. The Corvus-BC mission currently uses the Spectrolab UTJ cells with 28.3% efficiency, but higher efficiency cells are also available from Spectrolab and SolAero.

All body mounted panels include a 2-axis sun sensor with sun intensity measurement, a 3-axis magnetometer, a temperature sensor, an embedded magnetic torque coil, current/voltage monitors for torque coils, and a microcontroller for telemetry collection and command distribution. The X axis torque coils each have a dipole moment of 31 $mA*m^2$, the Y axis torque coils have 115 $mA*m^2$, and the Z axis torque coil has 114 $mA*m^2$. These moments are all derived from a 5 Volt solar panel digital power supply.

Figure 4: A view of the +X, -Z, -Y Fixed Smart Solar Panels

Payload – Multispectral Camera

The Corvus-BC payload consists of a 3 band multispectral camera developed in house at Astro Digital. Each spectral band consists of a 70 Mega Pixel panchromatic sensor, with an optical bandpass filter placed inside of the optics train. The colors chosen for the Corvus-BC spacecraft are Green, Red, and NIR with the primary mission of agricultural monitoring. The field of view is 21 deg by 14.9 deg. The sensors have a raw digitalization of 12 bits. This means each frame, consisting of all 3 bands, results in 315 MB of uncompressed data. The camera includes a dual-core Cortex-A15 ARM processor running 32 bit Linux and a 1 TB solid state drive (SSD) for image storage. The amount of data generated by this payload necessitated new development to inexpensively offload all of the data to the ground.

Figure 5: Corvus-BC Camera Payload

A Gigabit Ethernet bus connects the camera payload to the high speed Ka-band transmitter subsystem. Images are losslessly compressed, encrypted, and then streamed as UDP/IP packets over the Ka-band link.

KA-BAND TRANSMITTER DETAILS

Astro Digital has developed multiple generations of Ka-band transmitters and previously presented on them (see [1][2][3][4]). All results in this paper are on the Generation 3 Ka-band transmitters flying on the Corvus-BC3 and Corvus-BC4 spacecraft.

Table 1: Dish Specifications

Aperture Diameter	2.80 m
Aperture Efficiency	55%
Antenna Gain	55.3 dBi
-3 dB Beamwidth	0.28 deg
-1 dB Beamwidth	0.08 deg
LNA Noise Figure	1.65 dB
LNA Noise Temp.	125 K
System Noise Temp. 99.5% Link Availability (Rain) Clear Sky	 372 K 225 K
System G/T 99.5% Link Availability (Rain) Clear Sky	 28.5 dB/K 30.7 dB/K

The Ka-band transmitter operates at 26.8 GHz center frequency with a symbol rate of 72 Msps. The roll-off is 0.2, resulting in a spectral bandwidth of 86.4 Mhz. The Ka-band transmitter uses a non-deployed horn as the antenna, providing 23.5 dB of gain, with a Left Hand Circular Polarization (LHCP). The amplifier provides 0.6 Watts (+27.8 dBm) of RF output. Combined with the antenna gain this results in an EIRP of about 100 Watts (20 dBW). The 3 dB roll-off point of the antenna is 10.2 deg (5.1 deg half-angle). This requires the ADCS system to have pointing errors of less than 5 deg while target-tracking the ground station (with less than 3 deg preferred).

Figure 6: Ka-band Transmitter

The current Generation 3 Ka-band radio does not have any receive capability, requiring the data downlink stream to operate in a very low bit error rate (BER) mode, otherwise any dropped packets cannot easily be recovered. The Generation 4 Ka-band radio will operate in full-duplex mode eliminating this constraint.

The link-layer protocol used is DVB-S2, an industry standard allowing for off-the-shelf equipment in the ground station. We utilize the IP/GSE encapsulation on top of the DVB-S2 BB frame. The MPEG framing is not used for any image transfers. Thus, this protocol stack could be used for any type of payload mission and is not specific to imagery.

The DVB-S2 protocol has 28 different Modulation-Coding (MODCOD) steps. Each MODCOD step results in a different data rate, but requires a different signal to noise ratio (SNR) for the link to close. The higher the MODCOD step, a higher SNR is required (but a faster data rate is achieved). Our Ka-band transmitter is capable of operating all 28 MODCOD steps in the protocol. MODCOD step 1 results in an instantaneous data rate of 35.3 Mbps and step 28 results in 320.6 Mbps.

GROUND SEGMENT

Our downlink station is located in Svalbard, Norway and is operated by our partner Kongsberg Satellite Services (KSAT) through their KSAT^{LITE} service. The dish parameters are outlined in Table 1. Located onsite are a pair of redundant commercial off the shelf (COTS) DVB-S2 demodulators capable of demodulating and forwarding the UDP/IP packets in real-time to a local server. Combined with a high-speed undersea fiber optic Internet link, the requirements for storage and processing at the ground station are minimized; the imagery can be streamed into the cloud in near realtime.

Our equipment was installed in Svalbard during the summer of 2016 prior to any of our Corvus-BC spacecraft launches.

Figure 7: Ka-band Dish at Svalbard

To keep costs down, the dish operates only in an open-loop tracking mode. This means the dish must keep the spacecraft within the 0.26 deg beamwidth during the pass or communications cannot be maintained. The means of providing predicted spacecraft ephemeris data to the dish tracking software is simply a Two Lined Element (TLE).

ADCS

The ADCS is a critical component that enables the Corvus-BC Ka-band downlink. The system must point the antenna boresight at the ground station throughout the entire pass within the 10.2 deg full-angle beam width. The advantage of this Ka-band downlink solution is that it does not impose unreasonable attitude knowledge and control constraints on the spacecraft. The pointing requirements can all be met very easily with COTS ADCS components.

The technology that differentiates the ADCS system is the flight software that enables the operational efficiencies demonstrated by the Corvus-BC.

Software

The Corvus-BC spacecraft utilize the MAX Flight Software suite from Astro Digital partner Advanced Solutions, Inc. MAX is an off-the-shelf, full-featured flight software suite with features including a highly capable ADCS, command and telemetry system, and sequence engine. After being ported and integrated into the flight hardware, MAX requires only configuration with very little mission specific software development. The entire MAX suite was integrated, configured, tested, and ready for launch on the Corvus-BC spacecraft in less than 5 months.

Table 2 lists the key components of the flight software that enable the pointing required to downlink data over the ground station.

Table 2: Key ADCS Software Components

Component	Description
Orbit Determination	On-board, J4 propagator that is initialized and updated by GPS measurements through a fixed gain filter.
Attitude Determination	6-state Kalman filter that estimates attitude and rate bias. The filter is configured to accept asynchronous measurements from all sensors on the spacecraft.
Attitude Control	Attitude control is achieved using a PIID controller that commands the reaction wheel. The controller includes feed forward gyroscopic and guidance command torques.
Momentum Controller	The momentum controller commands the Smart Panel torque coils to drive momentum to the momentum target of 1 mNms on each axis. This ensures maximum agility to slew the spacecraft at all times while keeping the reaction wheels from excessive zero crossings.
Mode Controller	The MAX mode controller allows operators to configure as many guidance modes as desired. The guidance modes give operators the ability to define an alignment target and clocking target and assign body vectors to each. The alignment and clocking vectors can be anything the spacecraft has ephemeris for, including static and dynamic ground targets, orbit-based references like nadir and velocity, celestial bodies such as the Sun and Moon, even orbiting targets.
Sequence Engine	The FlightJAS sequence engine in MAX is adapted from the InControl JAS scripting language. Human readable FlightJAS files can be uploaded and executed on-board the spacecraft. The FlightJAS engine has access to all spacecraft telemetry and parameters, can perform complex vector math, and can be used to setup state machines. The capability of the sequence engine enables unprecedented flexibility and highly autonomous spacecraft operations.
RendezSlew	A proprietary slew algorithm that computes the optimal slew from the current attitude and rate to the commanded attitude and rate. Since the slew profiles starts and ends at the desired rate as opposed to zero rate, there is virtually no settling time. The spacecraft is smoothly tracking the target immediately after the slew ends. The algorithm uses actuator-based limits to determine the minimum amount of time required to safely perform the slew. This removes the need for the operations team to plan every slew ahead of time on the ground.

Maneuver Design

ADCS maneuvers impact almost every subsystem. As such, the maneuvers to track the ground station require coordination with all subsystems. The primary requirement for the maneuver is to point the Ka-band antenna boresight at the ground station. This alignment requirement provides rotational freedom about antenna boresight, generally called the clocking or constraint option. The secondary requirement is to clock to the Sun to collect maximum solar energy during downlinks. The symmetry of the Corvus-BC bus provides the flexibility to clock either the +Y or -Y panels at the Sun and produce equivalent power.

This is a complex set of requirements that generally requires operator planning for each maneuver that is performed. The MAX FSW architecture makes this planning seamless and enables a generic solution that requires minimal operator time. ADCS and mission planning is performed using the SOLIS tool with STK. SOLIS is a user interface within STK that allows operators to configure the MAX FSW, generate the actual flight sequences, and run closed-loop simulations executing the same FSW that is running on the spacecraft.

Using SOLIS, the operations team developed a sequence that automatically commands a slew to track the ground station anytime the spacecraft comes overhead. Based on the orbital geometry for the given pass, the sequence will determine which panel to clock to the Sun and configure the slew appropriately. The flexibility of this approach has enabled the operations team to develop, uplink, and execute sequences to perform downlinks at other ground stations around the world in a matter of a couple hours.

Figure 8 shows the attitude during a downlink. The spacecraft is moving from South to North and, in this case, the +Y axis is clocked to the Sun. The cyan cone pointed at the Svalbard ground station represents the 5.1 deg half-angle Ka-band beam. The dark blue cone coming out of the spacecraft -X axis represents the star tracker field of view pointed to space.

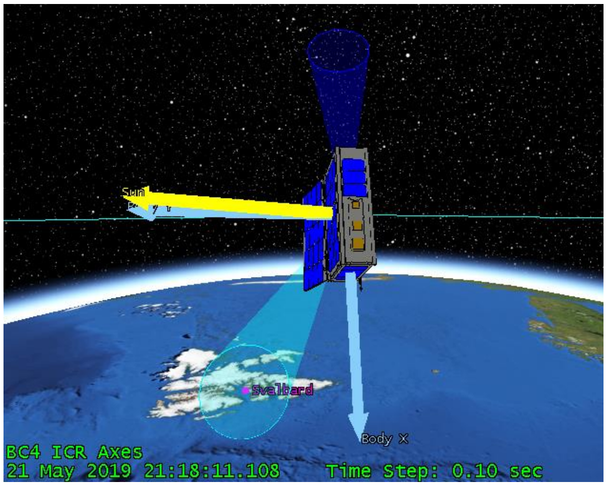


Figure 8: Spacecraft attitude, including Ka-band beamwidth and star-tracker FOV while downlinking over Svalbard

OPERATIONS

The Astro Digital operations team is responsible for coordinating and scheduling each Ka-band downlink pass with KSAT. For simplicity, each downlink pass with the Ka-band dish is manually scheduled on a weekly basis. This gives us the flexibility to test and tune this process, ultimately optimizing the downlink volume. The schedule, written in XML format, is uploaded to the KSAT scheduling FTP server, from which the Ka-band dish processes it and tracks the spacecraft. To assure accurate tracking, the latest JSPOC TLE is pushed to the dish 30min prior to the start of the pass via an FTP server.

The Ka-band downlink is also manually scheduled on the Corvus-BC spacecraft, albeit daily instead of weekly. To schedule a single downlink, several commands are sent to the spacecraft through the TT&C ground station a previous orbit. The parameters for these commands include the MODCOD step to be used, payload content, start time, and duration. The payload content scheduled for downlink is commanded as a list of files and is updated daily, based on the current downlink priorities. This list is then uploaded to the spacecraft, as part of the downlink commands, via FTP over the TT&C link. Finally, the target-track sequence will automatically slew the spacecraft to track the ground station when in view (completely offloading all GNC calculations from the operations team).

In accordance with the National Oceanic and Atmospheric Organization (NOAA) regulations on earth imagery data handling, our connection to the KSAT ground station exists in a virtual private network (VPN). During the Ka-band pass, the on-site DVB-S2 demodulators and payload data throughput are monitored realtime. The redundant demodulators forward the demodulated data to an on-site Linux virtual machine, where the data is then pushed to the data pipeline.

ON-ORBIT RESULTS

ADCS Results

Figure 9 shows the attitude rates for both the initial slew and the entire Svalbard track maneuver.

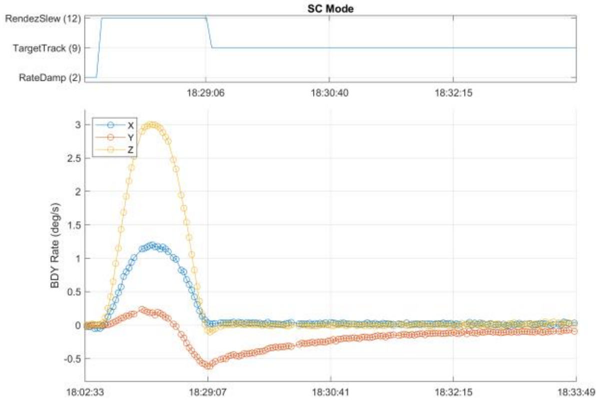


Figure 9: Attitude rates during target track maneuver

The maximum rate in the slew was roughly 3 deg/sec which required a third of the reaction wheel capacity. For the target track period itself, tracking Svalbard and clocking to the sun, the maximum rates required were less than 0.5 deg/sec in each axis.

Figure 10 shows the controller attitude and rate errors during the target track period. These values represent the error between the commanded attitude/rate and the estimate attitude/rate.

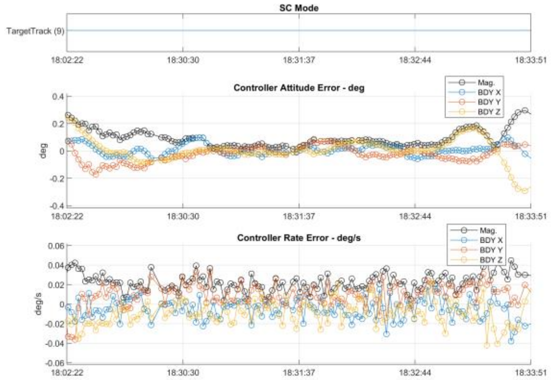


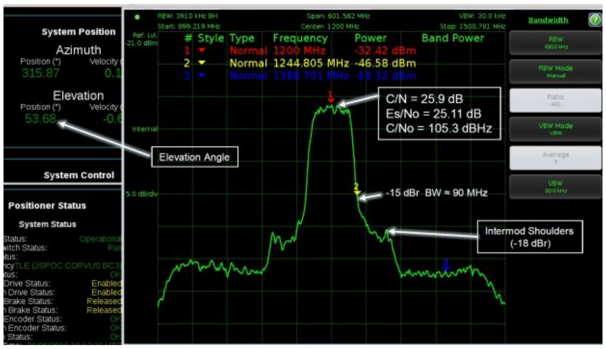
Figure 10: Controller errors during target track

The attitude errors throughout the entire Svalbard track period remain below 0.4 deg with rate errors below 0.05 deg/s. Additionally, the Kalman filter residual data from the star tracker is consistently below 0.5 deg which indicates an accurate attitude estimate (the majority of the error is due to uncalibrated sensor misalignment).

The flight ADCS telemetry and Ka-band downlink performance confirm that the spacecraft pointing is well within the 5.2 deg requirement with significant margin.

Ka-band results

During the initial transmit tests we connected a Signal Analyzer to the Intermediate Frequency port (post down conversion from 26.8 GHz to 1.2 GHz). As shown in Figure 11, the received signal strength was better than predicted. This meant that all 3 major systems (Ka-band transmitter, ground segment, and ADCS) exceeded their expected performance.



RBW: 3910 kHz BH
Start: 899.219 MHz
Span: 601.562 MHz
Center: 1200 MHz
VBW: 30.0 kHz
Stop: 1500.781 MHz
Ref. Lvl. 21.0 dBm
5.0 dB/div

#	Style	Type	Frequency	Power	Band Power
1	▼	Normal	1200 MHz	-32.42 dBm	
2	▼	Normal	1244.805 MHz	-46.58 dBm	
3	▼	Normal	1398.701 MHz	-58.32 dBm	

C/N = 25.9 dB
Es/No = 25.11 dB
C/No = 105.3 dBHz

Figure 11: Received signal at 53 deg elevation

Due to the improved performance we are able to operate the Corvus-BC spacecraft in a higher MODCOD mode (higher data rate), all the way to an elevation angle of 5 deg. As shown in Figure 12, the total system is able to maintain data lock with MODCOD step 18 (185 Mbps) from about 5 deg elevation during the start of a pass and all the way through to 5 deg at the end of a pass.

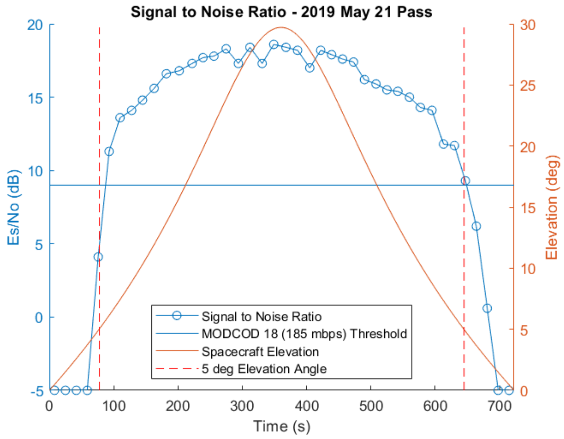


Figure 12: Typical received SNR during a pass

Example Imagery

Figures 13, 14, and 15 are examples of processed scenes taken from Corvus-BC spacecraft. On a typical pass we are able to download around 10 of these scenes.

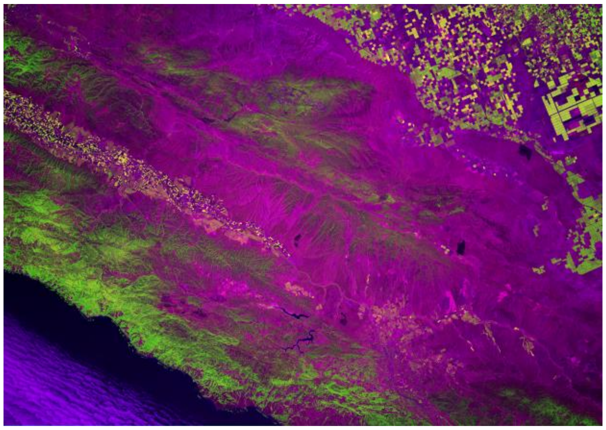


Figure 13: California central coast processed as NDVI

Figure 14: Shanghai processed as true color

Figure 15: View of the limb off the coast of southern California at an extreme angle

LESSONS LEARNED AND FUTURE IMPROVEMENTS

The original Corvus-BC spacecraft relied solely on a commercial rate sensor device intended for smart phones. While providing an attractive price point relative to traditional aerospace devices, the performance presented a couple of key challenges. First, thermal testing revealed that the rate sensor bias was highly dependent on temperature and could vary as much as 1 deg/sec over the temperature range seen in flight. This requires multiple thermal cycles to be performed so that a temperature compensation correction could be computed and applied. The temperature compensation provided relatively good performance but requires dedicated testing for each spacecraft. Additionally, the sensor noise and bias drift meant that the attitude solution would drift quickly when the star tracker becomes blinded. While these challenges did not impact the success of the mission, it has been decided to fly higher performance rate sensors on future missions. The elimination of the thermal characterization and the operational capability to fly through star tracker outages ultimately outweighs the higher acquisition cost.

Data and observations have been collected over dozens of Svalbard passes with maximum elevation angles ranging from around 40 deg up to 90 deg. On higher elevation passes, a minor decrease in signal strength is observed near maximum elevation. This is due to errors in the JSPOC TLE used to point the dish at the spacecraft. Errors in the TLE can be unpredictable and are largely dependent on the age of the TLE. At the current data rates, this does not impact the downlink. Better performance has been observed when the operations team generates a TLE based on recent GPS telemetry. However, since the JSPOC TLE has proven to be sufficiently accurate, that has been the preferred method because it greatly simplifies operations.

CONCLUSIONS

Multi-Gigabyte (GB) single pass downloads are now achievable by low cost CubeSats and low cost ground stations operating in open-loop tracking. Near term versions of the Astro Digital Generation 4 Ka-band transceiver should allow for over 10 GB per pass.

Relative to existing systems, the Astro Digital Ka-band solution provides cost-savings for equivalent or higher throughput than current X-band systems. To achieve similar data rates, X-band systems use ground dishes that are more than twice the diameter of our Ka-band dish. The requirement for a larger dish dramatically increases the cost to develop, operate, and maintain the ground segment. Furthermore, the Astro Digital Ka-band solution has demonstrated higher data rates than the near term proposed optical communication systems for CubeSats schedule to launch within the next few years. This is currently being achieved without the immense technical hurdles that these optical communications systems face.

Acknowledgments

Many people contributed to this project. We would like to thank the engineering and management teams at Astro Digital, especially Gordon Hardman, Jin Kim, and Duc Mai. At ASI Brandon Smith, Jeff Smernoff, Jeff Szmyd, Kyle Andringa, and Jason Wynn contributed many late nights to this project. We also could not have done this without the excellent support from the folks at KSAT, especially Atle Ursfjord, Trond Rokstad, Katherine Monson, Carolyn Belle, and Stig-Are Thrana.

References

1. King, Leveque, Bertino, Kim, and Aghahassan, “Ka-Band for CubeSats,” SmallSat Conference, August 2015.
2. King et al., “Ka-Band Transmitter Status,” Small Satellite Communications Workshop, August 2015.
3. King et al., “Third Generation Ka-Band Transmitter For CubeSat And NanoSat

Missions," Small Satellite Communications Workshop, August 2016.

4. King et al., "Ka-Band High Speed Data Systems for CubeSats and NanoSats," Small Satellite Communications Workshop, August 2018.