Early Results of the CASCADE Technology Demonstration Payload on CASSIOPE

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ABSTRACT

CASSIOPE (CASCADE, SmallSat and Ionospheric Polar Explorer) is a Canadian SmallSat mission that supports two distinct payloads, a suite of eight space science instruments which are referred to as e-POP (Enhanced Polar Outflow Probe) and an experimental technology demonstration payload, entitled CASCADE CX, which is the focus of this paper.

The experimental payload will be used to demonstrate key aspects of implementing a space-based high volume data transfer. The design has been specifically optimized to enable very large and timely data file transfers.

The CASCADE CX payload has been commissioned and several demonstration experiments have occurred which have validated key enabling technologies and demonstrated the end-to-end transfers of very large data files. The results of these experiments have shown that a scaled up version of the CASCADE CX experimental payload could be built to support a composite 2.4 Gbps data transmission rate enabling the pickup/delivery of data at a rate in excess of 15 Gigabytes per minute of satellite access at a BER no worse than $1x10^{-17}$.

INTRODUCTION

CASSIOPE was launched on September 29, 2013 on the first Falcon9 v1.1 from Vandenberg Air Force Base into a 325 km by 1500 km orbit at 81 degrees inclination.

The CASSIOPE mission has three primary goals – demonstrate a generic Smallsat Bus that could be used for future Canadian small satellite missions, perform scientific studies of Space Weather using a suite of eight science instruments called ePOP and demonstrate a large data file store and forward technology payload.

This paper focuses on the technology demonstration payload as well as the results of the commissioning and demonstration experiments performed to date.

CASCADE DEMONSTRATION PAYLOAD (CX)

Description

The CX payload provides two-way data communications capability to a Ground Terminal (GT). The payload consists of two major parts, the RF/Digital Subsystem and the Data Storage Unit. The payload is operated in a half-duplex mode, either transmitting or receiving, but not both simultaneously. Generally during a single contact with a ground station the payload will transmit or it will receive, however, nothing precludes the payload from switching between transmit and receive during a contact. In fact for CASSIOPE, this capability was demonstrated.

The RF/Digital Subsystem for the CX Payload was built up to demonstrate two channels of the CASCADE system. Common to both the uplink and downlink chains are the body mounted horn antenna, the Master Oscillator (MO) and the Frequency Generation Unit (FGU). The uplink chain also has a receiver as well as a two channel Demodulator, while the downlink chain has a primary and redundant Travelling Wave Tube Amplifier (TWTA) and a two channel Modulator. The two channels on the CX payload are RHCP and separated in frequency. Each channel operates at 350 Mbps.

A high capacity Data Storage Unit (DSU) is key to the store and forward mode of operation for CASCADE. The DSU has 1 Tb of storage broken over four storage sub-units. Two of these are dedicated to CX data storage and the others are dedicated to ePOP. The DSU has a data link to the ePOP Payload to allow the storage of science data on the DSU for Ka-band downlink.

Early in the CASSIOPE program, an opportunity to increase the amount of science downlinked was identified. By adding a data link between the ePOP Payload and the DSU, ePOP science could be downlinked on the CASCADE Ka-band link as well as the S-band link. Given the difference in the data rates (4 Mbps for S-band versus 350 Mbps for Ka-band), this was seen as a way to potentially increase the science yield by over an order of magnitude.

A block diagram of the CX payload can be found in Figure 1.

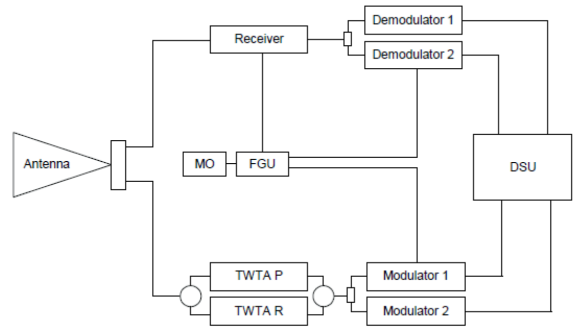

Figure 1: Block Diagram of CX Payload

Associated with the payload is the CX ground terminal. The CX ground terminal provides the terrestrial end of the high rate Ka-band link and allows data to be moved onto or off of the system. The terminal is both transmit and receive capable on a half-duplex basis. For convenience of operations, the CX ground terminal has been co-located with the Mission Operations team in Calgary, Alberta, Canada.

A picture of the CX Payload on its Payload panel can be seen in Figure 2 and the CX Payload on the CASSIOPE spacecraft can be seen in Figure 3.

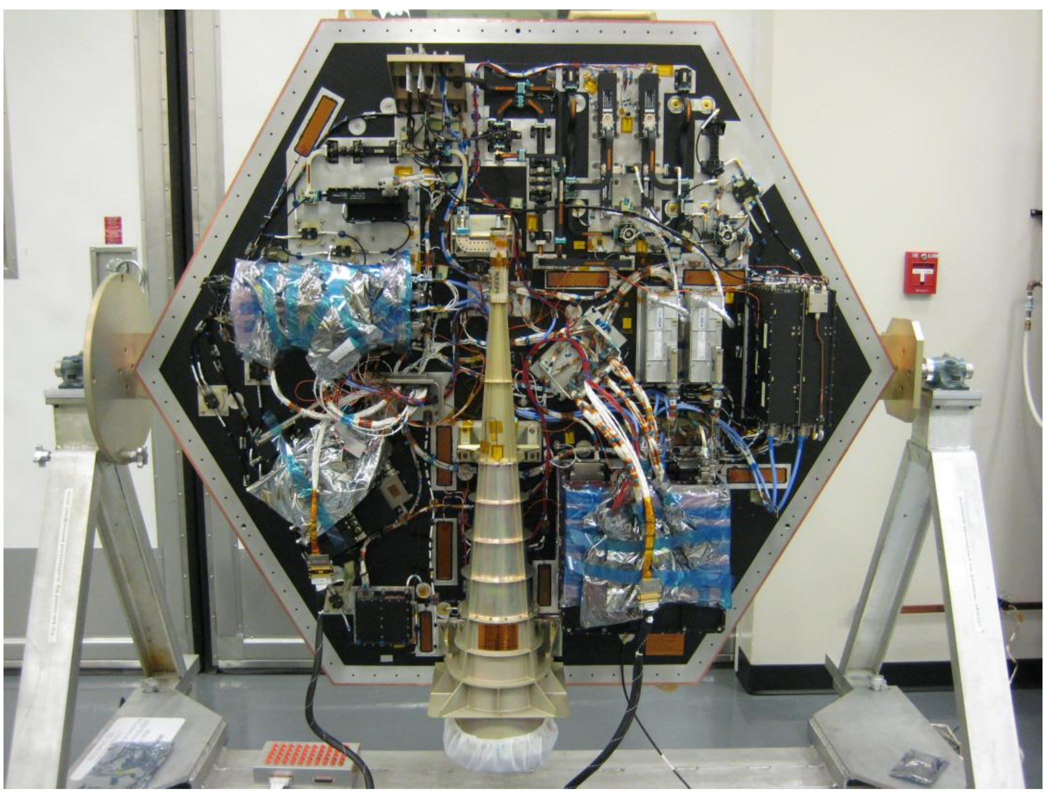

Figure 2: CX Payload installed on Payload Panel

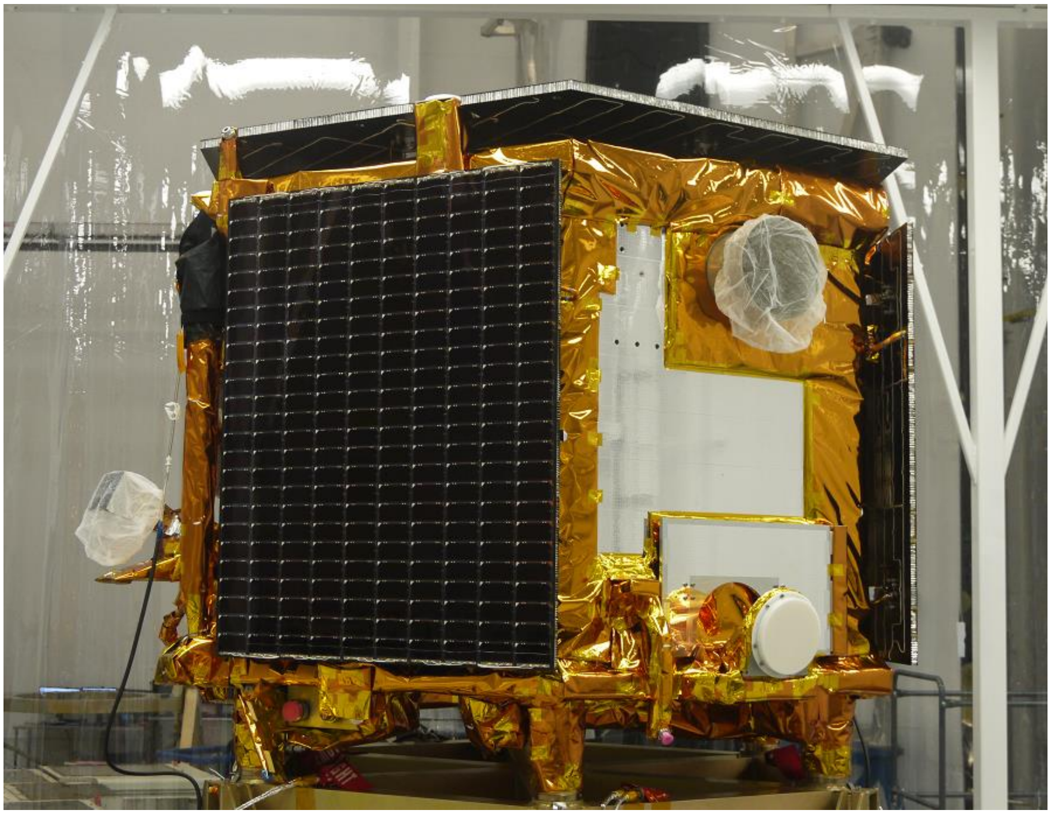

Figure 3: CX Payload installed on CASSIOPE Spacecraft

Concept of Operations

CASCADE's data rate is possible due to the Ka-band frequency, however such high frequency signals are more susceptible to 'rain fade' (attenuation by atmospheric water). In addition to being able to store and forward large data files, the system is intended to deliver the files with a very low Bit Error Rate (BER) of no worse than $1x10^{-17}$. One of the keys to achieving this low BER in all atmospheric conditions is the use of a beacon during transmissions. The receiving end of the chain broadcasts a beacon to the transmitting end of the chain. The transmitting end receives this beacon and modulate the transmit power based on the signal strength of the beacon. If the beacon signal is too low, the transmitter stops sending data and instead sends a fill pattern until the beacon signal improves.

This operational paradigm for the CX payload results in four potential 'day in the life' scenarios depending on the severity or type of degraded uplink and/or downlink, which are described below.

Nominal Case

This is the default case expected for the majority of data deliveries, with excellent uplink and downlink conditions. A few correctable bit errors have been included in this case, as they may occur during transmission, but are handled by the forward error coding mechanism at the destination ground terminal. This case is illustrated in Figure 4.

The source GT frames and encodes the user data file that has been copied to the terminal by the user. At the scheduled time the data file is uplinked to the CX Payload. Space has been allocated for the storage of user data on the CX Payload, which includes some margin for beacon dropouts. In this case, since there are no dropouts all the data is successfully uplinked to the CX Payload and for the remainder of the scheduled uplink the source GT uplinks fill data.

At the scheduled time the CX Payload downlinks the stored data to the destination GT. In a similar manner as the uplink the downlink includes some margin for beacon dropouts. The CX Payload downlinks the stored data with one data frame having a correctable error. Since there were no dropouts, after all the stored data was downlinked the CX Payload downlinks fill data for the remainder of the scheduled time.

The destination GT decodes all the data, correcting any correctable errors, and discards any fill data frames. The destination GT then rebuilds the original user data file and delivers it.

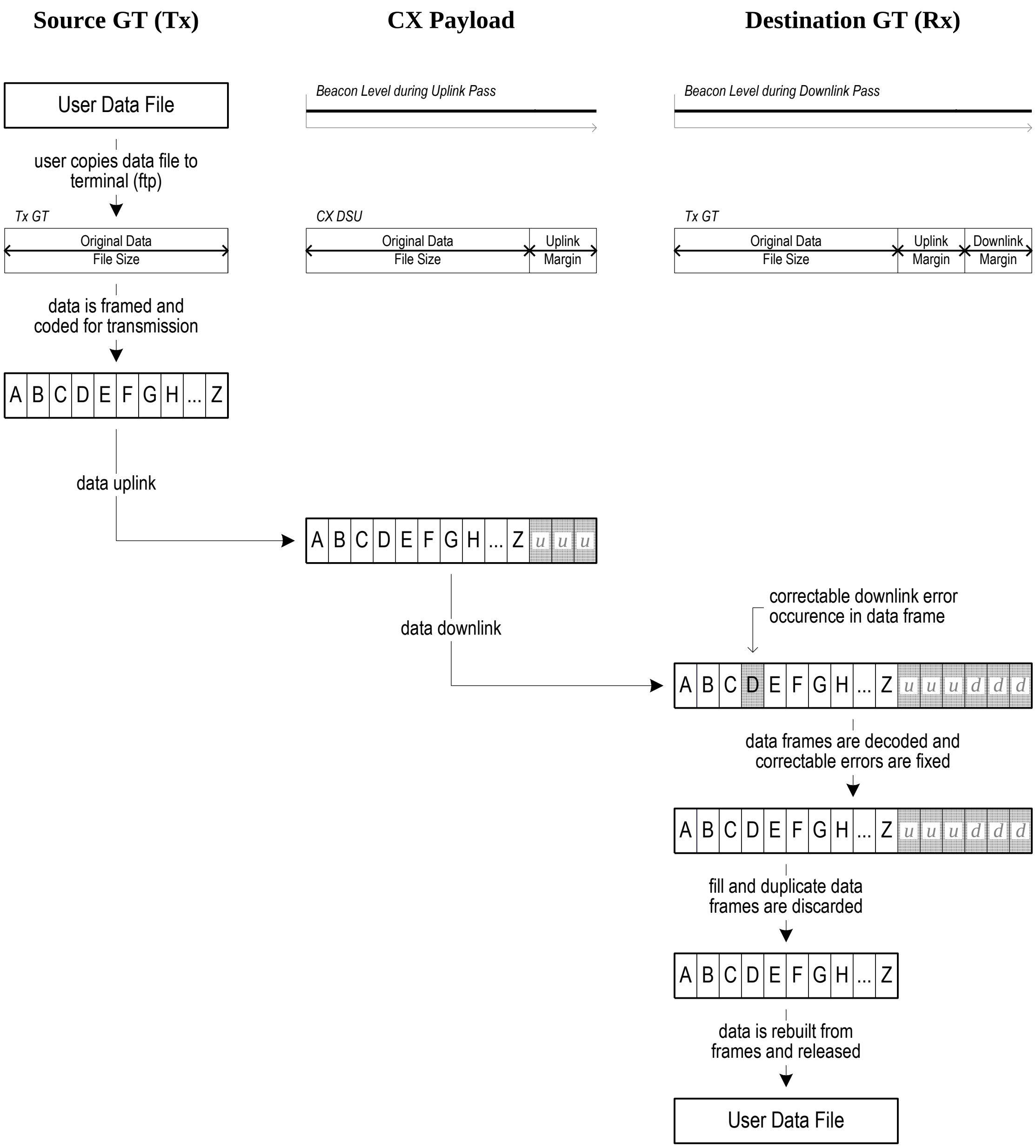

Figure 4: CX Nominal Case

Short Beacon Drop-Out Case

This is the case in which the beacon indicates, for a short period of time (i.e. less than the margin configured by the system), that the uplink or downlink conditions are sub-optimal for transmission such as during a rain fade event. This case is illustrated in Figure 5.

In this case, once the beacon level drops during an uplink, the data frame(s) being transmitted may be corrupted (i.e. have uncorrectable errors). Upon detection of the beacon level dropping below a threshold the source GT ceases transmission of the user data and instead transmit fill data until the beacon returns to an acceptable level. Once normal transmission conditions are re-established the source GT will 'rewind' for a configurable amount of data frames and complete the transmission from that point in the user data. This provides redundant frames for those that may have been corrupted at the onset of the fade.

After the destination GT receives the data the it again removes all the fill data frames and discards the corrupted frames, replacing them with the redundant frames included in the data (duplicate frames resulting from this redundancy are discarded).

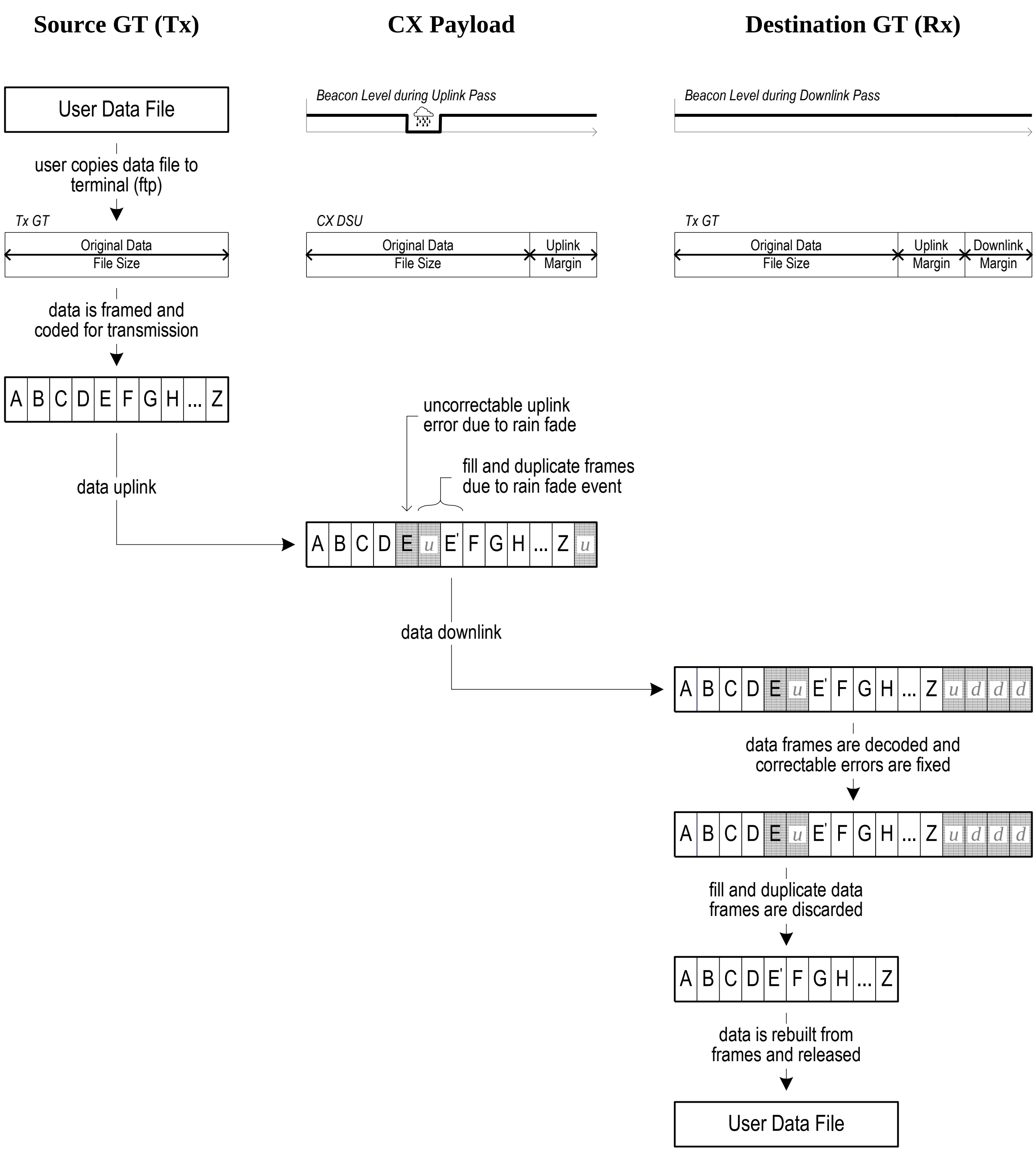

Figure 5: CX Short Beacon Drop-Out Case

Back-Haul Case

In this case there are a small number of uncorrectable data frames received at the destination GT, possibly due to an undetected (i.e. there is no beacon drop-out) interference event such as lightning. This case is illustrated in Figure 6.

Since the number of frames that must be replaced are small, these frames are requested by the SCC and sent from the source GT to the destination GT, through the SCC, via a low-bandwidth back-haul connection (i.e. not via the CX Payload). The destination GT then replaces the corrupted data frames with the new frames.

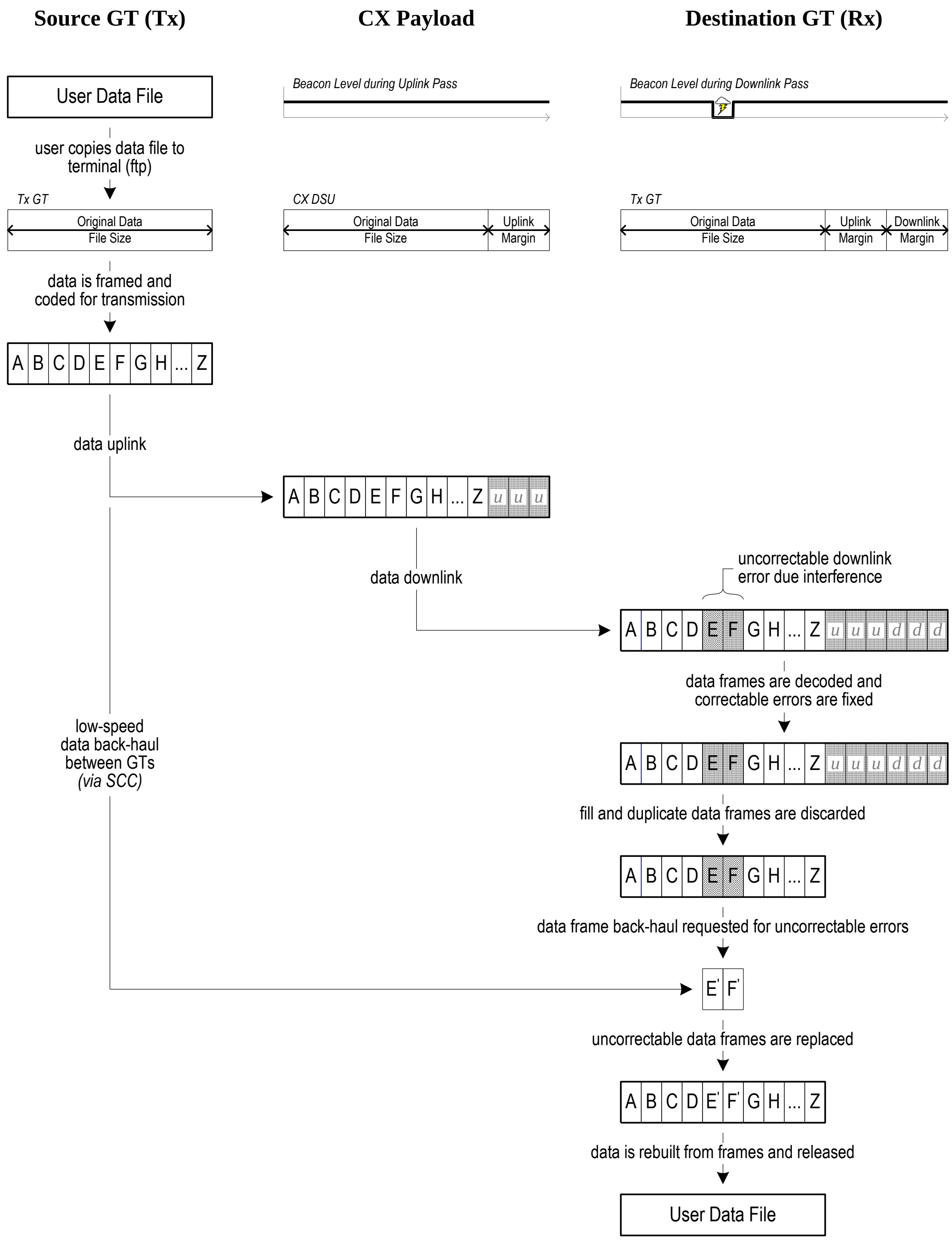

Figure 6: CX Back-Haul Case

Re-Transmission Case

In this 'worst' case there are a significant number of corrupted data frames (i.e. due to interference, such as certain man-made infrastructure) and/or a significant number of missing data frames such as due to an extended beacon drop-out such as during a rain storm. This case is illustrated in Figure 7.

In this case sending the replacement and missing frames via the low-bandwidth back-haul connection is not viable so the system will schedule a re-transmission of the data from the source GT to the destination GT via the CX Payload during another pass.

The destination GT then takes these re-transmitted data frames and replaces the corrupted and missing data frames.

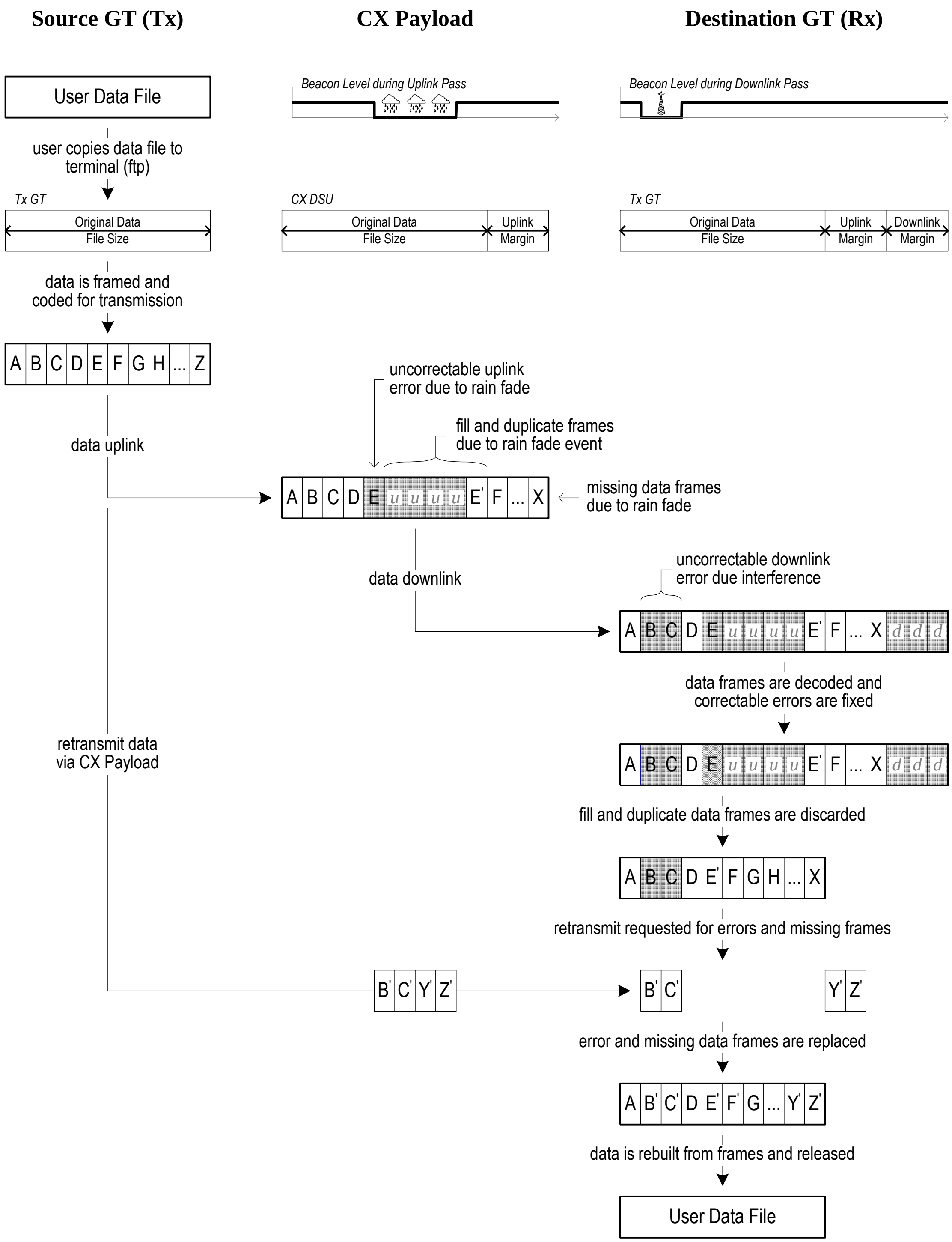

Figure 7: CX Re-Transmission Case

CX ON ORBIT RESULTS

Commissioning Activities

CX payload commissioning was interleaved with activities on Bus and ePOP subsystems, starting after confirmation of Bus thermal maintenance of the payload panel. Each unit was powered for the first time during a real-time pass with operators and a payload engineer in the command loop. In each case the unit was brought to an active state (stopping short of signal transmission or reception), and unit status and power telemetry were confirmed to be nominal. Units were checked in a sequence of logical groupings: Payload

Control Software (PCS), Master Oscillator, Data Storage Unit, the receive chain (Demodulator and Frequency Generator) and the transmit chain (Modulator, TWTA, and waveguides). The PCS and the Master Oscillator were left active after status confirmation as this is the normal state for operations, while other units were powered off after their activity was complete. Finally, as a bridge to the CX demonstrations, short transmissions with breaks were scheduled on GT passes; although the GT was not used to send/receive data the procedure was able to confirm back orbit control and timing for future CX demonstration activities.

On the ground, GT commissioning began by carrying out an antenna pointing calibration procedure using the following references: the sun, the geostationary satellite WildBlue and then CASSIOPE itself. Antenna power output was also calibrated by temporarily routing the GT TWTA output to a Ka-band power sensor and spectrum analyzer for verification. Sensitivity on the receive chain was confirmed during early downlink activities by comparing power observed to a single active channel to the apparent noise floor on the other, inactive channel.

CX Demonstration Activities

CX demonstrations included ‘round trip’ transfer of large data files from/to the GT and downlink of data collected in orbit by the ePOP science instruments. Data prerecorded and verified during the spacecraft Assembly, Integration and Test (AIT) phase was also available to support testing. GT files were ASCII numeric counting sequences generated as needed to suit available pass durations. The CX Payload performance was assessed from the payload pass telemetry, GT frame extraction reports, and more directly by comparing source and received files. Figure 8 and Figure 9 show the results of one of these demonstration activities. Figure 8 shows the telemetry from the CX Payload during an uplink from the GT. The upper plot shows that the Demodulator achieves lock and is able to maintain the lock throughout the uplink. The lower plot shows the beacon power that is being transmitted by the CX Payload to the GT during the uplink session. Figure 9 shows CX Payload telemetry during a downlink of data from the CX Payload to the GT. The upper plot shows the signal strength of the beacon being received by the CX Payload. About three-quarters through the downlink, the beacon strength goes below the minimum threshold for transmitting data, which triggers the CX Payload to stop transmitting data and start transmitting fill as it waits for the signal strength to improve. In this particular example, the beacon fails to go back above the required minimum level before the end of the pass, but it provides a good example of minimizing data loss nonetheless.

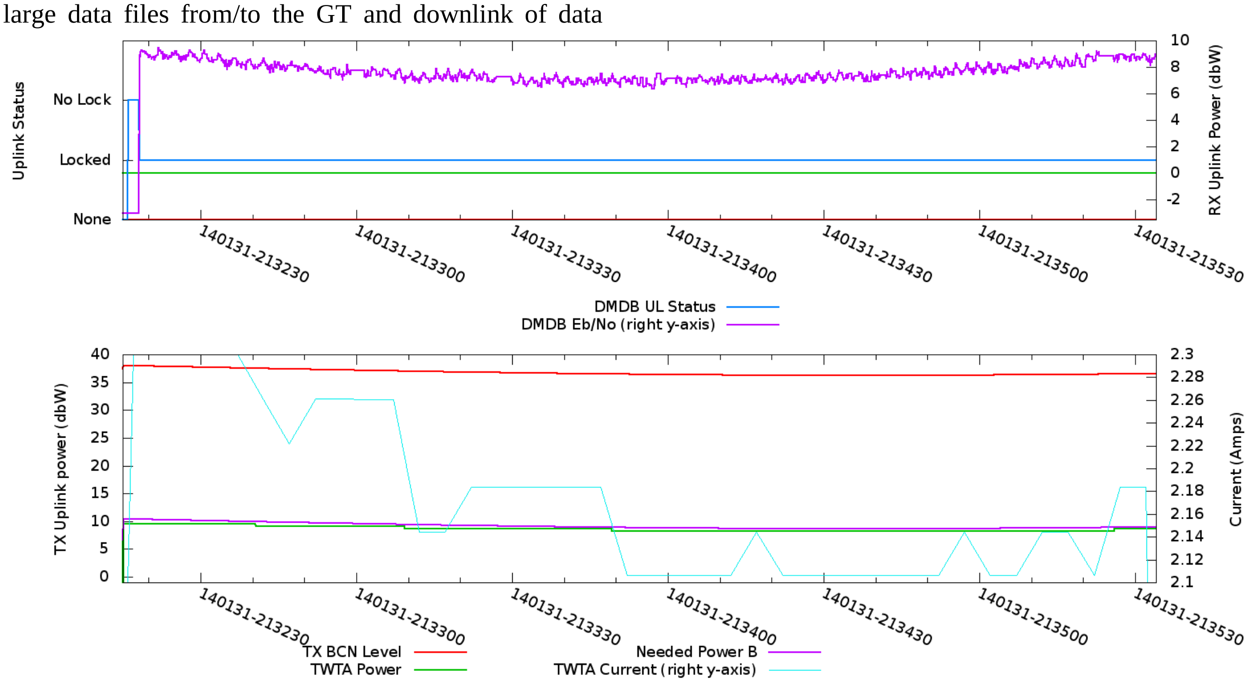

Figure 8: CX Signal and Power Telemetry During Uplink from GT

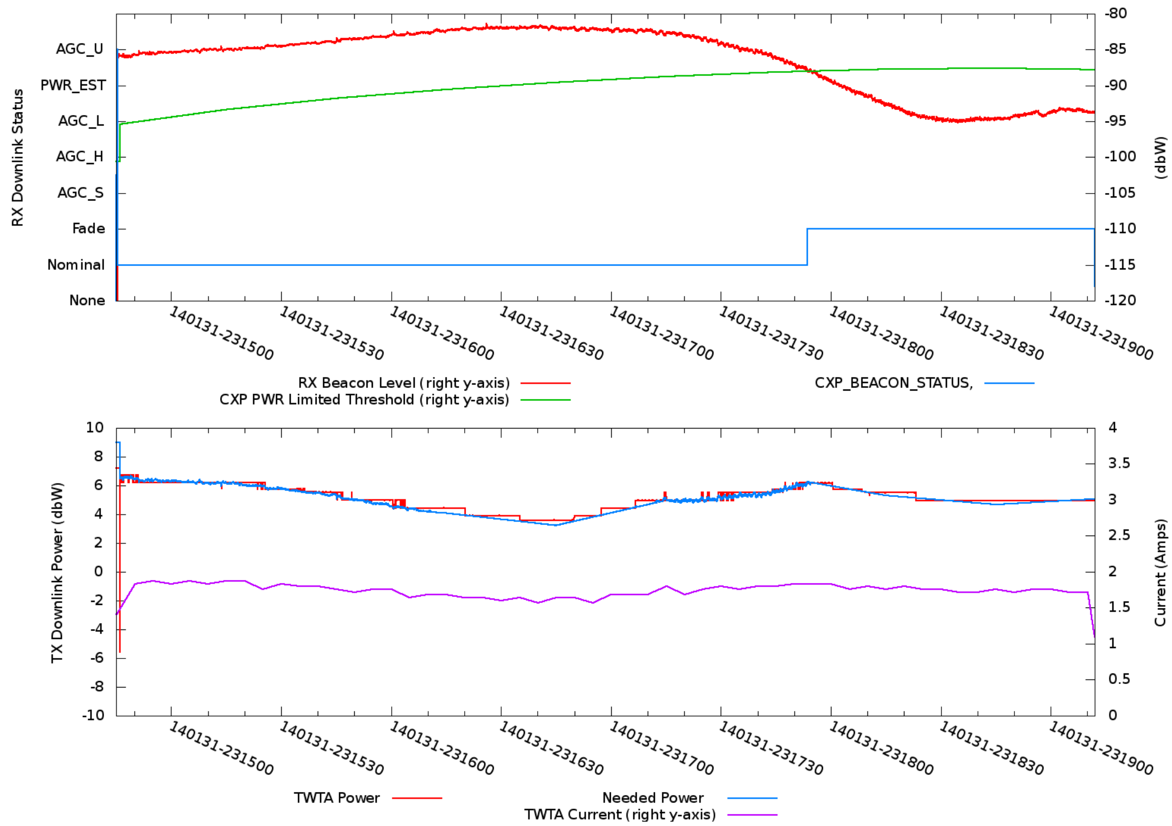

Figure 9: CX Signal and Power Telemetry During Downlink to GT

The figures above represent the largest GT uplink/downlink file transfer demonstration performed to date with the CX Payload. In this demonstration the CX Payload delivered 99.96% of a 6.3GB file, with the remainder being undelivered due to the fade conditions mentioned above. Had this occurred in an operational scenario, a backhaul or re-transmission would have been scheduled to provide the missing data.

In addition to uplink/downlink exercises with the GT, science data which had been collected and downlinked in relatively small segments for ePOP commissioning was also incrementally transferred to the CX payload, which was then downlinked to the GT. This 7.5GB of accumulated science data which had previously been downloaded over more than 25 S-band passes was successfully downlinked in a single Ka-band pass. In this case files could not be directly compared, but science data sequence and checksum fields were used to confirm completeness. At the end of the demonstration phase operators started conducting routine downlink of large (>3GB) science data collections. Unfortunately, due to an untimely failure of an RF converter in the GT low channel, all demonstrations were restricted to the high channel.

CONCLUSIONS

As a result of the demonstrations performed with the CX Payload, much of the technologies (both on-orbit and on the ground) and processes developed have been validated including:

- A proven Gigapackage format for transporting large amounts of data. A relatively high error level can be corrected in the files that are moved through the satellite, keeping the power and antenna size requirements on both the satellite and the ground terminals small.
- A proven technique for using a 30GHz beacon to assess the quality of a 20 GHz data link (and vice versa) By using a beacon to assess in real-time whether or not the link is in a fade, keeps power and antenna sizes on both the satellite and terminals can be kept much smaller than they would otherwise need to be.
- A qualified payload design. The architecture has been proven and critical units qualified (Modulator, Demodulator and DSU).

- A qualified Ground Terminal system design. Algorithms implemented on the existing Ground Terminal have been refined and validated, to be used as the core of any new Ground Terminals.

In addition to the technology validation, the CX Payload on CASSIOPE has also provided a benefit to the ePOP Science team. The ePOP Science team has been able to use the CX link to download additional science data that would have not been possible using the S-band link alone.

ACKNOWLEDGEMENTS

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