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Preliminary results from the CHOMPTT laser time-transfer mission

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ABSTRACT

CubeSat Handling of Multisystem Precision Time Transfer (CHOMPTT) is a demonstration of precision ground-to-space time-transfer using a laser link to an orbiting CubeSat. The University of Florida-led mission is a collaboration with the NASA Ames Research Center. The 1U optical time-transfer payload was designed and built by the Precision Space Systems Lab at the University of Florida. The payload was integrated with a NASA Ames NOdeS - derived spacecraft bus to form a 3U spacecraft. The CHOMPTT satellite was successfully launched into low Earth orbit on 16 December 2018 on NASA’s ELaNa XIX mission using the Rocket Lab USA Electron vehicle. Here we describe the mission and report on the status of this unique technology demonstration. We use two satellite laser ranging facilities located at the Kennedy Space Center and Mount Stromlo, Australia to transmit nanosecond, 1064 nm laser pulses to the CHOMPTT CubeSat. These pulses are timed with an atomic clock on the ground and are detected by an avalanche photodetector on CHOMPTT. An event timer records the arrival time with respect to one of the two on-board chip-scale atomic clocks with an accuracy of 200 ps (6 cm light-travel time). At the same time, a retroreflector returns the transmitted beam back to the ground. By comparing the transmitted and received times on the ground and the arrival time of the pulses at the CubeSat, the time difference between the ground and space clocks can be measured. This compact, power efficient and secure synchronization technology will enable advanced space navigation, communications, networking, and distributed aperture telescopes in the future.

INTRODUCTION

Ground-to-space clock synchronization with accuracies below the nanosecond level is important for navigation systems, communications, networking, remote sensing using distributed spacecraft, and tests of fundamental physics. The Global Positioning System is the most widely used tool for synchronizing spatially separated clocks. State-of-the art GPS time transfer is currently accurate to a few nanoseconds[1].

Several precision time transfer experiments between ground and space, beyond GPS, have been carried out recently and are planned in the near future. OCA (Observatoire de la Côte d'Azur) and CNES (Centre National d'Études Spatiales), France, launched T2L2 (Time-Transfer by Laser Link) in 2008 on the Jason-2 satellite[2]. Like CHOMPTT, the T2L2 experiment was based on the techniques of satellite laser ranging. It consisted of synchronizing ground and space clocks using short laser pulses travelling between the ground clocks and the satellite instrument. The measured T2L2 time transfer precision was ~50 ps. One-way laser ranging to the Lunar Reconnaissance Orbiter (LRO), commissioned in 2009, has been conducted successfully from NASA's Next Generation Satellite Laser Ranging System (NGSLR) at Goddard Geophysical and Astronomical observatory (GGAO) in Greenbelt, Maryland[3]. A one-way ranging technique was used, where the Earth laser station measured the transmit times of its outgoing laser pulses and the Lunar Orbiter Laser Altimeter (LOLA), one of the instruments onboard LRO, measured the receive times. The time transfer precision was limited to 100 ns by the NGSLR.

In the near future, the Atomic Clock Ensemble in Space (ACES) mission sponsored by the European Space Agency will fly aboard the International Space Station (ISS)[4]. ACES is a fundamental physics experiment that will use a new generation of atomic clocks operating in the microgravity environment of space, which will be compared to a network of ultra-stable clocks on the ground. The ACES clock time will be transferred between space and ground by microwave and optical links.

The CHOMPTT mission incorporates the novel compact, low-power Optical Precision Time-transfer Instrument (OPTI), developed by the Precision Space systems Laboratory (PSSL) at the University of Florida (UF), and a 3U CubeSat bus developed by the NASA Ames Research Center (ARC). The bus is derived from the NASA ARC's Edison Demonstration of Smallsat Networks (EDSN) CubeSat, which was also used for the Network & Operation Demonstration Satellite (NODeS) mission[5]. In our 2018 paper, we describe in detail the instrument and mission design, as well as the results of ground testing of the flight payload[6]. In this paper, we present some of the initial results of the CubeSat mission.

MISSION CONCEPT AND GOALS

The CHOMPTT mission employs an optical time-transfer scheme, which can be significantly more accurate than that for radio frequencies, due to lower propagation uncertainties through the Earth's ionosphere. A second advantage of optical frequencies is the high degree of beam collimation that enables a compact receiver for the space segment of the mission. A single photodetector with an aperture diameter less than 1 mm can be used to receive the optical signal transmitted from the ground, and a cm-scale retroreflector array can be used to return the signal back to the ground segment.

The mission's primary goal is to demonstrate an instantaneous ground-to-space time transfer with a precision of 200 ps, corresponding to a position error of 6 cm, which is sufficient for most navigation applications. A secondary goal of the mission include demonstrating the on-orbit performance of the two chip-scale atomic clocks (CSAC) incorporated into OPTI. Compared to previous experiments, this mission will demonstrate near state-of-the-art optical time transfer performance, but will do so on a power-limited and low cost nanosatellite platform. The 1U OPTI payload uses a time-transfer concept similar to that of the T2L2 mission. However, unlike the T2L2 mission, which was a secondary payload on board the Jason-2 satellite, OPTI will be incorporated into a dedicated CubeSat bus whose attitude control is dictated by the requirements of OPTI. CHOMPTT is the first CubeSat mission dedicated to precision optical time transfer and the first to successfully operate CSACs in space on a CubeSat platform.

The 3U CHOMPTT CubeSat was successfully launched into low Earth orbit on 16 December 2018 on NASA's ELaNa XIX mission using the Rocket Lab USA Electron vehicle. The orbit is a 500 km altitude circular Earth orbit with an inclination of 85 deg.

The two optical ground segments for the mission utilize a satellite tracking telescope, a pulsed 1064 nm laser system, an atomic clock and precision timing equipment. The primary facility is located at the Townes Institute Science and Technology Experimentation Facility (TISTEF), operated by the University of Central Florida, CREOL College of Optics and Photonics. The TISTEF is physically located at the Kennedy Space Center on Merritt Island, FL. The secondary optical ground segment is operated by EOS Space Systems and located on Mount Stromlo, Australia. The continental separation of these two facilities increases opportunities for time-transfer activities as discussed below. A UHF/VHF ground station located on the UF campus is used to send commands and receive telemetry from the CHOMPTT CubeSat. The mission duration is envisioned to span at least nine months.

The Optical Precision Time-transfer Instrument concept of operations is shown in Figure 1. The time-transfer scheme is similar to that of the T2L2 mission. A satellite laser ranging facility on the ground will transmit short (~2 ns-long) laser pulses to the CHOMPTT CubeSat. These pulses are timed with respect to the atomic clock on the ground and are detected by an avalanche photodetector mounted on the nadir face of OPTI. An event timer records the arrival time with respect to the on-board clock with a typical precision of less than 100 ps. At the same time, a retroreflector array returns the transmitted pulse back to the ground. By comparing the transmitted and received times on the ground and the arrival time of the pulse at the satellite, the time difference between the ground and space clocks can be measured. During a single SLR contact with the satellite, roughly 1,000 such measurements will be performed over a ~100 s interval to estimate the time transfer precision over time scales <100 s.

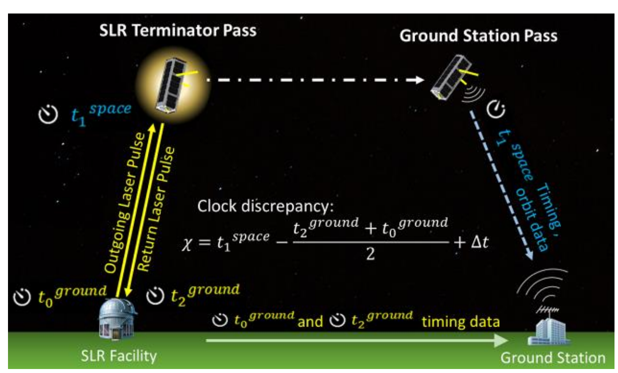

Figure 1: CHOMPTT time-transfer concept

The equation shown in Figure 1, describes how the three observables are used to compute the ground/space clock discrepancy, χ. A light pulse is transmitted from the ground at time t_0^{ground} (referenced to the ground clock) and is received at the satellite at time t_1^{space} (referenced to the space clock). The time that the returned pulse is received back at the ground is t_2^{ground}. The clock discrepancy is then the difference between the measured arrival time of the pulse at the satellite and the expected arrival time based on time measurements made on the ground. The expected time is the average of the emitted and received times on the ground plus a correction, Δt. The correction, Δt, accounts for the systematic time offset that is the sum of contributions from (a) asymmetry in the atmospheric delay between the uplink and downlink paths of the laser pulse, (b) the geometrical offset between the reflection and detection equivalent locations on OPTI, and (c) general and special relativity. The relativistic time offset is the only contribution that is significant and must be accounted for, while the atmospheric and geometric effects are negligible compared with the mission's 200 ps precision goal[6]. Estimates of the satellite's ephemeris based on on-board GPS data are used to compute both the relativistic rate difference between the ground and space clocks and the relativistic contribution to Δt.

In the baseline mission concept, shown in Figure 1, the measured arrival time of the optical pulse at the CubeSat is transmitted to the University of Florida ground station using the amateur radio frequency band. By combining these data with the timing measurements obtained at the SLR facility and the orbit determination information, the clock discrepancy, χ, can be calculated.

THE CHOMPTT PAYLOAD AND SPACECRAFT

The Optical Precision Time-transfer Instrument

The CHOMPTT spacecraft comprises the space instrument, OPTI, and its host CubeSat bus. The Optical Precision Time-transfer Instrument is a 1U, 1 kg device that incorporates all components of the space segment needed to perform ground-to-space optical time-transfer. All of the critical time-transfer elements are doubly redundant. These include two small atomic clocks, two picosecond event timers and microprocessor-based clock counters, and two nadir-facing avalanche photodetectors.

The design OPTI is shown in Figure 2. The electronics elements comprise two main instrument channels (A and B), a Supervisor, and an optical beacon. The two instrument channels are identical providing redundancy. Each contains one chip scale atomic clock (CSAC), one event timer, one avalanche photodetector, one microcontroller, and the ancillary electronics needed to support each of these components.

Each of the two main instrument channels house their own identical SA.45s chip scale atomic clocks, manufactured by Microsemi Frequency and Time Corporation, The primary output of the CSAC is a 10 MHz square wave. This signal is distributed to the event timer, channel board microprocessor, and the Supervisor using clock distribution electronics. The CSAC also provides temperature and other health and safety information to the Supervisor. The short-term frequency stability (Allan deviation) of the CSAC is one limiting factor in the overal time-transfer precision. The specified short-term ($\tau = 1$ s averaging time) Allan deviation for the CSAC is 3×10^{-10}, corresponding to a time error of 300 ps over 1 s. The measured short-term frequency stability of the CHOMPTT CSACs in a laboratory environment prior to launch was three times lower than the specification, equivalent to 100 ps at $\tau = 1$ s.

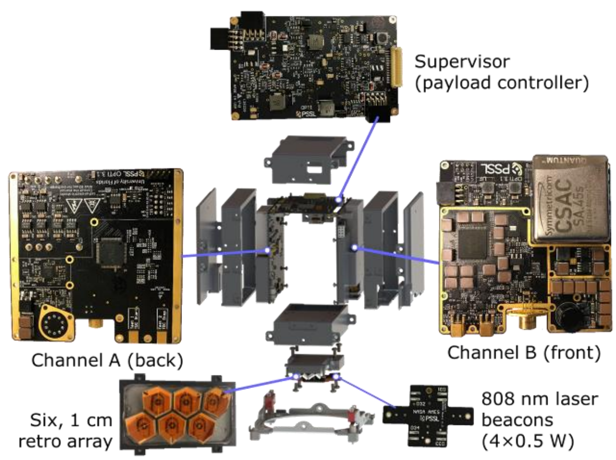

Figure 2: OPTI payload design

The event timer on each Channel is the precision electronics component the measures the arrival time of the optical pulses with respect to the on-board atomic clocks. The main even timer component is the TDC-GPX time-to-digital converter manufactured by Acam-Messelectronic GmbH[7]. It has a specified single shot precision of 10 ps, which was measured in the Precision Space Systems Lab to 12 ps (one standard deviation), and a maximum range of 7 µs. Due to the limited range of the TDC-GPX, a separate Texas Instruments MSP-430 microcontroller is incorporated on each instrument channel to count clock cycles over the entire lifetime of the mission. The clock counts recorded by the MSP-430 and the time stamps measured by the TDC-GPX event timer are combined digitally in software.

Each instrument channel is also equipped with one avalanche photodetector (APD) for recording the received light pulses. The APD are 200 µm active area diameter InGaAs photodiodes manufactured by Laser Components USA, Inc. A high voltage circuit on each channel is tuned to its specific APD to provide a reverse bias voltage that is less than but within 5 volts of the APD's breakdown voltage, which is typically in the range of 50-70 V. The temperature of the APDs are actively controlled during time-transfer events to improve their stability. The APDs are mounted on the edge of the channel electronics board and they protrude through a small hole in the nadir face of the OPTI structure. A bandpass optical filter mounted in front of the APD on the nadir face of OPTI prevents stray light from inadvertently triggering timing events.

The Supervisor acts at the payload controller, and it is the single electrical interface to the spacecraft bus. It uses a Texas Instruments MSP-430 microcontroller to route commands to each of the two channels and retrieve data from each channel, which is stored in flash memory on the Supervisor electronics board, until it is requested by the spacecraft bus. The Supervisor MSP-430 also controls the electronics that drive an optical beacon that aides in the tracking of the CubeSat by the SLR facility. The beacon electronics drive four 0.5 W vertical cavity surface-emitting laser (VCSEL) diode arrays. These arrays emit uncollimated 808 nm light with a collective divergence angle of ~14 deg (half-angle).

A single retroreflector array is mounted on the nadir face of OPTI. The space-capable array, which was custom designed by PLX, Inc. and consists of six, 1 cm effective diameter hollow retroreflectors integrated into a single package.

The Supervisor, Channels A and B, the retroreflector array, and the optical beacon are mechanically integrated by a custom structure that provides structural integrity during launch, thermal capacity and conductivity, and electromagnetic shielding for the Channel A and Channel B electronics boards. The OPTI structure is constructed from aluminum and is designed to be modular for ease of testing and integration. The OPTI structure is integrated inside a standard Pumpkin, Inc. 3U chassis and is mounted to the chassis by side fasteners. A Pumpkin, Inc. Large-aperture Cover Plate, also shown in Figure 1, mounted on the nadir face of OPTI, accommodates the payload's optical components and serves as the structural end plate of the spacecraft.

In 2014 we reported on the end-to-end time transfer performance of a breadboard version of OPTI[8], and in 2016 we reported on the measured performance of the OPTI Engineering Unit[6]. In Figure 3 we show the measured performance of the OPTI Flight Model in terms of Allan deviation, σ_y. On short time scales (τ = 1 second) where the limitation is the time-transfer precision, the measured Allan deviation was 75×10^{-12}. This corresponds to a time error of $\Delta t = \sigma_y \times \tau = 75$ ps. Over longer time scales the performance is limited by the CSAC, and over the period of one orbit (τ = 6,000s) the time error was <20 ns. These measurements show that the performance of the flight hardware is capable of achieving the 200 ps time-transfer performance goal for the mission.

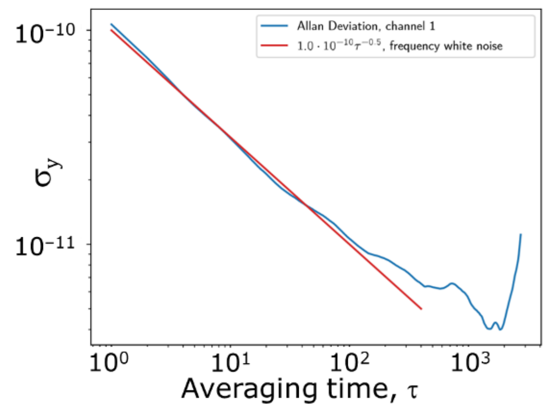

Figure 3: Measured Allan Deviation during optical time-transfer tests using the OPTI flight hardware

The CHOMPTT Spacecraft

The CHOMPTT satellite is a single 3U CubeSat with a total mass of 3.7 kg. An exploded view of the satellite, showing both the OPTI payload and the CubeSat bus is provided in Figure 4.

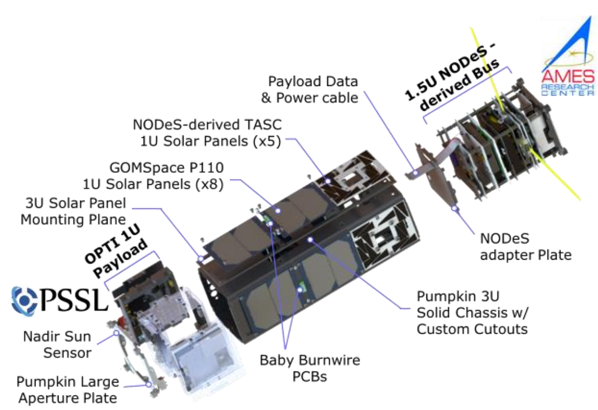

Figure 4: The 3U CHOMPTT spacecraft and payload

The Command and Data Handling Subsystem uses a Nexus S smartphone as the main processor. It autonomously schedules GPS acquisitions and uplink/downlink operations by propagating its own orbit and predicting when the spacecraft will be over the specified CHOMPTT RF ground stations. Additional distributed Arduino-based processors run other activity tasks such as interfacing with the payload, polling sensor data, and interfacing with the GPS.

The Attitude Determination and Control Subsystem (ADCS) consists of three orthogonal brushless motor reaction wheels and torque coils embedded in the solar panel PCBs (Printed Circuit Boards). Attitude determination uses a magnetometer sensor and inertial measurement unit (IMU) combined with coarse sun sensors also embedded in the solar panels. The ADCS has two distinct modes of operation. The first is magnetic control, which is used to de-tumble the spacecraft and align it with the local magnetic field for GPS acquisition and downlink activities. The second is 3-axis control, which uses the reaction wheels and attitude determination to point the nadir face of the CubeSat toward the SLR facility to enable time-transfer operations. The pre-launch estimate of the pointing accuracy in this mode was ±5 deg. A Novatel OEMV-1 GPS receiver is used to get position, velocity, and time fixes approximately once every 25 hours for activity scheduling.

The Electrical Power Subsystem (EPS) consists of the body mounted solar arrays, rechargeable lithium ion 18650 battery storage capable of sustaining subsystems during operating loads and orbit eclipses. The EPS also includes a watchdog timer to limit radio transmissions if command from Earth is lost.

The CHOMPTT Communications Subsystem uses two radios to perform two different tasks: beaconing and two-way ground communications. Two-way ground communications is performed with an Astrodev (Astronautical Development, LLC) Lithium 1 UHF transceiver and a deployable tape-measure monopole antenna. The Uplink and downlink rate is 9,600 bit/s under the AX.25 protocol with 1 W transmitted power from the satellite. The Astrodev transceiver is only powered when an uplink and downlink is scheduled over the ground station. The beacon uses a StenSat UHF transmitter with a tape measure monopole antenna, sending packets of data every 60 seconds at 1,200 bits/s when the Lithium transceiver is not on.

Figure 5 is a photo of the flight spacecraft during on-ground mission simulation tests in the University of Florida clean room. The nadir face of the spacecraft showing the OPTI payload can be seen on the right side of the image.

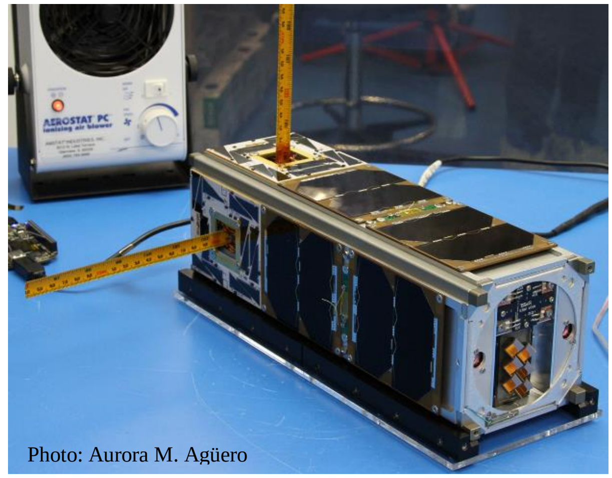

Figure 5: CHOMPTT flight spacecraft during mission simulation tests in the UF clean room

RF AND OPTICAL GROUND SEGMENTS

The ground segment of the mission consists of a radio frequency (RF) ground station located at the University of Florida, as well as primary and secondary satellite laser ranging (SLR) facilities. The UF RF ground station receives all telemetry and transmits all commands to/from the satellite. Both uplink and downlink communications use the amateur portion of the UHF band. Prior to launch the UF ground station included a Hy-Gain UB-7030 antenna with an iCOM IC-9100 transceiver. However, these equipment were later upgraded to improve the radio link to the satellite. This was needed because the receive sensitivity of the primary Lithium 1 radio system on board the spacecraft was worse than what was measured before launch. See the next section on flight operations for details.

Two SLR facilities are used for the CHOMPTT mission. The primary facility was developed by the Precision Space Systems Lab at UF, the University of Central Florida, NASA ARC, and the Naval Information Warfare Systems Command (SPAWAR). It is located at the Townes Institute Science and Technology Experimentation Facility (TISTEF) at the Kennedy Space Center on Merritt Island, FL. This facility, shown schematically in Figure 6, consists of a high energy, pulsed laser system and precision timing equipment integrated with a series of optical satellite tracking telescopes.

The most critical part of this SLR facility is TISTEF's 50 cm aperture optical telescope, capable of tracking satellites in low Earth orbit. A custom InGaAs avalanche photodetector system is mounted onto the backplane of this telescope to receive the returned laser pulses from OPTI and time-stamp them with respect to the ground atomic clock.

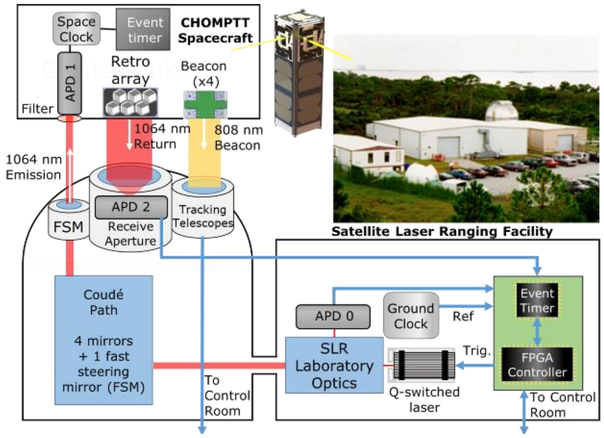

Figure 6: Primary optical ground station configuration at TISTEF, KSC, FL

The pulsed laser system is a FLARE 1064-50-50 manufactured by Coherent, Inc. It is a Q-switched laser, producing 2.5 ns-wide, 1 mJ pulses of 1064 nm light. A small fraction of the emitted light is redirected by a 10^3:1 beam splitter to the first ground detector, APD 0, which records t_0^{ground}. The bulk of the laser power is expanded from 1.1 mm diameter to 33 mm by a commercial Galilean beam expander. A pair of steering mirrors (not shown in Figure 6) direct the expanded beam into the entrance of a coudé path that uses a series of dichroic mirrors to align the out-going beam with the 50 cm receive telescope. The last coudé path mirror is a fast steering mirror (FSM), which is used to accommodate the point-ahead angle between the transmitted and returned laser beams.

The laser is driven by rising edge triggers produced by a Field Programmable Gate Array (FPGA)-based pulse modulator using a Microsemi Frequency & Time Corp. SmartFusion2 FPGA. This modulator can produce microsecond-level variations in the nominal 10 Hz repetition rate in order to correlate timing measurements made on the ground with those measured in space.

The ground clock at the SLR facility is a Microsemi Frequency & Time Corp. SA.31m Rubidium Clock. This clock has an Allan deviation that is ~3 times lower than that of the CSAC for averaging times less than 6,000 s. It will therefore not contribute significantly to the overall timing performance of the mission. The SLR facility event timer is an AMS TDC-GPX2 time-to-digital converter. This unit records timing events t_0^{ground} and t_2^{ground} based on pulse detections made by APD 0 and APD 2 respectively at the SLR facility.

Tracking of the CHOMPTT CubeSat is performed by the optical beacon incorporated into OPTI. The SLR telescopes will initially follow the azimuth and elevation track of the CubeSat based on orbit solutions using both GPS telemetry and data provided by the Combined Space Operations Center (CSpOC) (formerly the Joint Space Operations Center (JSpOC)). A series of tracking telescopes equipped with infrared imagers and covering a range of fields of view search for the optical beacon transmitted by OPTI. Once the beacon is detected, the telescope mount is driven by feedback control to keep the beacon signal centered in the image and bore sighted with the transmit laser.

The secondary SLR facility is located on Mount Stromlo, Australia and is owned and operated by EOS Space Systems. Functionally, it is very similar to the TISTEF facility. Key differences are the higher laser power and larger aperture telescopes used by EOS, which improve the optical link margin. The largest EOS SLR receive telescope has an aperture of 1.8 m, while the receive aperture at TISTEF is 0.5 m. The maximum average transmit laser power at EOS is roughly two orders of magnitude higher than the 1 W average power for the TISTEF laser.

OPERATIONS AND EARLY FLIGHT DATA

Launch and Early Operations

The CHOMPTT satellite was successfully launched into low Earth orbit on 16 December 2018 on NASA's Venture Class Launch Services (VCLS) ELaNa XIX mission using the Rocket Lab USA Electron vehicle from Mahia, New Zealand. The satellite was inserted into a near-circular orbit with a perigee altitude of 498.5 km and an apogee altitude of 502.8 km with an inclination of 85.0 degrees. At this altitude, we expect the spacecraft to remain on orbit for approximately 7 years before re-entry into Earth's atmosphere.

After deployment from its CubeSat dispenser on the Electron Kick Stage, the CHOMPTT spacecraft entered a quiescent-mode for 15 minutes where all of the subsystems were off. After the designated quiescent period, the spacecraft bus and payload powered on automatically. The spacecraft ADCS then began a 5-day de-tumble period using magnetorquers. The magnetorquers were activated for a period of 30 minutes every 2.5 hours during this 5 day period. When the OPTI payload was powered on, it entered a low power 'clock counting mode'. In this mode, only one of the two instrument channels is active with only that channel's CSAC turned on and the associated MSP-430 microprocessor counting clock cycles. During this early period of the mission, the spacecraft's StenSat UHF radio beaconed health and safety information to the ground every 60 seconds. This beacon data provided the first indication that both the spacecraft and payload survived the launch and orbit insertion.

Upon completion of the de-tumble activity, the satellite entered a cycle of activities that repeats every 25 hours. At the start of these 25 hour cycles, the spacecraft aligns its GPS antenna in the zenith direction and attempts to autonomously acquire GPS data. The spacecraft uses these data to propagate its orbit and determine when it is over either the UF ground station or over NASA ARC in the San Francisco Bay area. When the spacecraft is over one of these locations (alternating between locations each 25 hour cycle), the spacecraft turns on the primary Lithium 1 radio and listens for commands from the ground.

During each 25 hour cycle, spacecraft and payload health and safety data is recorded continuously. Some of these data are transmitted to the ground every 60 seconds via the Stensat beacon radio, except when the Lithium 1 radio is active to avoid interference. Both radios use the same carrier frequency. If no commands are received by the Lithium 1 radio within a specified time limit (typically 14 days), the watchdog timer turns off the beacon transmissions. Other spacecraft and payload activities occur during these 25 hour cycles when specifically commanded to do so.

Acquisition of GPS data and subsequent scheduling of Lithium 1 uplink activities by the spacecraft has occurred successfully during nearly every 25 hour cycle. One notable exception was the very first 25 hour cycle after the de-tumble activity. However, attempts to send commands to the spacecraft using the UF RF ground station were initially unsuccessful. This resulted in a timeout of the watchdog timer, causing beacon transmissions to cease for a short period. After multiple attempts to command the spacecraft from the UF ground station and additional successful commanding operations using the SRI International 18 m parabolic antenna in Stanford, CA, it was determined that the receive sensitivity of the CHOMPTT Lithium 1 radio on orbit was about –85 dBm. This is higher than the pre-launch measurements of –95 dBm taken in the anechoic chamber at NASA ARC. The 10 dB degradation is suspected to be caused by electrical noise from the bus, either due to the increased ADCS activity or the battery charging from the solar panels. Neither of those factors were present in the RF anechoic chamber tests.

From early 2019 until April 2019, flight operations continued in a limited capacity through the use of the SRI 18 m antenna. During this time period, the UF RF ground station was upgraded. The 75 W iCOM radio was replaced with an Ettus software defined radio (SDR) and a 550 W Beko amplifier. The Hy-Gain antenna was also replaced with a M2 436CP30 antenna with 1.5 dB of additional gain. With these upgrades, starting in late May 2019, the UF ground station has been able to close the RF link and command the CHOMPTT spacecraft reliably.

Spacecraft and Payload Status

As of June 2019, over 8,098 spacecraft beacon packets and over 6,038 OPTI payload packets were collected. Both the spacecraft and payload are functioning nominally. The majority of these beacon data were received by the Amateur Radio community and uploaded the PSSL database via our web portal. See: https://pssl.mae.ufl.edu/#chomptt/main/

Due to the sun-synchronous orbit, high-efficient GOM Space solar panels, high capacity batteries, and low power-state of the spacecraft, the spacecraft has remained in a nominally power positive state over the past six months. The bus battery maximum voltage is 8.4 V and the measured voltage never fell below 7.9 V.

The spacecraft has temperature sensors on the StenSat, EPS, C&DH smartphone, ADCS, Router, and Lithium PCBs as well as each of the solar panels. The measured on-orbit temperatures are within 10°C of the estimated values determined by a Thermal Desktop model, with on orbit maximum values near 50°C. The measured values fall well within the range of the bounding acceptable ratings of –10°C and +60°C for all spacecraft and payload components. Figure 7 shows one example of the spacecraft bus temperature variations over a four month period and the predicted steady state value under the hottest conditions. The gap in the data near the beginning of the mission was caused by the watchdog timer timeout, which halted beacon transmissions.

The OPTI payload temperatures typically fall within the range of 5°C and 30°C. This is consistent with prelaunch analyses as is the payload power consumption. Both chip scale atomic clocks continue to function nominally on orbit, although typically only the Channel A CSAC is operating.

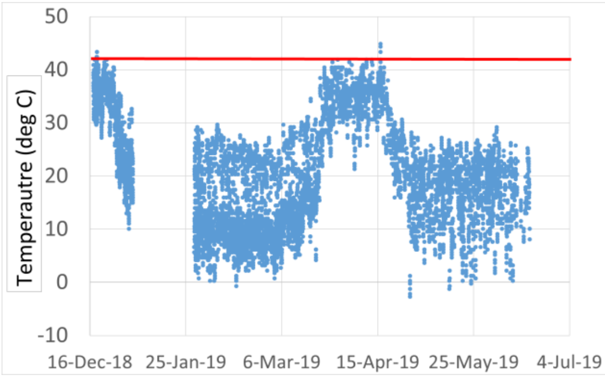

Figure 7: C&DH (Nexus S smartphone) temperatures (blue points) and pre-launch steady state high temperature predictions (red line) during the first six months of the mission.

Spacecraft Pointing Performance

Prelaunch analysis of the CHOMPTT spacecraft ADCS predicted a pointing accuracy that was within ±5 deg. Once the satellite was on orbit, a post launch calibration of the sun sensor photodiodes and the magnetometers was required to tune the ADCS. Most important was the estimation of the magnetometer bias in three axes and the gains and offsets of the sun sensor photodiodes on all faces of the spacecraft. Once these parameters were determined by analysis of the flight data on the ground, the new biases and gains were uploaded to the spacecraft. This calibration process reduced pointing errors from ±8 deg to ±0.5 deg.

Time-Transfer Operations

During nominal time-transfer operations, the CHOMPTT spacecraft first de-tumbles the spacecraft to a desired body rate. The spacecraft then uses its magnetometers, sun sensors, IMU, and reaction wheels to point itself in an inertially fixed direction that maximizes its contact duration with SLR facility. The OPTI payload is switched from its nominal clock-counting mode to time-transfer mode using one of its two channels. In this mode, the TEC temperature control for the APD is activated, the event timer is switched on and made ready to record timing events with respect to the CSAC, and the 808 nm laser beacon is switched on to assist SLR tracking of the CubeSat. The SLR facility initially uses CHOMPTT's ephemeris as the pointing reference for the optical telescopes. Tracking telescopes with various fields of view, boresighted with the main receive telescope, image OPTI's laser beacon or glints from the Sun reflecting off of the solar panels. Once the beacon or CHOMPTT image is acquired, the tracking telescopes are then used as the primary pointing reference for the SLR facility.

Active tracking of CHOMPTT is currently only reliable when the SLR facility is in darkness. Otherwise, daytime sky radiance reduces the signal-to-noise of the image and neither CHOMPTT nor its optical beacons can be seen. In addition, the primary pointing reference for the spacecraft ADCS is the Sun's orientation measured by the sun sensors. Because of this, nominal time-transfer operations have only been planned during 'terminator passes', in which the spacecraft is illuminated by the Sun and the SLR facility is in darkness. Terminator passes only occur just before sunrise or just after sunset at the SLR facility.

Due to regulatory issues regarding laser safety, CHOMPTT has not yet been lased by the TISTEF facility at KSC. These issues are set to be resolved by mid-June 2019. However, with the assistance of SPAWAR, TISTEF was able to passively track the spacecraft by imaging its optical beacons, which could be seen modulating at 1 Hz as expected on 24 April 2019. Telemetry from current monitors on the OPTI payload also show that the spacecraft optical beacons are functioning properly. This test provides confidence that we can acquire and track CHOMPTT from TISTEF with sufficient pointing accuracy to enable time-transfer operations.

CHOMPTT has also been successfully tracked from EOS Space Systems' Australian sites. Figure 8 shows an image of CHOMPTT taken by the EOS tracking telescopes in Western Australia. However, EOS Space Systems has not yet had an opportunity to lase the spacecraft from the Mount Stromlo site. This is primarily due to cloud cover during the acceptable terminator passes over the SRL facility or spacecraft mis-pointing at the SLR facility due to late-tracking and saturation of the reaction wheels.

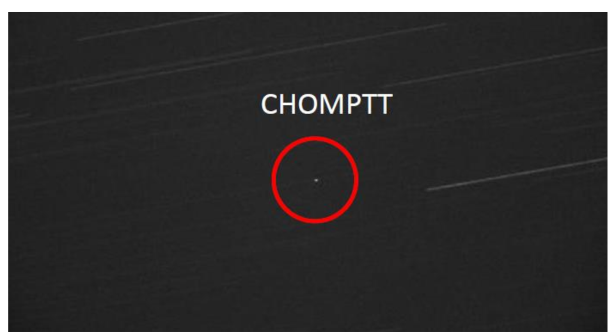

Figure 8: Image of the CHOMPTT spacecraft captured by the EOS WASSA SLR tracking camera on 28 March 2019 (credit: EOS Space Systems).

CHOMPTT currently relies on spacecraft terminator passes over either SLR facility to facilitate tracking and optical time-transfer. This condition occurs for approximately 1 month, every 3 months, with about 4-6 sufficient passes. While CHOMPTT was able to be tracked during the month of April from both stations, the next opportunity for time-transfer operations during terminator passes from both SLR facilities occurs in July 2019. Additional efforts are also underway to attempt daytime tracking with the EOS facility, where the both the spacecraft and ground station are in direct sun. We have procured a narrow band pass optical filter centered on the 808 nm wavelength of the OPTI beacon lasers. This would block a sufficient portion of the sky irradiance and allow the EOS tracking telescope to image the spacecraft's laser beacons for tracking.

SUMMARY AND OUTLOOK

The CHOMPTT laser time-transfer technology demonstration mission was successfully launched into low Earth orbit in December of 2018. The 1U OPTI payload was designed to transfer terrestrial time standards to a low Earth orbiting CubeSat using standard Satellite Laser Ranging facilities. The instrument incorporates two small atomic clocks, two picosecond event timers and microprocessor-based clock counters, two nadir-facing avalanche photodetectors, and a single retroreflector array. The measured short term performance of the OPTI flight unit was 75 ps, and over longer time scales, its timing precision is limited by the frequency stability of the on-board chip scale atomic clocks. The 1U OPTI payload was integrated with a 3U CubeSat bus, which has heritage from the NASA Ames Research Center EDSN/NODeS bus. There are two optical ground segments for the mission located at the Kennedy Space Center in Florida and Mount Stromlo in Australia. The NASA spacecraft bus and University of Florida payload are both operational and healthy after six months on-orbit. Both chip scale atomic clocks are performing nominally and the payload thermal environment and power draw are consistent with pre-launch analyses. We were able passively track the spacecraft from both SLR sites with sufficient accuracy, and we intend to perform optical time-transfer operations during the month of July, 2019. A successful demonstration of precision time-transfer by OPTI will enable future missions requiring precision time distribution on compact space platforms.

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