Optical time transfer for future disaggregated small satellite navigation systems

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ABSTRACT

Precision time-keeping is a critical requirement of any satellite navigation system, including GPS. Even the most stable space qualified atomic clocks drift over time to the point where they can significantly degrade navigation precision. Periodic re-synchronization of these clocks with respect to terrestrial time standards is therefore required. Time transfer through Earth's atmosphere using optical frequencies offers improved accuracy due to reduced time delay uncertainties relative to radio frequencies. In this paper we describe the design and laboratory testing of the Optical Precision Time Transfer Instrument, a compact device for real-time terrestrial-to-space clock corrections, using existing satellite laser ranging facilities. This instrument will comprise roughly 1U of a 3U CubeSat mission, sponsored by the Air Force's University Nanosatellite Program and slated for launch in the 2017 time-frame. The instrument will demonstrate time transfer with a short term accuracy of 100 psec, equivalent to 3 cm of position error, and a long term timing error of 6 nsec over one orbit, limited solely by the frequency stability of the on-board miniature atomic clocks. Future missions using this time transfer technology and equipped with higher stability clocks will enable disaggregated navigation systems, with precision time-keeping components separated from other functionality.

INTRODUCTION

The problem of time transfer between precision clocks separated by large (global) distances arises in navigation, communications, networking, fundamental physics experiments and astrophysics. Precise timing is required for accurate Global Positioning System (GPS) navigation. The transmitted signal from each GPS satellite is encoded with its own atomic clock time. By geometrically combining the time of flight of signals transmitted by at least four GPS satellites, the receiver is able to calculate its position in three dimensions, as well as correct its local clock with respect to GPS time.

Comparison of precision clocks also provides one method of testing fundamental physics laws, including the universality of gravitational redshift and local Lorentz invariance[1]. In astronomy, the goal may be to correlate observations made by two observatories on two different continents, or to coordinate spacecraft flying in precision formation to produce a distributed aperture telescope or gravitational wave observatory[2]. Finally, time transfer is used to evaluate the performance of the world's most accurate clocks. The only way this can be done is by comparing one clock with respect to another.

Several precision time transfer experiments between ground and space, beyond GPS, have been carried out recently using large satellites and additional experiments are planned in the near future. The Time Transfer by Laser Link (T2L2) experiment developed by OCA (Observatoire de la Côte d'Azur) and CNES (Centre National d'Études Spatiales), France, was launched in 2008 on the altimetric satellite Jason-2[3]. T2L2 is based on the techniques of satellite laser ranging and time-frequency metrology. It consists of synchronizing ground and space clocks using short laser pulses travelling between ground clocks and satellite equipment. The clock on board Jason-2 is an ultra-stable oscillator (USO) integrated with the DORIS (Doppler Orbitography and Radio-positioning Integrated by Satellite) satellite tracking system. The frequency stability (Allan deviation) of this clock is $\sim 2\times10^{-11}$ over short time scales (1 sec) and improves with increasing integration time τ, roughly at a rate proportional to $1/\tau$.

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[4]. A one-way ranging technique is used, where the Earth laser station measures the transmit times of its outgoing laser pulses and the Lunar Orbiter Laser Altimeter (LOLA), one of the instruments onboard LRO, measures the receive times. The clock associated with LOLA has a frequency stability of roughly 10^{-12} at 1000 sec. The time transfer accuracy is currently limited to 100 ns at 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[5]. ACES is a fundamental physics experiment using a new generation of atomic clocks operating in the microgravity environment of space, which are compared to a network of ultra-stable clocks on the ground. The ACES payload consists of two atomic clocks: PHARAO, a primary frequency standard based on samples of laser cooled cesium atoms, and the active hydrogen maser, SHM. The composite frequency stability of the ACES clocks is ~10^{-13} at 1 second, improving roughly as $1/\tau^2$. The ACES clock signal will be transferred between space and ground by a microwave time and frequency transfer link. ACES is scheduled to launch in 2016.

Here, we report on a new compact, low-power Optical Precision Time-transfer Instrument (OPTI) that will simplify the process of correcting for clock drift on spacecraft. Time transfer through Earth's atmosphere using optical frequencies offers improved accuracy due to reduced time delay uncertainties relative to radio frequencies. The operation of OPTI will be demonstrated on a low Earth orbiting 3U CubeSat in the 2017 time-frame as part of the Air Force's University Nanosatellite Program. In addition to improving the precision and simplifying the operation of satellite navigation systems, OPTI and its CubeSat demonstration mission CHOMPTT (CubeSat Handling of Multisystem Precision Time Transfer) will aide in the realization of disaggregated satellite navigation systems in the future.

A disaggregated navigation system is one in which the precision timing function is separated from the high gain pseudorange transmission component. A small number of timing satellites (1-3) would be placed in low Earth orbit and transmit timing updates to a larger constellation of broadcast satellites in higher orbits. These timing satellites could also provide precision time to any other space asset that required it, including communications satellites and science and astrophysics missions.

TIME-TRANSFER CONCEPT

The Optical Precision Time-transfer Instrument concept, shown in Figure 1, is similar to that of the T2L2 instrument. A satellite laser ranging (SLR) facility on the ground will transmit ~100 picosecond 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 on OPTI. An event timer records the arrival time with respect to the on-board clock with an accuracy of ~100 ps. 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 satellite, the time difference between the ground and space clocks can be measured.

Unlike the T2L2 mission, OPTI will be incorporated into a dedicated CubeSat bus whose attitude is dictated by the requirements of OPTI. An additional new capability of OPTI is real time clock corrections. The optical link will be used to promptly transmit the timing information from the ground to the satellite so that OPTI's atomic clock frequency and phase offset can be corrected in real time.

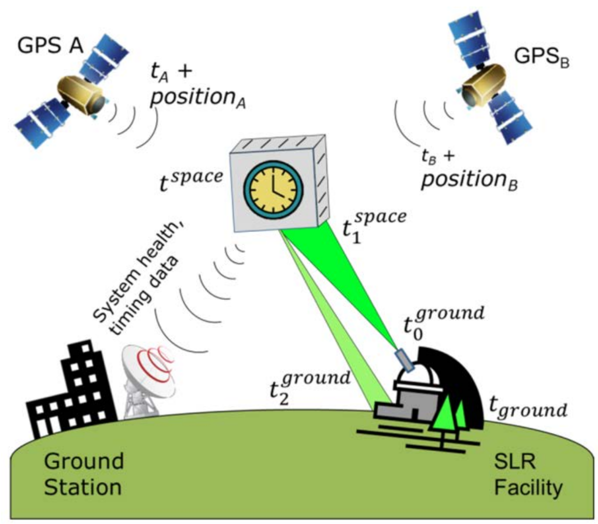

Figure 1: CHOMPT Mission Concept

Let superscripts *ground* and *space* refer to time as recorded by the ground and the space clocks respectively. Then the goal of OPTI is to accurately estimate the clock discrepancy $\chi = t^{space} - t^{ground}$ over a short period of time in order to determine both the relative clock phase and frequency offsets. Assume that a light pulse is transmitted from the ground at time t_0^{ground} (referenced to the ground clock) and that the light pulse is received at the satellite at time t_1^{space} (referenced to the space clock). Also let t_2^{ground} be the time that the returned pulse is received back at the 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 small correction, Δt:

$$\chi = t_1^{space} - \frac{1}{2}\left(t_2^{ground} + t_0^{ground}\right) - \Delta t \qquad (1)$$

The correction Δt accounts for time delays caused by (a) the geometrical offset between the reflection and detection equivalent locations on OPTI, which depend on satellite attitude, (b) relativity, and (c) asymmetry in the atmospheric delay between the outward and return path of the laser pulse.

A GPS receiver is also incorporated on the satellite for several reasons. GPS data will be used for orbit determination and for a verification of the optical range measurements. The GPS data will also be used to compare time as recorded by the atomic clocks on the satellite with GPS time.

INSTRUMENT DESCRIPTION

Overview

The main components of OPTI are a pair of the atomic clocks, a pair of event timers and time counters, a pair of avalanche photodetectors, and a single nadir-facing retroreflector. The following subsections describe each of these components.

Atomic Clocks

Two atomic clocks manufactured by Microsemi Frequency and Time Corporation (previously called Symmetricom, Inc.) is incorporated into the OPTI payload. Table 1 summarizes the design and performance characteristics of both. The rubidium-based MAC (SA.31m) is the primary clock due to its higher stability. One of the primary design drivers for the CHOMPTT satellite bus is the 5 W average power consumption of the MAC. This power is used to drive both the physics package itself, as well as heaters to maintain the physics package at a relatively high temperature. The cesium-based CSAC (SA.45s) is also incorporated for redundancy. The CSAC has minimal impact on the size, weight, and power (SWAP) budget.

The primary output of each clock is a 10 MHz square wave. This signal as well as temperature and other operational data will be distributed to the OPTI instrument using clock distribution electronics. Each clock is connected to its own clock distribution board and mounted inside thermally shielding aluminum enclosures. A breadboard version of the CSAC clock distribution electronics is shown in Figure 2.

Table 1: Comparison of the two OPTI clocks

Characteristic	CSAC[6]	MAC[7]
Standard	Cesium	Rubidium
1 sec Allan Deviation	2.5×10^{-10}	5×10^{-11}
6000 sec Allan Deviation	3×10^{-12}	9×10^{-13}
Average Power	0.12 W	5 W
Mass	35 g	85 g
Volume	16 cm^3	47 cm^3

Figure 2: Chip Scale Atomic Clock and breadboard version of the OPTI clock distribution electronics

Event Timer and Counter

The purpose of the event timer is to time stamp 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[8]. The TDC-GPX measurement principle is based on the propagation delay of a series of gates. It has a specified single shot accuracy of 10 psec, which was measured in our lab to 12 psec (one standard deviation), and a maximum range of 7 µsec. This low-power device consumes 132 mW.

Due to the maximum range limitations of the TDC-GPX, a separate Texas Instruments MSP-430 microcontroller is used to count clock cycles over the entire lifetime of the mission, which is expected to be at least a few months. Figure 3 describes how the TDC-GPX and the MSP-430 microcontroller combine course and fine time measurements. The MPS-430 continuously counts clock cycles at 10 MHz. When the photo detector (PD) receives a light pulse, the TDC-

GPX starts recording elapsed fine time. After a specified number of clock cycles, the TDC-GPX stops measuring the elapsed fine time. The recorded arrival time of the light pulse with respect to the clock is simply the course time associated with the clock pulse that stopped the fine time measurement minus the measured fine time. The first clock cycle after the light pulse is not used due to nonlinearities that occur in the TDC-GPX immediately following the start trigger. One TDC-GPX and one MSP-430 are used for each of the two on-board clocks. This provides measurement flexibility and some instrument redundancy.

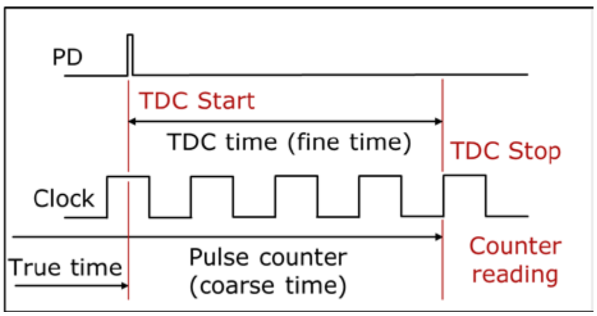

Figure 3: Course and fine time tracking scheme

A third MSP-430 microcontroller is used as the instrument controller. It sets the operational modes of the instrument, specifies which photodetectors and clocks are to be used for each time transfer event, collects timing and health and safety data and transmits it to the satellite bus Command and Data Handling system (CDH) controller. When the instrument is not performing time transfers, the microcontroller puts the instrument into a low power counting mode. In this mode the clocks are kept running and the MSP-430 continues to count clock cycles.

Optics and Light Detection

The two main optical components of OPTI are the photodetectors, and the retroreflector. The retroreflector selected is a space capable 25 mm equivalent diameter, ultra-stable, hard-mounted hollow corner cube manufactured by PLX Incorporated. It has a 50 deg field of view and a 5 arcsec maximum returned beam deviation. This retroreflector is shown in Figure 4.

Two different photodiodes are incorporated into OPTI. Both are avalanche photodiodes (APD) that are reverse-biased with ~100 V. One APD is Si-based and the other is InGaAs. Their relevant properties are provided in Table 2. Avalanche photodetectors were chosen for their high gain and resulting fast response times. These particular APDs were selected for their wavelength sensitivity, which allows for detection of both 1064 nm and 532 nm light pulses. The geometry of both APDs is similar to that shown in Figure 4.

Table 2: Charactaristics of the two APDs incorporated into OPTI

Characteristic	Si APD	InGaAs APD
Wavelength	400-1000 nm	900-1700 nm
Package	TO-46	TO-46
Active area diameter	0.5 mm	80 µm
Rise time	500 psec	140 psec

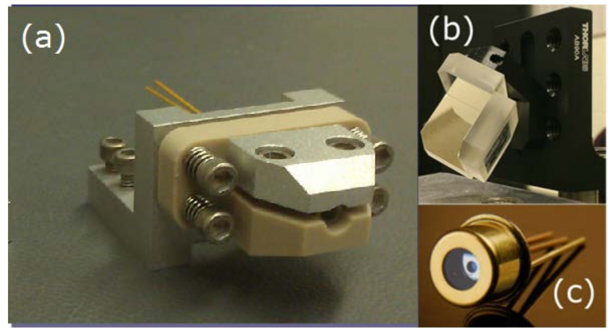

Figure 4: OPTI optical components: (a) Photodiode fiber optic coupler, (b) PLX retroreflector, and (c) Avalanche photodiode

The APDs are located close to the event timers so that time delay variations are minimized. The light pulses illuminating the satellite are coupled into the APDs via fiber optic cables that terminate on the nadir face of the satellite. The performance of both APDs are optimized by operating them at 0° C. Fiber coupled APDs that meet the OPTI requirements and incorporate temperature control do not exist. Therefore we developed custom opto-mechanical couplers, shown in Figure 4, that mechanically mount the APDs, control their temperature, and optically couple them to fiber optic cables. These assemblies, measuring roughly 2 cm in length, support thermo-electric coolers (TEC) against the back face of the APD TO-46 packages. A cylindrical groove is machined into the mechanical assemblies to align the axes of the APDs and the optical fibers. The cylindrical surface of the APD is mounted at one end of the groove and a glass ferrule with one end of the optical fiber epoxied inside it is mounted to the other end of the groove. A gradient-index (GRIN) lens is epoxied to the end of the glass ferrule, which focuses the received light onto the small active area of the APD. The opto-mechanical assembly is mounted directly onto the main instrument electronics board containing the event timers.

Real-time Clock Correction

In order to correct the measured phase and frequency offset of the space clocks in real time, t_0^{ground}, t_2^{ground} and other relevant data required to compute Δt, is transmitted to OPTI via a modulation of the laser pulses emitted by the SLR facility. The string of pulses used consists of an initial precision timing pulse, followed by a synchronization string, the timing data packet, and a checksum. The modulation scheme used is a 4-symbol Pulse Position Modulation (4PPM) code[9]. A total of only 20 Bytes of data must be transmitted to the spacecraft for each precision timing pulse. Therefore, a relatively low data rate is used (~1 kpbs) and fine time measurement recorded by the TDC-GPX is only needed for the initial timing pulse. The synchronization string that is transmitted immediately after the timing pulse provides phase and rate information and masks SLR facility delays.

Measured performance

In order to assess the time-transfer performance of OPTI and to determine its sensitivities to temperature and satellite attitude, a time transfer test-bed was constructed. This test-bed, shown in Figure 5, consists an SLR facility emulator mounted on one side of an optics table and a breadboard version of OPTI mounted on the other side.

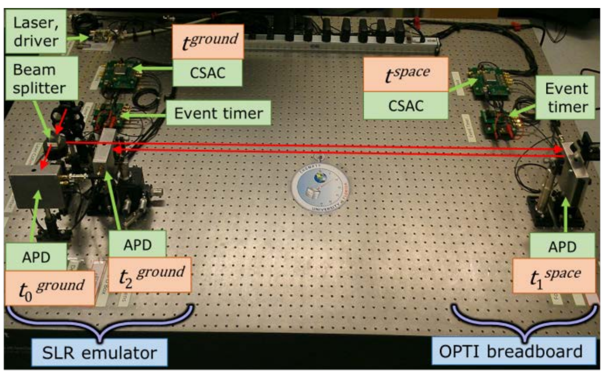

Figure 5: OPTI breadboard and a SLR facility emulator for time-transfer performance testing

The SLR facility emulator consists of a pulsed laser, two APDs mounted inside metal boxes for detecting the time that the pulse is emitted and the time that it is returned, an atomic clock and an event timer. The laser is fiber-coupled 1064 nm continuous wave laser diode. It is driven by a picosecond pulsed driver. The laser/driver combination is capable of producing < 1 nsec pulses of light with a power of ~50 mW at the output of a fiber optic collimator.

The light emitted by the collimator is split by a 90/10 non-polarizing beam splitter. Roughly 90% of the light is directed across the optics table to the OPTI breadboard, and the other 10% is promptly detected by an APD to produce t_0^{ground}. The light pulse that is directed toward the instrument is defocused by a convex lens so that the spatial size of the pulse is ~5 cm in diameter when it reaches OPTI. This defocusing of the pulse simulates the broadening of the beam through the atmosphere and allows the beam to simultaneously interact with both the retroreflector and the photodetector on OPTI. The pulse returned to the SLR emulator is detected by another APD, which records t_2^{ground}. The SLR emulator event timer records both t_0^{ground} and t_2^{ground} relative to the SLR emulator's CSAC. The event timer consists of TDC-GPX for recording fine time and an MSP-430 microcontroller for recording course time.

The OPTI breadboard, also shown in Figure 5, contains all of the components of OPTI described above. The PLX retroreflector described above is mounted just above the OPTI APD which records t_1^{space}. An event timer, identical to the one used for the SLR emulator, measures t_1^{space} relative to a second CSAC, which acts as the space clock.

Figure 6 shows the measured time deviation between the CSAC incorporated into the SLR emulator and the CSAC incorporated into OPTI over a period of roughly 7 hours. This clock discrepancy was calculated using the pulse times measured by the three APDs and Eq. (1), assuming $\Delta t = 0$ sec. Therefore, the clock discrepancy shown in Figure 6 includes all timing errors present in the entire measurement chain, including those associated with the APDs, event timers and electronics.

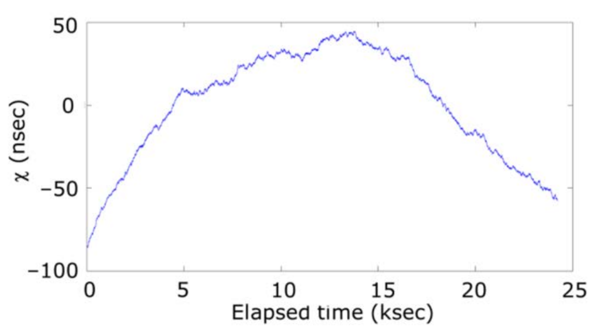

Figure 6: Clock Discrepancy as Measured by the OPTI Breadboard

Figure 7 shows the timing error (purple curve) as a function of averaging time, τ, associated with the measured clock discrepancy plotted in Figure 6. To produce the purple curve in Figure 7, the measured clock discrepancy was converted to Allan deviation, $\sigma_y(\tau)$, then to timing error, $\sigma_y(\tau) \cdot \tau$. Also shown in Figure 7 is the predicted timing error budget (blue dashed curve), the nominal performance of GPS time (red curve), the average time that corresponds to one orbit of the CHOMPTT satellite in Low Earth Orbit (brown line), and two performance goals (light blue and green).

The predicted timing budget on short time scales (≤100 sec) was based primarily on the response time of the avalanche photodetectors, which was overly conservative when compared to the measured performance. Indeed the short term (~1 sec) time-transfer performance of OPTI is ~100 psec. Over longer averaging times, the performance is limited by the frequency stability of the two CSACs. From Figure 7, it is clear that the specified frequency stability of the CSACs agrees very well with the measured performance of the time-transfer test-bed over time scales ≥ 100 sec.

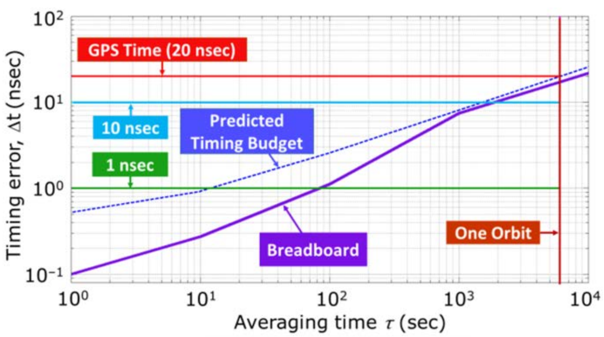

Figure 7: Measured Time Error and Error Budget

The measured performance of the CHOMPTT mission, when using the CSAC as the space clock, is similar to that of GPS time on time scales equivalent to one orbit. As previously stated, the timing performance on these time scales is limited by the clock performance. Using the rubidium-based MAC, the performance on long time scales should improve by a factor of 3-4. Since short time scale limit of OPTI is 100 psec, significant improvement on long time scales relative to that shown in Figure 7 can be achieved if a more stable clock is used.

THE CHOMPTT MISSION

CubeSat Bus Description

The CHOMPTT CubeSat bus, shown in Figure 8, uses a Pumpkin MSP-430-based motherboard, for the Command and Data-Handling system (CDH). This microcontroller runs the Salvo real-time operating system, and the entire satellite is controlled by an I2C bus.

The Electric Power System, incorporates a power distribution system (Clyde Space CS-XUEPS2-41), two 20 W-h batteries (Clyde Space CS-SBAT2-20), and solar panels on all 3U length sides plus two deployable 3U solar panels (Clyde Space SP-L-S3U-0016-CS-MGT) in a 180 degree deployed formation.

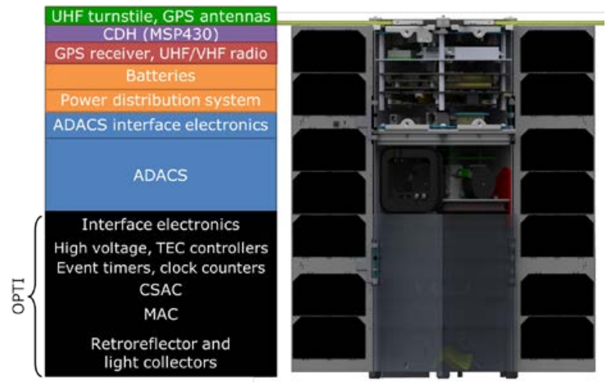

Figure 8: Layout of the CHOMPTT satellite

The communications subsystem incorporates a half-duplex transceiver (AstroDev Lithium L1 radio) and an ISIS turnstile deployable antenna. Uplink and downlink to the University of Florida ground station will use UHF amateur frequencies.

Active attitude control is required for SLR facility contact times of at least 5 minutes. Light collection on the nadir face of the satellite is achieved through pin-holes where the optical fibers that couple to the APDs terminate. Light will couple into these fibers as long as the incidence angle of the received light is less than 12 deg. This requirement, along with the pointing capabilities of SLR facilities and the desire to have contact times of at least 5 minutes drives the need for an active attitude control system with 10 deg pointing accuracy. The baseline Attitude Determination and Control System (ADACS) is the Maryland Aerospace MAI-100, which is mounted in the mid-section of the spacecraft. This ADACS uses 3 axis reaction/momentum wheels, electromagnets, magnetometers, and a sun sensor to measure and control the satellite's attitude.

A NovAtel GPS module is mounted near the top end of the 3U CubeSat, next to radio. The GPS module is connected to an AeroAntenna GPS patch antenna, which is mounted on the zenith face of the satellite in the center of the UFH turnstile antenna. GPS time and position data is sent to the CDH controller and telemetered to the ground along with the OPTI data.

Concept of Operations

The CHOMPTT satellite will be launched in the 2017 time-frame through NASA's Educational Launch of Nanosatellites program. The concept of operations for the mission is shown in Figure 9. After launch (1) and deployment (2), the satellite will enter a safehold mode (3). Communications will then be established via the University of Florida ground station using the UHF band in order to determine the health of the satellite and instrument. The satellite will then enter a standby mode (4), where the atomic clocks are activated, the instrument controllers are counting clock cycles, and the ADACS detumbles and orients the spacecraft in the nadir direction.

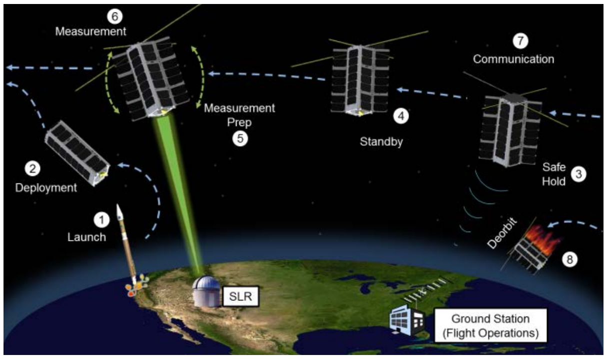

Figure 9: CHOMPTT Concept of Operations

Roughly 30 minutes prior to a prescheduled time transfer event, the instrument is placed in a measurement preparation mode (5). This mode prepares the instrument controllers and event timers for data collection, and cools the two APDs to 0 °C. Just prior to the time transfer event, the instrument is placed in measurement mode (6), where it is ready to detect light pulses, time them with respect to the instrument atomic clocks, and the transfer the resulting time stamps to the CDH microcontroller. These data, along all other science and health and safety data are transmitted to the ground with the satellite is in communication mode (7). Finally, after the end of the mission, the satellite naturally de-orbits due to atmospheric drag (8).

CONCLUSION

The OPTI time transfer instrument is designed to transfer terrestrial time standards to a low Earth orbiting CubeSat using standard Satellite Laser Ranging facilities. New capabilities that are incorporated into OPTI are state of the art timing performance in a low size, weight and power package, and real time, autonomous clock frequency and phase corrections. A breadboard version of this instrument has been built and tested, and its short term performance is ~100 psec. Over longer time scales, its timing accuracy is limited by the frequency stability of the two on-board miniature atomic clocks. The instrument will be demonstrated by the CHOMPTT 3U CubeSat mission in the 2017 time-frame. A successful demonstration of precision time-transfer by OPTI will enable future missions requiring precision time distribution, including disaggregated satellite navigation systems.

Acknowledgments

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