Demonstration of sub-nanosecond time transfer via optical links to nanosatellites

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Background and Motivation

Use of precision time transfer to space:
- Satellite navigation systems ($\Delta x = c \Delta t$)
- International time standards
- Test of general relativity
- Satellite encryption/authentication

Solution: exchange of light pulses
- Optical frequencies less affected by ionosphere than RF ($\sim 1/f^2$)
- CNES T2L2 (2008), hosted payload on Jason-2

CHOMPTT Objectives:
- <200 psec time transfer error
- <20 nsec clock drift after 1 orbit
- Real time clock update
CHOMPTT: CubeSat Handling Of Multisystem Precision Time Transfert (NS-8)

Clock discrepancy

$$\chi = t_{1}^{space} - \frac{t_{2}^{ground} + t_{0}^{ground}}{2} + \Delta t$$
Application to Navigation

Improved time transfer accuracy
- Better time standard on navigation satellites

Robust against signal interference/jamming

Disaggregated Navigation System:
1. Command station performs time transfer to timing satellite
2. Navigation satellites synced to timing satellite using RF
3. End-users determine location and time from navigation satellites

Acknowledgement:
Leo Hollberg (Stanford)
Optical Precision Time-transfer Instrument (OPTI)

SLR Facility

Laser

Beam Splitter

t_0

ground

t_2

ground

Event Timer

Clock
t_{ground}

Atmosphere

Photodiode

Space Instrument

Event Timer

Photodiode

Retroreflector

Clock
t_{cubesat}

t_{1}

cubesat

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# Atomic Clocks

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Chip Scale Atomic Clock (CSAC)</th>
<th>Miniature Atomic Clock (MAC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>Cesium</td>
<td>Rubidium</td>
</tr>
<tr>
<td>Allan Deviation (time error)</td>
<td>$3.3 \times 10^{-12} @ 6000$ sec (20 nsec)</td>
<td>$9.5 \times 10^{-13} @ 6000$ sec (6 nsec)</td>
</tr>
<tr>
<td>Power</td>
<td>0.12 W</td>
<td>5 W</td>
</tr>
<tr>
<td>Mass</td>
<td>35 g</td>
<td>85 g</td>
</tr>
<tr>
<td>Size (LxWxH)</td>
<td>40.64 x 35.31 x 11.42 mm</td>
<td>51 x 51 x 18 mm</td>
</tr>
</tbody>
</table>

Clocks from Microsemi
Photodetectors

2 avalanche photodiodes:
- InGaAs for 1064 nm, 150 ps rise time
- Si for 532 nm, 500 ps rise time

Photodetector in linear mode

Temperature regulated by Thermo-Electric Coolers

Photodetectors are fiber-coupled

Pulse sent back by a PLX retroreflector
- 25 mm diameter, 50° FOV
- Space Capable
Optics

Band-pass filters
- Increase SNR

Light collected by a multimode optical fiber on the nadir face
- 12° max incidence
- 200 µm diameter

GRIN Lens focuses light onto APD
10 psec Event Timers – fine time

2 independent channels

Fine time on short intervals, course time over long duration

Time-to-digital converter – measures fine time
  ◦ Integrated, off-the-shelf: Acam TDC-GPX
  ◦ Measurement based on propagation delays
  ◦ Autonomous calibration using Delay Lock Loops
  ◦ Low power (<150 mW)
  ◦ 10 ps single shot accuracy
    (12 ps measured)
10 psec Event Timer – course time

Counter – measures course time
  ◦ Ti MSP430 microcontroller used as counter

TDC and Counter are synchronized on an a chosen clock rising edge.
  ◦ Within 7 µs TDC range
OPTI Laboratory Demonstration

SLR Emulator

Laser, Pulse driver
Beam Splitter

$ t_{\text{ground}}$
CSAC
Event Timer

APD
$t_{0, \text{ground}}$
$t_{2, \text{ground}}$

Space Segment

Event Timer

CSAC
$ t_{\text{space}}$

APD
$t_{1, \text{space}}$
Measured Performance

Clock difference (2 CSACs) measured using OPTI breadboard

![Graph showing measured performance over elapsed time (ksec)]
Timing Error Budget

GPS Time (20 nsec)

10 nsec

1 nsec

Predicted Timing Budget

Measured

One Orbit

Timing error, $\Delta t$ (nsec)

Averaging time $\tau$ (sec)
OPTI Flight Instrument

- Interface and power regulator
- TEC controllers, reverse bias voltage
- Event Timers
- Photodetectors
- Atomic Clocks
- Light collectors
- Retroreflector (not shown)

CSAC
MAC
MAC

CSAC

Event Timers

TEC controllers and reverse bias voltage

Interface and power regulator (balloon launch configuration)
The CHOMPTT 3U CubeSat

<table>
<thead>
<tr>
<th>Component</th>
</tr>
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<tbody>
<tr>
<td>UHF turnstile, GPS antennas</td>
</tr>
<tr>
<td>CDH (MSP430)</td>
</tr>
<tr>
<td>GPS receiver, UHF/VHF radio</td>
</tr>
<tr>
<td>Batteries</td>
</tr>
<tr>
<td>Power distribution system</td>
</tr>
<tr>
<td>ADACS interface electronics</td>
</tr>
<tr>
<td>ADACS</td>
</tr>
<tr>
<td>Interface electronics</td>
</tr>
<tr>
<td>High voltage, TEC controllers</td>
</tr>
<tr>
<td>Event timers, clock counters</td>
</tr>
<tr>
<td>CSAC</td>
</tr>
<tr>
<td>MAC</td>
</tr>
<tr>
<td>Retroreflector and light collectors</td>
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Concept of Operations

1. Launch
2. Deployment
3. Safe Hold
4. Standby
5. Measurement Prep
6. Measurement
7. Communication
8. Deorbit

SLR
Ground Station (Flight Operations)
Laser Communication

2-Pulse Position Modulation (2 slots per pulse)

Synchronization string provide phase and rate for communication, masks SLR delays

High precision measurement only on the first pulse

Timed laser pulse

- Synchronization string
- Timing data (20 bytes)
- Checksum (2 bytes)

TRUE/1
FALSE/0
Sync. error
Comm. Loss or sync. error
Status and Future

Engineering Model of OPTI fabricated, currently under test

High altitude balloon launch
  ◦ In space a few hours ago

2015: OPTI integrated into CHOMPTT satellite bus

Qualification testing at NASA KSC

2016-2017: ELaNA launch

Satellite Laser Ranging collaborators
  ◦ Townes Institute Science & Technology Experimentation Facility at University of Central Florida, CREOL
  ◦ NGSLR managed by NASA GSFC, MD
  ◦ Starfire optical range at Kirtland AFB, NM
High Altitude Balloon Launch