Optical Time Transfer for Future Disaggregated Small Satellite Navigation Systems

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Background and Motivation

- Precision time transfer to space important for:
  - Satellite nav systems, e.g. GPS ($\Delta x = c \Delta t$)
  - International time standards
  - Test of general relativity
  - Satellite encryption/authentication
- Technique: exchange of light pulses
  - Optical frequencies less affected by ionosphere relative to RF ($\sim 1/f^2$)
  - European T2L2 (2008) was hosted payload
- CHOMPTT Objectives:
  - <200 psec time transfer error
  - <20 nsec clock drift after 1 orbit
  - Real time clock update

GPS constellation
Gravity Probe A (1976)

Common View
Non-common View

T2L2 mission [P. Guillemot et al 2006]
CHOMPTT: CubeSat Handling Of Multisystem Precision Time Transfer (NS-8)

\[ \chi = t_{1 \text{space}} - \frac{t_{2 \text{ground}} + t_{0 \text{ground}}}{2} + \Delta t \]
Application to Navigation

- Improved time transfer accuracy
- Robust against signal interference/jamming
- Disaggregated Nav 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
Optical Precision Time-transfer (OPTI) Overview
# Atomic Clocks (Microsemi)

<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>3.3x10^{-12} @ 6000 sec (20 nsec)</td>
<td>9.5x10^{-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>
10 psec Event Timer

- **Time-to-digital converter** – measures fine time
  - Measurement based on propagation delay
  - Autonomous temperature compensation using DLL
  - Low power (132 mW)
  - 10 ps single shot accuracy (12 ps measured)
- **MSP430 microcontroller** - course time

![Diagram of TDC-GPX and Ti MSP430]
OPTI Laboratory Demonstration

SLR Emulator
- Laser, Pulse driver
- Beam Splitter
- APD
- Event Timer
- CSAC
- \( t_{\text{ground}} \)
- \( t_{0 \text{ground}} \)
- \( t_{2 \text{ground}} \)

Space Segment
- Event Timer
- CSAC
- \( t_{\text{space}} \)
- \( t_{1 \text{space}} \)
Measured Performance

- Clock difference (2 CSACs) measured using OPTI breadboard
Timing Error Budget

Timing error, $\Delta t$ (nsec)

Averaging time $\tau$ (sec)

GPS Time (20 nsec)

10 nsec

1 nsec

Predicted Timing Budget

Measured

One Orbit

10^{-1}

10^{0}

10^{1}

10^{2}

10^{3}

10^{4}
OPTI Flight Instrument

TEC controllers, reverse bias voltage

Time-to-digital converters, clock counters

APDs
1. Si: 532 nm, 500 ps
2. InGaAs: 1064 nm, 140 psec

Fiber coupler / TEC

Light collectors, filters

PLX Retroreflector
The CHOMPTTT 3U CubeSat

- UHF turnstile, GPS antennas
- CDH (MSP430)
- GPS receiver, UHF/VHF radio
- Batteries
- Power distribution system
- ADACS interface electronics

**ADACS**

- Interface electronics
- High voltage, TEC controllers
- Event timers, clock counters
- CSAC
- MAC

- Retroreflector and light collectors

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**OPTI**
Rendered View of the CHOMPTT Satellite
Concept of Operations

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

Ground Station (Flight Operations)

SLR
Laser Communication

- 2-Pulse Position Modulation (2 slots per pulse)
- Synchronization string provides phase, rate, & masks SLR delays
- Fine time required only for first ‘timing’ pulse

Timed laser pulse

Synchronization string

Timing data (20 bytes)

Checksum (2 bytes)

Repeated if low link quality

TRUE/1

FALSE/0

Sync. error

Comm. Loss or sync. error
Status and Future

- EM of OPTI fabricated, currently under test
- High altitude balloon launch, Sept. 2014 (Sage Cheshire)
- OPTI integrated into CHOMPTT satellite bus, 2015
- Qualification testing at NASA KSC
- ELaNA launch
  - 2016-2017
- SLR collaborators
  - NGSLR managed by NASA GSFC, MD
  - Starfire optical range at Kirtland AFB, NM
Backup slides ...
Optics & Light Detection

- **PLX retroreflector**
  - 25 mm diam, 50° FOV
  - Space capable
- **Avalanche photodetectors (2)**
  - Si (532 nm, 1064 nm): 500 ps rise
  - InGaAs (1064 nm): 140 ps rise
- **Light collection**
  - Light collected by optical fiber terminating on nadir face
    - 12° max incidence
  - GRIN lens focuses light onto APD
SLR Emulator

- Laser and pulsed driver
- Clock
- Event timer
- Beam splitter
- Laser collimator
- APD box $t_2$ ground
- De-focusing lens
- APD box $t_0$ ground

Emulated SLR Facility
Space Segment

- Focusing lens
- APD Box
- Retroreflector
- Event timer
- Clock

$t_1^{\text{space}}$
Timing Error Budget (MAC)

- GPS time (20 nsec)
- MAC timing error
- Predicted timing budget
- APD rise time
- One orbit

Timing error, $\Delta t$ (nsec)

Averaging time $\tau$ (sec)
Timewalk Correction

- Apparent timing variations due to pulse amplitude variations
  - Atmosphere, attitude, range, ...
- Solution: Time both rising and falling edges of pulse

![Threshold](image)

Time-to-digital converter

Start → Stop 1 → Stop 2

0.5 V to 2.5 V → Δt = 230 psec