The Cubesat Laser Infrared Crosslink mission (CLICK)

Myles Clark, on behalf of the CLICK Team
Precision Space Systems Lab, University of Florida

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CHOMPTT - Cubesat Handling Of Multi-system Precision Time-Transfer

University of Florida – Precision Space Systems Lab
NASA - Ames Research Center
• LV Integration: April 2018
• Launch: 18 Dec 2018
• NASA ELaNa XIX
• Rocket Lab’s 4th Launch
  • “This One’s for Pickering”
  • First NASA Launch
• 500 km circle × 85 deg
• ~7 years to re-entry
Clock discrepancy

\[ \chi = t_1^{\text{space}} - \frac{t_2^{\text{ground}} + t_0^{\text{ground}}}{2} + \Delta t \]
Optical Precision Time-transfer Instrument (OPTI) - v3.1 (flight)

• Primary CHOMPTT mission payload element

• Custom PSSL design:
  • APD-based Photoreceiver
    • Tunable reverse bias for gain control, adjustable threshold
    • Thermo-electric cooler control → stable breakdown voltage
  • Precision oscillator (Chip Scale Atomic Clock)
    • Allan Dev. 3.3x10–12 @ 90 min → 20 ns (6 m)
  • Time-to-Digital Converter: ACAM TDC-GPX
    • 10 ps (3 mm) time-stamping (fine time)
  • Microcontroller: TI MSP-430
    • CSAC clock counter @ 10 MHz (course time)

• Two identical A/B OPTI channels flown
Long Term Performance
Clock Comparison Mode

• Both CSACs disciplined to Rb standard ~1 year before launch

• Allan Deviation calculated from $\chi$ time-series using IEEE, Stable32

• Timing error calculated explicitly at $\tau = 6,000$ s (1 orbit)
  • $\sigma_y(6,000) \times 6,000 = 19 \pm 12$ ns
  • Level 1 requirement: Error <20 ns @ tau = 1 orbit ✓
  • Excluded first orbit data

![Graph showing Allan Deviation Results](image)

Measured frequency offset after 7 months: $\Delta f = 70$ mHz
CLICK - The CubeSat Laser Infrared Crosslink Mission

Massachusetts Institute of Technology – Space Telecommunications, Astronomy and Radiation Laboratory Lab
University of Florida – Precision Space Systems Lab
NASA - Ames Research Center
CubeSat Laser-Comm

- **The CubeSat Standard**
  - A satellite made from ‘units’ of 10x10x10 cm³ (1L)
  - Standardized launch & deployment systems
- Can enable new **distributed & coordinated sensing missions**
- There is a need for:
  - **Mbps-rate** full-duplex crosslinks
  - **Precision ranging** and timing
- **Goal**: Development of miniaturized optical transceivers based on COTS components & compatible with CubeSat SWaP constraints
- CLICK-BC’s objective:
  - **20 Mbps** and **6 cm instantaneous** at **580 km** in **1.5U**
    - (<0.5 m orbit average)
The CLICK-BC Mission

- Pair of **1.5 U, ~1700 g, <25 W** payloads flown on two 3U CubeSats
- **200 mW** avg. Tx, **70 µrad** divergence
- **2.5 cm** receive aperture
- **500 mW** beacon at 976 nm for PAT
- Full-duplex **PPM** crosslinks 1537/1565 nm
  - **50 Mbps**, 4-PPM, <450 km
  - **25 Mbps**, 16-PPM, <920 km
- **200 ps** timing accuracy & time transfer
- Primary success criteria:
  - >20 Mbps full-duplex @ 580 km
  - <0.5 m ranging w/o GPS @ 580 km
Optical Bench Layout

Transmit
200 mW, 1537 nm
120 µrad $1/e^2$

Receive
1563 nm
20 mm aperture

Beacon
250 mW, 976 nm
22 mrad $1/e^2$
Payload Layout

- Chip-Scale Atomic Clock (CSAC)
- Electronics Backstack
- Optical Bench
- Fibre Raceway & EDFA
Fiber Raceway

FPGA \(\rightarrow\) Daughterboard \(\rightarrow\) Optoelectronics Board

\[\text{Tunable Seed Laser} \rightarrow \text{SOA} \rightarrow \text{PD} \rightarrow \text{EDFA} \rightarrow \text{Laser Collimator} \rightarrow \text{Beacon Collimator} \rightarrow \text{To EDFA} \]

\[\text{Thorlabs SOA Optical Shutter} \rightarrow \text{To Beacon} \]

To EDFA
Electronics Backstack

- Optical Bench
- Fibre Raceway
- CPU Board
- CSAC
- FPGA Board
CPU Board

- Ground Support Connector
- RPi CPU Power Converters
- Tracking Camera Connector
- USB Hub
- FPGA Board Data Connector
- Spacecraft Bus Connector (Power & Data)
- Differential SPI Buffers for Bus Data
- Power Control and Monitoring
- FPGA Board Power Connector
- FPGA CSAC Reference Clock Connector
FPGA Board

ScioSense TDC-GPX2

Pulse Edge Detection

Clock Management

Power Conversion

DDR3 ECC DRAM

CPU Board Power Connector

CPU Board Data Connector

Transmitter Connector

Quadcell Board Connector

APD Board Connectors

12b 500 MHz ADC

Microsemi M2S150TS-1

FlashPro5 Debugger
Fine Pointing And Tracking (PAT)

Beacon Laser
976 nm, 250mW
3 kHz sine modulation

Free space
22 mrad $1/e^2$

~25 to 855 km

Telescope
MEMS Tip-tilt mirror

4 Quadrants Si PIN detector

AMC and filtering

High voltage Amplification

PID Adjustable Gains
Deviation $dx, dy$

CORDIC
$I^2 + Q^2$

I-Q Demodulation Adjustable BW

DAC

Slide: H. Tomio
PPM Pulse Encoding

- Data encoded into symbols, which vary the pulse emission time
- Typical setting: $M = 16$, $\tau = 10$ ns, $T_g = 40$ ns => 20 Mbps
  - $D_{PPM} = \frac{\text{data per pulse}}{\text{time per pulse}} = \frac{\log_2 M}{M\tau + T_g}$

![Diagram of PPM Pulse Encoding with symbols and time parameters](image-url)
Receiver Timestamping
The Time to Digital Converter

- **ScioSense TDC-GPX2**
  - 4-channel, 20ps RMS single-shot
  - Used at 12.5 MSps @ ~5ps resolution

- **Hardware timing jitter measurement**
  - Direct electrical input from modulator @ 4.5 MHz
  - Difference taken between adjacent timestamps

- **Measured standard deviation of time difference: ~76 ps**
  - Single-shot jitter: 54 ps
The Symbol Decoder

- \( T_n = T_{n-1} + (M\tau + T_g) \)
- \( t_n = T_n + m\times\tau \)
- \( T_{res} = f_{error}([t_n - T_n] - [m_{bound}\times\tau]) \)

\( (\Delta t_{meas}) \quad (\Delta t_{perfect}) \)

\[ T_{res} \approx T_{offset} + \chi \]
CLICK-BC Timeline

CLICK-BC Payload Delivery to BCT:  
**Early 2023**

Launch to ISS on SpaceX CRS Mission:  
**NET Oct 2023**

CLICK is supported by the NASA STMD Small Spacecraft Technology Program
Backup Slides
TDC Timestamping Pipeline

- 12.5 MHz Reference Clock
- 3.125 MHz Index Reset Clock
- 100 MHz LVDS Data Clock

16-bit Transfers (12.5 MSps):
- 14 stop bits: $\frac{80 \text{ ns}}{2^{14}} \approx 5 \text{ ps}$
- 2 index bits: $80 \text{ ns} \times 2^2 = 320 \text{ ns} \equiv 3.125 \text{ MHz}$
Serialisation... already exists

- The SerDes module is provided a 100 MHz reference
- It has an internal x20 PLL that locks to the reference
- At 100 MHz, it is “fed” a 20-bit binary number, emitted bit-by-bit at 2 GHz