A high-precision continuous-time positioning-navigation-timing (PNT) compact module for the LunaNet small spacecraft

2022 SmallSat Technology Partnerships (STP) Technology Exposition

NASA STP Technical Monitor: Rodolphe De Rosee
PI: Prof. Chee Wei Wong, UCLA
Co-I: Jaime Flor Flores, UCLA
NASA Center: Dr. A. Matsko, Dr. V. Iltchenko, and Dr. W. Zhang, JPL

STP 2020 Project: 80NSSC20M0082

June 8, 2022
Desired accelerometer performances for applications

- **Bandwidth (Hz)**
  - $10^{-6}$
  - $10^{-4}$
  - $10^{-2}$
  - $10^{-1}$
  - $10^{1}$
  - $10^{2}$
  - $10^{3}$
  - $10^{4}$
  - $10^{6}$

- **Navigation**
  - FGM-148 Guidance system
  - Double charge and detonation system
  - Smart Ammunition
  - Health Tracking
  - Gravimetry
  - Inertial Navigation

• **Size Weight and Power (SWaP)**. SWaP vs. time to achieve a 1 nautical mile (nmi) error in seconds, for different accelerometers and technologies.
• Commercial accelerometers are shown and labeled by model and technology they use.
• Optomechanical accelerometers presented in red are our SSTP-STP device modules (pre-STP: bare chiplet lab demonstration).
### Precision inertial navigation – detailed performance metrics

**Via this 2020 STP program**

<table>
<thead>
<tr>
<th>Inertial sensor metric</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume/Weight</td>
<td>full package 2.8 cm³ [chiplet is 0.034 cm³]</td>
</tr>
<tr>
<td></td>
<td>31.5 grams [chiplet is 0.08 grams]</td>
</tr>
<tr>
<td>Power</td>
<td>58 mW [1-2 W cont. operation of TEC]</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>Future testing at 60 g</td>
</tr>
<tr>
<td>Velocity random walk</td>
<td>8 μg/Hz¹/₂</td>
</tr>
<tr>
<td>Bias sensitivity</td>
<td>1.3 mg/Hz</td>
</tr>
<tr>
<td>Scale factor repeatability</td>
<td>optical resonance repeatability at ~0.7 ppm</td>
</tr>
<tr>
<td>Bias instability</td>
<td>52 μg</td>
</tr>
</tbody>
</table>

- Demonstrated metrics of the chip-scale inertial sensor, in support of the LunaNet PNT technology mission

Packaged inertial navigation unit with significant experience from JPL
Inertial navigation – fundamental operating architecture

1. Light forces at the Nanoscale

- Gram-scale mirror
- Silicon nitride membrane
- Sub-millimeter mirror
- AFM cantilever mirror
- Silica microtoroid cavity
- 50 μm micro-mirror
- 2 μm dwarf mirror
- Nano-resonator

2. Coupled mode and first-order perturbation theory

\[ \frac{da}{dt} = i\Delta(x)a - \left( \frac{1}{2\tau_0} + \frac{1}{2\tau_{\text{ex}}} \right)a + i\sqrt{\frac{1}{2\tau_{\text{ex}}}}s \]

\[ \Delta(x) = \Delta + g_{OM}x = (\omega - \omega_0) + g_{OM}x \]

\[ \frac{d^2x}{dt^2} + \frac{\Omega_m}{2Q_m} \frac{dx}{dt} + \Omega_m^2x = \frac{F_0}{m_{\text{eff}}} + \frac{F_{\text{th}}}{m_{\text{eff}}} = -\frac{|a|^2}{m_{\text{eff}}} \frac{g_{OM}}{\omega_0} + \frac{F_{\text{th}}}{m_{\text{eff}}} \]

3. Optomechanical coupling

\[ g_{om} = \frac{d\omega}{dx} \quad L_{om}^{-1} = \frac{1}{\omega} \frac{d\omega}{dx} \]

4. First-order perturbation theory

\[ g_{om} = \frac{1}{2\omega} \int dA \left( \mathbf{q} \cdot \hat{n} \right) \left[ \Delta\varepsilon |E|^2 - \Delta \left( \varepsilon^{-1} \right) |D|^2 \right] \]

\[ \int dV\varepsilon |E(r)|^2 \]

- H. A. Haus, Waves and Fields in Optoelectronics.
Cavity optomechanics: optimized slot-cavity nanofabrication

- 2 nm shot size per pixel
- 100 pA
- proximity correction
- controlled pattern/etching

D. Wang and M. Dadgar (Wong) et al.
Inertial accelerometer: optical & mechanical design

- **Mechanical modes** designed for the oscillation-mode accelerometer.
  - Fundamental mode at 45.12 kHz.
  - Forbidden modes in grey. These modes are not allowed due to symmetry constraints.
  - Finite-element modeling.

- **Simulated optical modes.** Figures c-f represent the calculated electric field (V/m)^2 of the optical mode for the fully integrated photonic crystal:
  - c. Fundamental mode
  - d. x-z view of the zoomed in z-component electric field (V/m)
  - e. Second-order mode.
  - f. Third-order mode.

- \( Q_{\text{theory}} \sim 4,000,000 \quad (Q_{\text{expt}} \sim 200,000) \)
- Mode volume \( V \sim 0.02(\lambda/n_{\text{air}})^3 \)
Inertial optomechanical oscillator: high dynamic range and precision force sensing

- RF mode of the optomechanical accelerometer with integrated waveguides
- Transmission spectra is monitored for cavity coupling, the main measurements are done in parallel by RF optical readout.
Inertial acceleration signal detection

Oscillation and pre-oscillation modes performance

- Allan deviation measured at the pre-oscillation and oscillation modes.
- 220× Improvement in the oscillation mode compare to pre-oscillation.
- optomechanical coupling rate of 37.1 GHz/nm.
- further stability can be improved with laser stabilization.

Inertial accelerometer noise sources: kT, backaction and relative intensity noise

- theoretical limit includes thermal (kT) noise components as well as backaction noise.
- measurement noise sources such as laser intensity noise can be accounted for inertial navigation system.
- estimated maximum sensitivity to laser intensity noise is 0.2 Hz/nW at maximal inertial motion. Smaller displacements present smaller noise contributions.
1. 3D view of the optomechanical inertial accelerometer (OMI) package design

OMI: optomechanical inertial accelerometer

2. OMI integration and design

3. Integrated optomechanical transducer with on-chip detector
Precision inertial accelerometer: packaging tests

- 3D view of the accelerometer package design components
- guided by JPL rich experience

- laser-drive power and detectors are coupled by tapered lensed fibers.
- triple-stage inverse couplers and waveguides on-chip implemented for coupling to photonic crystal cavity sensor.
- accelerometer package optimized for thermal expansion coefficient matching
  - AlN subcarrier provides a coupling interface between the butterfly package and the Si chiplet.
  - CuW block for enhanced heat transfer.
  - hermetic package.
  - active alignment is externally controlled.
  - external TEC.
Hermetic UV sealing
Details of active alignment packaging process

- Microscope image of nanofabricated optomechanical inertial sensor packaged at UCLA
  - active alignment on 6-axis system.
  - optimized multiple epoxies for controlled adhesive bonding to minimize optical power loss.
  - images describe the fiber active alignment process as the adhesive is cured for and the tapered optical fibers held in place.
- Ni-Co butterfly package with hermetic sealing

- active alignment setup to couple custom-made lensed fibers to the on-chip inverse couplers.
- optical fiber bonding process during optical active alignment
- optomechanical inertial accelerometer after active alignment and support mechanism released: laser coupling to chip maintained and stabilized.
**Frequency Counting: frequency-to-voltage approach**

**a, Designed circuit block**

- Optomechanical Inertial accelerometer readout circuits & drivers
  - Instrumentation amplifier
  - 2 stage bandpass filter
  - Signal conditioner
  - Frequency to voltage converter
  - Connected to main processing unit

- Breadboard and PCB implementation.
  - compact size for final integration with OMA

**b, Initial testing, and anticipated frequency resolution of inertial accelerometer readout**

### InAmp Response

<table>
<thead>
<tr>
<th>Reference</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MHz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>10 MHz</td>
<td>1 Hz</td>
</tr>
<tr>
<td>100 MHz</td>
<td>100 mHz</td>
</tr>
<tr>
<td>1 GHz</td>
<td>10 mHz</td>
</tr>
<tr>
<td>10 GHz</td>
<td>1 mHz</td>
</tr>
</tbody>
</table>

**Diagram:**

- Bandpass filter stage 1
- Bandpass filter stage 2
- Instrumentation Amplifier
- F/V converter
- Signal conditioner
Floor planning of subsystem boards with 3U CubeSat housing
Small Spacecraft Technology Program

A high-precision continuous-time positioning-navigation-timing (PNT) compact module for the LunaNet small spacecraft

2022 SmallSat Technology Partnerships (STP) Technology Exposition

**NASA STP Technical Monitor:** Rodolphe De Rosee  
**PI:** Prof. Chee Wei Wong, UCLA  
**Co-I:** Jaime Flor Flores, UCLA  
**NASA Center:** Dr. A. Matsko, Dr. V. Ilchenko, and Dr. W. Zhang, JPL

STP 2020 Project: 80NSSC20M0082