Optimetrics for Precise Navigation

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Table of Contents

1. Overview of Radiometrics for Navigation
2. Tracking Examples: TDRSS and TDORS
3. Optimetrics Measurements in Optical Communication
4. Summary
5. References
1. Overview of Radiometrics for Navigation
Radiometrics and Optimetric Parameters for Navigation

- Ranging (distance via time of flight)
- Doppler (velocity via frequency shift or carrier phase)

Radiometrics in RF Communication (over RF carrier)
- PN ranging; Tone ranging
- Carrier Doppler

Optimetrics in Optical Communication (over Optical Carrier)
- Data frame and clock ranging
- Data Clock Doppler
- Come with signal pointing angles
## Radiometrics Accuracy Limiting Factors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limit (Allan Deviation)</th>
<th>Condition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock Stability</td>
<td>$10^{-13}$</td>
<td>Space Qualified crystal with 1000s average [4]</td>
<td>Optical frequency standard can reach [5] $10^{-18}$</td>
</tr>
<tr>
<td>Frequency Standard</td>
<td>$10^{-15}$</td>
<td>Hydrogen Maser</td>
<td>Optical frequency standard can reach [5] $10^{-18}$</td>
</tr>
</tbody>
</table>
| Plasma Introduced group delay variation | 20cm - 60 cm            | X-band in Ionosphere [4]            | $\Delta t = k/f^2$
Higher Optical Frequency ($10^{14}$Hz) than X-band ($10^{10}$Hz), reduces this noise by 8 orders of magnitude |
| Plasma Introduced group delay variation | 1m - 75m             | X-band in interplanetary medium [4] |                                                                     |
2. Tracking Examples

Tracking and Data Relay Satellite System (TDRSS)

Tracking and Data Optical Relay Satellite (TDORS)
Traditional TDRSS Radiometrics

1. Tracking and Data Relay Satellite System (TDRSS) provides two-way coherent range (PN ranging) and range rate (carrier Doppler) observations
2. The signal path transverses 4 paths (legs 1 – 4) during the observation
3. The TDRS payload is coherent to the Telemetry, Tracking, and Command (TT&C) uplink (leg 5), which is coherent to a common time and frequency source (CTFS)
4. Knowledge of absolute time onboard the TDRS is unnecessary to support TDRSS radiometrics
5. Range and Doppler observations are referenced to the ground system/modem, and are time tagged according to the CTFS
6. Calibrations of the ground system and TDRS payload are necessary to mitigate delays introduced by ground and spacecraft electronics

Observations referenced to the ground
1. The Range and Doppler observations are referenced to the Relay system/modem.
2. The Measurements are time tagged
3. Measurements of leg 1&4 are between Relay and Ground
4. Measurements of leg 2&3 are between Relay and User
5. The Relay station movement contribution are common to both 1&4 and 2&3, and the measurements are conducted at the same time
6. User to ground measurement (like TDRSS) can be mathematically constructed by subtracting common contributions from the Relay.

Legend
- **RSDO**
- **User**
- **Optical**
- **RF**

Observations referenced to the relay

**TDORS**

RF Link for time & Frequency Transfer

**White Sand (WSC)**

User MOCC
3. Optimetric Measurements Implementation
## Missions with Radiometrics or Optimetric

<table>
<thead>
<tr>
<th>Area</th>
<th>Missions</th>
<th>Carrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation Flying for Gravitational scientific measurements</td>
<td>GRACE, GRAIL</td>
<td>RF</td>
</tr>
<tr>
<td>Space Doppler Tracking via Radio Science Beacon</td>
<td>Cassini, GRAIL</td>
<td>RF/OpNav</td>
</tr>
<tr>
<td>Doppler and Ranging for Spacecraft Navigation</td>
<td>All navigation</td>
<td>RF</td>
</tr>
<tr>
<td>Optical Ranging and Doppler Demo</td>
<td>LLCD [1]</td>
<td>Optical</td>
</tr>
</tbody>
</table>
Optical Tracking Current Status

• LLCD demonstrated two-way coherent range and Doppler measurements [3]

• Current LCRD payload doesn’t support coherent clock and frame loopback.

• Future TDORS requires Optimetric measurements be implemented
Optimetric over Optical Communication

Payload Modem
Optometric
Measurements

User Modem
Frame and Clock
Coherent loopback

TxFrame

RxFrame

Tx Bit clock

Rx Bit clock

Three rulers for ranging
1. \(N_{\text{frame}}\) = number of frame between transmit and receive
2. \(N_{\text{bit}}\) = Number of Bit between Tx and Rx Frame
3. \(\Delta\text{Phase}\) = Phase Diff between Tx and Rx clock

Total Range Time = \((N_{\text{frame}} \times T_{\text{frame}} + N_{\text{bit}} \times T_{\text{bit}} + \Delta\text{Phase})/2\)
Experimental Setup [2,3]

**Ground Terminal**
- SFP Tx
- SFP Rx
- CDR
- Pattern Gen
- Power Divider
- RF Source A 622MHz

**Space Terminal**
- Attn
- SFP Rx
- Free Space
- CDR
- SFP Tx

**Additional Components**
- Clock Data Recovery (CDR)
- Dual Mixer Time Difference (DMTD)
- Time Interval Counter

**Definitions**
- SFP: Small Form-factor Pluggable optical transceiver
- CDR: Clock Data Recovery
- DMTD: Dual Mixer Time Difference phase measurement
Breadboard and Test Equipment
With DMTD phase measurement, the instrument noise is improved by three orders of magnitude from 20 ps (HP time interval counter) to 50 fs.
Space Terminal and Ground Terminal Closed Loop Performance Data Rate at 622MBPS

Transmit clock, recovered data, and recovered clock waveforms captured in scope plots
Tone Modulation at 622MHz

The relative error reaches $10^{-13}$ (or 30 $\mu$m) at 1 second average time.

Noise floor $10^{-15}$ (or 0.3 $\mu$m) at 1 second average time.
The performance is independent of RX power

The relative error reaches $8 \times 10^{-14}$ (or 23 $\mu$m) at 1 second average time.
The measurement accuracy is not dependent on the Rx power, or Bit error rate. The performance is two orders of magnitude better than TDRSS.
### Ranging and Range Rate Accuracies [2,3]

<table>
<thead>
<tr>
<th>Average Time (s)</th>
<th>Instrument Noise Floor</th>
<th>622MHz Tone AM Modulation</th>
<th>622MBPS Data Communication</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.28</td>
<td>19.74</td>
<td>23.1</td>
</tr>
<tr>
<td>10</td>
<td>0.06</td>
<td>0.27</td>
<td>2.1</td>
</tr>
</tbody>
</table>

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<td>1</td>
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<td>19.74</td>
<td>23.10</td>
</tr>
<tr>
<td>10</td>
<td>0.62</td>
<td>2.67</td>
<td>21.00</td>
</tr>
</tbody>
</table>
4. Summary
Advantages of Optimetric

- High Optical Frequency enables
  - Immunity from ionosphere and interplanetary Plasma noise floor, which is a performance limitation for RF tracking
  - High antenna gain reduces terminal size and volume, enables high precision tracking in Cubesat, and in deep space Smallsat.

- High Optical Pointing Precision provides spacecraft orientation

- Minimal additional hardware to implement Precise Optimetrics over optical comm link (TRL>6)

- Continuous optical carrier phase measurement will enable the system presented here to accept future optical frequency standard with much higher clock accuracy (10^{-18})
Conclusions and Future Works

Achievements:
- Achieved 2.7 mm range accuracy for average window size of 10s
- Achieved 0.27 mm/s range rate accuracy for average window size of 10s
- Demonstrated range and range-rate accuracy are independent of optical communication link noise bit error rate.

Future work
- Implementation of Optimetrics in TDORS
- Research on continuous optical phase measurement Optimetrics in coherent optical communication
- Engage with planetary and earth scientists for application of this technology
- Engage with the next NASA laser comm mission, Laser Communication Relay Demonstration (LCRD) to study infusing optimetrics into their system.
5. References


[2]. SPIE Photonic West Proceeding (2016), Guangning Yang etc, :Innovative free space optical communication and navigation system with high data rate communication, precision ranging, range rate measurements, and accurate spacecraft pointing”

[3]. IEEE Aerospace Conference (2016), Guangning Yang etc. “High-Precision Ranging and Range-Rate Measurements over Free-Space-Laser Communication Link”


[5]. David B. Hume* and David R. Leibrandt, PHYSICAL REVIEW A 93, 032138 (2016) “Probing beyond the laser coherence time in optical clock comparisons”
Backups
“Optimetrics for Precise Navigation” will be implemented on existing optical communication links. The ranging and Doppler measurements are conducted over communication data frame and clock. The measurement accuracy is two orders of magnitude better than TDRSS. It also has other advantages of:

The high optical carrier frequency enables

- Immunity from ionosphere and interplanetary Plasma noise floor, which is a performance limitation for RF tracking
- High antenna gain reduces terminal size and volume, enables high precision tracking in Cubesat, and in deep space smallsate.

High Optical Pointing Precision provides spacecraft orientation

Minimal additional hardware to implement Precise Optimetrics over optical comm link

Continuous optical carrier phase measurement will enable the system presented here to accept future optical frequency standard with much higher clock accuracy.
Two Primary navigation functions
1. Orbit Determination (OD)
2. Guidance

Two Relevant Tracking Techniques for Discussion
1. Radiometric based range and Doppler (earth based radio frequency tracking)
   Optimetric Provides similar measurements with higher precision
2. Optical Based Navigation (optical image of the target or satellite against the known star background)
Dual Mixer Time Difference (DMTD) phase measurement setup. To Increase the measurement sensitivity by heterodyne mixer gain
The relative error reaches $10^{-15}$ (or 0.3 μm) at 1 second average time.
Continuous Phase Error, 622MHz AM modulation (sampling rate 1KHz)

622MHz AM modulated optical signal presents a zero-to-peak noise at 300 fs
Phase Measurement with 1KHz Sampling Rate

622MHz Data (Pattern PRBS31-1) modulated optical signal presents a zero-to-peak noise at 2 ps