Spacecraft Navigation Using Optical Astrometry & Ranging

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Workshop on Emerging Technologies for Autonomous Space Navigation
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Opportunity: Optical Communications Systems

Deep-space optical links could revolutionize space communications

Those same links could also be used for deep space navigation

Ground Laser Transmitter (GLT)
Table Mtn., CA
5kW, 1m-dia. Telescope

Ground Laser Receiver (GLR)
Palomar Mtn., CA
5m-dia. Hale Telescope
Opportunity: ESA’s Gaia Star Catalog

Topic covered by Chris Jacobs

Will provide reference star positions than can be used to perform spacecraft astrometry at a level comparable to that possible with VLBI

~37 million stars down to $15^m$ accurate to 0.12 nrad
~1 billion stars down to $20^m$ accurate to 2 nrad
Spacecraft position components relative to telescope can be measured optically:
- LOS Range (R) and Doppler (D)
- POS Astrometry (RA, DEC)

- Background star locations req’d for pointing knowledge and frame tie

- Measurements processed on-board or on-ground to determine trajectory

(x, y) define plane-of-sky (POS)
z defines line-of-sight (LOS)
Building block: Ground-based High-power Lasers

- High-powered laser for testing being installed at the OCTL
- It should allow for reflector-based astrometry and ranging up to lunar distances
- It can also be used for deep-space transceiver-based experiments
Building block: Spacecraft Optical Terminal

• Goals:
  • **Precision ranging (5 mm)** with high BW receiver & transmitter using accurate on-board time-tagging of sent and received laser-optical signals;
    – Either 2-way, or 1-way when equipped with a precise on-board clock
  • **On-board high-precision astrometry (10 uas)** with a large-format, multi-megapixel, low noise, fast CCD camera;

• Approach:
  • Build and demonstrate performance of proof-of-concept for new instrument capable of communication, ranging, and astrometry.
On-board Astrometry

- On-board multi-megapixel CCD camera integrated into DOT would enable precision astrometry to ~20 μas
  - Beacon-less acquisition and comm (current DSOC needs an Earth-based optical comm beacon);
  - Autonomous nav relying on an over 10,000 increase in onboard astrometric capabilities;
    » Using asteroids or moons as targets
    » Using other laser-equipped spacecraft as targets
Building block: Ground-based Telescopes and Detectors

• 5 nrad spacecraft astrometry could be achievable with a 1 m telescope, and 1 nrad with a 5 m telescope.

• It may be more efficient to have two different types of ground telescopes:
  – One with large apertures for telemetry and ranging
  – Smaller, low-cost telescopes for all kinds of astrometry, including spacecraft tracking
Point of Departure for Astrometry

Field distortion: optics and detector
~ 250 nrad

Streaked image due to motion
~ 1000 nrad

Atmospheric turbulence
~ 150 nrad

Photon noise

30 s integration

Pre-Gaia Catalog Error
~ 250 nrad

Credit: Chengxing Zhai
Goal for Precise Astrometry

**Field distortion:**
- **optics and detector**
  - $\sim 0.7$ nrad

**Atmospheric turbulence**
- $\sim 0.4$ nrad

**Differential chromatic refraction**
- $\sim 0.5$ nrad

**Streaked image due to motion**
- $< 0.1$ nrad

**Gaia Catalog Error**
- $\sim 0.1$ nrad

**Photon noise**
- $\sim 0.1$ nrad
- $\sim 0.4$ nrad
- $\sim 0.7$ nrad

**Field distortion modeling**
- using Gaia and dense field image (1 arcmin field)

**Synthetic tracking**
- $30$ s -> $3600$ s

Credit: Chengxing Zhai
New Camera on Pomona College 1m Telescope a JPL’s Table Mountain Observatory

• A new camera has been installed at TMO for precision astrometry and it is being calibrated using the 2016 release of the Gaia catalog.

• Currently being tested observing asteroids, as analog of observing interplanetary spacecraft.

Credit: Chengxing Zhai
Optical Comm Nav Pros and Cons

Pros:

• Single-station plane-of-sky measurements
  – Possible without changes to the spacecraft optical terminal
  – Feasible with smaller, low-cost apertures

• Not affected by charged particles (ionosphere or solar plasma)
  – Solar plasma is the dominant error source for X-band tracking

• Improved ranging accuracy
  – Ranging requires changes to the spacecraft optical terminal
Optical Comm Nav Pros and Cons

Cons:

• Ground-based optical tracking precluded by cloud cover
  – Could be mitigated by regional diversity

• Astrometry less accurate or impossible with increased levels of sky brightness
  – Astrometry not available for small Sun-Earth-probe angles

• Requires precise pointing, no optical LGA at deep-space distances
  – It may not be possible to track and operate the payload at the same time
    • Solvable with a gimballed optical terminal
Optical Astrometry Constraints

- Elevation: optimal within ~30° of zenith
- Brightness: astronomical twilight (18°) observed

Can observe fine

30° off-zenith

Twilight 18°

Gets worse
FY16 Navigation Analysis

• Radio and optical data types simulated
• Different mission scenarios considered
  – Mars lander case based on Mars 2020
  – Mars orbiter case based on MAVEN (Mars Atmosphere and Volatile Evolution)

Mars 2020 schematic. Image courtesy of NASA.

MAVEN at Mars. Image courtesy of NASA.
## Comparing Radiometrics and Optometrics

<table>
<thead>
<tr>
<th></th>
<th>Radiometrics</th>
<th>Optometrics</th>
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</thead>
<tbody>
<tr>
<td><strong>Data types</strong></td>
<td>Two-way Doppler, two-way range, ΔDOR</td>
<td>Optical range, ground-based astrometry</td>
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<tr>
<td></td>
<td>e.g. for X-band: Doppler: 0.10 mm/sec Range: 3 m</td>
<td>Range: 5 cm (360 sec integration)</td>
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<td></td>
<td>ΔDOR: 60 ps (2.25 nrad)</td>
<td>Astrometry depends on:</td>
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<tr>
<td></td>
<td></td>
<td>• elevation angle,</td>
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<td></td>
<td></td>
<td>• time of the day,</td>
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<tr>
<td></td>
<td></td>
<td>• telescope diameter,</td>
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<tr>
<td></td>
<td></td>
<td>• integration time</td>
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<tr>
<td></td>
<td></td>
<td>➢ 1 nrad for a 5 m telescope at zenith, at night, with 1 hour integration</td>
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<tr>
<td><strong>Data uncertainties</strong></td>
<td></td>
<td></td>
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<tr>
<td><strong>Error sources</strong></td>
<td>Earth orientation, station location, ephemeris, GMs, clock</td>
<td>Troposphere only</td>
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<tr>
<td></td>
<td>Troposphere, ionosphere, solar plasma</td>
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<td>Quasar catalog</td>
<td>Star catalog</td>
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Mars Lander Results

• Assuming continuous availability, optical can outperform traditional radiometric tracking data

• Optical outperforms direct radiometric analog (Radio range + ΔDOR)

• Could meet MSL, Mars 2020 requirements

Credit: Sarah Elizabeth McCandless
Mars Lander Results

- Navigation performance most sensitive to telescope diameter

Credit: Sarah Elizabeth McCandless
Mars Orbiter Results
April 18-19, 2016

- Based on MAVEN, currently in orbit at Mars
- Reconstruct orbit to within 3.0 km
- Optical outperforms radio during tracking passes & tracking gaps

Credit: Sarah Elizabeth McCandless
Mars Orbiter Results
May 5-6, 2015

- Degraded OD performance due to occultations
- Optical outperforms radio during tracking passes but not tracking gaps
- Still meets navigation requirements

Credit: Sarah Elizabeth McCandless
Other Navigation Scenarios to be Analyzed

• Asteroid rendezvous
  – Simultaneous imaging of spacecraft and target
  – Use of the on-board camera for target imaging
  – On-board autonomous navigation

• Mars spacecraft-to-spacecraft tracking
  – Complementing short-haul data links
  – On-board autonomous navigation

• Gravimetry of planets and moons
Conclusion

- Optical tracking has the potential to provide viable deep-space navigation data types with performance comparable to that achievable with radio.

- Optical tracking will be affected by some unique operational constraints that will limit its availability:
  - Cloud cover
  - Sky brightness for astrometry
  - Need for precise pointing – no optical LGA