Navigating a Crewed Lunar Vehicle Using LiAISON

Jeffrey S. Parker, Jason M. Leonard, Kohei Fujimoto
Ryan M. McGranaghan, and George H. Born

Colorado Center for Astrodynamics Research
University of Colorado at Boulder

Rodney L. Anderson
Jet Propulsion Laboratory
California Institute of Technology
Navigating this Presentation

- Motivation
- Proposed Crewed Mission to the Moon
- Crew Disturbance Model (FLAK)
- Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON)
- Navigation Trade Studies
- Conclusions
Motivation

- Proposals to send humans to an orbit about the Earth-Moon L₂ point.
  - Such orbits are unstable.
  - Questions about how to navigate a noisy vehicle on an unstable orbit.
  - CU and JPL are studying the benefits of adding satellite-to-satellite tracking (SST) to the navigation system.
Motivation

- Proposals to send humans to an orbit about the Earth-Moon L\textsubscript{2} point.
  - Such orbits are unstable.
  - Questions about how to navigate a noisy vehicle on an unstable orbit.
  - CU and JPL are studying the benefits of adding satellite-to-satellite tracking (SST) to the navigation system.

- Need to formulate a baseline.
  - Study the navigation of a noisy, crewed vehicle in a low lunar orbit \(\rightarrow\) direct comparison with Apollo data.
  - Study the costs and benefits of SST in that environment.
  - Apply lessons to L\textsubscript{2} mission.
Crewed missions, including Apollo and the proposed Orion, typically experience significant unmodeled disturbances:

- Wastewater dumps
- Momentum desaturation maneuvers
- Attitude control burns
- Venting of gasses, such as CO$_2$
- Thermal venting
- Water sublimation

These disturbances have become known as FLAK (unfortunate Lack of Acceleration Knowledge)

The Apollo lunar spacecraft experienced position uncertainty growth of about 500 meters in an hour while in low lunar orbit.
FLAK is not well understood yet for proposed crewed vehicles, such as Orion.

It is reasonable to expect that FLAK will be the same order of magnitude for future missions as for Apollo.

FLAK model in current study:
- Accelerations that accumulate in a 500 meter growth in position uncertainty when the vehicle is not being tracked.
- Applied in a spherically-symmetric fashion.
- Day/Night dependency:
  - Day cycle: full FLAK
  - Night cycle (8 hours/day): 10% FLAK

This all requires significant tracking efforts for precision navigation.
Ground Networks

IDAC4B = Integrated Design and Analysis Cycle 4B
Linked, Autonomous, Interplanetary Satellite Orbit Navigation (LiAISON)

- Uses scalar satellite-to-satellite tracking (SST)
  - Range, Doppler

- Navigation satellite placed in orbit about L₁ or L₂.
  - Fixed to both the Earth and the Moon

- Achieves absolute navigation of both vehicles even without any ground observations.

- Huge geometrical benefit when supplementing ground tracking.
Mission Design

- Crewed vehicle placed in a low lunar orbit:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$</td>
<td>1/1/2020 00:00:00 ET</td>
<td>The epoch, ephemeris time</td>
</tr>
<tr>
<td>$h$</td>
<td>100 km</td>
<td>Altitude, relative to mean lunar radius of 1737.4 km</td>
</tr>
<tr>
<td>$i$</td>
<td>90°</td>
<td>Inclination, relative to IAU Moon Fixed coordinate frame</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>30°</td>
<td>Longitude of Ascending Node in IAU Moon Fixed frame</td>
</tr>
</tbody>
</table>

- Navigation satellite placed in either an L$_1$ or L$_2$ halo orbit:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_z$</td>
<td>35,500 km</td>
<td>The $z$-axis amplitude</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0°</td>
<td>The initial phase angle of the orbit</td>
</tr>
<tr>
<td>$t_{\text{ref}}$</td>
<td>1/1/2020 00:00:00 ET</td>
<td>The reference epoch, ephemeris time</td>
</tr>
</tbody>
</table>
Dynamical Model

- **Gravity**
  - Point-mass Earth, Sun, Moon, and all planets
  - Moon: LP150q gravity field truncated to 20x20
  - DE405 ephemerides

- **Solar Radiation Pressure**
  - Area-to-Mass ratio: 0.01 for both vehicles
  - Flat plate model with $C_R = 1$
  - Conical shadow model for Moon; neither vehicle ever enters the Earth’s shadow
The following architectures have been considered:

- Crewed lunar orbiter tracked by any of 5 options:
  - DSN
  - IDAC4B
  - LiAISON
  - DSN + LiAISON
  - IDAC4B + LiAISON

- Lunar navigation satellite tracked by either of 2 options:
  - LiAISON
  - DSN + LiAISON

- Tracking data types: 3 options:
  - Range
  - Doppler
  - Range + Doppler

- Lunar navigation satellite placed in either:
  - L1 orbit
  - L2 orbit
• Tracking schedule:

Tracking Schedule for LiAISON at L2
Tracking Schedules

- **FLAK:**
  - Day cycle: 16 hours / day: full FLAK
  - Night cycle: 8 hours / day: 10% FLAK
• LiAISON
  ■ 24/7 tracking
  ■ Occultations

■ Note: from L₁, LiAISON occurs on the near side of the Moon; from L₂, LiAISON occurs on the far side.
Three DSN stations track the crewed lunar orbiter 24/7

- One at a time
- Priority: Goldstone, Madrid, Canberra
- 10 deg elevation mask
- Future study: add Delta-DOR, though that is only intermittently available
• Three IDAC4B stations are receive-only, optionally providing 3-way tracking of crewed lunar vehicle
  ■ Tied to one partner DSN station
  ■ 10 deg elevation mask
  ■ Santiago, Chile tied to Goldstone, California
  ■ Hartebeesthoek, S. Africa tied to Madrid, Spain
  ■ Usuda, Japan tied to Canberra, Australia
  ■ Delta-DOR may be possible in 3-way configuration
• Three DSN stations optionally track the lunar navigation satellite
  ■ No occultations
  ■ 24/7, one at a time
  ■ Priority: Goldstone, Madrid, Canberra
Measurement Model

- Scalar, instantaneous range and range-rate measurements

\[
\rho_{12} = \sqrt{(r_1 - r_2) \cdot (r_1 - r_2)} + \rho_{12}^{bias} + \rho_{12}^{noise}
\]

\[
\dot{\rho}_{12} = \frac{(r_1 - r_2) \cdot (\dot{r}_1 - \dot{r}_2)}{\rho_{12}} + \dot{\rho}_{12}^{bias} + \dot{\rho}_{12}^{noise}
\]

- Biases are drawn from a Normal distribution and applied to all observations between two antennae.
- White noise is also drawn from a Normal distribution, but sampled once for each observation.
- Observations every 60 seconds
### Measurement Model

- **Bias and white noise statistics**

<table>
<thead>
<tr>
<th>Tracking Link</th>
<th>Bias 1-σ</th>
<th>White Noise 1-σ</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPO - LLO 2-way range</td>
<td>3 m</td>
<td>1 m</td>
<td>LiAISON range SST</td>
</tr>
<tr>
<td>LPO - LLO 2-way range-rate</td>
<td>1 mm/s</td>
<td>1 mm/s</td>
<td>LiAISON range-rate SST</td>
</tr>
<tr>
<td>DSN - LPO 2-way range</td>
<td>30 m</td>
<td>10 m</td>
<td>DSN ground tracking of the halo orbiter</td>
</tr>
<tr>
<td>DSN - LPO 2-way range-rate</td>
<td>1 mm/s</td>
<td>0.5 mm/s</td>
<td></td>
</tr>
<tr>
<td>DSN - LLO 2-way range</td>
<td>30 m</td>
<td>10 m</td>
<td>DSN ground tracking of the crewed vehicle</td>
</tr>
<tr>
<td>DSN - LLO 2-way range-rate</td>
<td>1 mm/s</td>
<td>0.5 mm/s</td>
<td></td>
</tr>
<tr>
<td>IDAC4B - LLO 3-way range</td>
<td>30 m</td>
<td>10 m</td>
<td>IDAC4B ground tracking of the crewed vehicle</td>
</tr>
<tr>
<td>IDAC4B - LLO 3-way range-rate</td>
<td>1 mm/s</td>
<td>0.5 mm/s</td>
<td></td>
</tr>
</tbody>
</table>

**Note:**

LPO = Libration Point Orbit  
LLO = Low Lunar Orbit
Simulation

- Covariance study
  - Since FLAK is poorly understood, it is unrealistic to perform a full navigation simulation.

- Kalman Filter linearized about the truth trajectories
  - Cramér-Rao Lower Bound (CRLB)
  - Estimates the best a filter can do, i.e., the lower bound of the state uncertainty.
## Simulation Details

<table>
<thead>
<tr>
<th>State Parameter</th>
<th>( a \ priori ) uncertainty 1-( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Position of LPO</strong></td>
<td></td>
</tr>
<tr>
<td>( R^LPO_x )</td>
<td>100 meters</td>
</tr>
<tr>
<td>( R^LPO_y )</td>
<td>100 meters</td>
</tr>
<tr>
<td>( R^LPO_z )</td>
<td>100 meters</td>
</tr>
<tr>
<td><strong>Velocity of LPO</strong></td>
<td></td>
</tr>
<tr>
<td>( V^LPO_x )</td>
<td>1 m/s</td>
</tr>
<tr>
<td>( V^LPO_y )</td>
<td>1 m/s</td>
</tr>
<tr>
<td>( V^LPO_z )</td>
<td>1 m/s</td>
</tr>
<tr>
<td><strong>Position of Crewed LLO</strong></td>
<td></td>
</tr>
<tr>
<td>( R^LLO_x )</td>
<td>10,000 meters</td>
</tr>
<tr>
<td>( R^LLO_y )</td>
<td>10,000 meters</td>
</tr>
<tr>
<td>( R^LLO_z )</td>
<td>10,000 meters</td>
</tr>
<tr>
<td><strong>Velocity of Crewed LLO</strong></td>
<td></td>
</tr>
<tr>
<td>( V^LLO_x )</td>
<td>10 m/s</td>
</tr>
<tr>
<td>( V^LLO_y )</td>
<td>10 m/s</td>
</tr>
<tr>
<td>( V^LLO_z )</td>
<td>10 m/s</td>
</tr>
</tbody>
</table>
Simulation Results

- LiAISON-only with large \textit{a priori}
Simulation Results

- DSN-only for both vehicles

L1 Sat: <10 meters

LLO Crewed Sat: 100-2000 meters
• **L₁ vs. L₂ orbits**

  - **L₁ orbiter** tracks simultaneously with ground. Long gaps per orbit.
  - **L₂ orbiter** alternates tracks with ground. Smoother performance.
Simulation Results

Expected 3σ Position Uncertainty of the Crewed Lunar Orbiter

Bars = mean RSS 3σ position uncertainty from 3+ days
Extensions = 99 percentile RSS 3σ position uncertainty

a = Range + Range-rate
b = Range only
c = Range-rate only
Summary

- Satellite-to-satellite tracking (LiAISON) may be used without ground tracking and obtain a good estimate of the state of both satellites.

- LiAISON supplements the ground tracking very well.
  - IDAC4B is only moderately better than DSN
  - DSN+LiAISON is significantly better than DSN only

- LiAISON is a better substitute than 3 IDAC4B receiving stations.
Navigating a Crewed Lunar Vehicle Using LiAISON

Jeffrey S. Parker, Jason M. Leonard, Kohei Fujimoto
Ryan M. McGranaghan, and George H. Born

*Colorado Center for Astrodynamics Research*
*University of Colorado at Boulder*

Rodney L. Anderson
*Jet Propulsion Laboratory*
*California Institute of Technology*

**Acknowledgements:**
The research presented in this paper has been partially carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Government sponsorship acknowledged.