National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

CCAR
Colorado Center for
Astrodynamics Research

Navigation Between Geosynchronous and Lunar L_1 Orbiters

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LiAISON Satellite Navigation

What it is:

A new navigation technique using a satellite in a lunar libration orbit.

The satellite brings GPS-like navigation to GEO, the Moon, and beyond.

Relative range measurements produce absolute navigation knowledge!

Results:

Navigation position accuracy:

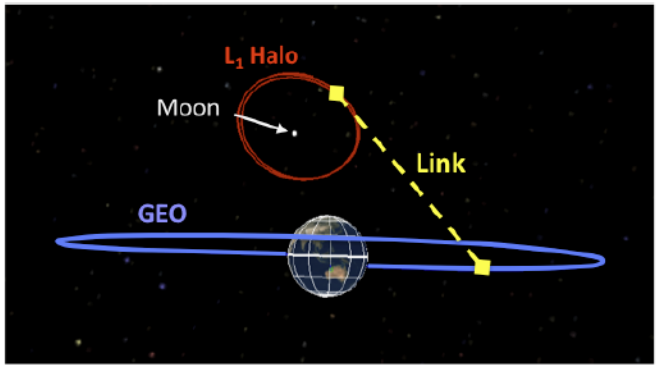
- *< 100 meters for lunar libration orbiters*
- *< 10 meters for low lunar orbiters*
- *< 1 meter for GEO / LEO orbiters*

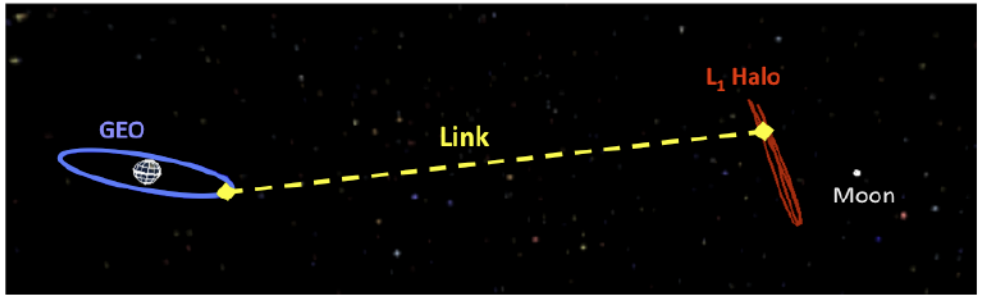
Applications:

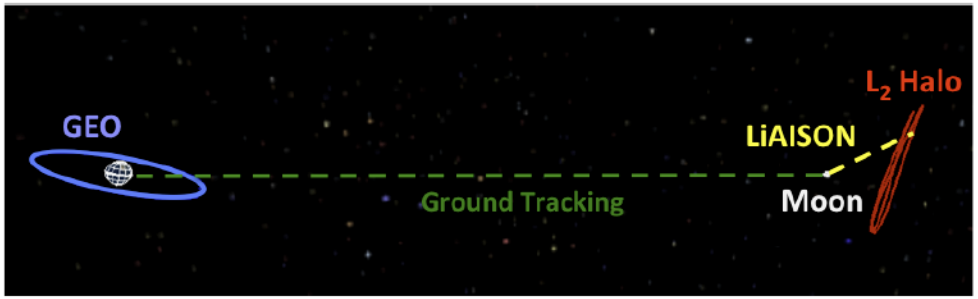
- *Lunar exploration: orbiters, landers, rovers, far-side tracking*
- *GEO navigation*
- *Interplanetary departures*
- *Crewed missions to the Moon*

LiAISON:

Linked
Autonomous
Interplanetary
Satellite
Orbit
Navigation







Background

- **Satellite-to-Satellite Navigation**
  - **Satellite-to-satellite tracking (SST): relative range and range-rate**
  - **Typical SST in Keplerian orbits only reveals certain aspects of each satellite's orbit:**
    - **Semi-major axis of both satellites' orbits**
    - **Eccentricity of both satellites' orbits**
    - **True anomaly of both satellites' positions**
    - **Relative angular information (Δi, $\Delta\Omega$, $\Delta\omega$)**

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    - Relative angular information (Δi, $\Delta\Omega$, $\Delta\omega$)

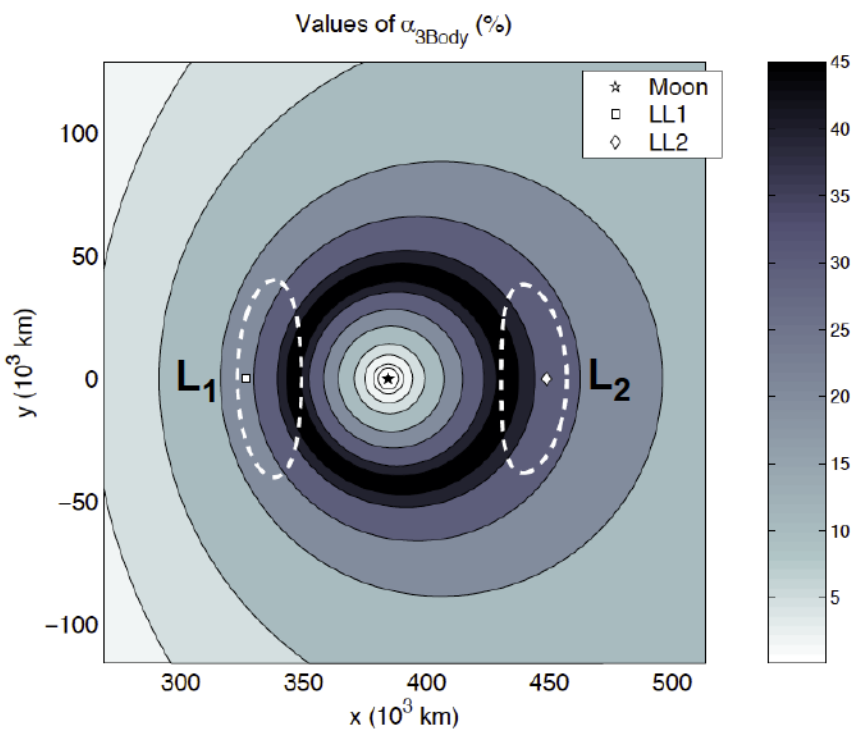
- **Asymmetries in the force field improve knowledge of absolute orbits**
  - J2 and other realistic perturbations from a point-mass gravity field
  - Solar radiation pressure
  - The Moon's gravity / other third bodies

- **Asymmetries must be observable**
  - Larger than observation errors and uncertainty in force model

Background

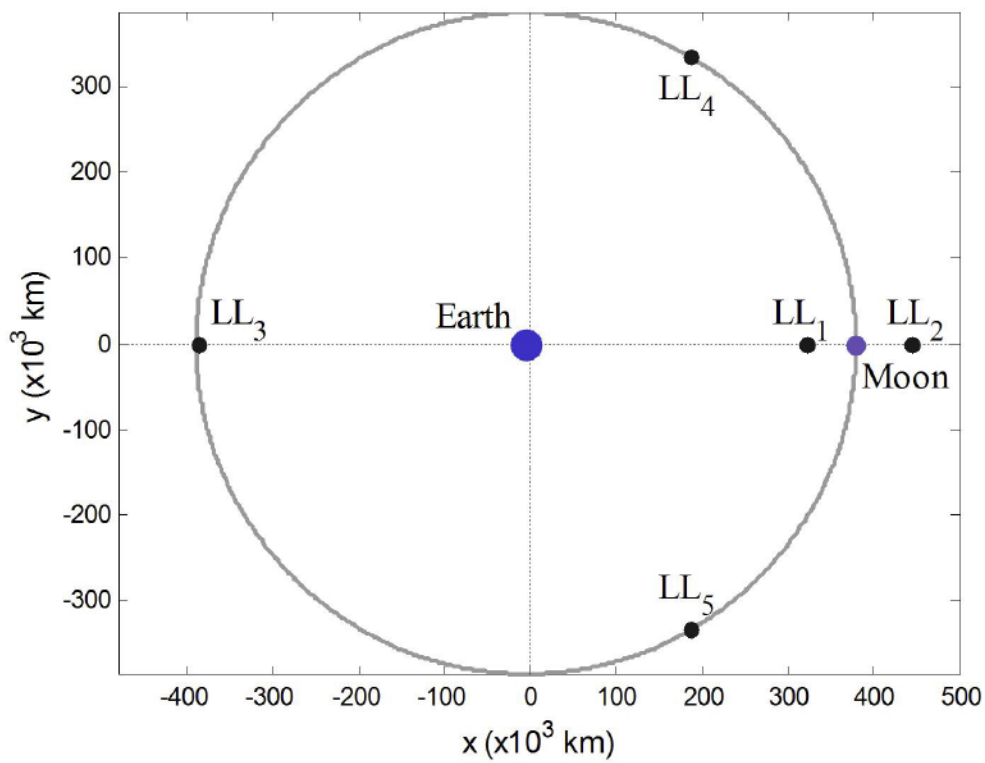
- **Lunar LiAISON**
  - **The Moon's gravity results in very large force field asymmetries**

$$\alpha_j(x,y,z) = \frac{|\ddot{\mathbf{r}}_\mathbf{j}(x,y,z)|}{\sum_{i=1}^{n}|\ddot{\mathbf{r}}_\mathbf{i}(x,y,z)|}$$



Earth-Moon System

- The Earth and Moon orbit their barycenter in nearly circular orbits.
- Motion of a satellite within the Earth-Moon system may be approximated by the Circular Restricted Three-Body Problem (CRTBP)



Lunar Libration Orbits

- **"Libration Orbits" are trajectories that revolve about the Lagrange points.**
  - **Lagrange points are *Fixed Point* solutions to the CRTBP**
  - **Libration orbits are *periodic* or *quasi-periodic* solutions to the CRTBP**

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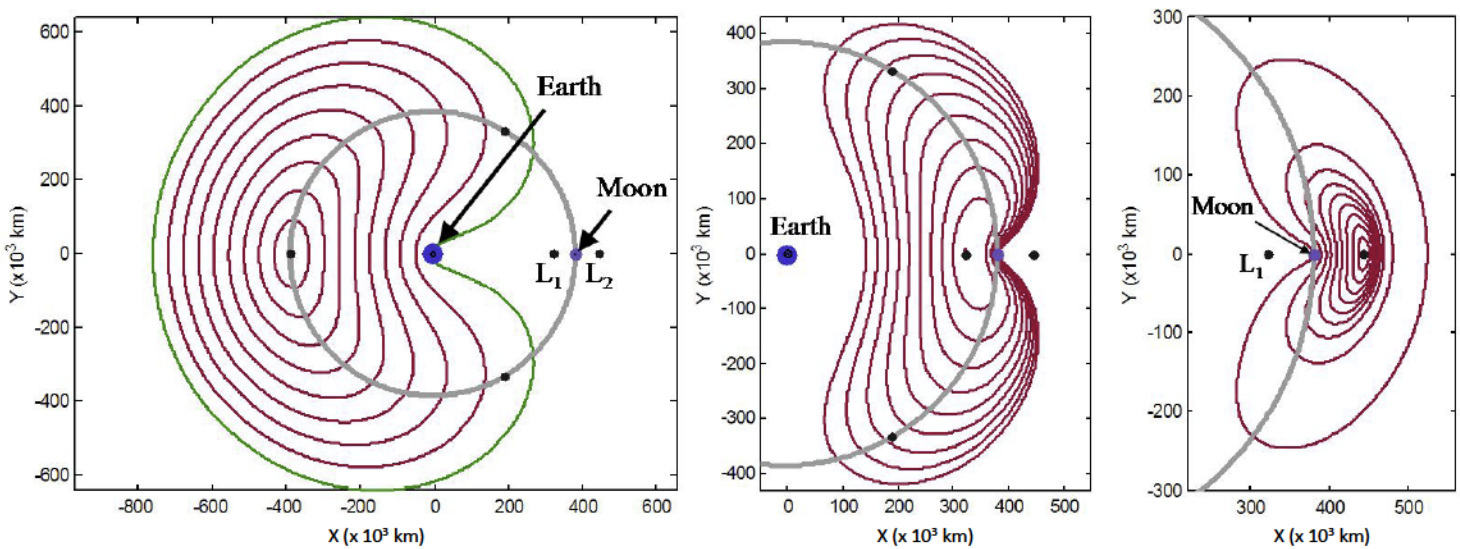
  - Planar Lyapunov orbits about L_1, L_2, and L_3



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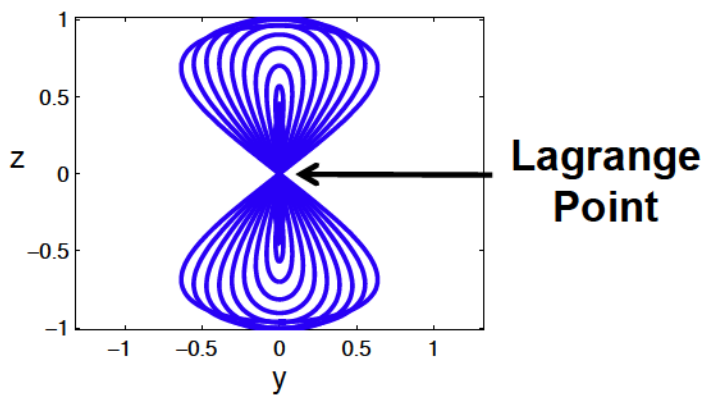
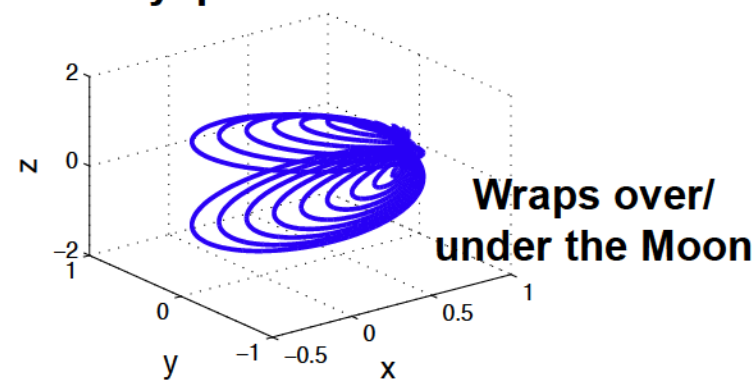
View from Earth or Moon toward Lagrange Point



Oblique view of Vertical Lyapunov Orbits



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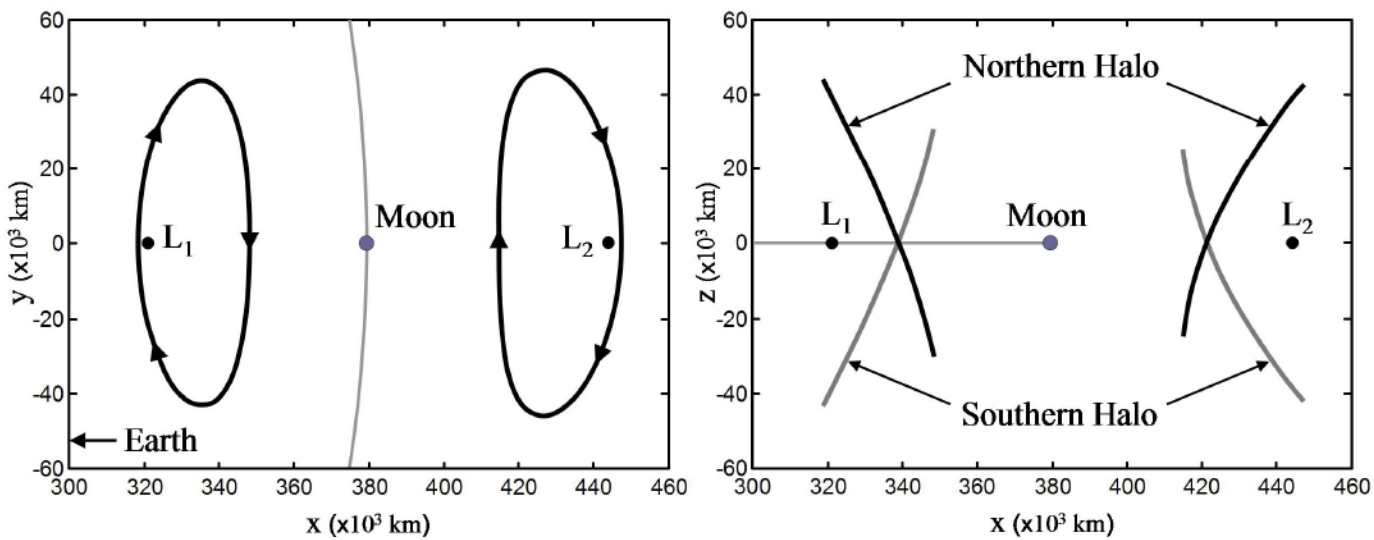
  - Halo orbits about L_1, L_2, and L_3



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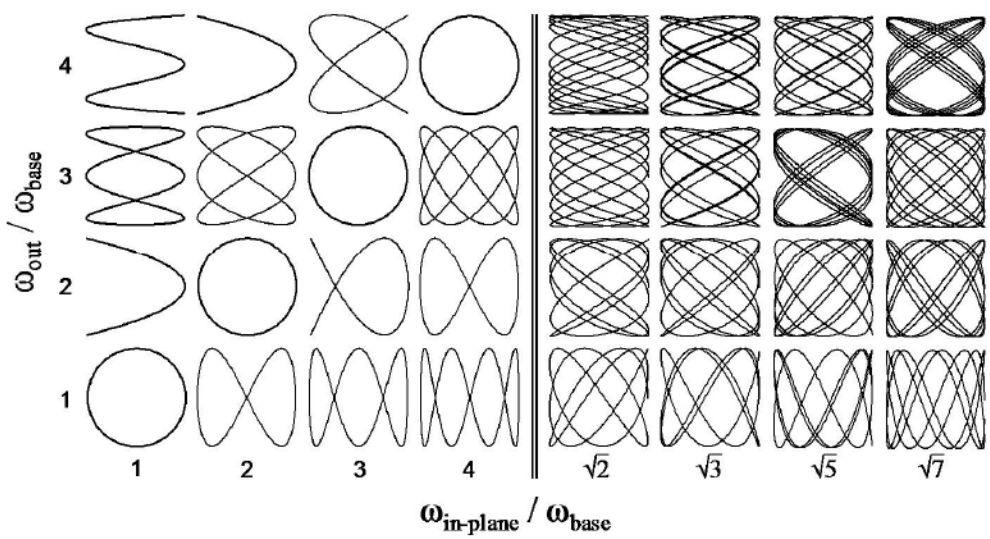

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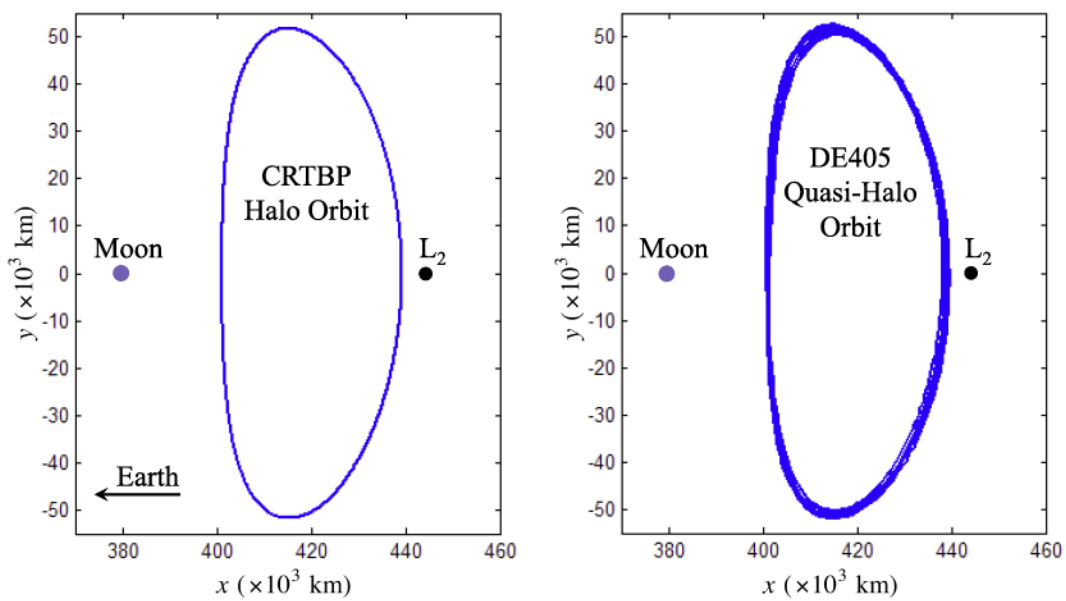
  - Halo orbits about L_1, L_2, and L_3
  - Lissajous orbits about L_1, L_2, and L_3
- Numerous other orbit types exist in the CRTBP:
  - Distant Retrograde Orbits (DROs)
  - Distant Prograde Orbits (DPOs)
  - Resonant orbits
  - Orbit chains

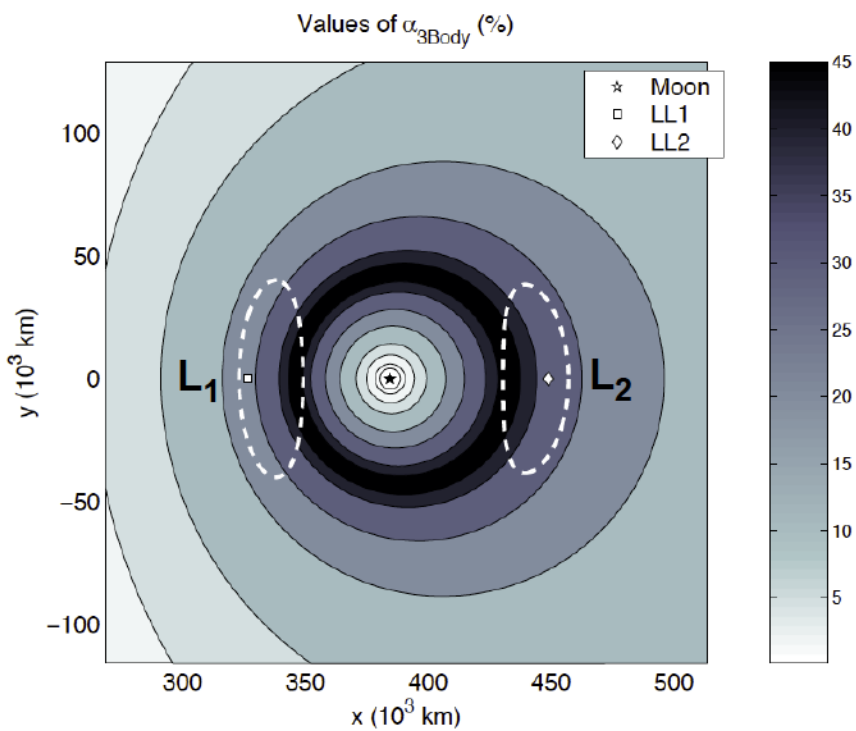
Realistic Lunar "Halo" Orbits

- **We convert an approximate CRTBP halo orbit into the high-fidelity force model using a multiple-shooting differential corrector.**
- **High-fidelity:**
  - **Sun, Earth, Moon, and all planets modeled as point-masses**
  - **Planetary positions modeled from Jet Propulsion Laboratory's Planetary and Lunar Ephemerides DE405**
  - **Solar radiation pressure**



Background

- **Lunar LiAISON**
  - **The Moon's gravity results in very large force field asymmetries**



- **Libration orbits about LL_1 and LL_2 traverse through very asymmetric regions in the Earth-Moon system.**
- **SST between an LL_1 or LL_2 orbiter and another satellite generate *unique* tracking signatures.**
- **Hill studied many lunar configurations:**
  - **LL_1 – LLO (Low Lunar Orbit)**
  - **LL_2 – LLO**
  - **LL_1 – LL_2**
  - **LL_2 – LL_2**
  - **LL_2 – LL_2 – LLO**
  - **etc**

LL_1 Nav < 100 meters
LLO Nav < 10 meters

LiAISON Applications

Lunar Missions from L1

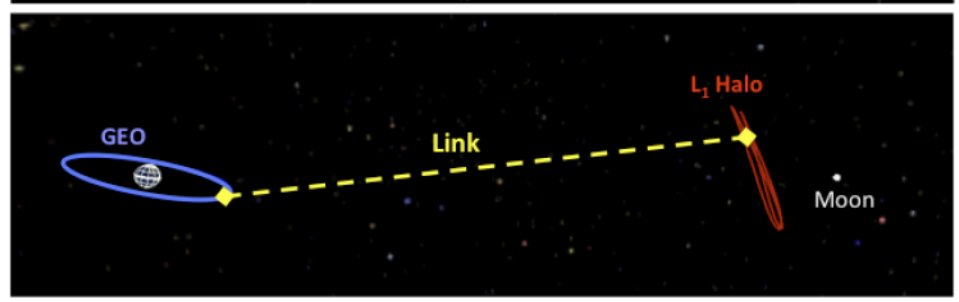
< 10-meter navigation accuracy to orbit, surface
VS. 50 – 250 meter accuracy now

Lunar Missions from L2

Same performance
Far-side tracking and communication

GEO

~1 meter accuracy with a relatively small amount of LiAISON and ground tracking



Crewed Lunar Missions

LiAISON supplements the DSN, reducing the number of stations required.

GEO Navigation

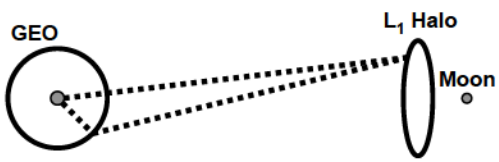
- **State of the art in GEO Navigation**
  - Range measurements from several ground stations: nav accuracy on the order of ~30 meters
  - GPS signals may be used from the far side of the Earth: ~15 meters
  - Optical tracking using several ground stations: ~10 meters
  - Multiple tracking types including GPS and radiometric: ~10 meters

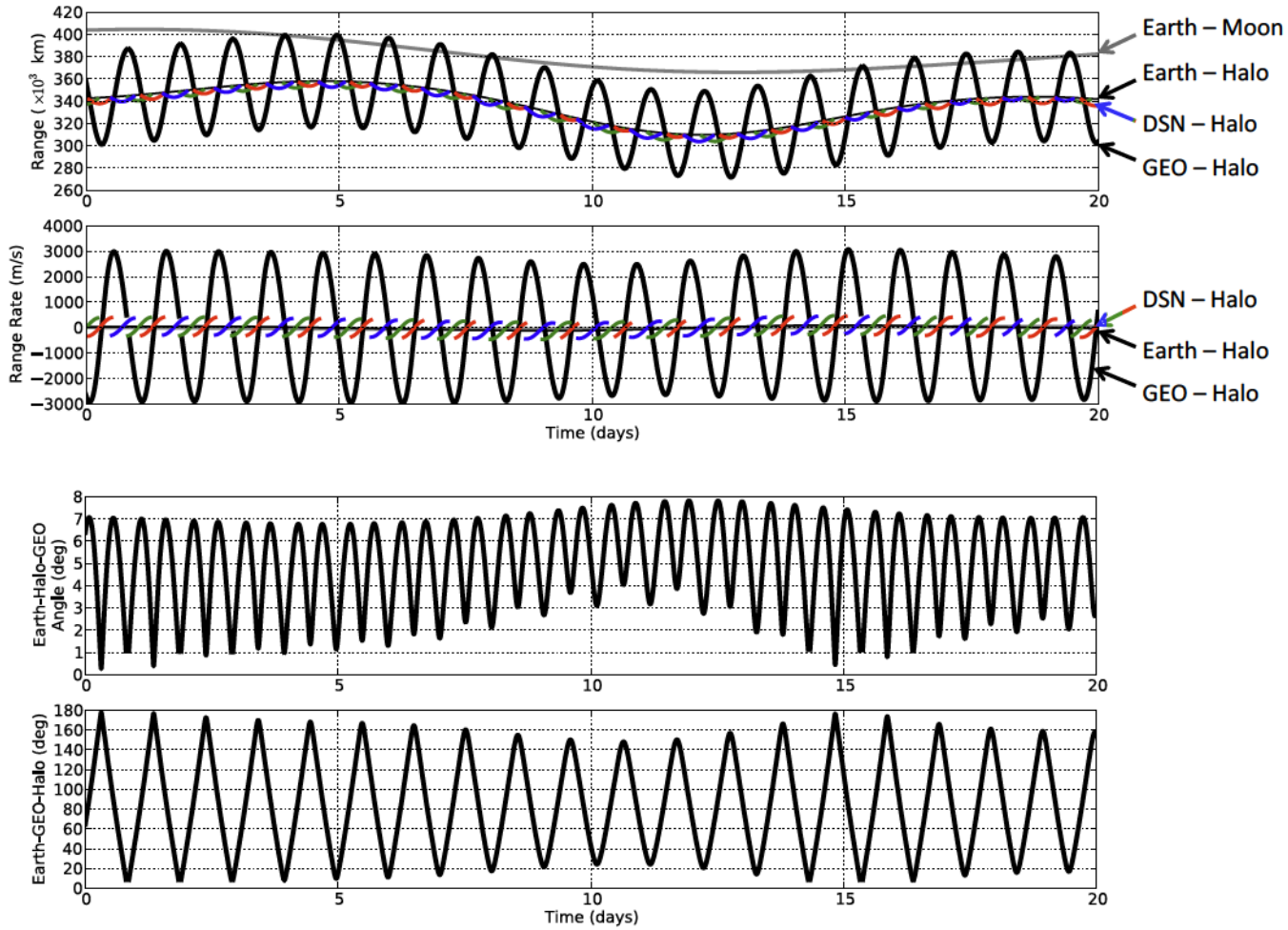
- **Hypothesis: LiAISON will improve this accuracy and/or significantly reduce the number of ground tracks needed to achieve a given accuracy.**

- **LiAISON navigation may be available in any case; may as well take advantage of it!**

Information Content in GEO-L_1 SST

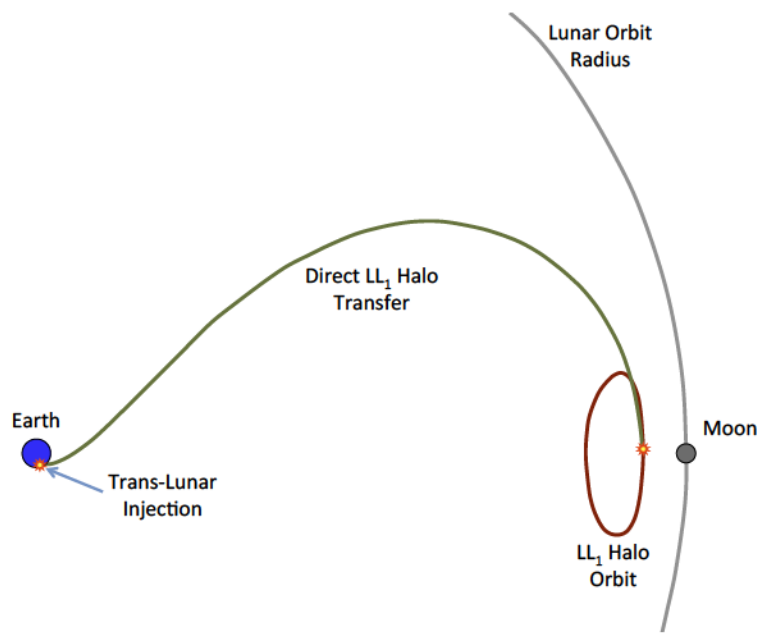
- **Dynamic profile of a GEO-L_1 link over time**

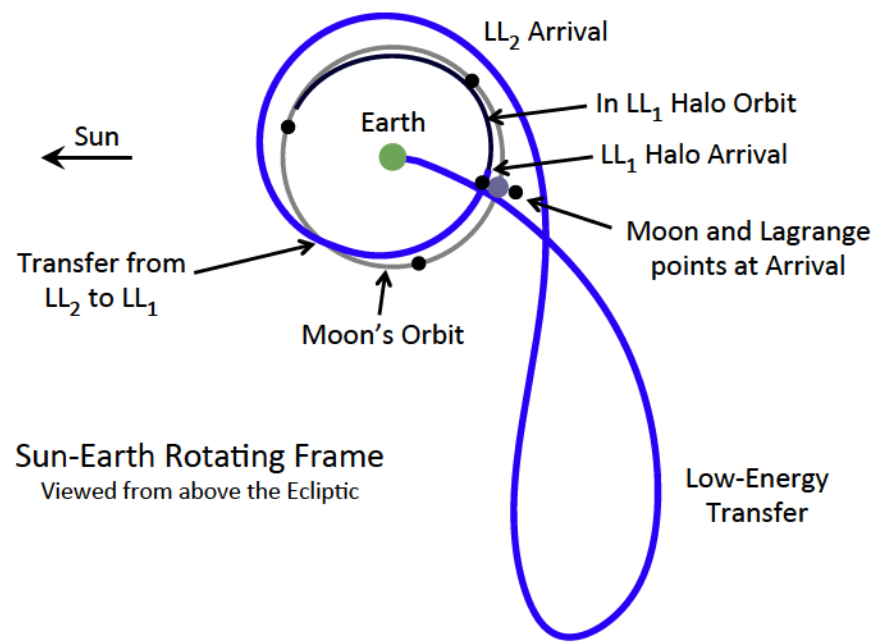




Simulated Configuration

- This study used the following L_1 halo orbit:
  - A_z = 35,500 km
  - ϕ = 0 deg
  - Reference epoch: 1/1/2020 00:00:00 ET
- Equatorial GEO orbit, set over a longitude of 0 deg.





Navigation Simulations

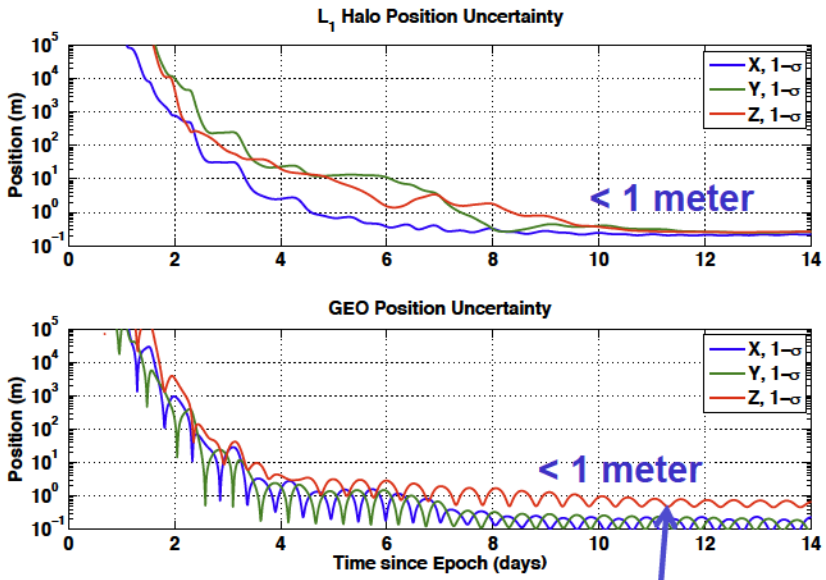
- **Observations:**
  - Instantaneous range with a constant bias and Gaussian noise
    - Bias ~ N(0,3) meters
    - Noise ~ N(0,1) meters
  - Instantaneous range rate with Gaussian noise
    - Noise ~ N(0,1) cm/s
  - Both observations at 0.01 Hz, though no observations when the Earth blocks the signal.

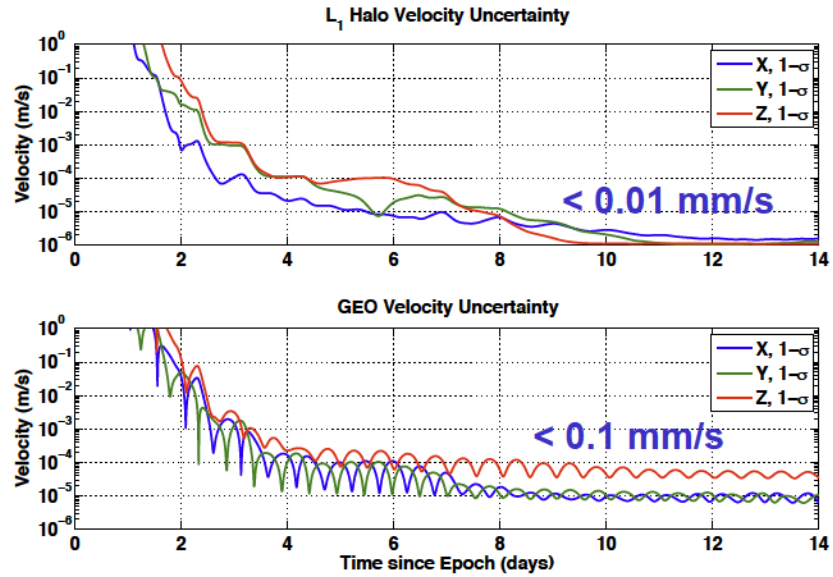
- **Truth Dynamics**
  - Sun, Moon, all planets
- **Filter Dynamics**
  - Sun, Earth, Moon
- **Integrator:** Runge-Kutta DOPRI8(7)13 with step tolerance of 10^{-14}

- **State**
  - Position and velocity of Libration orbiter
  - Position and velocity of GEO satellite
  - 12 variables in total

CRTBP Simulation

- **Cramér-Rao Lower Bound:**
  - An estimate of the lower bound on the uncertainty that an unbiased estimator may achieve if it is optimal.
  - Essentially tracks the information matrix along the truth trajectory



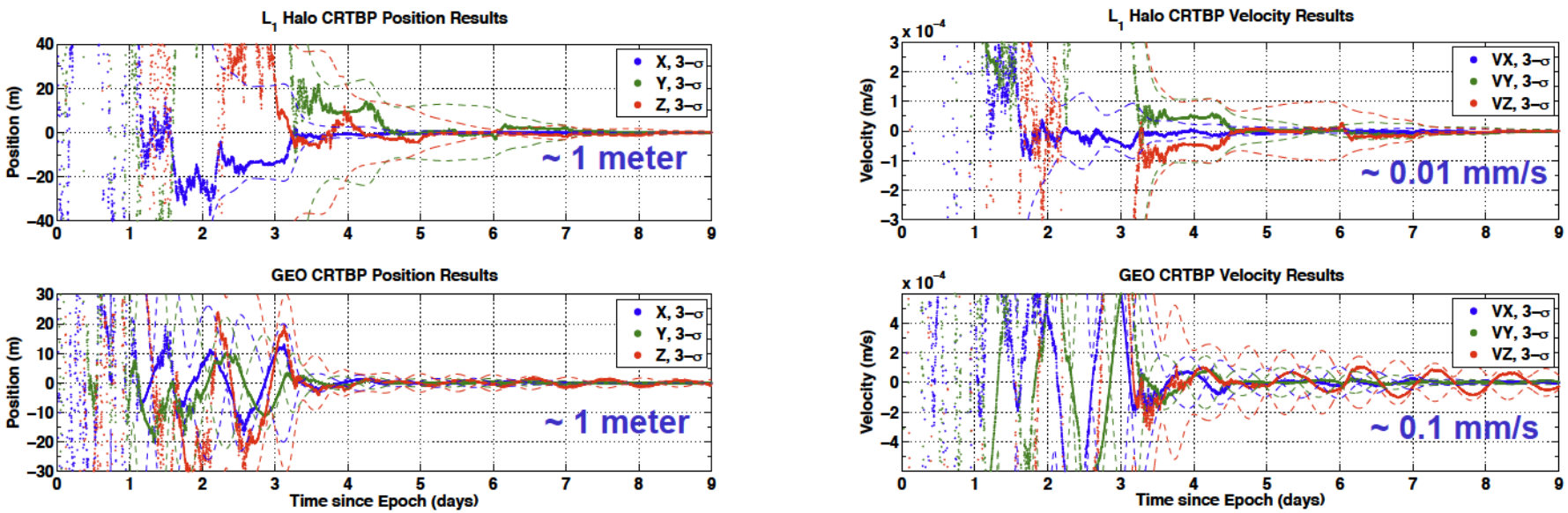


z-axis uncertainty ~2.4 times greater than planar: expected due to Earth's obliquity

a priori uncertainty set to near infinite: $\mathrm{Diag}(10^{20})_{12x12}$

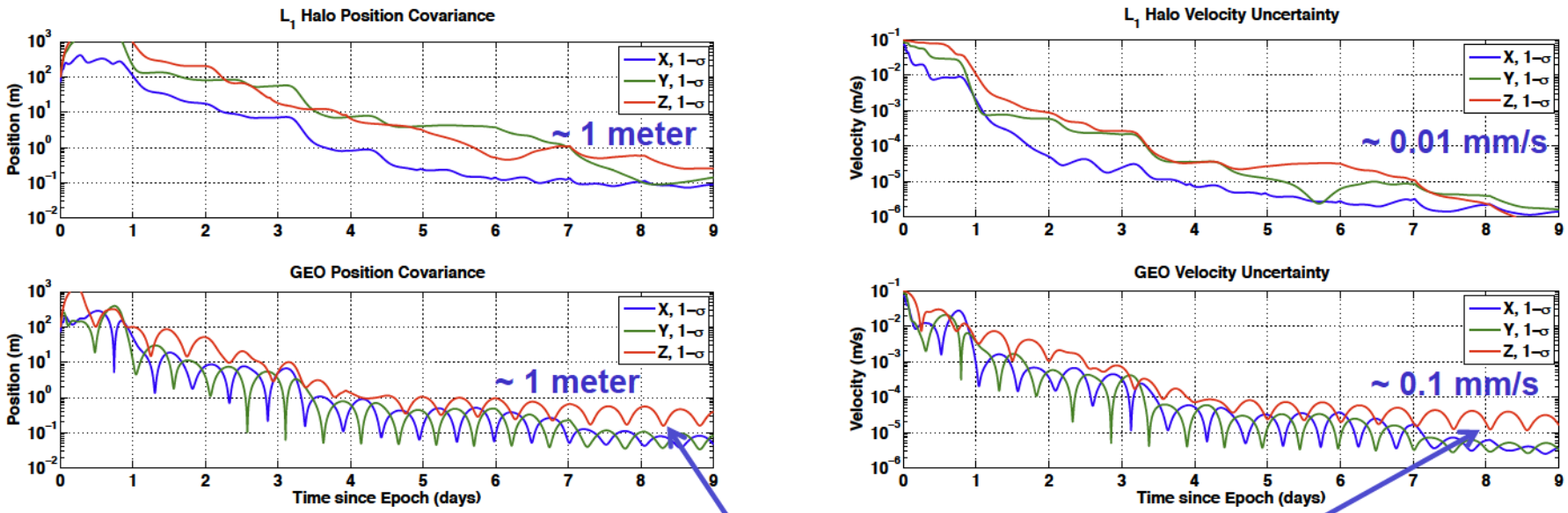
CRTBP Simulation

- Initial state is perturbed by N(0,100) meters in position and N(0,1) cm/s in velocity.
- *a priori* covariance: (100 meters)^2 in position and (10 cm/s)^2 in velocity for both satellites.
- State Noise Compensation: $\sigma = 10^{-13}$ m/s^2 for halo and 10^{-14} m/s^2 for GEO
- Extended Kalman Filter, starting with the first observation.



CRTBP Simulation

- **Covariance analysis during simulation**



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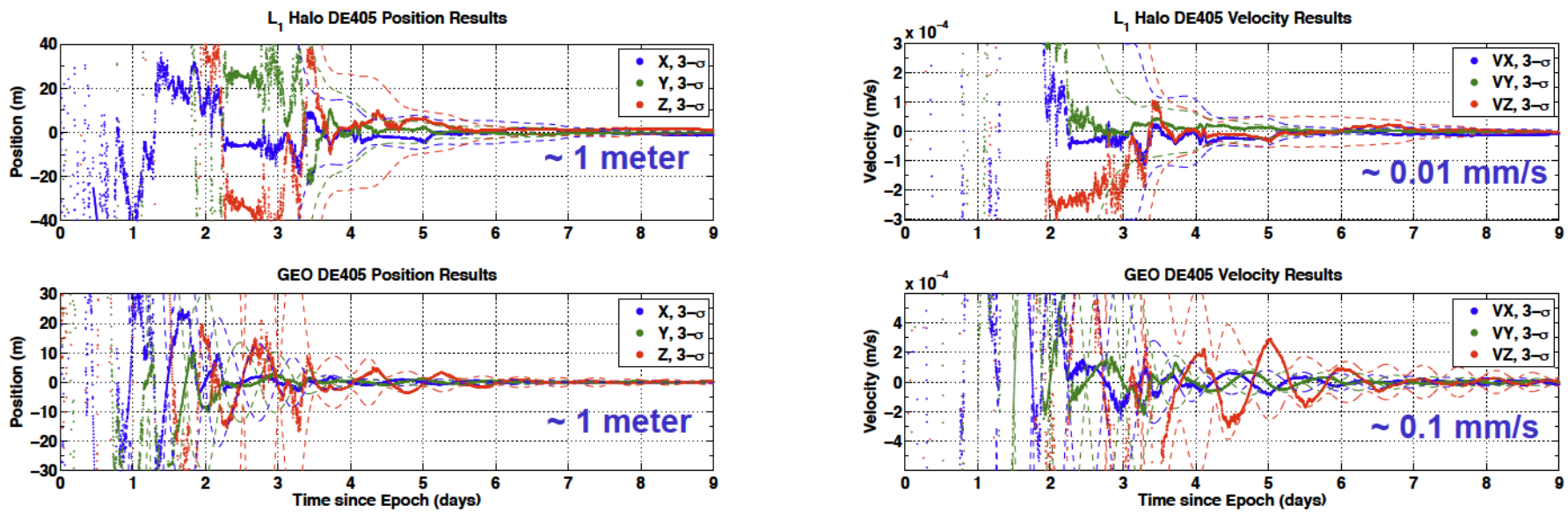
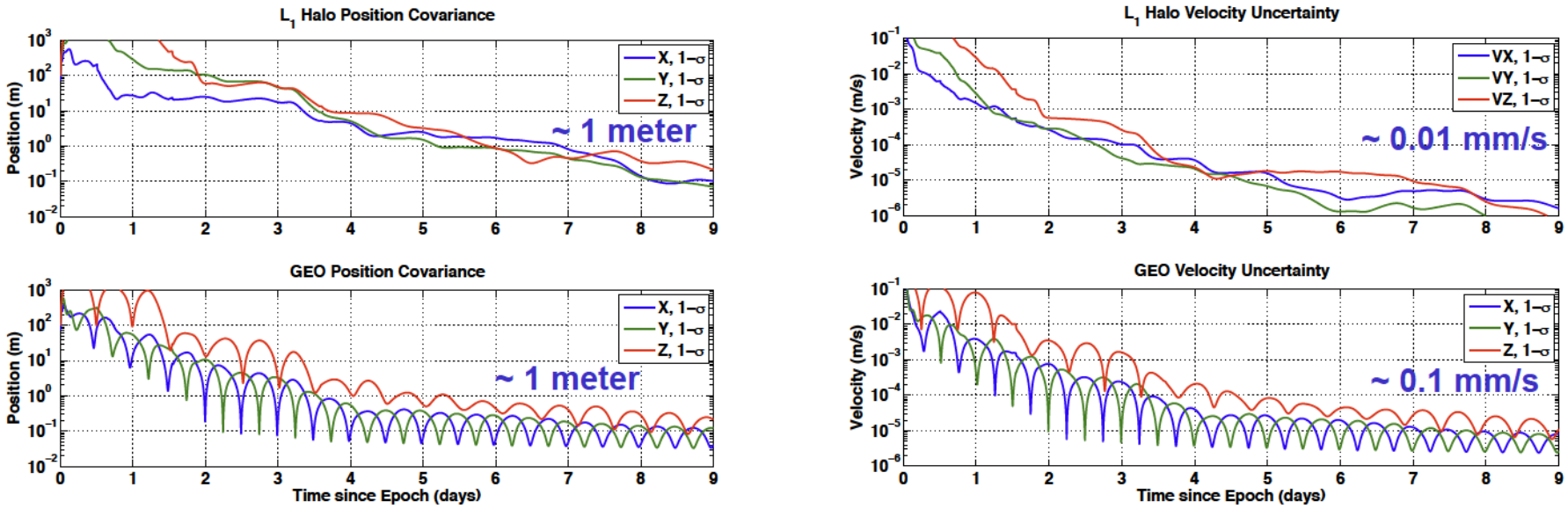
High-Fidelity

- **Repeated the simulation, but using the planetary ephemerides, realistic halo and GEO orbits, and more dynamical errors.**



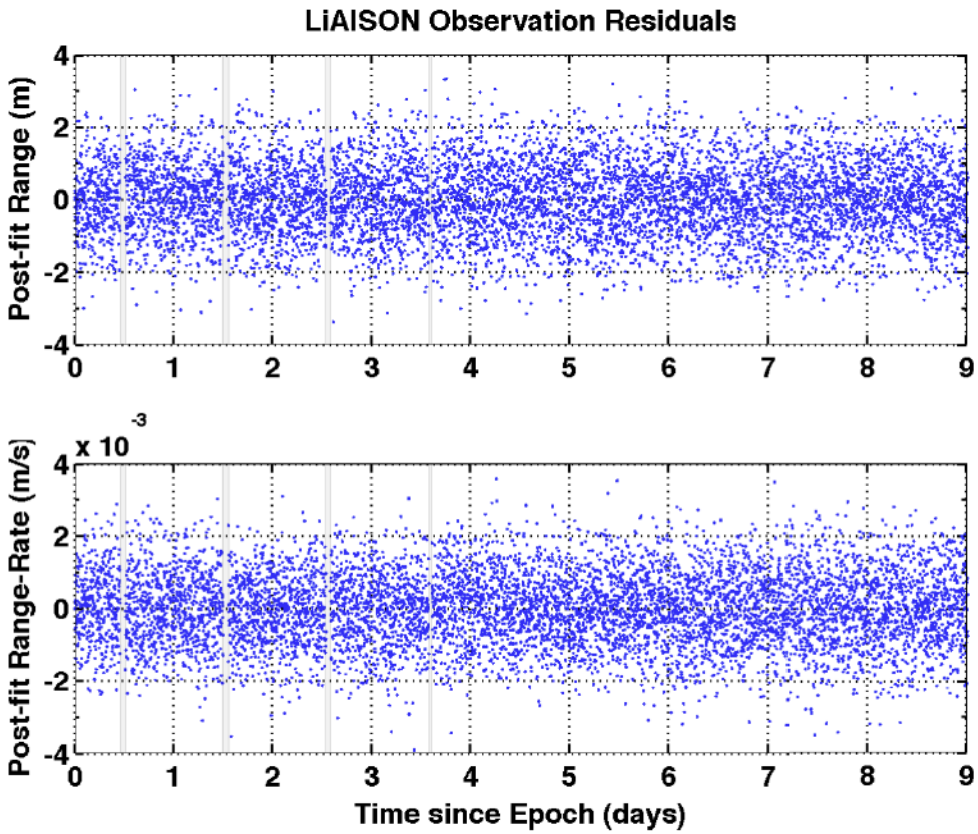
High-Fidelity

- **High-fidelity covariance matrix evolution is very similar to the CRTBP covariance matrix evolution.**



High-Fidelity

- **Post-fit residuals from the high-fidelity simulation.**
- **RMS ~ 1 meter, 1 mm/s**



Summary

- The results presented here have demonstrated the viability of generating good orbit estimates using only crosslink data between L1 and GEO, with large *a priori* uncertainties.
- The entire state – all 12 parameters – is observable.
- The orbit uncertainty requires ~1 week to converge, given poor *a priori* information.
- The orbit uncertainty falls to the level of observation noise once it has converged.
- The Extended Kalman Filter performs very near the expected limit, as predicted by the Cramér-Rao Lower Bound.

Additional Steps

- **The authors have extended this work into a concurrent paper:**
  - Leonard, J. M., McGranaghan, R. M., Fujimoto, K., Born, G. H., Parker, J. S., and Anderson, R. L., "LiAISON-Supplemented Navigation for Geosynchronous and Lunar L1 Orbiters"
- **Additional fidelity:**
  - **Large observation gaps**
  - **Ground station tracks in addition to LiAISON**
  - **Spherical harmonics for Earth's gravity**
  - **More dynamical errors (solar radiation pressure, Earth's gravity)**
- **Results:**
  - **Ground station tracks help navigation solution**
  - **Larger gaps and larger errors reduce navigation accuracy**
  - **A few radiometric ground tracks and a few LiAISON tracks per week may be used to achieve navigation accuracies below 10 meters for GEO and below 100 meters for L1.**
- **Next steps:**
  - **Add fidelity to observations**
  - **Add maneuvers, crew implications**

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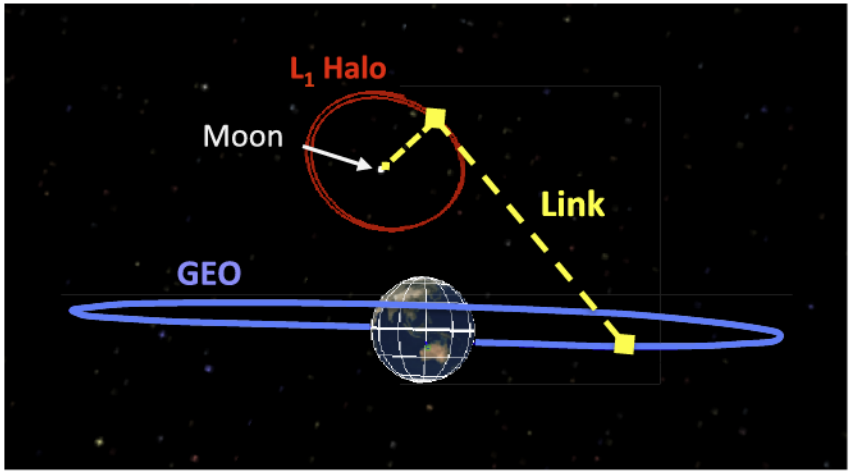
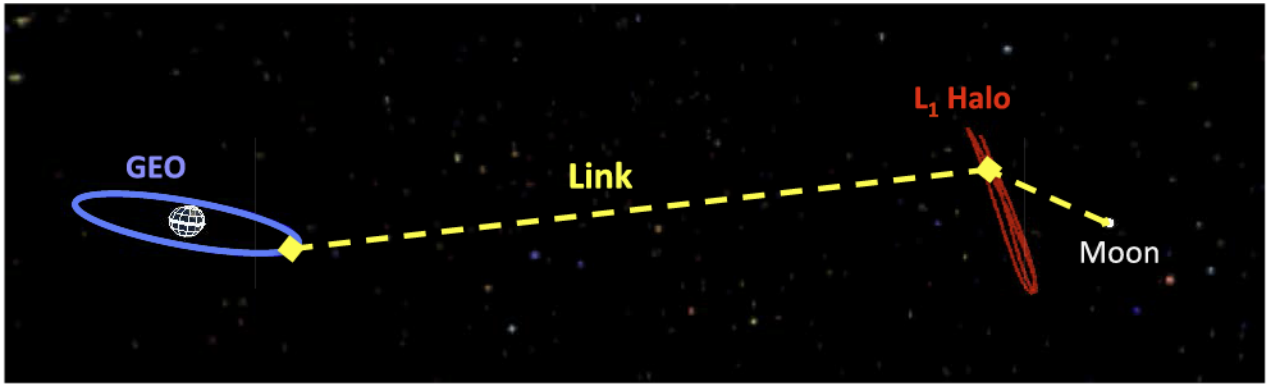




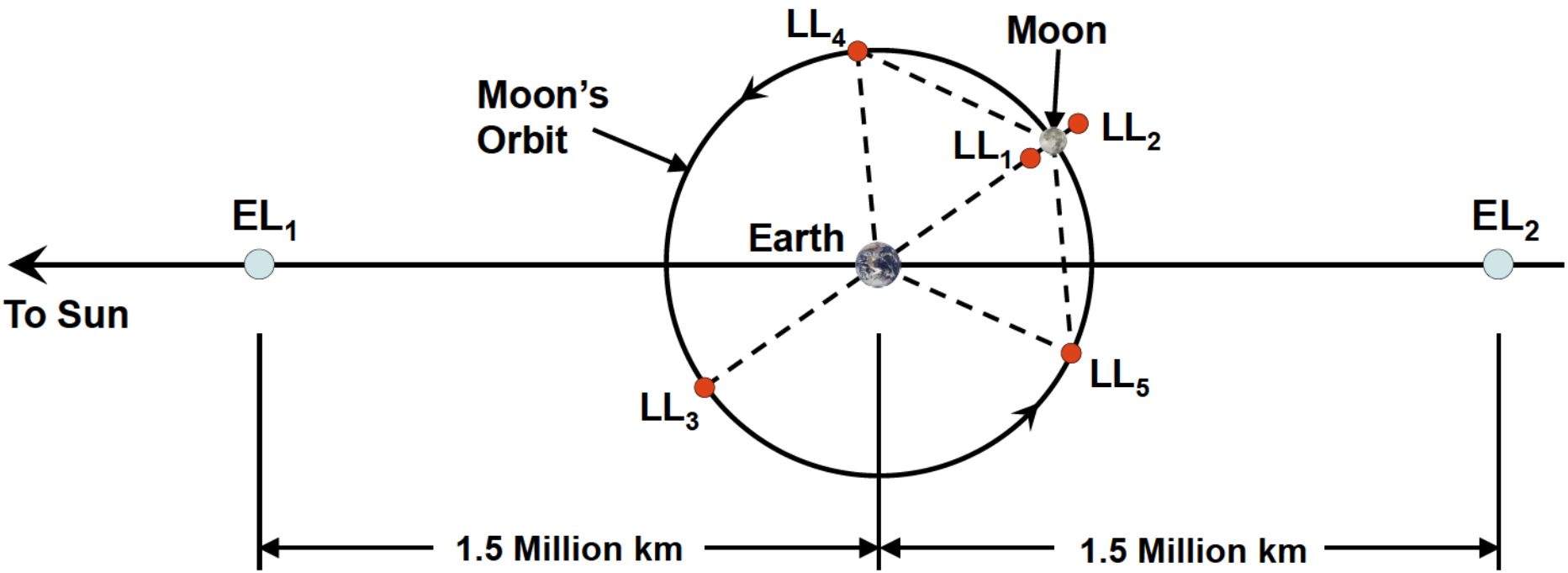
Appendix

LiAISON Video

Questions?

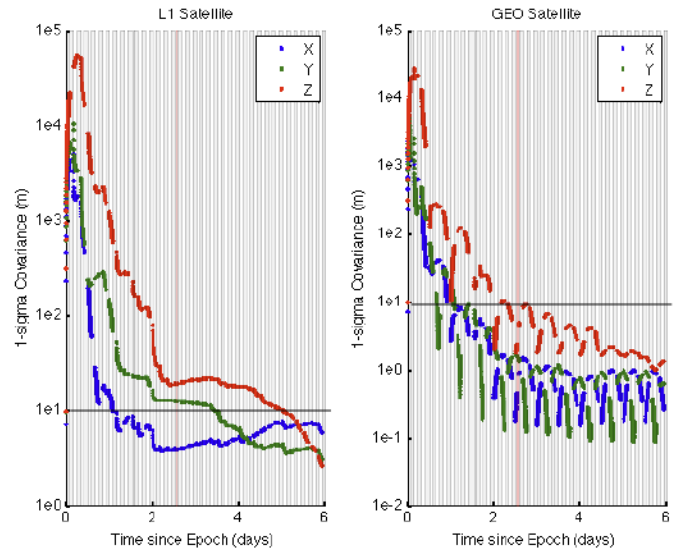
Near Earth Environment

- The Earth-Moon CRTBP is a close approximation near the Earth and Moon.
- The Sun-Earth/Moon CRTBP becomes more accurate further away.

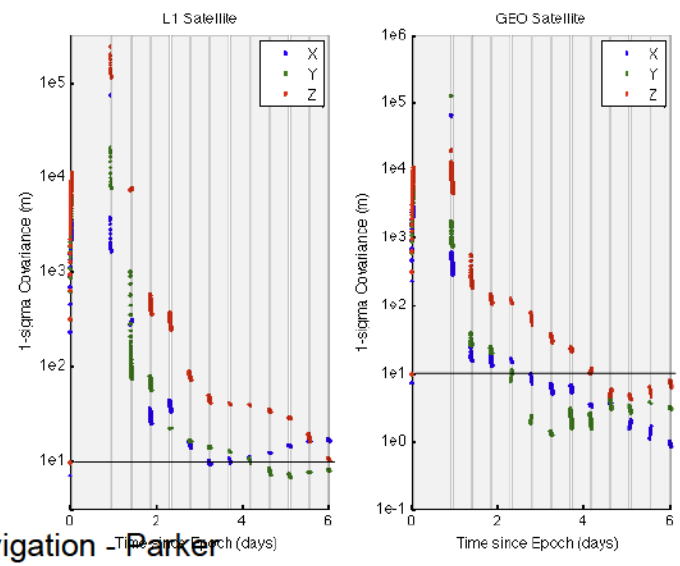


Quantifiable Results

- **High fidelity simulation development:**
  - Implementation of DSN tracking for L1 and ground-station tracking for GEO
  - Measurement gaps
  - Data noise
  - Measurement bias
  - Gravity errors
  - Solar radiation pressure
  - Maneuver estimation
  - Application of LiAISON to interplanetary departures



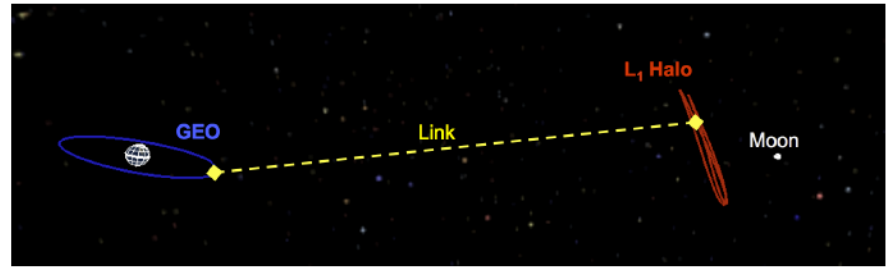
10 meter position

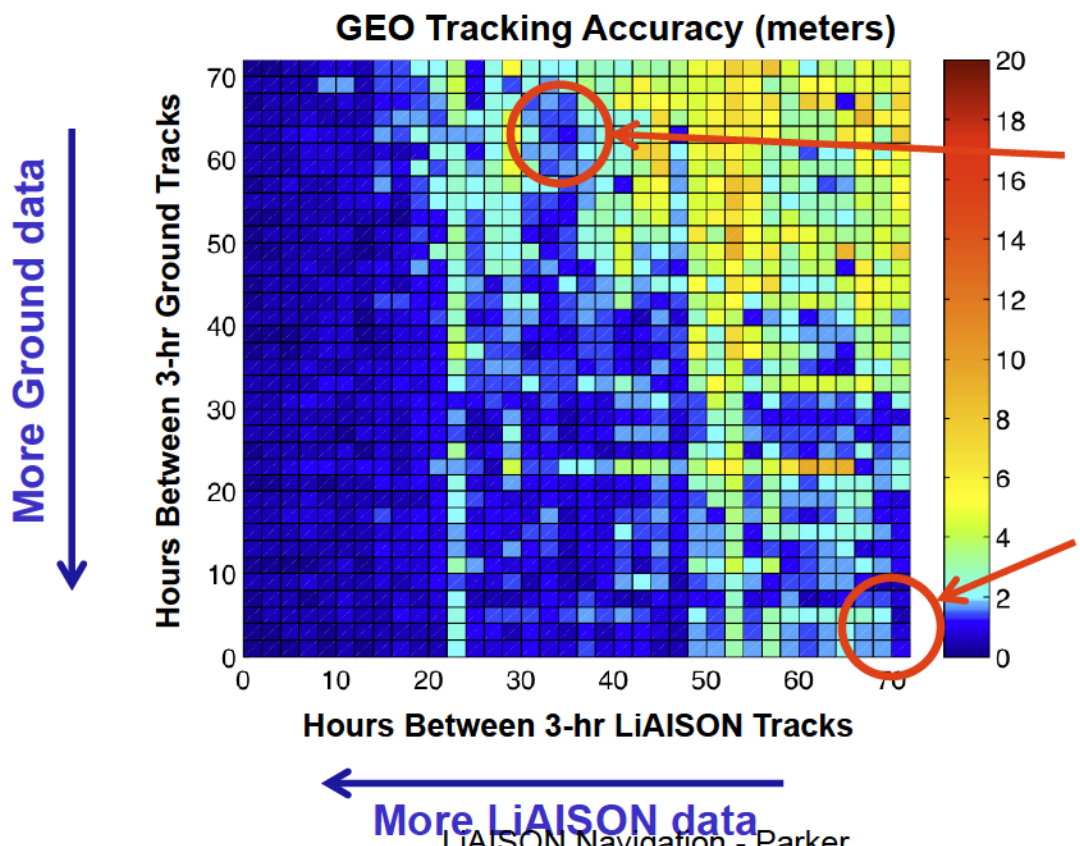


10 meter position

LiAISON Navigation Example Results

- Example results for tracking a GEO satellite using ground stations and LiAISON
- We've shown that you can reduce the number of ground tracks *tremendously* and achieve even better nav accuracy by using LiAISON.





Cheaper GEO nav:

Short, 3-hour tracks,
1 ground track every 2-3 days,
1 LiAISON track every 1-2 days:
~2 meter accuracy

Fewer ground tracks, better accuracy!

Normal GEO nav:

Near-continuous ground observations with little (or no) LiAISON:
~3 meter accuracy

LiAISON's Direction

- **LiAISON's benefits are clear**
  - Even without lunar missions, LiAISON can still benefit dozens of GEO missions.
  - Minimal impact to customers – DSAC enables GPS-like beacon, making the L1 satellite similar to a ground station.

- **Direction for work: push for a demonstration mission**
  - Design the communication system
  - Cost this system (hosted or dedicated satellite)
  - Bring TRL to 6 using ARTEMIS data (PI Vassilis Angelopoulos has already agreed to this partnership)
  - Develop full navigation and mission plan

Publications

- **Papers in progress, the first three to be presented at the AIAA/AAS Astrodynamics Specialist Conference in Minneapolis, MN, 13-16 August 2012.**
  - Parker, J.S., Anderson, R.L., Born, G.H., Fujimoto, K., Leonard, J.M., and McGranaghan, R.M., "Navigation Between Geosynchronous and Lunar L1 Orbiters"
  - Leonard, J.M., McGranaghan, R.M., Fujimoto, K., Born, G.H., Parker, J.S., and Anderson, R.L., "LiAISON-Supplemented Navigation for Geosynchronous and Lunar L1 Orbiters"
  - Fuijimoto, K., Leonard, J.M., McGranaghan, R.M., Parker, J.S., Anderson, R.L., and Born, G.H., "Simulating the LiAISON Navigation Concept in a GEO + Earth-Moon Halo Constellation"
  - McGranaghan, R.M., Anderson, R.L., Born, G.H., Fujimoto, K., Leonard, J.M., and Parker, J.S., "Utilization of LiAISON Navigation in Interplanetary Mission Orbit Determination"
- **Completed papers, sponsored by the CIF:**
  - Parker, J.S., Anderson, R.L., Born, G.H., and Fujimoto, K., "Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON) Between Geosynchronous and Lunar Halo Orbits", D-72688, Jet Propulsion Laboratory, California Institute of Technology, 2012.
- **CCAR has published numerous papers in this field during the last decade.**