Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON)

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ASEN 5070: Statistical Orbit Determination
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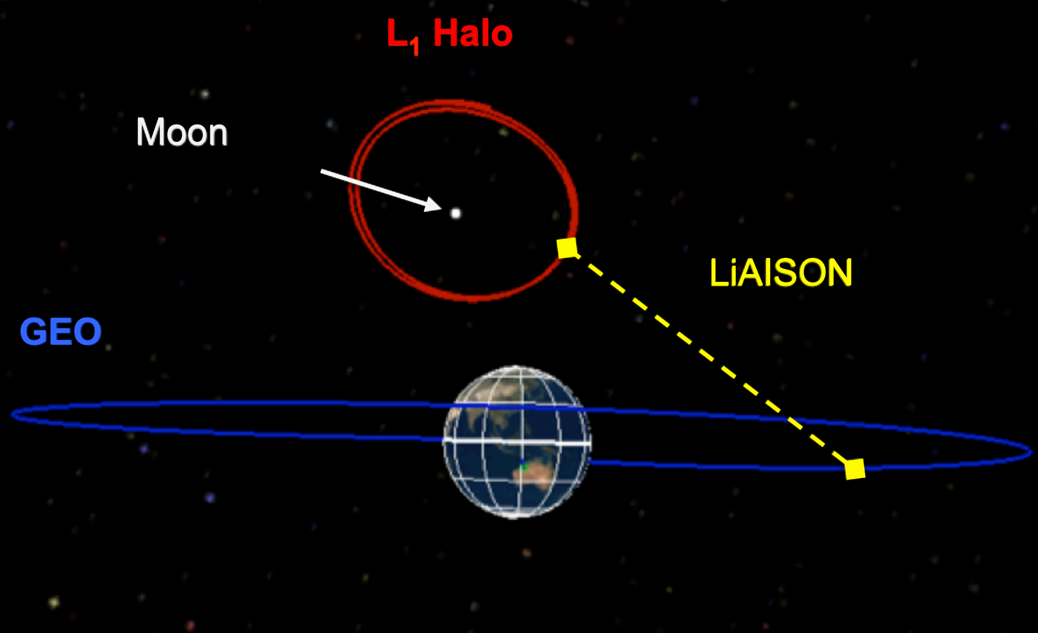
Outline

- Introduction
- Satellite-to-Satellite Tracking
- LiAISON for Dummies
- LiAISON Research
  - LL_1 and LL_2
  - LL_1 and GEO
  - Crewed LLO



What it is:

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

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

Relative range measurements produce absolute navigation knowledge!

Allows for autonomy in spacecraft operations

Results:

Navigation position accuracy:

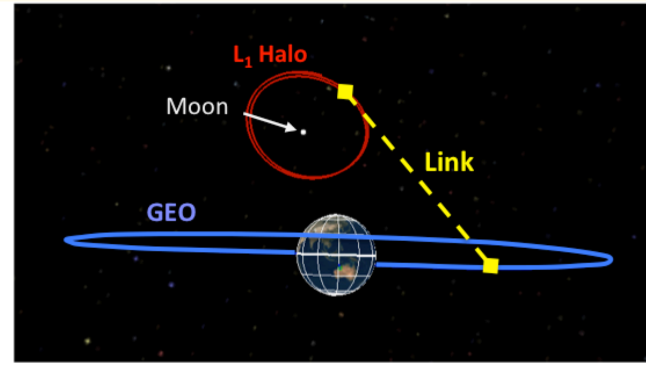
- *< 100 meters for lunar libration orbiters*
- *< 10 meters for low lunar orbiters*
- *< 10 meters for GEO / LEO orbiters*

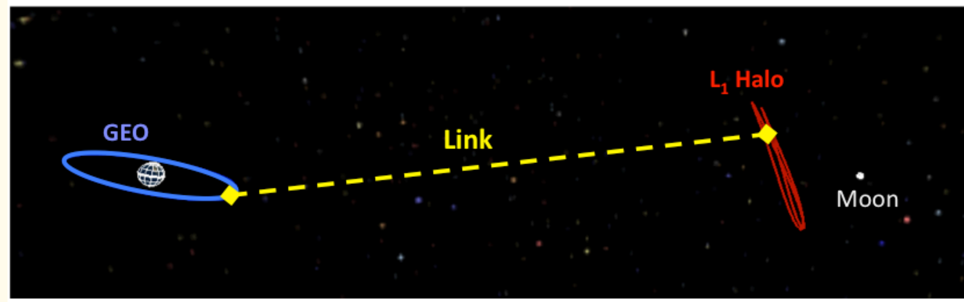
Applications:

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

LiAISON:

Linked
Autonomous
Interplanetary
Satellite
Orbit
Navigation

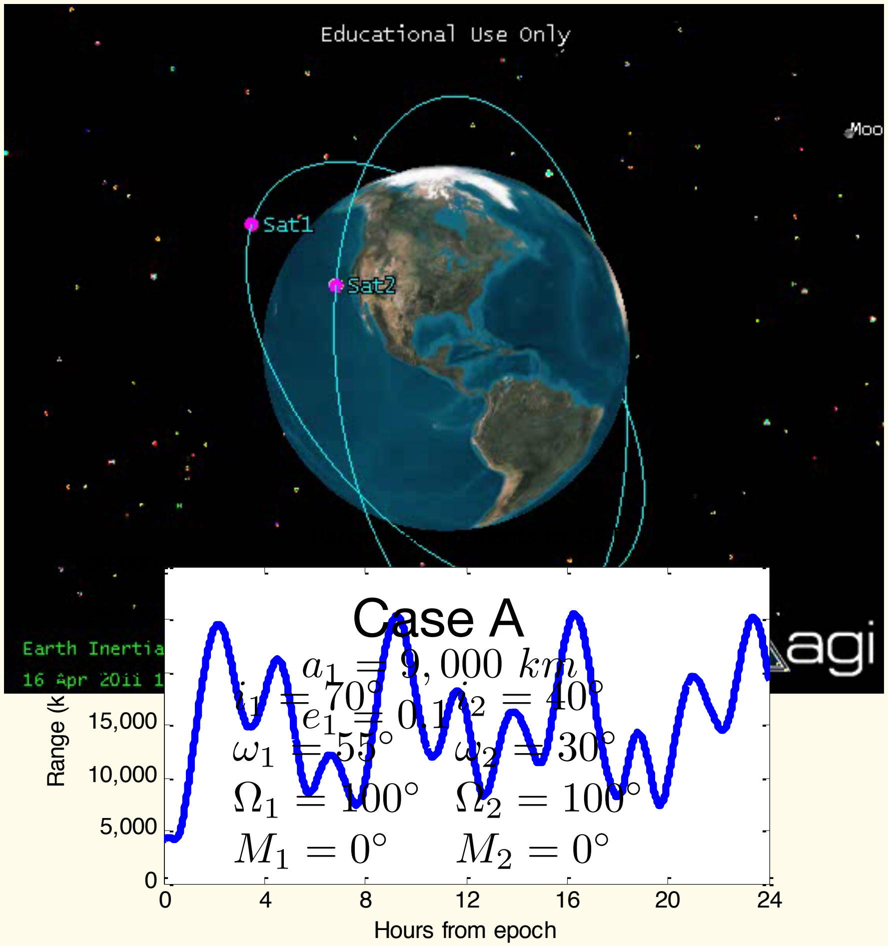




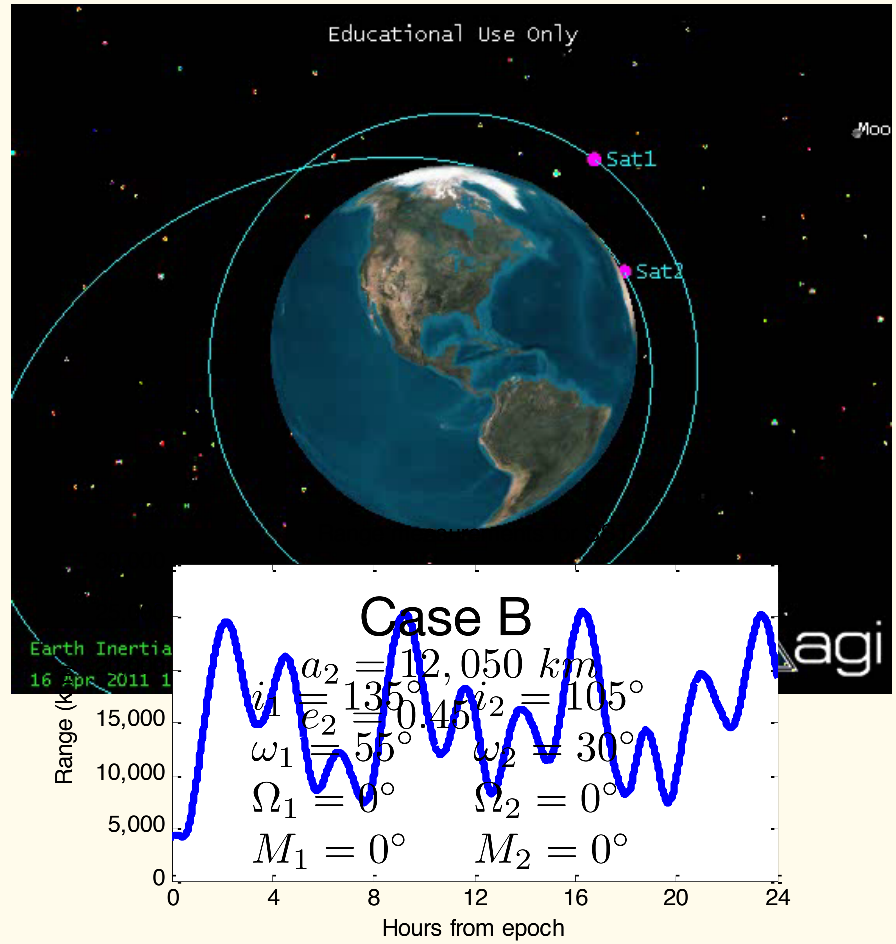
Satellite-to-Satellite Tracking

Satellite-to-Satellite Tracking

Case A



Case B



SST Case Study

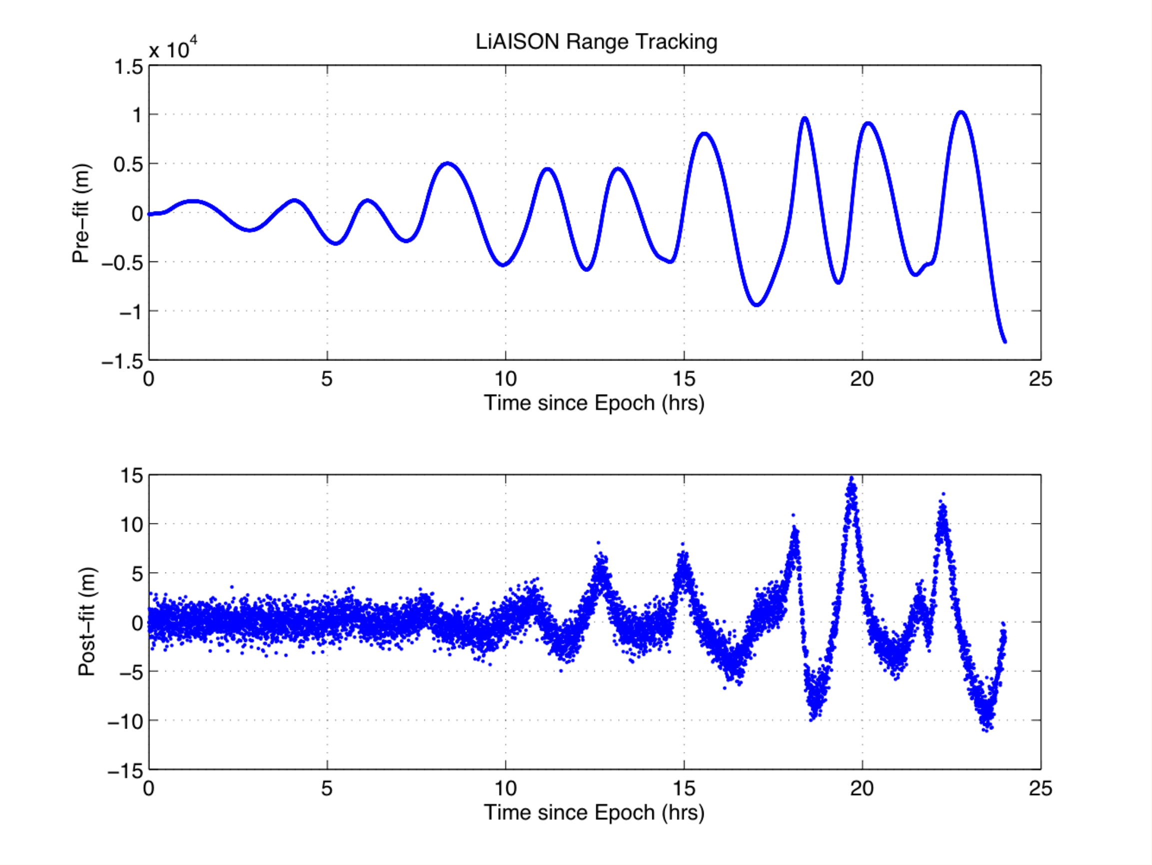
- What would happen if we ran a CKF for Case A using:
  - Typical state vector:

$$\mathbf{X} = \begin{bmatrix} \mathbf{r}_1^{\mathrm{T}} & \mathbf{v}_1^{\mathrm{T}} & \mathbf{r}_2^{\mathrm{T}} & \mathbf{v}_2^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}}$$

  - SST range and range-rate measurements
  - No ground observations
- Some of your options
  - Filter saturates
  - Filter diverges
  - Filter explodes?!?
  - Other options?

Case A Results: Residuals

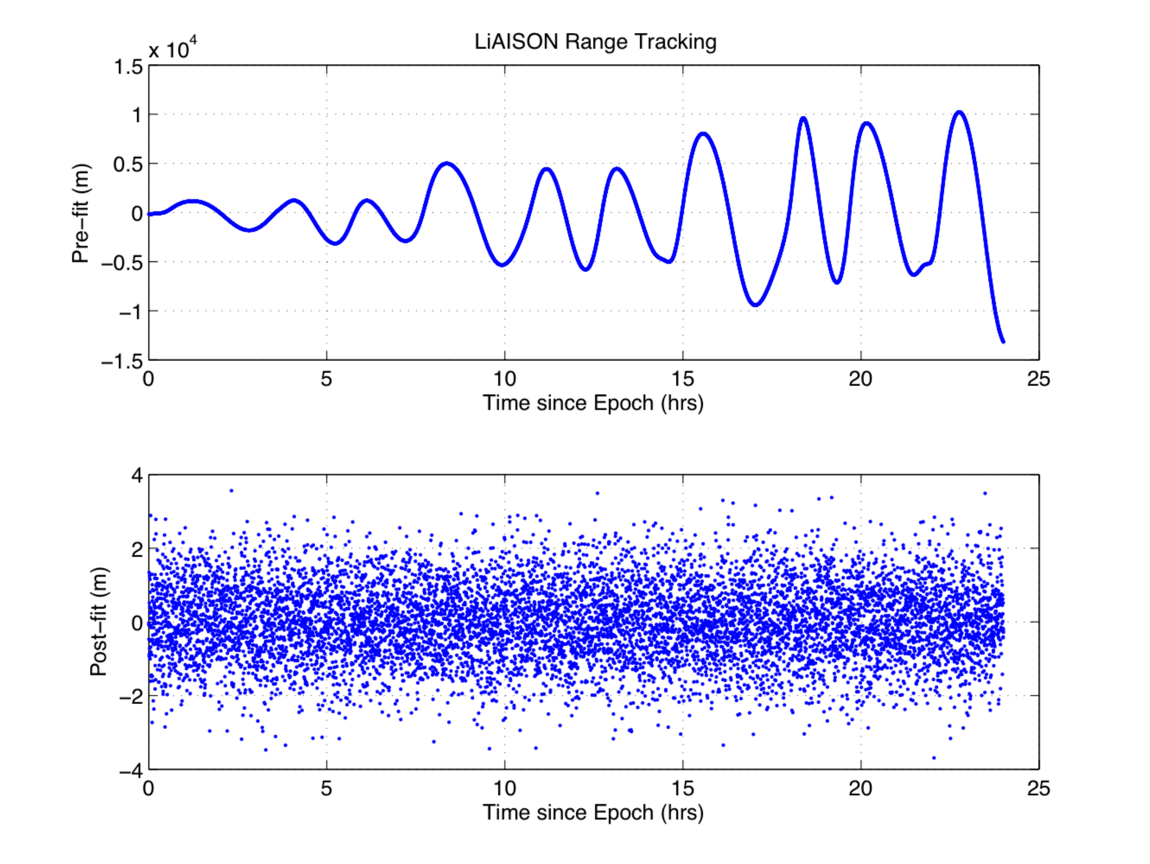
- Previous Case A CKF Results



What happened?

Case A Results: Residuals

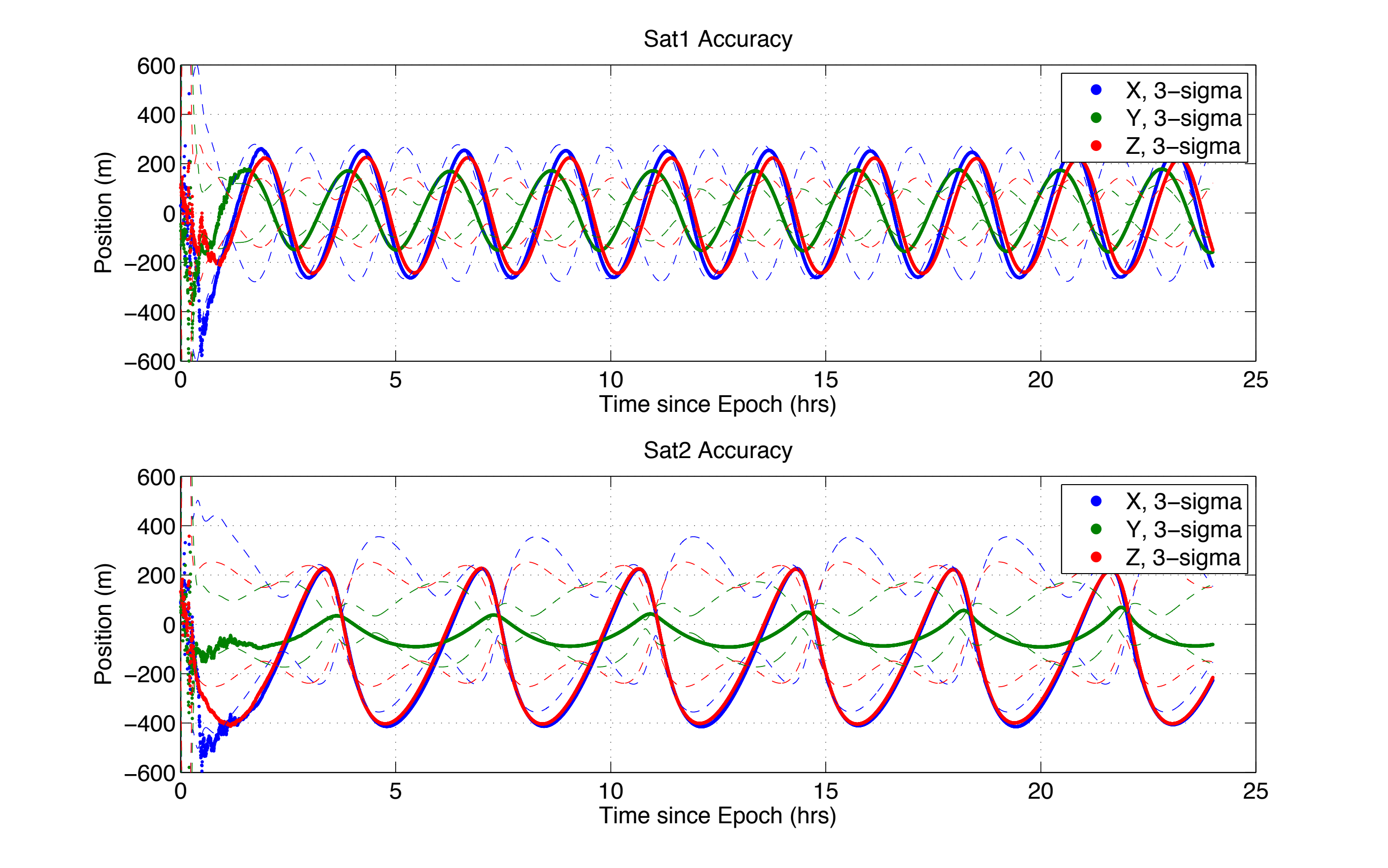
- Previous Case A CKF Results with SNC



What happened?

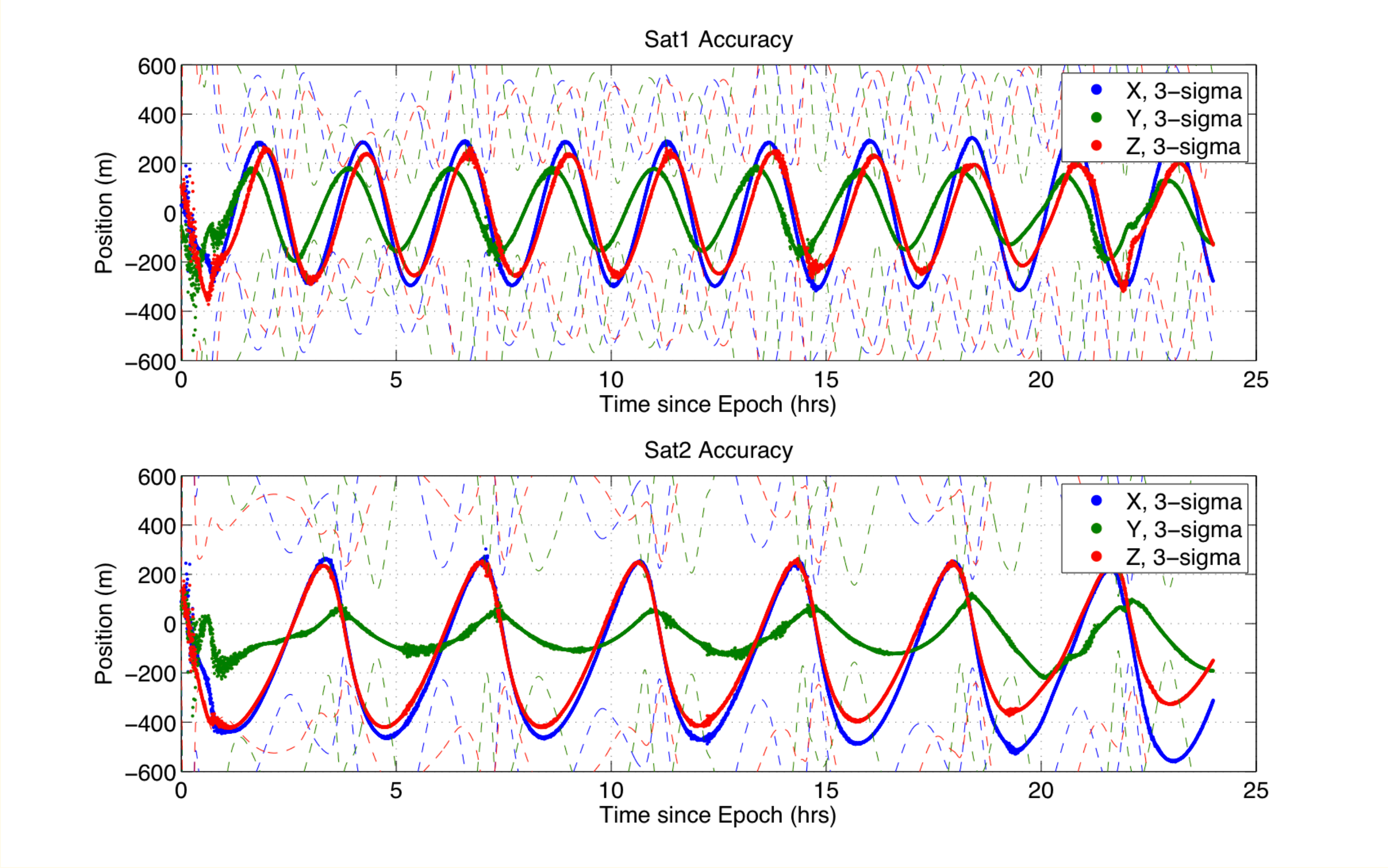
Case A Results: Accuracy

- Previous Case A CKF Results



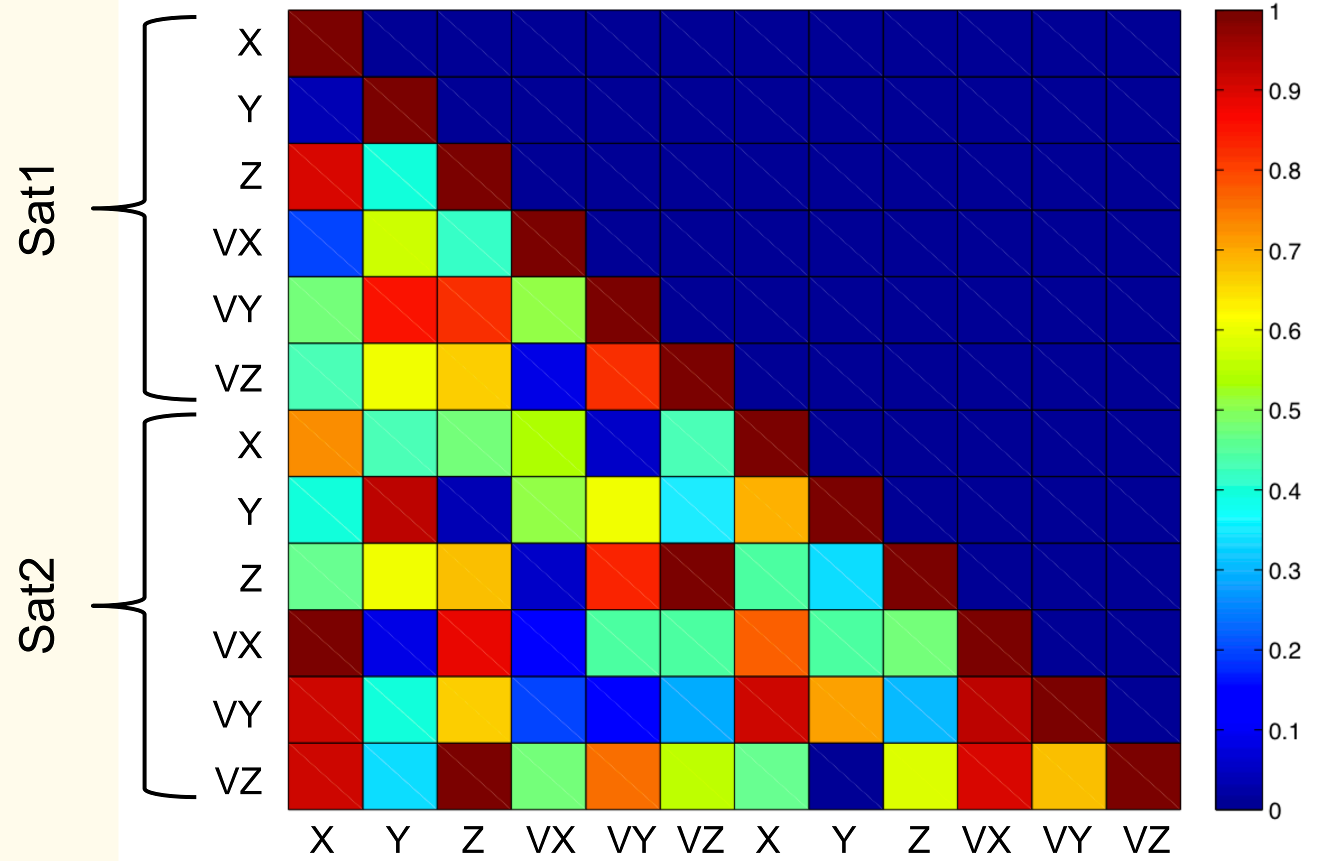
Case A Results: Accuracy

- Previous Case A CKF Results with SNC



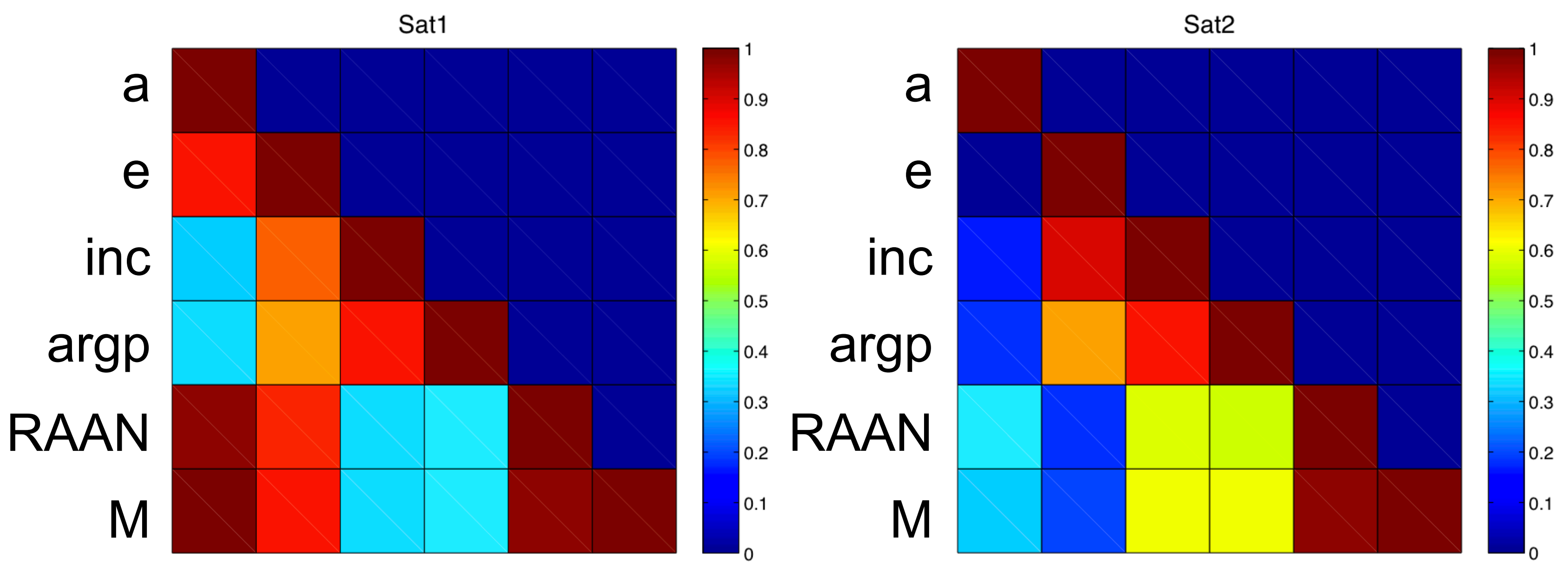
Case A Results: Covariance Matrix

- Correlation Coefficient in Cartesian Space



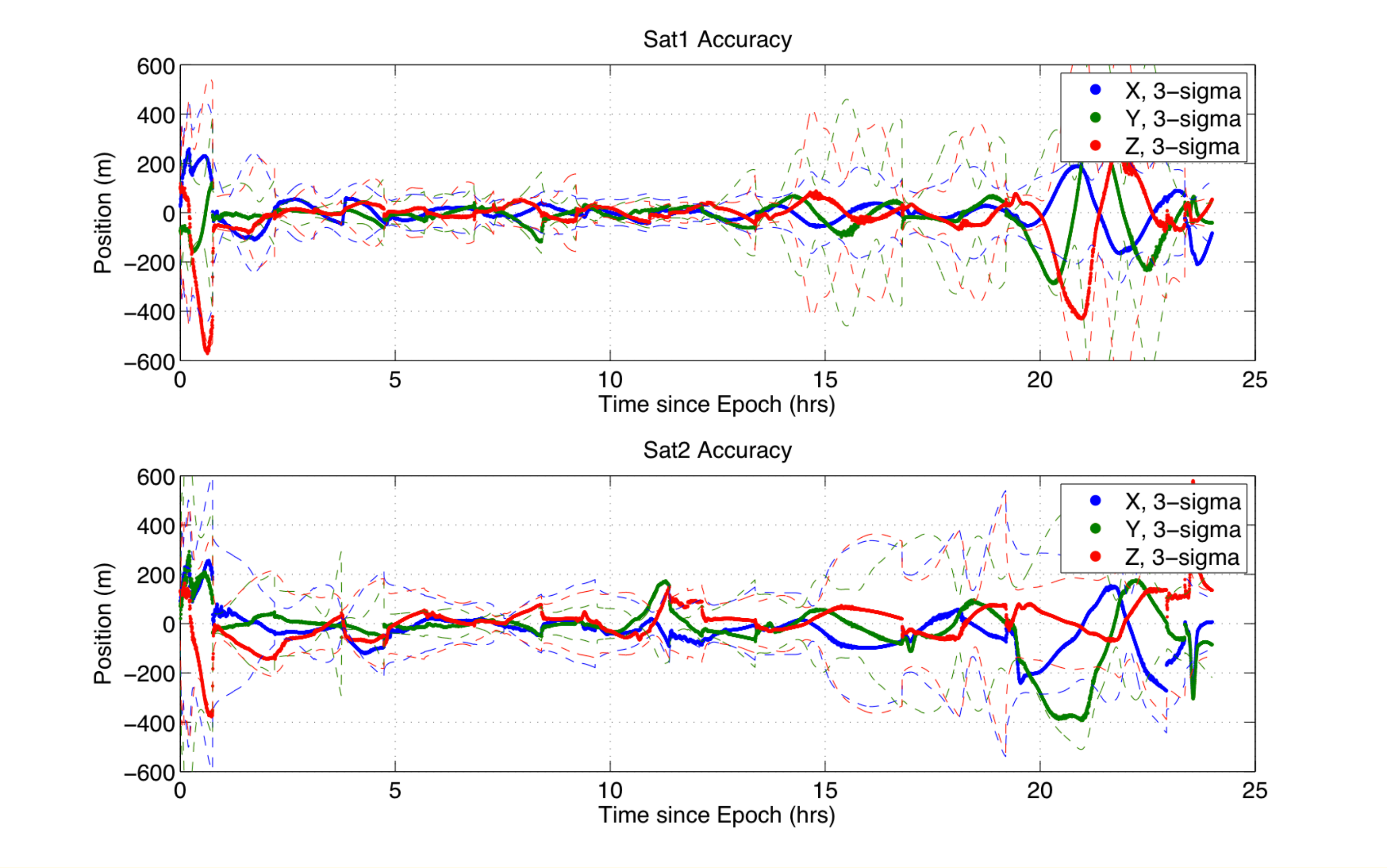
Case A Results: Covariance Matrix

- Correlation Coefficients in Keplerian Elements



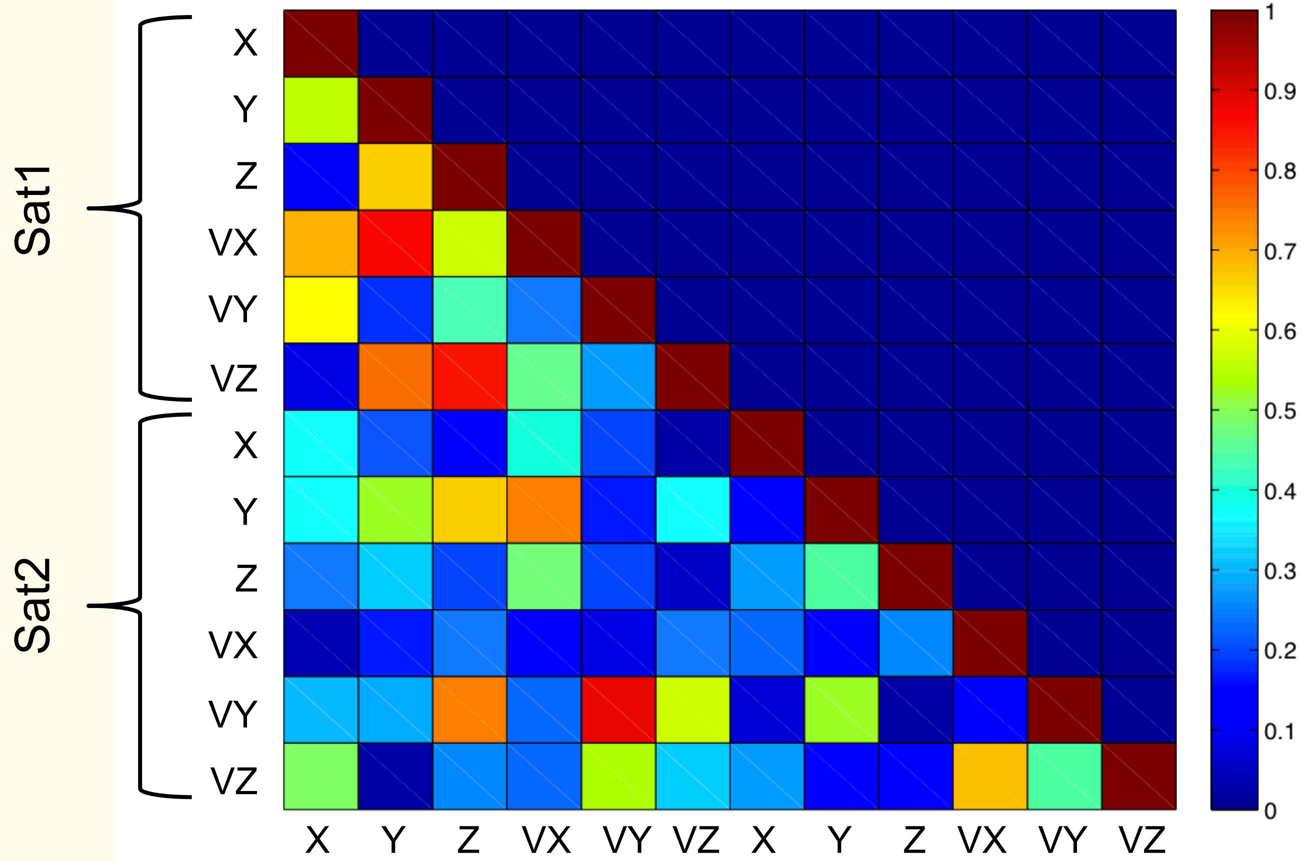
Case A Results: Accuracy with Ground Obs

- Uncertainty is greatly reduced!



Case A Results: Covariance Matrix with Ground Obs

- Not as many high correlations

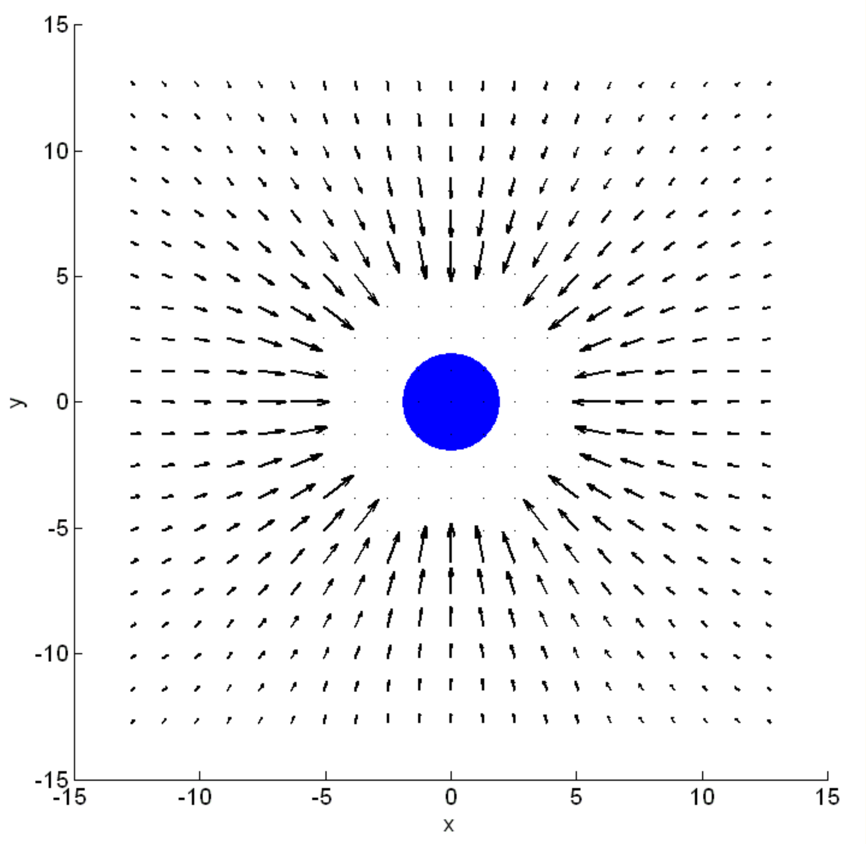


Satellite-to-Satellite Tracking

- SST only provides information about size, shape and relative orientation about the orbits of the participating spacecraft
- Changes in the absolute orientation of the constellation do not show in the crosslink measurements… as long as the relative orientation of the orbits does not change
- Supplemental ground tracking needed to solve for complete state vector

LiAISON for Dummies

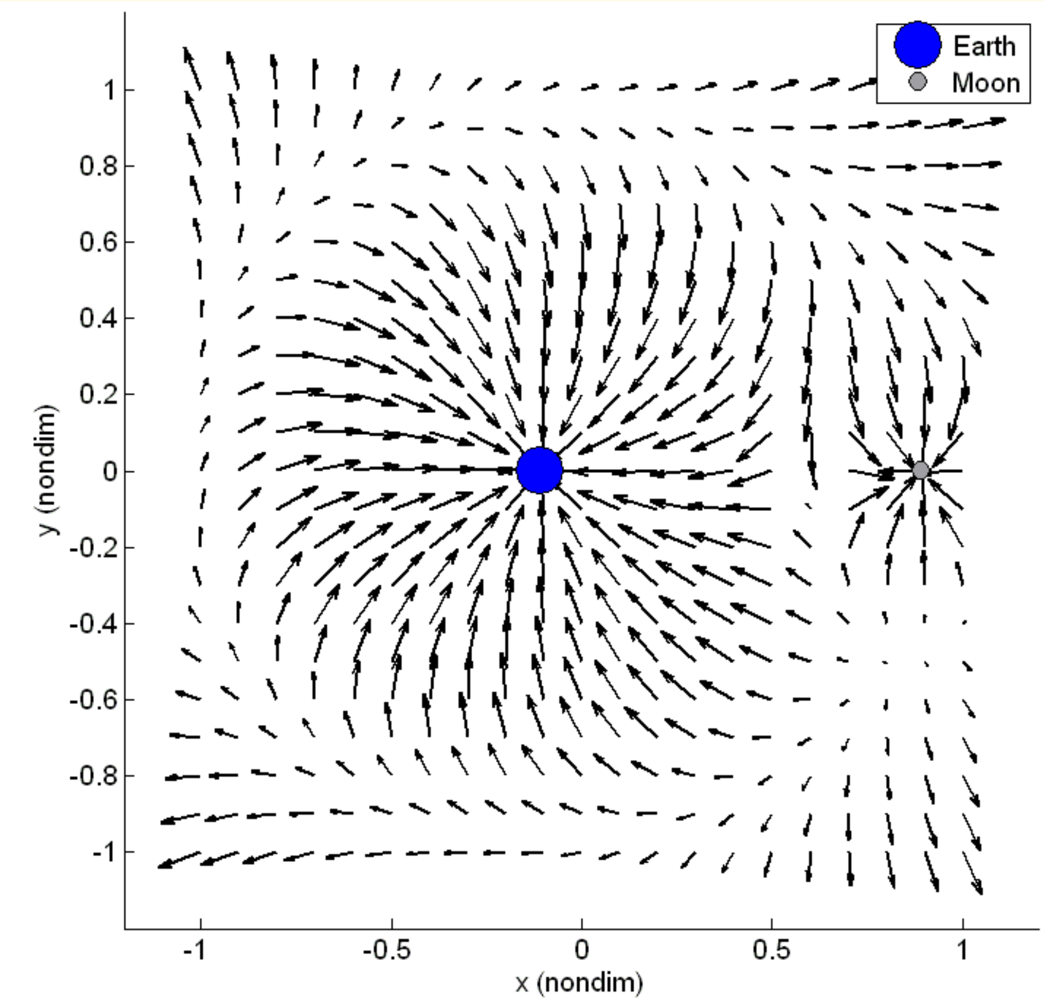
Two-Body Problem



Acceleration vectors in the two-body problem

- Symmetrical gravity field
- Unique orbits do not exist

Three-Body Problem



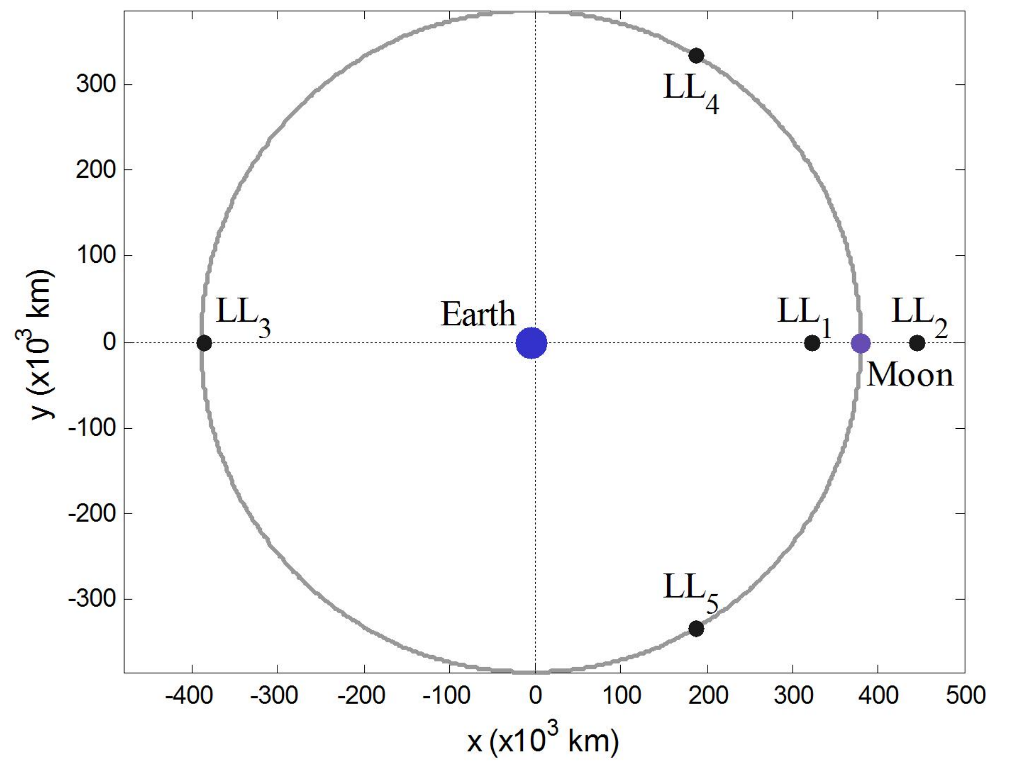
Acceleration vectors in the CRTBP (rotating frame)

- Third body provides an asymmetrical gravity field
- Locally unique orbits exist as long as they are not restricted to the orbit of the primaries

- LiAISON is more likely to work in regions where the asymmetry is strong

Earth-Moon System

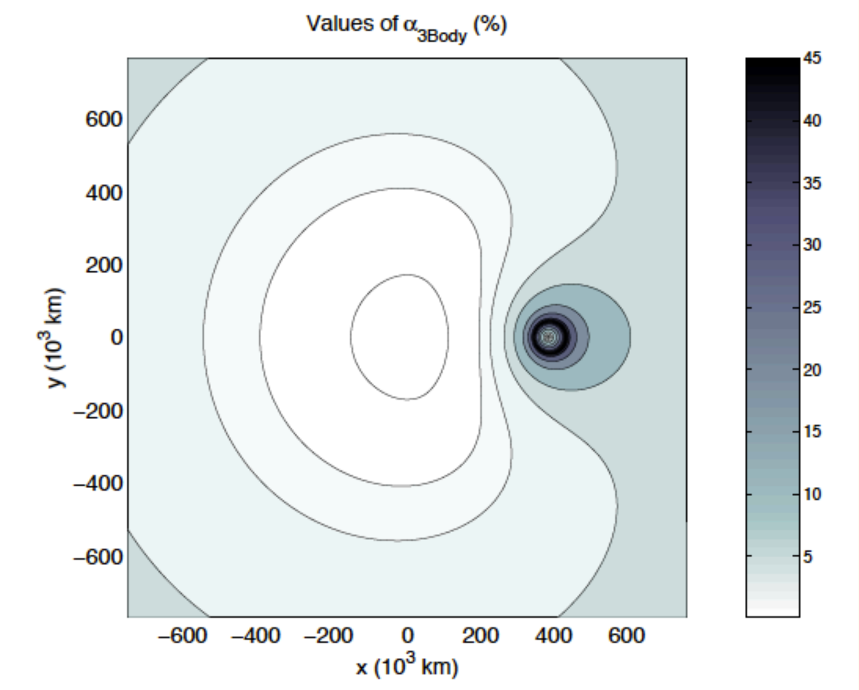
- The Earth and Moon orbit their barycenter in nearly circular orbits.
- Motion of a satellite within the Earth-Moon system may be approximated by the Circular Restricted Three-Body Problem (CRTBP)



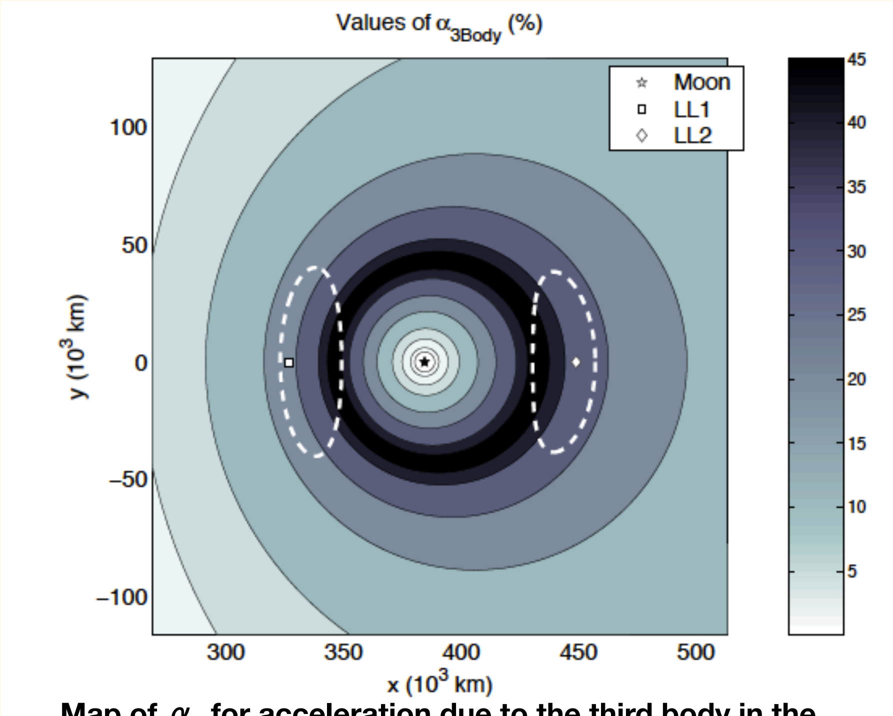
Three-Body Problem

- α is relative strength of perturbations
- Looked at J_2 and SRP
  - Neither provide enough asymmetry
- Third-body perturbations provide the necessary asymmetry

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



Map of α for acceleration due to the third body in the Earth-Moon system.



Map of α for acceleration due to the third body in the Earth-Moon system zoomed in on the Moon.

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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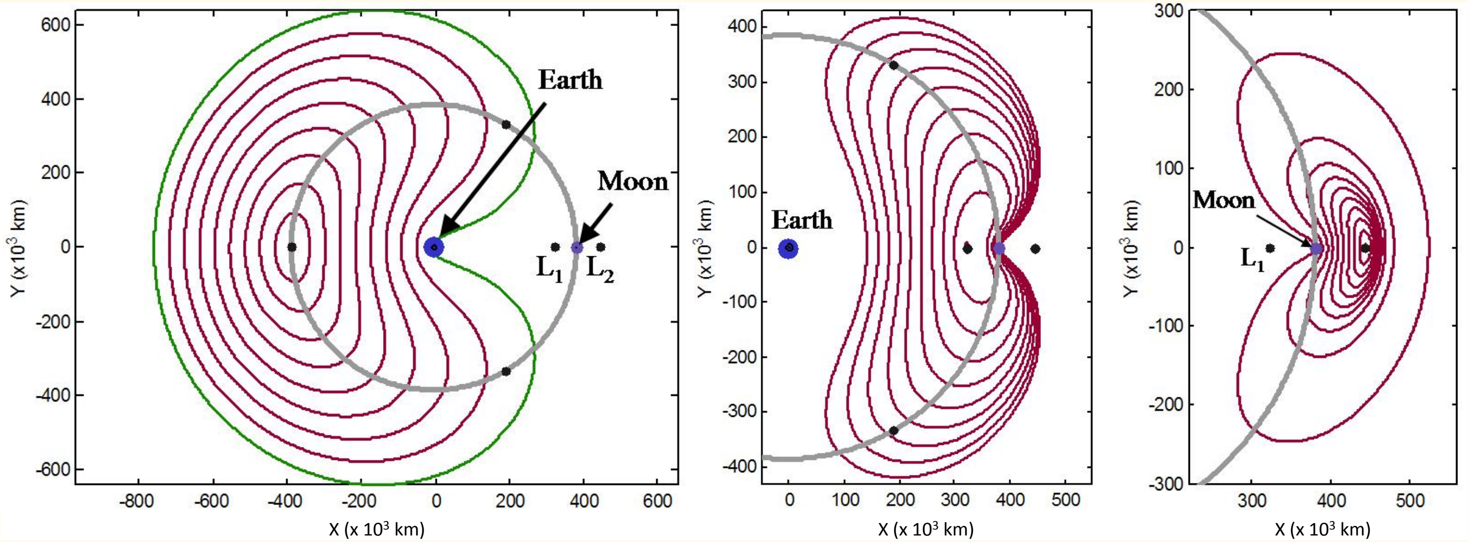
  - Planar Lyapunov orbits about L_1, L_2, and L_3



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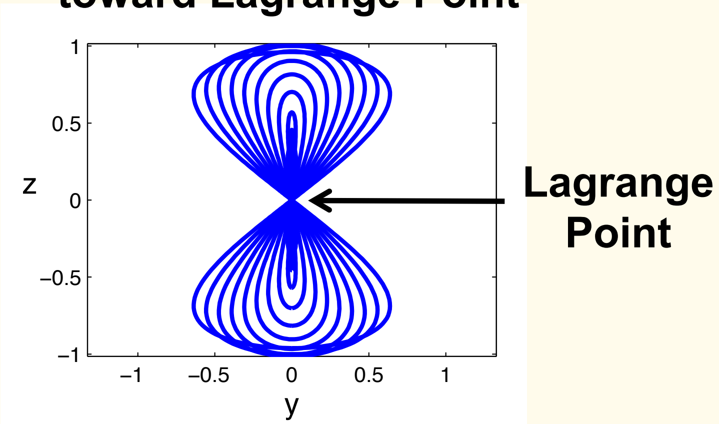
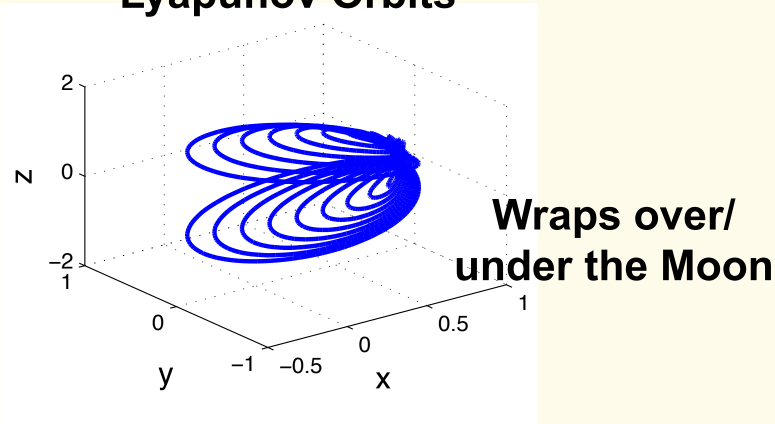
View from Earth or Moon toward Lagrange Point



Oblique view of Vertical Lyapunov Orbits



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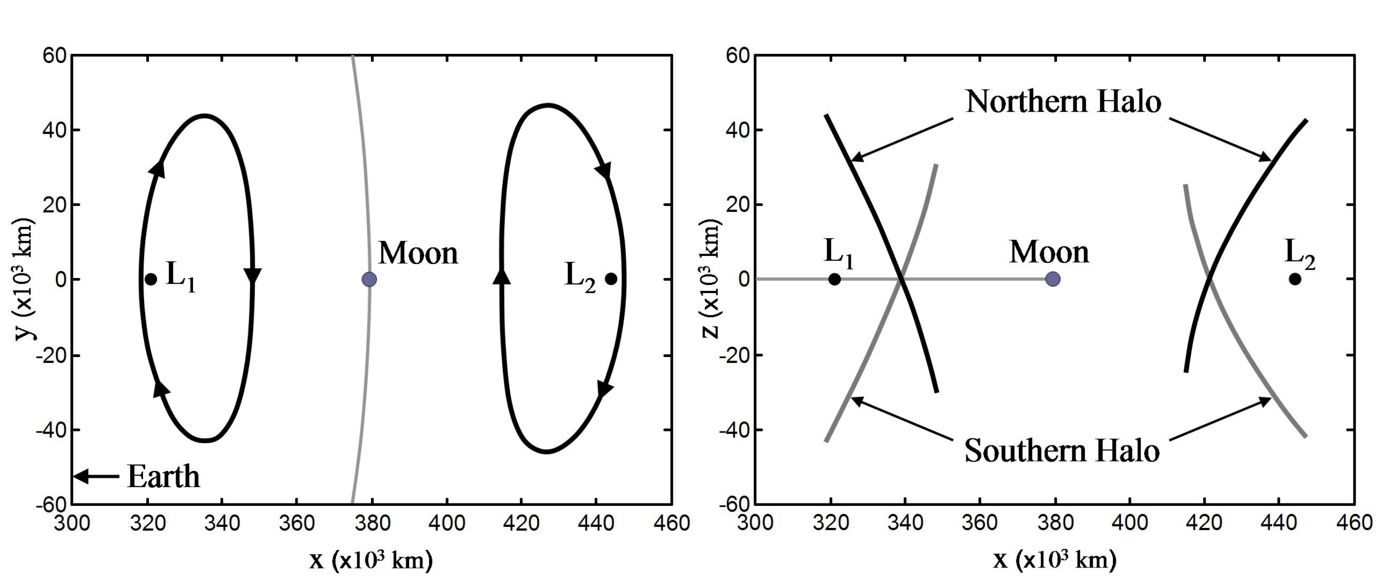
  - Halo orbits about L_1, L_2, and L_3



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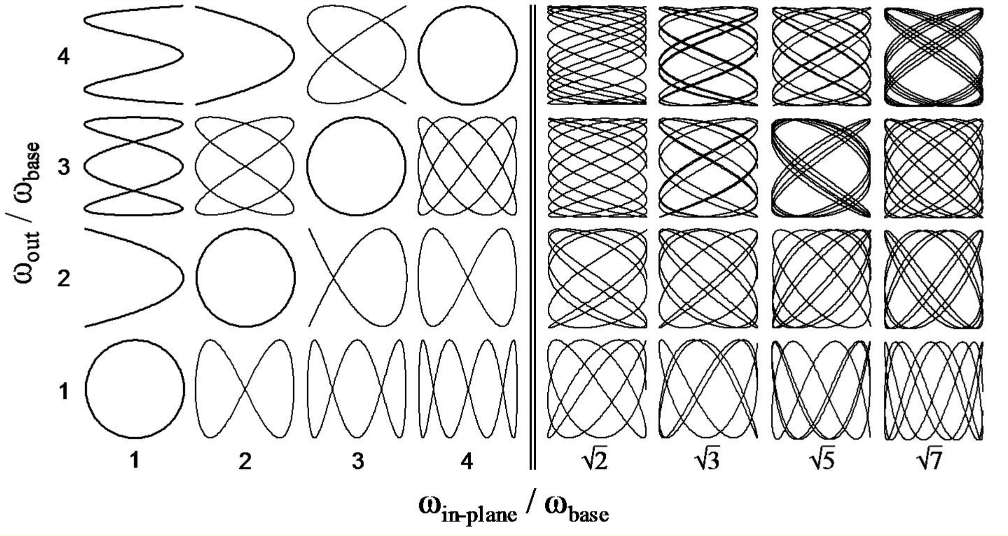
  - Halo orbits about L_1, L_2, and L_3
  - Lissajous orbits about L_1, L_2, and L_3



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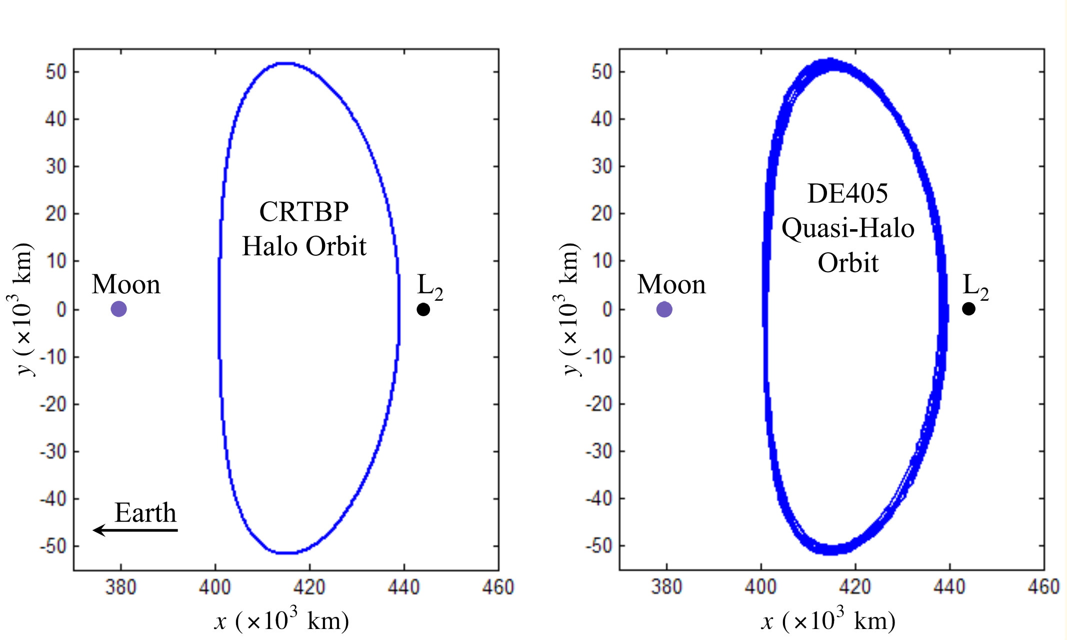
  - Vertical Lyapunov orbits about L_1, L_2, and L_3
  - Halo orbits about L_1, L_2, and L_3
  - Lissajous orbits about L_1, L_2, and L_3
- Numerous other orbit types exist in the CRTBP:
  - Distant Retrograde Orbits (DROs)
  - Distant Prograde Orbits (DPOs)
  - Resonant orbits
  - Orbit chains

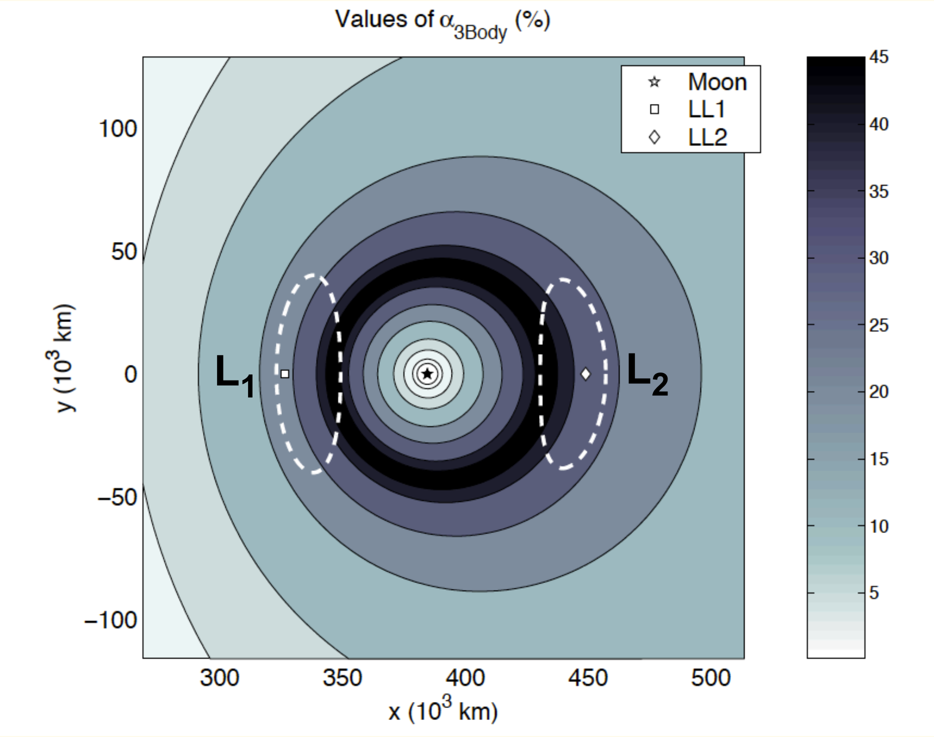
Realistic Lunar "Halo" Orbits

- 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.**

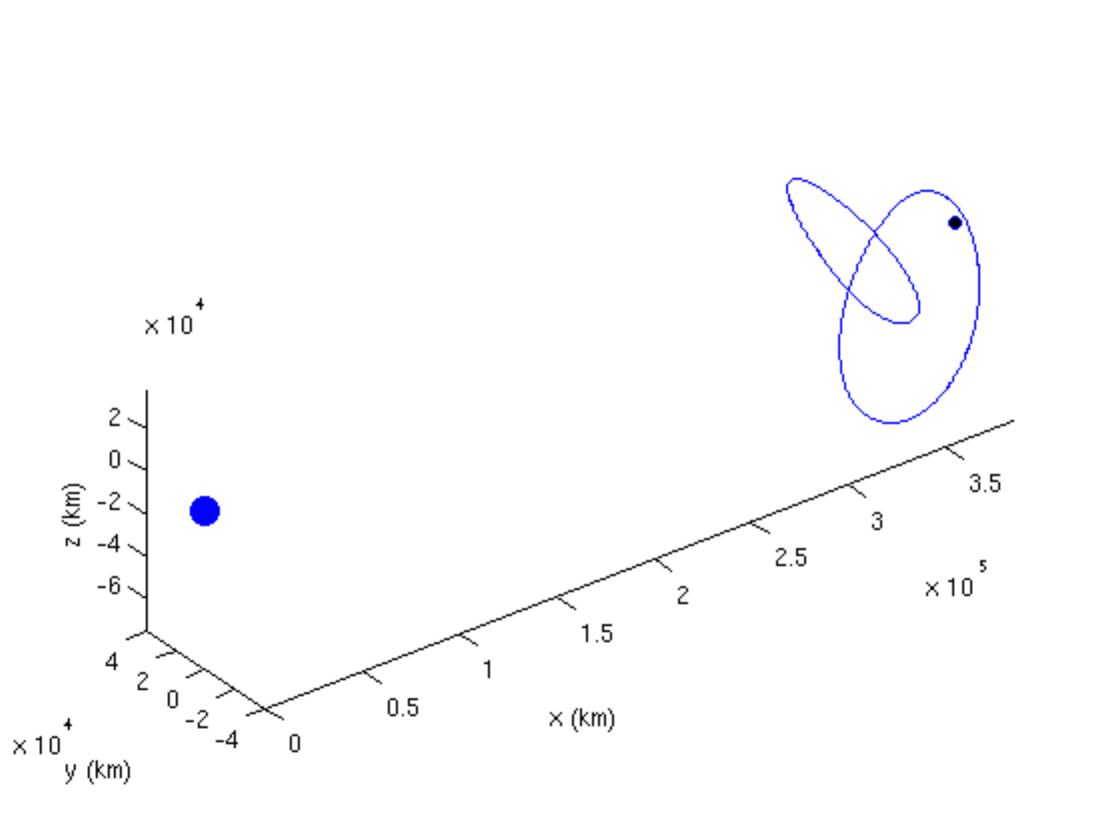
– **SST between an LL_1 or LL_2 orbiter and another satellite generate *unique* tracking signatures.**

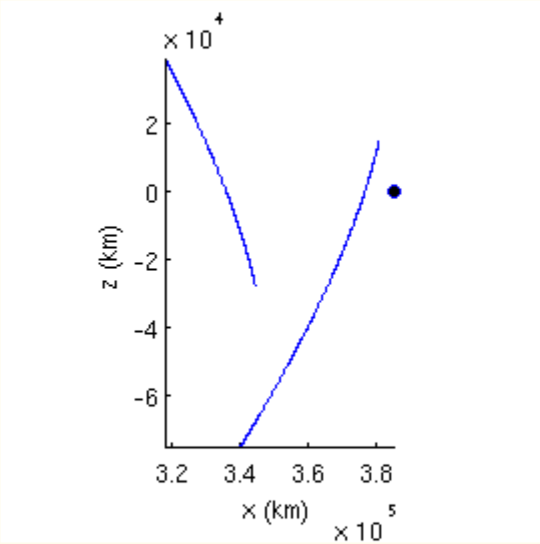
– **Hill studied many lunar configurations:**
  - **LL_1 – LLO (Low Lunar Orbit)**
  - **LL_2 – LLO**
  - **LL_1 – LL_2**
  - **LL_2 – LL_2**
  - **LL_2 – LL_2 – LLO**
  - **etc**

LL_1 Nav < 100 meters
LLO Nav < 10 meters

LiAISON Research

Lunar L_1 LiAISON





Two halo orbits at L1
Periods of about 15 days

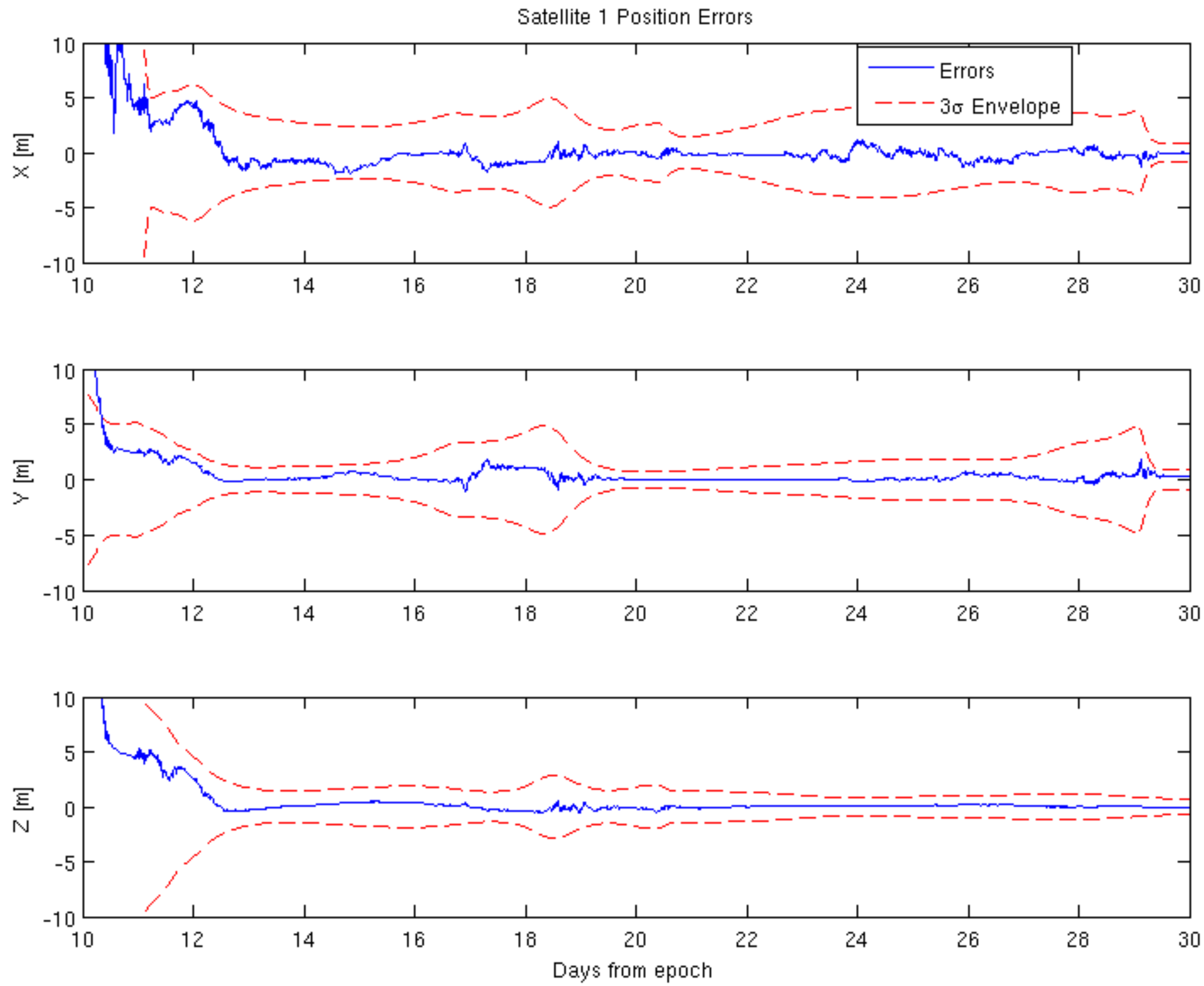
Observations
Range, generated with 1 m white noise (every 375 seconds)

Process noise of 10^{-13} km/s^2

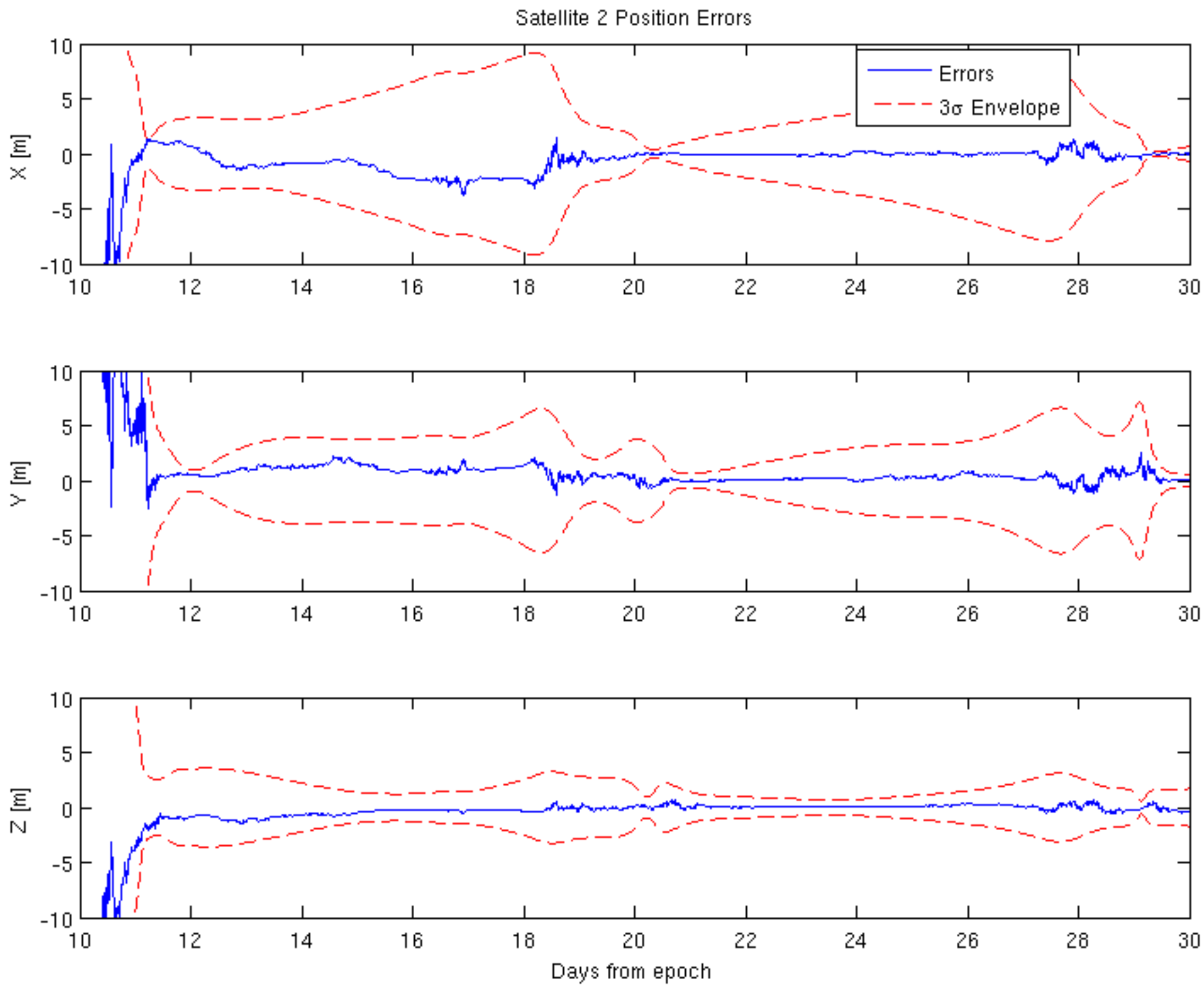
<u>Orbit Determination</u>
Extended Kalman Filter

Perturbations in ICs: m-level pos, cm/s-level vel
A priori covariance: 1 km pos, 10 m/s vel
Fit span: 30 days

EKF Results: Sat 1



EKF Results: Sat 2



Other LiAISON Applications

Lunar Missions from L1

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

Lunar Missions from L2

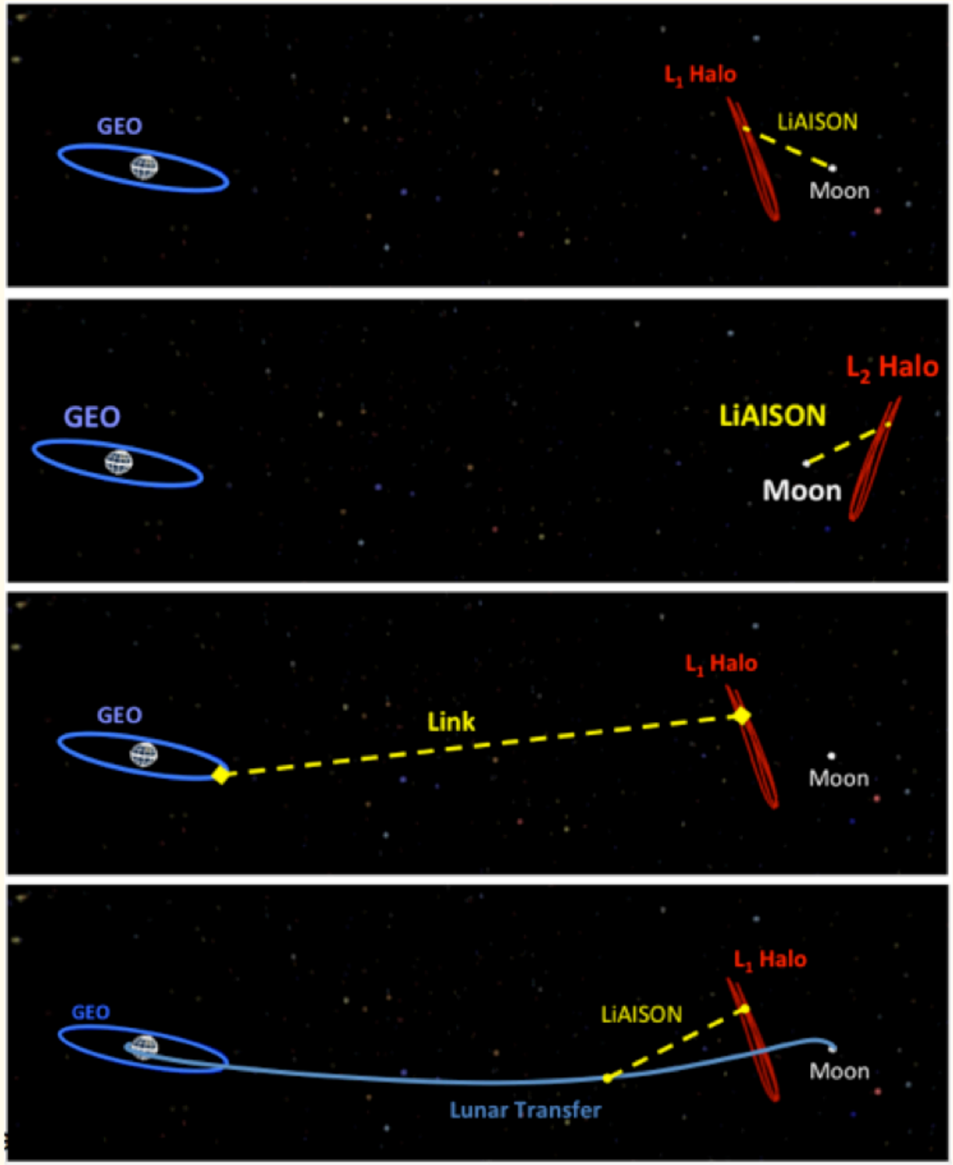
Same performance
Far-side tracking and communication

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

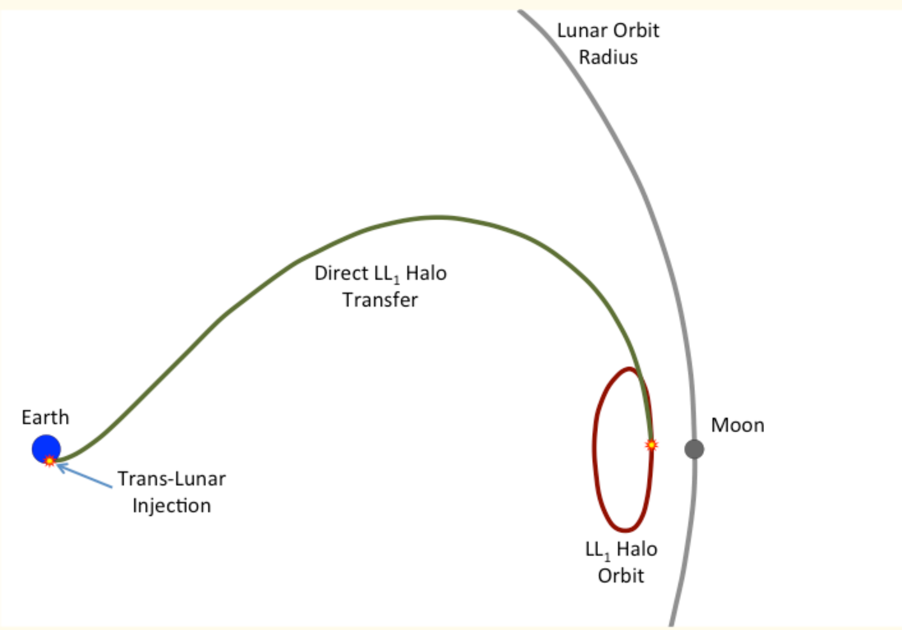
- State of the art in GEO Navigation
  - Range measurements from several ground stations: nav accuracy on the order of ~30 meters
  - GPS signals may be used from the far side of the Earth: ~15 meters
  - Optical tracking using several ground stations: ~10 meters
  - Multiple tracking types including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

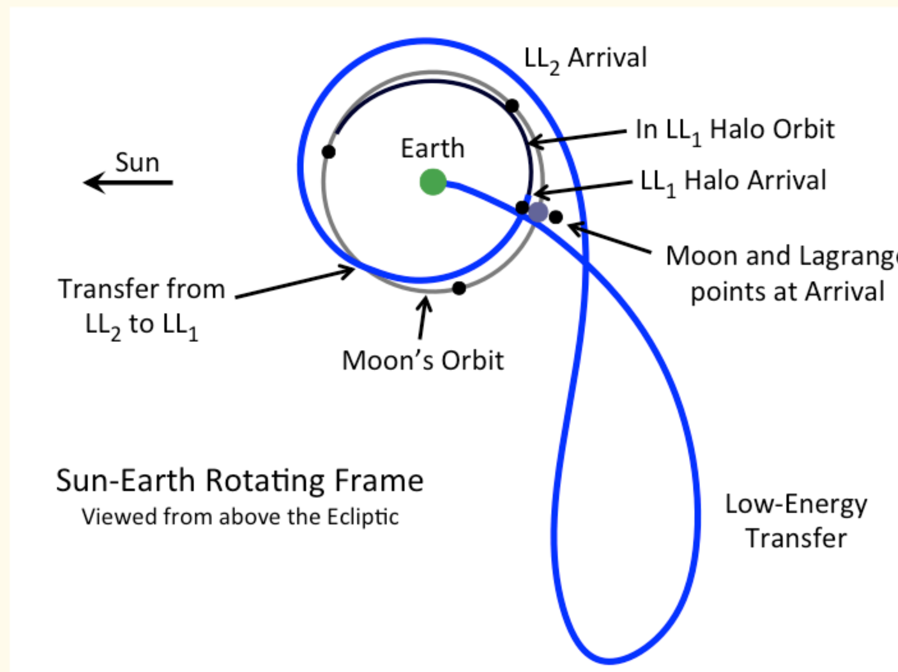
Simulated Configuration

- This study used the following L_1 halo orbit:

Parameter	Value	Comments
A_z	35,500 km	The z-axis amplitude
ϕ	0°	The initial phase angle of the orbit
t_{ref}	1/1/2020 00:00:00 ET	The reference epoch, ephemeris time

- Equatorial GEO orbit, set over a longitude of 0 deg.

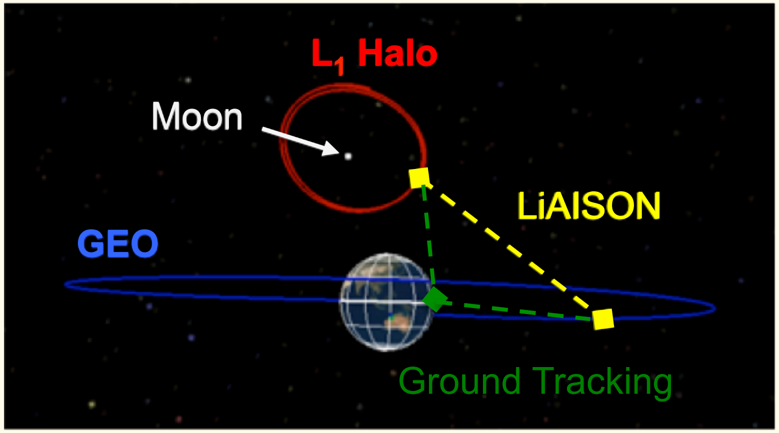




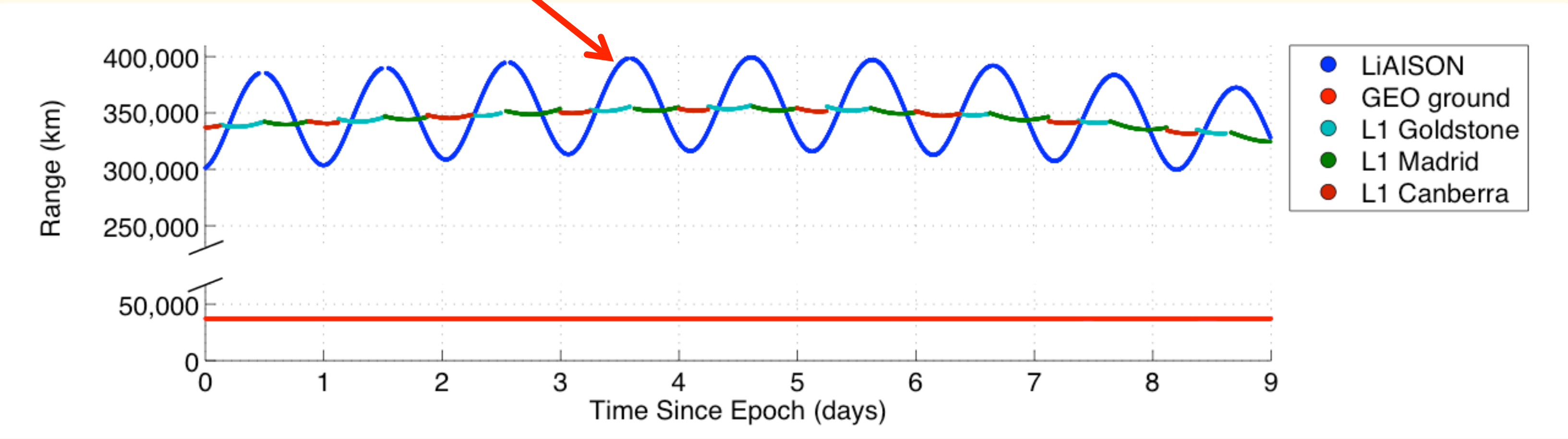
LiAISON Observation Geometry

The geometry

- Ground – GEO: Static observations
- Ground – L_1: Relatively static observations
- L_1 – GEO: Dynamic observations
  - *Observable geometry*



Very clear signal

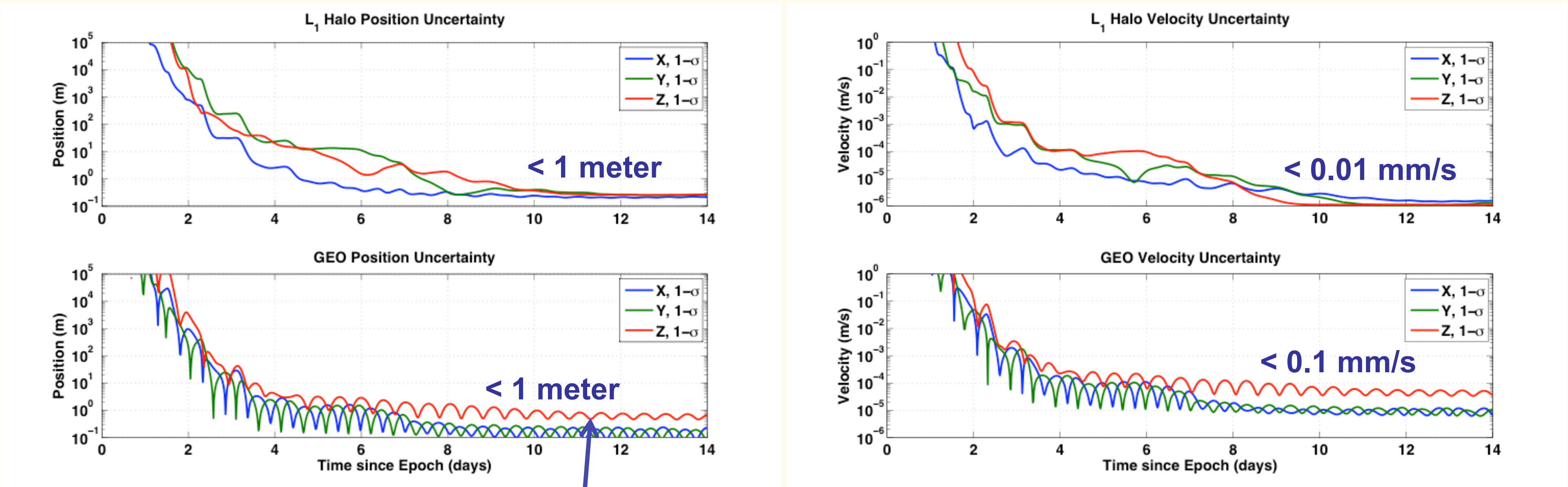


Navigation Simulations

- 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

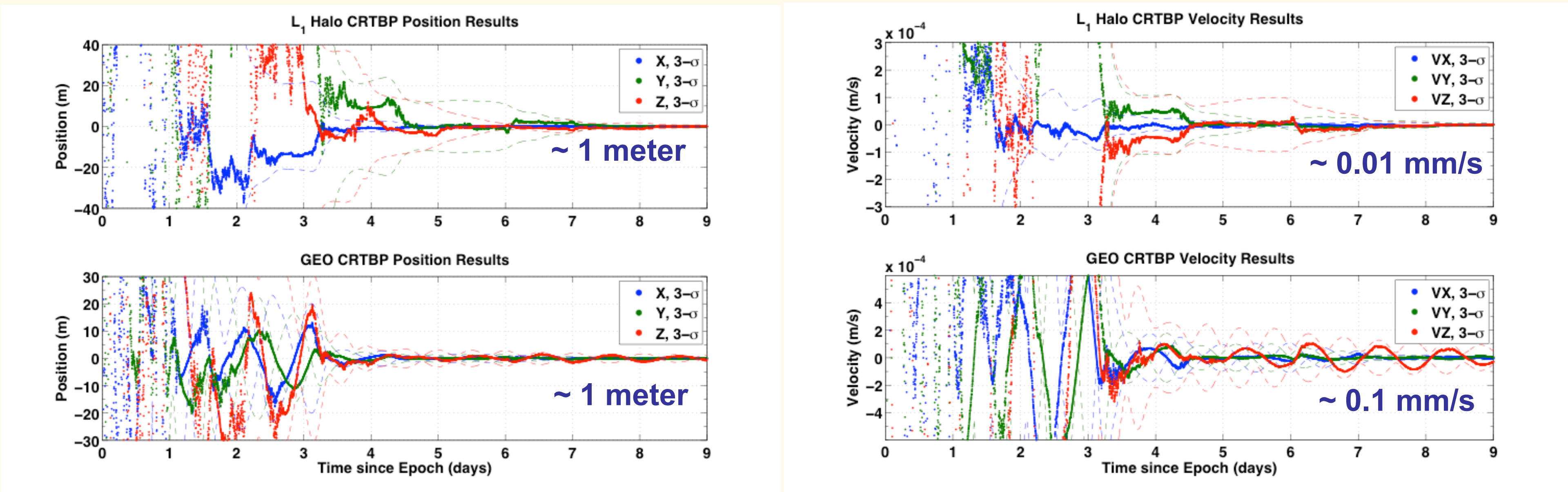


z-axis uncertainty ~2.4 times greater than planar: expected due to Earth's obliquity

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

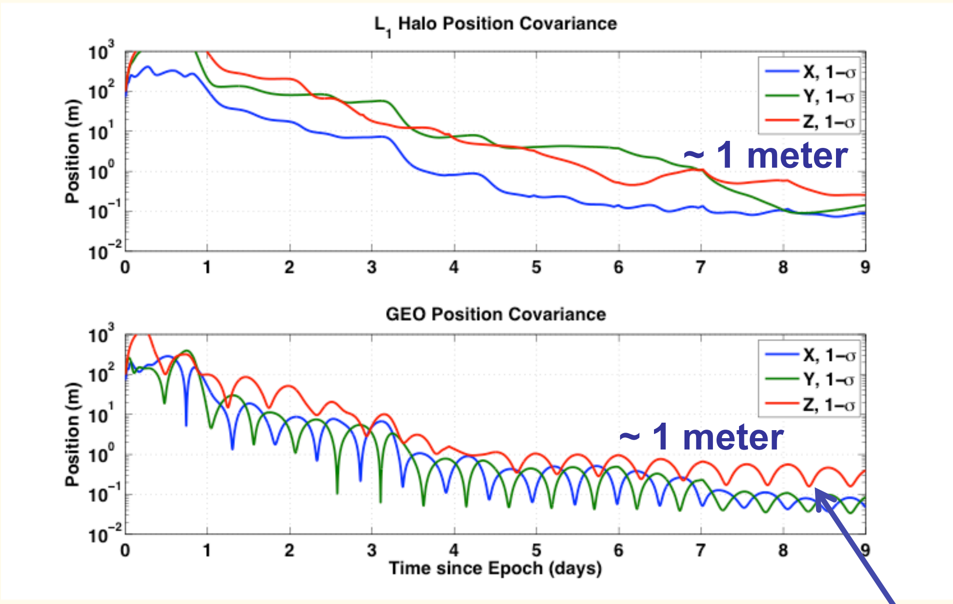
CRTBP Simulation

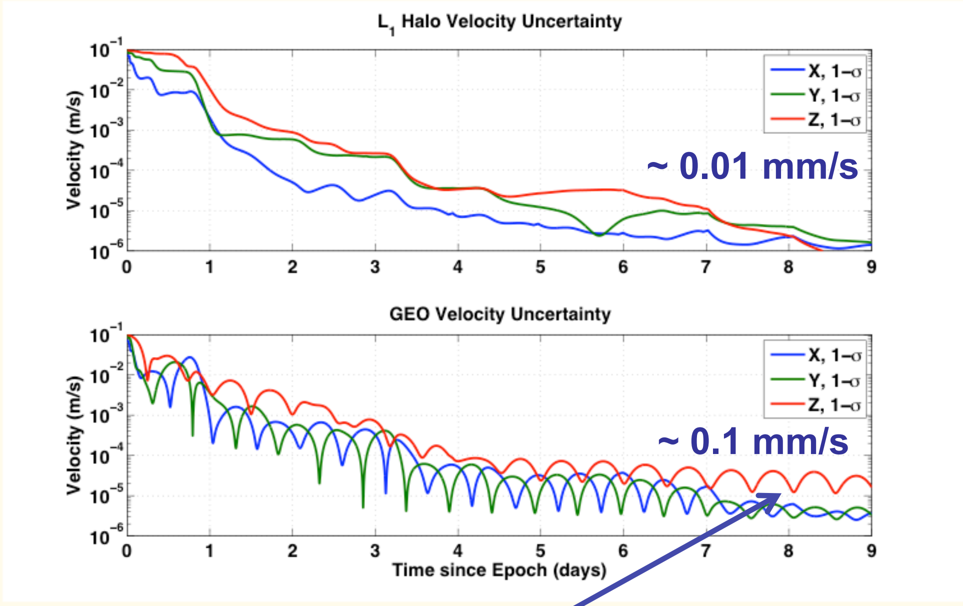
- Initial state is perturbed by N(0,100) meters in position and N(0,1) cm/s in velocity.
- *a priori* covariance: (100 meters)^2 in position and (10 cm/s)^2 in velocity for both satellites.
- State Noise Compensation: $\sigma = 10^{-13}$ m/s^2 for halo and 10^{-14} m/s^2 for GEO
- Extended Kalman Filter,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



CRTBP Simulation

- Covariance analysis during simulation





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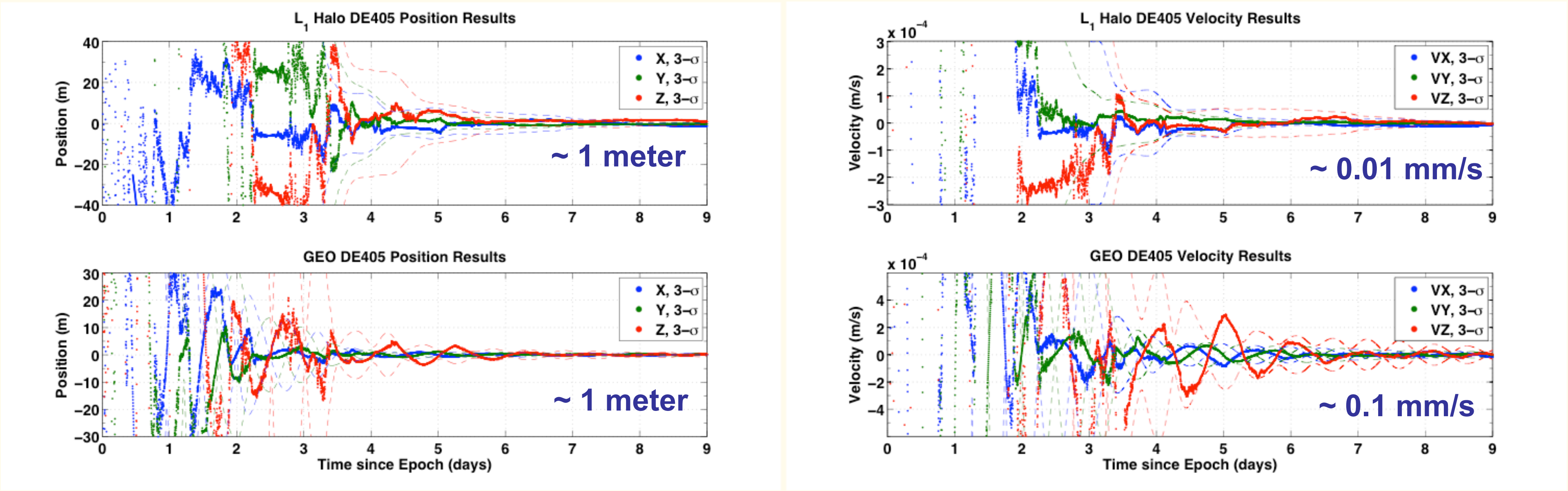
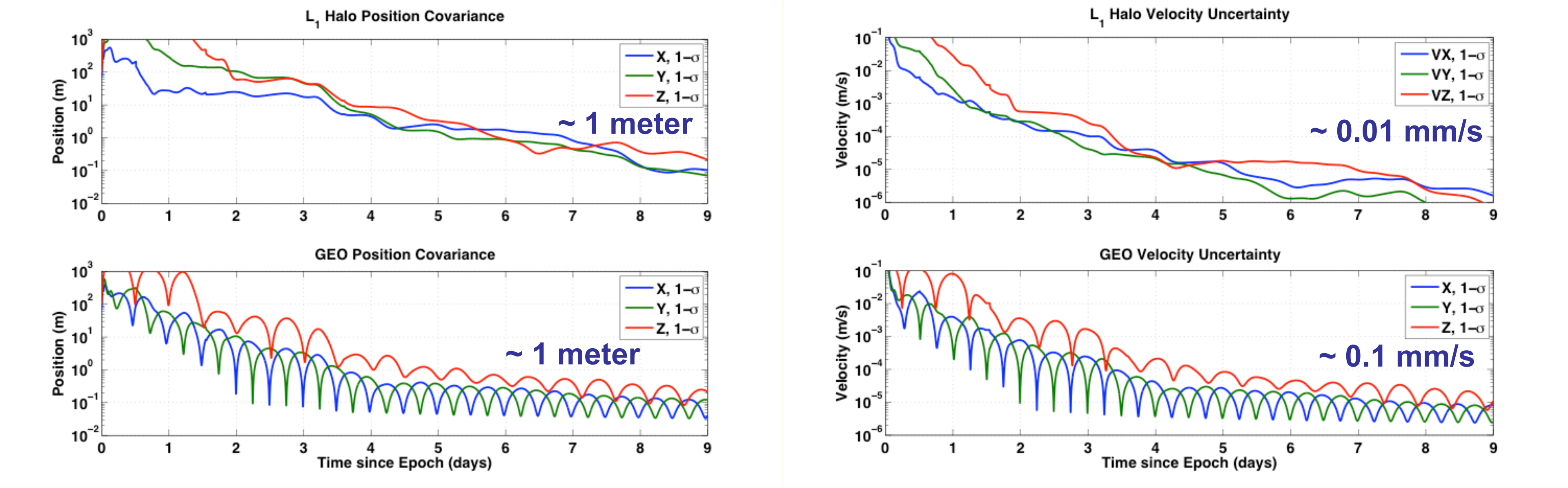
High-Fidelity

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



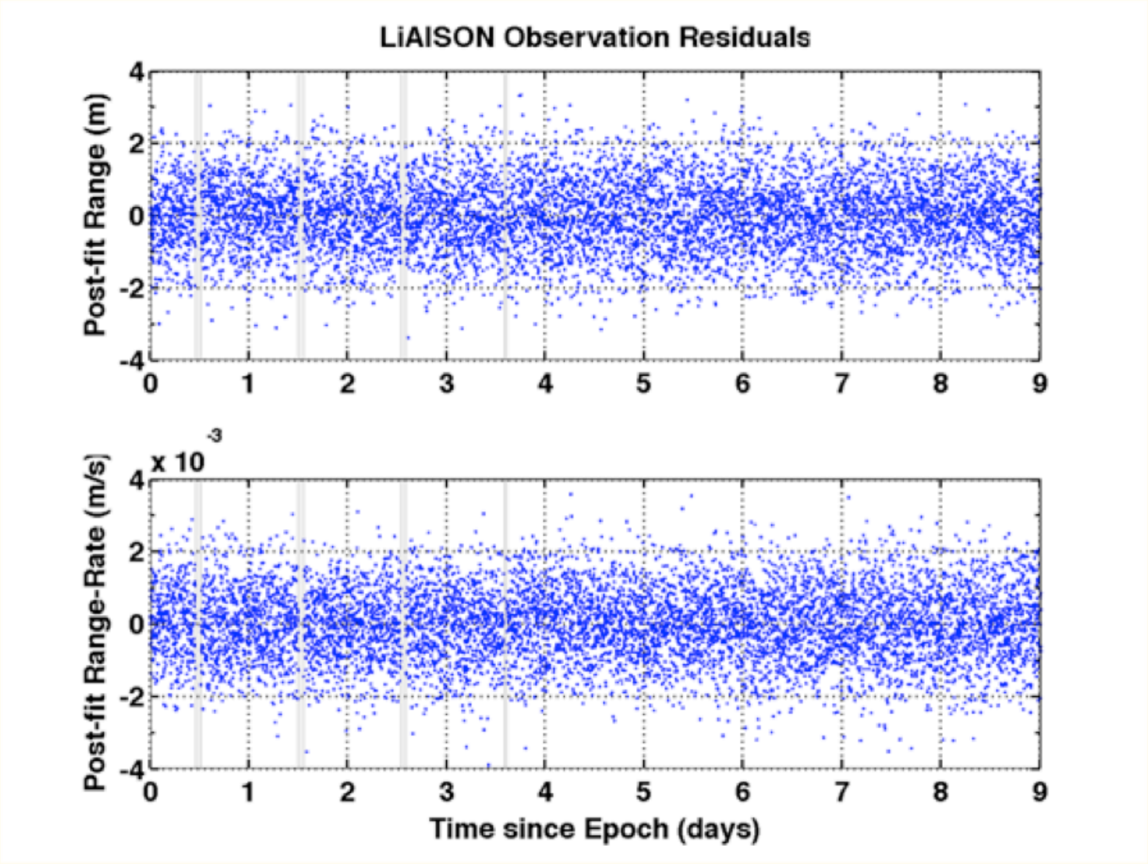
High-Fidelity

- 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.

LiAISON Navigation: Trade Study Overview

- **High fidelity trade study utilizing varying levels of LiAISON tracking and ground tracking. This will answer the questions:**
  - "How many ground tracks may we remove and still obtain the same level of accuracy for our mission?" – this quantifies the cost-savings by using LiAISON over ground-only tracking.
  - "How much improvement may we expect by adding LiAISON to our mission?" – this quantifies the improvement in satellite navigation accuracy by adding LiAISON.
  - "How does general observation scheduling influence the expected accuracy and uncertainty?" – this quantifies the necessity as to when observations should be obtained.
  - This research applies directly to GEO missions like TDRSS, but also easily applies to LEO missions, lunar missions, and any mission near the Earth or Moon.

Dynamic Models

- State Vector

$$\mathbf{X} = \begin{bmatrix} \mathbf{r}_1^{\mathrm{T}} & \mathbf{v}_1^{\mathrm{T}} & \mathbf{r}_2^{\mathrm{T}} & \mathbf{v}_2^{\mathrm{T}} & \delta C_{R,1} & \delta C_{R,2} & \mathbf{w}_1^{\mathrm{T}} & \mathbf{w}_2^{\mathrm{T}} & \boldsymbol{\rho}_{\mathrm{bias}}^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}}$$

- Reference Frame
  - Geocentric Celestial Reference Frame (GCRF) with 1976 IAU Precession and 1980 IAU Nutation with no corrections.
- Planetary Ephemeris
  - DE405
- Force Models
  - Two-Body
  - Geopotential (20x20 GGM02C for GEO)
  - N Body
    - JPL DE405
  - Solar radiation pressure
    - A/m = 0.01 m²/kg

LiAISON:

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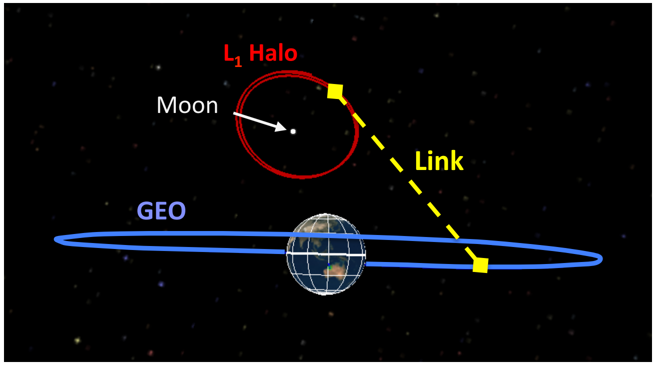
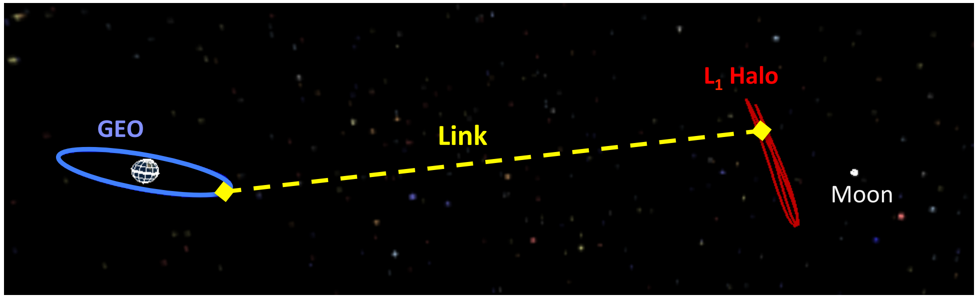
Orbit
Navigation





$$\begin{bmatrix} \dot{\mathbf{r}}_i \\ \dot{\mathbf{v}}_i \end{bmatrix} = \begin{bmatrix} \mathbf{v}_i \\ \mathbf{a}_g(t, \mathbf{r}_i) + \mathbf{a}_{SRP}(t, \mathbf{r}_i) + \mathbf{a}_{n\text{-}body}(\mathbf{r}_i, \mathbf{r}_{\oplus 3}) + [\gamma]_{RTN}^{\mathrm{T}}\, \mathbf{w}_i \end{bmatrix}$$

Measurement Models

- Simplified measurement models for range and range-rate.
- No light time is assumed.
- Geometric range plus a constant bias and Gaussian noise.

$$\rho = \sqrt{(\mathbf{r}_1 - \mathbf{r}_2) \cdot (\mathbf{r}_1 - \mathbf{r}_2)} + \rho_{bias} + \rho_{noise}$$

- Idealized range-rate with Gaussian noise.

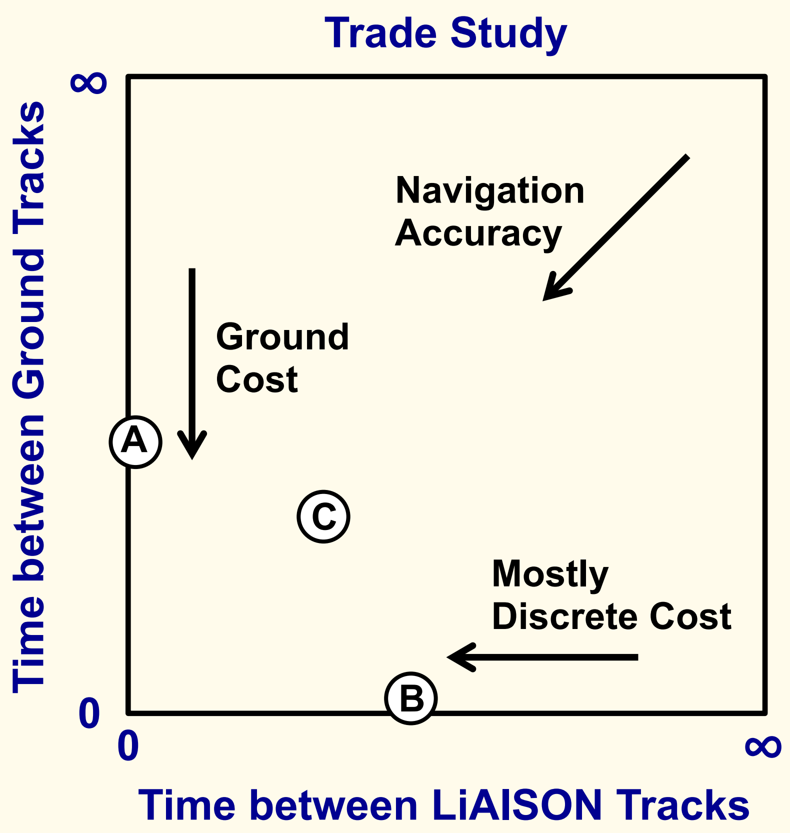
$$\dot{\rho} = \frac{\boldsymbol{\rho} \cdot \dot{\boldsymbol{\rho}}}{\rho} + \dot{\rho}_{noise}$$

- DSN stations used to track the L_1 orbiter
  - Goldstone, California
  - Madrid, Spain
  - Canberra, Australia
- Ground station tracking GEO
  - Sky Valley, California

LiAISON Trade Study

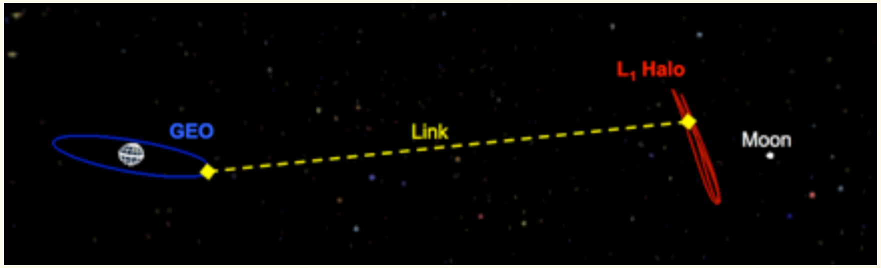
- Quantify the cost and accuracy of LiAISON compared to ground-only navigation.
  - We'll illustrate this objective using:
    (A) a continuous LiAISON with sparse Ground tracking solution, and
    (B) a continuous Ground with sparse LiAISON tracking solution

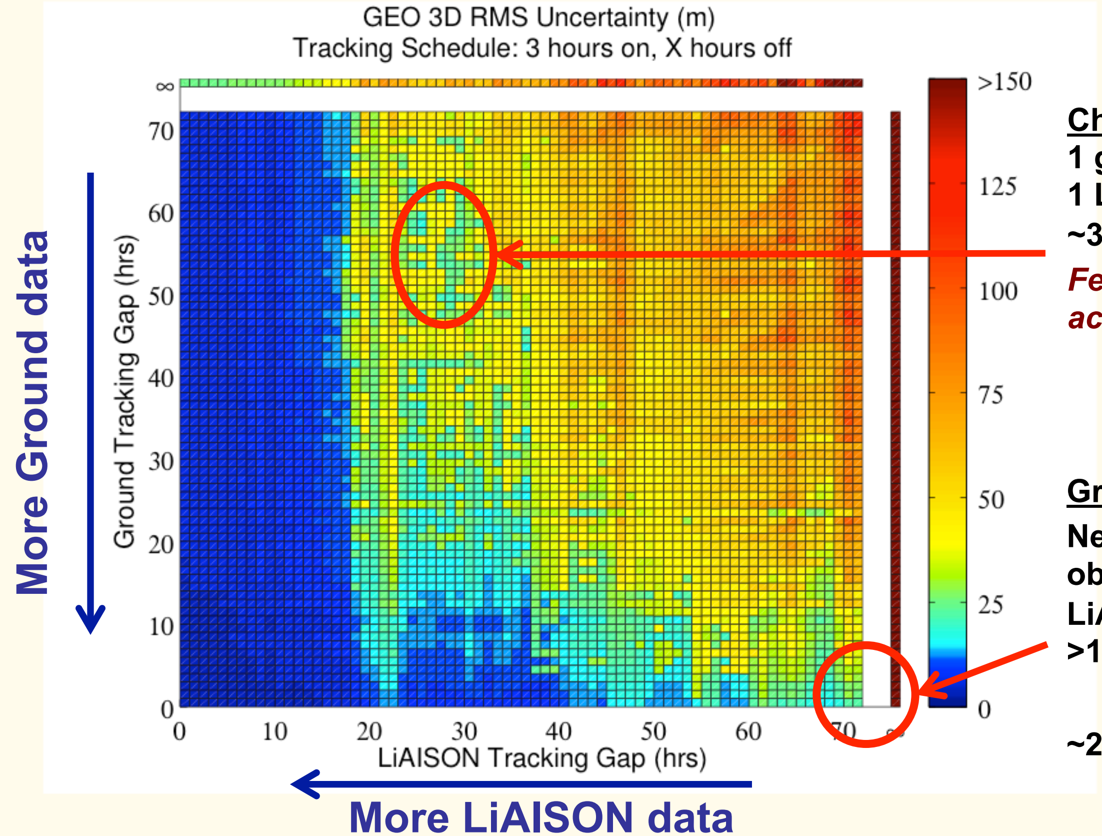
- Determine how many ground tracks may be removed and achieve the same navigation accuracy.
  - We'll illustrate this objective using:
    (B) a continuous Ground with sparse LiAISON tracking solution, and
    (C) a LiAISON-supplemented solution.
  - such that both result in similar tracking uncertainty.



Trade Study 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 navigation accuracy by using LiAISON.



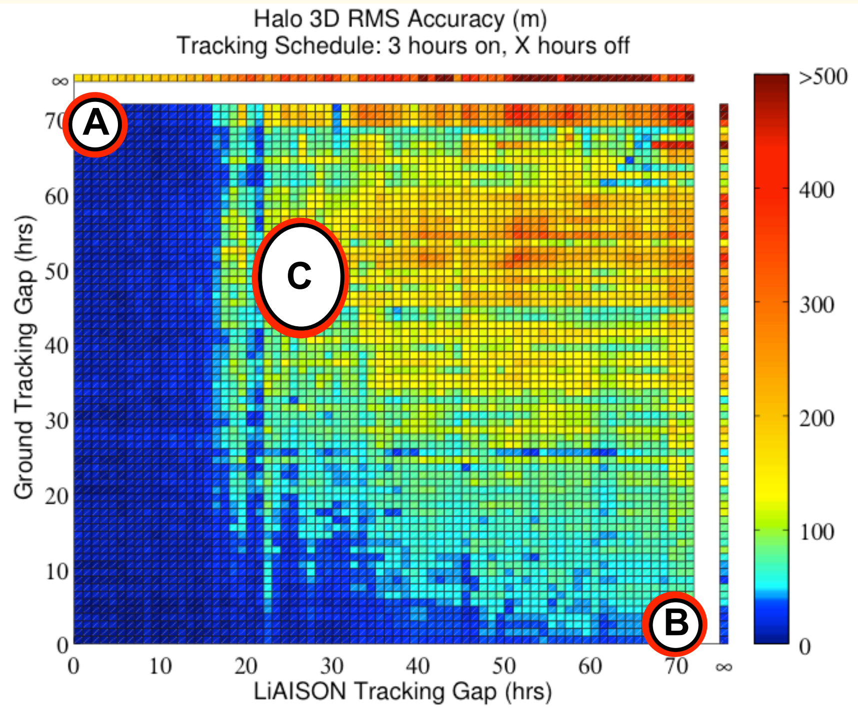


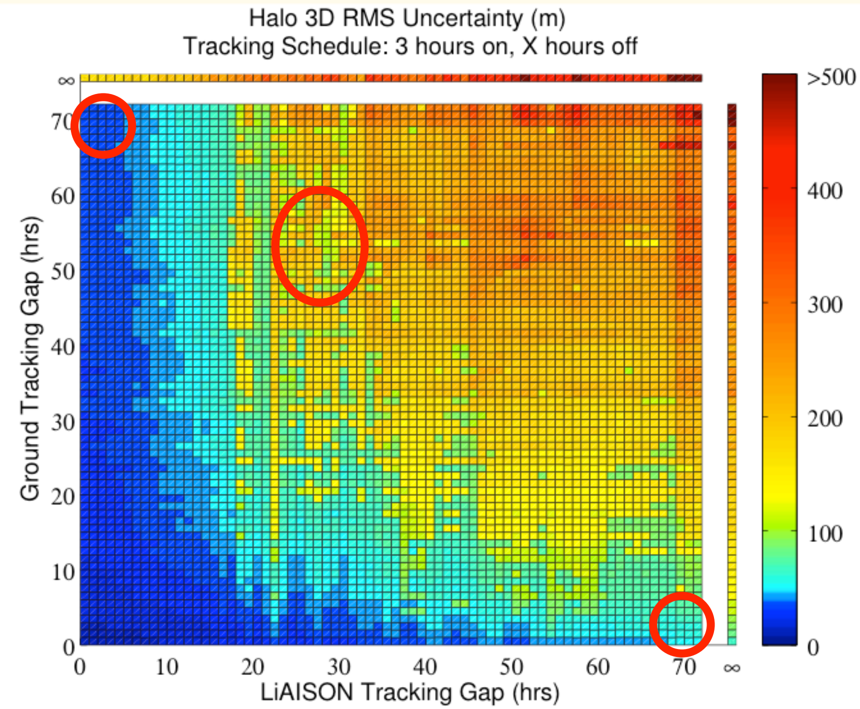
Cheaper GEO nav:
1 ground track every 2-3 days,
1 LiAISON track every 1-2 days:
~30 meter uncertainty
Fewer ground tracks, better accuracy!

Ground-only GEO nav:
Near-continuous ground observations with little (or no) LiAISON:
>150 meter uncertainty w/o LiAISON
~25 meter uncertainty w/ LiASION

L_1 Results

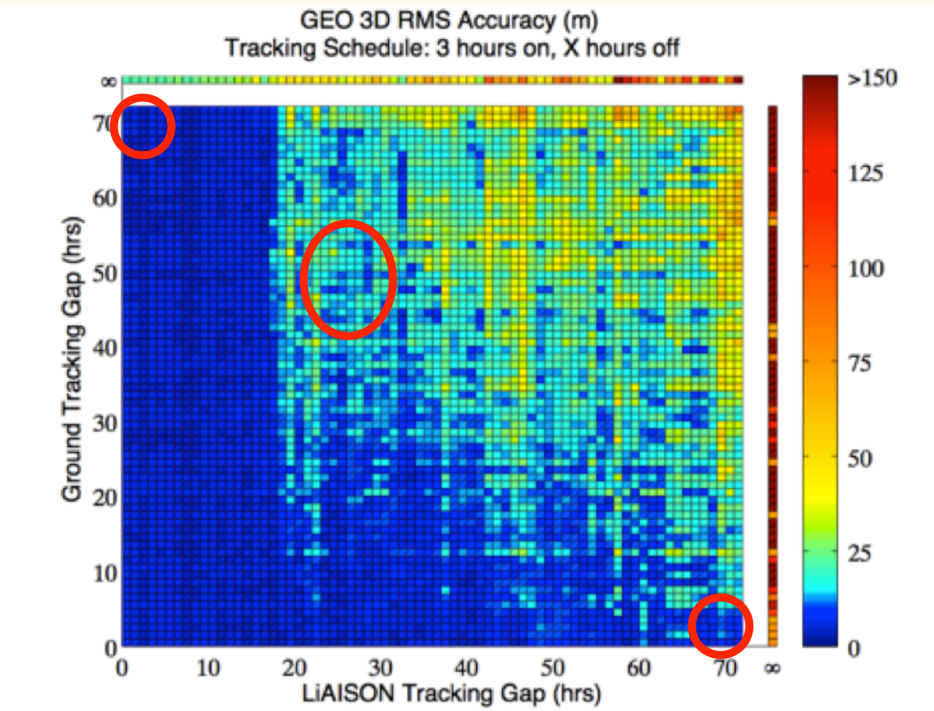
- L_1 3D RMS position accuracies (left) and uncertainties (right).
- Tracking schedule ranges from continuous, to 72 hour tracking gaps.
- Infinity corresponds to LiAISON or ground tracking only (no mixed schedule).
- Continuous ground tracking only gives an estimate with an uncertainty of 70 meters.
- Continuous LiAISON tracking only gives an estimate with an uncertainty of 150 meters.

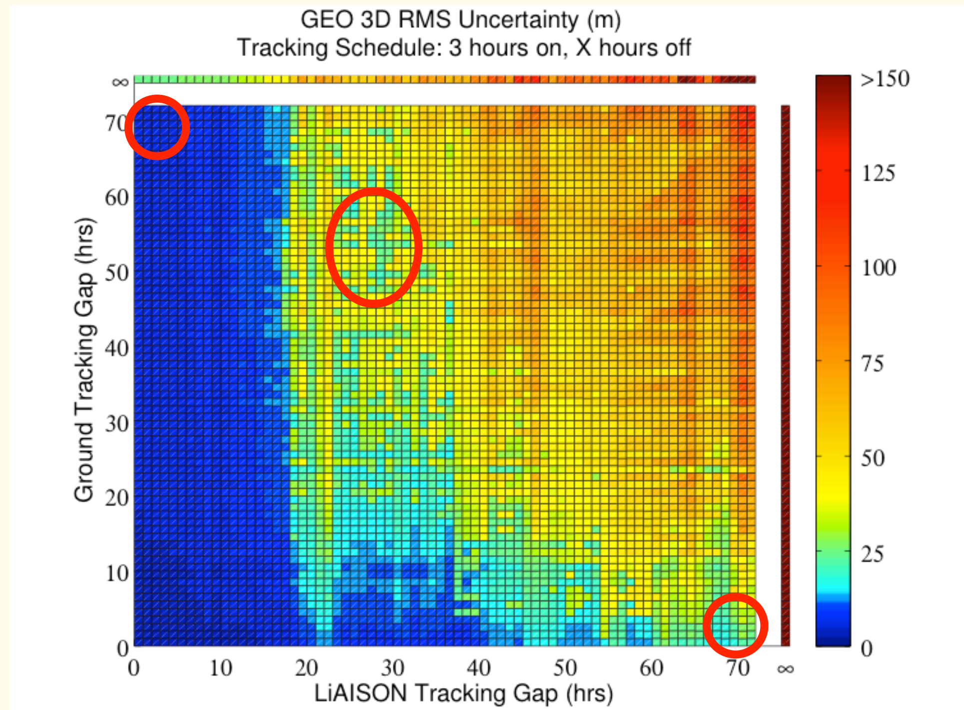




GEO Results

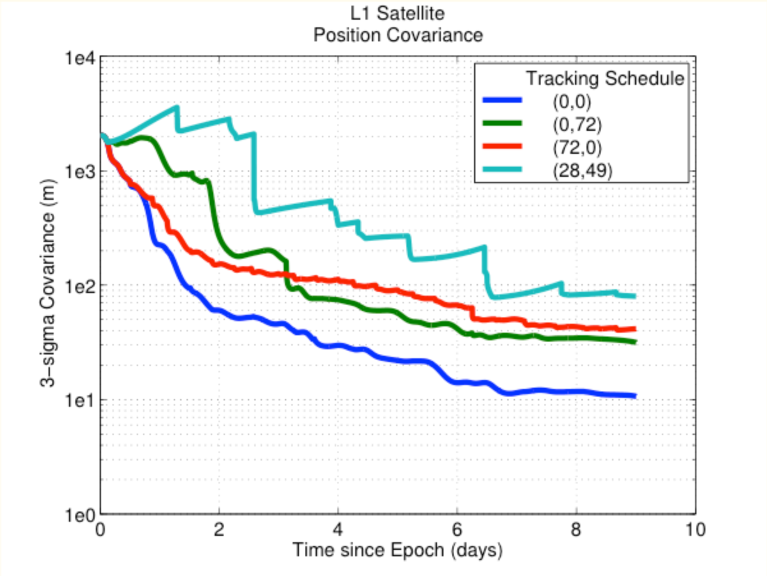
- GEO 3D RMS position accuracies (left) and uncertainties (right).
- Tracking schedule ranges from continuous, to 72 hour tracking gaps.
- Infinity corresponds to LiAISON or ground tracking only (no mixed schedule).
- Continuous ground tracking only gives an estimate with an uncertainty greater than 150 meters.
- Continuous LiAISON tracking only gives an estimate with an uncertainty of 30 meters.

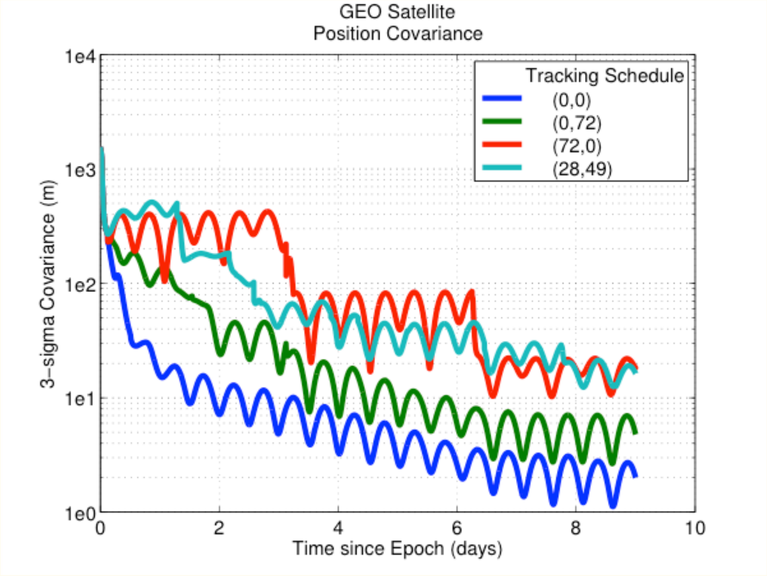




Tracking Schedule Analysis

- Trade study was analyzed for four different tracking schedules.
  - Continuous (0,0)
  - Sparse LiAISON (72,0)
  - Sparse ground (0,72)
  - Mixed Tracking (28,49)



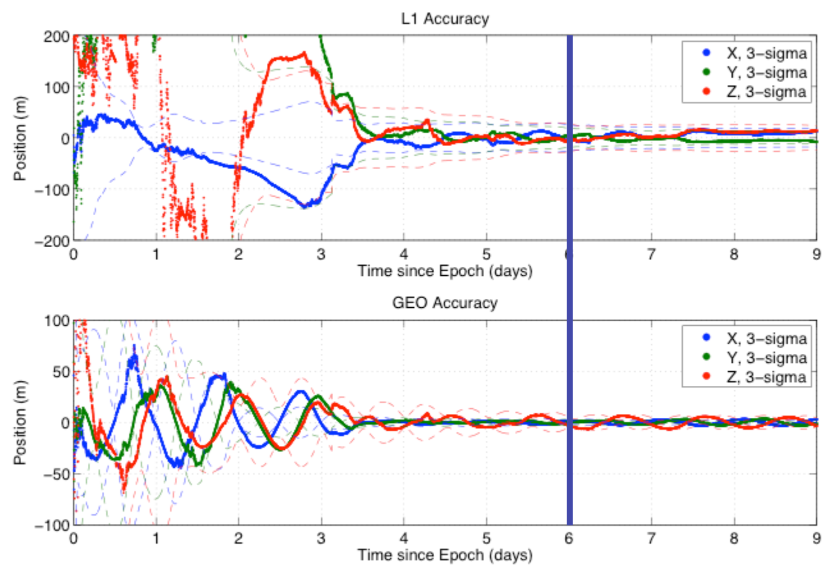


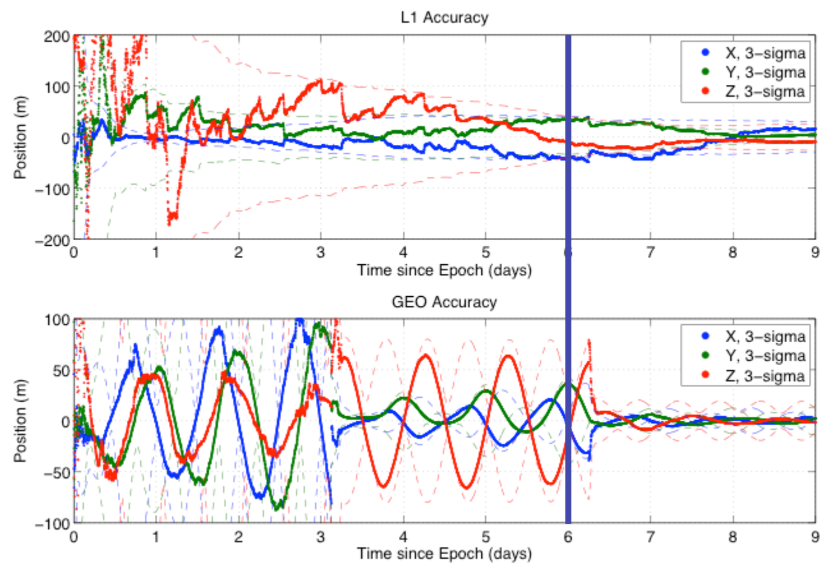
- **Continuous tracking (0,0) of both data types is the best solution.**
- **Mixed schedule (28,49) gives about the same uncertainty after 6 days as continuous ground with sparse LiAISON (72,0).**

(A) LiAISON vs. (B) Ground Trade

(A) Continuous LiAISON schedule with some ground: 3 hours on, 72 hours off

(B) Continuous Ground schedule with some LiAISON: 3 hours on, 72 hours off





L1 Satellite: 13.52 m ± 35.03 m (3σ)

GEO Satellite: 4.96 m ± 5.65 m

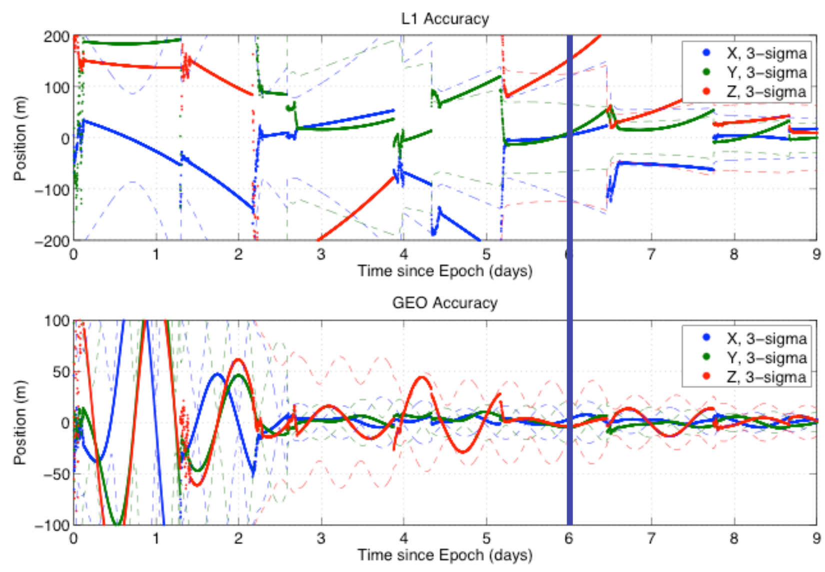
L1 Satellite: 35.01 m ± 47.17 m

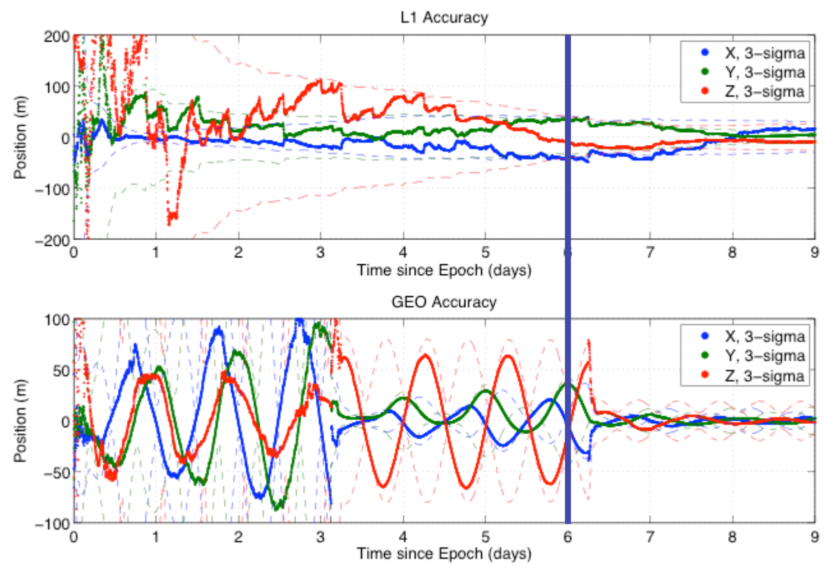
GEO Satellite: 17.11 m ± 26.40 m

(C) Mixed vs. (B) Ground Trade

(C) Mixed schedule. LiAISON: 3 hours on, 28 hours off. Ground: 3 hours on, 49 hours off.

(B) Continuous Ground schedule with some LiAISON: 3 hours on, 72 hours off





L1 Satellite: 66.98 m ± 88.89 m

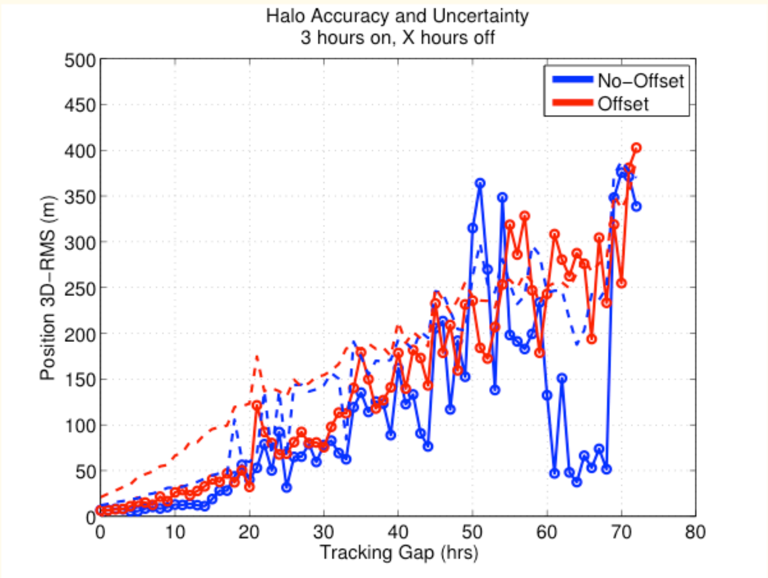
GEO Satellite: 8.09 m ± 19.13 m

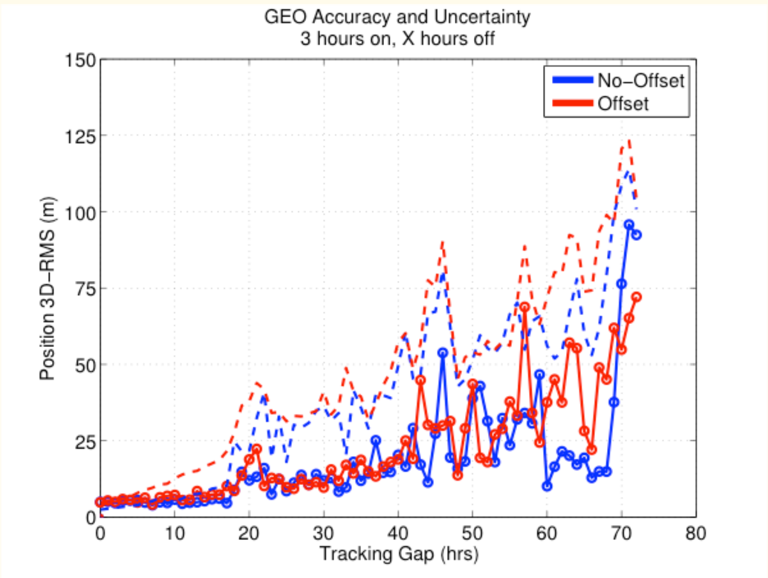
L1 Satellite: 35.01 m ± 47.17 m

GEO Satellite: 17.11 m ± 26.40 m

Measurement Offset Analysis

- Investigating the diagonal of the Trade Study for measurement offset sensitivity.





- **No-offset has less uncertainty when Tracking Gap < 22 hours**
- **Resonance at 22 hours is seen in both GEO and Halo uncertainties due to observation geometry.**

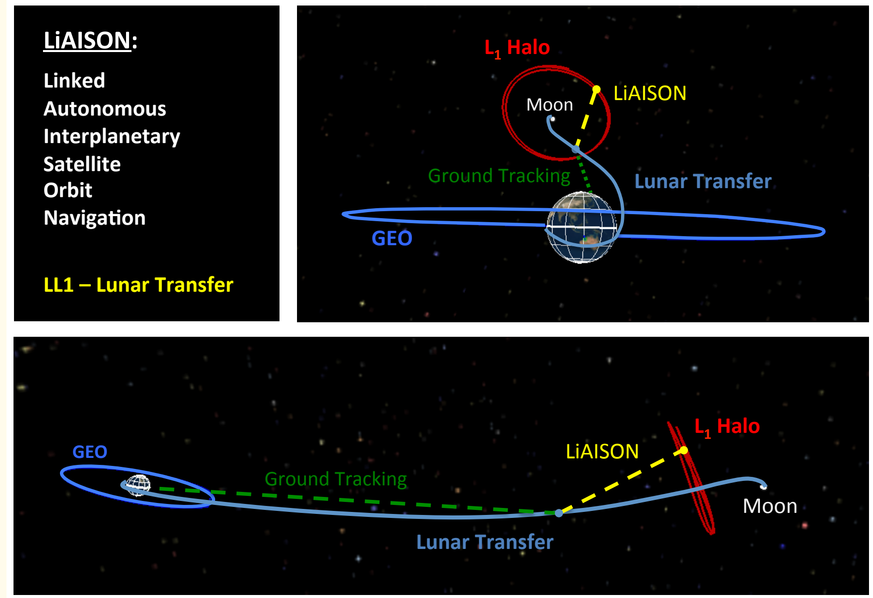
- **No-offset approaches Offset uncertainty for Tracking Gaps > 22 hours**
- **Offset analysis for Tracking Gaps > 22 hours has little effect on the accuracy and uncertainty.**

Trade Study Summary

- Relative and absolute positioning of the L_1 and GEO satellite is possible using only LiAISON.
- LiAISON is a valuable measurement type to improve radiometric measurements from DSN.
- High fidelity simulations and filter show that supplementing radiometric DSN with LiAISON can improve the solution greatly.
- There exists regions of mixed tracking that produces the same uncertainties as continuous tracking.
- We've shown that you can reduce the number of ground tracks *tremendously* and achieve even better navigation accuracy by using LiAISON.
- A simple measurement offset analysis showed that for large tracking gaps one could expect the same filter performance.
- However, for tracking gaps of less than a day, a no-offset in the measurement

LiAISON Support of Crewed Lunar Exploration

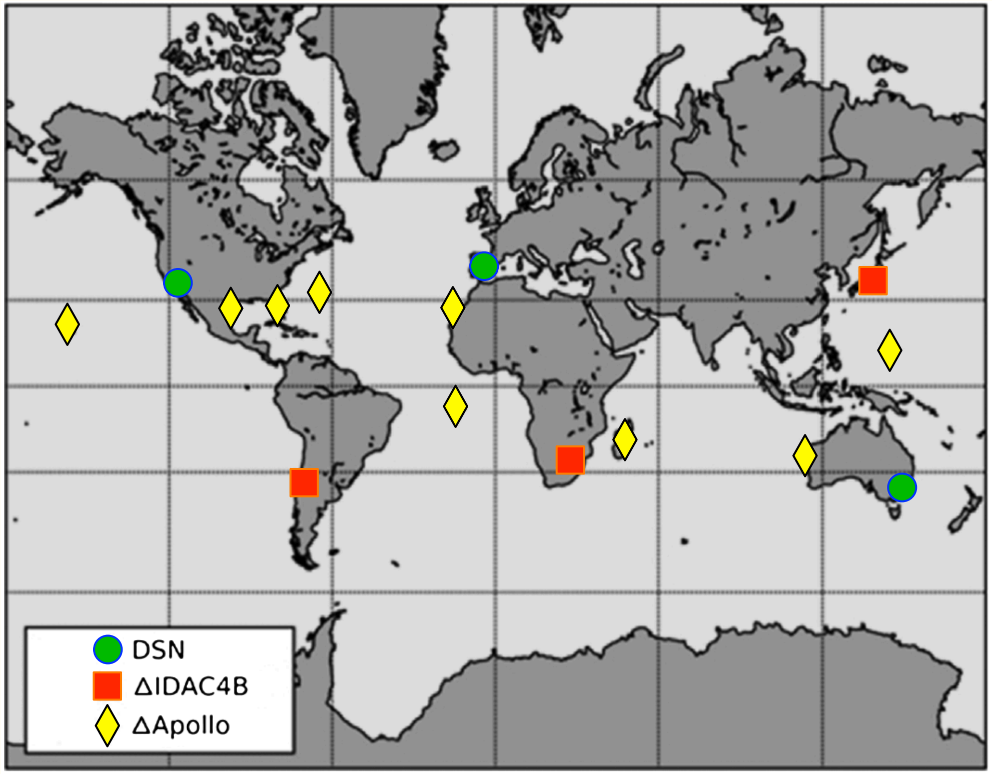
- Crewed vehicles such as Apollo, Orion, and Altair include significant effects of FLAK
- Un**f**ortunate **L**ack of **A**cceleration **K**nowledge
- FLAK includes several components:
  - Wastewater dumps
  - Momentum desaturations
  - Attitude control burns
  - CO_2 venting
  - Thermal venting, water sublimation



- **FLAK is more significant during “Active” periods when the crew is awake.**
- **Thermal control via water sublimation may not be required except when docked to ISS or L_2 Habitat.**

Ground-based Tracking Networks

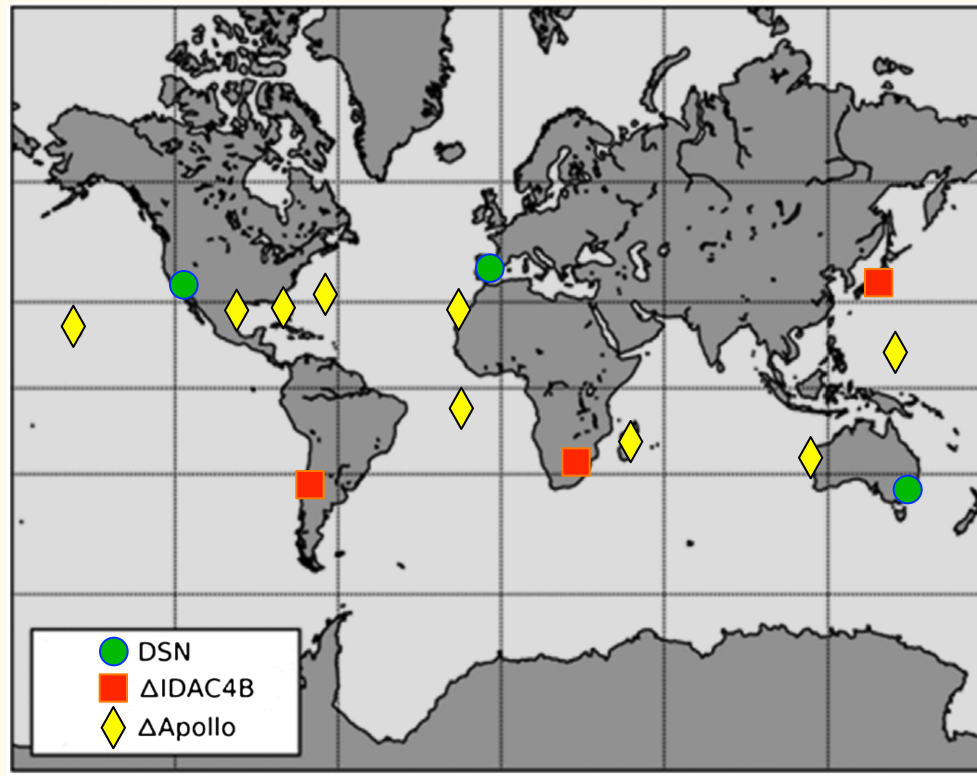
- The Deep Space Network includes 3 ground stations (●):
  - Goldstone, California
  - Madrid, Spain
  - Canberra, Australia
- Apollo's "Manned Space Flight Network" included 12 ground stations located on land and in the sea (● + ◆).
- A proposed "IDAC4B" network includes the 3 DSN sites plus 3 complementary sites (● + ■).
  - Notice the N-S symmetry



LiAISON's Benefits

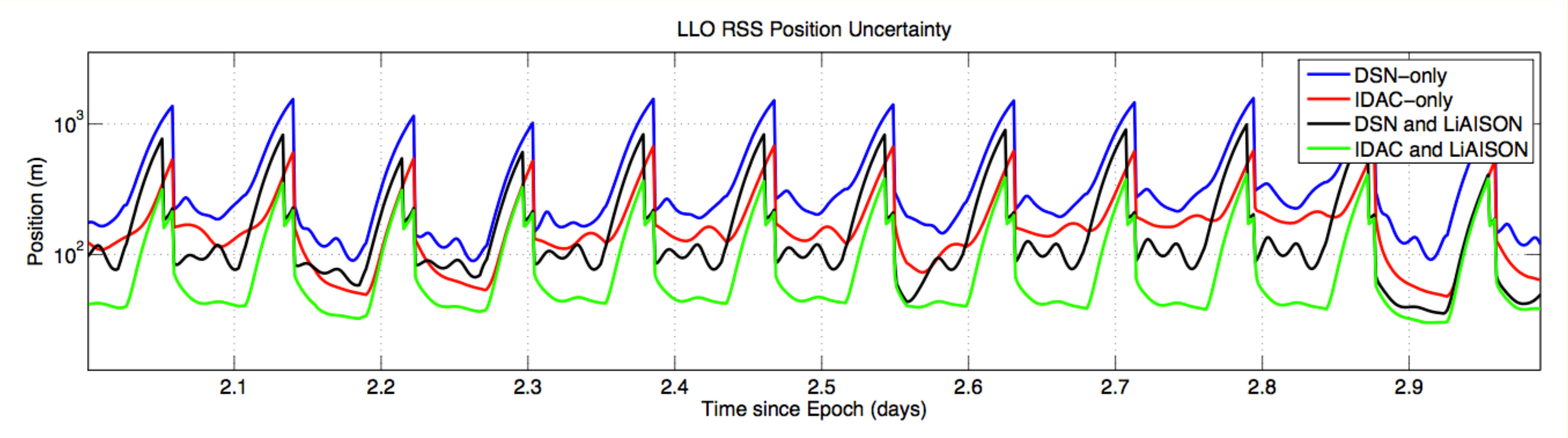
- LiAISON supplements ground-based tracking
- If Orion can be navigated with the (+) stations and nothing else, LiAISON may make it possible to just use the DSN () stations.
- Fewer ground stations reduces the cost.

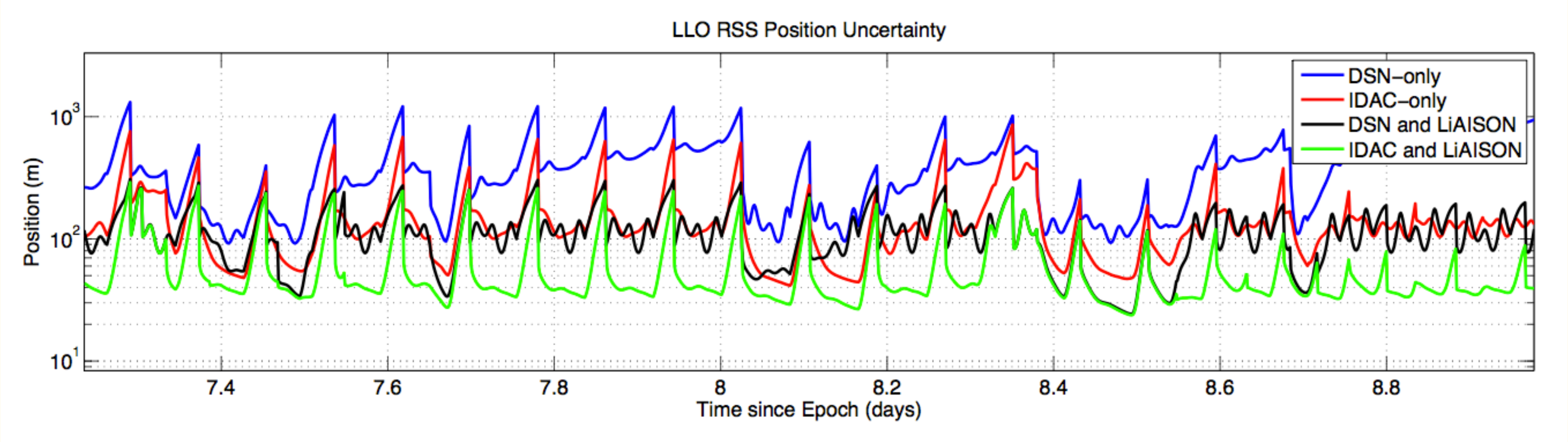
- Completed Studies:
  - LiAISON-only
  - DSN + LiAISON
  - IDAC4B + LiAISON
  - Lunar Transfer, L_2 orbit, and Low Lunar Orbit



LiAISON-supplemented nav

- Comparison of each configuration





FLAK Study Summary

- The IDAC ground network achieves navigation uncertainty that peaks around 1000 meters.
  - Involves 6 ground stations, tracking non-stop
- LiAISON may be used to *replace 3 ground stations*.
  - LiAISON + 3 DSN sites performs the same as IDAC
- LiAISON + IDAC cuts the nav uncertainty in half or better.

Questions?