SUPPORTING CREWED LUNAR EXPLORATION WITH LIAISON NAVIGATION

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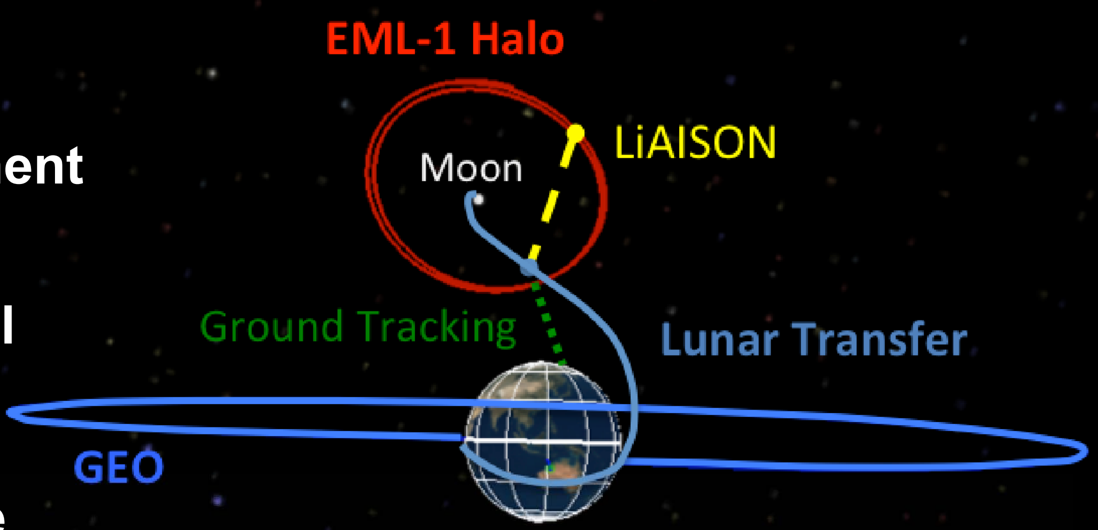
Outline

- LiAISON Navigation
- Mission Design
- Dynamic and Measurement Models Used
- Crew Disturbance Model
- Covariance Study
- Navigation Performance
  - Standard FLAK
  - Sensitivity to FLAK
- Conclusions



LiAISON Navigation: Introduction

LiAISON: ***Linked Autonomous Interplanetary Satellite Orbit Navigation***

- **Extends a GPS-like navigation capability to the Earth-Moon system**
- **A single navigation satellite at the Earth-Moon L_1 point tracks other satellites anywhere near the Earth and Moon.**
- **This research focuses on tracking crewed spacecraft, but works for any Earth / Moon orbits.**

***Costs*:**

- **Requires a navigation satellite, which may double as a communication relay if needed.**
- **The customer satellite may require additional communication hardware, like a GPS receiver.**

Objective:

- **Measure the benefit of LiAISON Navigation applied to future crewed missions to the Moon.**
- **Quantify the cost and accuracy of LiAISON compared to ground-only navigation.**
- **Determine how many ground stations may be removed and achieve the same navigation accuracy.**

***Benefits*:**

- **The L_1 location provides a huge geometrical advantage for navigation.**
- **Improves navigation accuracy.**
- **Reduces the number of DSN/ground tracking passes per mission.**
- **With ultra-stable clocks currently being demonstrated, one navigation satellite can track any number of customers – just like GPS.**

Mission Design

LiAISON:

Linked
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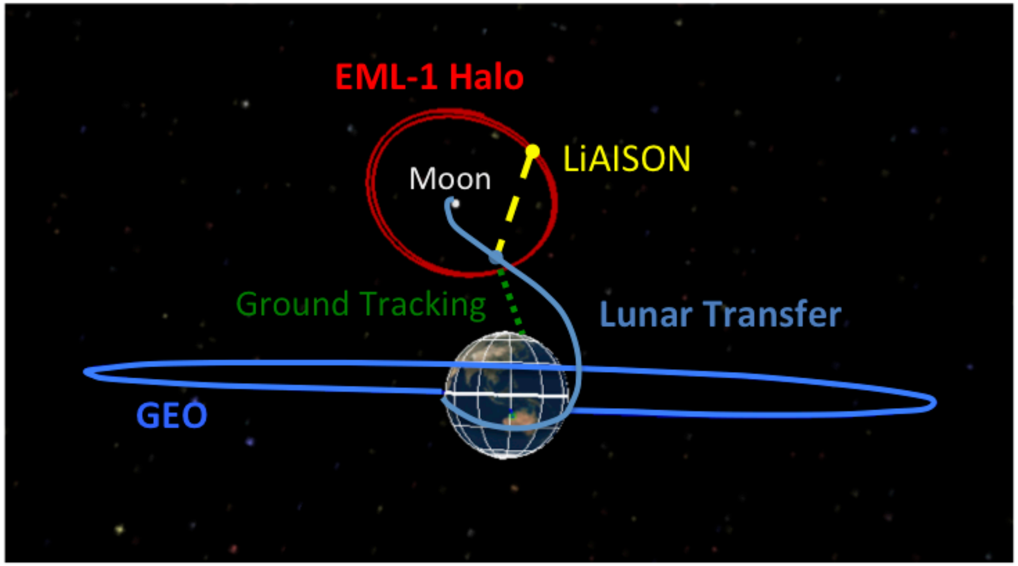
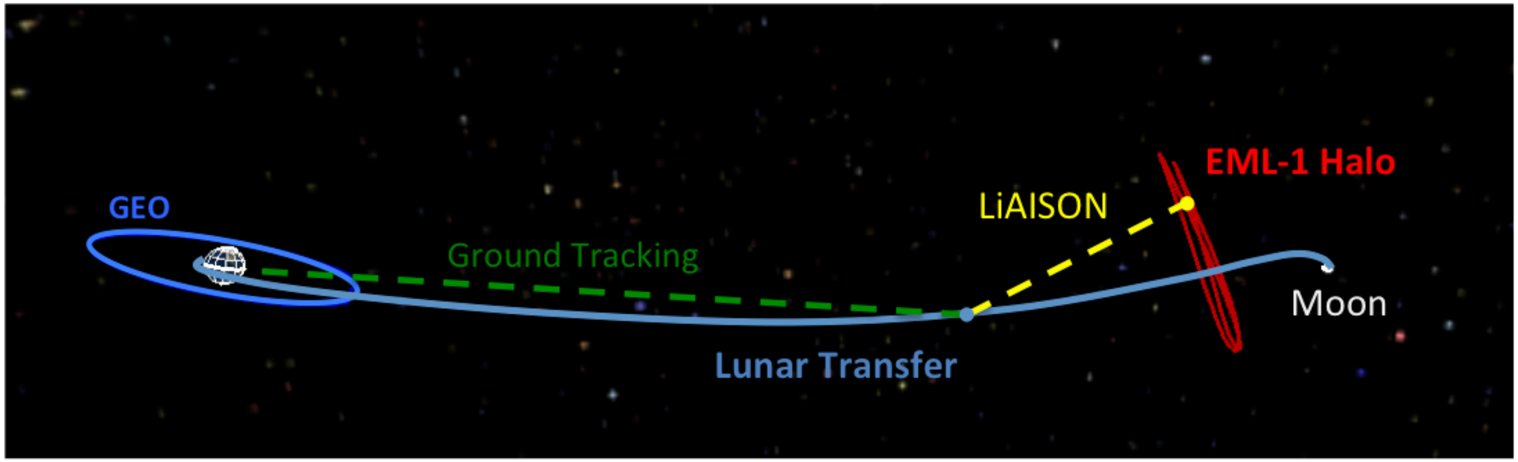
Satellite
Orbit
Navigation





Mission Design

Objectives: Track a crewed spacecraft on a TLC to the Moon via ground networks and a dedicated EML-1 navigation satellite.

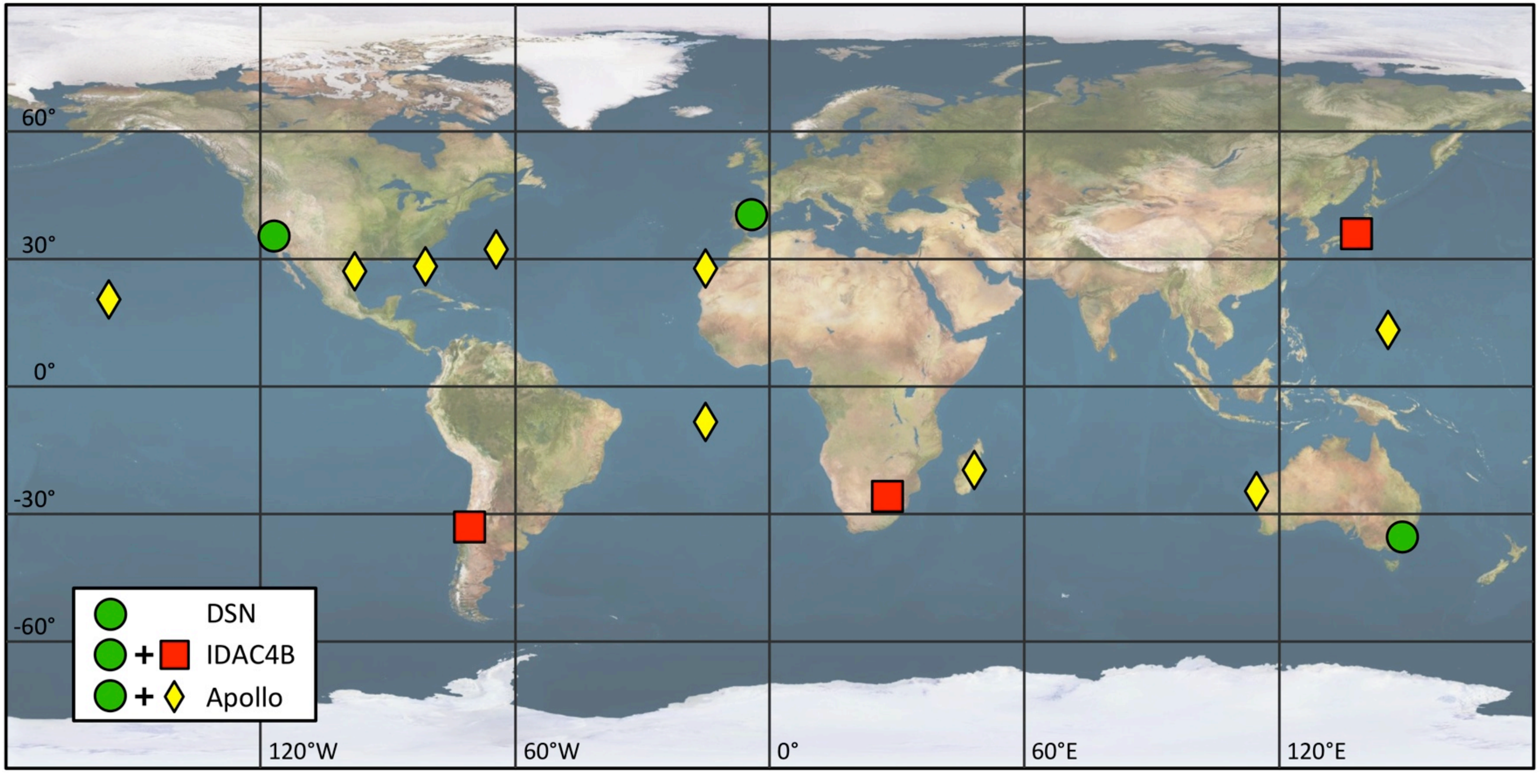
Compare navigation uncertainties for a variety of tracking scenarios

- EML-1 Navigation Satellite

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

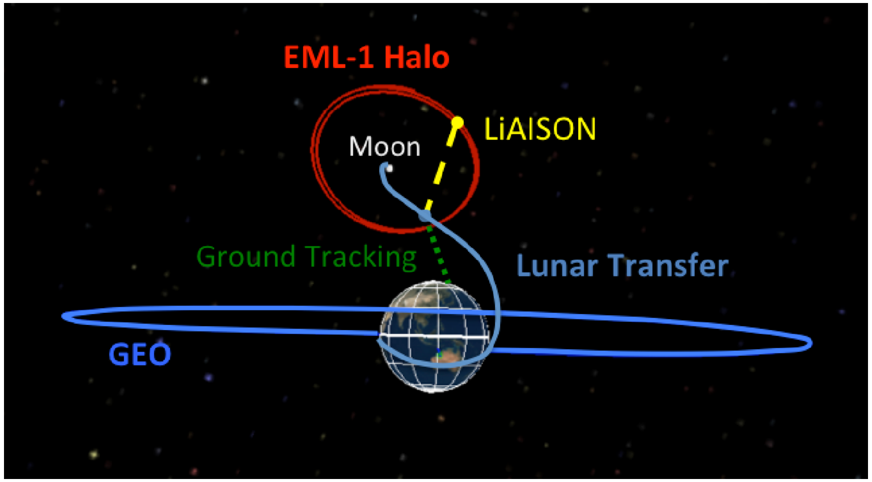
- Trans-lunar Cruise
  - Parking orbit: 185 km Altitude, 28.5 deg inclination
  - Inject into TLC on 1/14/2020 00:00:00 ET
  - Lunar flyby on 1/17/2020 16:28:1.9163 ET

Ground Tracking Network



- Apollo needed 12 land- and sea-based tracking stations for reasonable nav.
- The 3 DSN stations alone do not provide desired nav. uncertainty for future crewed missions.
- A 6 station IDAC4B configuration was proposed and analyzed.
  - Will provide desired nav. uncertainty

Dynamic Models



- State Vector

$$\mathbf{X} = \begin{bmatrix} \mathbf{r}_1^{\mathrm{T}} & \mathbf{v}_1^{\mathrm{T}} & \mathbf{r}_2^{\mathrm{T}} & \mathbf{v}_2^{\mathrm{T}} & C_{R,1} & C_{R,2} \end{bmatrix}^{\mathrm{T}}$$

- Reference Frame
  - Geocentric Celestial Reference Frame (GCRF) with 1976 IAU Precession and 1980 IAU Nutation with no corrections.
- Gravity Models
  - Two-Body
  - Nonspherical Body
    (20x20 GGM02C for Earth)
    (20x20 LP150Q for Moon)
- Planetary Ephemeris
  - JPL DE405
- N-Body
  - All planets
- Solar radiation pressure
  - A/m = 0.01 m^2/kg

$$\begin{bmatrix} \dot{\mathbf{r}}_i \\ \ddot{\mathbf{r}}_i \end{bmatrix} = \begin{bmatrix} \mathbf{v}_i \\ \mathbf{a}_{2-body}(t, \mathbf{r}_i) + \mathbf{a}_{nonspherical}(t, \mathbf{r}_i) + \mathbf{a}_{n\text{-}body}(\mathbf{r}_i, \mathbf{r}_{\oplus 3}) + \mathbf{a}_{SRP}(t, \mathbf{r}_i) \end{bmatrix}$$

Measurement Models

- Simplified measurement models for range and range-rate.
- No light time 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 crewed TLC and EML-1 halo orbiter:
  - Goldstone, California
  - Madrid, Spain
  - Canberra, Australia
- IDAC4B stations used to track crewed TLC:
  - Santiago Chile
  - Hartebeesthoek, South Africa
  - Usuda, Japan

Crew Disturbance Model

- Crewed missions typically experience significant nongravitational disturbances.
  - Wastewater dumps
  - Momentum desaturation maneuvers
  - Attitude control burns
  - CO_2 venting
  - Thermal venting
  - Water sublimation
- During Apollo these were described as FLAK
  - Un**f**ortunate **L**ack of **A**cceleration **K**nowledge
- Apollo experienced 500 m position uncertainty dispersion over the course of 1 hour due to these disturbances.

Crew Disturbance Model

- Apollo disturbance levels will be used as a baseline.
- **Assumption**: stochastic acceleration process creates a spherical position dispersion of 500 m (1-σ) every hour.
- Discrete white noise acceleration process:

$$\begin{bmatrix} x_{k+1} \\ v_{k+1} \\ a_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & \Delta t & \Delta t^2/2 \\ 0 & 1 & \Delta t \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_k \\ v_k \\ a_k \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u_k$$

- Uncertainty over time can be approximated as

$$\mathbf{P}_k \approx q \begin{bmatrix} \frac{n^3}{3}\Delta t^4 & \frac{n^2}{2}\Delta t^3 \\ \frac{n^2}{2}\Delta t^3 & n\Delta t^2 \end{bmatrix}$$

- FLAK strength for a Δ*t* of 100 s is $\sqrt{q} = 2.3148e\text{-}7 \ \ \mathrm{km/s}^2$
- This FLAK strength is for active periods when the crew is awake and is reduced an order of magnitude for quiet periods.

Cramér-Rao Lower Bound

- Cramér-Rao Lower Bound gives the limit on the best possible performance of any nonlinear system.
- Truth trajectory must be known.
- The estimation error covariance is determined by

$$\mathbf{P}_k \geq \mathbf{P}_k^* \equiv \mathbf{J}_k^{-1}$$

- Extended Kalman filter equations linearized about the truth trajectory give the CRLB.
- Commonly used as an observability and covariance study method.
- CRLB can be computed recursively by

$$\begin{aligned}\mathbf{J}_k &= Q_{k-1}^{-1} + \tilde{H}_k^{\mathrm{T}} \mathbf{R}_k^{-1} \tilde{H}_k \\ &\quad - Q_{k-1}^{-1} \mathbf{\Phi}(t_k, t_{k-1}) \left(\mathbf{J}_{k-1} + \mathbf{\Phi}(t_k, t_{k-1}) Q_{k-1}^{-1} \mathbf{\Phi}(t_k, t_{k-1})^{\mathrm{T}} \right)^{-1} \mathbf{\Phi}(t_k, t_{k-1})^{\mathrm{T}} Q_{k-1}^{-1}\end{aligned}$$

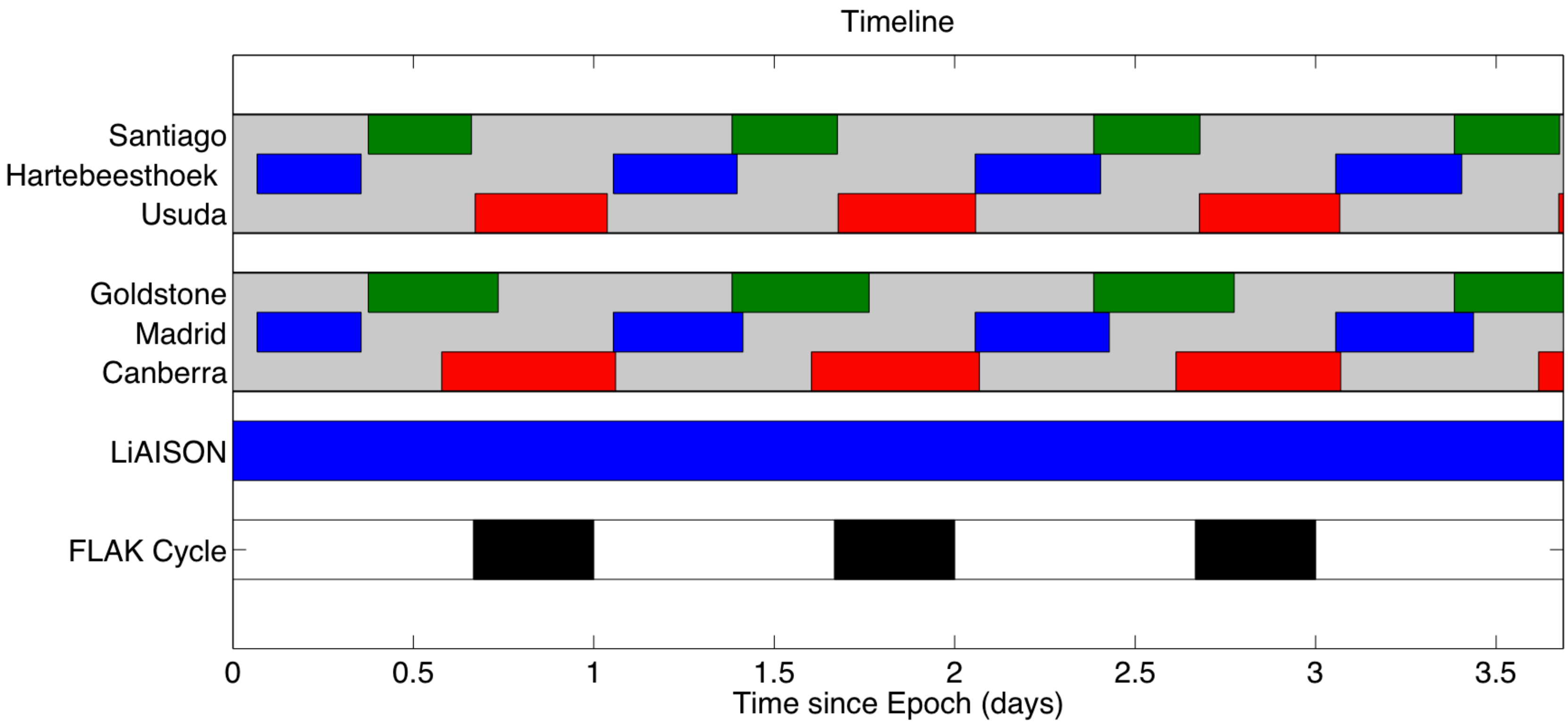
TLC Navigation Performance

Initial navigation uncertainties

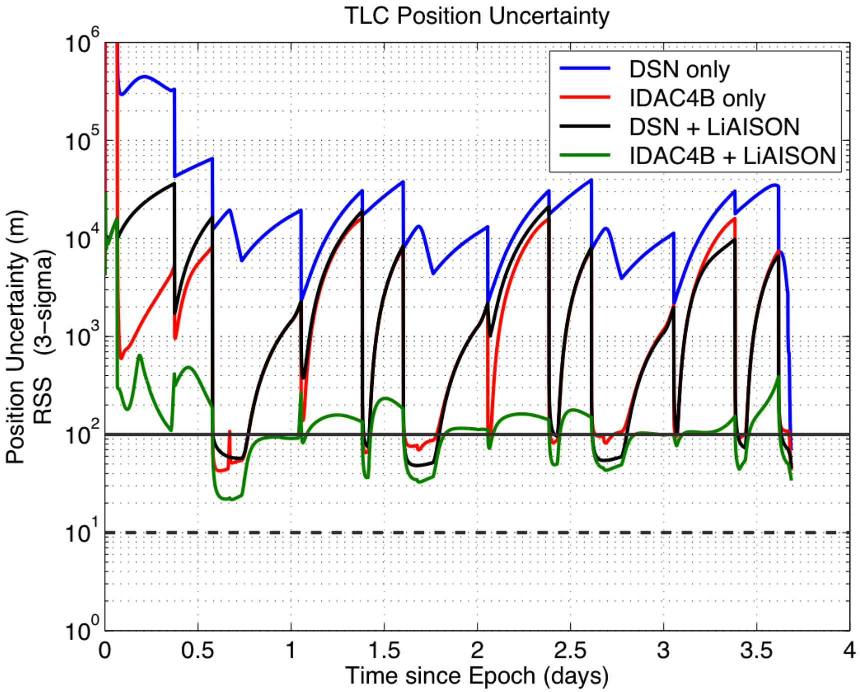
Estimation Parameters	*a priori* uncertainty (1- σ)	Number of Parameters
TLC spacecraft position	1,000 m	3
TLC spacecraft velocity	500 m/s	3
EML-1 spacecraft position	100 m	3
EML-1 spacecraft velocity	1 m/s	3
SRP Coefficient	5%	2
Active FLAK	2.3148e-7 km/s^2	–
Quiet FLAK	2.3148e-8 km/s^2	–
LiAISON measurements		
range	1 m	–
range-rate	1 mm/s	–
Ground measurements		
range	2 m	–
range-rate	0.5 mm/s	–

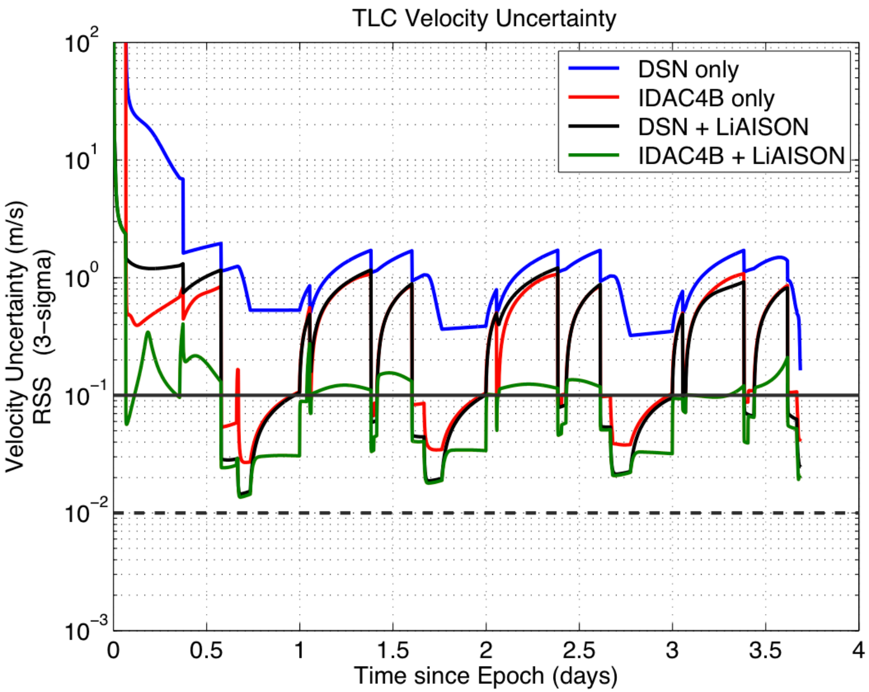
TLC Navigation Performance

Tracking Schedule



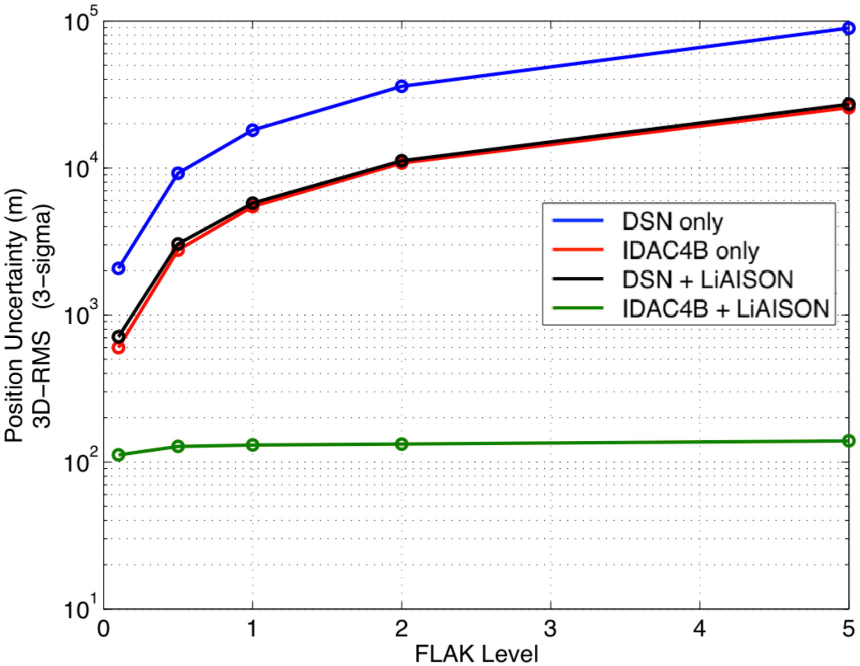
Standard FLAK

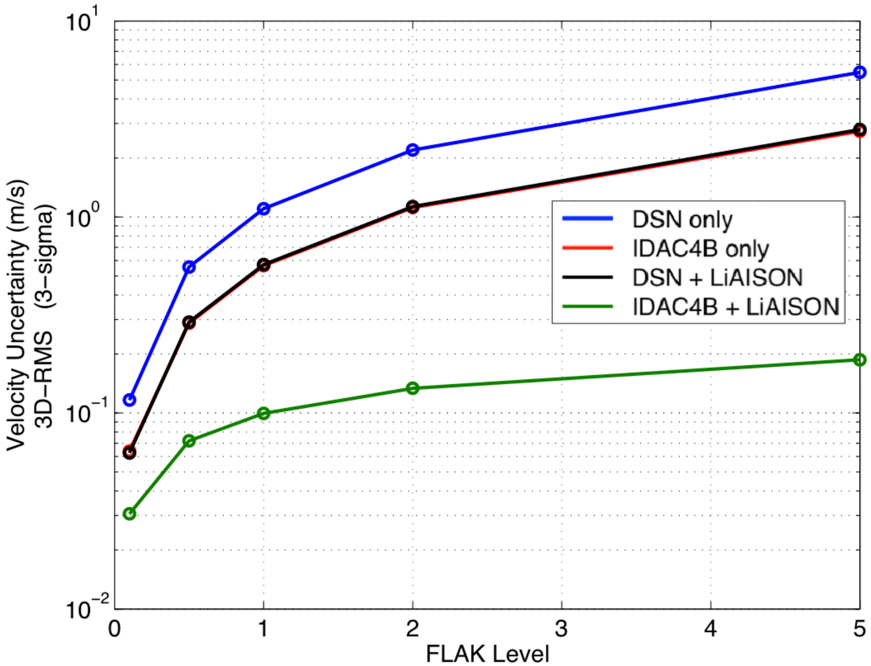




Architecture	3D-RMS Position Uncertainty (m)	3D-RMS Velocity Uncertainty (m/s)
DSN only	18,113.7	1.1028
IDAC4B only	5,467.3	0.5645
DSN + LiAISON	5,772.0	0.5713
IDAC4B + LiAISON	130.4	0.0996

Sensitivity to FLAK





- Most sensitive to FLAK levels
  - DSN only
  - IDAC4B only
  - DSN and LiAISON

- Least sensitive to FLAK levels
  - IDAC4B and LiAISON

- Velocity is more sensitive to FLAK levels than position

Summary

- A crewed trans-lunar cruise mission was designed.
- An acceleration uncertain model based on historical Apollo data was derived.
- Benefits of crewed navigation were analyzed for both ground tracking and LiAISON tracking.
- Four tracking architectures were examined.
- Best navigation uncertainty was achieved using the IDAC4B with LiAISON.
- Worst navigation uncertainty was achieved with DSN only.
- DSN with LiAISON performed the same as the IDAC4B network.
- IDAC4B with LiAISON was the least sensitive to FLAK levels.

Thank You

Questions?

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