Navigating a Crewed Lunar Vehicle Using LiAISON

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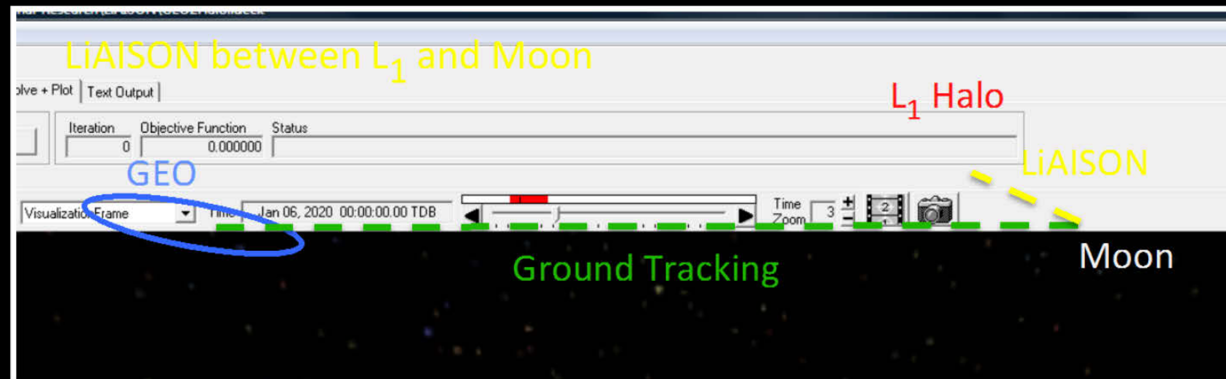
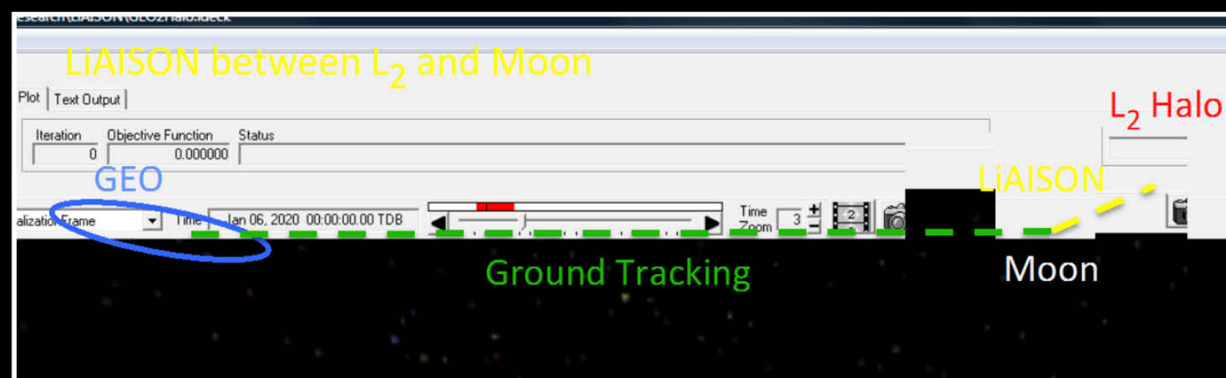
Navigating this Presentation

- Motivation
- Proposed Crewed Mission to the Moon
- Crew Disturbance Model (FLAK)
- **L**inked **A**utonomous **I**nterplanetary **S**atellite **O**rbit **N**avigation (LiAISON)
- Navigation Trade Studies
- Conclusions





Motivation

- Proposals to send humans to an orbit about the Earth-Moon L_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.

Motivation

- Proposals to send humans to an orbit about the Earth-Moon L_2 point.
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  - 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 → direct comparison with Apollo data.
  - Study the costs and benefits of SST in that environment.
  - Apply lessons to L_2 mission.

Apollo Flight Experience

- 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

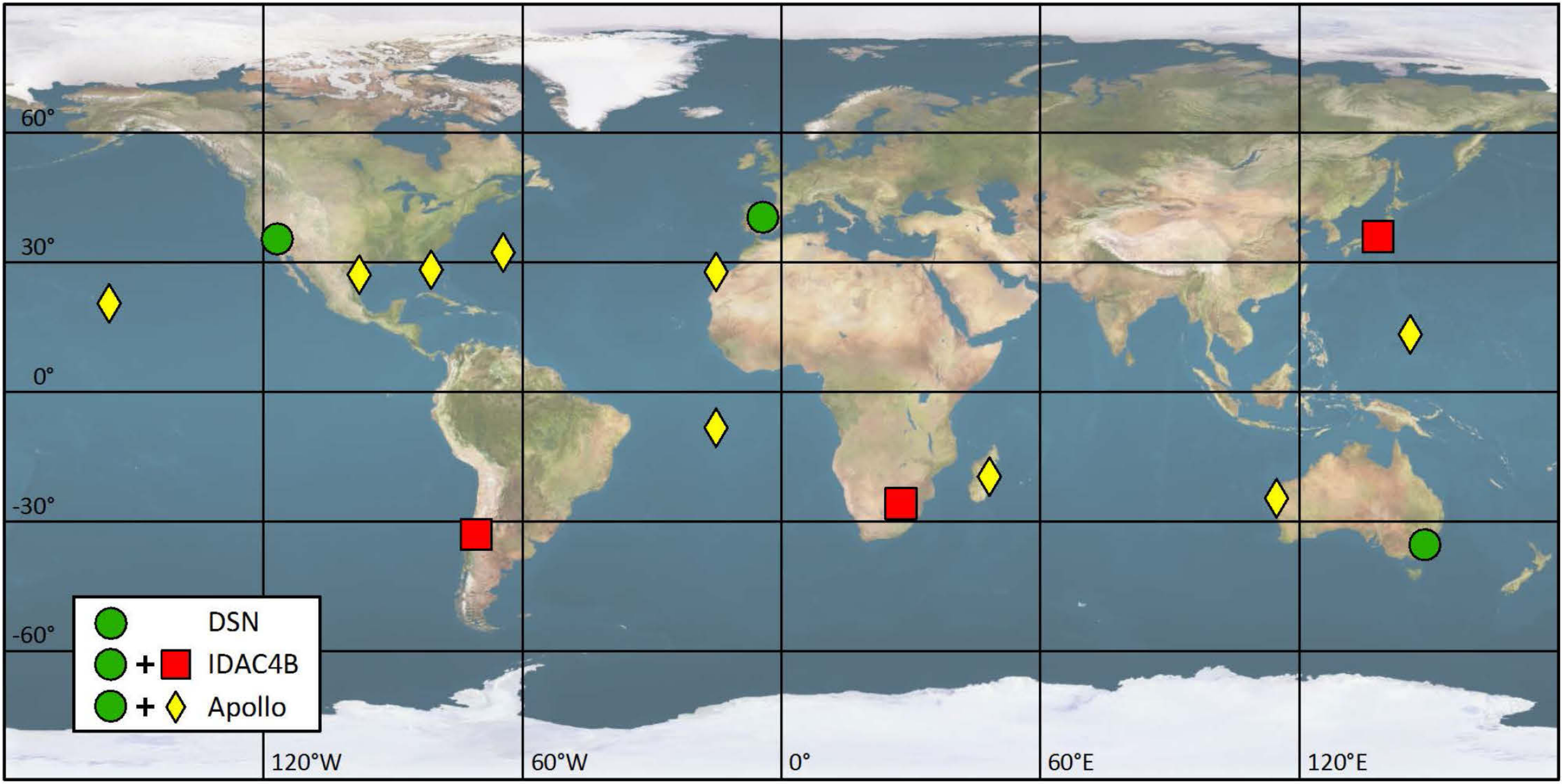
- These disturbances have become known as FLAK (un**f**ortunate **L**ack of **A**cceleration **K**nowledge)

- The Apollo lunar spacecraft experienced position uncertainty growth of about 500 meters in an hour while in low lunar orbit.

Modeling FLAK

- 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.

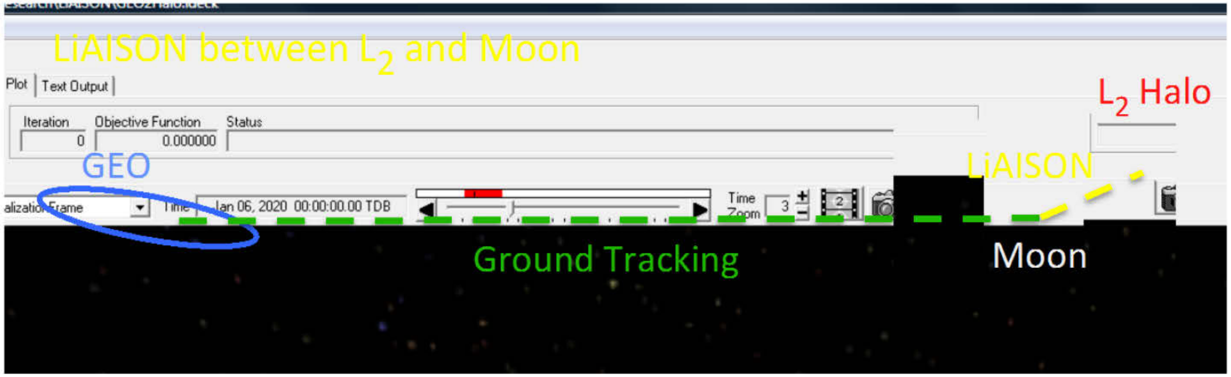
Ground Networks



IDAC4B = Integrated Design and Analysis Cycle 4B

Satellite-to-Satellite Tracking

- Linked, Autonomous, Interplanetary Satellite Orbit Navigation (LiAISON)



- Uses scalar satellite-to-satellite tracking (SST)
  - Range, Doppler
- Navigation satellite placed in orbit about L_1 or L_2.
  - 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:

Parameter	Value	Comments
t	1/1/2020 00:00:00 ET	The epoch, ephemeris time
h	100 km	Altitude, relative to mean lunar radius of 1737.4 km
i	90°	Inclination, relative to IAU Moon Fixed coordinate frame
Ω	30°	Longitude of Ascending Node in IAU Moon Fixed frame

- Navigation satellite placed in either an L_1 or L_2 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

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

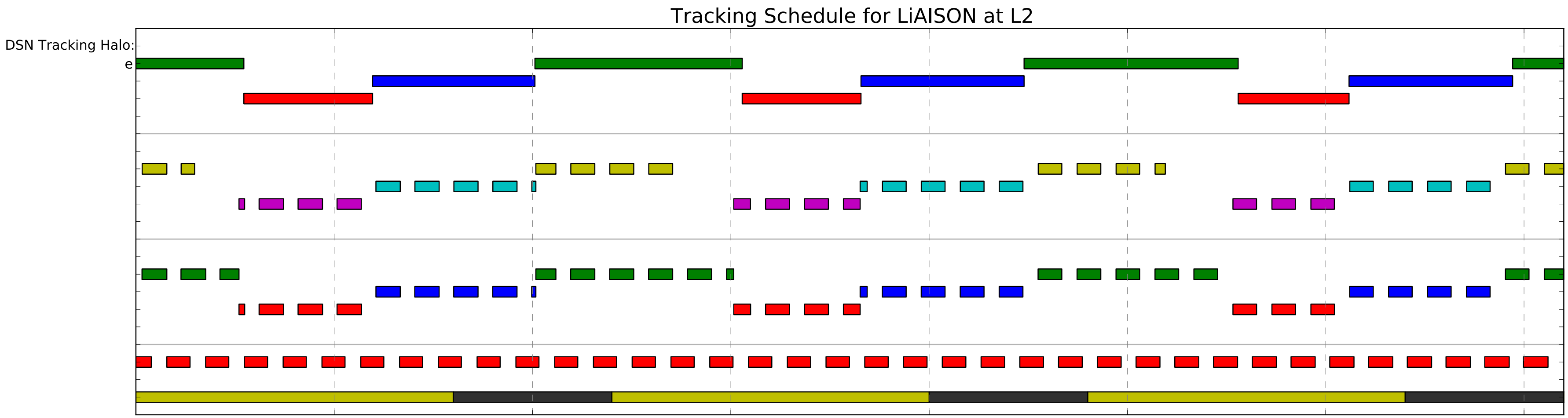
Tracking Architectures

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 placed in either:
  - L1 orbit
  - L2 orbit
- Lunar navigation satellite tracked by either of 2 options:
  - LiAISON
  - DSN + LiAISON
- Tracking data types: 3 options:
  - Range
  - Doppler
  - Range + Doppler

Tracking Schedules

- Tracking schedule:



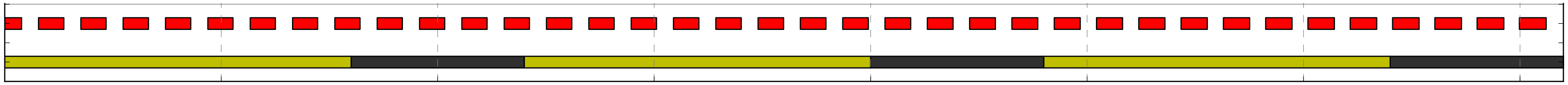
Tracking Schedules

- FLAK:
  - Day cycle: 16 hours / day: full FLAK
  - Night cycle: 8 hours / day: 10% FLAK

Tracking Schedules

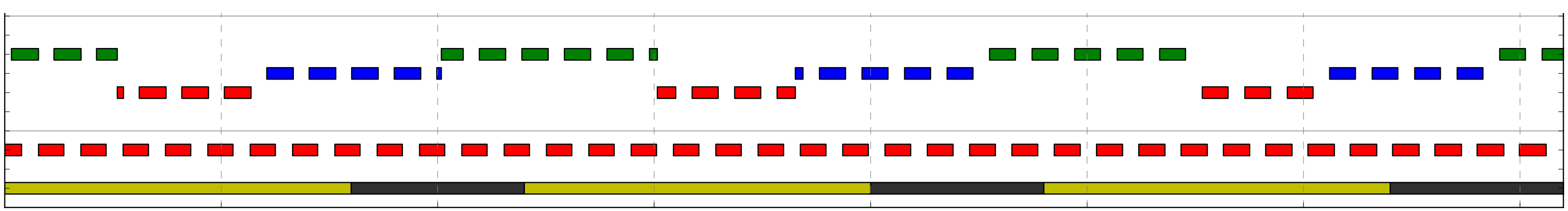
- LiAISON
  - 24/7 tracking
  - Occultations

  - Note: from L_1, LiAISON occurs on the near side of the Moon; from L_2, LiAISON occurs on the far side.



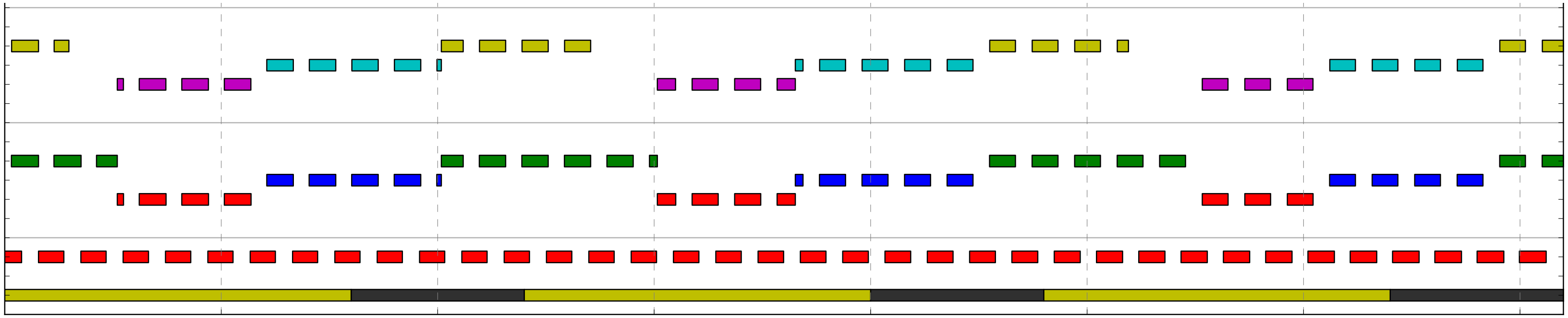
Tracking Schedules

- 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



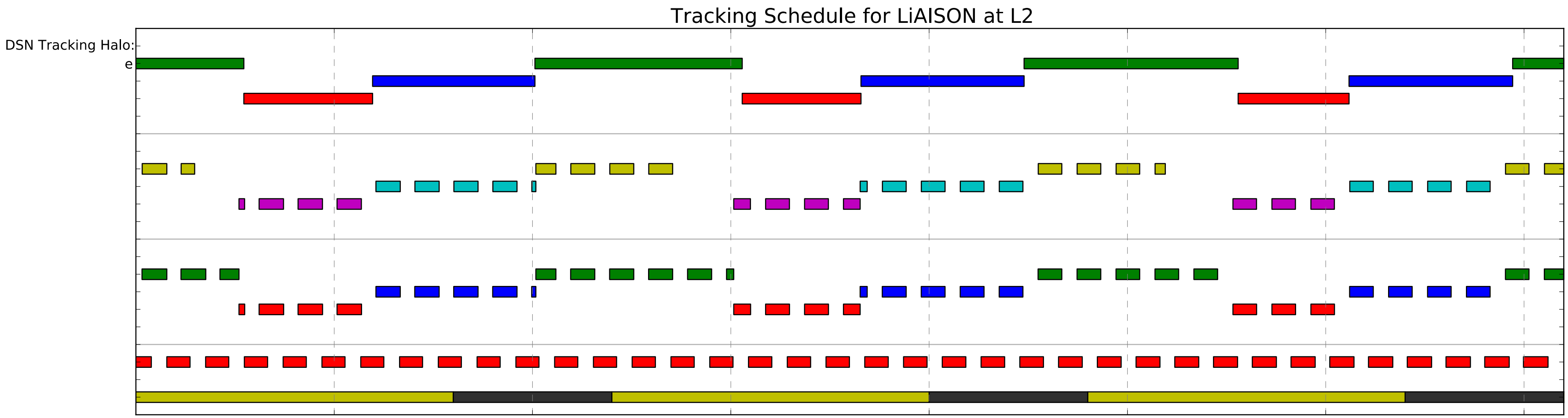
Tracking Schedules

- 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



Tracking Schedules

- 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

$$\rho_{12} = \sqrt{(\mathbf{r}_1 - \mathbf{r}_2) \cdot (\mathbf{r}_1 - \mathbf{r}_2)} + \rho_{12}^{bias} + \rho_{12}^{noise}$$

$$\dot{\rho}_{12} = \frac{(\mathbf{r}_1 - \mathbf{r}_2) \cdot (\dot{\mathbf{r}}_1 - \dot{\mathbf{r}}_2)}{\rho_{12}} + \dot{\rho}_{12}^{bias} + \dot{\rho}_{12}^{noise}$$

- 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

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

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.

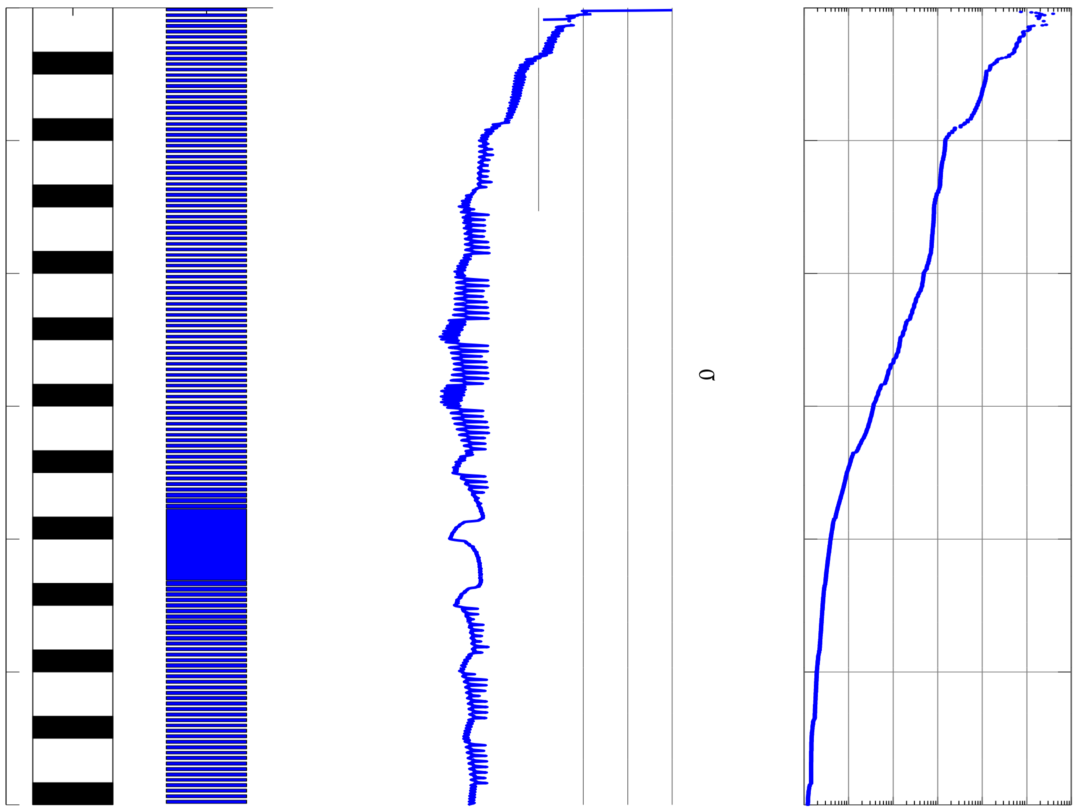
- Kalman Filter linearized about the truth trajectories
  - Cramér-Rao Lower Bound (CRLB)
  - Estimates the best a filter can do, i.e., the lower bound of the state uncertainty.

Simulation Details

State Parameter		*a priori* uncertainty 1-σ
Position of LPO	R_x^{LPO}	100 meters
	R_y^{LPO}	100 meters
	R_z^{LPO}	100 meters
Velocity of LPO	V_x^{LPO}	1 m/s
	V_y^{LPO}	1 m/s
	V_z^{LPO}	1 m/s
Position of Crewed LLO	R_x^{LLO}	10,000 meters
	R_y^{LLO}	10,000 meters
	R_z^{LLO}	10,000 meters
Velocity of Crewed LLO	V_x^{LLO}	10 m/s
	V_y^{LLO}	10 m/s
	V_z^{LLO}	10 m/s

Simulation Results

- LiAISON-only with large *a priori*

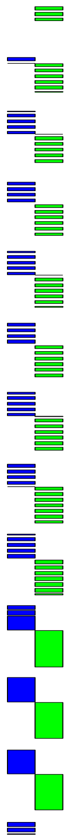


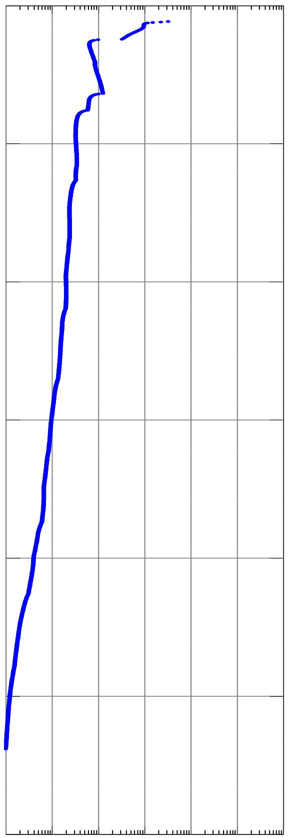
L1 Sat:
10 meters

LLO Crewed Sat:
300-800 meters

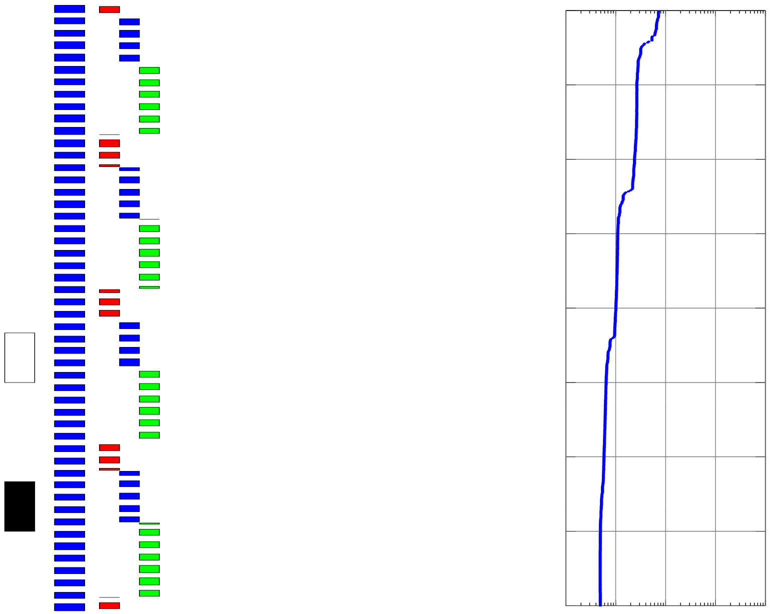
Simulation Results

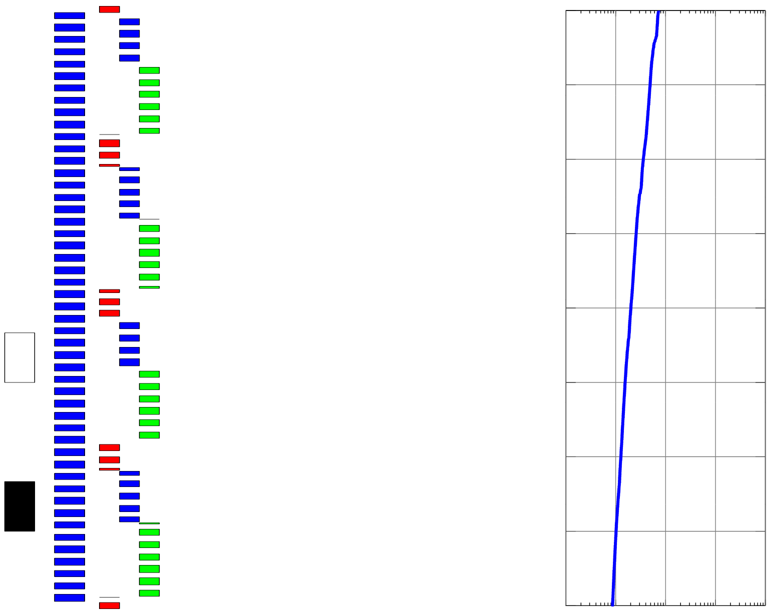
- DSN-only for both vehicles





- L_1 vs. L_2 orbits

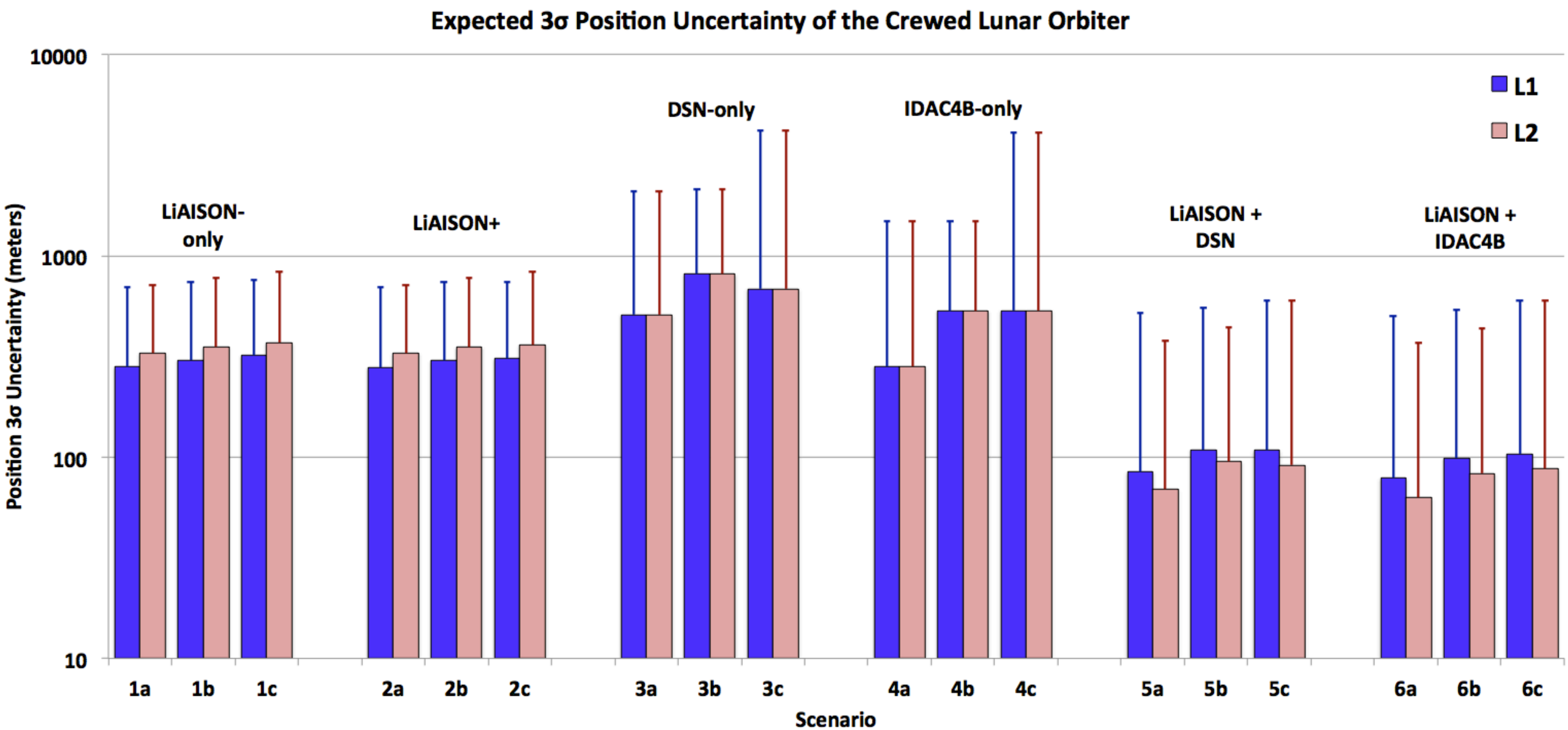




L_1 orbiter tracks simultaneously with ground.
Long gaps per orbit.

L_2 orbiter alternates tracks with ground.
Smoother performance.

Simulation Results



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

Bars = mean RSS 3σ position uncertainty from 3+ days

Extensions = 99 percentile RSS 3σ position uncertainty

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.

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Thank You

Questions?

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