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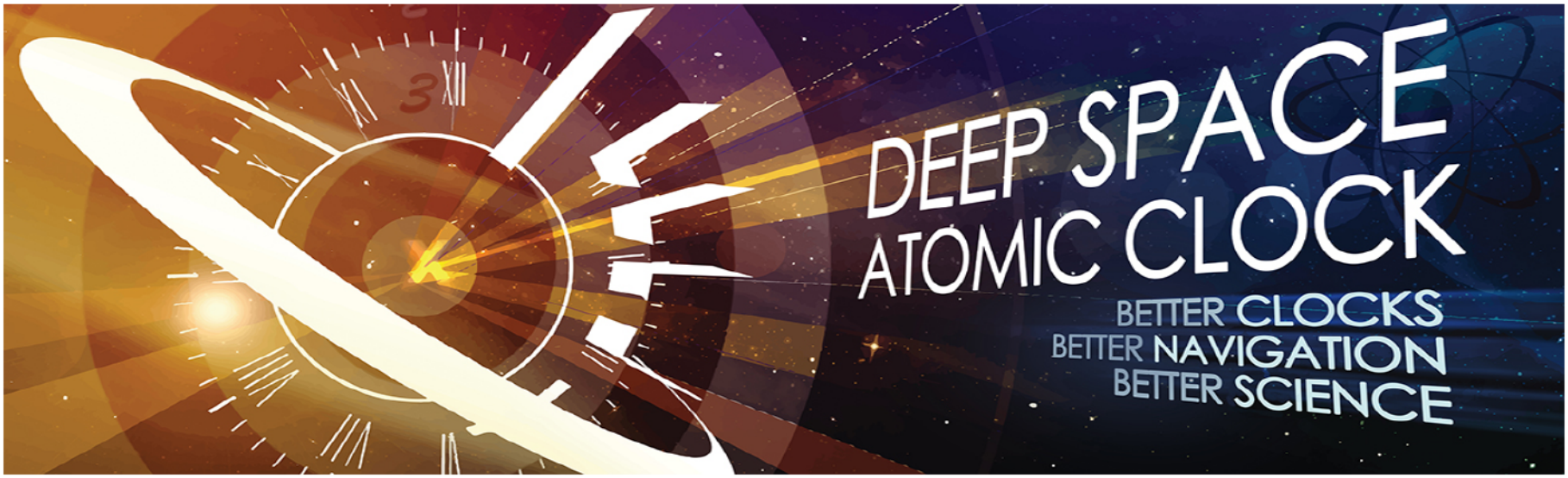

Utilization of the Deep Space Atomic Clock for Europa Gravitational Tide Recovery

AAS15-244

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Agenda

- Europa gravitational tide estimation via a flyby mission
- Low Gain Antennas for deep space tracking
  - Uplink-only telecommunication system design
  - Expected DSAC performance
  - Doppler tracking data quality
- Analysis of gravitational tide estimation performance
  - Linearization issues for perturbed initial conditions
  - B-plane target constraints to maintain filter linearization
- Approach orbit determination to satisfy B-plane constraints
- Conclusions

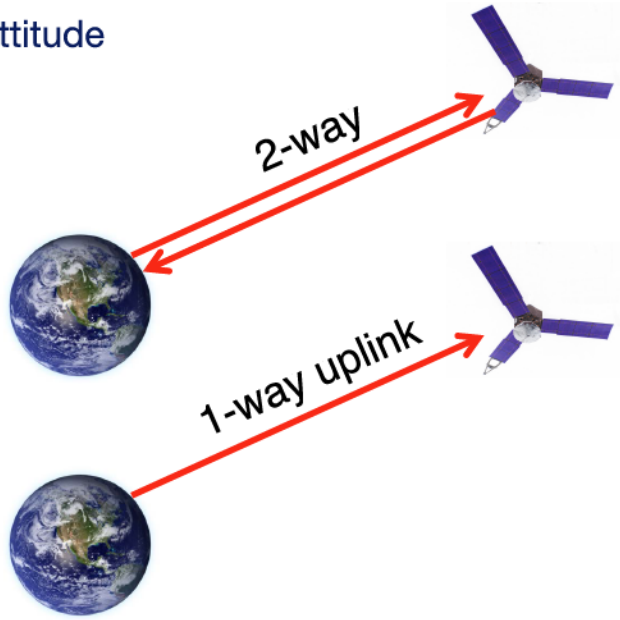
Europa Gravity Science: Subsurface Ocean Confirmation

- Primary science goal at Europa to confirm existence of and characterize Europa's subsurface liquid ocean
- Liquid/ice ocean perturbed by Jupiter and causes Europa gravitational fluctuations
  - Europa tidally locked to Jupiter, with k_{22} gravitational tide coefficient dominating time-varying response
  - Estimating k_{22} term with uncertainty < 0.05 strongly supports ocean's existence
- Europa flyby mission has limited radiometric data to estimate gravity field coefficients and their time variations
  - Gravitational tide sensitivities limited to close approach
- Potential ~ 2.5-year tour includes 45 flybys of Europa, and accumulates a few hours of useful X-band tracking data per flyby
  - Gravity information from each flyby accumulated to produce a global gravity solution; solution quality strongly correlated to Doppler quantity and quality
  - Jovian moon tour designed in part to optimize Europa gravity science return

http://www.jpl.nasa.gov/spaceimages

Low Gain Antennas for Deep Space Tracking

- Deep space telecommunications design limited by vast distances signal must traverse and achievable spacecraft transmit power
- Deep Space Network (DSN) typically utilizes two-way radiometric tracking
  - Downlink requires large spacecraft transmit antenna gain from high gain antenna (HGA) or medium gain fan beam antennas
- Small HGA/fan beam field of view and spacecraft attitude constraints may result in limited amount of flyby tracking data
- Desire solution to provide ample tracking data regardless of flyby attitude
- One-way uplink low SNR tracking possible with low gain antennas (LGAs) which are typically baselined into s/c design
  - Open-loop Doppler carrier tracking, collected onboard during flybys and stored until later downlink to Earth
  - Hemispherical LGA FOV imposes no attitude constraints while providing complete tracking coverage
- One-way Doppler data includes onboard clock errors
- High accuracy/stability onboard frequency source such as Deep Space Atomic Clock necessary to produce high-quality one-way Doppler data

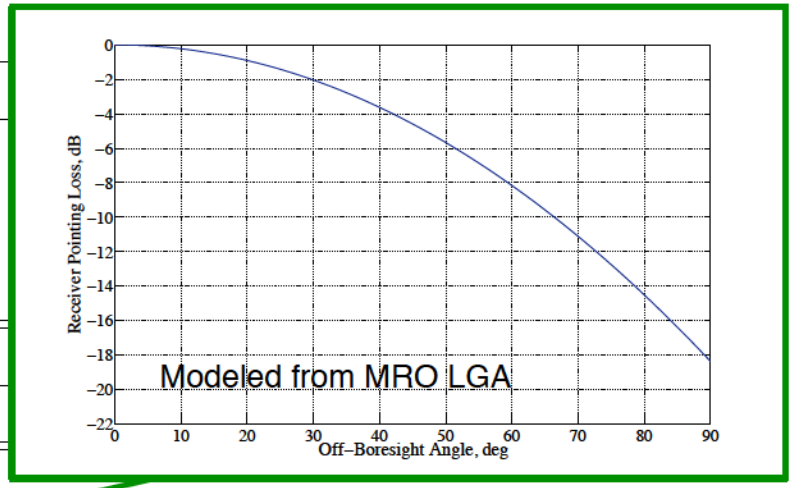


LGA Telecommunication System Design

- LGA uplink-only link budget assessed to determine whether sufficient SNR can be realized at the spacecraft
- Received power-to-noise requirements for tracking (including 3 dB-Hz margin):
  - Closed-loop ≥ 20 dB-Hz
  - Open-loop ≥ 10 dB-Hz
- Standard LGA and DSN values represent realistic telecommunication design parameters:

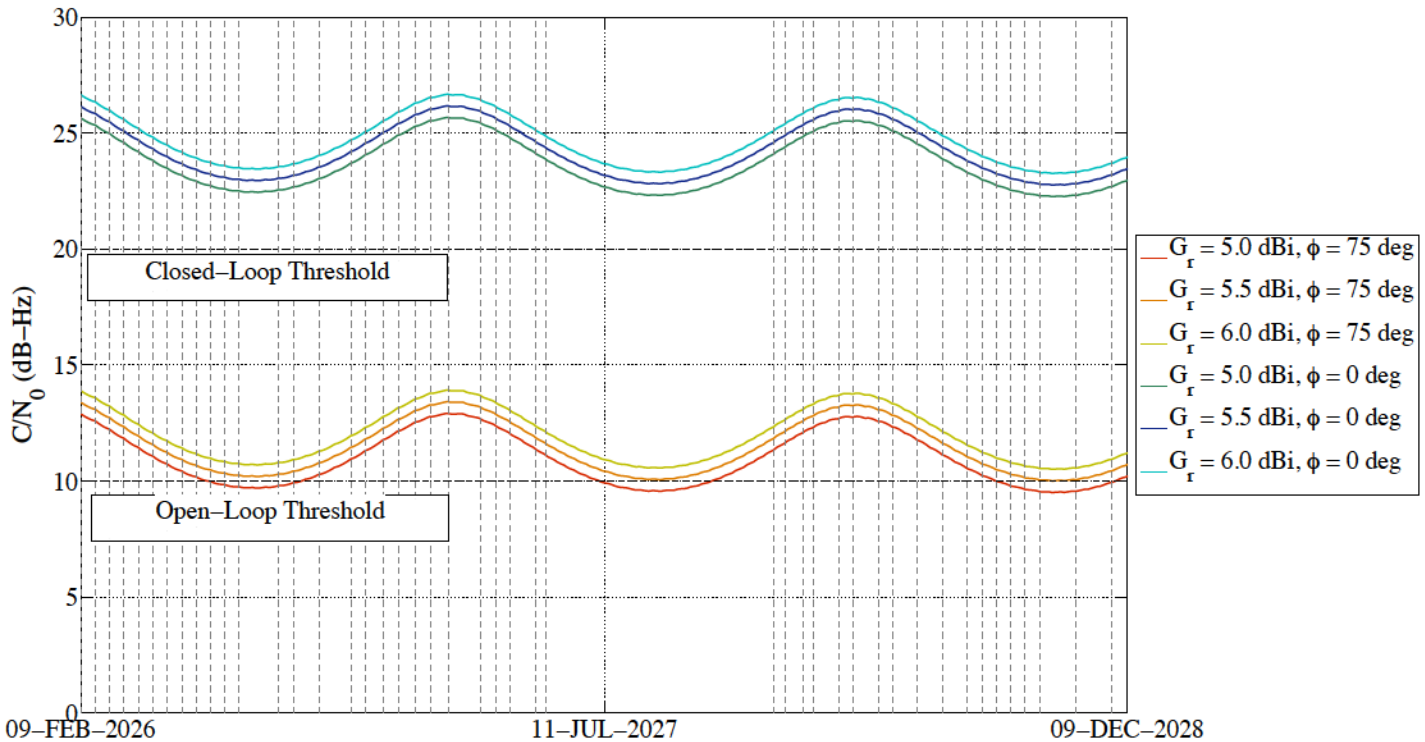
Table 1. X-Band Uplink Link Budget

Transmitter Parameters	
Transmit Frequency (f)	7.1531 GHz
Transmitter Power (P_x)	20 kW
Transmitt Antenna Gain (G_t)	66.96 dBi
Wave Guide Loss (L_{wg})	-0.6 dB
Transmit Antenna Pointing Loss ($L_{point,X}$)	-0.2 dB
Path Parameters	
Atmospheric Attenuation Loss (L_a)	-0.2 dB
Receiver Parameters	
Polarization Loss (L_{pol})	-0.04 dB
Receive Antenna Pointing Loss ($L_{point,R}$)	[-12.75 dB, 0 dB] for ϕ = [75°, 0°]
Receive Antenna Gain (G_r)	[5 dBi, 6 dBi]
Lumped Ckt/Antenna Loss (L_{ckt})	-4.5 dB



Spacecraft Received Power-to-Noise

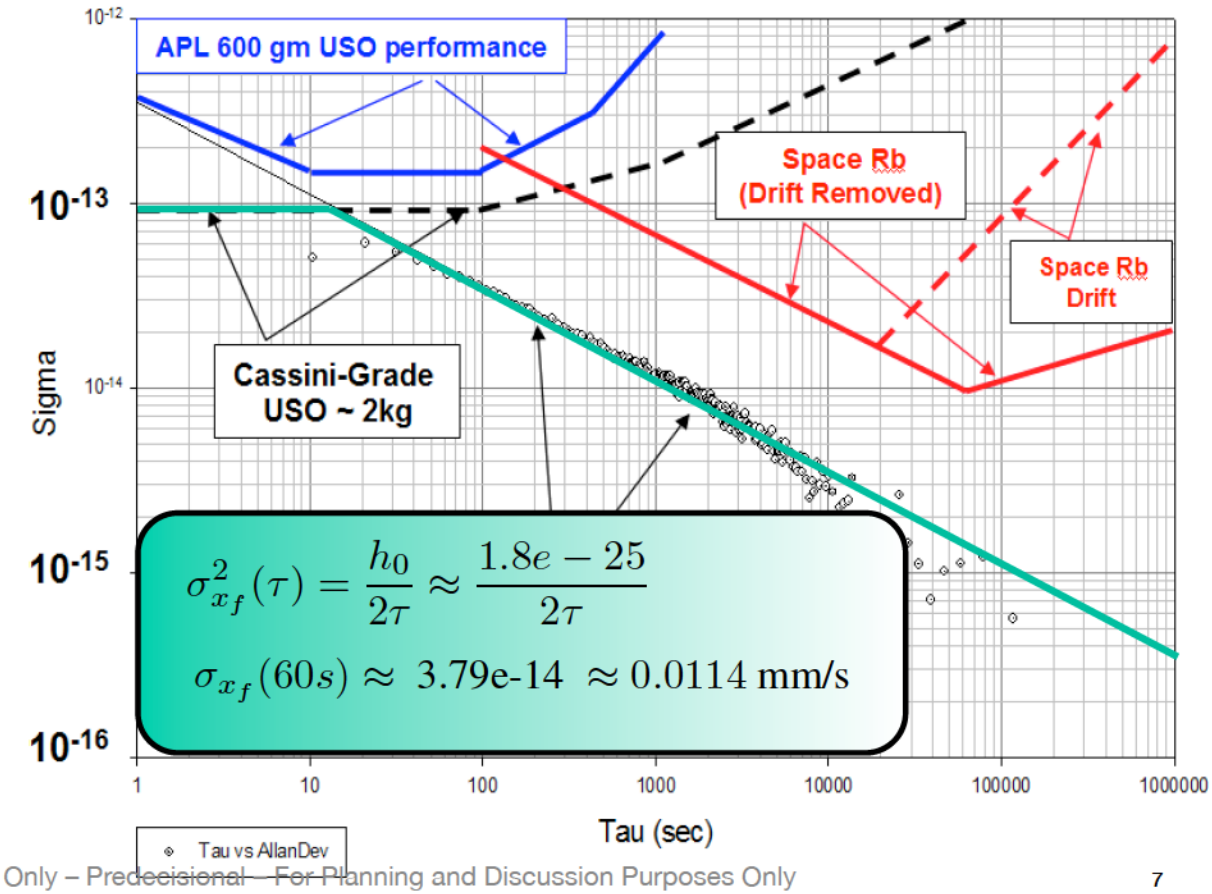
- Assessment of received C/N_0 over flyby tour shows that LGA can supply sufficient gain for open-loop uplink-only tracking
  - With 5.5 dBi of gain, can tolerate off-boresight angle up to ~ 75°
  - Assume one LGA per spacecraft side ➔ continuous LGA coverage (open-loop)



Expected DSAC Performance

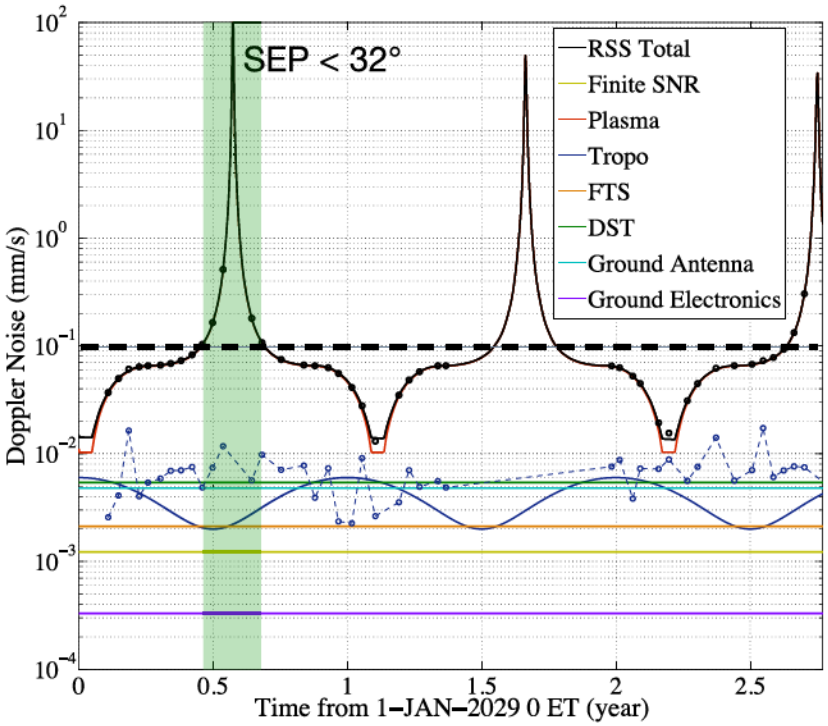
- Deep Space Atomic Clock (DSAC) Technology Demo Mission will demonstrate on-orbit performance of small, low-mass mercury ion atomic clock in LEO
  - Planned launch in May 2016 as hosted payload (SST-US Orbital Test Bed)
  - TRL 5 ➔ TRL 7

- Expected LEO performance < 3e-15 at 1 day
- Performance on par with DSN Frequency and Timing System
- DSAC corrects USO-generated frequency signal
  - USO frequency errors randomly walk with large integration times
  - After control cycle, frequency noise falls off as white noise

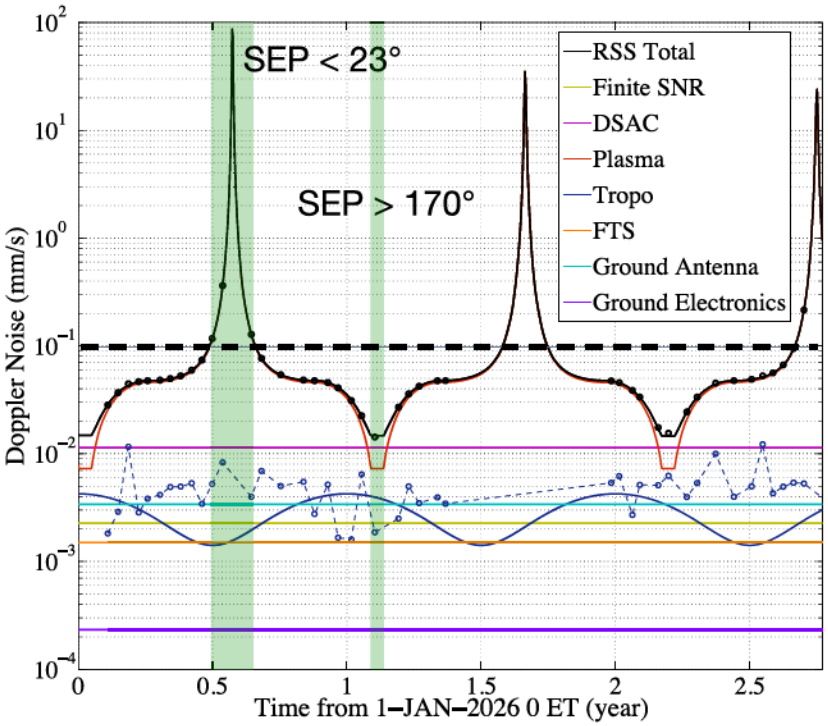


Doppler Data Quality

- 60-second X/X and X-up Doppler noise profiles generated over course of flyby tour
- With small DSAC onboard clock noise, both X/X and X-up signal noise dominated by plasma variations
- Generally, X-band two-way noise ~ $\sqrt{2}x$ one-way noise, with $2x$ measurement sensitivity



X/X Two-way



X-up One-way

Gravitational Tide Recovery: Simulation Configuration

- Gravity science filter performance assessed via numerical simulation
- 4-hour truth trajectory numerically integrated for each flyby (± 2 hours about periapsis)
  - Point mass gravity (Sun, planets, other Jovian moons), 20x20 Europa static gravity field + gravitational tide ($k_{20} = k_{21} = k_{22} = 0.2$)
- X-band one-way uplink Doppler tracking data generated from truth trajectory
  - LGAs on each s/c face ➔ continuous tracking data available
  - Measurements degraded with white phase noise based on flyby-dependent Doppler noise model
- Filter nominal initial conditions perturbed by *a priori* errors on all estimated states
- Sequential UD Kalman filter configuration:

Unique to each flyby

Universal parameters

Estimated Parameter	Parameter Type	*A Priori* Uncertainty
Position (EME2000)	Local	10 km
Velocity (EME2000)	Local	1 cm/sec
RTN accelerations	Local	5e-12 km/sec^2 (8 hr stochastic batches)
Europa μ	Global	320 km^3/sec^2
Europa k_{20}, k_{21}, k_{22}	Global	0.3
Europa 20x20 spherical harmonic coefficients: n = 2	Global	$\sigma = 10000 * \left(\frac{28e\text{-}5}{n^2}\right)\left(\frac{R_{mantle}}{R_e}\right)^n$
Europa 20x20 spherical harmonic coefficients: n > 2	Global	$\sigma = \left(\frac{28e\text{-}5}{n^2}\right)\left(\frac{R_{mantle}}{R_e}\right)^n$

Gravitational Tide Recovery: Stitching Flyby Solutions Together

- Filter nominal initial conditions defined via truth values + Gaussian random errors (1σ)
  - Local parameters: *a priori* errors injected on each flyby
  - Global parameters: *a priori* errors injected on first flyby only, with filter solutions from flyby N passed forward to initialize flyby N+1 nominal states
  - Love number error injection constrained such that filter nominal Love numbers > 0
- *A priori* covariance definition reflects feed-forward of global parameter solutions
  - Flyby *1 a priori* covariance initialized as diagonal matrix with nominal 1σ values
  - After first flyby, *a priori* global covariance is initialized as the previous flyby's covariance solution
  - *A priori* local covariance always reinitialized as uncorrelated nominal values

Flyby N solution covariance:

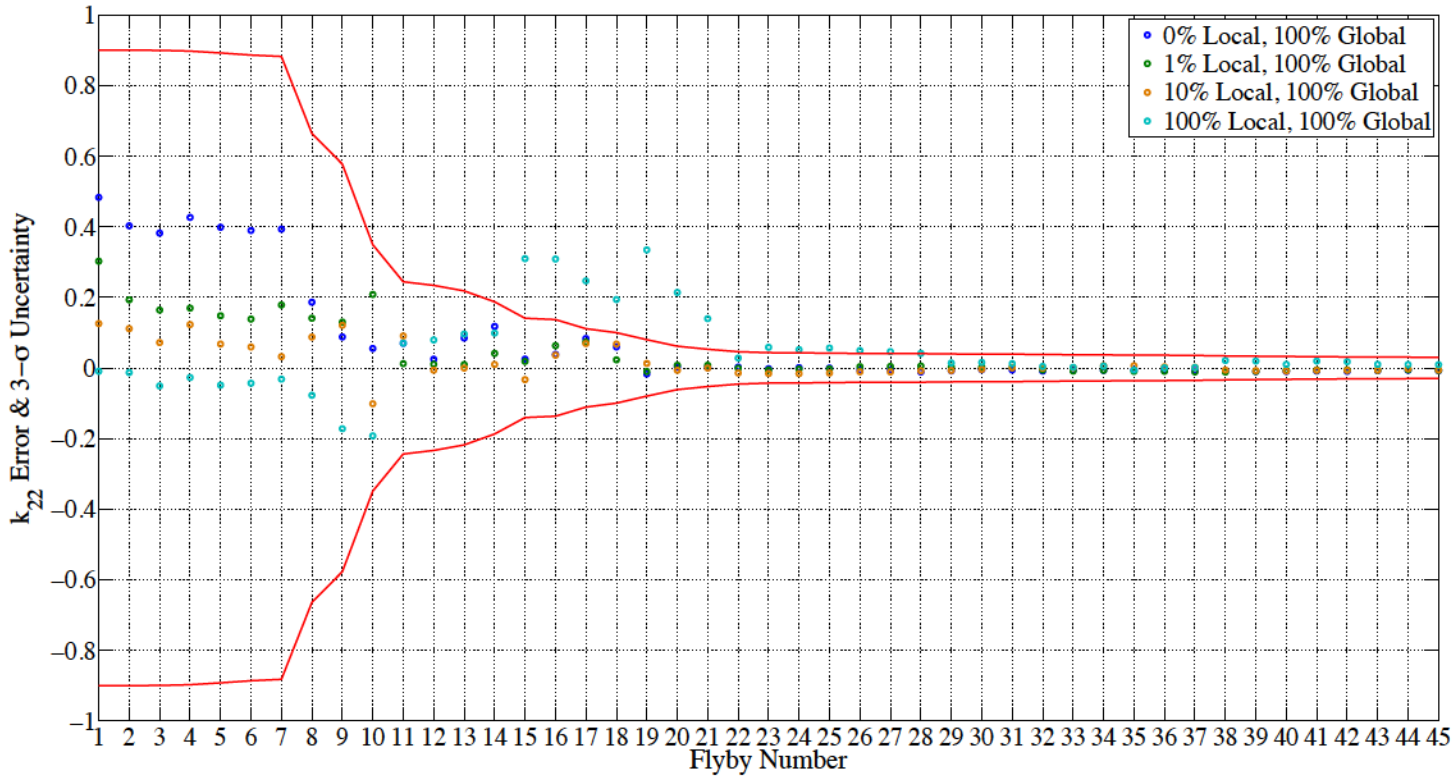
$$P(N) = \begin{bmatrix} P(N)_{local} & P(N)_{local/global} \\ P(N)_{local/global} & \boxed{P(N)_{global}} \end{bmatrix}$$

Flyby N+1 *a priori* covariance:

$$\bar{P}(N+1)_0 = \begin{bmatrix} \bar{P}_{0,local} & [\vec{0}] \\ [\vec{0}] & \boxed{P(N)_{global}} \end{bmatrix}$$

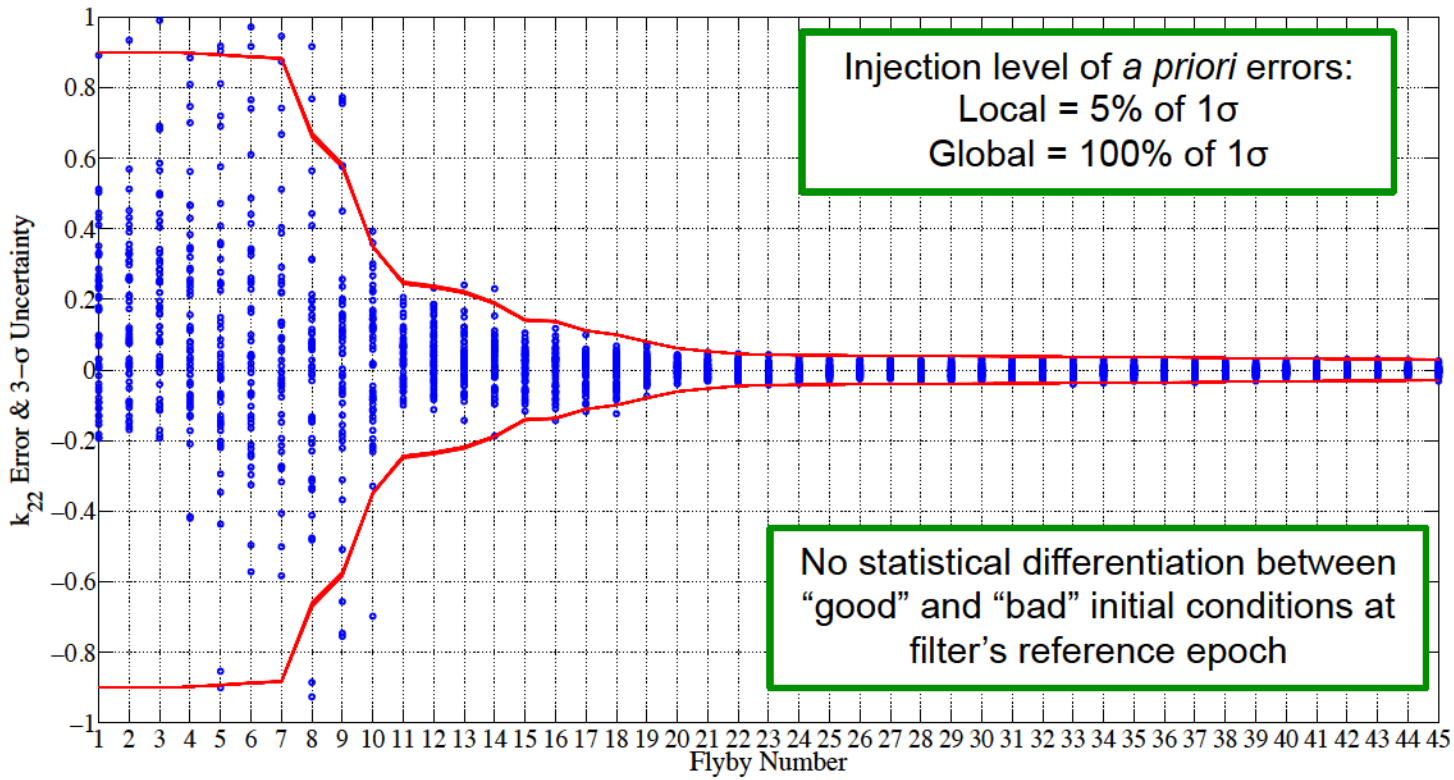
Gravitational Tide Recovery: Initial Results

- Initial simulations injected *a priori* local errors at 0%, 1%, 10%, and 100% of 1σ levels
  - Global state errors injected at 100% of 1σ level
- Filter performs well when little to no local errors injected, but errors deviate outside formal uncertainty bounds as *a priori* errors are increased ➔ filter linearization issues



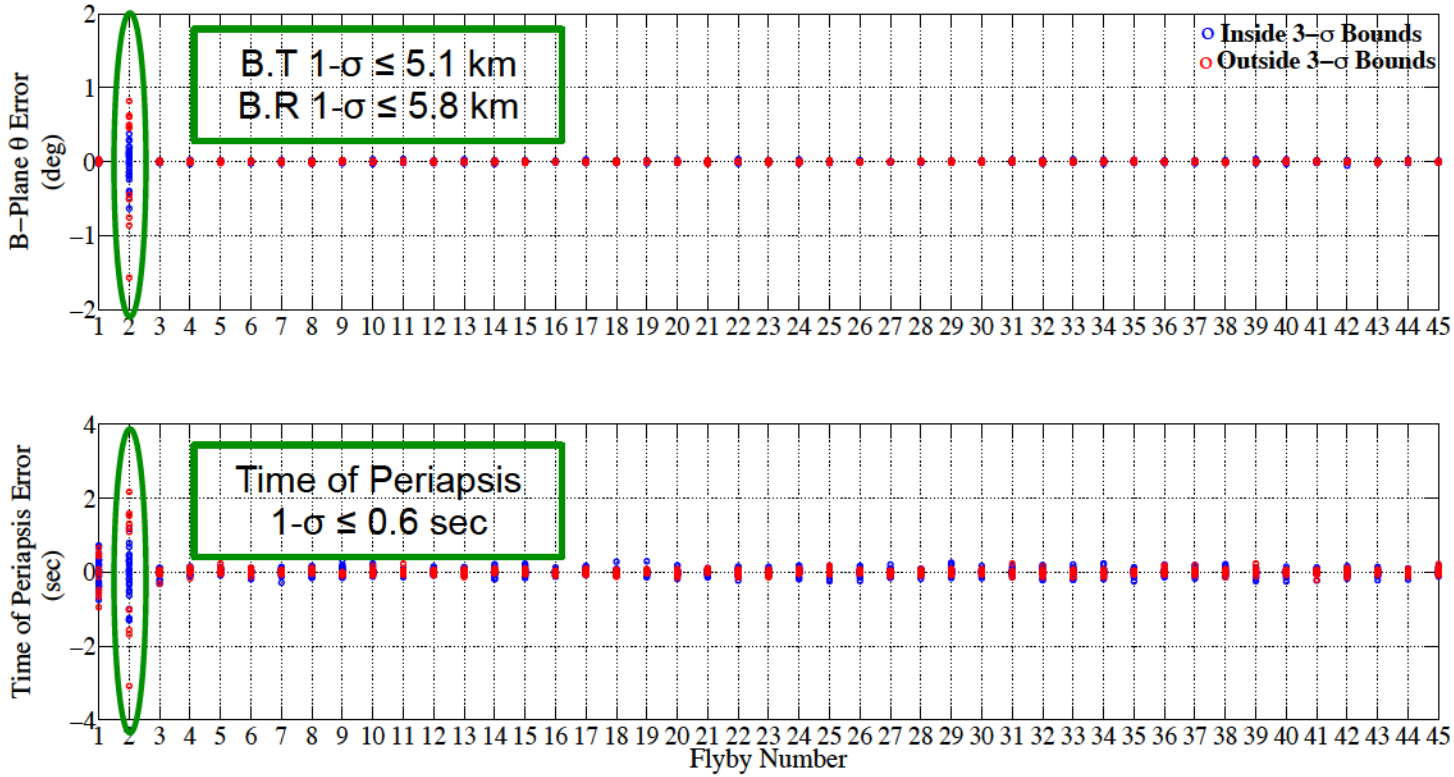
Statistical Assessment of Linearization Conditions

- Randomization of local state initial conditions utilized to develop constraints such that filter's linearization assumptions are not violated
- 100+ randomized realizations generated ➔ 3.7% of solution errors outside 3σ bounds



Statistical Assessment of B-Plane Target Errors

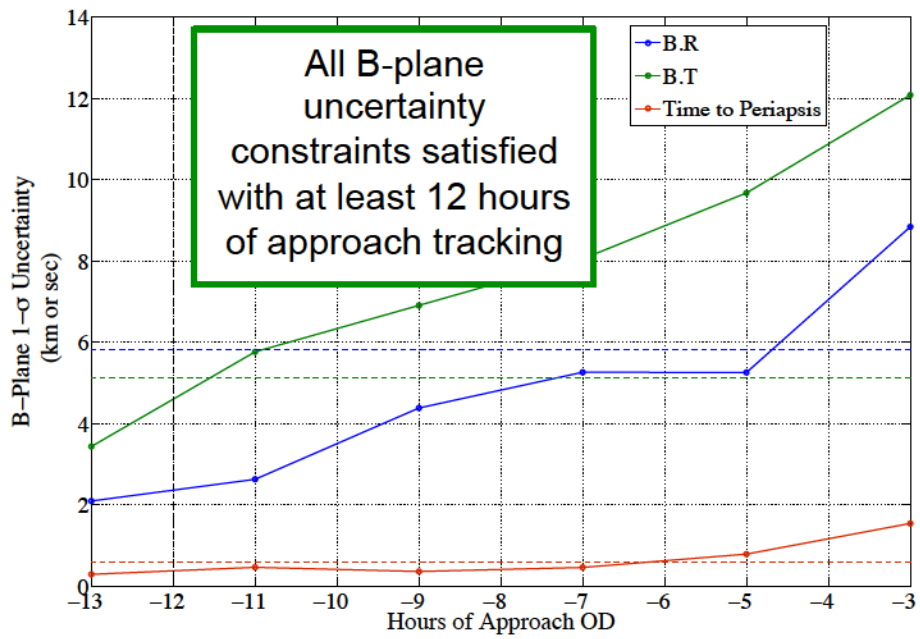
- Mapping each realization to close approach B-plane reveals conditions which will drive filter's linearization assumptions to be violated
- Flyby 2 is first very low altitude Europa encounter (100 km) ➔ coupling of large gravity *a priori* uncertainties & measurement sensitivity can push filter solution outside of linear region



Approach Orbit Determination: B-Plane Targeting Constraint

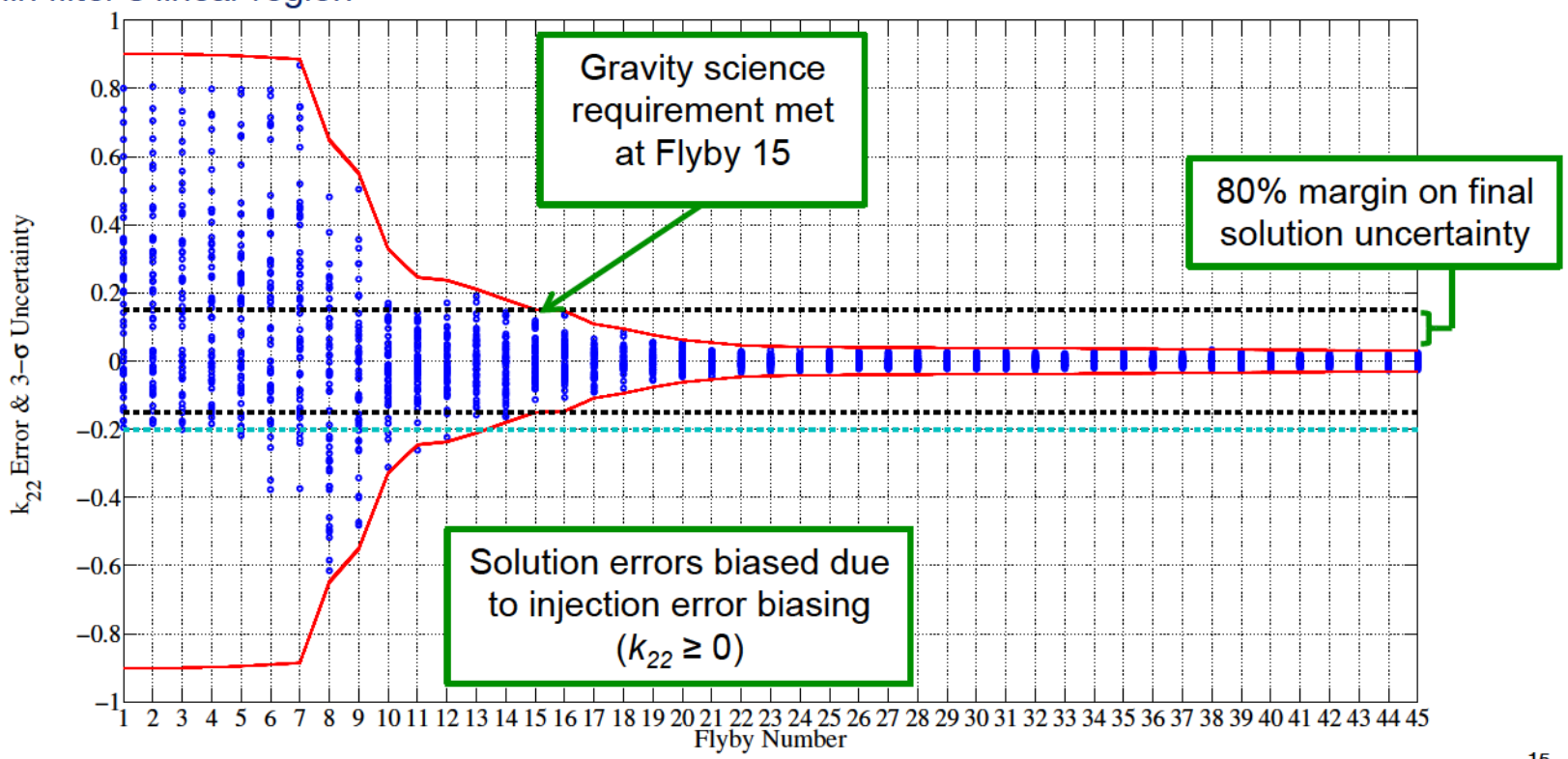
- Statistically-derived B-plane constraints may be satisfied with additional pre-flyby tracking
  - Process tracking data preceding flyby period to estimate corrections to the local states at the gravity science filter's reference epoch
  - No additional s/c attitude constraints given LGA (hemispherical FOV)

- Parametrically determine required approach tracking arc to meet Flyby 2 B-plane constraints
  - Process tracking data up to 2 hours before close approach (gravity science reference epoch)
  - Map formal state uncertainty at data cut off (DCO) to close approach B-plane
  - Compare mapped uncertainties against statically-determined B-plane requirements



Approach Orbit Determination: Solution for 12 Hours Pre-Flyby Tracking

- 50+ realizations generated to assess gravitational tide estimation with the addition of 12 hours of pre-flyby approach OD tracking
- All initial conditions perturbed at the 1-σ level (local & global states)
  - State errors injected at approach orbit determination filter's reference epoch
- Results demonstrate that the approach orbit determination successfully constrains nominal trajectory to within filter's linear region



Conclusions

- Explored the feasibility of using LGAs and DSAC for deep space uplink-only open-loop Doppler tracking
  - LGAs provide sufficient gain across a nearly hemispherical FOV for Jovian tour
  - Doppler tracking via LGAs imposes no attitude constraints on spacecraft
- DSAC provides onboard frequency accuracy, stability performance necessary to realize high-quality uplink-only Doppler data
- Numerical simulation of Europa flyby gravitational tide estimation revealed filter linearization issues tied to E2 B-plane targeting performance
- 12+ hours of approach OD tracking provides a solution to maintain filter linearization assumptions and produce a gravity solution that is accurately represented by formal uncertainty bounds
  - DSAC+LGA tracking configuration satisfies gravity science requirement in first15 flybys, with 80% margin on the final solution

Acknowledgements

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- Thanks to: Brent Buffington, Try Lam, Bill Folkner, Peter Ilott (JPL)

Backup Slides: Link Budget Equations

- Effective isotropically radiated power:

$$EIRP = P_x + G_x + L_{wg} + L_{point,x}$$

- Space loss:

$$L_s = \left(\frac{\lambda}{4\pi R}\right)^2$$

- Spacecraft received power:

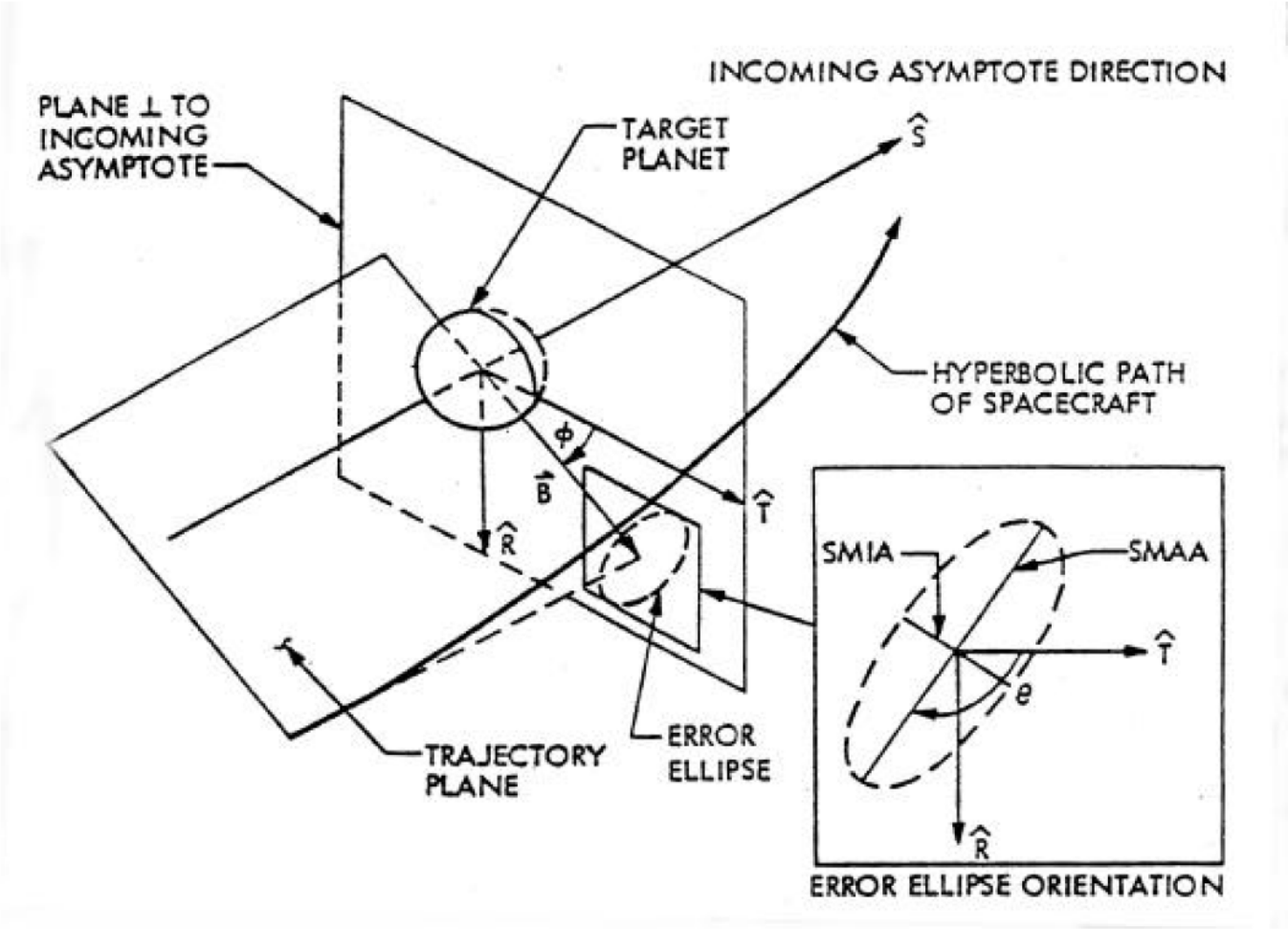
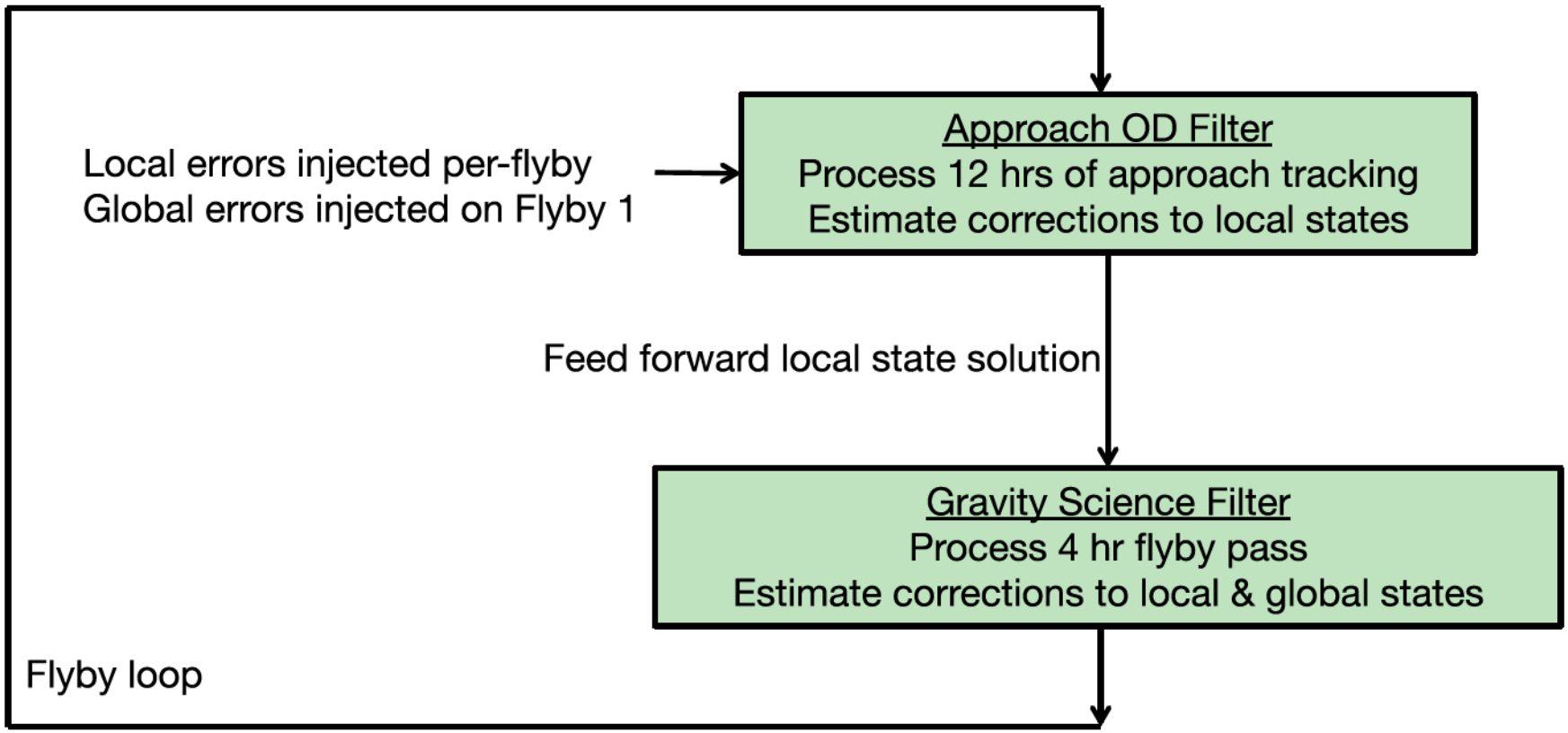
$$C = EIRP + L_s + L_a + L_{pol} + L(\phi)_{point,r} + G_r + L_{ckt}$$

- Receiver noise spectral density:

$$N_0 = kT_s$$

Backup Slides: B-Plane Description

- "Derivation of the B-plane (Body Plane) and it's Associated Parameters", Moriba Jah:



Backup Slides: Approach Orbit Determination Implementation