National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Deep Space Atomic Clock Technology Demonstration Mission Onboard Navigation Analog Experiment

AAS 16-258

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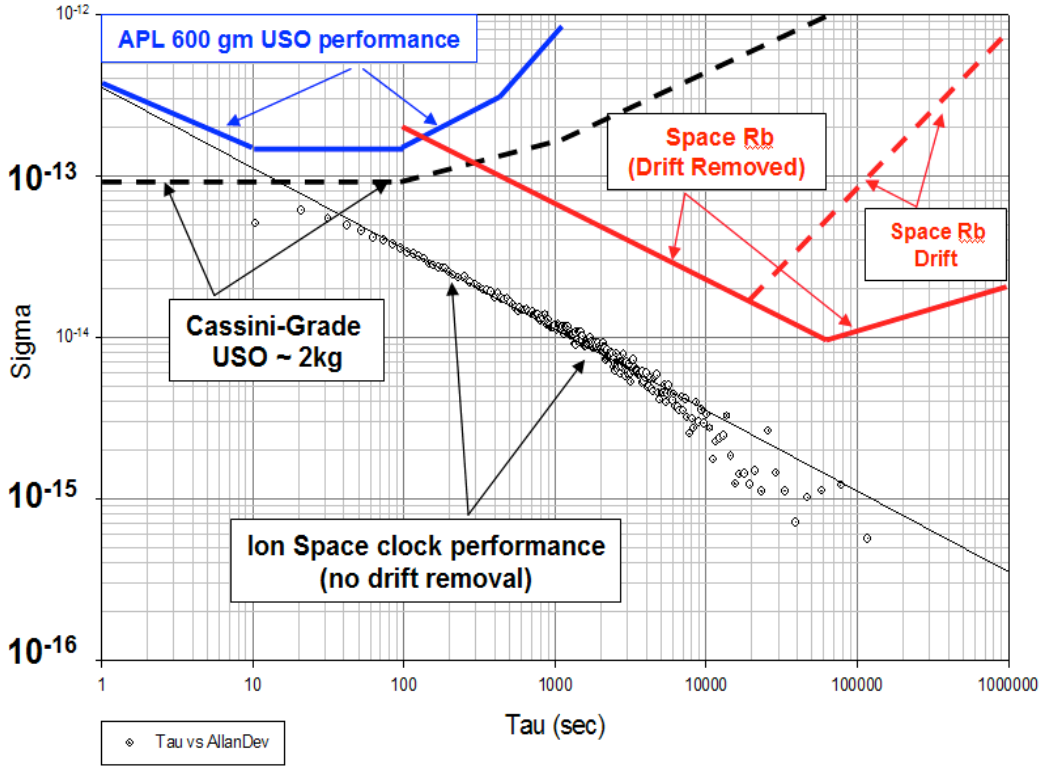
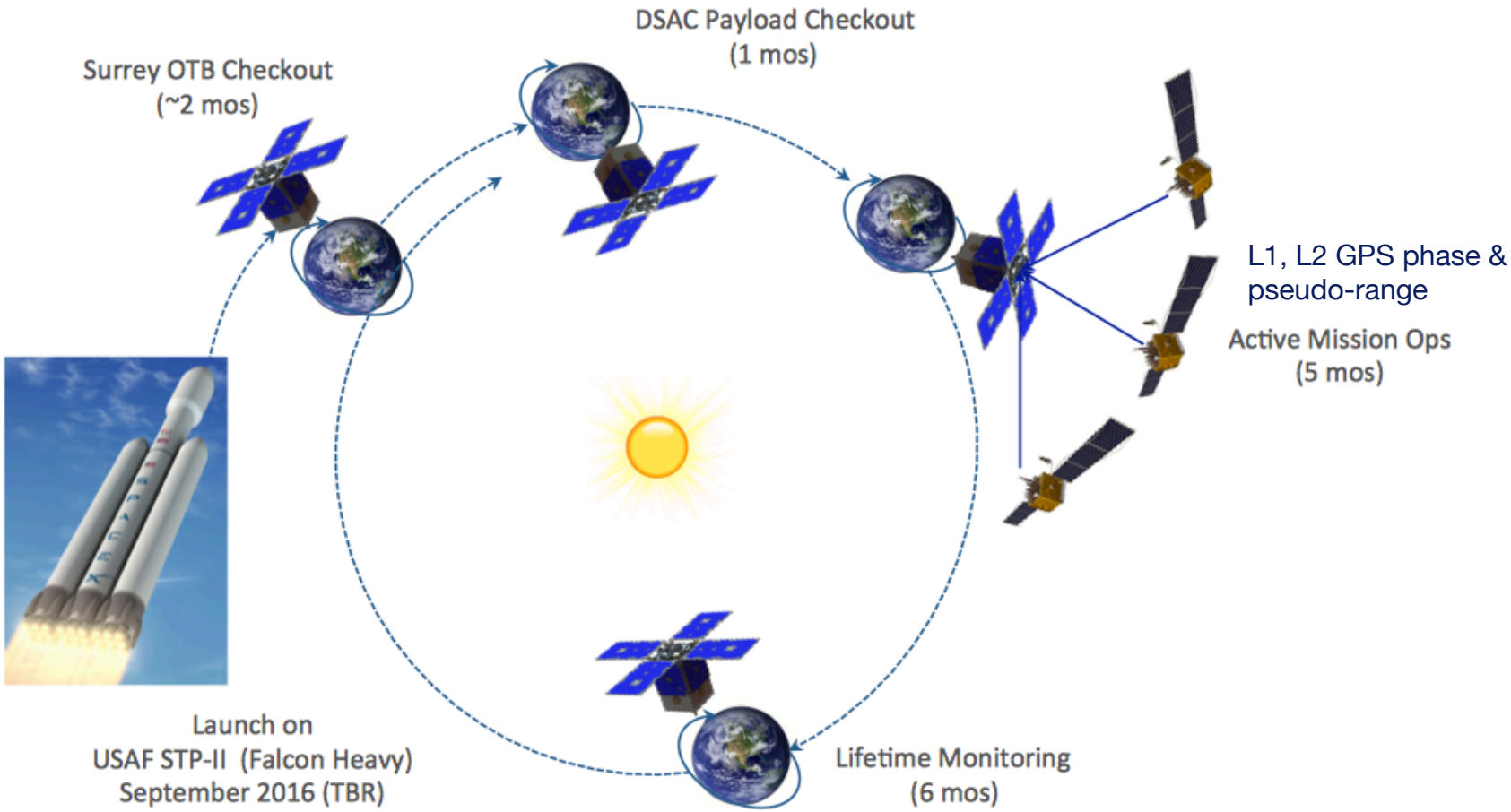
Deep Space Atomic Clock

- Deep Space Atomic Clock (DSAC) Technology Demonstration Mission will demonstrate on-orbit performance of small, low-mass mercury ion atomic clock in Low Earth Orbit
  - TRL 5 ➔ TRL 7
- DSAC corrects USO-generated frequency signal
  - Short term (< 10 sec) noise driven by USO behavior
  - After control cycle, frequency noise falls off as white noise
- Ground-based testing performance < 3e-15 at 1 day
  - Stability & accuracy on par with DSN ground clocks
- Enables one-way deep space radiometric tracking data accuracy equivalent to current two-way tracking



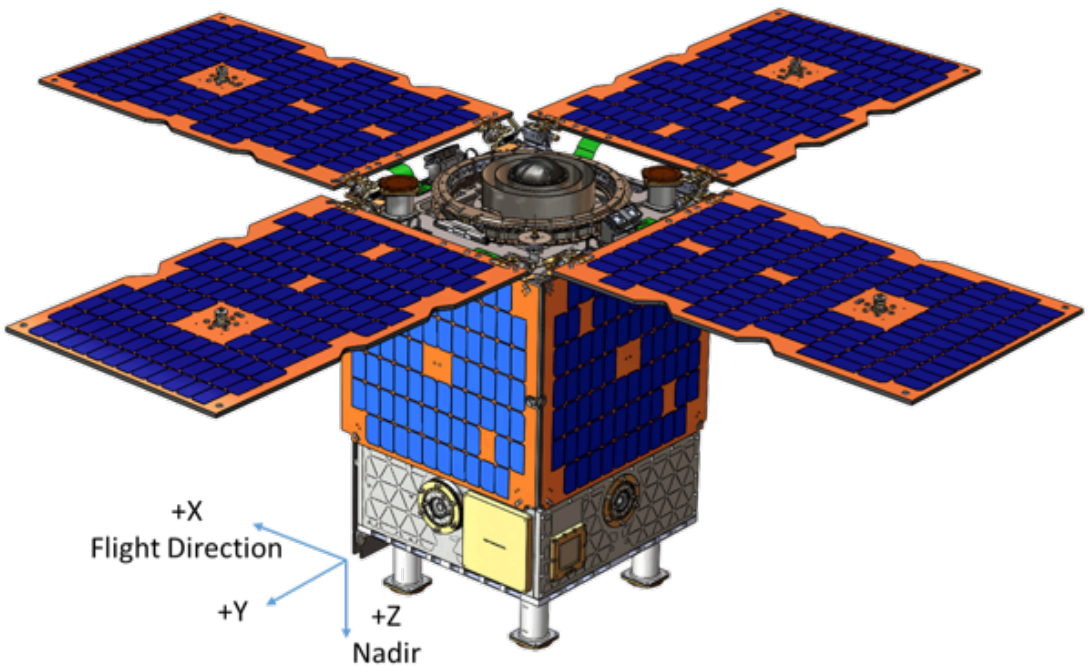
DSAC Technology Demonstration Mission



- Objectives:
  - Verify DSAC's on-orbit Allan Deviation is < 2e-14 at 1 day
  - Demonstrate that DSAC is a viable deep space navigation instrument

Orbital Test Bed (OTB) Spacecraft

- OTB host spacecraft launched into near-circular, near-equatorial orbit
  - Altitude = 720 km, inclination = 28°
- ESPA-compatible spacecraft (180 kg)
- No active propulsion system
- Choke-ring antenna nominally zenith-pointed
- Solar arrays oriented in X-Y plane



Deep Space Navigation Analog Experiment

- Project requirement to demonstrate DSAC's potential as deep space navigation instrument
  - In limited context of Low Earth Orbit demonstration

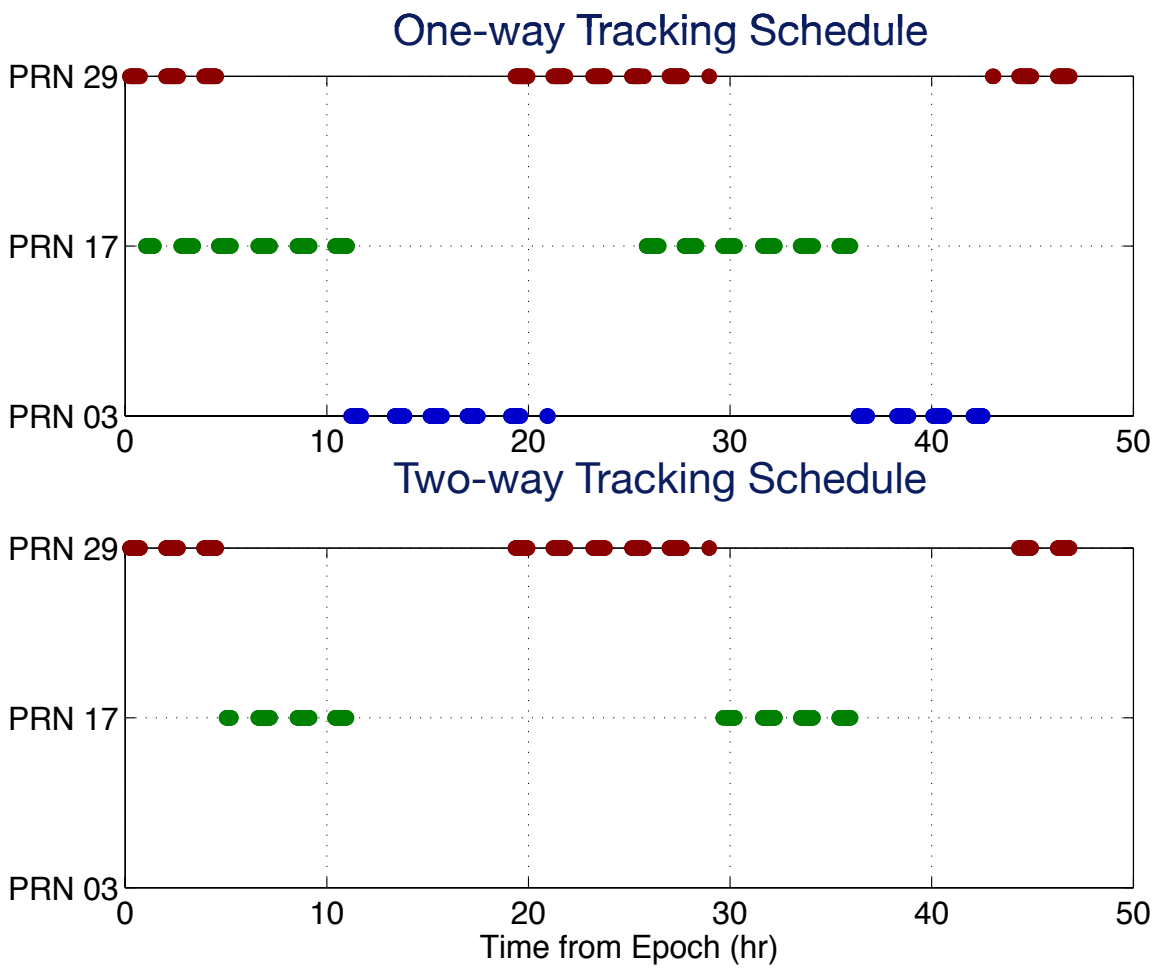
- Careful setup of OTB orbit determination as surrogate for actual deep space demo allows validation of DSAC's viability in comparable conditions
  - Leverage similarities between OTB & low-altitude Mars orbiter environment
    - Drag accelerations
    - Tracking schedules
    - Tracking measurements
  - High-fidelity linear Kalman filter mimics ground-based MRO operational orbit reconstruction

Down-Selection of GPS Tracking Data

- Continuous GPS tracking data down-selected to represent DSN tracking of Mars orbiter
- Selected 3 GPS satellites equally-spaced throughout same orbital plane

Longitudinal separation of DSN complexes

DSN committed to tracking other spacecraft



DSN can receive multiple signals simultaneously

Spacecraft can't receive/ turnaround multiple signals

GPS Doppler Measurements

- GPS "transmit-only" measurements manipulated to create data "operationally similar" to deep space navigation tracking data
- GPS Doppler data generated by differencing phase:

$$\Delta f(t - \frac{T}{2}) = \frac{f_{LC}}{cT}\Big(\phi(t) - \phi(t-T)\Big)$$

- One-way GPS Doppler: onboard clock error entirely manifested in measurements
  - Directly analogous to one-way DSN Doppler data
- Two-way GPS Doppler: truth clock removed from phase data

$$\phi_{\text{2-way}}(t) = \phi(t) - c\delta t_r(t)$$

  - Analogous to two-way DSN Doppler data, but may be utilized in simulations only
- Pseudo two-way GPS Doppler: estimated clock removed from phase data

$$\phi_{\text{P2-way}}(t) = \phi(t) - c\delta t_r^*(t)$$

  - Clock solution estimated with full GPS data set & highest fidelity models
  - Serves as a proxy to true two-way GPS Doppler

High-Fidelity Modeling of OTB Orbital Environment & GPS Measurements

- Orbital dynamics:
  - Gravity (EGM-96 360x360 static gravity field, luni-solar point mass gravity)
  - Solar radiation pressure (semi-empirical surface material properties, 8-plate s/c model)
  - Atmospheric drag (DTM-2012 semi-empirical density model, 8-plate s/c model)
  - Earth albedo & thermal emissivity pressure
- LC/PC GPS pseudo-range and phase measurement models
  - Validated with GRACE flight data
- Expected on-orbit errors included in truth trajectory and simulated GPS data

Error Source	Error Model	Error Source	Error Model
OTB attitude	Sunlight: $\sigma_x = \sigma_z = 0.6°$, $\sigma_y = 0.8°$ Shadow: $\sigma_x = \sigma_y = \sigma_z = 1.5°$	Thermal Noise	White noise LC = N[0, 1] cm PC = N[0, √10] m
DSAC	White frequency noise AD = 1e-15 at 1 day	Antenna phase center location	Random bias $\sigma_x = \sigma_y = \sigma_z = 5/\sqrt{3}$ mm
Atmospheric Drag	ECRV $\sigma = 0.1$, $\tau = 30$ sec	Reference clock	White frequency noise AD = 5e-16 at 1 day
GPS orbits & clocks	Final – Rapid Products	Solar pressure	ECRV $\sigma = 0.1$, τ = ½ x orbital period
Multipath	GRACE-A multipath map	GPS receiver temperature	LC = -41.25 sin(nt + T_0) ps + N[0, 40] ps PC = 35.50 sin(nt + T_0) ps + N[0, 40] ps

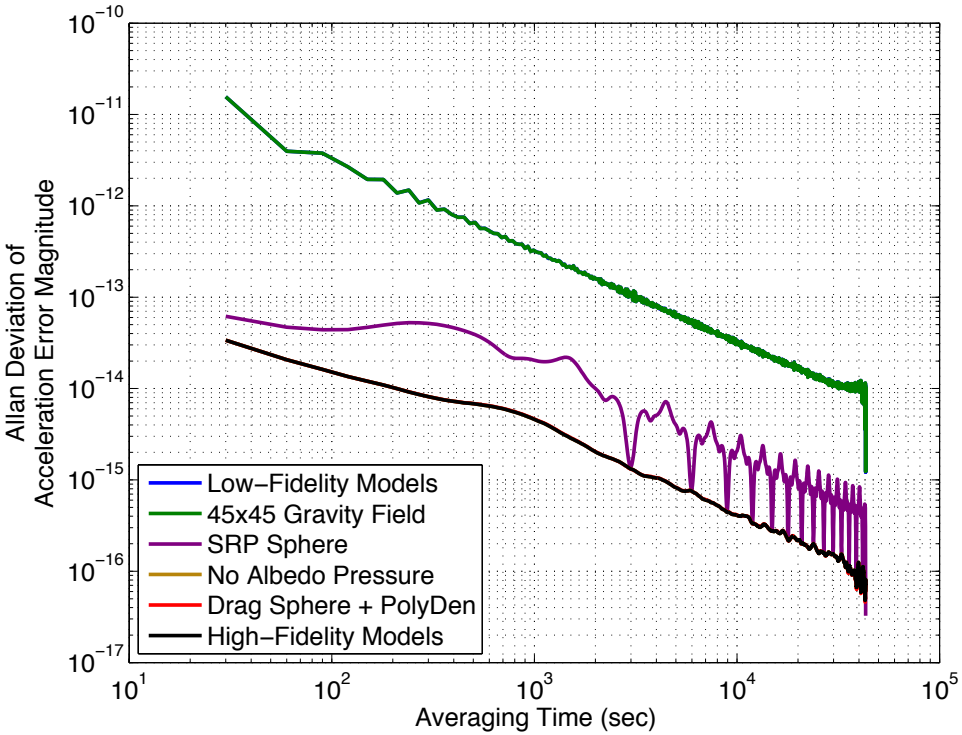
Onboard Navigation Analog Experiment

- Deep Space Analog Experiment reconstructed orbit uncertainty < 1 m (3σ)
  - Optimally-tuned LKF & high-fidelity models
  - Only errors are nominal expected on-orbit errors
- Ground-based operations effectively not limited by computational efficiency, data storage
  - Telemetry, media calibrations available for post-processing orbit reconstruction
- Onboard navigation capabilities limited by spacecraft computer architecture & post-processing data latency
  - Nominal models & filter configuration must be sized appropriately
  - Piping attitude & small force telemetry (if applicable) complicates data flow, requires onboard filtering
  - High-accuracy media calibrations not available in real time
- **Identify candidate filter configuration & dynamic model simplifications**
- **Assess impact on orbit reconstruction performance**

Simplifications to Dynamic Models

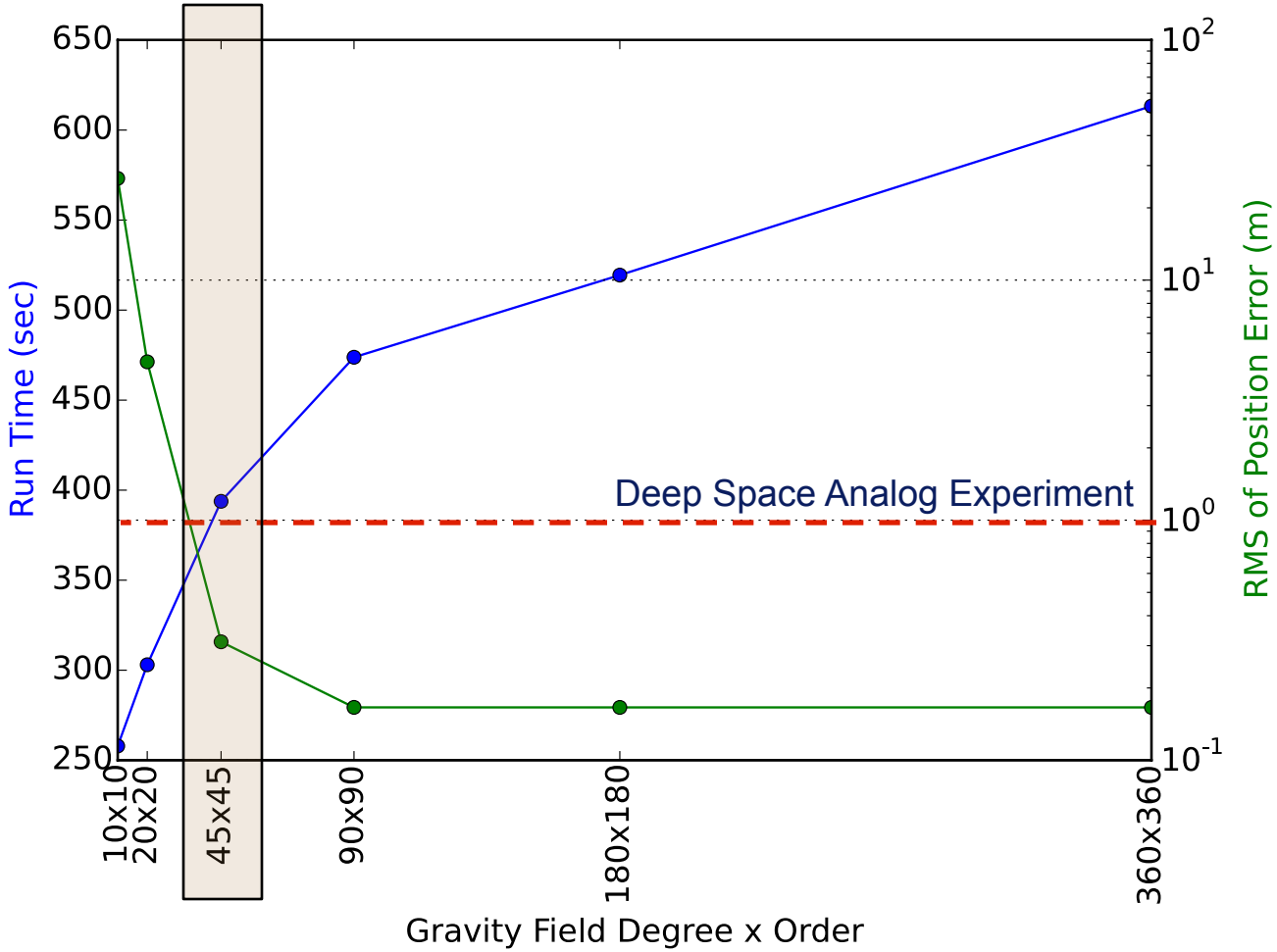
High-Fidelity (Truth)	Low-Fidelity
360x360 EGM-96 gravity field	Truncated to 45x45
DTM-2012 atmospheric density	Polynomial fit to DTM-2012 densities (PolyDen); independent variable = TLST
8-plate solar pressure shape model	Spherical spacecraft (attitude-independent); Radius = 0.74 m, κ_d = 0.15, Υ_d = 1.0
8-plate drag shape model	Spherical spacecraft (attitude-independent); Radius = 0.38 m
Earth albedo & thermal emissivity pressure	Omitted

- Low-fidelity model acceleration errors dominated by 45x45 gravity field reduction
- Drag, albedo/thermal emissivity errors commensurate with expected on-orbit errors
- No simplifications to luni-solar gravity models



Truncation of EGM-96 Gravitational Model

- Gravity model truncation generally results in reduced run time & reduced solution accuracy



Simplification to Filter Configuration

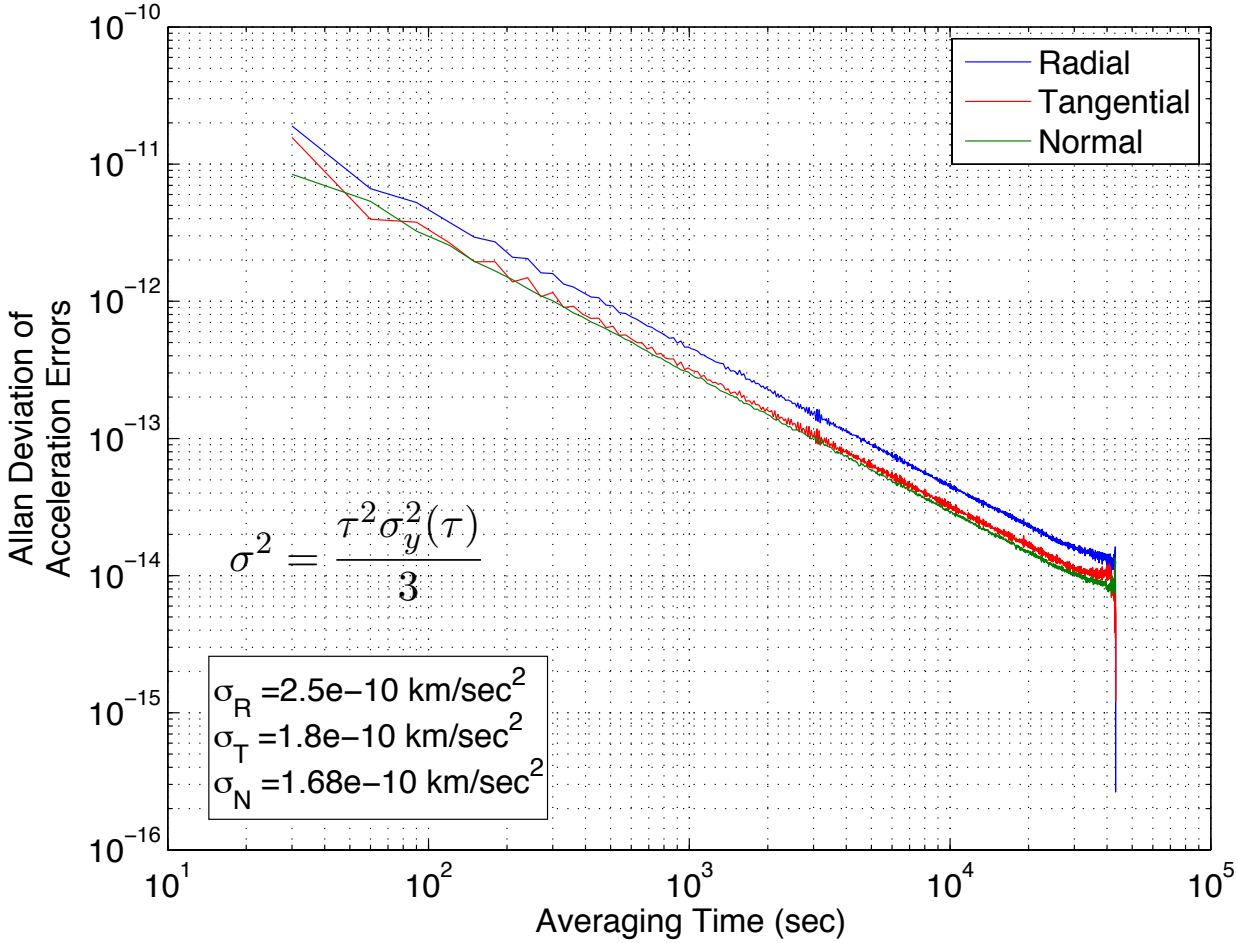
- Ground-based high-fidelity LKF filter mimics MRO operational orbit reconstruction
  - Optimally-tuned to expected on-orbit errors

Estimated Parameter	**Parameter Type**	**Uncertainty Model**
Position, Velocity (EME2000)	Dynamic	σ = 1 km, 0.23 cm/sec
Gravity / Earth / J_{14}, J_{15}	Bias	σ = 1e-9
Radial Acceleration	Stochastic	Determined from Allan Deviation Estimated per measurement
Tangential Acceleration	Stochastic	Determined from Allan Deviation Estimated per measurement
Normal Acceleration	Stochastic	Determined from Allan Deviation Estimated per measurement

- Onboard filter process noise models reduced to spacecraft-frame stochastic accelerations
  - Account for expected on-orbit errors & low-fidelity dynamic modeling errors

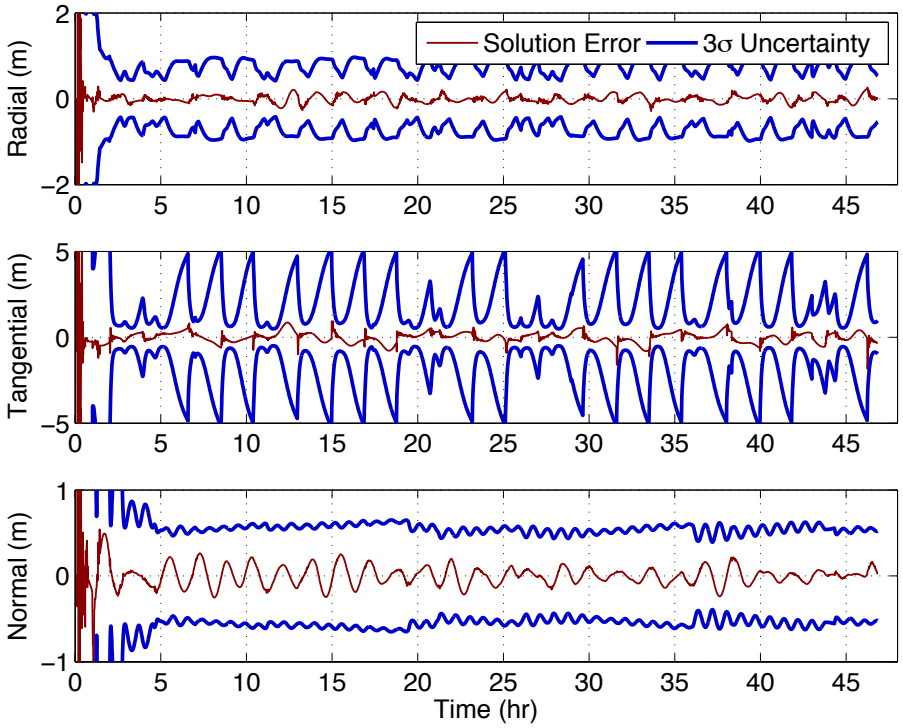
Allan Deviation of Low-Fidelity Model Acceleration Errors

- White process noise models accurately represent dynamic modeling errors
- RTN process noise strengths determined by converting Allan Variance into standard variance

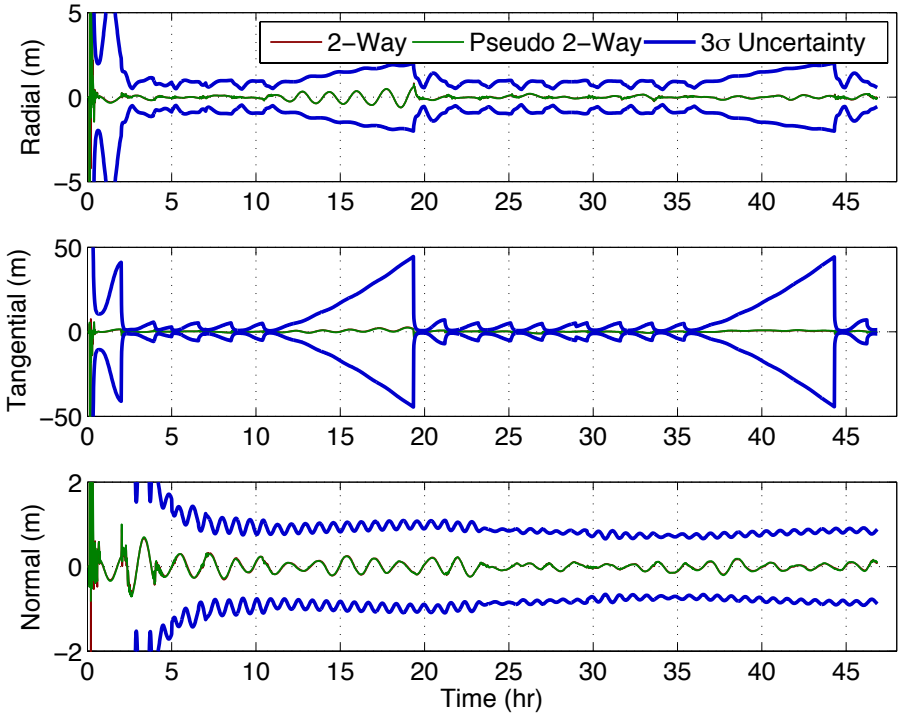


Simplified Filter Performance: Orbit Solutions

- Low-fidelity LKF orbit solutions are degraded compared to high-fidelity solutions (< 1 m), but still meet post-processing MRO orbit reconstruction requirements
- DSAC onboard clock errors do not significantly impact solution quality
- Pseudo two-way GPS Doppler is suitable for use in lieu of true two-way data



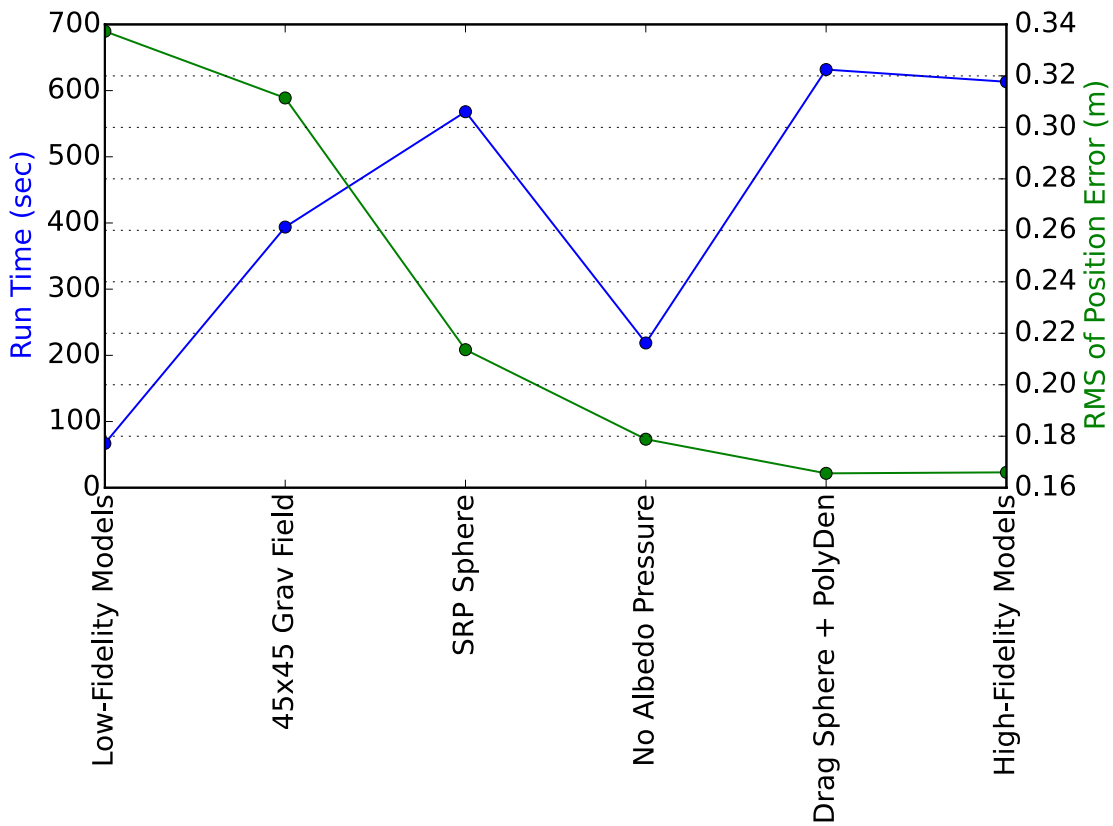
One-way GPS Doppler



Two-way & Pseudo Two-way GPS Doppler

Simplified Filter Performance: Solution Accuracy & Run Time

- Lower orbit solution accuracy compensated by improved filter run time
- Earth albedo & thermal emissivity models computationally expensive, but omission does not significantly degrade low-fidelity orbits
- Preliminary results yield ~ 88% improvement in run time, & solutions still satisfy MRO reconstruction requirements

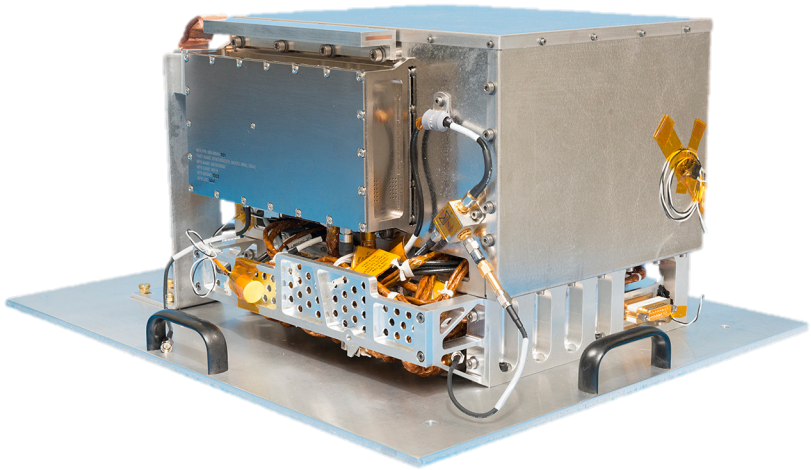


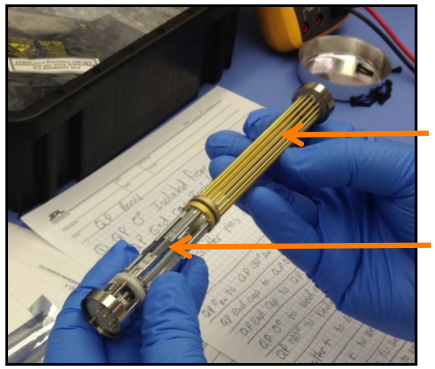
Acknowledgements

- This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

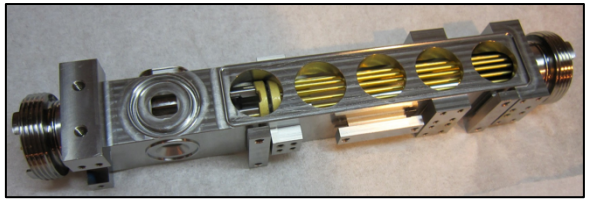
DSAC Demonstration Unit

- Current clock payload SWaP:
  - 29 cm x 26 cm x 23 cm (complete payload)
  - 16.5 kg (clock package)
  - 46.6 W (clock package)
- TriG POD GPS receiver
- Identifying pathways to build deep space infusible version (5 kg/20W)

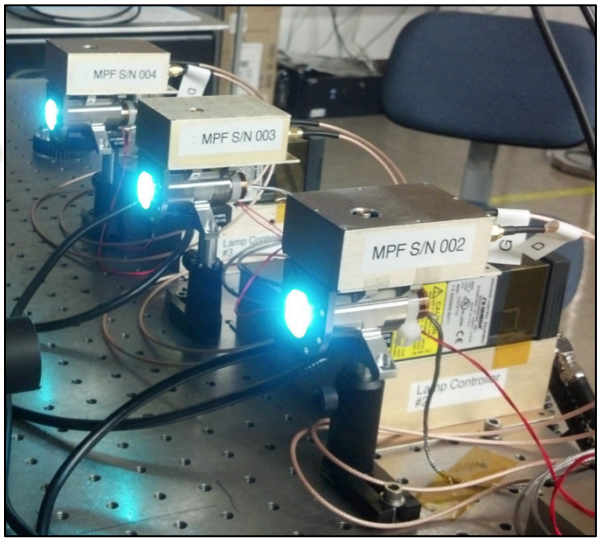


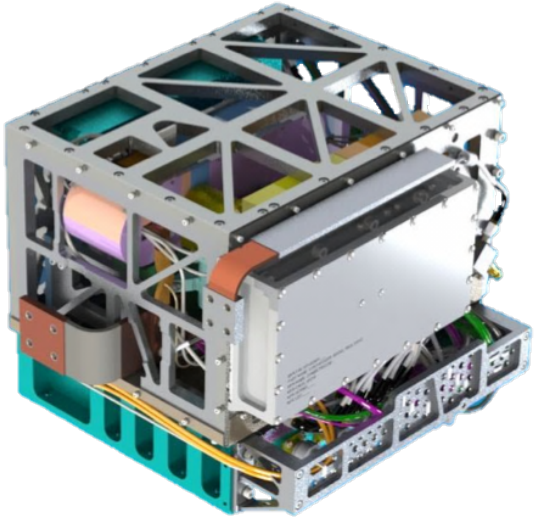


Titanium Vacuum Tube



Mercury UV Lamp Testing



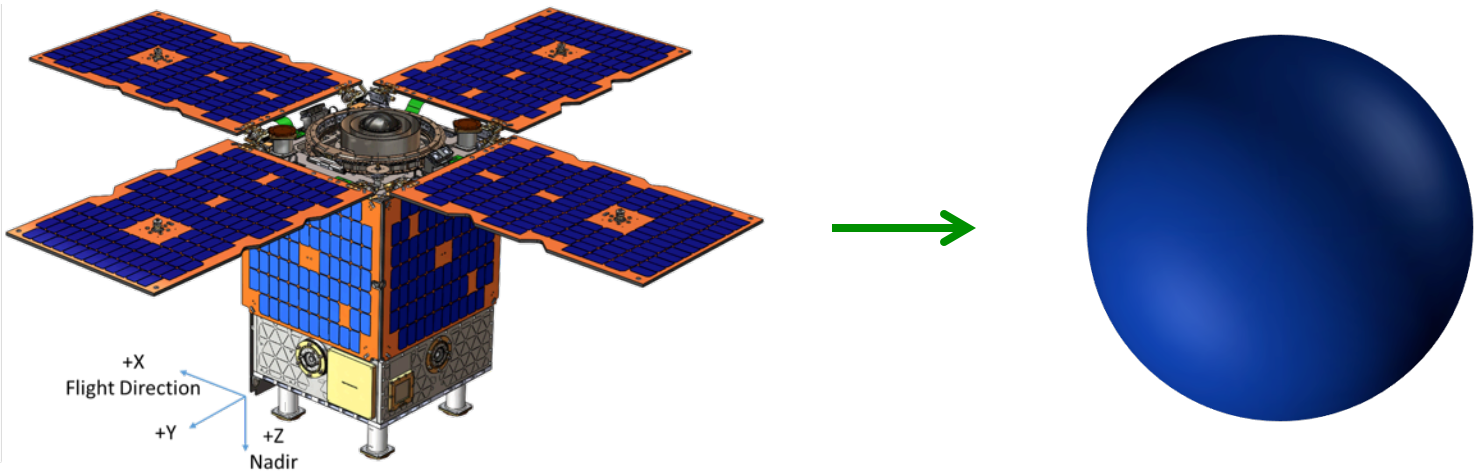


Spacecraft Shape Model

- High-fidelity shape model:
  - 8 flat plates oriented in spacecraft-fixed frame
  - Semi-empirical surface reflectivity properties

- Solar pressure & drag models require attitude knowledge to compute cross-sectional area and effective reflectivity coefficient

- Reducing spacecraft model to sphere removes attitude knowledge requirement, simplifies geometric computations

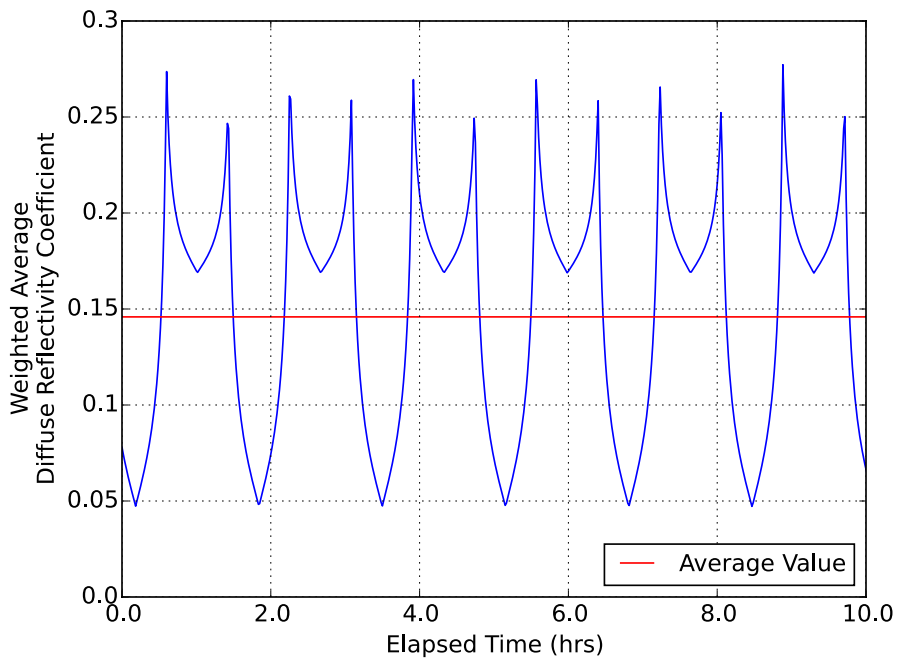


Spacecraft Surface Reflectivity Model

- Spherical spacecraft model uses a weighted average reflectivity coefficient
  - Computed from 8-plate model & nominal attitude profile:

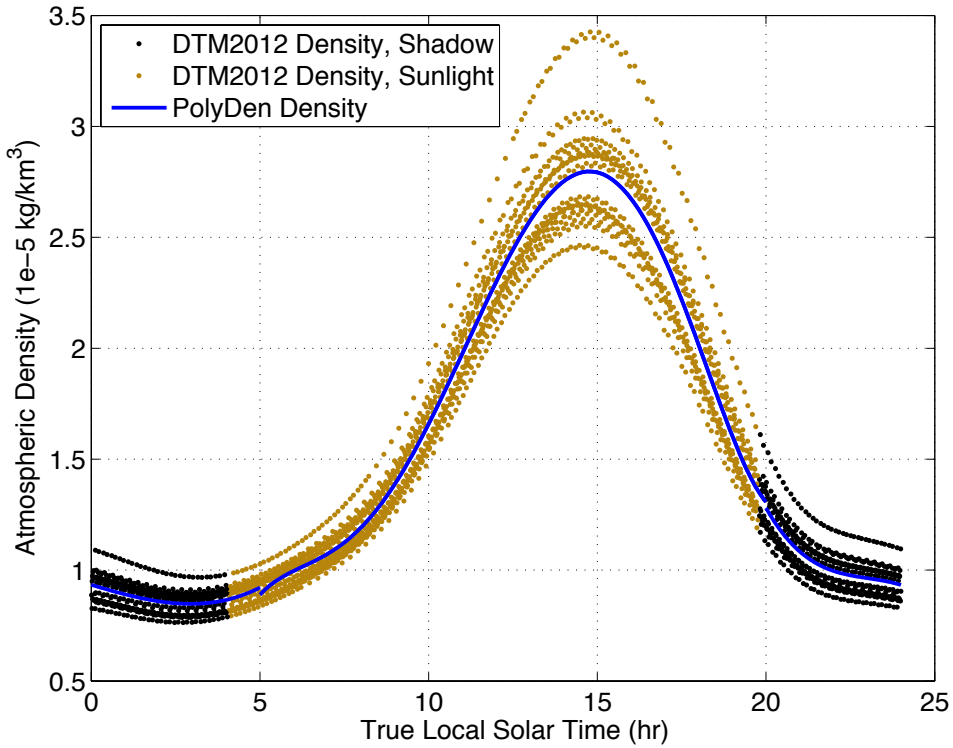
$$\bar{\nu}_d(t) = \sum_{i=1}^{8} \frac{a_{\odot,i}(t)}{A_{\odot}(t)} \nu_{d,i}$$

- Spherical spacecraft model uses mean of weighted average reflectivity coefficient (~0.15)
- Spherical model does not account for specular reflectivity of flat plates



PolyDen Atmospheric Density Model

- DTM-2012 model based on solar flux, geomagnetic activity, thermosphere constituents at spacecraft altitude, latitude, & local solar time
- Simplified density model developed by fitting polynomials to DTM-2012 density values
  - Independent variable = true local solar time
- When necessary, updated DTM-2012 densities computed on ground and new polynomials uploaded to spacecraft



PolyDen Atmospheric Density Model

- θ = true local solar time

$$f(\theta) = \begin{cases} f_1(\theta), & \text{if } \theta \in [5 \text{ hr}, 20 \text{ hr}] \\ f_2(\theta), & \text{if } \theta \in [0 \text{ hr}, 5 \text{ hr}) \\ f_3(\theta), & \text{if } \theta \in (20 \text{ hr}, 24 \text{ hr}) \end{cases}$$

$$f_1(\theta) = 7.29\text{e-}10(\theta^5) - 4.33\text{e-}8(\theta^4) + 9.41\text{e-}7(\theta^3) - 9.30\text{e-}6(\theta^2) + 4.34\text{e-}5(\theta) - 6.83\text{e-}5$$

$$f_2(\theta) = 1.47\text{e-}8(\theta^3) + 1.32\text{e-}8(\theta^2) - 4.58\text{e-}7(\theta) + 9.34\text{e-}6$$

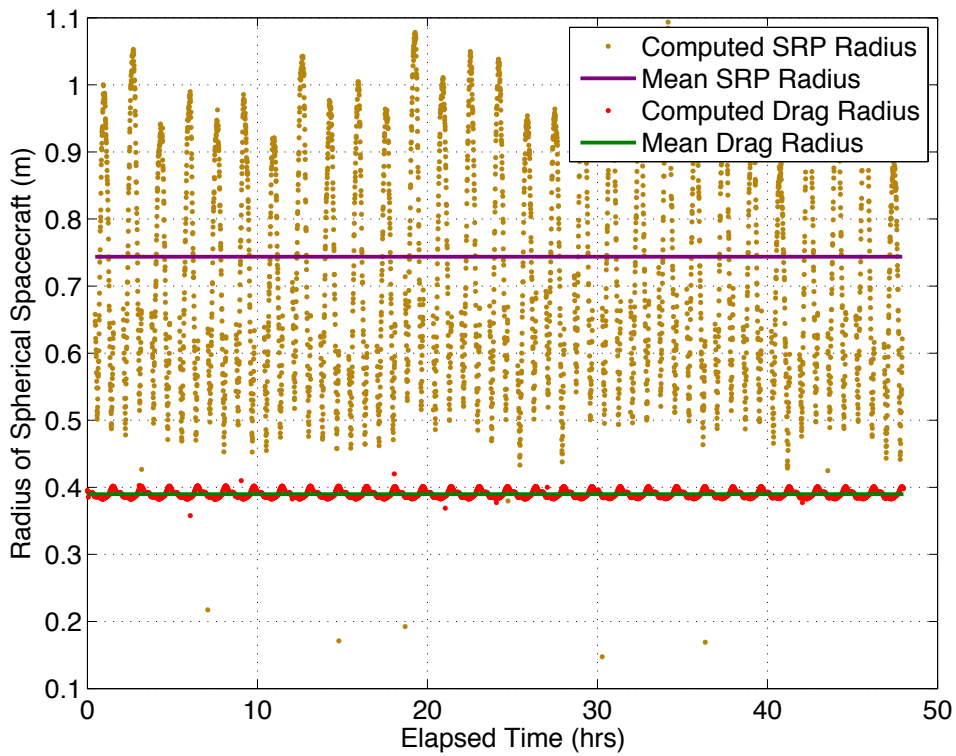
$$f_3(\theta) = -8.96\text{e-}8(\theta^3) + 6.19\text{e-}6(\theta^2) - 1.43\text{e-}4(\theta) + 1.11\text{e-}3$$

Spacecraft Shape Model

- Spherical solar pressure & drag shape models derived from high-fidelity model accelerations

$$\vec{a}_{SRP}(t) = -\frac{Sf(t)C}{mR_{\odot}(t)^2}\left\{\pi r^2\left(1+\frac{4}{3}\kappa_d\nu_d\right)\right\}\hat{u}_{\odot}(t)$$

PolyDen density

Weighted average values

$$\vec{a}_{Drag}(t) = -\frac{\rho(t)C_D\pi r^2 v_B(t)^2}{2m}\hat{v}_B(t)$$