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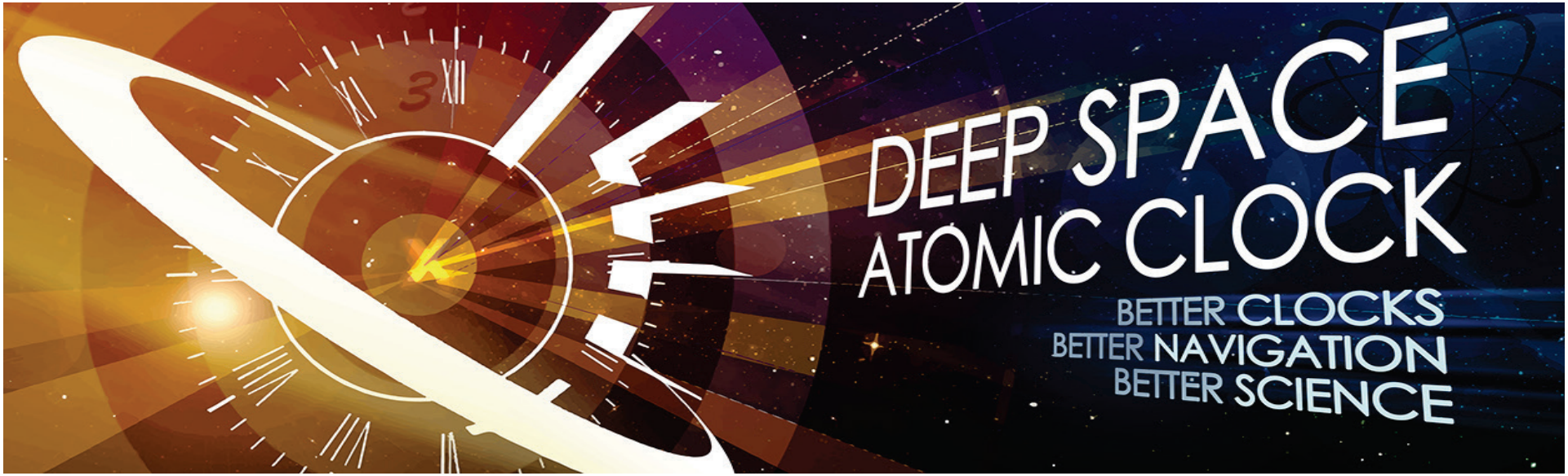

Preliminary Investigation of Onboard Orbit Determination using Deep Space Atomic Clock Based Radio Tracking

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February 2016

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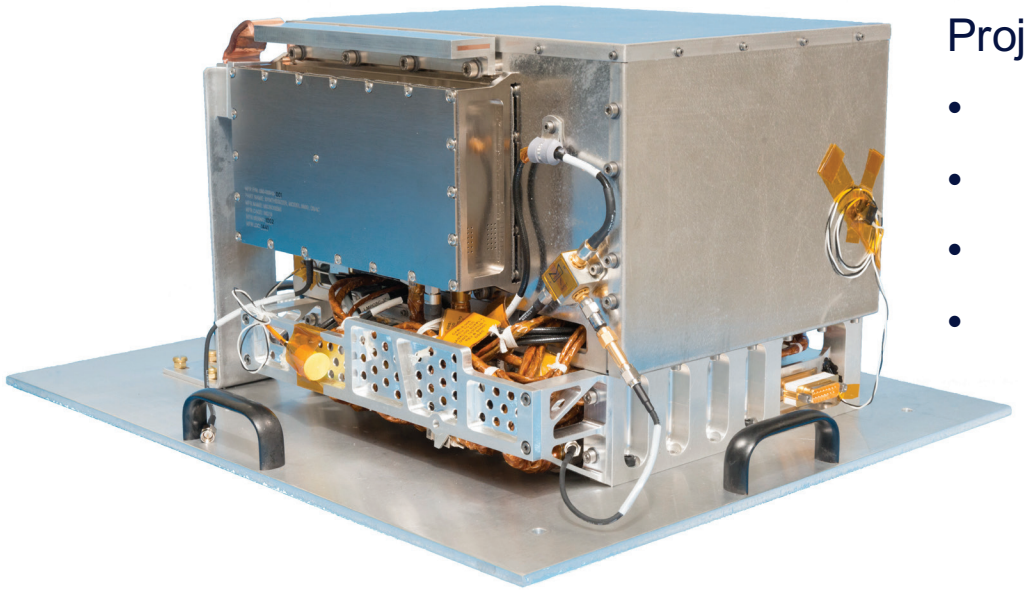
NASA's DSAC Technology Demonstration Mission

Develop advanced prototype (the 'Demonstration Unit') mercury-ion atomic clock for navigation/science in deep space and near Earth space

- Perform year-long space demonstration with launch Spring 2017 – achieving TRL 7
- Focus on technology maturation – ion trap and optical systems – other system components (i.e. payload controllers, USO, GPS) size, weight, power (SWaP) dependent on resources/schedule
- Identify pathways to 'spin' the design of a future operational unit (TRL 7 → 9) to be smaller, more power efficient



Project Status

- Demonstration Unit assembled and tested
- Performance pointing to < 3e-15 stability
- Currently integrating and testing full payload
- Spacecraft integration and test this summer

For More Information, Contact: Todd.A.Ely@jpl.nasa.gov, Website: http://www.nasa.gov/mission_pages/tdm/clock/

DSAC Enables Routine Use of One-Way Radio Tracking

Enable routine use of one-way tracking - more flexible/robust mission ops than two-way

- No degradation in measurement accuracy - one-way tracking with DSAC as accurate as its equivalent two-way counterpart
- Fully utilize multiple spacecraft per aperture tracking – increases tracking to all spacecraft at Mars
- Enable use of uplink tracking with low gain antennas on spacecraft – removes most attitude constraints for tracking

Fundamental to enabling real-time, on-board deep space radio navigation

- Using one-way on the uplink coupled with low gain antennas enables use of the DSN as a broadcast navigation system

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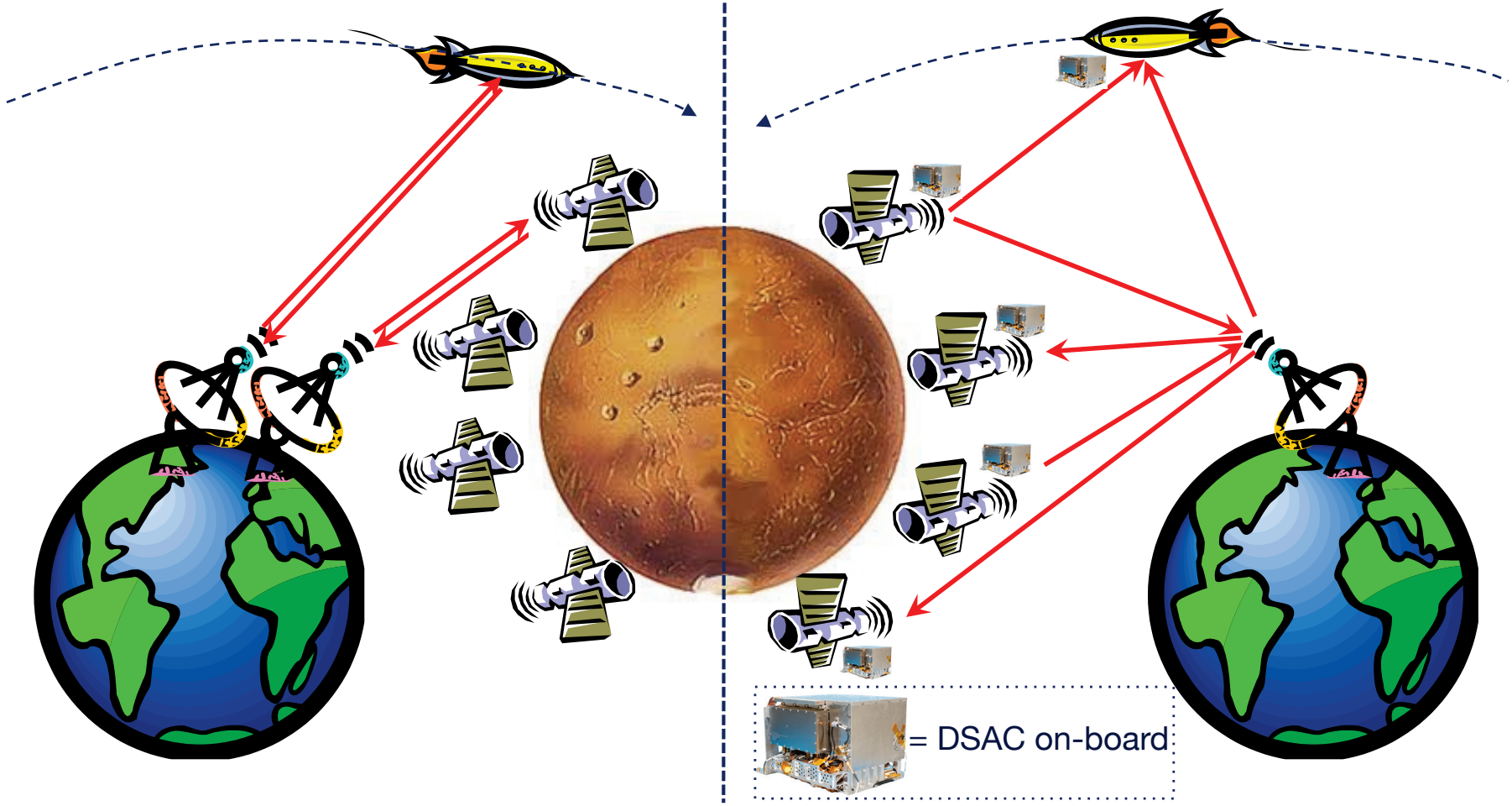
Deep Space Atomic Clock Project

Implementing a Deep Space Tracking Architecture

Today's 2-Way Radio Navigation

Tomorrow's 1-Way Radio Navigation



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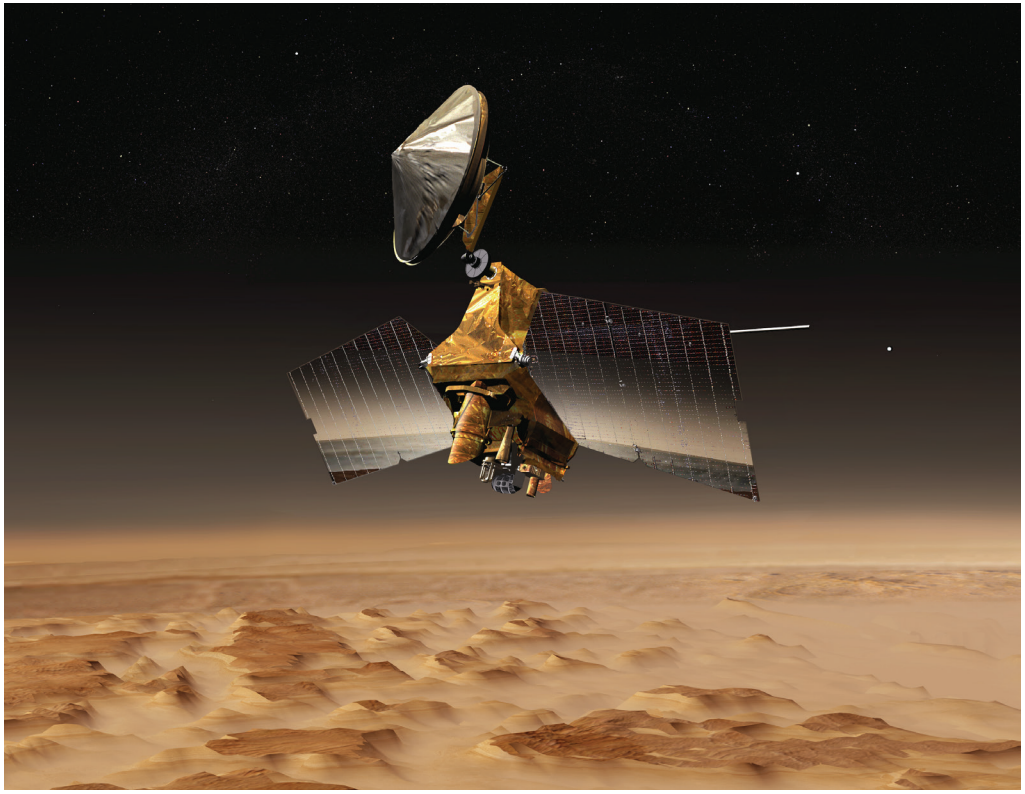
Considerations for Onboard Orbit Determination

- Prior analysis demonstrated accuracy of one-way radiometric tracking produced with DSAC as the receiver's reference is sufficient for precision orbit determination (OD)
  - Two-way radiometric or one-way with DSAC solutions using state of the art high fidelity models and ground-based software produce similar orbit accuracies
    - 1 to 2 meters for a typical Mars orbiter

- Translating to an onboard application presents challenges
  - JPL has a proven system – AutoNav – that processes passive optical imagery for onboard OD
    - Successfully demonstrated on Deep Space 1, Deep Impact, and Stardust
  - Onboard CPU speed, throughput, memory, and storage are constrained resources
  - Adding radio data processing to AutoNav will rely much more heavily on model-based dynamics than optical data

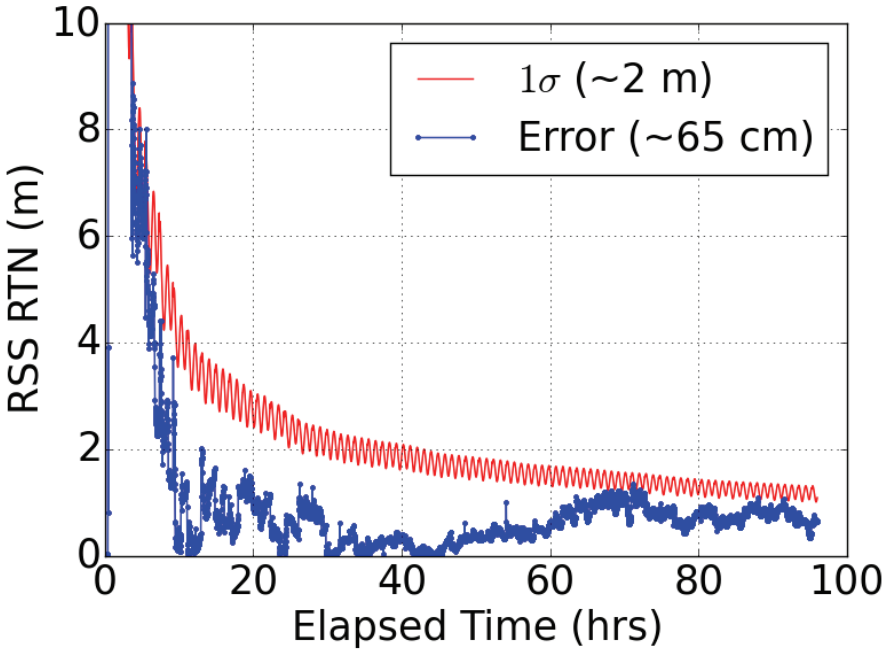
- Useful to explore model simplifications and trades on OD accuracy in the context of a relevant problem – for this study a low-altitude Mars orbiter selected

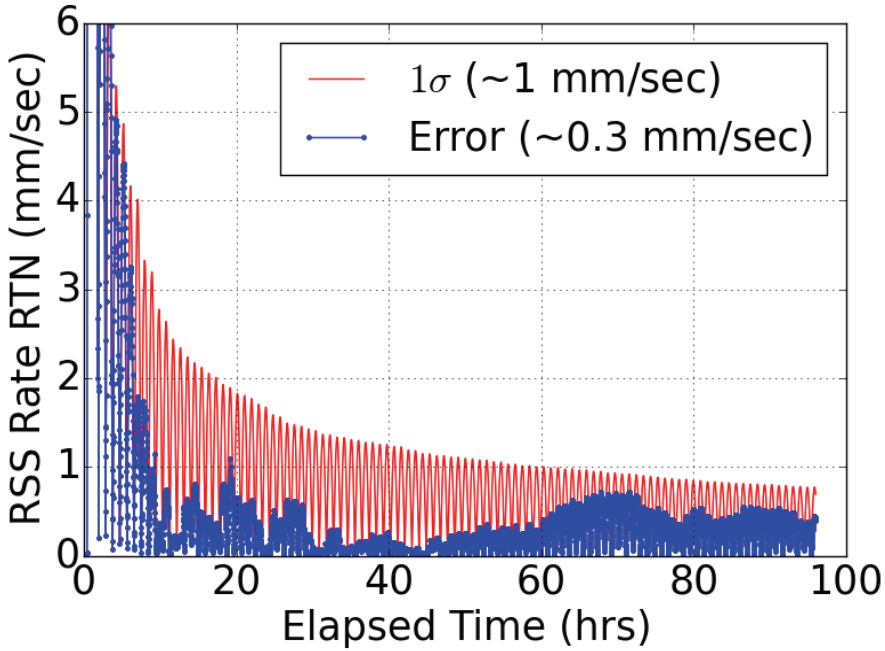
Mars Orbiter Model Problem



- Reference case is Mars Reconnaissance Orbiter (MRO)
- OD using one-way uplink radio tracking with DSAC to achieve
  - Radial error < 0.5 m
  - Transverse error < 33 m
  - Cross-track error < 13 m
- What model simplifications are possible to still meet these requirements
  - Drag model?
  - Spacecraft shape?
  - SRP?
  - Gravity field size?
  - OD filter?

Baseline Solution with HiFi Models and One-Way Uplink Radio Tracking



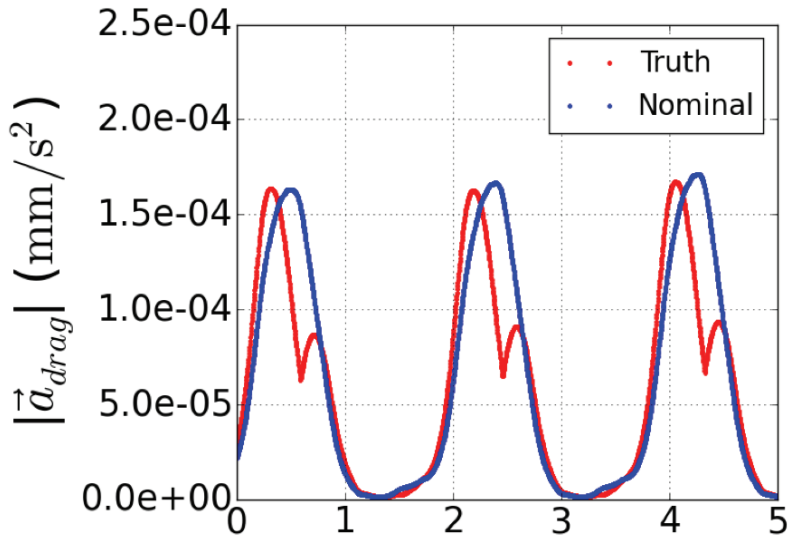


- High fidelity models with injected truth errors simulated at current operational levels
  - Stochastic drag noise a Gauss-Markov (ECRV) process at 10% steady state levels
  - Solar pressure scale factor bias error at 10%
  - Initial condition errors at 5 cm, 5 mm/s – more on this later
  - Observed Earth media delays, range bias errors at 2 m each pass, DSAC modeled as white frequency noise with Allan Deviation (A.D.) of 3.e-15 @ 1-day
- Filter is a linearized Kalman filter with UD factorization

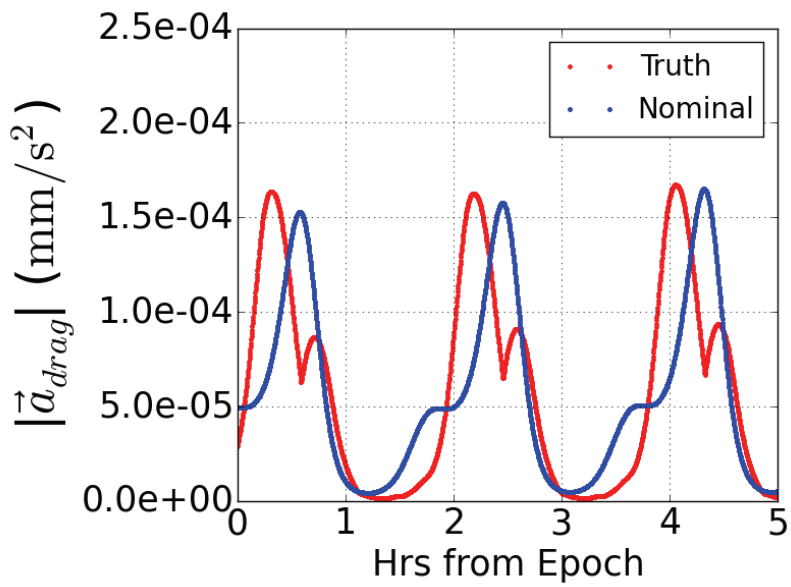
Model Simplifications – Drag Model and Spacecraft Shape

- Replace complex Mars Gram 2005 with a simplified model that only accounts for long period solar flux changes

$$\rho(h,t) = \rho_o \exp\left[-\frac{h-h_o}{H}\right] D(t)$$

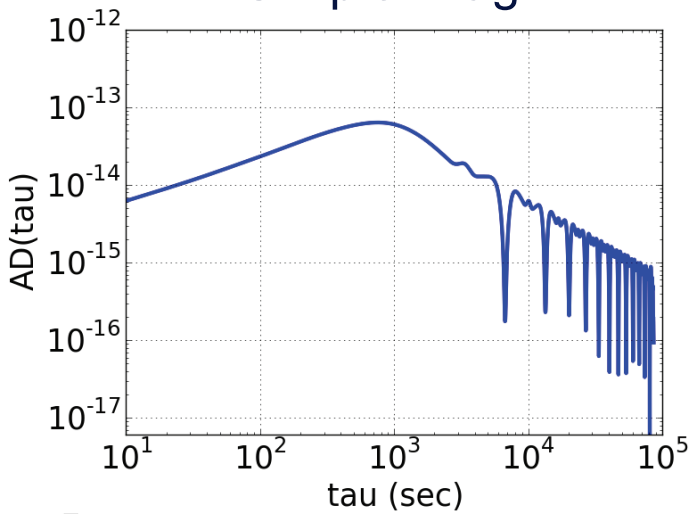


- Replace complex spacecraft shape with a simple – attitude independent – spherical shape and combine with simple density model
  - Eliminate connectivity to the spacecraft attitude system

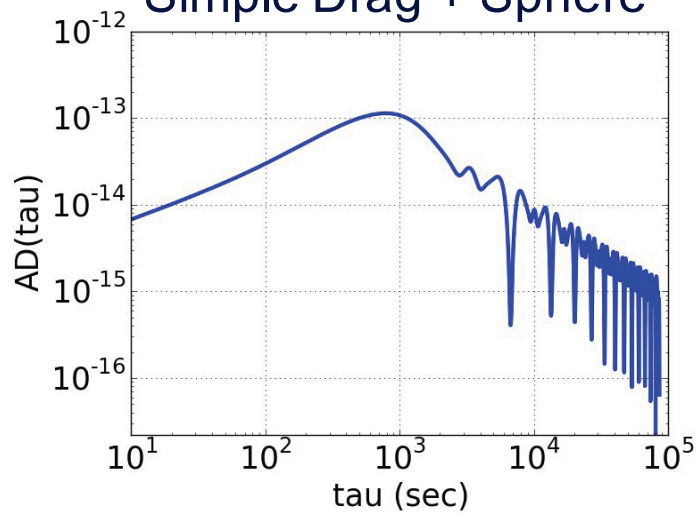


Model Simplifications – Drag Model and Spherical Shape

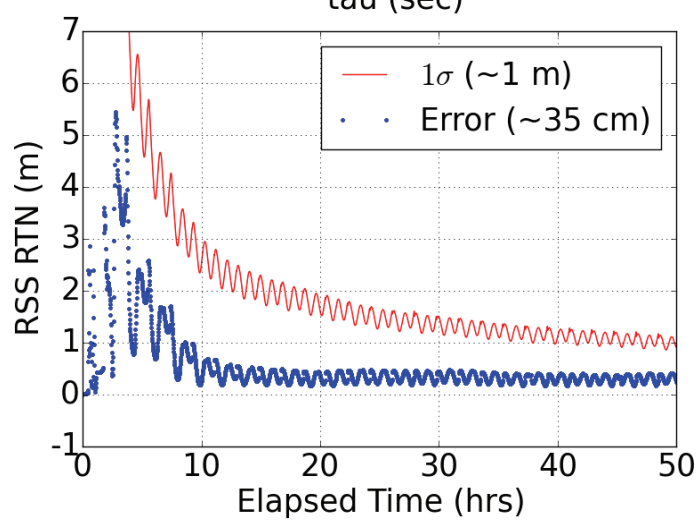
Simple Drag

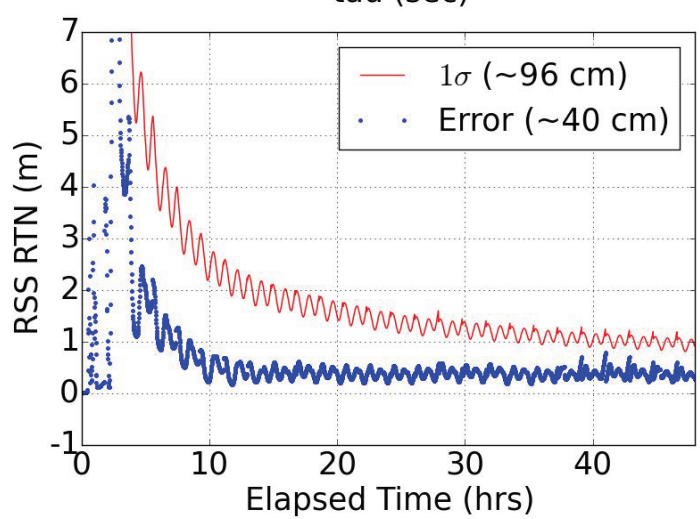


Simple Drag + Sphere



ECRV

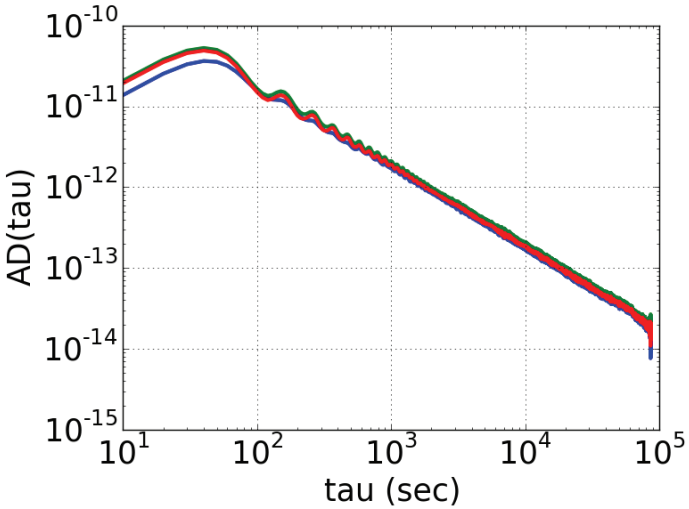




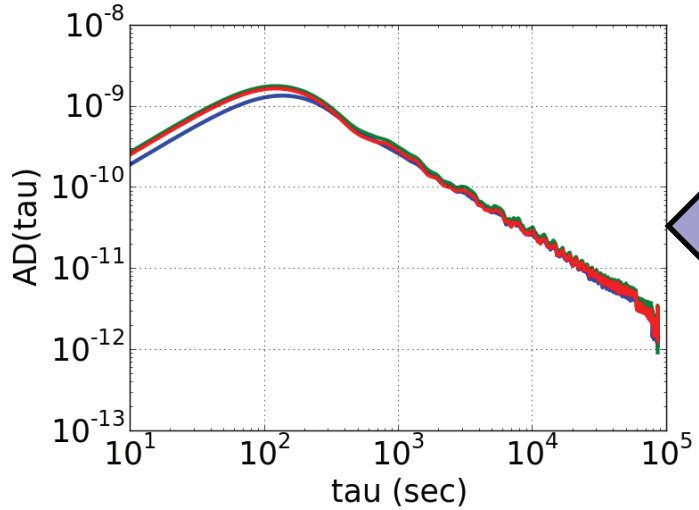
Filter tuned w/ RTN acceleration process noise @ 2 x AD peak

Model Simplification – Reduced Gravity Fields from 95 x 95

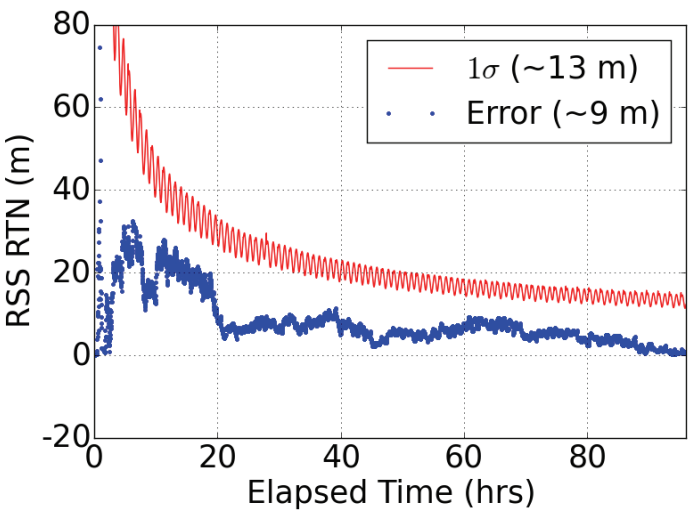
60 x 60

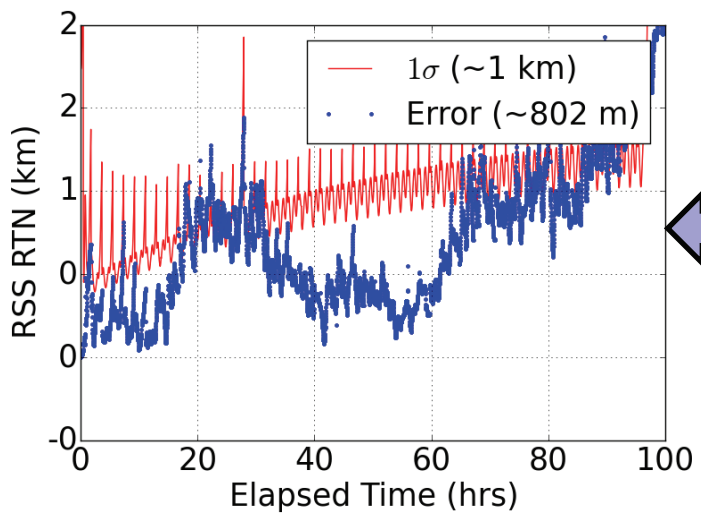


10 x 10



- ECRV, mostly white past 100 s
- 100 x larger than drag



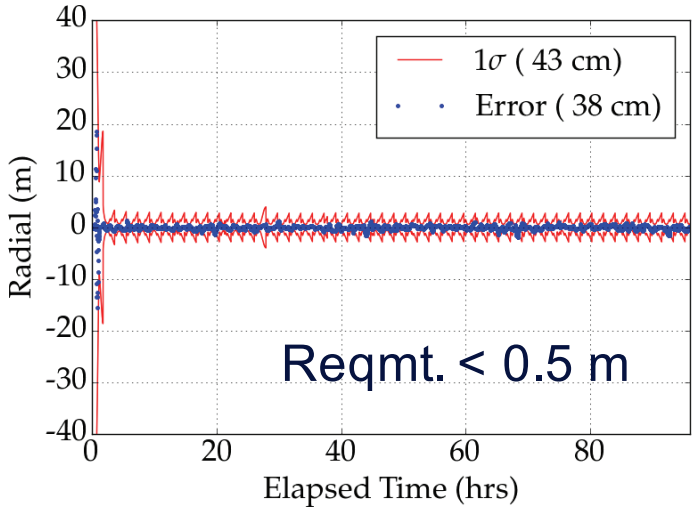


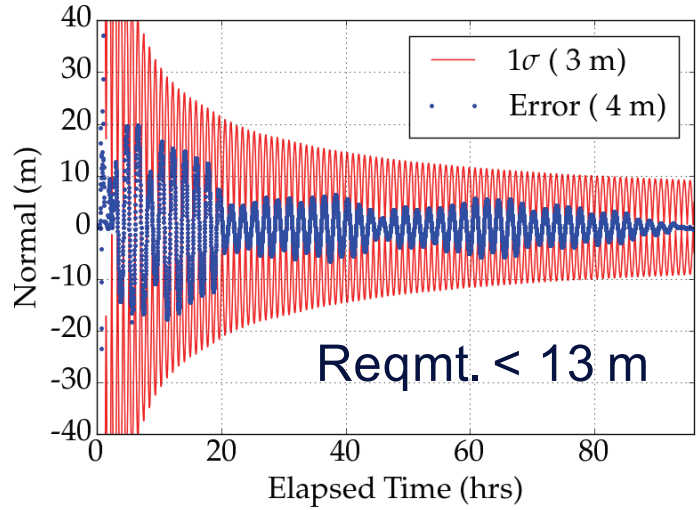
- 60 x 60 satisfies reqmts.
- 10 x 10 diverges

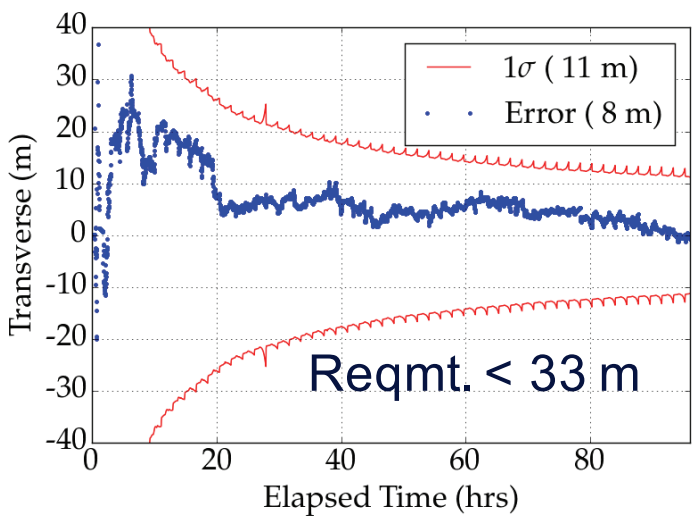
Comparing all of the model simplifications

Case	RMS Pos Err	RMS Vel Err	Accel Mag (km/s^2)	Accel Diff (km/s^2)
Gravity 10x10	800 m	40 cm/s	0.6e-6 to 1.6e-6	1.5e-7
Gravity 40x40	29 m	1.5 cm/s	0.6e-6 to 1.6e-6	6.9e-9
Gravity 60x60	9 m	4 mm/s	0.6e-6 to 1.6e-6	1e-9
Drag Sphere SC	33 cm	0.2 mm/s	1.7e-10	6e-10
Drag Sphere SC & Simple Atm	42 cm	0.3 mm/s	1.7e-10	9e-10
SRP Sphere SC	5 cm	0.03 mm/s	7e-11	4e-12

Filter Performance with all Model Simplifications







- 60 x 60 field selected
  - 50 x 50 doesn't satisfy radial requirement
- Simplified density
- Spherical drag and solar pressure shape
- Process noise tuned for gravity acceleration error
  - Other errors sufficiently small to not effect solution accuracy
- What about the initial condition error?

LKF Sensitive to Initial Condition Error – Experiments with an EKF

EKF Solution Exceedance Rates with Only I.C. Errors

I.C. Error (1σ)	Seed 1 Exceedances	Seed 2 Exceedances	Seed 3 Exceedances	Seed 4 Exceedances	Seed 5 Exceedances
100 m	0 %	0 %	0 %	0 %	0 %
1,000 m	0 %	0 %	0 %	0 %	0 %
10,000 m	6.9 %	0 %	69.2 %	0 %	19.7 %

EKF Solution Exceedance Rates with All Errors

I.C. Error (1σ)	Seed 1 Exceedances	Seed 2 Exceedances	Seed 3 Exceedances	Seed 4 Exceedances	Seed 5 Exceedances
100 m	16.9 %	97.1 %	19.7 %	97.2 %	42.5 %

- EKF is not recommended – will need to examine iterated LKF which will increase the computational load

Conclusion

- Significant model simplifications possible that yield viable OD orbit solution accuracy
  - For low altitude Mars orbiter reduced gravity is the biggest error contributor – other errors well within the gravity error
- EKF not recommended for this application – other method needed for robust acquisition and steady state solutions
- Different missions will have different needs, but for a Mars orbiter, onboard OD possible with reduced computational complexity
- Next steps:
  - Quantify computational improvement
  - Improve solution robustness (with editing and adaptive techniques)
  - Explore other mission phases – such as approach and orbit insertion