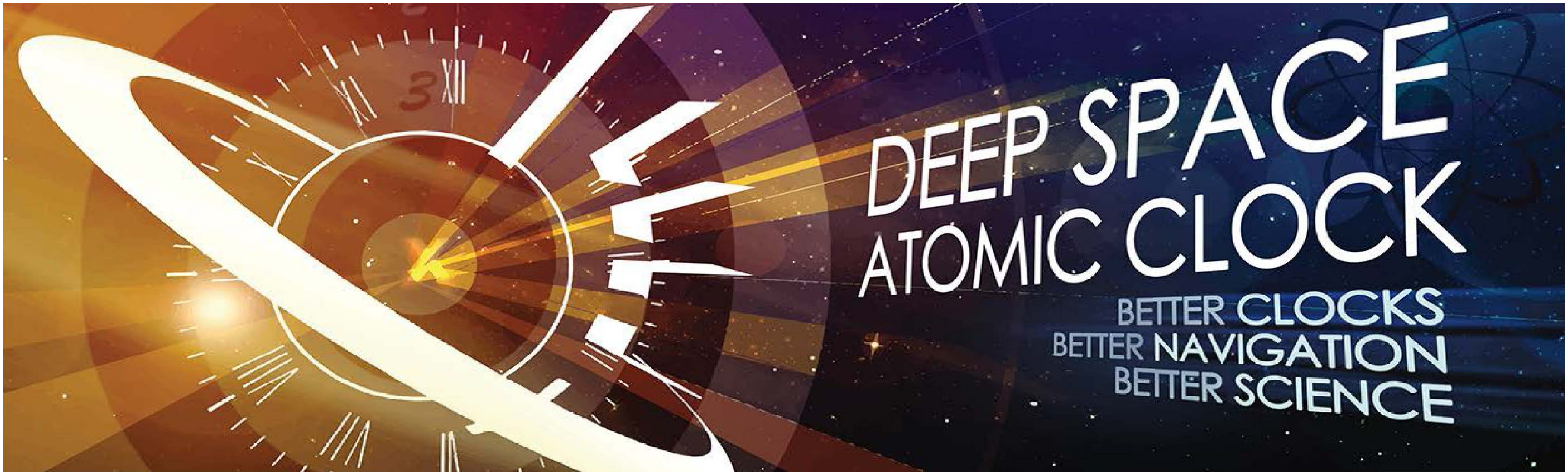
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



Advancing Navigation, Timing, and Science with the Deep Space Atomic Clock

Todd Ely
Principal Investigator

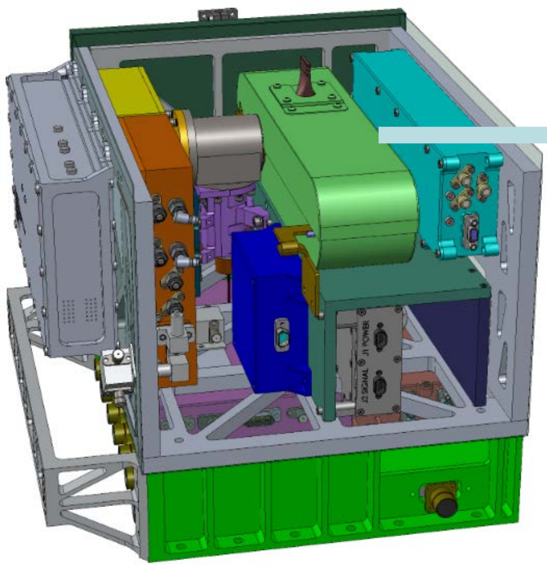
Jill Seubert
Investigation System Engineer

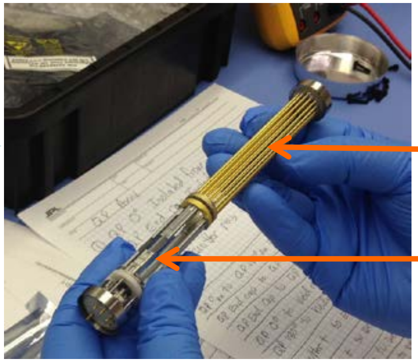
Julia Bell
Project Systems Engineer

18th Century Navigation and Clocks – Harrison's H4

H4 lost 5 seconds of time in its first 62 day trans-Atlantic journey in 1762 leading to an unprecedented longitude knowledge with only a 2 km error; paving the way for a new era of safe shipping and exploration.

21st Century Navigation and Clocks - DSAC





Multi-pole Trap

Quadrupole Trap

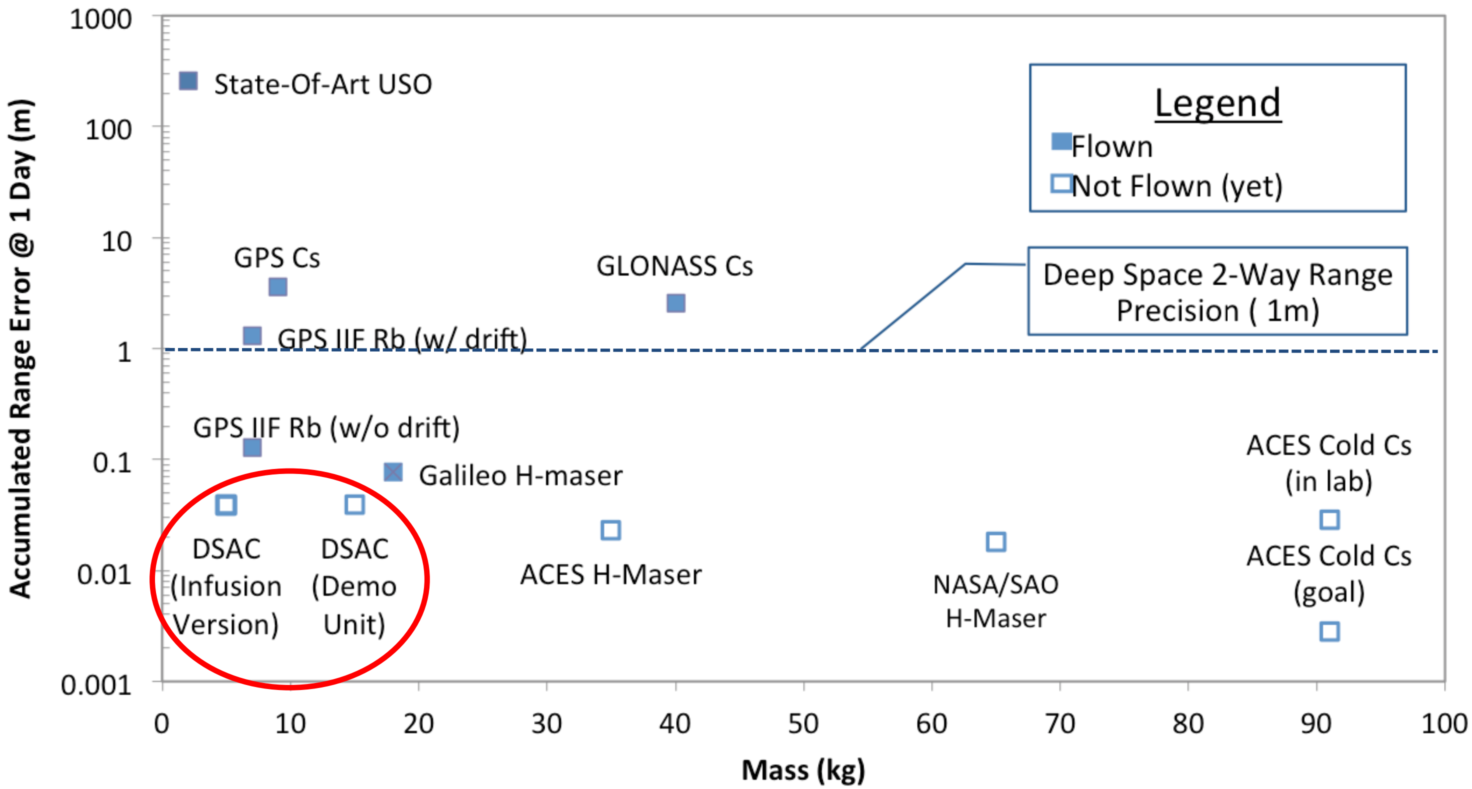
Titanium Vacuum Tube

DSAC is a small, low-mass mercury-ion clock suitable for deep space flight.

In a 62 day space expedition DSAC would drift 5 nanoseconds resulting in 2 m contribution to a range measurement error. Roughly the same performance as the existing Deep Space Network (DSN) ground clocks.

DSAC TDM flight in 2015 will enable development of a more power efficient and smaller clock for a deep space flight opportunity soon thereafter.

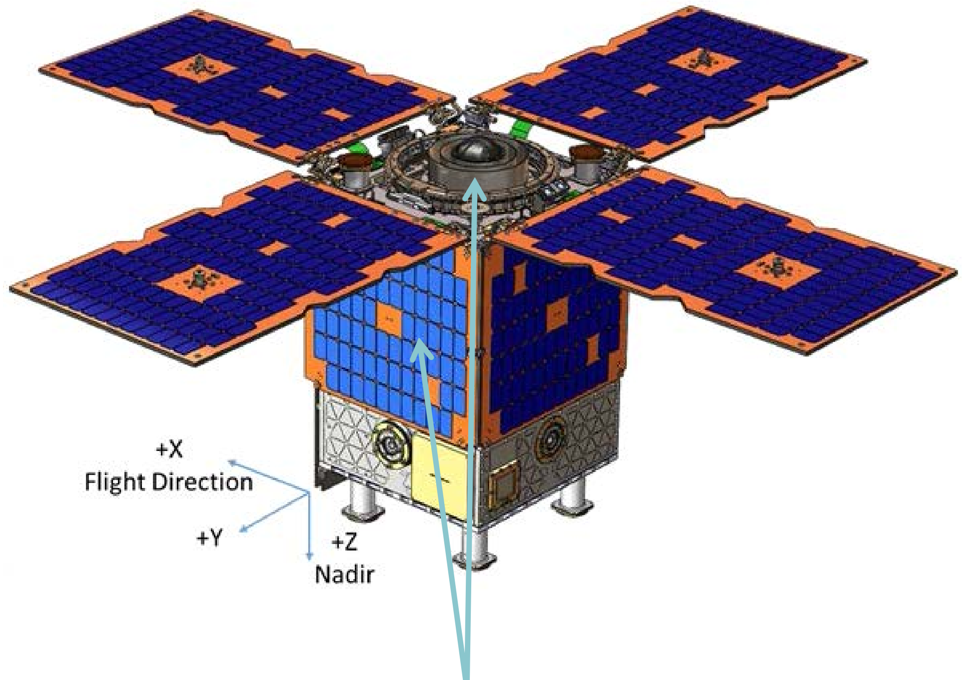
DSAC vs Other Space-Based Clocks



- DSAC outperforms (current CBE AD ~ 1.5e-15 at one day) any other space based oscillator/clock on a per mass basis.
- Combined with long-life potential, DSAC is an ideal technology for infusion into deep space exploration as well as GNSS applications

DSAC Demonstration Payload Objective and Hosting

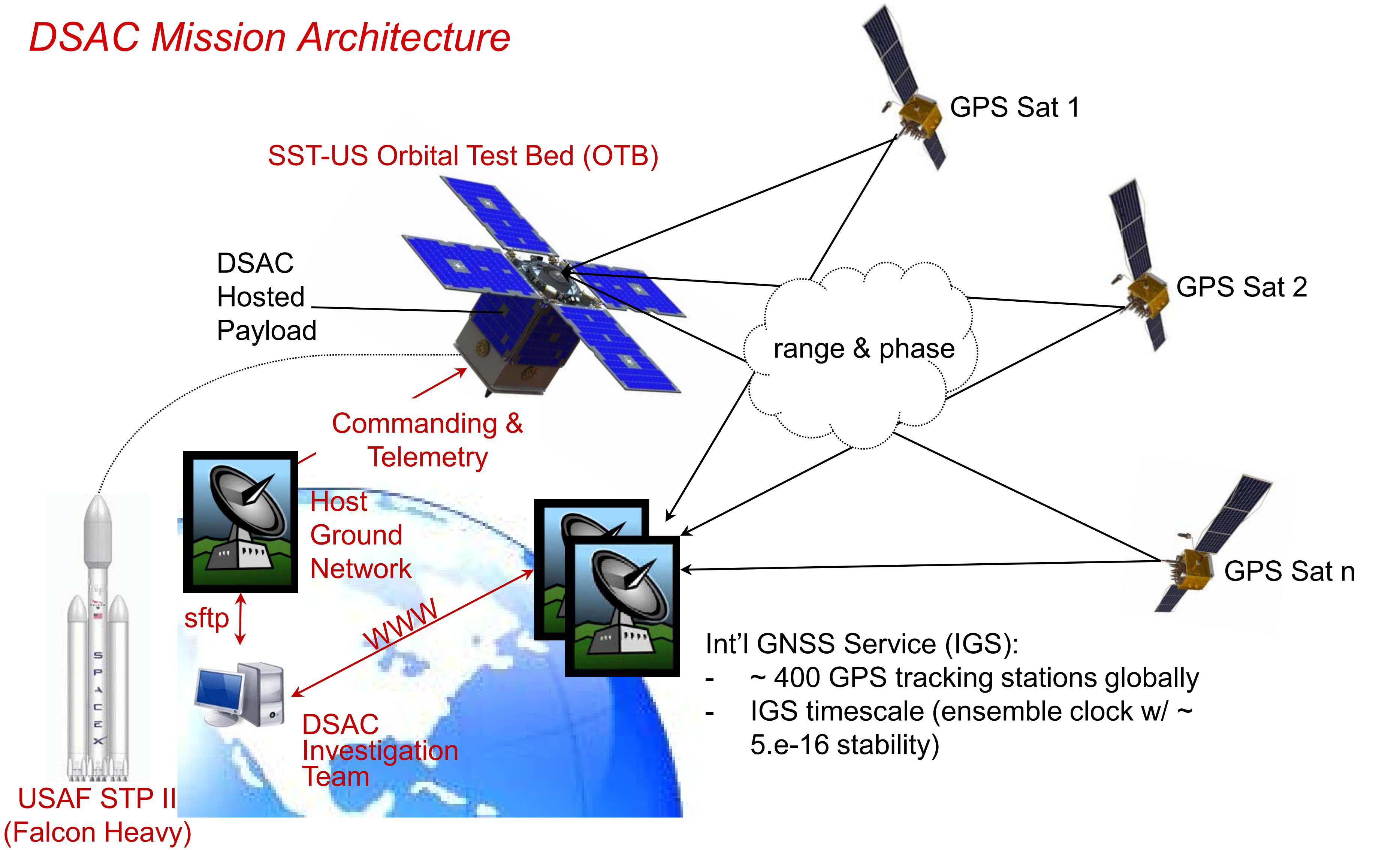
- Technology Demonstration Mission to mature DSAC from current TRL 5 to TRL 7 via one-year flight experiment of a demonstration unit
- Hosted payload on Surrey Orbital Test Bed (OTB) spacecraft launched as part of USAF STP II (a Space X Falcon 9 Heavy) currently scheduled for March 2016
- Project’s focus is maturing the technology – ion trap and optical system (aka, the ‘Physics Package’)
  - Other system components (i.e. payload controllers, USO, GPS) SWaP dependent on resources/schedule
- Future infusible version (TRL 7 → 9) would ‘spin’ this design to produce a smaller, more power efficient flight unit



DSAC Payload

- USO (FEI)
- DSAC demonstration unit
- TriG GPS receiver (Moog Broad Reach)
- Zenith-oriented choke ring GPS antenna

DSAC Mission Architecture



Int'l GNSS Service (IGS):

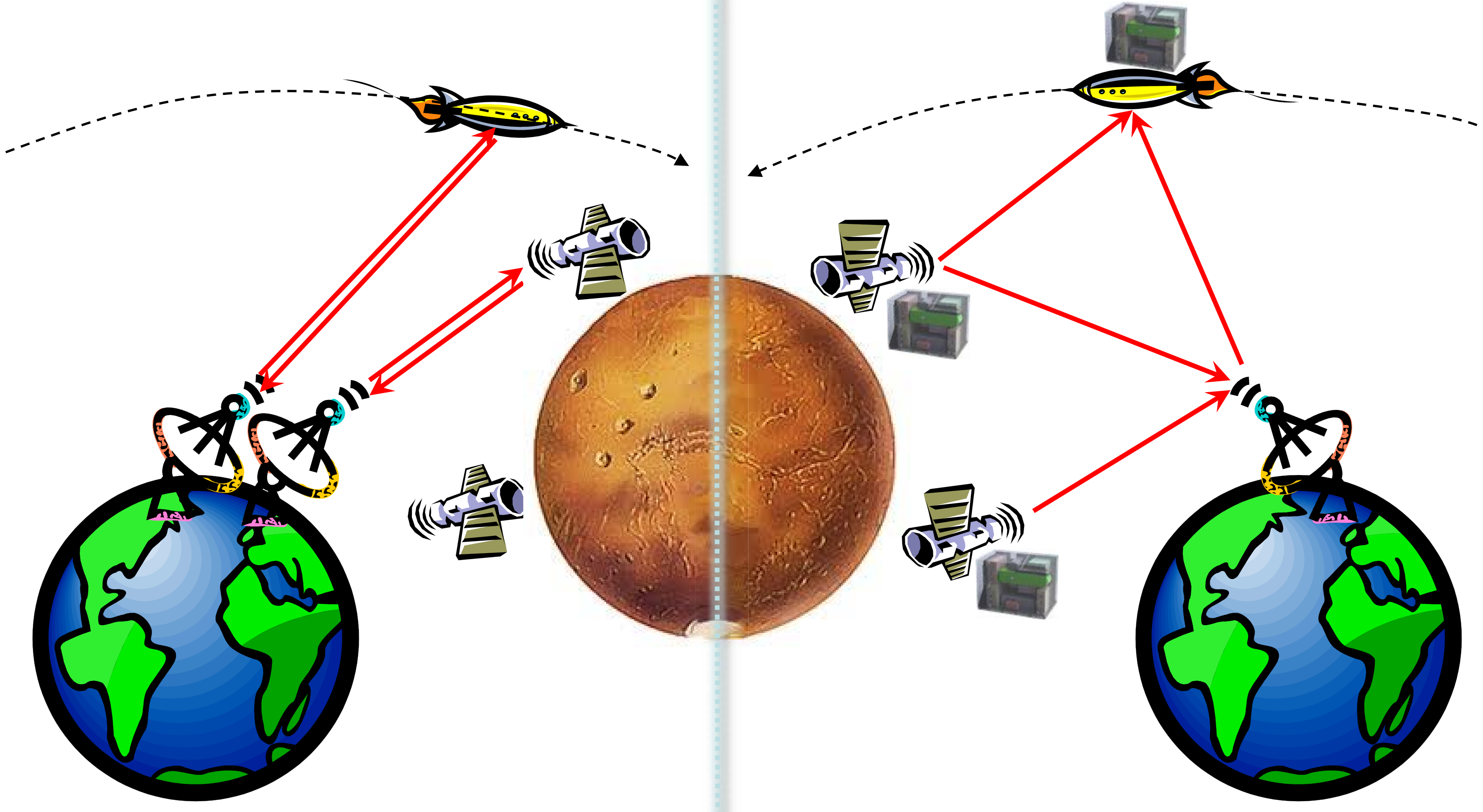
- ~ 400 GPS tracking stations globally
- IGS timescale (ensemble clock w/ ~ 5.e-16 stability)

DSAC's Crosscutting Benefits

Near Space Navigation/Timing	Deep Space Navigation	Science	Deep Space Timing	Autonomy
• Diversifies clock industrial base - enhancing national security • Provides needed time accuracy/stability for next generation secure communications • Significant aid to users with compromised GPS visibility – need only 3 in-view to position	• Multiple Spacecraft Per Aperture at Mars - doubles useful tracking • Full use of Ka-band tracking – OD uncertainty at Mars < 1 m (10 x improvement) • Outer planets users gain significant tracking efficiency – 15% at Jupiter 25% at Saturn	• Would enhance gravity science at Mars, GRACE-level determination of long term gravity with one satellite, at Europa, robust gravity science solution • Enhance planetary occultation science with 10 x better data	• Significantly reduce spacecraft timekeeping overhead • Improve reliability of critical time-dependent autonomous spacecraft functions • Reduce risks to long-term spacecraft hibernation	• Enables autonomous radio navigation (robotic and crewed) • Enhances EDL and precision landing • Key component to autonomous aerobraking • Coupled with OpNav, enhances primitive body exploration

A More Efficient and Flexible Deep Space Tracking Infrastructure

Today's 2-Way Radio Navigation | *Tomorrow's 1-Way Radio Navigation*



DSAC and the Deep Space Network

- 1-Way tracking
  - w/MSPA nearly doubles data to customers with the existing infrastructure
  - at Jupiter is 15 % more efficient, Saturn is 25 % more efficient
- No need for 3-Way ranging
- More flexible 1-Way DSN architecture for asynchronous services
  - Uplink ranging frees bandwidth on the downlink for more science data
- Enables space-based network navigation and communication service provided by orbiting satellites at key destinations such as Mars, Moon, etc.
- Spacecraft timing becomes more autonomous
- 1-Way Ka-band carrier tracking up to 10 x more precise than 2-Way at X-band

Timing and Operational Complexity

- Precise knowledge of onboard time necessary for successful execution of many deep space activities
  - Orbit insertion, encounters, EDL, hibernation
- DSAC eliminates much complexity of onboard time keeping, expands operational flexibility and reduces operational risk
  - Traditional maintenance of onboard time involves frequent correlations of onboard and ground clocks
  - Up to daily correlation activities must be performed by ground processing team in order to satisfy mission requirements
  - Risk of science/engineering data misinterpretation
  - Risk of incorrect time stamps in critical data and/or inconsistencies among coordinated teams resulting in mission failure
- DSAC enabled onboard maintenance of precise absolute time sufficient for autonomous navigation scenarios
- DSAC-enabled onboard time will be accurate to 1 microsecond in 10 years – much more stable than typical 1 millisecond accuracy required for most mission critical events
  - No requirement for time calibration activities following initial pre-launch calibration
  - Risk associated with updates to ground-based timing in series with critical flight sequences development significantly reduced or eliminated

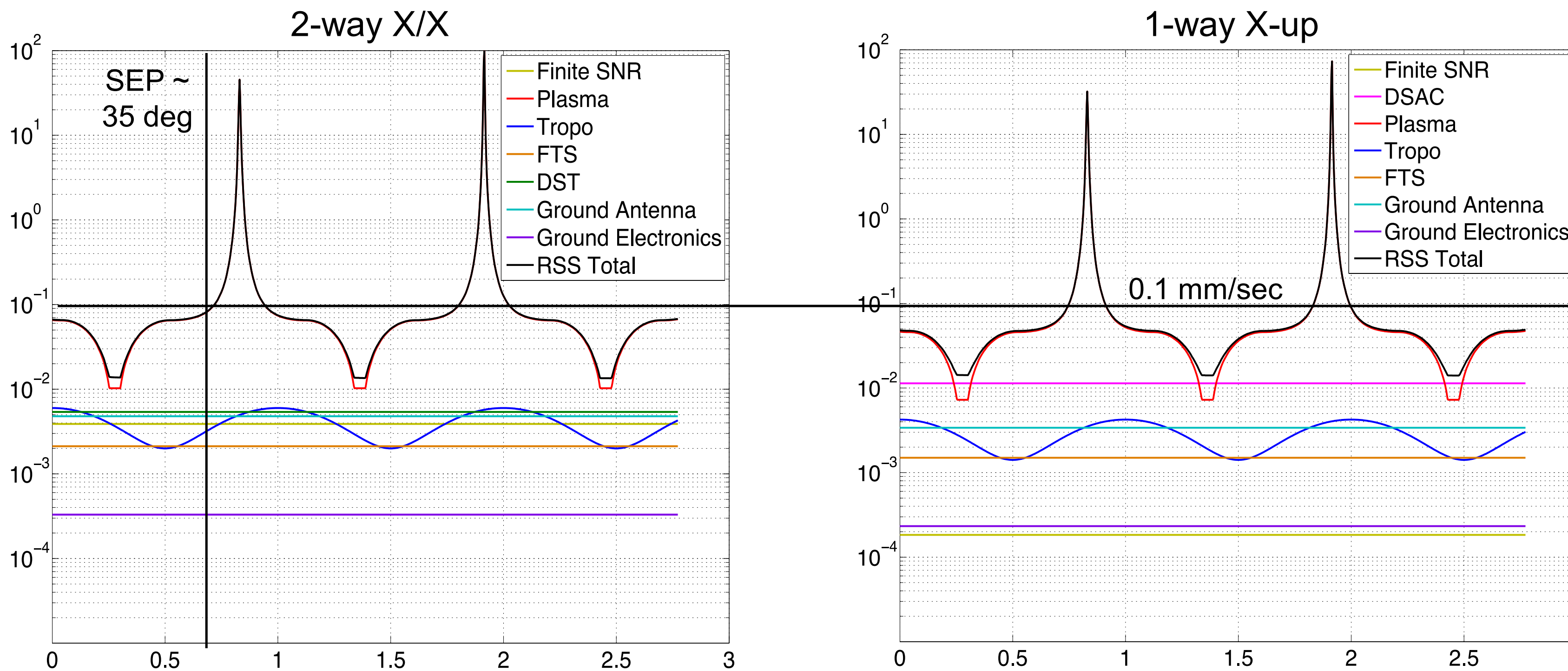
Expected 1-way and 2-way Doppler Data Quality

- Expected of DSAC-enabled 1-way Doppler must be understood in comparison to analogous 2-way data in order to quantify impact on deep space navigation and radio science performance

Source	Model	Comments
Finite SNR	Function of telecom system design	Baselined for Cassini telecomm design
Solar/Ionosphere Plasma	Function of Sun-Earth-Probe (SEP) angle	Allan Deviation is frequency dependent; assumed uncorrelated on up/downlink; Scaled to account for long-term noise correlations
Troposphere	Seasonal sinusoidal model at zenith, scaled by 1/sin(elevation)	Allan Deviation is frequency independent; assumed uncorrelated on up/downlink
DSN Frequency and Timing	White frequency noise	Allan Deviation is frequency independent
DSAC	CBE performance	Allan Deviation is frequency independent
Transponder	White frequency noise	Allan Deviation is frequency dependent; Baselined for Cassini Deep Space Transponder
Ground antennas	White frequency noise	Allan Deviation is frequency independent
Ground electronics	White frequency noise	Allan Deviation is frequency independent

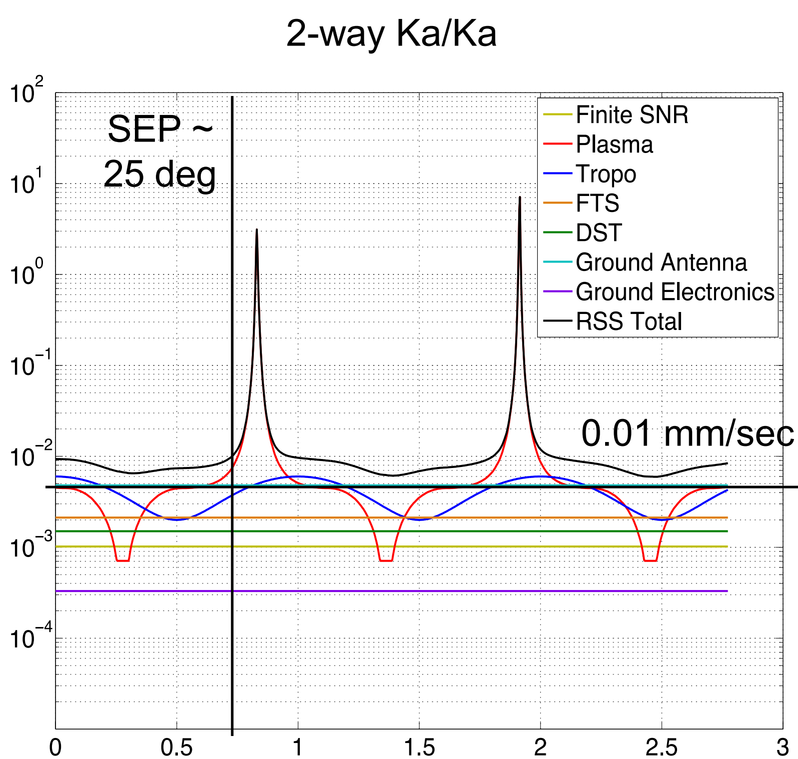
1-way and 2-way X-Band Doppler Quality (60-sec)

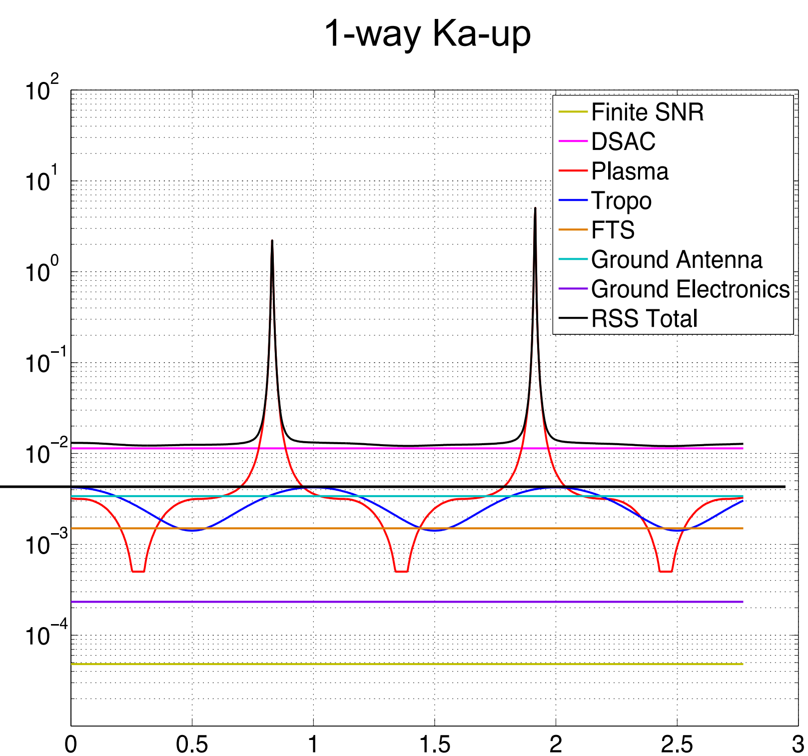
- Doppler noise profiles shown for potential mission at Europa
  - Solar plasma scaled by 2.7x to capture dominant flyby timescale
  - Troposphere model shown for zenith tracking from the Southern hemisphere
- Both 2-way and 1-way profiles dominated by solar plasma noise
  - Traditional 0.1 mm/sec data weight conservative for SEP > 35 deg, optimistic for SEP < 35 deg
  - 1-way data ~ 30% better than 2-way data excepting near solar opposition, where it is ~ equivalent



1-way and 2-way Ka-Band Doppler Quality (60-sec)

- Both 2-way and 1-way profiles only dominated by solar plasma noise for SEP < 25 deg
- For SEP > 25 deg, noise dominated by troposphere, ground antenna, and DSAC (1-way only)
- Traditional Ka-band data weight of 0.01 mm/sec appropriate for 2-way data, excepting solar conjunction
- 1-way Ka-up noise dominated by DSAC stochastic clock noise (~ 0.014 mm/sec), practically equivalent to analogous 2-way Ka/Ka Doppler noise





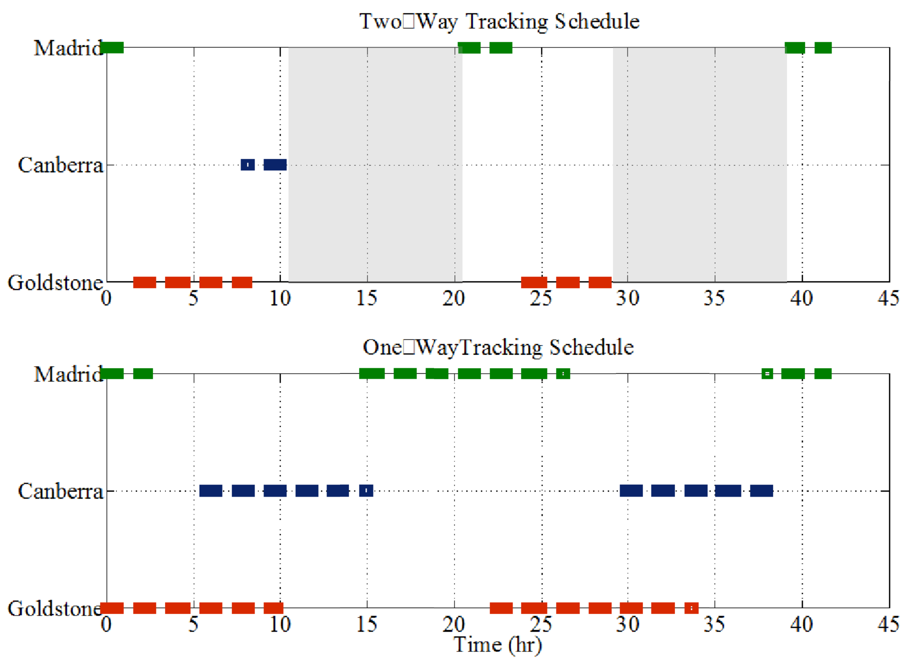
Deep Space Examples

- Mars orbiter and Europa flyby (potential future missions) studies illustrate specific examples of DSAC benefits to deep space navigation & radio science
  - A Mars orbiter case demonstrates the orbit determination & gravity estimation performance using DSAC-enabled 1-way Doppler tracking data, and compares the solution quality to that achieved using current 2-way & 1-way (w/ USO) capabilities
    - Assess impact of increased tracking coverage (MSPA) & tracking data accuracy (Ka-Band versus X-Band tracking)
  - Estimation of Europa's gravitational tide provides an example of the utilization of DSAC-enabled 1-way Doppler tracking data for Europa gravity science, and compares the performance against a baseline 2-way tracking architecture
    - Highlights the significance of Doppler measurement quantity and quality for satisfying Europa flyby* gravity science objectives
    - Illustrates the benefits of operating in an uplink-only configuration to allow for low SNR open-loop carrier tracking

*Mission Concept Only – Predecisional – For Planning and Discussion Purposes Only

Simulated DSN Tracking of Mars Orbiter

- Traditional 2-way tracking of a Mars orbiter suffers sometimes-lengthy tracking gaps when the DSN is committed to tracking other spacecraft
- Analysis of MRO and Odyssey tracking schedules shows an average gap length of a few hours, with lengthy gaps (~ 8 to 10 hrs) occurring a few times each month
  - Gap duration and/or frequency predicted to increase with arrival of MAVEN later this year
- 1-way downlink tracking can take advantage of the DSN's existing MSPA capability, such that a signal is available anytime an antenna is pointed at Mars (assumed continuous)



Mars Orbiter Simulated Tracking Data

- Simulation set up to mimic MRO navigation operations
  - Near-polar sun-synchronous orbit (sma = 3649 km, ecc = 0.013, inc = 92.6 deg)
  - Orbit perturbations include solar pressure (s/c shape modeled as a spherical bus + sun-pointed flat plate), Mars atmosphere (MarsGram2005), point mass gravity for sun, moon, & planets, & a 30x30 Mars spherical harmonic gravity field
  - A truth orbit propagated for two days with a perturbed set of nominal dynamics (20% white noise variation of the atmospheric density & a 10% bias on the solar pressure)
  - Ideal 2-way and 1-way Doppler measurements degraded with Gaussian noise & stochastic clock noise
    - Noise processes created according to DSN, MRO USO and CBE DSAC stochastic models

Data Type	Integration Time	Frequency	Gaussian Noise	Stochastic Clock(s)	Data Weight
2-way Doppler	60 s	X/X	0.1 mm/s	DSN FTS	0.1 mm/sec
1-way Doppler w/ DSAC	60 s	X	0.1 mm/s	DSN FTS, DSAC	0.1 mm/sec
1-way Doppler w/ DSAC	60 s	Ka	0.01 mm/s	DSN FTS, DSAC	0.01 mm/sec
1-way Doppler w/ USO	60 s	X	0.1 mm/s	DSN FTS, USO	0.285 mm/sec

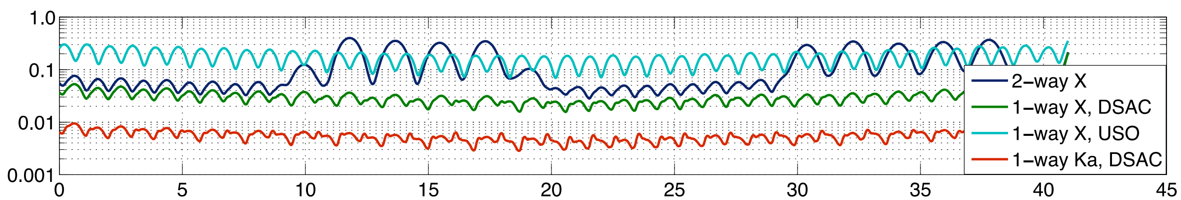
Mars Orbiter Navigation Filter Configuration

- Navigation filter defined to mimic MRO navigation operations
- Additional frequency states estimated when 1-way data processed
  - DSAC: per-measurement white frequency stochastic
  - USO: frequency offset and drift re-estimated at each station handoff and reacquisition following tracking gap
    - Very large *a priori* uncertainty required to encompass large long-term frequency drift

Estimated Parameters	Type	A Priori Uncertainty
Position (EME2000)	Dynamic	σ = 100 km
Velocity (EME2000)	Dynamic	σ = 10 m/s
Solar pressure scale	Bias	σ = 10% of nominal (1.0)
Atmospheric drag scale	Stochastic	Estimated at periapsis, σ = 20% of nominal (1.0)
Mars J_{12}, J_{13}	Bias	σ = 1e-9
Frequency Offset (DSAC)	Stochastic	X-Band: σ = 0.3 mHz; Ka-Band: σ = 1.2 mHz
Frequency Offset (USO)	Stochastic	σ = 10 Hz
Frequency Drift (USO)	Stochastic	σ = 1e-6 Hz/sec

Mars Orbiter Trajectory Reconstruction

- Comparison of Radial, Tangential, and Normal (RTN) position uncertainty (3σ) demonstrates utility of DSAC-enabled 1-way tracking data compared to current capabilities
  - USO-enabled 1-way tracking resolves trajectory to ~ 10 m, limited by increased short-term noise and re-estimation of long-term frequency offset and drift
  - X-band 2-way & DSAC 1-way solutions comparable when tracking data present (~ 5 m orbits)
    - 2-way solution uncertainty inflation over tracking data gaps; mitigated via MSPA for 1-way tracking
  - Ka-band 1-way with DSAC resolves trajectory to < 1 m uncertainty

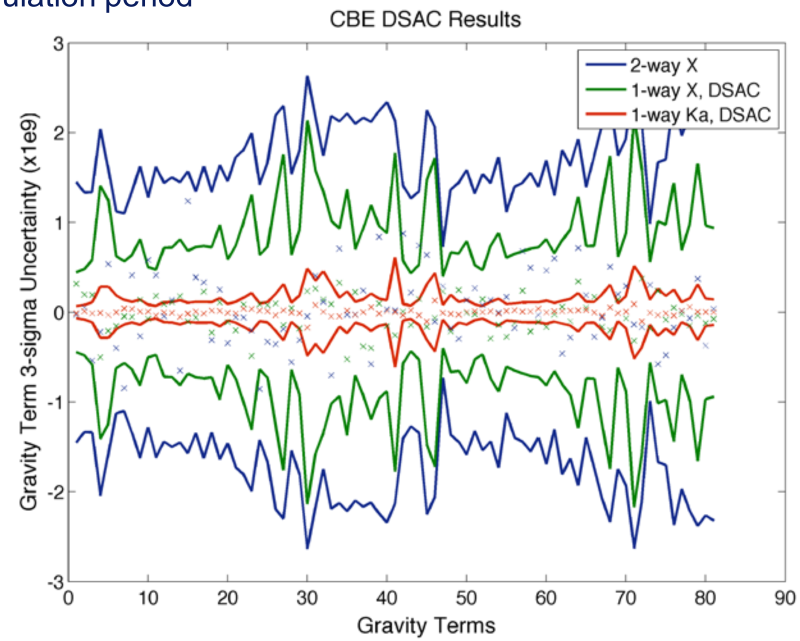


Average overall improvement over 2-way solution:
- X-band: 1.4x (MSPA)
- Ka-band: 5.1x (MSPA and 10x better data)

hr]

Mars Orbiter Static Gravity Field Estimation

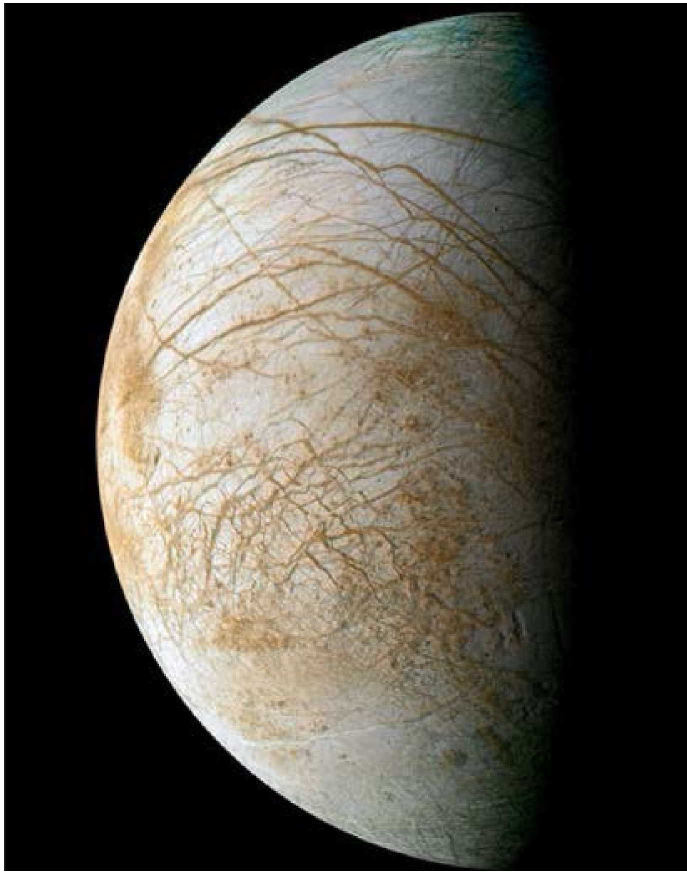
- Mars orbiter simulation also utilized to highlight improvements to Martian gravity field reconstruction via DSAC-enabled 1-way tracking data
- Modifications to simulation configuration:
  - Truth trajectory propagated for a 4-day span with a 50x50 Mars spherical harmonic field
  - Discontinuous 2-way tracking schedule created by concatenating 2-day schedule
  - No estimation of frequency stochastic parameters; instead inflated Ka-band Doppler weight to account for DSAC short-term noise (no change necessary for X-band noise as 0.1 mm/sec is appropriate upper bound)
  - Expanded estimated gravity field parameters to include all terms in a 40x40 field which are observable over simulation period



Average overall improvement over 2-way solution:
- X-band: 2x (MSPA)
- Ka-band: 12x (MSPA and 10x better data)

Europa* Gravity Science: Subsurface Ocean Estimation

- Primary science goal at Europa would be to confirm the existence of and characterize Europa's subsurface liquid ocean
- A liquid/ice ocean is perturbed by the presence of Jupiter, and it follows that Europa will exhibit gravitational fluctuations
  - Europa is tidally locked to Jupiter with k_{22} gravitational tide coefficient dominating the time-varying response
  - Estimating the k_{22} term within an uncertainty of 0.05 would confirm the ocean's existence
- In contrast to a Europa orbiter mission, a Europa flyby mission would suffer limited radiometric data for estimation of the gravity field coefficients and their time variations
  - Gravitational tide sensitivities limited to close approach
- A potential ~ 2.5-year tour would include 45 flybys of Europa, and accumulate a few hours of useful X-band tracking data per flyby
  - Jovian moon tour* designed in part to optimize Europa gravity science return
  - Gravity information from each flyby accumulated to produce a global gravity solution; solution quality strongly correlated to Doppler quantity and quality



Low SNR Open-Loop Tracking: 2-way and 1-way Options

- Given large Earth-spacecraft distances and spacecraft power limitations, two-way closed-loop tracking requires HGA access
- However, flyby attitude requirements and body obscurations combined with fixed high gain antenna may result in limited visibility during close approach
  - A viable gravity science solution is not possible with most trajectory options
- Possible to perform low SNR open-loop tracking of the Doppler carrier signal with medium or low gain antennas, which can be positioned to increase tracking coverage
  - Medium gain fan beam antennas provide sufficient gain (~10 dB) for open-loop two-way tracking with 34-m DSN
    - Limited (long but narrow) FOV over which this gain is realized
  - Low gain antennas provide sufficient gain (~5-6 dB) for open-loop one-way uplink-only tracking with 34-m DSN
    - Provide an extensive field of view; MRO LGA can realize required gain for ~70 deg half-angle
    - Doppler carrier tracking data may be collected during flybys and stored onboard for later downlink to ground

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Deep Space Atomic Clock Project

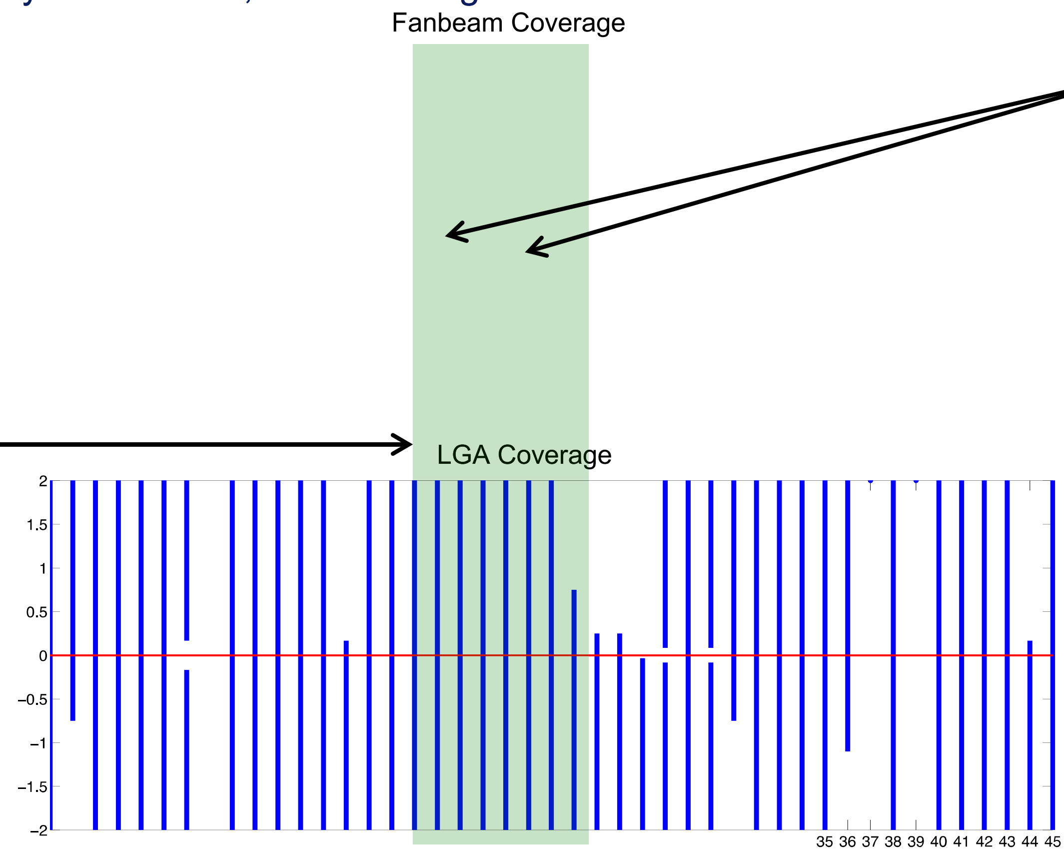
Fan Beam and LGA Access Profiles

- Profiles demonstrating viable tracking access generated over a baseline 4-hour window for three optimally-positioned fan beam antennas and three optimally-positioned LGAs, utilizing DSN network
  - Tracking profiles take into account sensor FOV, link budget, planetary body obscuration, spacecraft body obscuration, and a 10 deg DSN elevation mask

Flybys E18 and E22 missed due to low downlink elevation

Fan beam coverage is limited even when optimally positioned

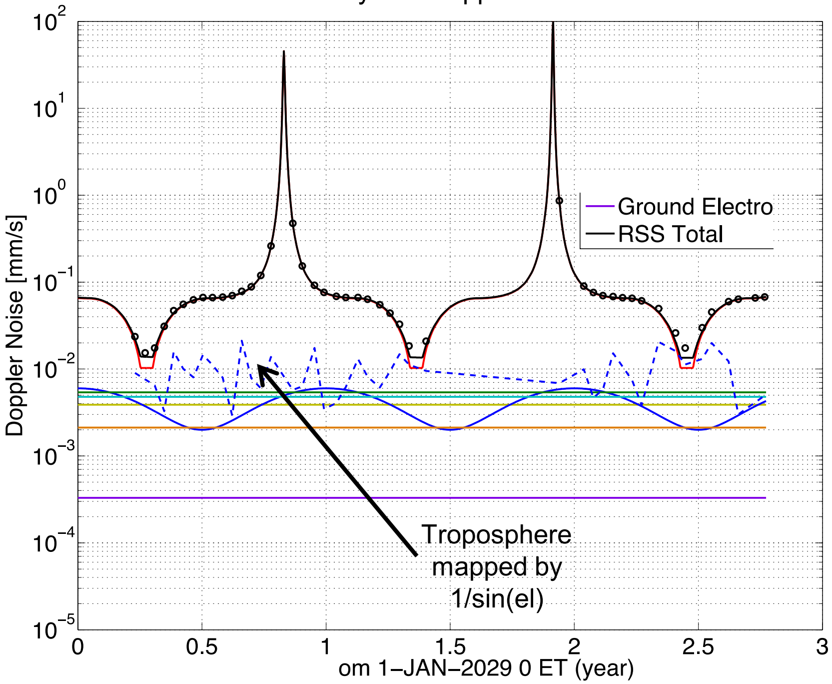
Key passes designed to optimize Gravity Science return

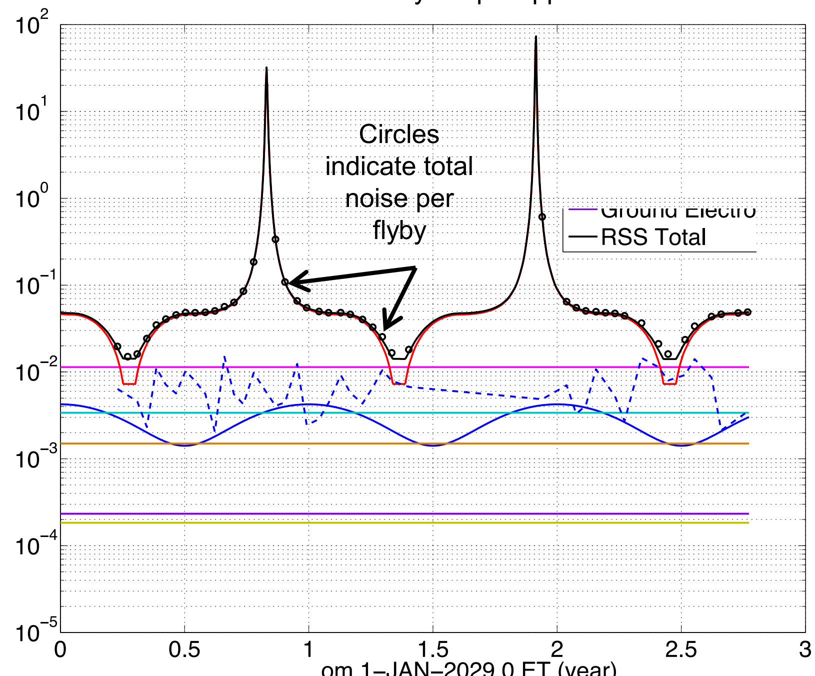


LGAs provide nearly continuous 1-way uplink access

X-Band Doppler Noise for Europa Flyby Mission Concept

- While LGAs provide a wealth of open-loop carrier signal tracking, high-quality X-band 1-way uplink-only tracking data is only feasible with a stable onboard frequency source such as DSAC
- 2-way and 1-way X-band Doppler measurement noise has been modeled for a potential Europa flyby trajectory assuming:
  - CBE DSAC performance
  - SEP and tracking elevation defined through baseline trajectory
- Dominated by solar plasma, 1-way X-up noise ~ 30% less than 2-way X/X noise





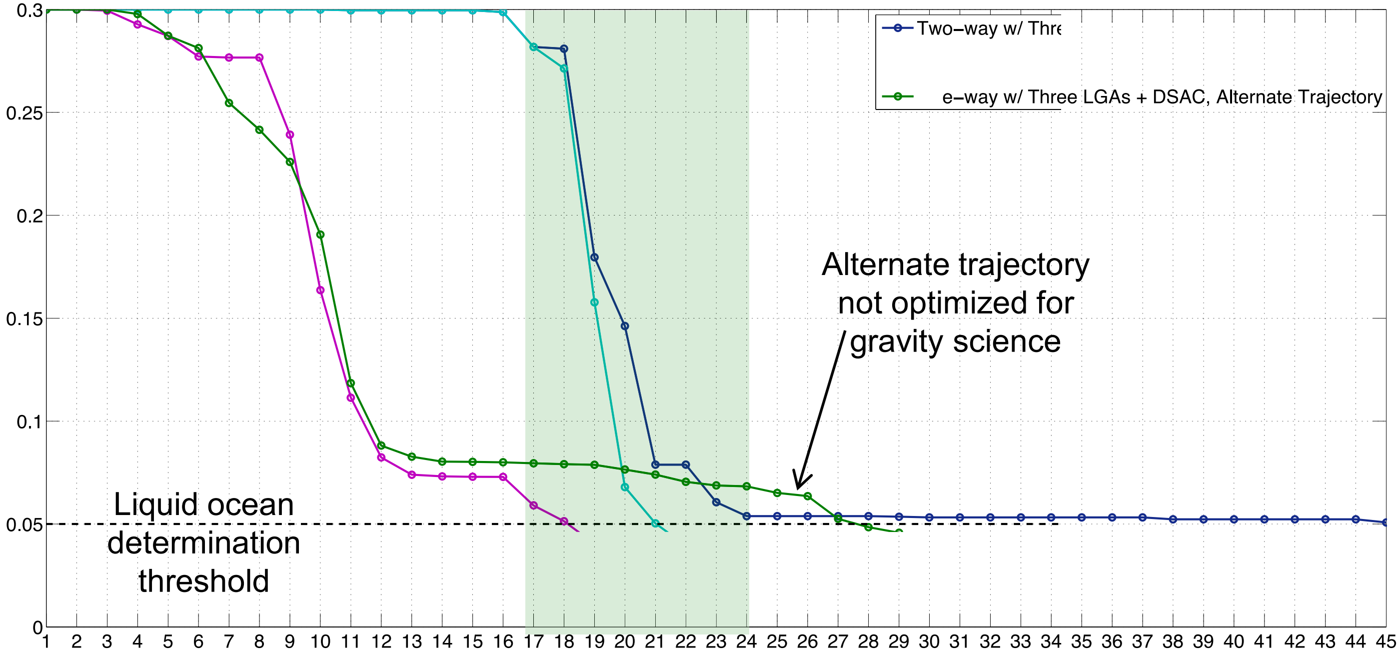
Europa Gravity Science Covariance Analysis

- Covariance analysis quantifies and compares gravitational tide recovery via two-way fan beam configuration and one-way LGA + DSAC configuration
- Generated 60-second X-band 2-way and 1-way Doppler measurements using baseline trajectory, fan beam and LGA access profiles
  - Filter data weights defined by Doppler noise profiles
- Kalman filter configured to estimate dynamic state, acceleration biases, and gravity field parameters
  - Europa Love numbers and second-degree spherical harmonics assigned very large *a priori* uncertainties to essentially initialize the filter with zero ocean tide information
- Measurements for each flyby processed sequentially
  - Local parameters (position, velocity, acceleration) reinitialized with uncorrelated *a priori* uncertainty for each flyby
  - Global parameters (gravity) *a priori* covariance for flyby *N+1* set to a posteriori covariance for flyby *N*

Estimated Parameters	Type	A Priori Uncertainty
Position (EME2000)	Dynamic	σ = 100 km
Velocity (EME2000)	Dynamic	σ = 1 m/s
RTN acceleration biases	Bias	σ = 5e-11 km/s^2
Europa gravitational parameter	Bias	σ = 320 km^3/s^2 (10%)
Second-degree Europa Love numbers (k_{20}, k_{21}, k_{22})	Bias	σ = 0.3
Europa spherical harmonic gravity coefficients (20x20)	Bias	, s = 10,000 for n = 2 , s = 1 for n > 2

Europa Gravitational Tide Recovery

- Solution quality is inherently limited by the quantity of available tracking data
  - Baseline fan beam solution just reaches gravity science objective at last flyby
- Fan beam configuration with ESA tracking to capture low-elevation flybys provides a viable solution, but is not robust to mission design changes or missing key flybys
- DSAC-enabled uplink-only tracking provides ample high-quality data to satisfy the requirement early in primary mission with the DSN alone, adding robustness to missing key flybys
- LGA + DSAC data-rich environment allows for gravity science objective to be met when on a trajectory not optimized for gravity science, i.e. prioritizing other instrument mission design needs

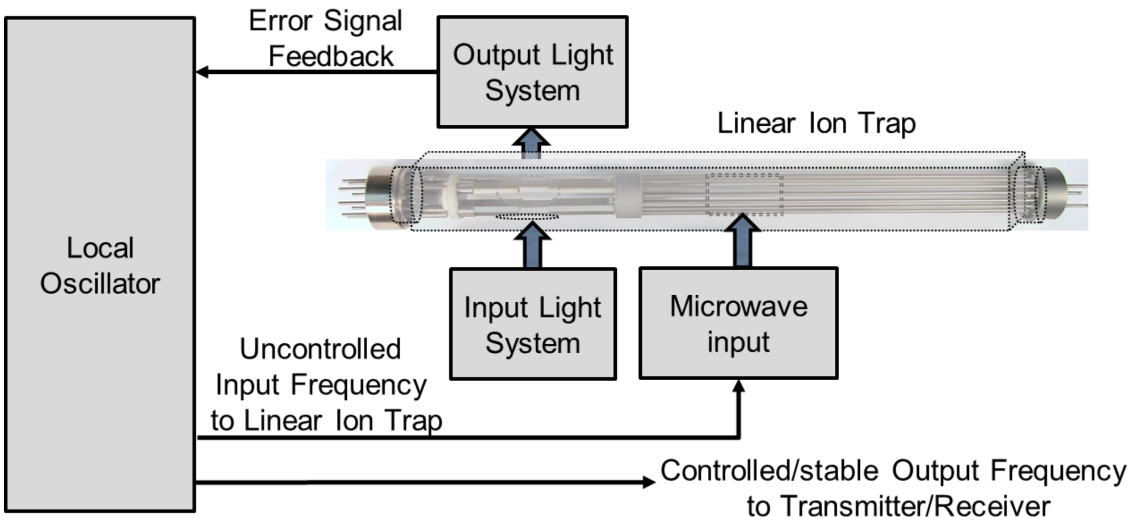


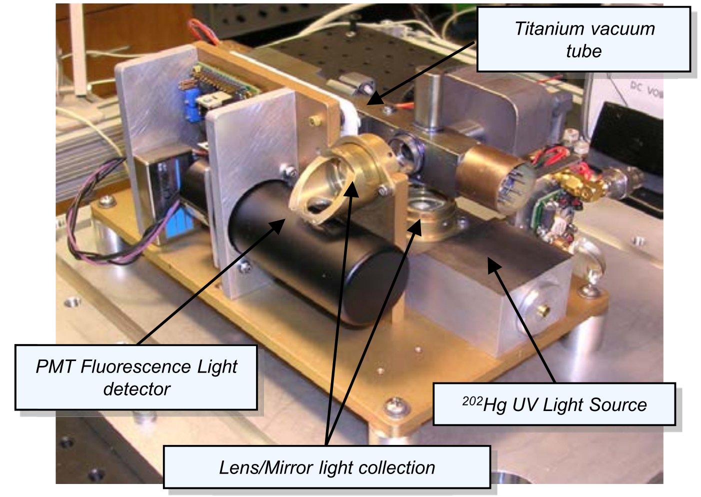
Summary

- The Deep Space Atomic Clock mission will demonstrate the unprecedented space performance of a highly accurate and highly stable yet small and low-mass mercury ion atomic clock in the low Earth orbit environment
- The current expected Allan Deviation is ~1.5e-15 at 1 day, which is equivalent to DSN ground clock performance and better than most existing space clocks
- The utility of DSAC-enabled high-quality one-way signals for deep space navigation and radio science can:
  - Improve data quantity and quality, including during low SNR scenarios
  - Enhance tracking architecture flexibility and robustness
  - Enable fully-autonomous onboard absolute navigation
- DSAC has the potential to transform the traditional paradigm of deep space radiometric tracking to a more flexible, efficient and extensible one-way tracking architecture

Backup Slides

DSAC Technology & Operation





Ion Clock Operation

- Short term (1 – 10 sec) stability depends on the Local Oscillator
- Longer term stability (> 10 sec) determined by the “atomic resonator” (Ion Trap & Light System)

Key Features for Reliable, Long-Life Use in Space

- No lasers, cryogenics, microwave cavity, light shift, consumables
- Low sensitivity to temperature changes, magnetic fields, radiation, zero-g

Ion Clock Technology Highlights

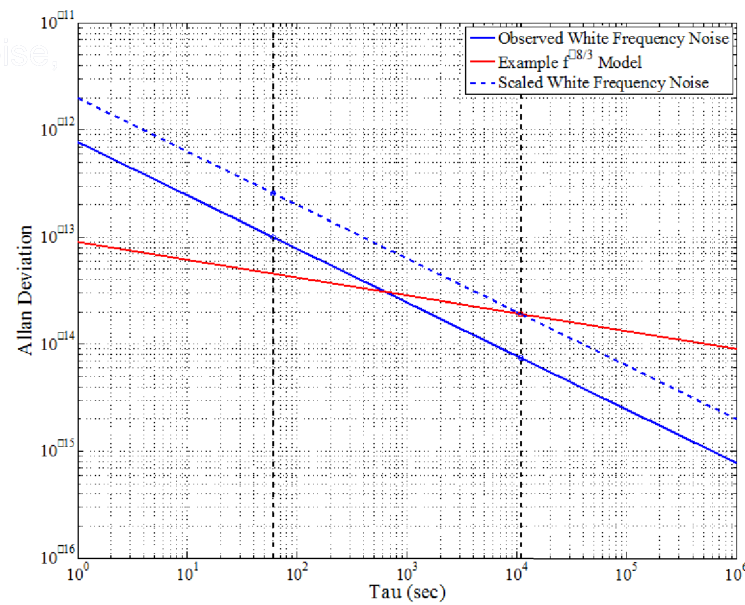
- State selection of 10^6-10^7 $^{199}Hg^+$ trapped ions via optical pumping from $^{202}Hg^+$
- High Q microwave line allows precision measurement of clock transition at 40,507,347,996.8 Hz
- Ion shuttling from quadrupole to multipole trap to best isolate from disturbances
- 1-2 UV photons per second scattered
- Ions are in an uncooled buffer-gas (Ne) (as opposed to other atomic clocks)

Long-term Correlations in Plasma Noise

- Solar plasma model only captures the short-term (60-sec) stochastic behavior of plasma noise[1]:

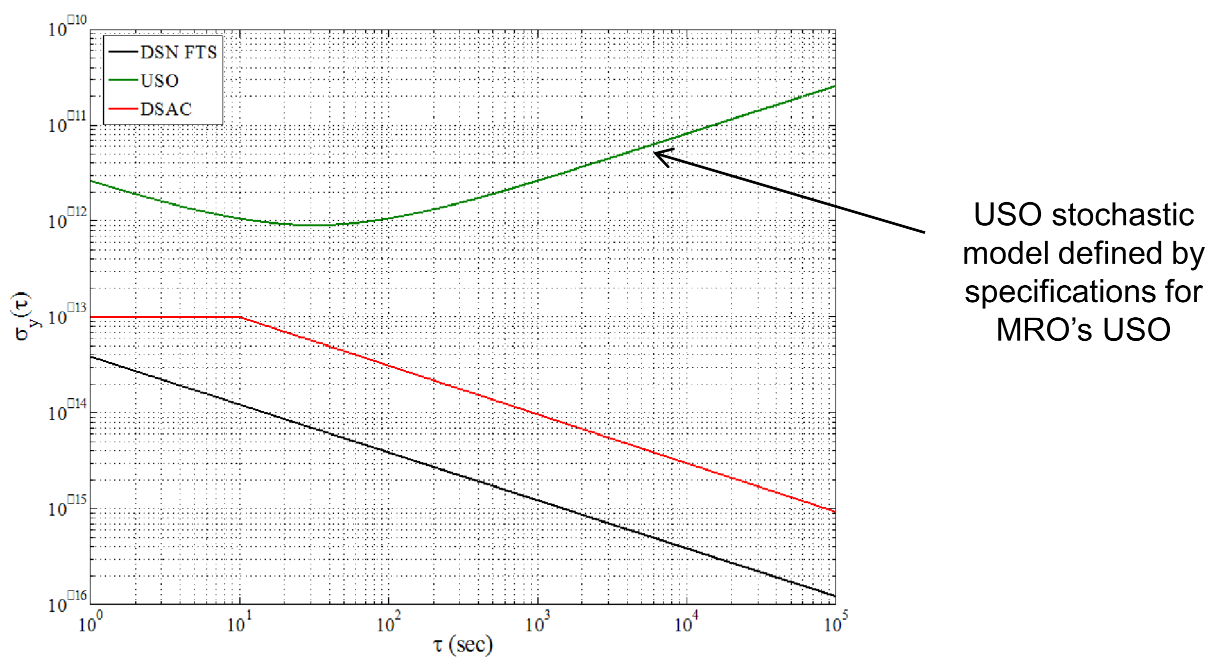
(X/X Model)

- Plasma noise has a $f^{-8/3}$ frequency power spectrum; Kalman filters assume a f^{-2} uncorrelated frequency power spectrum (white noise)
  - White frequency model defined by short-term noise significantly underestimates true noise at longer time scales
- Kalman filter data must be handled appropriately to prevent un-modeled correlations in Doppler data aliasing into estimation solution
  - Pre-whiten data, tune filter to estimate correlated noise, or scale short-term noise accordingly
  - Scaling parameter defined as:
    - T = dominant underlying signal time scale
      - Interplanetary cruise: T = 24 hours
      - Flyby: T ~ 3 hours
    - τ = Doppler integration time
      - 60-sec Doppler



Ground and Onboard Clocks

- Imperfect ground and spacecraft oscillators introduce Doppler noise via fluctuations in the signal frequency
- DSN Frequency and Timing Subsystem (FTS) maintains hydrogen masar Allan deviation to within 5e-15 to 1e-14 at 60 seconds
    - Assumed white frequency noise model with Allan Deviation = 5e-15 at 60 sec
- Onboard oscillator frequency variations only manifest as noise on 1-way signals
    - DSAC clock stochastic behavior modeled at CBE level
        - 1e-13 Flicker floor up to 10 sec, white frequency noise after 10 sec with Allan Deviation = 1e-15 at 1 day



Finite SNR, DST, Ground Antennas & Electronics

- Finite SNR introduced on the uplink and/or downlink of the carrier signal, and typically dominated by limited spacecraft transmit power on the downlink

  - Cassini cruise telecom system design baselined for finite SNR noise model
- DST noise modeled as white frequency noise, in accordance with Cassini DST:
  - X-Band 60-sec Allan Deviation = 1.8e-14; Ka-Band 60-sec Allan Deviation = 5.0e-15
  - DST noise introduced via signal turn-around, hence only included in 2-way Doppler noise model
- Thermal (temperature gradients) and mechanical (wind and gravitational loading) deformations of DSN ground antennas modeled as white frequency noise (uncorrelated such that $\sigma_{2-way} = \left(\sigma^2_{1-way,up} + \sigma^2_{1-way,down}\right)^{1/2}$)
  - 60-sec Allan Deviation = 1.6e-14 for 2-way; 1.1e-14 for 1-way
- DSN ground electronics noise has been empirically shown via end-to-end zero 2-way light time tests to be white frequency noise; assumed uncorrelated at transmission & reception times
  - 60-sec Allan Deviation = 1.1e-15 for 2-way; 7.8e-16 for 1-way

Solar and ionosphere plasma

- Plasma noise, including both solar and ionosphere effects, is dominant error source on X-band tracking data, significant contributor for Ka-band
  - Function of distance from sun and geometry of signal line-of-sight relative to the Sun direction, defined by Sun-Earth-Probe (SEP) angle
- Empirically demonstrated to be largely captured by SEP angle beyond 2.0 AU:
  - 2-way 60-sec X-band solar plasma noise model:
  - Assuming uplink and downlink noise is uncorrelated and equivalent in strength:

$$\sigma_{2-way} = \left(\sigma^2_{1-way,up} + \sigma^2_{1-way,down}\right)^{1/2}$$

  - X-band noise converted to Ka-band noise through inverse relationship between plasma noise and square of the signal frequency:

$$\sigma_{Ka} = \left(\frac{f_X}{f_{Ka}}\right)^2 \sigma_X$$

Troposphere

- Dry troposphere component (~ 80% of troposphere noise) well-modeled and removed from empirical Doppler data
- Wet troposphere component (remaining ~20% of troposphere noise) may be calibrated to ~ 80% by Microwave Radiometer (MWR) techniques
- Total zenith-tracking 2-way Doppler noise from wet troposphere modeled as frequency-independent seasonal sinusoid centered at ~ 0.02 mm/sec with an amplitude of ~ 0.01 mm/sec
  - Maximized in summer; minimized in winter
  - Zenith effect reduced by 80% to reflect MWR calibration
  - Scaled to lower elevation by $\frac{1}{\sin(el)}$ mapping function
  - 2-way troposphere noise scaled to 1-way noise by $\frac{1}{\sqrt{2}}$