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THE DEEP SPACE ATOMIC CLOCK: USHERING IN A NEW PARADIGM FOR RADIO NAVIGATION AND SCIENCE

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The Deep Space Atomic Clock (DSAC) mission will demonstrate the on-orbit performance of a high-accuracy, high-stability miniaturized mercury ion atomic clock during a year-long experiment in Low Earth Orbit. DSAC's timing error requirement provides the frequency stability necessary to perform deep space navigation based solely on one-way radiometric tracking data. Compared to a two-way tracking paradigm, DSAC-enabled one-way tracking will benefit navigation and radio science by increasing the quantity and quality of tracking data. Additionally, DSAC also enables fully-autonomous onboard navigation useful for time-sensitive situations. The technology behind the mercury ion atomic clock and a DSAC mission overview are presented. Example deep space applications of DSAC, including navigation of a Mars orbiter and Europa flyby gravity science, highlight the benefits of DSAC-enabled one-way Doppler tracking.

INTRODUCTION

Currently, deep space navigation depends primarily on ground-based atomic clocks for the formation of accurate two-way coherent radiometric measurements. Space-based clocks have lacked the high-caliber accuracy and stability to conduct navigation based solely on one-way radiometric signals. The use of one-way tracking data is currently limited by the correlation between long-term frequency drift and orbital parameters; recovering large clock bias and drift terms following long periods of no tracking significantly degrades the orbit solution quality. The National Aeronautics and Space Administration (NASA) Deep Space Atomic Clock (DSAC) project is a Technology Demonstration Mission (TDM) slated to launch as a hosted posted in 2015. This mission will bridge this gap between ground and space clocks by validating the on-orbit performance of a small, low-mass mercury ion (^{199}Hg) atomic clock (Figure 1) with long term stability and accuracy on par with that of the Deep Space Network (DSN). The Allan deviation of DSAC will be less than 2E-14 at one day, with a ground laboratory version currently demonstrating an Allan deviation of less than 1E-15 at one day. Such low spacecraft clock error will enable one-way radiometric tracking data with accuracy equivalent to or better than current-day two-way tracking data, allowing a shift to a more efficient and flexible one-way navigation architecture.

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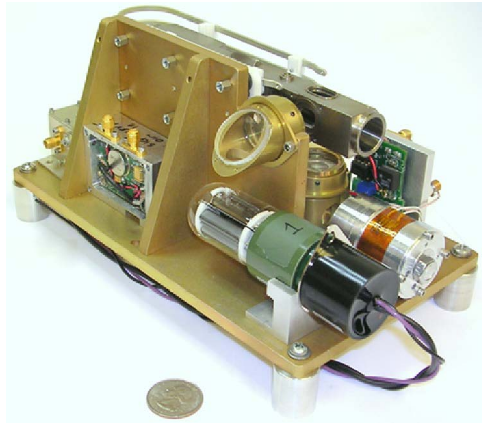

Figure 1. Mercury trapped ion atomic clock

This work focuses on the space suitability and deep space navigation applications of DSAC. An overview of the mercury ion atomic clock technology is first presented. A comparison of DSAC to other space clocks, including rubidium and cesium atomic clocks as well as hydrogen masers, is discussed. A brief overview of the DSAC mission and experimental validation path is provided. Finally, benefits of DSAC to deep space navigation and radiometric science are highlighted, and specific examples demonstrate the advantages of DSAC-enabled one-way Doppler navigation. The example scenarios include trajectory estimation of a Mars orbiter and gravitational tide recovery for a Europa flyby mission.

MERCURY ION TRAP TECHNOLOGY

Mercury ion clocks based on the ground state hyperfine transition in trapped ^{199}Hg ions are a promising technology to simultaneously address reliability, size, weight and power (SWaP), operability, and stability performance requirements. Trapped ions are easy to handle in a microgravity environment, and the 40.5 GHz hyperfine transition is the highest frequency and least magnetically sensitive of the alkali-like atoms and ions that have been investigated for atomic clock applications. Room temperature,lamp-based mercury quadrupole and multi-pole linear ion trap based frequency standards have been highly developed for ground applications resulting in three generations of reliable and continuously operating mercury ion frequency standards with good accuracy and very high stability.[1,2,3,4,5,6] Multi-pole[3] and compensated multi-pole ion traps[5] have effectively eliminated residual ion number sensitivity, resulting in UTC-level timescale demonstration with a single mercury ion trap standard having long term frequency variation at the low 1E-17 level per day.[4,6] NASA technology efforts continued small ion trap development and very long ion trap lifetimes have been obtained in a getter pumped vacuum assembly designed to be baked to 450 °C, and stable signal-to-noise has been demonstrated over several years.[7,8] Long term stability and environmental sensitivity in this high temperature bake-out ion trap assembly are currently being characterized, though operation with only a sealed getter pump evacuating a larger multi-pole ion trap assembly baked to 200 °C has demonstrated very stable clock operation over 9 months.[9] These continued NASA/JPL advances in ultra-stable timekeeping and small ion trap vacuum tube technology have positioned the mercury ion technology to be realized as a spacecraft-based mercury ion frequency standard.

Mercury ion clocks developed at JPL are used to steer a local oscillator (LO). DSAC produces an accurate and stable frequency source by precisely measuring the frequency at which mercury ions transition from one hyperfine energy state to another (^{199}Hg). As shown in Figure 2, optical pumping is used to initialize trapped mercury ions to a baseline energy state. An input microwave frequency, derived from the LO, probes the ion transition frequency (approximately 40.5 GHz). When the input frequency is equal to the atomic ion transition frequency, the flourescent optical signal will show a peak in the number of transitioned ions. Having measured this frequency precisely due to the very fine atomic line resolution, the in-stability and drift in the LO frequency is corrected and a steered frequency signal is output.

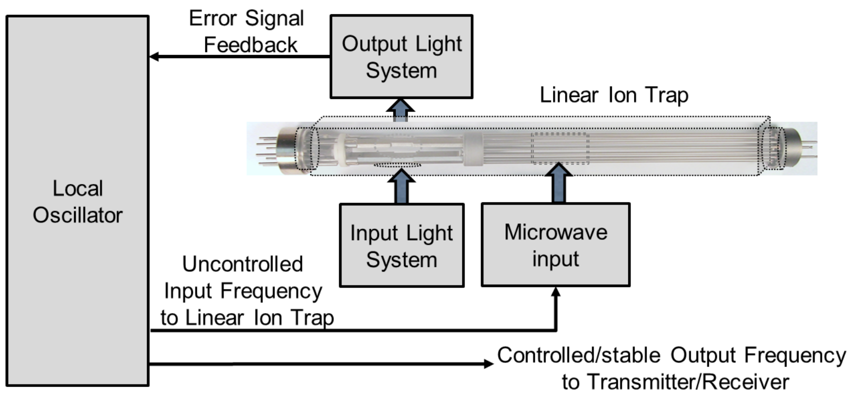

Figure 2. Schematic of DSAC system

While the long-term stability of the clock is driven by the atomic resonator, the short-term stability is driven by the noise qualities of the LO. In the laboratory several LO options are available such as a cryogenic oscillator or hydrogen maser, but for spaceflight we are restricted to a quartz-based LO. The first mercury ion clock implemented at JPL was able to control each of the three LOs with mercury ions confined in a quadrupole ion trap assembly with the performance dependent on the LO implementation.[2] While the ion cloud size in the quadrupole ion trap was small (approximately 2 mm diameter by 7 cm long), the surrounding vacuum/optics/magnetic system was built with larger vacuum system, optics, and electronic components. The entire ion clock assembly originally required 2 racks of space and more than 1 kW of power. Four of these standards disciplining quartz LOs were developed and several years of operational experience were obtained in JPLs Frequency Standards Test Laboratory and at remote sites in the DSN.

In contrast to these early ground versions, a space ion clock for deep space navigation[10] and/or Global Navigation Satellite System (GNSS) applications[11] should consume little power (less than 20 W for deep space operations and less than 30 W for GNSS), fit in a volume of a few liters, have simplified external interfaces, and be very reliable. Small, low-powered prototype ion clock technologies for potential application in deep space have been under development at JPL. A small, hardened ion/vacuum tube assembly has been operated in the lab demonstrating an Allan deviation at one day near 1E-15, as shown in Figure 3.[10] For comparison, the performance of current state-of-the-art ultra-stable oscillators (USO) and rubidium (Rb) atomic standards are also shown in the figure. A low-power ion clock instrument discipling a quartz based USO that includes all ion trap and optical system electronics, clock controller, and 40.5 GHz microwave synthesizer has also been demonstrated.[11] These successful laboratory demonstrations were key elements that paved the way for the DSAC project being selected as a NASA TDM in August 2011.

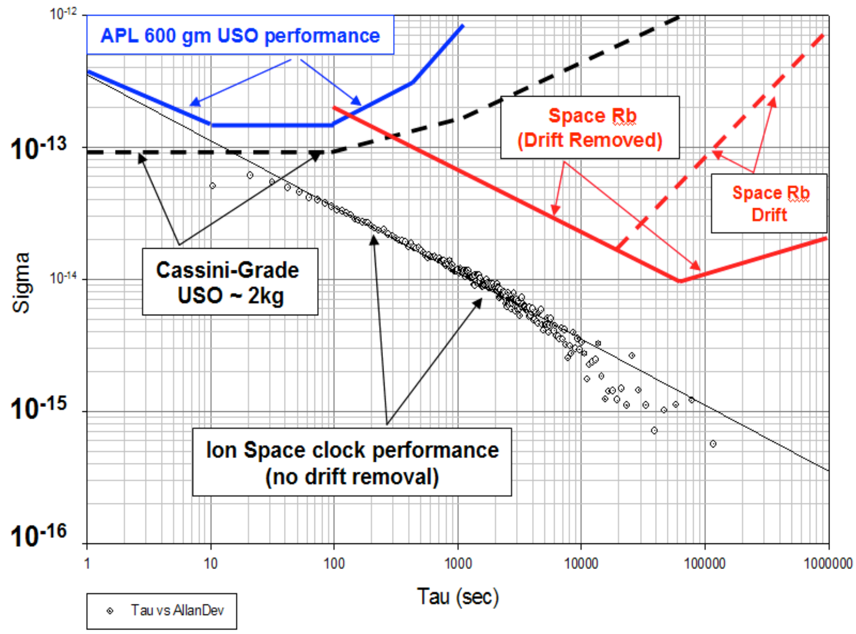

Figure 3. Experimental ^{199}Hg ion clock stability and representative USO, Rb atomic clock stability (Allan Deviation)[10]

SUITABILITY FOR SPACE AND COMPARISON TO EXISTING SPACE CLOCKS

All atomic clocks must in some fashion contain a sample of reference atoms or ions; using trapped mercury ions leads not only to enhanced space suitability, but also improved operability and performance. Specific examples of DSAC's space suitability in addition to its small size and mass include:

- No consumables: unlike hydrogen masers or cesium beam tubes, the mercury ion atomic clock is based on a sealed vacuum tube with a trace amount of ^{199}Hg vapor inside, and ions will not be lost to interactions with background gases.
- Reduced frequency perturbations: as the ion population is contained via radio-frequency electric trapping fields, contact between material walls and the mercury ions cannot occur. In comparison, rubidium clocks contain their atoms via glass cells, and collisions between the rubidium and their cell walls cause perturbations to the ion transition frequency. The removal of such perturbations via the mercury ion trap design reduces clock frequency drift by a factor of 100.
- Minimized magnetic and temperature sensitivity: Mercury ions transition at a higher frequency than other atoms and thus have a lower sensitivity to magnetic field perturbations. The mercury ions are hosted in an uncooled buffer gas (Neon) and require less temperature control than other space atomic clocks in order to achieve the required stability.

- Radiation tolerant: The radiation tolerance of DSAC is similar to that of the Global Positioning System (GPS) rubidium clocks, which have demonstrated over 10 years of operation in Earth orbit.

- Zero-gravity tolerant: As the mercury ion trap holds the ions electromagnetically and has no dependence on gravity for operational purposes, the clock performance is not expected to change from ground laboratory to space environment.

DSAC's technological advancements introduce several advantages over traditionally used space atomic clocks, such as the cesium and rubidium clocks used in GNSS systems. Figure 4 presents a comparison of the mass and accuracy of a selection of space-based clocks. Some of these clocks, including DSAC, have not yet been flown and as such their laboratory-tested performance is indicated. DSAC fulfills a need for a low-mass, high-accuracy/high-stability space-suitable clock.

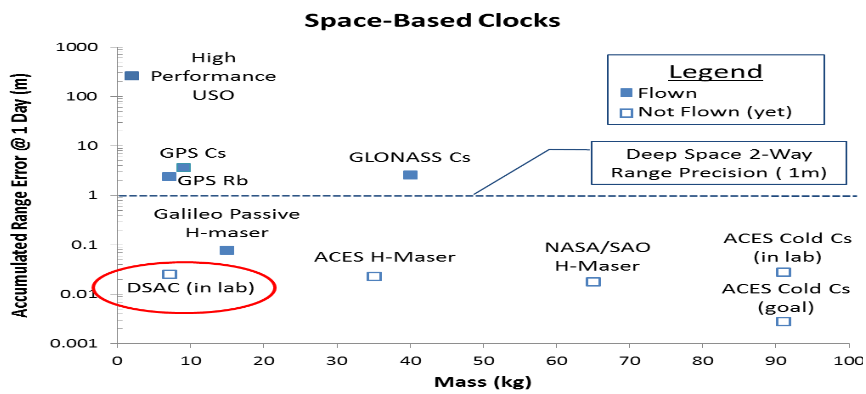

Figure 4. Comparison of mass and navigation accuracy of space-based clocks

DSAC MISSION OVERVIEW

The DSAC project will advance the clock from Technology Readiness Level (TRL) 5 (laboratory-qualified) to TRL 7 (space-qualified) by validating the clock's performance and functionality in a space environment and demonstrating DSAC's viability as navigation hardware. The DSAC mission will be a hosted payload onboard a Surrey Satellite Technology (SST-US) Orbital Test Bed (OTB) spacecraft, to be launched into Low Earth Orbit (LEO) in 2015. The clock validation will be conducted through a year-long demonstration. The current manifestation of the demonstration atomic clock payload is approximately 14 kg, requires 56 W of power, and is accommodated in a volume of 30 cm x 22 cm x 18 cm. A second project objective is to identify steps to develop future versions of the clock for infusion into deep space and GNSS missions. A deep space infusion version of DSAC is targeting 5 kg and less than 20 W, and a GNSS version approximately 10 kg and 30 W. These infusion variations will optimize SWaP and performance requirement trade-offs for the specific application.

The DSAC payload consists of three primary components: an ovenized crystal USO with a short-term stability better than 3E-13 over short time scales and frequency drift of under 1E-10 per day, the mercury trapped ion atomic clock, and a GPS system comprised of a JPL-developed TriG receiver and a zenith-pointing choke ring antenna for multipath suppression. The TriG receiver is designed to autonomously begin collecting data following start up, and will collect L1 and L2 carrier phase and pseudorange data from all GPS satellites in view. The GPS data will be transferred from the payload to the OTB host spacecraft for transmission to the ground station, where the GPS data is then processed to determine the stability of the ion clock. JPL's GNSS-Inferred Positioning System and Orbit Analysis Simulation Software (GIPSY-OASIS) will be used to reconstruct the orbit, relevant dynamic parameters, and the clock performance.

The mission requirement is to validate the clock's stability and drift to an Allan deviation (fractional frequency) of less than 2E-14 at a time constant of one day. Initial analysis indicates that stability of 1E-15 at one day can be recovered given orbits known to a few centimeters. The DSAC payload will nominally operate with the ion clock steering the output frequency . Without the clock steering the output frequency, the USOs long-term drift should be clearly observed via the GPS system, further demonstrating the ion clocks influence on the frequency corrections. Finally, a deep space analogous navigation experiment simulating typical DSN data coverage will be performed to demonstrate the stability retainment over lengthy gaps in tracking coverage.

NAVIGATION AND SCIENCE BENEFITS

A high-accuracy, high-stability onboard frequency source is an enhancement to both navigation and radio science by providing a high quality and quantity of tracking data and increasing tracking system flexibility, when compared to the current two-way navigation architecture. Additionally, the necessity for ground-based processing of tracking data and subsequent uplinking of a trajectory solution could be reduced to onboard processing, enabling fully-autonomous radiometric navigation. The following expands upon these specific benefits to deep space applications.

Increased Tracking Data Quantity

The DSN can support multiple downlinks on a single antenna (Multiple Spacecraft Per Aperture, MSPA), but only one uplink signal may be supported at any given time. When multiple spacecraft are simultaneously in view of a DSN antenna (e.g., at Mars) they must share time utilizing the uplink signal, thus limiting the amount of two-way Doppler tracking data. For a spacecraft outfitted with DSAC, one-way downlink data would suffice for navigation purposes, and the spacecraft could also take advantage of the MSPA capability. Tracking data could then be provided throughout the entirety of each spacecraft's visibility period at no tracking cost to the other spacecraft in view.

For missions in which the round trip light time is significant, two-way tracking inherently reduces the tracking time by the round trip light time. In contrast, deep space users of DSAC can utilize the full view period, which in some cases may increase the amount of tracking data by several hours per day. As an example, Cassini's Northern hemisphere view periods at Goldstone and Madrid are on the order of 11 hours, so a round trip light time in the 4 to 5 hour range yields an effective two-way tracking pass of approximately 6 hours. A one-way pass using DSAC can utilize the full view period of 11 hours, a near doubling of the usable data, eliminating the need for a complicated three-way tracking operation across multiple ground stations.

Increased Tracking Data Quality

Radio signal perturbations due to solar plasma can be a significant tracking data error source, particularly for spacecraft traveling at low Sun-Earth-Probe (SEP) angles. In fact, X-band two-way Doppler measurement noise is dominated by the solar plasma induced noise even at moderate SEP angles. As the plasma disturbance is inversely proportional to the square of the signal link frequency, two-way Ka-band tracking at 32 GHz reduces the signal noise by a factor of approximately 15 compared to X-band tracking at 8.4 GHz (and reduces the noise by approximately 10 times compared to an X-band uplink/Ka-band downlink combination). While Ka-band uplink and downlink capabilities are available at the Goldstone DSN site, the Canberra and Madrid DSN sites can only support X-band on the uplink, but can receive X-band or Ka-band on the downlink.[12] A spacecraft utilizing DSAC could thus operate entirely on the downlink and can then utilize the Ka-band regardless of the DSN ground station in view, effectively reducing the measurement noise by a factor of 10.

With the solar plasma noise reduced at 32 GHz, the Ka-band Doppler measurement noise is dominated by signal delay introduced by the Earth's troposphere. The dry troposphere, constituting 80% of the total tropospheric delay, is typically well-calibrated and can be removed as an error source. Water vapor radiometers (WVRs) may be utilized to remove up to 90% of the remaining wet troposphere error; however, WVRs cannot be used during periods of heavy cloud cover and/or precipitation. Futhermore, the accuracy of GPS troposphere calibrations is larger than the wet troposphere noise itself on 60-second Ka-band Doppler data. Without calibration and removal of the wet troposphere error, the Ka-band Doppler noise may be increased by a factor of approximately 3 in the zenith direction. A DSAC-enabled one-way downlink signal could mitigate this signal degradation by allowing for any suitable Ka-band receiver within view to receive the signal, avoiding weather conditions at a particular ground site.

Planetary atmosphere investigations using radio occultations can benefit from DSAC as well. Today's radio occultations rely on one-way tracking data derived from USOs. DSAC-enabled measurements are upwards of 10 times more accurate on the time scales relevant to these experiments (that is, the several minutes that a spacecraft radio signal to Earth rises and sets as it passes through the atmosphere of interest before being occulted by the planet).

Fully Autonomous Deep Space Navigation

A one-way uplink received by a DSAC-enabled spacecraft with a properly configured and capable on-board navigation system is able to self-navigate in deep space. Aspects of deep space navigation autonomy have been demonstrated using optical navigation with the Deep Space 1 (DS1) and Deep Impact missions.[13,14] However, a complete implementation of a fully-autonomous on-board navigation system would couple a DSAC-enabled one-way forward radiometric tracking system with optical tracking from a camera system.[15] This would combine the strengths of radio navigation for determining absolute location in deep space and in planetary orbits with the target relative navigation provided by the optical system. A combined one-way radiometric and optical autonomous navigation system would provide a powerful solution for robotic missions where ground-in-the-loop operations are unfeasible (deep space encounters, planetary capture, real-time orbital operations, etc.), as well as supporting human exploration missions beyond low Earth orbit that require crewed operations without ground support.

DEEP SPACE NAVIGATION EXAMPLES

To demonstrate the navigational benefits of DSAC, two deep space examples are presented. The first scenario investigates the orbit estimation quality that can be achieved given one-way or two-way Doppler tracking of a Mars Orbiter, and compares the one-way orbit estimation performance when the signal frequency is driven by a standard space USO or alternatively by DSAC. A second example investigates radio science applications by analyzing the performance of gravitational tide estimation for a Europa flyby mission utilizing DSAC one-way Doppler tracking given a variety of tracking architectures.

Mars Orbit Determination Example

As the introduction of DSAC to a deep space platform will alter the current tracking paradigm by allowing for navigation based on one-way Doppler signals, the orbit solution quality given one-way tracking data must be understood in comparison to a two-way baseline case. This comparison was conducted in the context of a Mars orbiter placed in a near-polar sun-synchronous orbit configuration similar to that of the Mars Reconnaissance Orbiter (MRO), and the simulation was configured to mimic operational navigation. A nominal orbit was produced via numerical propagation incorporating perturbations due to solar pressure, the Martian atmosphere (using the MarsGram2005 density model), Newtonian gravity for the sun, moon, and planets, and a 30 x 30 Mars spherical harmonic gravity field. A truth orbit was created by perturbing the nominal dynamics with 20% white noise variations of the atmospheric density scale factor and a 10% bias error on the solar pressure scale factor. Two-way and one-way Doppler measurement sets spanning a period from 30-Apr-2012 00:00:00 ET to 01-May-2012 18:00:00 ET are respectively fit to determine the spacecraft state and several dynamic model parameters. Four measurement sets are exercised: two-way X-band Doppler, one-way X-band Doppler with DSAC, one-way Ka-band Doppler with DSAC, and one-way X-band Doppler with a Frequency Electronics, Inc. (FEI) USO with performance similar to that of MRO's USO. The USO scenario provides a direct metric of the improvement DSAC provides over current one-way navigation capabilities.

A realistic two-way Doppler tracking schedule is detailed to represent the orbiter sharing DSN antennae time with other spacecraft. Although the orbiter is visible by at least one DSN ground station at all times, lengthy gaps exist in the tracking schedule (Figure 5). Note that such tracking gaps are not present in the one-way Doppler tracking schedule as it is assumed given the current population of Mars flight missions that MSPA may be exploited for this example.

Sixty-second integrated one-way and two-way Doppler measurements were generated from the truth trajectory and degraded with Gaussian noise. The Doppler data weights were defined to be 0.1 mm/s and 0.01 mm/s for X-band and Ka-band, respectively. Troposphere noise was assumed to be removed via water vapor radiometer calibration. In addition to the Gaussian noise, the two-way and one-way observations were further degraded with stochastic clock noise. Independent stochastic clock noise processes were generated for each DSN ground station, DSAC, and the onboard USO as defined by the Allan deviations of each frequency source. Assuming the DSN frequency stability is driven by a hydrogen maser, the ground clock frequency can be expected to exhibit white frequency noise with a fractional frequency of 5E-15 at 60 seconds. The onboard DSAC performance was assumed to be white noise at 1E-15 at 1 day, and the USO clock was defined to drift on par with the FEI USO specifications.[16] Figure 6 presents the stochastic Allan deviations of the DSN ground clocks, DSAC, and the FEI USO used for this simulation.

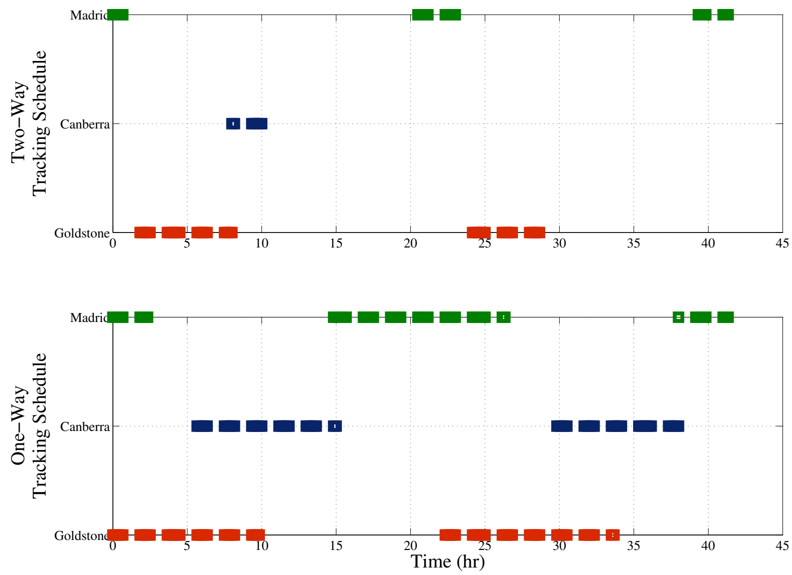

Figure 5. Simulated DSN tracking of the Mars orbiter given a 10 degree elevation mask

The observations were processed with a sequential Kalman filter to recover the parameters listed in Table 1. Note that the atmospheric density scale factor stochastic was modeled as white process noise and recovered at each periapsis. In addition to this set of baseline parameters, an onboard frequency offset stochastic parameter was estimated when one-way data was processed. The frequency offset was estimated as a per-measurement white noise stochastic parameter for the DSAC scenario and as a per-pass bias and drift for the USO scenario, with the *a priori* uncertainty values reflective of the associated Allan deviation value evaluated at the measurement sampling interval (60 seconds) and the signal frequency band (X-band or Ka-band).

Table 1. Baseline Estimated Parameters for Mars Orbiter Example

Parameter	Parameter Type	*A priori* Uncertainty
EME2000 Position	Dynamic	100 km
EME2000 Velocity	Dynamic	0.01 km/s
Solar pressure scale factor	Bias	0.1 (10% of nominal)
Atmospheric density scale factor	Stochastic	0.2 (20% of nominal)
J_{12}, J_{13}	Bias	1E-9

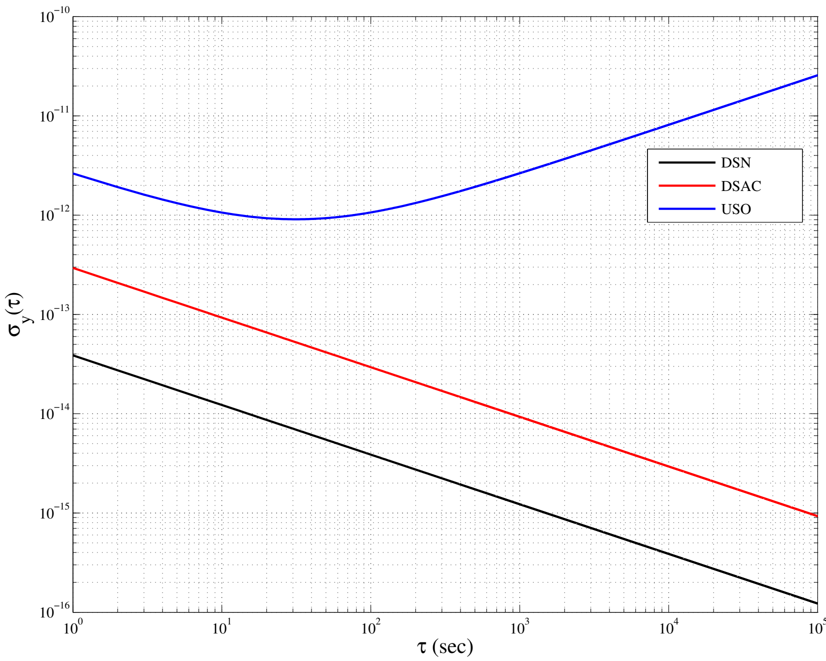

Figure 6. Allan deviation models for stochastic clock noise used for the Mars orbiter scenario

Figure 7 presents the estimated EME2000 (Earth Mean Equator and Equinox of Epoch J2000) position uncertainty (3σ) in the rotating radial, tangential, and normal (RTN) frame. The X-band two-way and one-way DSAC solutions are comparable, with the orbit known to approximately five meters for both cases. The two-way Doppler solution uncertainty inflation over hours 11 through 19 and 31 through 38 corresponds to tracking data gaps; during these tracking gaps, the solution degrades by a few meters. Using DSAC along with the Ka-band downlink reduces the uncertainty to approximately one meter overall. The one-way Ka-band case outperforms the two-way X-band case by a factor of approximately 2 to 4 when tracking data is available, and by a factor of approximately 10 during tracking gaps. Finally, using the FEI USO one-way X-band data results in position uncertainties on the order of tens of meters. The order of magnitude improvement by using DSAC on the Ka-band may be credited to the increased clock stability as well as the decreased Ka-band Doppler measurement noise. These results demonstrate that implementing DSAC onboard a Mars orbiter allows for one-way Doppler navigation with no loss of orbit knowledge compared to two-way Doppler navigation. In fact, utilizing DSAC on the Ka-band reduces the position uncertainty from 5 m to 1 m.

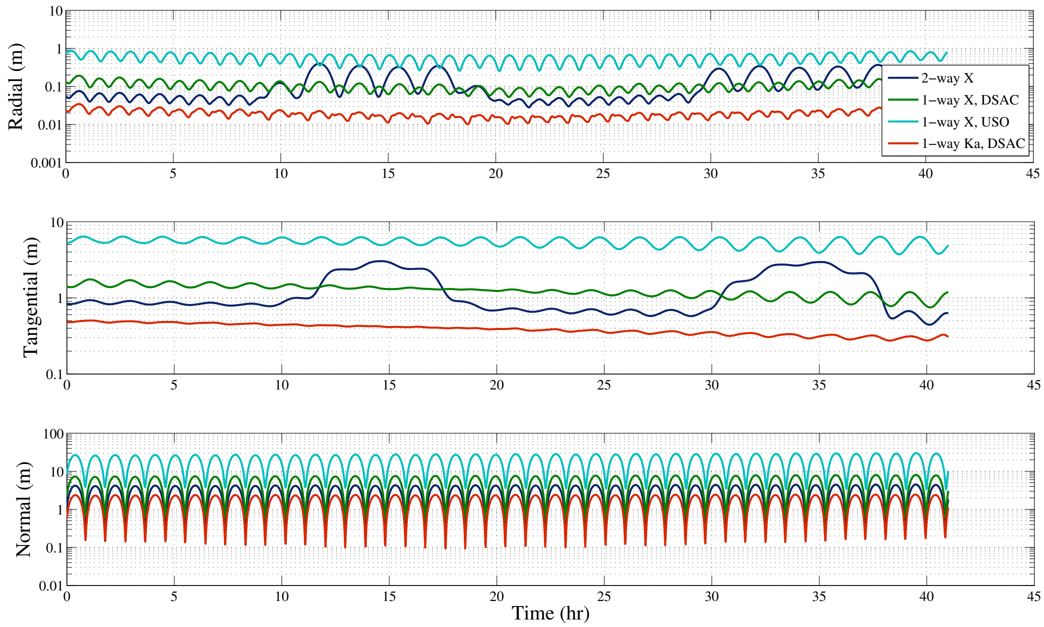

Figure 7. Smoothed orbit position uncertainty for Mars orbiter scenario (3σ)

Europa Flyby Mission Gravity Science Example

Several proposed and selected outer planetary missions intend to further explore the Jovian system, with Europa of notable interest due to the possibility of a subsurface liquid water ocean. As various combinations of ice and liquid layer thickness and viscosity provide different time-varying responses of Europa's gravity field as perturbed by Jupiter, reconstruction of Europa's gravitational tide can provide information regarding the ocean and ice properties. As Europa is tidally locked to Jupiter, the sectorial harmonics will be most affected by Jupiter's presence; knowledge of the second-order, second-degree Love number (k_{22}) to within 0.05 will allow scientists to determine whether or not a liquid ocean exists.[17]

A proposed Europa flyby mission will perform 34 flybys between February 2029 and August 2030, and it has been shown that this mission can accomplish the science objective of reducing k_{22} below 0.05 in 11 flybys, provided that two-way Doppler measurements are available at a noise level of 0.01 mm/sec.[18] This assumption requires the use of Ka-band signal transmission and reception at all DSN stations, an unavailable option at the current time. A one-way downlink tracking approach removes the uplink frequency constraint, and tracking solely on the Ka-band from any DSN site becomes a reality. Furthermore, any suitable antenna outfitted with a Ka-band receiver can track the downlink signal, resulting in the possibility of increased ground coverage and receiver robustness as a contingency for receiver downtime and weather outages. This work investigates the gravity science performance given one-way Ka-band DSAC-enabled Doppler measurements, and compares the performance to that achieved using various two-way Doppler tracking architectures: X-band only, Ka-band only, and a combination of Ka-band at Goldstone and X-band at Madrid and Canberra.

This work assumed that continuous radiometric tracking is available for a four hour window centered on the close approach of each flyby. Figure 8 presents the geometric visibility of each flyby window using a nominal trajectory[18] and applying a 10 degree elevation mask. Goldstone (the only station with Ka-band uplink and downlink capabilities) has limited visibility of the first 11 flybys, which are primarily viewed by both Canberra and Madrid. Sixty-second two-way Doppler measurements were simulated from the nominal trajectory on both X-band and Ka-band and degraded with Gaussian measurement noise (0.1 mm/s for X-band and 0.01 mm/s for Ka-band, assuming troposphere noise has been removed via calibration). One-way Ka-band measurements were also generated and degraded with both Gaussian noise (0.01 mm/s) and DSAC stochastic clock noise modeled as white frequency noise with an Allan deviation of 1E-15 at one day.

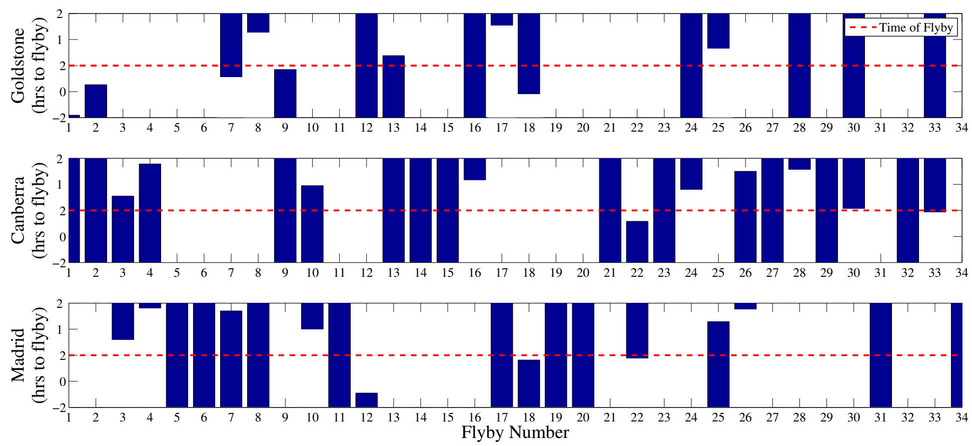

Figure 8. DSN visibility of Europa flybys

Table 2. Baseline Estimated Parameters for Europa Flyby Example

Parameter	Parameter Type	*A priori* Uncertainty
EME2000 Position	Dynamic	100 km
EME2000 Velocity	Dynamic	1 m/s
RTN accelerations	Bias	5E-11 (km/s^2)
μ_{Europa}	Bias	320 km^3/s^2 (10% of nominal)
k_{20}, k_{21}, k_{22}	Bias	0.2 (100% of nominal)
20x20 Spherical harmonic coefficients	Bias	According to Kaula's rule

Table 2 lists the parameters that were estimated by fitting the two-way and one-way Doppler measurements with a sequential Kalman filter. Note that the RTN accelerations represent the non-gravitational acceleration modeling errors that may be encountered over each flyby window, and were estimated as per-flyby biases. μ_{Europa} denotes the Europa gravitational parameter, and k_{2m} represent Europa gravitational tide Love numbers of degree 2 and order m. The spherical harmonic coefficient *a priori* uncertainty values are defined according to Kaula's rule, shown by Equation 1, in which R_{mantle} is the Europa mantle radius (assumed to be 1465 km) and R_{Europa} is the mean radius of Europa (1565 km).[18] In addition to the baseline parameters listed in Table 2, a frequency offset stochastic parameter was also estimated when the one-way Doppler measurements were processed.

$$\sigma_{C_{n,m}} = \sigma_{S_{n,m}} = \frac{28E-5}{n^2}\left(\frac{R_{mantle}}{R_{Europa}}\right)^n \text{ for m = 0, 1, ..., n and n = 2, ..., 20} \quad (1)$$

The Europan gravity field information content from each individual flyby was accumulated via manipulation of the *a priori* and *a posteriori* covariance matrices. Subdividing the parameters into local parameters (position, velocity, and acceleration) and global parameters (μ_{Europa}, k_{2m}, and the 20 x 20 spherical harmonic coefficients), the variance-covariance matrix P may be represented as:

$$P = \begin{bmatrix} P_{pva} & P_{pva,gravity} \\ P_{pva,gravity} & P_{gravity} \end{bmatrix} \quad (2)$$

in which P_{pva} is the local portion and $P_{gravity}$ is the global portion (variances) and $P_{pva,gravity}$ is the local-global covariance. The global information accumulation is performed by defining the *a priori* global variance of flyby *m* as the *a posteriori* global variance of flyby *m-1*. The *a priori* local variance is always set to a diagonal matrix with the diagonals set to the uncertainty values shown in Table 2, and the local and global *a priori* uncertainty is assumed to be uncorrelated.

Figure 9 shows the estimated k_{22} uncertainty (1σ) as a function of the flyby number, and demonstrates the significance of the selected tracking architecture (i.e., data weight) on the gravitational tide estimation. Ka-band two-way tracking meets the desired k_{22} uncertainty in 11 flybys, while X-band two-way tracking does not meet the objective within the 34 planned flybys. This large discrepancy in performance is due to the selected Doppler data weights, as the X-band measurement noise is ten times the Ka-band measurement noise. A minimum of 27 flybys is required to meet the gravity science objective given a combination of Ka-band two-way data from Goldstone and X-band two-way data from Canberra and Madrid. The performance of this X-band and Ka-band scenario, which is slightly better than that of the X-band scenario, is expected given the flyby visibility shown in Figure 8, which show the first 11 flybys to be primarily tracked by the X-band stations. The drastic degradation of solution quality from Ka-band to X-band highlights the need to shift to Ka-band operations for better science returns.

As expected given the significance of the Doppler measurement noise, the Ka-band two-way and one-way tracking architectures perform quite similarly. The one-way Ka-band tracking scenario is able to meet the objective in 12 flybys. Compared to the best two-way performance given current DSN capabilities (Ka-band and X-band "mixed" tracking architecture), the DSAC one-way solution provides a 56% reduction in the amount of required flybys. The final k_{22} uncertainty after processing all 34 flybys is approximately 0.02 for the one-way Ka-band scenario and 0.04 for the two-way Ka-band/X-band scenario, demonstrating that utilizing DSAC-enabled one-way Doppler tracking improves the overall k_{22} science return by 50%. Additionally, relying on DSAC one-way radiometric data reduces mission risk by decreasing the number of flybys required to meet the minimum science objective.

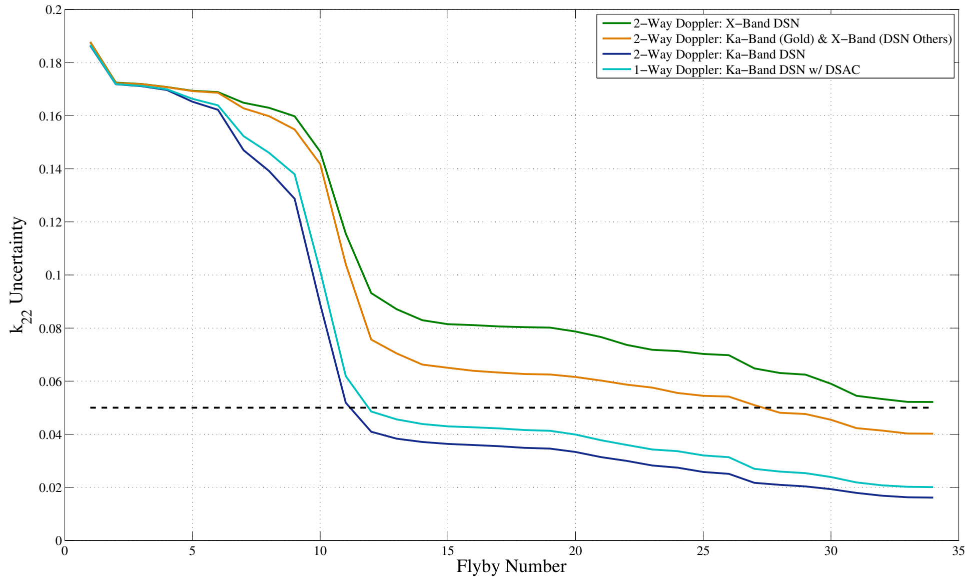

Figure 9. Estimated uncertainty of k_{22} gravitational tide parameter

SUMMARY

The Deep Space Atomic Clock (DSAC) mission holds the possibility to alter the traditional paradigm of radiometric tracking by allowing navigation to rely upon unprecedented high-stability, high-accuracy one-way signals for navigation and radio science purposes. Not only will this provide improved data quantity and quality, but it will also enhance tracking architecture flexibility and increase robustness to ground station outages. DSAC will also enable fully-autonomous onboard navigation, enhancing trajectory knowledge during key time-sensitive mission events. Demonstration of DSAC-enabled pin-point landing of a Mars lander, similar in size and mass to the Mars Science Laboratory, is currently under development. As was shown through the deep space examples presented in this work, navigation and radio science using DSAC-enabled one-way tracking performs as well as its two-way counterpart, and combining the high accuracy and stability of DSAC with the increased measurement accuracy provided by the Ka-band improves upon the best two-way tracking architecture available today.

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