The Deep Space Atomic Clock Mission

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ABSTRACT

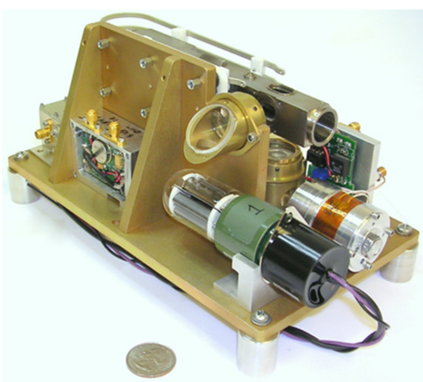

Figure 1: The laboratory brassboard version of DSAC is accurate to 1 ns in 10 days.

The Deep Space Atomic Clock (DSAC) project will develop a small, low-mass atomic clock based on mercury-ion trap technology and demonstrate it in space, providing the unprecedented accuracy and stability needed for the next-generation deep space navigation and radio science (Figure 1).

Ground based atomic clocks are the cornerstone of spacecraft navigation for most deep space missions because of their use in forming precision 2-Way coherent Doppler and range measurements. DSAC will provide an equivalent capability on-board a spacecraft for forming precision 1-Way radiometric tracking data (i.e., range, Doppler, and phase). With an Allan Deviation (A.D.) at 1 day of better than 2.E-14, DSAC will have a long term accuracy and stability that is equivalent to the existing Deep Space Network (DSN). Indeed, an early laboratory version of DSAC (shown in the figure above) has demonstrated an A.D. < 1.E-15 @ 1 day. By virtually eliminating spacecraft clock errors from this data, DSAC enables a shift to a more efficient, flexible, and extensible 1-Way navigation architecture.

In today's 2-Way navigation architecture, the Earth ground network tracks a user spacecraft and then a ground-based team performs navigation. Relative to this, a 1-Way navigation architecture delivers more data (doubling/tripling the amount to a user), is more accurate (by up to 10 times), and is enabling for future autonomous radio navigation (improving performance, robustness, and safety of time critical events such as probe landings or flybys). More specifically, a navigation

infrastructure based on 1-Way radiometric tracking on the return link has the following immediate benefit to NASA missions:

1. It capitalizes on the DSN's ability to support multiple downlinks on a single antenna, called Multiple Spacecraft Per Aperture (MSPA), since no uplink is required for DSAC enabled 1-Way radiometric tracking. For instance, at Mars two spacecraft equipped with DSAC can be tracked simultaneously on the downlink by a single antenna, while, with current 2-Way tracking capability, those two spacecraft must split their time on the uplink. The result is a near *doubling* of the usable tracking for each spacecraft. Preliminary studies have indicated that this additional data can yield relative improvements in both orbit and gravity estimation by several factors.
2. Deep space users with DSAC can take full advantage of view periods for tracking; unlike 2-way tracking time, which is reduced by round trip light time. As an example, Cassini's Northern hemisphere view periods at Goldstone and Madrid are on the order of 11 hrs, so a round trip light time in the 4 – 5 hr range yields an effective ~ 6 hr 2-Way pass. Whereas a 1-Way pass using DSAC can utilize the full view period of 11 hrs; a near *doubling* of the usable data without needing to transition into a complicated 3-Way tracking operation across multiple ground stations.
3. Planetary atmosphere investigations using radio occultations can benefit from DSAC as well. Compared to today's radio occultations that rely on 1-Way tracking derived using ultra stable oscillators, 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).
4. For outer planet missions, solar corona plasma effects are a frequency dependent error source that dominant over other measurement errors and affect radiometric tracking across both short and long time scales. Indeed, the Cassini mission navigators deweight their 2-Way measurement data by a factor of 3 over other measurement errors to account for this effect. Use of a Ka-only 1-Way downlink reduces these effects by 10 times relative to the typical user on an X-up/Ka-down 2-Way. So in Cassini's case, this solar corona effects are now 3/10ths the size of the other errors, versus 3 times. Outer planets missions, such as the Europa Orbiter/Flyby Mission, can benefit from this by potentially eliminating the need for a dual frequency electronics system (which allows removal of the solar corona effect at the expense of a noisier measurement); resulting in an overall mass and power savings. Gravity science is a particular beneficiary of these benefits because of both an increase in data quantity and improvement in data quality.

The preceding benefits are realizable with little to no modification to the typical navigation paradigm of collecting data on the ground and processing it on the ground. What DSAC also enables is a shift towards autonomous radio navigation where the tracking data is collected (from the DSN uplink) and processed on-board. In the current ground processing paradigm the timeliest trajectory solutions that are available on-board are stale by several hours to account for light time delays and ground navigation processing time. Timelier trajectory solutions are enabled via on-board 1-Way radio tracking with DSAC coupled with an autonomous GNC capability that uses this data. Such a capability can significantly enhance real time GNC events such as entry, descent, and landing; orbit insertion; flyby; or aerobraking via improving the trajectory knowledge necessary to execute these events robustly, efficiently, or with more accuracy.

As a specific example, delivery of a Mars lander to the top of the atmosphere (i.e., entry) using current ground based navigation procedures typically yields a knowledge uncertainty of 2 – 3 km (3 sigma), which is results from uploading a final trajectory solution upwards of 6 hours from entry. With DSAC 1-Way radio-tracking on the uplink and an onboard GNC system this knowledge uncertainty reduces to a *handful of meters* because the tracking and associated trajectory solution is available continuously and nearly instantaneously, including entry. This coupled with active guidance during the lander's hypersonic descent phase can effectively 'fly-out' any residual top of the atmosphere delivery error to get the lander back on its nominal descent trajectory prior to parachute deployment. By essentially eliminating the effects of atmosphere delivery errors, the powered descent portion of a pin-point landing need only correct for wind drifts and map tie error, thus reducing the overall delta V required. Use of DSAC for entry is a key step towards achieving an efficient (resource friendly) pin-point landing.

The mercury ion-trap atomic clock technology is currently being advanced to TRL 7 by the DSAC project, a NASA Technology Demonstration Mission, which plans to validate the clock by demonstrating it in a space environment. During a one year experiment scheduled to begin in early 2015, the payload (consisting of DSAC, a USO, and a GPS receiver/antenna) will be hosted on an Earth orbiting spacecraft and collect pseudo-range and phase data to any and all in-view GPS satellites almost continuously. This data will be telemetered to the ground and processed to simultaneously determine both precision orbits and DSAC's performance relative to the IGS (International GNSS [Global Navigation Satellite System] Service) time scale (that is aligned to UTC). A diagram illustrating this is shown in the Figure 2 below. This TRL 7 demonstration will allow the DSAC technology to be readily incorporated into multiple future missions.

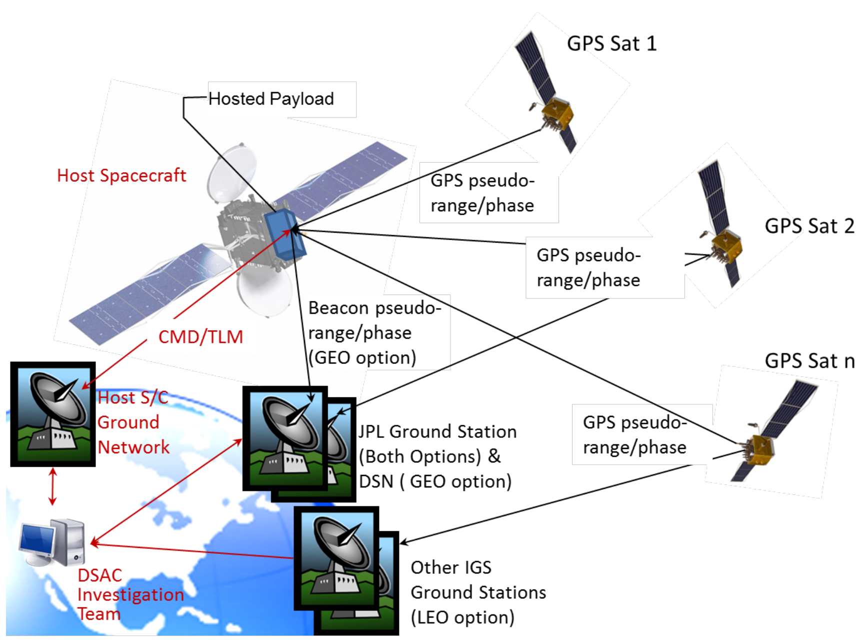

Figure 2: DSAC's Earth orbiting mission architecture.