Topical: Clocks are Foundational – Cross Cutting Technology Investments for Navigation and Science

A White Paper for the Decadal Survey on Biological and Physical Sciences (BPS) Research in Space 2023-2032

Todd A. Ely[1], Eric Burt, Joseph Lazio, Robert Tjoelker
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

Abstract

Emerging capabilities for space-based atomic clocks for space navigation and potential science, including fundamental physical science, are discussed. Navigation and science represent complimentary uses for space atomic clocks, and the case is made that continued investment in improving space clock capabilities will benefit both uses.

Atomic clocks form the backbone of the tracking networks we use to navigate whether here on Earth or in space. Terrestrial or Earth orbiting navigation often employs Global Navigation Satellite Systems (GNSS) that utilize rubidium, cesium, or passive hydrogen masers to provide precision one-way range and phase measurements. For space navigation, the Deep Space Network (DSN) and the European Space Agency's network ESTRACK use active hydrogen masers to provide precision radiometric tracking services that typically include two-way or one-way range and Doppler, and delta differential one-way range (DDOR), in addition to their communications service (GNSS systems are solely used for tracking). A noteworthy comment about the deep space networks (DSN and ESTRACK) is that they also serve as radio science telescopes for a variety of space science objectives (including atmospheric and ionospheric structure of planets and satellites, planetary gravitational fields, shapes, masses, planetary rings, ephemerides of planets, solar corona, magnetic fields, cometary comae, and such aspects of the theory of general relativity as gravitational waves and gravitational redshift [1]). As such, the requirements for their frequency and timing systems derive from the needs of all three areas, communications, navigation, and science and, at the risk of over simplifying, the associated stability requirements become progressively more aggressive in that respective order. In short, science needs have driven the performance of the deep space networks' frequency standards since their inception, but navigation has not been far behind in driving those requirements as well. Below is a snapshot of the DSN frequency standard stabilities from the DSN Telecommunications Link Design Handbook [2] that are provided:

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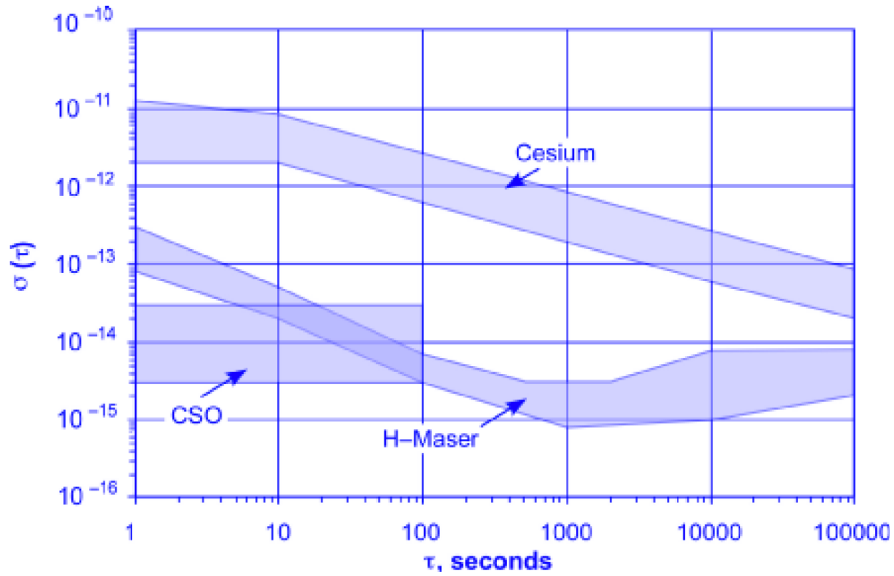
[1] Todd Ely (phone) 818-393-1744, (email) Todd.A.Ely@jpl.nasa.gov



Atomic clocks in space have been available for decades with a primary use being for GNSS systems and other defense systems, but their use for space exploration, both navigation and science, has been much more limited. A partial reason for this is cost, but another is that the long-term drift of the existing space clocks is relatively large such that the use of ground-based frequency standards has clear advantages. Indeed, the frequency drift of current space clocks requires significant monitoring and calibration or, as is often the case with deep space navigation, preferential use of two-way data over one-way data, which is dominated by large frequency drifts (typically from a USO). For example, the GPS control system determines and uploads clock corrections twice a day to the GPS satellites to ensure that the clock calibration parameters are accurate and up to date. There is a subtle implication to this need that makes it more difficult to use these frequency standards for navigation and science, and that rests on the question, 'If my signal has a frequency shift is that an artifact or is it a behavior of the 'effect' I am trying to measure?' Where the 'effect' could be the orbit of a spacecraft, or, as I will discuss later, the signature of a gravitational redshift or gravity wave. In fact, a reference with a significant linear frequency drift or any other form of long-term frequency instability is tantamount to obscuring any low frequency behaviors that you would like to observe, whether this is a scientific aim (i.e., gravity wave searches with space-based baselines) or navigation (is the frequency error being seen a spacecraft velocity error or is it the clock?). Additionally, since frequency stability on all timescales is relevant to a wide range of investigations (i.e., improved short term stability is important for increasing the coherence time of a space VLBI mission to observe an event horizon), it would be desirable, if not required, for the frequency reference to have superior stability characteristics on timescales that range from seconds to weeks. The recent demonstration of a mercury ion clock, the Deep Space Atomic Clock (DSAC) in low Earth orbit, represents a pathfinder towards better space-based standards. Indeed, DSAC demonstrated a stability <1.5e-13 at 1 second, < 3e-15 at a day, and a linear frequency drift < 3e-16/day, with the later representing a record setting value [3]. These performance levels are sufficient for routine use of one-way radiometric navigation [4] and make the case for onboard autonomous navigation [5]. Indeed Ely, et. al. [5] shows that onboard, one-way radiometric tracking when combined with onboard optical navigation yields an order of magnitude improvement in trajectory knowledge as compared to each data type by itself. The result is a robust, fault tolerant onboard navigation system that could be useful for autonomous robotic space exploration or for future human exploration to distant planets. But the DSAC demonstration represents the beginning of a new capability that paves the way towards even better performing space-based reference standards that could serve the future needs of GNSS here at Earth or for new satellite navigation systems deployed at high interest destinations such as at the Moon or Mars.

As with the existing DSN, these frequency standards will exist to serve many aims ranging from communication, navigation, to science. Science, in this context, ranges from planetary science such as radio occultations and gravity field estimation [6], but could venture into realm of fundamental science such solar system general relativity tests [7] or searches for low-frequency gravitational waves experiments [8], [9]. Tinto, et. al. [8] demonstrate that with the combination of a precision clock with stability similar to DSAC, a properly configured spacecraft digital radio, and the long baselines possible from a deep space interplanetary spacecraft that derived Doppler data types using one-way links may be sensitive enough to observe low frequency gravitational waves with almost an order of magnitude greater sensitivity than traditional two-way Doppler. Soyuer, et. al. [7] further illustrates that future missions to Uranus and Neptune could yield sufficient sensitivity to make meaningful GW observations. Indeed, Soyeur shows that with Allan Deviation improvements of only 3 times beyond current two-way Doppler levels demonstrated by Cassini and some categories super massive black hole mergers become observable. With a 10 times improvement, even more events can be observed. Hence, combining Tinto's and Soyeur's results leads to a conclusion that one-way Doppler using precision space-based atomic clocks may yield sufficient sensitivity to observe a variety of gravitational wave events. The fact that the atomic clock and radio can be readily co-manifested on probe-class deep space missions along with other science instruments implies that these fundamental physics investigations can be cost effective (vs the expense of dedicated missions with more complex instrumentation).

The preceding examples are just a few on the utility that space-based atomic clocks bring to navigation and science, it is not meant to be exhaustive but illustrative of the cross-cutting options that become possible if these clocks could be made more readily available or even ubiquitous if advances are maintained in improving performance while at the same time reducing their size, weight, and power (SWaP). My appeal to those who read this is that requirements for space clock performance or SWaP don't exist for one purpose alone and that, as you consider experiments for fundamental physics investigations, development of a space clock with suitable stability and accuracy could be an option as long as we maintain investments and forward progress in their development. Recently, NASA selected the next generation DSAC, DSAC-2, for demonstration on the VERITAS mission to Venus. The DSAC-2 design reduces the SWaP and a measurable improvement in stability relative to DSAC-1. But this should not be last investment in space clocks. Each future design should represent an advance that opens up new science discoveries. Indeed, on the horizon are optical clocks that could improve stability by several orders of magnitude relative to microwave clocks. However, to get there requires each community (communication, navigation, and science) to advocate for and collectively invest in their development – because clocks are foundational. Specifically, advancing space microwave clocks to pair with better space local oscillators (and/or developing space optical clocks) with short term stabilities at 1 second near 1e-14 would be commensurate with the best ground station clock capabilities and enabling for space-based science (such as VLBI imaging in support of the EHT, planetary gravity recovery or atmospheric radio occultations). Continuing to improve stability on longer time scales to better than 1e-15 at a day (approaching 1e-16) opens up even more possibilities for low frequency space science (such as gravity wave detections from a greater variety of sources). These objectives are also consistent with supporting space navigation and a future deployment of GNSS at the Moon or Mars.

Acknowledgements

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

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