ENHANCING THE ART OF SPACE OPERATIONS – PROGRESS IN JHU/APL ULTRA-STABLE OSCILLATOR CAPABILITIES

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Abstract

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) Ultra-stable Oscillator (USO) has been demonstrated in nearly 50 years of space applications to be a strategic asset to the space timekeeping and signal technologies of the United States. Therefore, advancing the JHU/APL USO capability by improving its frequency stability, without diminishing reliability, is uniquely valuable to the operations of space communication and navigation systems. Ultimately, we expect that the call for expanded mission requirements involving the real-time coordination of mission assets will become commonplace in distributed space sensor systems and robotic planetary exploration. As these missions mature, the requirements for high bandwidth communication and precise navigation will call for better time and frequency control infrastructure with exceptional reliability.

INTRODUCTION

Since 2001, JHU/APL has achieved significant milestones in our USO technology capability while also providing flight USO hardware to missions such as the NASA Gravity Recovery and Climate Experiment (GRACE) and JHU/APL's New Horizons (NH) mission to Pluto. We will show the specification and performance comparison of these USO requirements to discuss the progression of our USO improvements. We will also discuss the accomplishments made in 2006, under the NASA Mars Technology Program (MTP), for reducing USO mass to < 0.5 kg and steady state power in vacuum to ~ 1.1 W while adding Direct Digital Synthesis (DDS), generating all 35 channels correlated to the NASA Deep Space Network (DSN). The utility of this MTP USO feature removes the delay in payload instrumentation integration caused by waiting for a DSN channel assignment.

We will discuss our work toward a disciplined USO, a method for optimal removal of deterministic drift to improve frequency stability. We expect that the call for expanded mission requirements involving the coordination of mission assets will become commonplace in formation flying space sensor systems and robotic planetary exploration **[1]**. As these future missions mature, the requirements for high bandwidth communication and precise navigation will drive the need for better time and frequency control infrastructure. JHU/APL expects that a USO with disciplining offers a solution for robust extraterrestrial clocks with an operational life requirement greater than 10 years. Disciplined USO systems could be placed in very remote circumstances and maintain local time within a few microseconds from an Earth-based time reference for periods extending to several weeks, as one might expect in lunar and other deep space missions **[2]**.

We also recognize that missions will emerge where both the precision of local timekeeping and increased autonomy will only be supported by the addition of an onboard atomic reference. In this manner, we are pursuing USO clock system architectures that use the short-term frequency stability, mass, and power advantage achieved in the MTP USO with an atomic frequency standard **[3]**. At present, atomic clocks operate on spacecraft in Earth orbits, but there are none in use in deep space. In future deep space missions, atomic clocks onboard spacecraft will provide frequency stability sufficient for autonomous one-way navigation methods. Hybrid clock systems which combine JHU/APL USOs with next generation atomic frequency sources can mitigate the inherent risk of experimental deployment by assuring that the frequency generation of the remote system relies on the robust flight performance of the USO.

RELIABLE MISSION SERVICE AND USO PERFORMANCE

Since the beginning of the U.S. space program, JHU/APL has continuously supplied leadership in USOs and has introduced many innovations to oscillator and clock technology for space applications. JHU/APL USOs have figured prominently in missions of high notability. Starting with the Transit satellite navigation program and continuing through the NH interplanetary mission, JHU/APL has achieved mass, power, and size reduction while steadily improving frequency stability performance. Figure 1 illustrates a chronology of missions along with the evolution of JHU/APL-introduced USO capabilities extending over four decades of service.

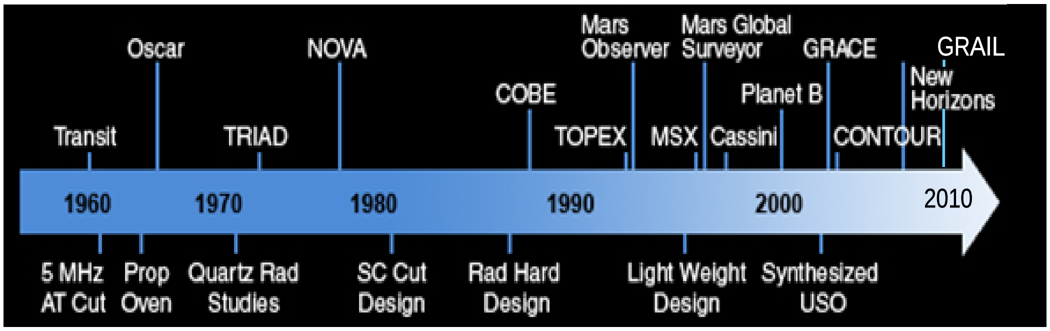

Fig. 1. JHU/APL USO missions with innovations to USO capabilities. The NASA Gravity Recovery and Interior Laboratory (GRAIL) mission is expected to launch in 2011.

JHU/APL quartz-based USOs demonstrate excellent reliability in space operation until mission obsolescence or unrelated spacecraft failure. An example is the JHU/APL USO flown on the Mars Global Surveyor (MGS) satellite. MGS launched in 1996 and began collecting orbital science data at Mars in 1998. While the primary mission ended in 2000, the spacecraft continued to supply mission data until a mishap in an upload command forced the depletion of its batteries in late 2007 **[4]**. The performance of the two most recent operating JHU/APL USO missions, GRACE and NH, are also good examples of how JHU/APL USO reliability and frequency stability performance continue to provide space science with extended mission service.

The GRACE mission launched two formation flying spacecraft into Earth orbit in 2002. The twin satellites utilize a dual-frequency inter-satellite ranging instrument to measure the relative line-of-sight position between the satellites. From these measurements, the relative velocity between the two satellites can be determined and gravitational force computed. The accuracy of the GRACE ranging measurement is highly dependant on the frequency stability of the reference oscillator. The frequency stability of the JHU/APL USOs onboard GRACE has enabled a relative accuracy of about 40 micrometers in 220 km.

Fig. 2 shows the frequency drift of the active onboard USOs in each GRACE satellite over 1000 days from launch. In both cases, the initial frequency drift has diminished from a positive rate and then changed to a much reduced negative rate. The reversing frequency drift behavior observed in the GRACE USOs is not typical with other reported JHU/APL USOs, like Cassini and MGS, and does not correlate with the onboard temperature and voltage telemetry trending from the units **[5,6]**. Nonetheless, the frequency drift of either USO is still much better than the requirement of 5×10^{-10}/day and the USOs continue to service the GRACE mission, exceeding 2500 days in early 2009. This long-term service and stability performance has allowed the GRACE project to extend its mission to realize an important goal of measuring the changing nature of the Earth's hydrologic cycle, most recently observing the loss of ice in Greenland and Antarctica attributed to the trend in global warming **[7]**.

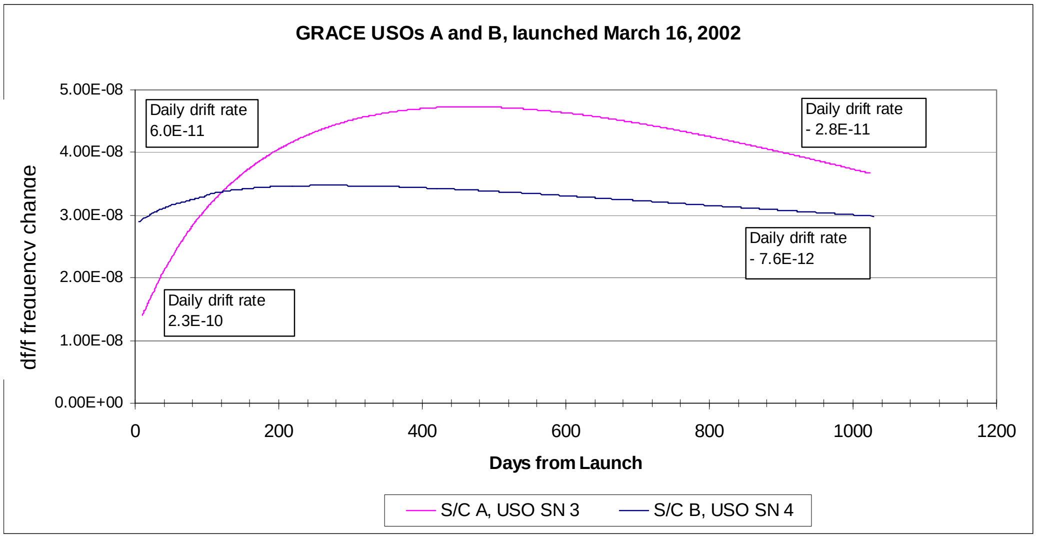

Fig. 2. Frequency drift of GRACE USOs for 1000 days after launch.

Gravity recovery is a recent role for USOs in space applications, while the support of radio science experiments for planetary exploration has been long established. JHU/APL USOs for MGS, Cassini, and NH respectively for the discovery of atmospheric constituents at Mars, Saturn, and Pluto are all selected to support radio science because of their extremely low noise and excellent frequency stability in the time intervals of 1 to 100 s. During transits behind a planet, the radio emission from a spacecraft is shifted in phase, proportional to the density of the atmosphere, in the brief time of ingress and egress over which the radio wave transverses the atmosphere. Radio science experiments can use this phenomenon to assess the details of a planet's atmospheric layers. Since the phase shift measurement and the noise due to frequency stability are indistinguishable to a receiver on Earth, the uncertainty in the recovered information is directly related to the frequency source's noise and stability. Figure 3 shows the measured Allan deviation of the Cassini, MGS, and NH USOs.

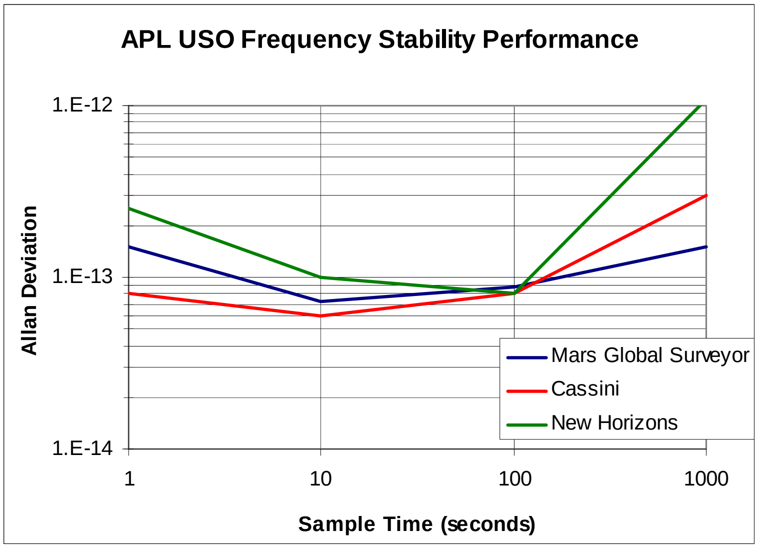

Fig. 3. Measured frequency stability of JHU/APL USOs used in planetary radio science experiments.

The most significant aspect revealed in the USO frequency stability of Fig. 3 is the relatively flat region from 10 to 100 s, often referred to as the FM flicker floor. This unique low noise character in the FM flicker floor for quartz-based USOs enables radio science experiments to measure extremely fine details and structure. In Cassini, the Radio Science Subsystem has resolved amazing detail of Saturn's ring structure, revealing gravity wave propagation in particles < 2 cm in diameter **[8]**. The span of the FM flicker floor in time is also highly valuable, as it determines the transit period over which valid radio science data can be collected. Although the primary role of the NH USO is the support of the radio science experiment, the USO also supports a unique navigation capability known as one-way non-coherent Doppler.

There are two JHU/APL USOs, called A and B, on the NH spacecraft that support both the frequency reference for the REX (Radio science Experiment) instrument and the communications transceiver. USO A has been selected as the mission primary, with USO B operating as a "warm-boot" standby. Within the transceiver, a comparison of the uplink carrier frequency and the downlink carrier frequency is made periodically and the result is included in the downlink telemetry. Doppler measurements are made in the routine manner at the NASA Deep Space Network (DSN). Doppler measurements delivered by the DSN to the New Horizons Mission Operation Center at JHU/APL are processed along with the spacecraft generated frequency comparisons to produce two-way Doppler measurements, equivalent to those that would have resulted from the use of a coherent transponder. Consequently, navigation is entirely similar to the two-way coherent method, while the processing of the Doppler measurements does not involve any knowledge of the spacecraft motion or the light time between the ground station and the spacecraft. It is completely self-contained and is known as the non-coherent Doppler tracking system **[9]**.

The NH spacecraft communications transceiver includes additional RF circuitry to provide the ability to characterize the frequency stability of USOs A and B as a byproduct of non-coherent Doppler-based tracking. Consequently, a history of the long-term frequency stability of USOs A and B have been accurately measured with a precision of $< 5\times10^{-12}$ since launch. This capability to determine USO frequency has a two-fold benefit by providing a one-way Doppler navigation method for at the spacecraft from the ground-based uplink signal and a measure of confidence in the merit of the USOs for spacecraft timekeeping. Specifically, anomalous frequency jumps and interactions with the deep space environment can create undesirable effects in quartz-based oscillators for precision navigation. JHU/APL experienced these effects in the Comet Nucleus Tour (CONTOUR) spacecraft during the first use of non-coherent Doppler based navigation **[10]**. However, frequency anomalies in the NH spacecraft USOs have been infrequent and appear correlated with significant events in the spacecraft's operational history.

Fig. 4 shows the frequency history of USOs A and B onboard the NH spacecraft for 700 days since launch on 19 January 2006. The frequency data have been adjusted for both general and special relativity effects so that the trend is reported as if the units were on Earth **[11]**. Overall, the rate of frequency drift of the two USOs has gradually diminished with no prominent reversals, as those observed in the GRACE data of Fig. 2.

Two events are highlighted in Fig. 4 that show small interactions in the recovered frequency data from the USOs. The first was an apparent effect caused by the Shapiro delay experienced by the downlink signal as the NH spacecraft trajectory formed an occultation with the Sun. During this brief time, the error in the recovered frequency data became greater, eventually forming a gap of a few days. The second interaction is considered a real effect in the USOs, due to the encounter of the NH spacecraft with the magnetopause of Jupiter in February 2007. The cause for these frequency anomalies has been attributed to ionizing radiation sensitivity of the quartz resonators of the USOs, which is a known phenomenon in space application. Although the frequency sensitivity of USO A and B quartz resonators to ionizing radiation was not measured prior to launch, correlation of the frequency anomalies with the flux of heavy ions and protons measured by the Pluto Energetic Particles Spectrometer Science Investigation (PEPSSI) onboard NH provides strong confidence for a radiation induced frequency shift in the USOs **[12]**.

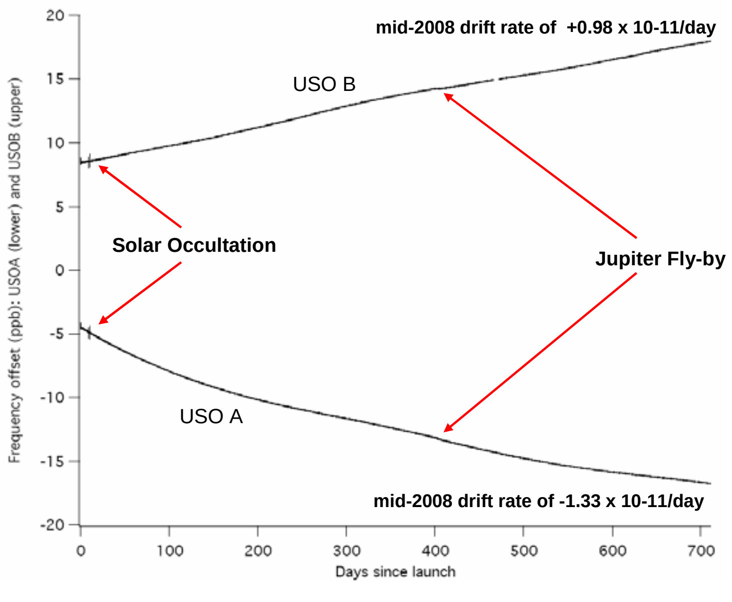

Fig. 4. Frequency drift of NH USOs for 700 days after launch.

The NH USOs A and B demonstrate frequency drifts (aging) of ~ $\pm 1\times10^{-11}$/day with frequency stability of 1×10^{-13} or better over time intervals of 10 to 100 s. Since the gravitational assist from Jupiter, the USOs have shown a remarkably steady frequency performance, providing the non-coherent Doppler system excellent stability as it assists the navigation of NH through the nine-year deep-space interplanetary cruise phase of the mission. In this manner, NH represents an emerging application for USOs where the capabilities of reliable extended service life and excellent frequency stability, both short and long term, are utilized to enable advanced mission needs.

In 2008, JHU/APL was awarded the contract by the Jet Propulsion Laboratory (JPL) to produce the USOs for the Gravity Recovery and Interior Laboratory (GRAIL) lunar mission. GRAIL is a formation flying, GRACE-like NASA Discovery mission at the moon with the goals of completely mapping the entire lunar gravity field and, through the geodesy determined from this result, attempting to define the most likely model for the moon's deep interior **[13]**. Unlike GRACE, GRAIL has no continuous GPS viewpoint. To compensate for this lack of a continuous positioning reference system, the twin satellites of GRAIL will form a time transfer link, periodically assisted by ground mission operations. This GRAIL mission design feature places an additional demand on the USO frequency stability requirements with a drift rate goal of $< 5\times10^{-11}$/day, 10 times better than the GRACE requirement discussed previously. Table 1 lists the GRAIL USO short- and long-term frequency stability requirements and goals.

Table 1. Comparison of GRAIL USO frequency stability requirements and goals.

Parameter	**GRAIL USO REQUIREMENTS**	**GRAIL USO GOALS**
Allan deviation	$\leq 3 \text{ x } 10^{-13}$ at 1 s $\leq 3 \text{ x } 10^{-13}$ at 10 s $\leq 3 \text{ x } 10^{-13}$ at 100 s $\leq 6 \text{ x } 10^{-13}$ at 1000 s $\leq 5 \text{ x } 10^{-11}$ at 57600 s	$\leq 2 \text{ x } 10^{-13}$ at 1 s $\leq 1 \text{ x } 10^{-13}$ at 10 s $\leq 1 \text{ x } 10^{-13}$ at 100 s $\leq 4 \text{ x } 10^{-13}$ at 1000 s $\leq 3 \text{ x } 10^{-11}$ at 57600 s
Daily frequency drift after 30 day operation	$7 \text{ x } 10^{-11}$ / 24 hours	$5 \text{ x } 10^{-11}$ / 24 hours

The frequency stability performance goals of GRAIL represent the most demanding performance placed on JHU/APL USO technology to date. These goals, like NH, follow the emerging mission needs for both excellent short-term stability and low noise for metrology and long-term stability for assisting spacecraft navigation.

A LOW-POWER, LOW-MASS USO WITH DDS FOR MARS

The previous section discussed the recent evolution of JHU/APL USO performance capabilities through their realization in space mission requirements. The next two sections will discuss research and development activities at JHU/APL conducted since 2001 to advance USO technology as low power, agile frequency sources for communication, and timekeeping systems (TKS) for navigation and the local coordination of distributed mission assets.

The communication bands of the NASA DSN are divided into 35 X-band channel frequencies, and any Mars communications architecture requires its frequency source to be a sub-multiple of these DSN X-band frequencies. Consequently, the source frequency cannot be established until the DSN channel has been assigned to the mission. Traditionally, USOs such as those discussed previously rely on harmonic multipliers to generate their output frequency, forcing the quartz resonator frequency to be directly related to the DSN channel assignment.

In 2006, JHU/APL completed the development of a synthesized USO under the sponsorship of the NASA/JPL Mars Technology Program (MTP) **[14]**. The resulting MTP USO provides a frequency reference that is stable enough for radio science applications (Allan deviation $< 1.5\times10^{-13}$ at 10 s), and is electronically selectable to cover the entire DSN communications band. The synthesizer allows for in-flight reassignment of the spacecraft's communication system. The in-flight programmable USO output frequency enables greater flexibility in designing overlapping or extending Mars missions in close spatial proximity.

The MTP USO offers additional advantages. Because of its programmable frequency synthesizer, the resonator frequency can be standardized at 5 MHz. This provides a reduction in USO production lead-time. With the traditional USO driven communications system, the lengthy process of mission design, DSN channel assignment, resonator procurement and screening, USO fabrication, and, finally, integration of the spacecraft are constrained to be performed in series. With the field-programmable MTP USO, the resonator and USO fabrication tasks can occur in parallel with the mission design and frequency channel selection, greatly reducing the overall lead-time. The MTP USO development also realized a significant reduction in mass and DC power consumption compared with heritage USO designs.

Several technology developments were required to realize the design of the synthesized MTP USO with reduced mass and power. First, a low-power oven control scheme was designed to provide a highly stable crystal oscillator temperature with the minimum DC power consumption. Then a lightweight packaging approach was developed to minimize size and mass while enabling in-air operation. Finally, a DDS-based up-converter architecture was developed to provide the required tunable output frequency with the minimum impact on DC power, phase noise, and frequency stability **[15]**.

Table 2 summarizes the measured performance of the MTP USO engineering model against the design goals set out by the MTP development program. In most aspects, the MTP USO engineering model achieved the performance goals. While the measured performance for phase noise, voltage sensitivity, and DC power under vacuum were slightly outside the goals, they were considered acceptable by NASA for the anticipated future mission requirements at Mars. At the MTP engineering design review in 2006,

Table 2. Performance summary of the JHU/APL MTP USO engineering model against design goals.

Parameter	**MTP Design Goals**	**Measured performance**
Output frequency and accuracy	76.364198 MHz to 76.783951 MHz (35 channels at 12.346 kHz spacing)	Maximum error to desired frequency within ± 9.8 ppm
Aging rate	$< 1 \times 10^{-10}$ per 24 hrs (spec after 30 days)	4×10^{-11} per 24 hrs (after 96 hours)
Allan deviation	$< 5 \times 10^{-13}$ at 1 s $< 2 \times 10^{-13}$ at 10 s $< 5 \times 10^{-13}$ at 100 s $< 30 \times 10^{-13}$ at 1000 s	3.6×10^{-13} at 1 s 1.6×10^{-13} at 10 s 2.9×10^{-13} at 100 s 10.2×10^{-13} at 1000 s
Single sideband phase noise	< -95 dBc/Hz at 1 Hz < -110 dBc/Hz at 10 Hz < -120 dBc/Hz at 100 Hz < -125 dBc/Hz at 1 KHz	-95 dBc/Hz at 1 Hz -107 dBc/Hz at 10 Hz -117 dBc/Hz at 100 Hz -122 dBc/Hz at 1 KHz
Frequency vs. temp.	$< 1 \times 10^{-12}$ per degree C	7×10^{-13} per degree C
Frequency vs. load	$< 2 \times 10^{-12}$ over 45 to 55 Ohms	4×10^{-13} over 45 to 55 Ohms
Frequency vs. voltage	$< 1 \times 10^{-12}$ over 22 to 35 Volts	$< 4 \times 10^{-12}$ over 22 to 35 Volts
Input DC power at 28 V spacecraft buss	< 0.8 W steady-state in vacuum	< 1.1 W steady-state in vacuum < 2.2 W operating in air 4.4 W warm up at 35 V
Mass	< 550 grams	480 grams
Performance and operating temperature	+20 to +40 C (performance) +15 to +45 C (proto-flight) -25 to +65 C (operating survival)	+15 to +45 C (verified performance over proto-flight) -25 to +65 C (operating survival)

JPL confirmed a technology readiness level of 6 (TRL 6) to the JHU/APL MTP USO, meaning:

> "A high-fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions."

TRL 6 is the highest readiness state a development can have without being deployed in a spaceflight mission **[16]**. JHU/APL recognizes the MTP USO as ready for flight level development.

IMPROVED USO TIMEKEEPING WITH DISCIPLINING

The synthesized MTP USO promoted our notion of using fine frequency synthesis for frequency drift correction in a disciplined oscillator scheme. In 2005, JHU/APL developed and demonstrated a method for optimal drift removal using the Allan deviation as the basis for clock model characterization **[2]**. The performance of the USO over a 35-day period of autonomous operation without intervening updates to the clock model estimator established high confidence that quartz-based USO frequency control systems could be placed in very remote applications and maintain local time as good as a few microseconds with respect to the Earth-based mission standard for extended periods, as one might expect in lunar and planetary missions.

The 2005 JHU/APL research measured the frequency performance of an USO in simulated space conditions to establish the feasibility of the frequency disciplining technique. The primary interest was to assess the predictability of the USO after clock characterization using Allan deviation. Coordinately, the research studied the need for updating the drift estimation and removal process with the focus on establishing the likely period for which a disciplined USO could be expected to run autonomously.

Figure 5 shows the expected frequency stability computed from the USO-measured research data using our optimal frequency drift correction based on Allan deviation characterization. The sawtooth pattern in the frequency data (plotted in pink) is the result of the frequency correction of about $+8\times10^{-12}$ being mathematically applied at daily increments. The natural drift of the free-running USO is seen during the period between the corrections. This behavior in frequency would be evident in our notional disciplined system, as the synthesizer would be stepped in a similar manner.

In a practical sense, the corrected frequency shown in Fig. 5 would represent the recovered signal quality of a remotely located USO timekeeping system during autonomous operation over 35 days in a space environment. Impressively, this recovered frequency error would be well within $\pm 1\times10^{-11}$, a factor of 15 improvement in frequency stability over the USO measured in our research. Also note in Fig. 5 that the Allan deviation (plotted in green) has mostly been reduced to below 5×10^{-13} for 1-day (86,400-s) time intervals. This Allan deviation performance is close to the FM flicker floor of 2.5×10^{-13} of the USO measured in our research, indicating that the drift removal is nearly optimal.

The data plotted in Fig. 6 represent the estimated timekeeping of the frequency-corrected USO data in Fig. 5 as compared to UTC (APL). UTC (APL) is maintained by the JHU/APL Time and Frequency Laboratory and the accuracy of UTC (APL) routinely stays within ± 20 ns of UTC.

In Fig. 6, the flat red lines delimit the mean time offset from UTC (APL) of about 48.5 µs with a maximum time interval error (MTIE) of ± 1.0 µs over the autonomous operating period of 35 days. This performance is very good for a free-running quartz oscillator and shows effective frequency stability under 1×10^{-13} for time intervals spanning as much as 35 days.

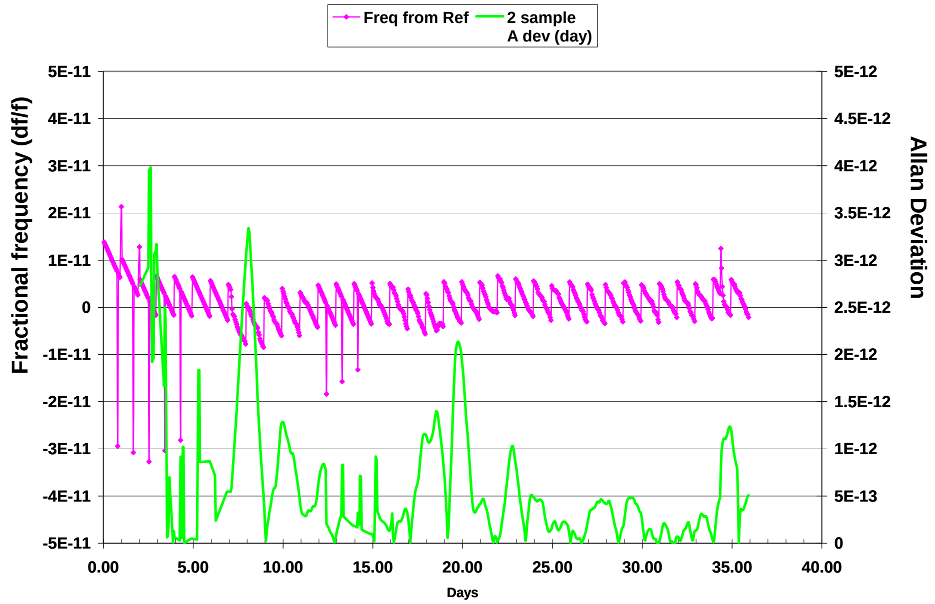

Fig. 5. Calculated frequency performance of JHU/APL disciplined oscillator research.

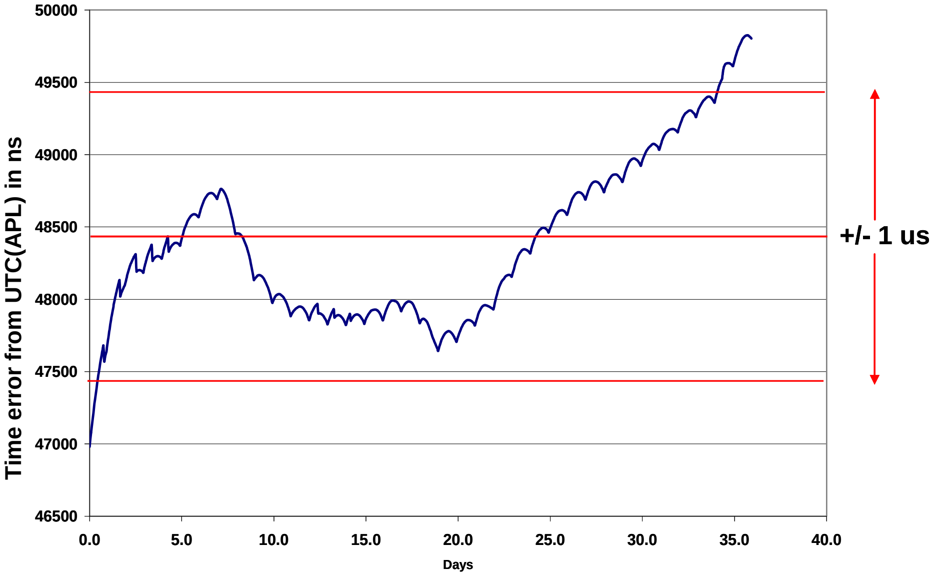

Fig. 6. Calculated timekeeping performance of JHU/APL disciplined oscillator research.

FUTURE USO TECHNOLOGY MATCHED WITH MISSION NEEDS

JHU/APL USOs have consistently met the space mission needs of our U.S. government sponsors. In recent NASA missions, such as NH and GRACE, a short-term stability of $< 1\times10^{-13}$ over 10 to 100 s and a reliable mission life exceeding 10 years have enabled planetary atmospheric exploration using radio-science techniques and formation-flying satellites for gravitational recovery and Earth geodesy. Looking at the needs of NH and GRAIL, JHU/APL USOs with enhanced long-term frequency stability provide onboard remote clock capabilities to support time transfer and one-way navigation methods for deep space vehicles. These extending timekeeping roles in advanced science missions, as well as in future communication and navigation infrastructure, are driving USO capability toward higher-performance remote space clocks.

In 2006, the NASA Space Communications Architecture Working Group made recommendations for the position, navigation, and timing system needs for future robotic science missions and human exploration. These recommendations include the notional deployment of a solar system scalable architecture for timekeeping and dissemination **[17]**. More recently, in 2008, the Systems Planning program under the NASA Space Communications and Navigation office discussed the architecture for a Lunar Network Radiometric Tracking Service similar in operation to the heritage Transit system, predecessor to GPS **[18]**. The expectation for such a one-way radiometric lunar infrastructure system requires onboard clocks derived from frequency sources with a frequency stability of $< 1\times10^{-13}$ over a 1-day time interval. The performance goal of the proposed synchronous lunar network clock system is to maintain ± 10 ns to a mission-related Earth time standard. This accuracy requirement will enable wireless cooperative robotic communication and the automated landing of robotic and cargo vehicles within ± 100-meter repetitive targeting.

Emerging mission planning goals such as those of the proposed Lunar Network will require both the timekeeping precision and increased autonomy provided by the addition of an atomic reference. In this manner, JHU/APL is pursuing clock system architectures, as described in Fig. 7, that expand a disciplined USO system by coupling its short-term character to an atomic frequency reference. In such a system, the embedded computer implements the USO drift removal and allows periodic alignment of the atomic reference for its optimal operation, with holdover action provided by the free-running USO. The use of such a system will also mitigate the inherent risk in the experimental deployment of possible next generation atomic frequency sources by assuring that the frequency generation of the remote system relies on a quartz-based USO with demonstrated flight performance lasting decades.

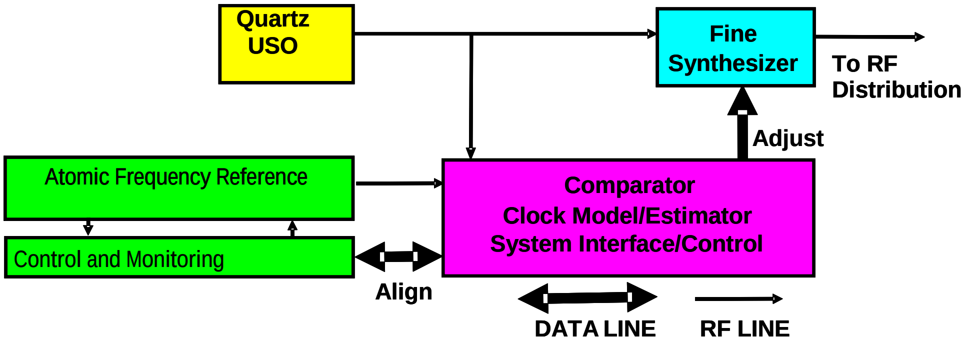

Fig. 7. Disciplined oscillator with hybrid expansion for atomic frequency standard.

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