THE IN-FLIGHT FREQUENCY BEHAVIOR OF TWO ULTRA-STABLE OSCILLATORS ONBOARD THE NEW HORIZONS SPACECRAFT

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Abstract

The New Horizons spacecraft has been on its extensive journey to Pluto, Charon, and the Kuiper Belt since January 2006. New Horizons uses two ultra-stable quartz oscillators as onboard references for radio science and the communications transceiver. One USO is configured as primary and the other is maintained in a "warm-boot" backup mode. The implementation of the transceiver for noncoherent navigation provides the opportunity for precise determination of the intrinsic USO frequency behavior during travel through deep space. In this paper, we report on the frequency behavior observed since launch. We show the effects of general and special relativity, including the Shapiro delay, and present the differences in the spacecraft reference frequency history when observed from different frames of reference. Both USO frequency behaviors demonstrated distinct interaction with Jupiter's radiation belt during the period prior to closest approach in February 2007. The frequency drifts are -1.33×10^{-11}/ day and $+0.98 \times 10^{-11}$/day, with each USO demonstrating a slight decrease in drift rate from that determined immediately after launch.

I. INTRODUCTION

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) New Horizons spacecraft (NH s/c), en route to the Pluto/Charon system with an expected extension for exploration into the Kuiper Belt, has so far met and exceeded expectations in both the science recovery from its instruments and the necessary low-cost operations and reliability required for a 9-year cruise through the deep space environment of our solar system. Launched 19 January 2006, the NH s/c completed its gravitational assist after an encounter with Jupiter in February 2007 **[1]**.

This maneuver through the Jupiter system not only provided a key opportunity to perform an operational check of the NH s/c instruments, such as the PEPSSI (Pluto Energetic Particles Spectrometer Science Investigation), but also offered a unique measurement of the in-situ frequency performance of the two onboard ultra-stable oscillators (USOs) during transit through the Jovian magnetosphere. These two USOs, called A and B, have a novel role in the NH s/c, providing both the frequency reference for the REX (Radio science Experiment) instrument and the master oscillator for the communications transceiver and the noncoherent Doppler regenerative ranging system. USO A has been selected as the mission primary with USO B operating as a "warm-boot" standby.

The NH s/c communications transceiver includes additional RF circuitry to provide the ability to characterize the frequency stability of USOs A and B as a byproduct of noncoherent Doppler based ranging. Consequently, a history of the long-term frequency stability of the USOs has been accurately maintained within several parts in 10^{12} since launch. This capability to determine USO frequency has a two-fold benefit by providing a one-way navigation method for ranging 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 noncoherent transceiver based navigation **[2]**.

However, frequency anomalies in the NH s/c USOs have been infrequent and appear correlated with significant events in the spacecraft's operational history. This paper will discuss the observed operational frequency stability for the NH s/c USOs and provide an explanation for the occurrence of these anomalies. We will also discuss the necessary considerations in compensating for physical effects, such as atmospheric propagation, and frame of reference issues that are presented in the raw frequency data collected during ground-based observations by the NASA Deep Space Network (DSN). The deconstruction of the raw frequency data to resolve USO frequency behavior has yielded insight into the importance of special and general relativity for deep space navigation and timekeeping.

II. NH TRANSCEIVER, TWO-WAY RANGING WITH NONCOHERENT DOPPLER

The NH s/c differs from most deep space probes in that the communications system is a transceiver rather than the conventional transponder **[3]**. In a transceiver, the uplink and downlink elements may share a common frequency reference, but the downlink signal is not phase-locked to the uplink. This type of communication system was included in the design of the NH s/c because it is well suited to the radio science experiments that will be done during the flyby of Pluto and Charon and it is the product of an evolutionary development of deep space communication systems at JHU/APL.

A critical function of the NH communications system is the support of two-way Doppler velocity measurement for use in navigation. Although the NH s/c transceiver cannot support Doppler navigation without the addition of some special purpose hardware, the necessary modifications could be easily incorporated into the design. 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 DSN **[4]**. 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 an innovation in the set of Doppler measurements, equivalent to those that would have resulted from the use of a transponder **[5]**. Consequently, navigation is entirely similar to the two-way 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.

The design goal for the processing of the Doppler measurements was the removal of any effects that might be due to the offset and drift of the USOs that serve as the spacecraft frequency reference. As a byproduct of this processing, the frequency of the oscillator can be very accurately determined. In this system, there are two unknowns: the Doppler velocity and the spacecraft frequency reference; and there are two measurements: the Doppler measurement made by the DSN ground station and the frequency comparison made at the spacecraft. These two measurements are sufficient for a determination of the Doppler velocity and the USO frequency. Measurement of the spacecraft oscillator frequency has been a regular activity since launch in January 2006.

III. RESOLVING USO FREQUENCY FROM PHYSICAL EFFECTS AND FRAME OF REFERENCE

Highly accurate determination of the spacecraft oscillator frequency is based on Doppler measurements and the transmitted telemetry data, as described above, but it also requires the use of an orbit determination for the spacecraft, knowledge of the ground station position and motion, and models for such effects as the optical thickness of the atmosphere. Three different methods of computing the oscillator frequency have been developed and used in parallel.

Two-way calculation - The uplink frequency is combined with the processed and unprocessed Doppler measurements to compute the oscillator frequency. This method makes minimum use of the orbit determination. It is only required to compensate for the motion of the ground station during the round-trip light-time.

One-way calculation - Processed and unprocessed Doppler measurements are used without regard to the uplink frequency history. The formulation of this method is a bit simpler, but it makes heavier use of the orbit determination than does the two-way calculation.

Light-time calculation - The unprocessed Doppler measurement is used with the light-time that is computed directly from the orbit determination. This method makes maximum use of the orbit determination. This method is of interest because it is closely related to the timekeeping activity for the spacecraft.

Because these three methods make different use of the available data types, they provide a cross-check of each other. A critical element in the development of the oscillator frequency measurement was the reconciling of these methods into agreement. This process of reconciliation brought forward some subtleties that might have otherwise been overlooked. These include the fact that the orbit determination is performed in a frame of reference that is fixed to the solar system barycenter, while the Doppler measurements are made in a frame of reference that follows the ground station. The three methods did not agree until the transformations between reference frames were correctly included in the oscillator frequency calculation. For example, during the two occurrences of the NH s/c solar conjunction, in November 2006 and December 2007, the Shapiro time delay did not have a noticeable effect on the two-way calculation, because it affects the Doppler measurement and telemetry in the same way as a change in the spacecraft orbit, and this method relies weakly on the orbit determination. The one-way calculation and the light-time calculation will deviate from the two-way calculation when the Shapiro time delay is not included in those calculations, because they rely more heavily on the orbit determination.

The Shapiro time delay is an increase in the travel time of a photon passing a massive body. Even with no change in the geometric distance between an observer and a spacecraft, the distance is effectively increasing as the spacecraft approaches a solar conjunction **[6]**. This causes a Doppler-like dip in the observed frequency. The opposite effect is present following solar conjunction. If the Shapiro time delay is not properly included in the one-way and light-time calculations, the resulting ground observed frequency will be as shown in Fig. 1. The frequency data of Fig. 1 is the observed frequency of USO A during the NH s/c solar conjunction of November 2006. The oscillator frequency does not form a continuous trend.

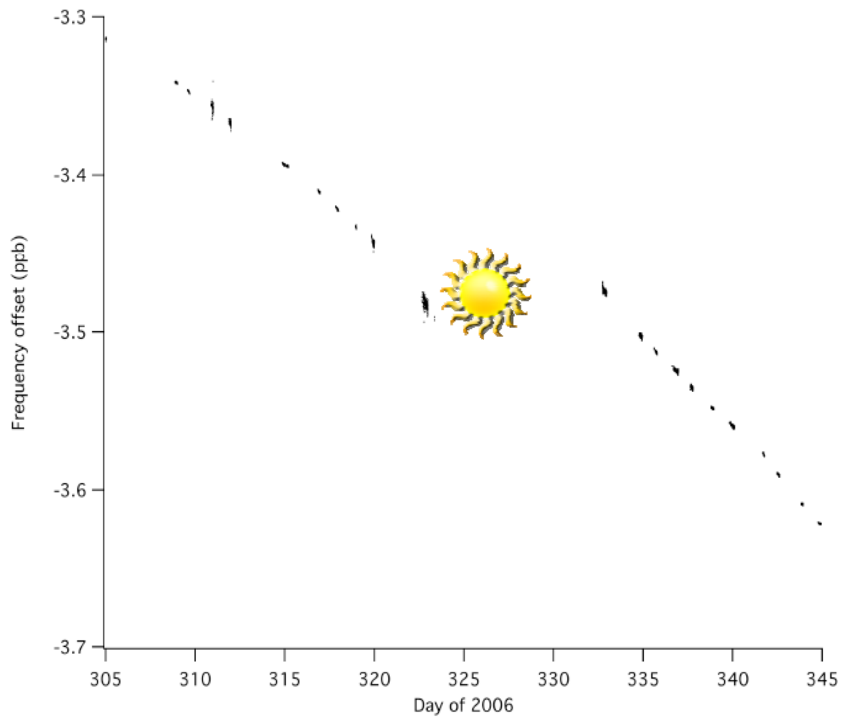

Figure 1. Observed USO A frequency during solar conjunction, without Shapiro compensation.

When the Shapiro delay is compensated, the result is a shown in Fig. 2. The two-way calculation is not significantly affected by inclusion or neglect of the Shapiro time delay, because it does not rely on the orbit determination for the underlying range rate, which is modulated by the Shapiro time delay. This is one of the cases where the multiple calculations of the oscillator frequency provided a cross-heck on the inclusion of the proper physical effects. Bringing the three calculation methods into agreement provides confirmation that all physical and frame of reference effects, such as the Shapiro time delay, have been correctly compensated.

Consideration of the different frames of reference is a necessary part of the calculation of the spacecraft oscillator frequency, but it also leaves open the question about which frame of reference the results should be expressed. Four frames of reference are included in the routine processing of the New Horizons data.

Ground station - This is the frame of reference in which the Doppler measurements are made. It is a natural frame for processing those measurements.

Solar system - This is the frame of reference in which the orbit determination is expressed and in which the light-times are expressed. This is a natural frame of reference for reconciling the Doppler calculations with the light-time calculation.

Spacecraft, local gravity - This is the frame of reference of the spacecraft as it moves and experiences changes in gravity due to proximity to the Earth, Sun, and Jupiter.

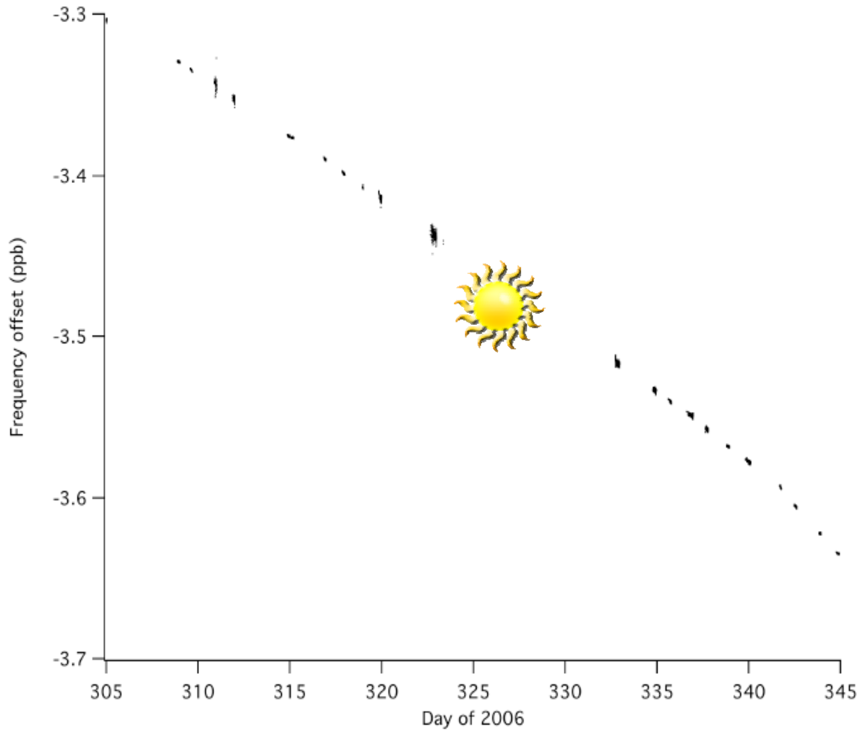

Figure 2. Observed USO A frequency during solar conjunction, Shapiro compensation included.

Spacecraft, reference gravity - This is the frame of reference that represents the oscillator frequency that would be observed if the oscillator was brought back to the launch site. Changes in the local gravitational potential do not affect the computed oscillator frequency in this frame of reference. This is the frame of reference in which a perfect oscillator would be stable. In all of the other frames of reference, variations in the observed frequency would be observed even for a perfect, stable oscillator.

The following four figures represent the frequency data history of the primary spacecraft frequency reference, USO A, over the 675-day measurement period since launch in January 2006. Note that the NH s/c closest approach in the Jupiter encounter occurred at day 405 into the mission. In all of the figures, the frequency offset is relative to the nominal NH s/c RF system reference of 30 MHz and is expressed in terms of parts-per-billion (ppb).

Fig. 3 shows the oscillator frequency offset in the ground station frame of reference. The ground station reference frame history is dominated by the annual variation of the relative velocity between the Earth and the spacecraft. The rotation of the Earth adds or subtracts 30 km/s to this relative velocity. The small kink at about 400 days after launch is the result of the Jupiter flyby, which will be more noticeable in the following figures as the actual frequency of USO A is resolved from the frame of reference effects. Not easily seen in Fig. 3 is the pass-by-pass variation in the computed oscillator frequency. At the scale of Fig. 3, this pass-by-pass variation appears as a broadening of the trace. Just as Earth revolution modulates the relative velocity, the Earth's rotation introduces a variation of as much as 0.5 ppb to the observed oscillator frequency.

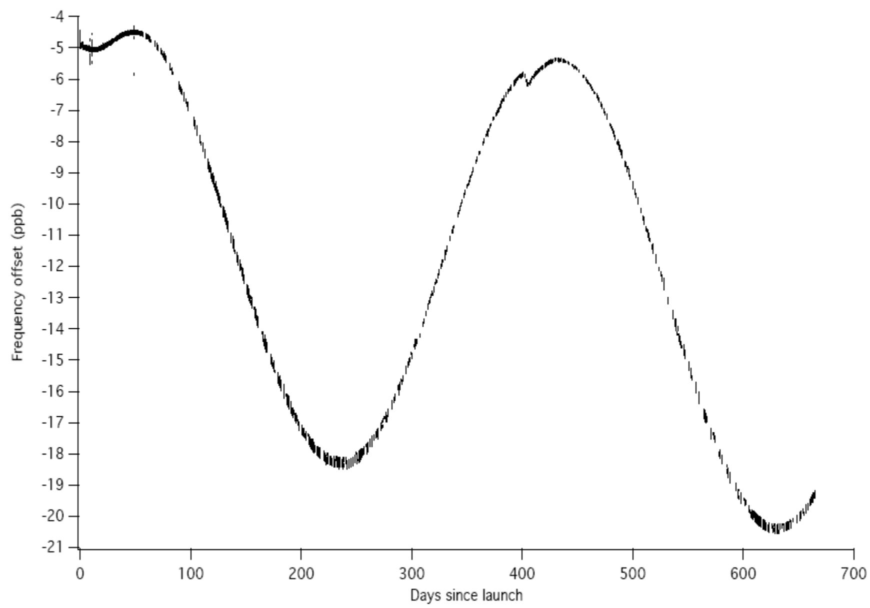

Figure 3. USO A frequency history in the ground reference frame, raw data as determined by the DSN.

Fig. 4 shows the oscillator frequency in a frame of reference fixed to the solar system barycenter. The complex shape of the frequency data curve is the result of many competing factors. These include the slowing of the spacecraft as it moves away from the Sun, the changes in gravitational potential, and the frequency drift of the oscillator. The sharp dip in frequency data around mission day 400 is coincident with the Jupiter flyby, mentioned earlier. Both special and general relativity are evident here. The sharp dip is the result of the increase in gravitational potential near Jupiter. The frequency offset noticed after the encounter with Jupiter is the result of the boost in the spacecraft speed that was achieved from the flyby. Another aspect to the transformation from the ground reference frame to the solar system frame is a negative frequency shift of about 4 ppb at the zero-day mission intercept. This frequency shift is the result of moving the reference of frame to the higher gravitational potential at the solar barycenter.

Fig. 5 shows the oscillator frequency behavior in the spacecraft's frame of reference. Again, the behavior is somewhat complex. Because this frame of reference moves with the velocity of the spacecraft, no time dilation effects due to special relativity are present, but changes in gravitational potential and oscillator aging are apparent. Again, the dip in the frequency at Jupiter is still visible, but the frequency offset observed in Fig. 4 is not present with a total recovery of the frequency drift trend that exists prior to the flyby.

Finally, Fig. 6 shows the oscillator offset after changes in the local gravitational potential have been removed. The reference potential for this panel is the potential that existed at the Earth or ground reference frame. Fig. 6 can be viewed as the oscillator frequency history that would have been observed if the oscillator had never left the launch site. Much of the complex behavior seen in the other figures has been removed in Fig. 6 and only the intrinsic changes in the oscillator frequency remain. A small frequency offset and change in drift rate still remains at day 400 and will be attributed to interaction with ionizing radiation in Jupiter's magnetosphere, to be discussed later in this paper. The behavior here is a continuous decrease in frequency of about -1.5×10^{-11}/day, which is consistent with expectations for a high-stability quartz USO.

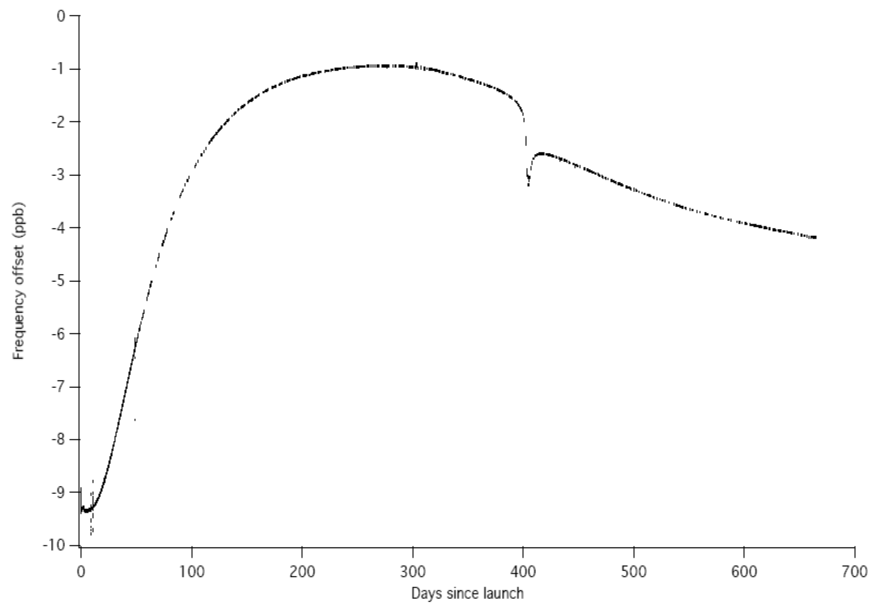

Figure 4. USO A frequency history in the solar system reference frame.

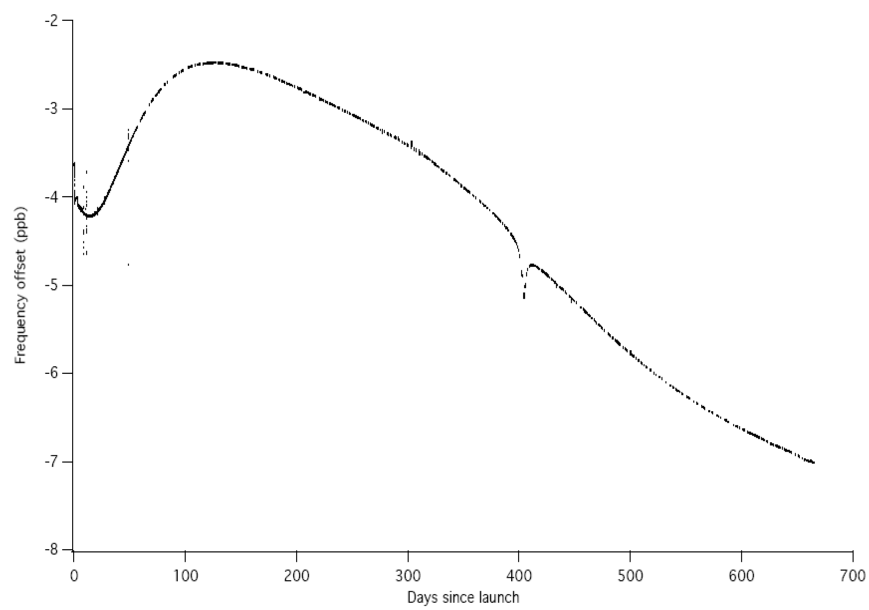

Figure 5. USO A frequency history in local spacecraft reference frame, no special relativity effect.

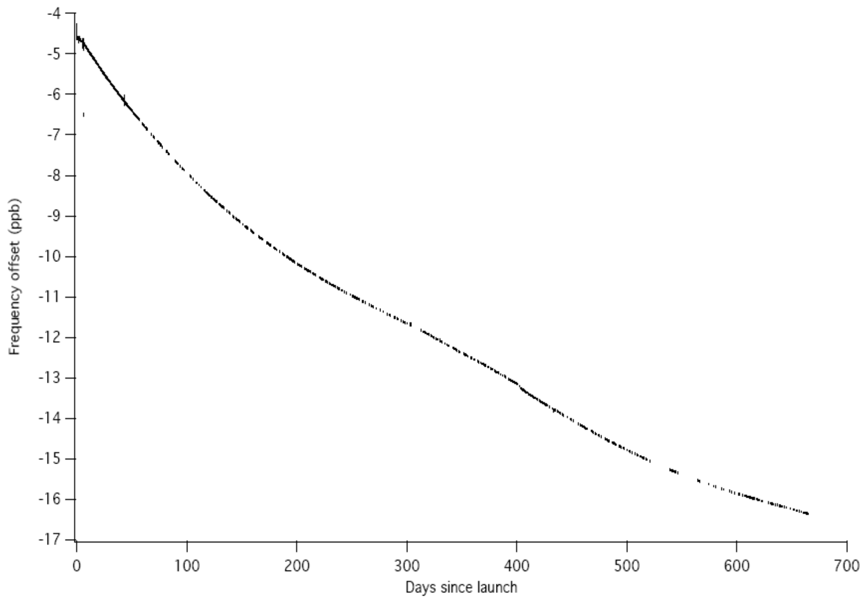

Figure 6. Intrinsic USO A frequency history in spacecraft reference frame at ground potential.

The previous four figures can be reviewed in reverse order. Starting with the smooth intrinsic behavior of the oscillator in Fig. 6, local gravitational effects are added due to the Sun, Earth, and Jupiter in Fig. 5, with variations in velocity added to get to the solar system barycenter frame of reference in Fig. 4. Finally, the revolution and rotation of the Earth are added in Fig. 3 to get the raw oscillator frequency observations at the DSN. Without consideration of all these effects, the gradual, monotonic aging of the USO frequency drift would not be readily assessable.

While essentially all of the in-flight radio observations and navigation of the NH s/c pertain to the selected primary USO A, the frequency behavior of USO B can also be determined from within the operation of the communications system. Each of the USOs produces a one pulse-per-second signal and the phase offset between these signals is included in the downlink telemetry. If this phase offset was constant, that would imply that both USOs are running at the same frequency offset from 30 MHz. In reality, USO B is running faster than USO A and so the phase changes at a rate that is indicative of this difference. Fig. 7 is the frequency history of USO B as determined using the phase comparative method against USO A since launch in January 2006. USO B continues to increase in frequency as it has since launch with a drift rate of $+0.98 \times 10^{-11}$/day measured over the last 100 days of 2007.

The left panel of Fig. 8 shows the intrinsic frequency history of USO A for the first 180 days of 2007. This period contains two important events; the encounter with Jupiter's magnetosphere starting at day 57 of 2007 and the change in spacecraft from three-axis-stabilized to five-RPM-spin-stabilized at day 78 of 2007. The right panel of Fig.8 corresponds to USO B during the same period. These frequency histories have been transformed to the spacecraft frame of reference with local gravity effects removed (essentially returned to Earth). Due to the indirect method of observation and the coarseness of the relative phase measurement, the history of USO B is not as precisely determined as that for USO A.

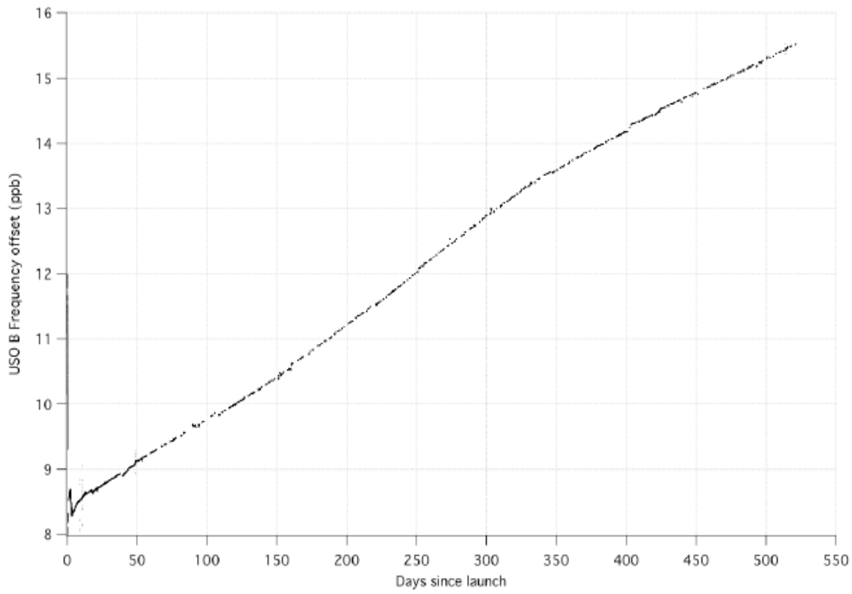

Figure 7. Intrinsic USO B frequency history in spacecraft reference frame at ground potential.

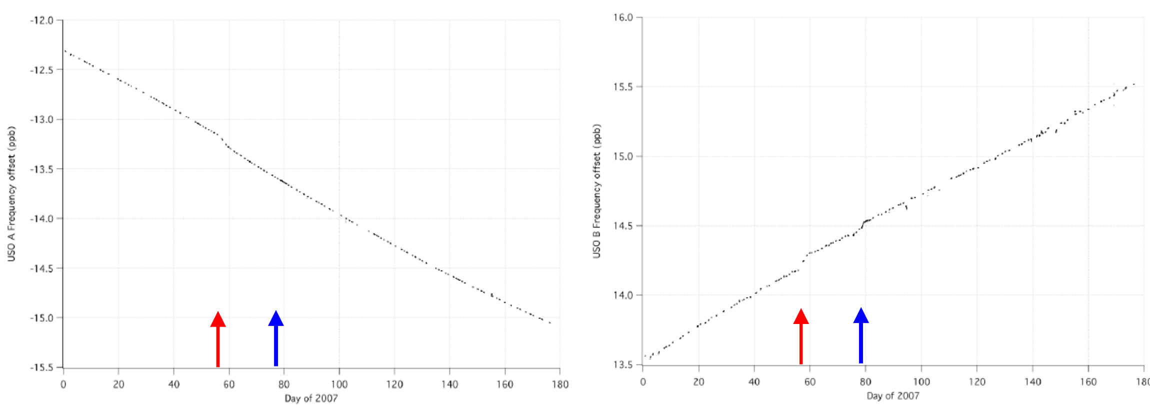

Figure 8. Comparison of USO A (left) and USO B frequency history during 2007; red arrows indicate first time of Jupiter encounter; blue arrows NH s/c change to 5RPM spin.

Nevertheless, some interesting observations can be made from the comparative frequency histories of USO A and B. First, the frequency drift of USO B is positive and has remained mostly at the same drift rate since launch, while USO A is drifting negative and appears to be slightly improving in drift rate. The frequency anomalies observed in both oscillators during the beginning Jupiter encounter was to increase the frequency offset for USO B and to decrease it for USO A. Finally, USO B appears substantially more sensitive to changes in the spacecraft spin rate than USO A.

IV. PLAUSIBLE EXPLANATIONS FOR USO ANOMALIES IN THE NH S/C

The performance of the two USOs onboard the NH s/c has been excellent and well within the system specifications of $\pm 1 \times 10^{-10}$/day and meeting the goal of $\pm 1 \times 10^{-11}$/day in the case of USO B, with USO A just marginally greater than the goal. At initial mission concept, concern was expressed over the radiation induced frequency change associated with the radioisotope thermoelectric generator (RTG) used to power the NH s/c over its extended mission life **[7]**. Under initial mission analysis, the shielding effectiveness of the mechanical structures surrounding the resonator was estimated, with the conclusion that the RTG neutrons, and electrons associated with Jupiter's magnetosphere, would be completely blocked. The estimated remaining proton and gamma radiation exposures at the resonator were as follows:

RTG: 2.85 Krads (Si) gamma radiation only, distributed over 15 years
Solar maximum: 0.15 Krads (Si) proton radiation distributed over first 2 years after launch.

JHU/APL has reported previously on the testing of quartz crystal resonators for sensitivity to gamma radiation and proton radiation **[8]**. The following Figs. 9 and 10 depict some of the measured sensitivity found in swept quartz, Bliley BG-61 5 MHz, 3rd overtone SC cut resonators, similar to those used in the NH s/c USOs to these types of radiation. The sensitivity is shown as a fractional frequency shift per rad (Si) dose.

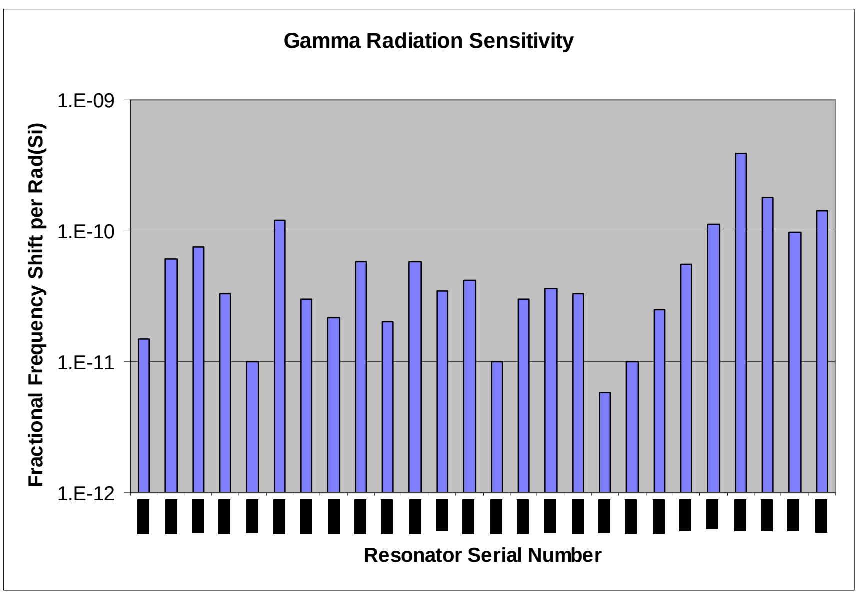

Figure 9. Fractional frequency shift in BG-61 resonators per rad (Si), gamma.

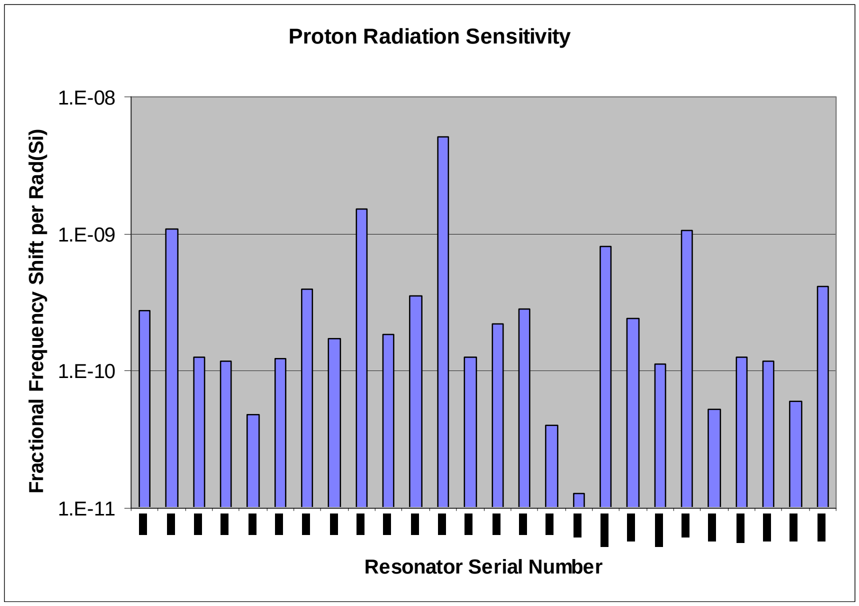

Figure 10. Fractional frequency shift in BG-61 resonators per rad (Si), 60 MeV protons.

As shown, there is considerable variation in the response of these quartz resonators to a given type of radiation. When comparing the frequency sensitivity between gamma radiation and proton radiation, in general, there is a greater response from the proton radiation, but a consistent factor has never been found.

The observed gamma sensitivity ranges from 5.8×10^{-12} to 4.0×10^{-10} $\Delta f/f$ per rad (Si)
The observed proton sensitivity ranges from 1.3×10^{-11} to 5.1×10^{-9} $\Delta f/f$ per rad (Si).

Using these estimates and measurements, the frequency drift associated with gamma radiation from the NH s/c RTG has the possibility to range from 3×10^{-12}/day to 2×10^{-10}/day and 2.6×10^{-11}/day to 1×10^{-9}/day for proton irradiation from the solar wind. Given these large ranges, the initial system analysis based on frequency drift seemed to warrant the use of screening to select resonators for the mission. However, an alternative analysis showed that sufficient end-of-life margin existed in the channel spacing, tracking correction, and system timekeeping; additionally, the impact to these system aspects could be well compensated, since the process of radiation induced frequency change was comparatively slow. Moreover, the typical gamma sensitivity is in the order of 3×10^{-11} per rad (Si), so the expected RTG frequency change would be 1.5×10^{-11}/day. Likewise, with a typical proton radiation of 1×10^{-10} per rad (Si), the frequency change would be 2×10^{-11}/day during the 2-year period of the solar wind influence. For these reasons, resonator screening for radiation-induced change was not performed on the resonators used in the USOs of the NH s/c. This economical decision in initial mission requirements planning would prove to be unfortunate in the scope of our efforts to establish a cause for the frequency anomaly observed in both USOs during the encounter with Jupiter's magnetosphere.

As we considered the source of the contemporaneous frequency anomalies observed in both USOs at the beginning of the Jupiter encounter, it seemed apparent that the event was likely an external interaction with ions. As shown in Fig. 11, an important aspect to this notion was that the frequency perturbations occurred near DOY 56, 2007, when the NH s/c crossed the Jovian magnetopause, where particles of the solar wind are concentrated in the magnetic-bow shock of Jupiter. We knew that previous radiation shielding analysis completely diminished electrons from incidence with the resonators, so we had to establish heavier particles, such as protons and nuclei. Fortunately, we were aware of the observations made by the New Horizon's science team in the data obtained by the PEPSSI, which was enabled during the Jupiter flyby for both science and engineering functional check. The PEPSSI is a broad-energy mass spectrometer that simultaneously records the incident energy and flux of electrons, protons, and nuclei **[9]**.

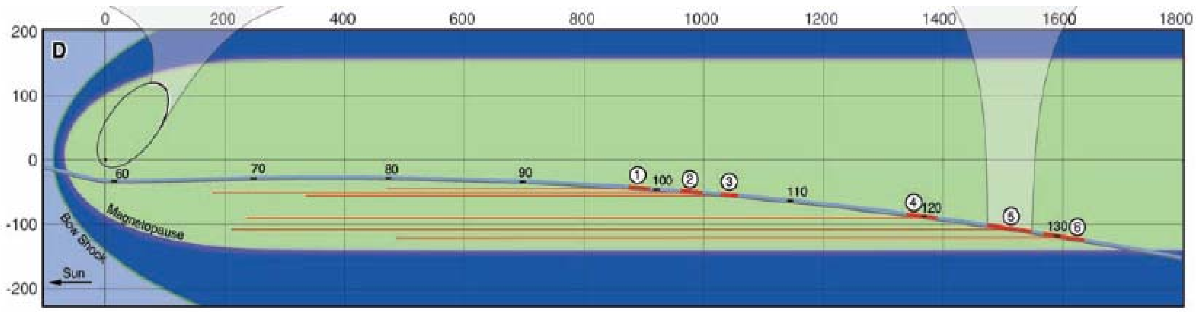

Figure 11. Track of NH s/c through Jupiter region; horizontal and vertical scales are in Jupiter radii; small black numbers are DOY 2007 at 10-day intervals.[1]

Fig. 12 is the PEPSSI energy time spectrogram for protons, nuclei species, and electrons during the nearly 100-day period of 2007 that the NH s/c was influenced by the Jovian magnetopause. Notice that the energy and flux of both protons and nuclei are greatest just before the crossing of the spacecraft into the Jovian magnetopause. The flux of electrons occurs later, after the spacecraft crossing into the magnetosphere. Taken altogether, the magnitude of the contemporaneous frequency perturbations in USOs A and B of a few parts in 10^{11} and the PEPSSI record of coincident heavy ion flux provide high confidence for radiation-induced frequency change as the cause of the anomalies, an exciting opportunity in the study of quartz frequency sources in deep space.

Our next task for attributing plausible cause to the anomaly recorded in the frequency history of USO B was straightforward, as we could directly associate the event with the change of stabilization in the NH s/c at DOY 78, 2007. This maneuver in the mission operation placed the NH s/c into a 5-RPM spin along the central bore sight axis of the high gain antenna from a thee-axes-stabilized position during the Jupiter flyby, in preparation for the long cruise toward Pluto. It is well known that quartz resonators are sensitive to acceleration. Again, though not specifically measured in the NH s/c USOs, we know that the Bliley BG-61 type resonators typically range 1.5×10^{-9} to 2×10^{-9} per g in frequency change with acceleration.

Fig. 13 is a mechanical diagram that shows the spin axis of the spacecraft and the locations of USO A and USO B in relation to this axis. The position of USO B is 21" from the central spin axis. The position of USO A is 5" from the central spin axis. The stabilizing rotation of the NH s/c at 5 RPM imparts ~0.015 g's to USO B, resulting in a frequency shift in the order of 2 to 3×10^{-11} for an assumed resonator acceleration sensitivity of $\sim 2 \times 10^{-9}$ per g, similar to that observed in USO B at DOY 078. The acceleration at USO A is about 77% less forceful.

[1] McNutt et al., 2007, **Science, 318**, 220, Fig. 3D with AAAS permission.

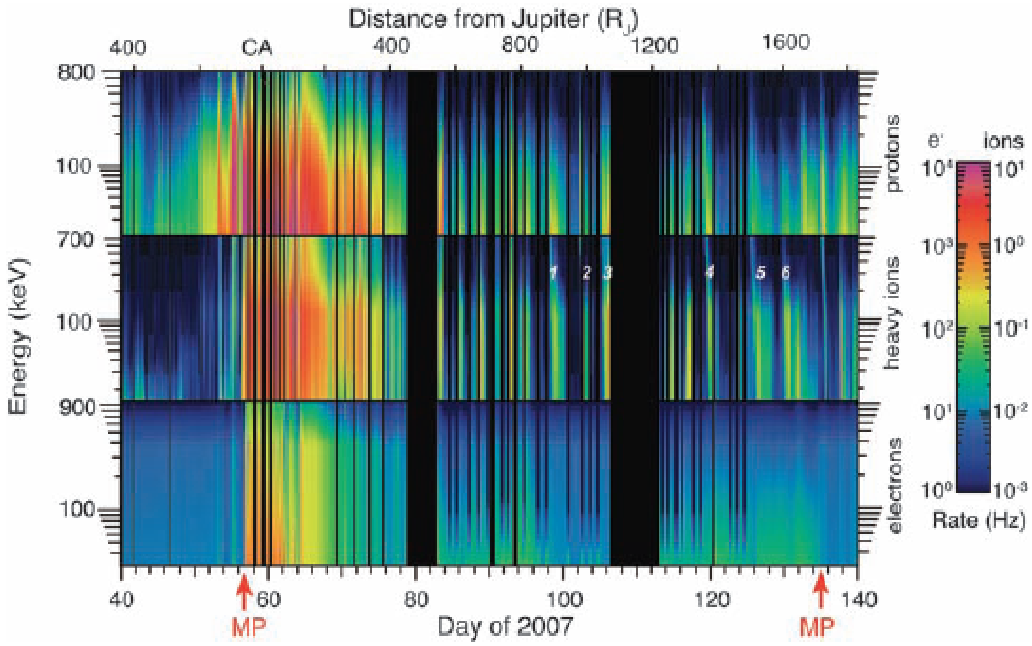

Figure 12. Spectrogram data from the NH s/c Pluto Energetic Particles Spectrometer Science Investigation, PEPSSI Instrument; MP indicates spacecraft crossing of Jovian magnetopause.[2]

As described above, both USOs showed frequency perturbations in their data due to changes in the centripetal forces exerted on the resonators due to changes in the spacecraft spin rate. However, as USO B is farther from the spin axis than is USO A, this difference explains most of the anomaly being prevalent in USO B, but other contributors are necessary to explain the full difference.

V. SUMMARY OF NH USO OBSERVATIONS

The design of the NH RF transceiver with the feature of supporting noncoherent Doppler navigation provides an exciting opportunity to examine the in-situ USO frequency stability of ultra-stable oscillators in deep space. The two science-grade USOs required for radio science experiments (REX) at Pluto are also incorporated as the transceiver's master reference and provide the high frequency stability necessary for the one-way tracking of the DSN uplink, accomplished at the spacecraft. Because these USOs are integral to the navigation of the NH s/c, they are constantly monitored as a byproduct. The two USOs A and B are also simultaneously powered, for the possibility of a warm boot, allowing their intrinsic frequency stabilities to be compared as a check for common frequency perturbations, most likely caused by interactions with environmental influences. This was most evident in the coincident interaction of USO A and B with the Jovian magnetopause, plausibly from the flux of heavy ionizing particles found in the PEPSSI data.

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[2] McNutt et al., 2007, **Science, 318,** 220, Fig. 1 with AAAS permission.

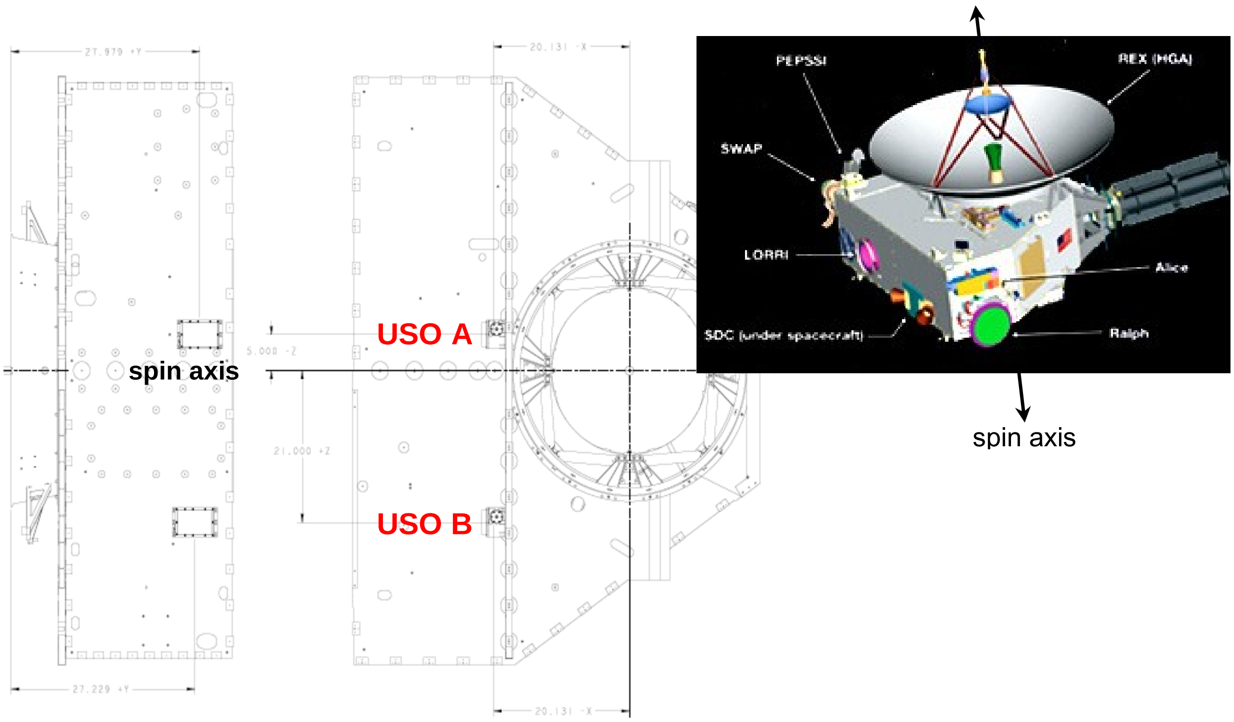

Figure 13. Positions of USO A and B in the NH s/c with respect to the 5-RPM stabilizing spin axis created DOY 78, 2007; the spin axis is centered with the bore sight of the high gain antenna. Inset: cartoon of NH s/c with spin axis.

The observation of relativistic Doppler effects within the downlink frequency data emphasizes the requirements to properly transform these data through the important frames of reference for adjustment in deep space navigation. The addition of noncoherent Doppler tracking permitted the use of a three-equation navigation method, each equation with differing dependence of downlink telemetry, orbit determination, and one-way light time. Placing the requirement on this three-equation method to form tight agreement provided the motivation to present spacecraft knowledge in four frames of reference; ground raw data, barycentric, spacecraft local gravity, and spacecraft ground reference gravity. The resolution of the downlink frequency data into these four frames of reference each provided an important viewpoint in spacecraft position and condition of the USOs.

The resolution of interaction with the magnetopause at Jupiter suggests science value in characterization of USO radiation sensitivity and acceleration sensitivity prior to launch. As the other intrinsic frequency stability factors such as temperature dependence, power supply susceptibility, and long-term resonator aging are highly constrained in USOs, the results so far in the NH s/c show that USOs, with properly calibrated sensitivities, can be an important adjunct to mission science collection and experiments in the deep space environment.

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