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Stability of DSS-25 Ka-band Station Delay During the Juno Prime Mission

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ABSTRACT. — One of the goals of the Juno mission is to precisely measure the gravitational field of Jupiter. This is accomplished by measuring the Doppler shift of the X-band and Ka-band carrier signals during closest approach periods. Calibration of the station phase delay is crucial to the determination of the spacecraft trajectory and gravitational field as well as their associated uncertainties. The extreme dynamics experienced by the Juno spacecraft make the radiometric measurements sensitive to small errors in the calibration. In 2018, the station delay was measured along the three signal paths used by Juno: X-up/X-down, X-up/Ka-down, and Ka-up/Ka-down. Although the X-band paths were measured consistently with previous estimates, the estimated delay was found to be unexpectedly larger on the Ka-band uplink path. In this work, we estimate the Ka-up/Ka-down round-trip system phase delay using the uplink sweep to the spacecraft. The uplink sweep provides sensitivity to the station delay and allows it to be measured from the carrier frequency observables on a regular basis without the need for specialized ground tests. The Ka-up/Ka-down delay was found to be consistent at 179 microseconds from orbit insertion in July 2016 until the Block 6 Exciter was installed in November 2020, when the delay decreased to 157 microseconds. This change was attributable to the removal of approximately 4.2 km of cable on the Ka-band uplink path during the Block 6 Exciter upgrade.

I. Introduction

The Juno Radio Science investigation uses two-way, coherent frequency observables at X-band and Ka-band, and the primary link configuration is simultaneous X-up/X-down and Ka-up/Ka-down. The simultaneous observations at both frequency bands allow for a calibration of charged particle contents (e.g., solar plasma) to reduce the noise on the radio link [1], allowing the recovery of a more accurate gravity field of Jupiter. Juno's trajectory in the prime mission (July 2016–June 2020) was designed so that closest approach passes occur over the Deep Space Network's (DSN) Goldstone complex in order to use the Ka-band transmitter and Advanced Water Vapor Radiometers (AWVR) at Deep Space

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Station-25 (DSS-25) [2]. The primary source of the downlink frequency observables are derived from open-loop recordings and processed using the JPL Planetary Radar and Radio Sciences Group's Radio Science Visualization and Processing (RSVP) toolkit [3].

The general link configuration is shown in Figure 1. At Goldstone's Signal Processing Center (SPC10), X-band (7.1 GHz) and Ka-band (34 GHz) Doppler-compensated uplink frequency profiles (i.e., ramps) are commanded into the exciters. The exciter frequencies then travel ~10 km line-of-sight to the transmitter amplifiers at the DSS-25 antenna, which amplify the signal and transmit it out-the-horn to the Juno spacecraft at Jupiter. On Juno, the Small Deep Space Transponder (SDST) receives the X-band uplink and the Ka-band Transponder (KaT) receives the Ka-band uplink. Both transponders then multiply the received signals by corresponding turnaround ratios, and transmit them back to DSS-25. The DSS-25 antenna receives the X-band (8.4 GHz) and Ka-band (32 GHz) signals, amplifies them through the Low Noise Amplifiers (LNA), and down-converts them to an intermediate frequency (IF). The IF is then sent from DSS-25 back to SPC10 for distribution to the closed-loop and open-loop receivers.

Prior to the analysis of Juno gravity science data, the DSS-25 system delay was assumed to be 154 microseconds, split evenly between uplink (77 microseconds) and downlink (77 microseconds). During the analysis of the linear combination of the X-band and Ka-band signals, it became apparent that there was a bias in the frequency observables at X-band and/or Ka-band coming from a calibration error. By analyzing in-flight testing in October 2018, our team hypothesized that this calibration error could be attributed to a station delay [4]. The station delay was measured in a ground-only test in November 2018 [5] and was shown to be fully consistent with the earlier in-flight testing. The ground-only test measured an additional 24 microseconds of delay on the Ka-band uplink path.

Various DSN equipment was updated throughout the Juno Prime Mission. A major overhaul of the DSS-25 LNA and Ka-band uplink occurred between February and July 2018. From orbit insertion in July 2016 until May 2019, the primary open-loop receivers were the Radio Science Receiver (RSR) for X-band and the Wideband VLBI Science Receiver (WVSR) for Ka-band. The next-generation Open Loop Receiver (OLR) was used and the RSRs and

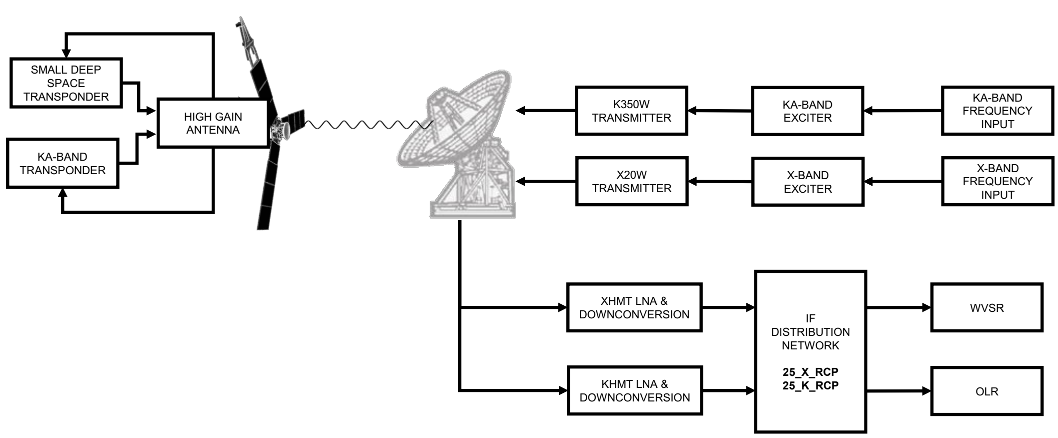

Figure 1. Block diagram of the key systems and link configuration during Juno gravity science observations.

WVSRs were decommissioned in May 2019. The DSN transitioned the IF distribution network to a new “common platform” in 2019. The Ka-band exciters were upgraded twice, once between February and July 2018 from the Block 5 Direct Digital Synthesizer (DDS) to the Block 5 Uplink Signal Generator (USG), and again in November 2020, when the exciter was upgraded to the Block 6 Exciter.

In this report we analyze in-flight testing with Juno to determine the stability of the Ka-up/Ka-down station delay during the Juno prime mission. Juno conducts regular Ka-band engineering tracks with DSS-25 to verify operational readiness prior to science data collection during closest approach periods. Through careful analysis of the data collected during these engineering tracks, the Ka-up/Ka-down system delay can be estimated.

II. Methodology

When the DSN initiates the uplink to the Juno spacecraft, an uplink sweep is conducted when the transmitter is turned on. The sweep drives the uplink frequency first above the spacecraft’s best-lock frequency (BLF), then ramps the signal down below the BLF, and then ramps it back to the nominal BLF for tracking. Sweeping the uplink allows the spacecraft’s transponder to acquire the uplink signal within its tracking threshold, which may change due to oscillator drift from temperature variations or spacecraft trajectory uncertainties. For risk mitigation, Juno Radio Science integrates a second acquisition sweep at a lower ramp rate into the commanded Ka-band uplink frequency profile for every Ka-band uplink pass. This gives the transponder a second chance to acquire the signal, if the first one is unsuccessful.

Because this second Ka-band sweep runs at a rate much larger than the classical Doppler shift, it makes the signal more sensitive to changes in the total system delay (including ground uplink delay, spacecraft transponder delay, and ground downlink delay). Thus, we can apply a modified ramped ranging technique to determine the system delay, as was originally done during the November 2018 ground test [5]. Figure 2 shows an example of the second acquisition sweep, which runs with a sweep range of ±20 kHz at a rate of 1 kHz/second. The first upsweep duration is 20 seconds, the downsweep duration is 40 seconds, and the final upsweep is another 20 seconds.

The second sweep is observed on the ground in a round-trip light-time after execution by the exciter-transmitter system. Frequency observables are extracted from the recorded open-loop data using a phase-locked loop at an output count-time of 1 second using the same technique as done for the gravity science frequency observables [3].

The dynamic effect of Juno’s orbit must be removed to estimate the delay, assuming the phase delay on the Ka-band path is zero. This requires a custom orbit determination filter, since the trajectories delivered by the navigation team do account for the nominal X-band station delay. JPL’s Mission Analysis, Operations, and Navigation Toolkit Environment (MONTE) software suite [6] is used as the orbit determination filter for this analysis. The orbit determination process is set up to estimate the spacecraft state vector at the start of the DSN pass, using the Ka-band frequency observables, plus X-band range measurements.

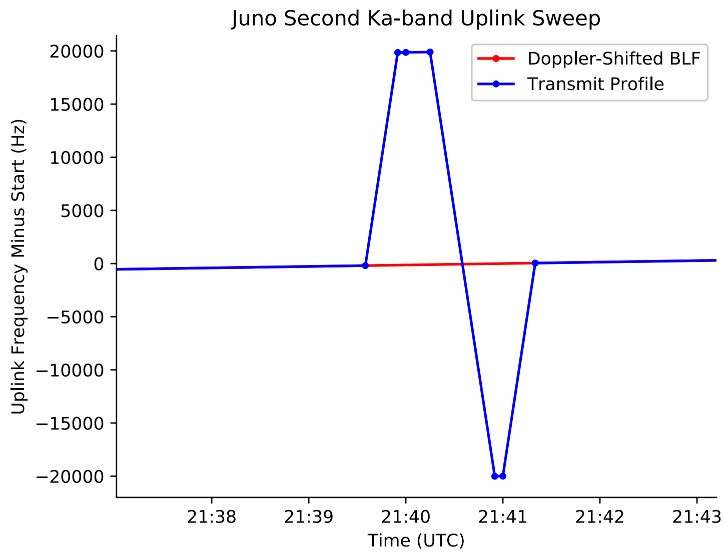

Figure 2. Example of Juno's second Ka-band acquisition sweep.

Ka-band frequency observables assume the station delay is equal to zero and are compressed to an integration time of 10 seconds to reduce thermal noise. X-band range measurements, which are calibrated for station delay during the DSN pre-calibration prior to the pass, constrain the light-time. The outputs of the orbit determination are a new estimate of the spacecraft trajectory and a set of frequency residuals (Δf), which are the observed (f_{obs}) value minus the predicted value (f_{pred}) from the spacecraft trajectory:

$$\Delta f = f_{obs} - f_{pred}. \quad (1)$$

If the station delay was accurate, the frequency residuals would have a zero mean. Ramping the uplink during the sweep will effectively introduce a bias into the frequency residuals during the time of spacecraft ramping, inversely proportional to the ramp rate and spacecraft turnaround ratio as shown in Equation (2) [5]:

$$d = -\frac{\Delta f}{f_{TX} * TAR}, \quad (2)$$

where d is the total system delay, f_{TX} is the transmit ramp rate, and TAR is the spacecraft turnaround ratio (Juno's Ka/Ka turnaround ratio is 3360/3599). Figure 3 shows the frequency residuals around the time the second acquisition sweep is received on the ground (i.e., round-trip light-time after transmission).

The initial upsweep takes 20 seconds. The downsweep takes 40 seconds, and since the frequency integration time is 10 seconds, about three frequency residuals are observed during the downsweep. Likewise, the upsweep takes 20 seconds thus only one frequency residual is observed during each upsweep.

To estimate the station delay, we compute the mean value of the three biased frequency residuals on the downsweep, perform a table lookup of the transmit ramp rate, then compute the delay based on Equation (2). The single-point observations on the upsweep

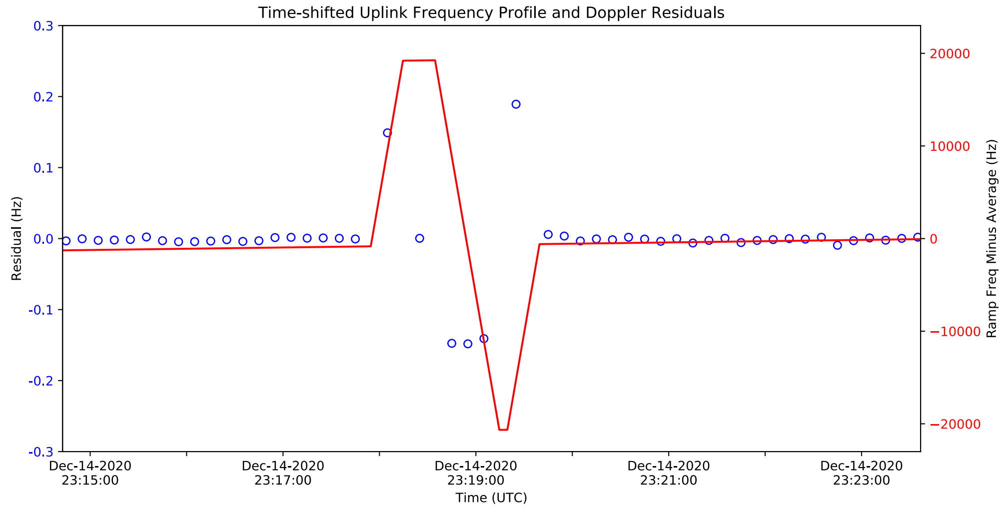

Figure 3. Plot of uplink frequency (red), time-shifted by the round-trip light-time, and the Ka-band frequency residuals (blue). It is clearly seen during the portions of the sweep, the residuals are non-zero, caused by the system delay.

are not used, as any given single frequency observable point could be biased from other noise sources (e.g., plasma, thermal). The uncertainty on this measurement is bound by the data noise, which is the standard deviation of the frequency residuals during the pass where the uplink is not sweeping.

In addition, two dedicated test passes were conducted in October 2018 and February 2021. During the first test pass, multiple uplink sweeps were performed at Ka-band with an increasing ramp rate, from a minimum of 1.2 kHz/s to a maximum of 2.5 kHz/s, for about 4 hours. During the second test pass, the Ka-band uplink sweeps were performed with a rate of 2.5 kHz/s, for about 1.5 hours. Figure 4 shows the uplink sweeps adopted during these tests. The increased rate greatly improves sensitivity to instrumental delays.

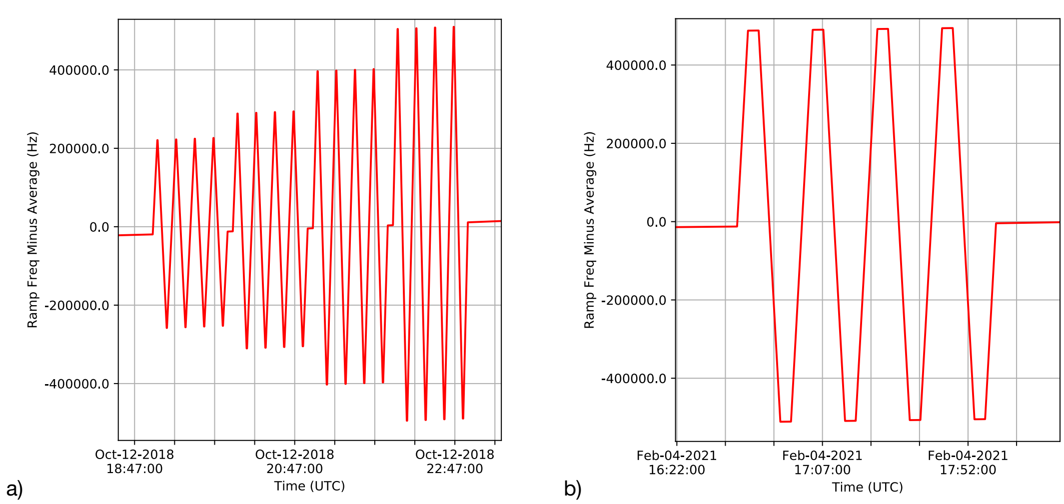

Figure 4. Plot of the uplink ramp frequency during the testing in October 2018 (left) and February 2021 (right).

III. Ka/Ka Delay Results

The round-trip system delay from 10 Juno Ka-band engineering tracks are shown in Table 1. These tracks were spaced roughly throughout the prime mission duration alongside the configured uplink and downlink equipment used for the track. It is important to note this round-trip system delay includes the uplink delay, spacecraft transponder delay, and downlink delay. Ground tests of Juno's internal Ka-band Translator delay have shown they are small, <700 nanoseconds, and are thus negligible in this analysis.

Table 1. In-flight estimates of Ka-up/Ka-down total system delay.

Date	Uplink Exciter	Downlink Receiver	Estimated Delay
2016-NOV-30	Block 5 DDS	WVSR	179 ± 4 μs
2017-NOV-30	Block 5 DDS	WVSR	185 ± 5 μs
2018-OCT-12	Block 5 USG	WVSR	180 ± 3 μs
2018-DEC-03	Block 5 USG	WVSR	181 ± 6 μs
2019-JUL-15	Block 5 USG	OLR	171 ± 14 μs*
2019-OCT-25	Block 5 USG	OLR	180 ± 4 μs
2020-MAY-22	Block 5 USG	OLR	179 ± 10 μs
2020-OCT-22	Block 5 USG	OLR	178 ± 4 μs
2020-DEC-14	Block 6	OLR	156 ± 4 μs
2021-FEB-04	Block 6	OLR	157 ± 2 μs

**One apparent outlier occurred in July 2019; however, the noise during that track was high due to increased troposphere noise and is reflected in the weighted uncertainty*

The average delay, prior to the introduction of the Block 6 Ka-band exciter, was 179 ± 6 microseconds. This is fully consistent with the ground-only measurement of 175 ± 1 microseconds done in November 2018 [5]. After the introduction of the Block 6 Ka-band exciter, the delay was reduced by ~22 microseconds to 157 ± 3 microseconds. No significant change was seen during the transition from the downlink WVSR and OLR receivers.

IV. Discussion and Conclusion

At the time when the original ground testing was conducted to investigate the station delay at DSS-25 in November 2018, the cause of the extra 24 microseconds of delay on the Ka-band uplink path was not known. Later tests revealed the reasons. Ka-band uplink was originally installed to support the Cassini Gravity Wave Experiment, conducted while Cassini was en route to Saturn between 2001–2003. The DSS-25 antenna is spaced approximately 10 km line-of-sight away from the Goldstone SPC in the Mojave Desert. Temperature fluctuations in the desert ground cause the cable to expand and contract, introducing a variable path delay. To counteract this effect, a spool of cable (called the fiber compensator reel) was placed in a temperature-controlled room inside the SPC. The fiber compensator reel had a spooled length of 4.2 km; the actual length of cable may have been longer. This would introduce a minimum uplink delay of 21 microseconds.

During the installation of the Ka-band Block 6 Exciter in November 2020, the fiber compensator reel was bypassed since the Gravity Wave Experiment requirement was no longer needed. This removes the additional delay measured during the November 2018 test.

The introduction of the DSN common platform and the effect it has had on the station delays is worth further discussion. The common platform was introduced during the year 2019, causing significant increases in the station delay on closed-loop data (both radiometric Doppler and range observables). Due to the digitization and distribution of the received IF to these receivers, an additional 802.65 microseconds delay is added on top of the normal delay. Although the OLR also uses the common platform, the delay on the OLR was predicted only to be an additional 1.6 microseconds (thus the closed-loop 802.65 microseconds are not detectable during these tests). This is close to the DSN Time Code Translator accuracy, which maintains the absolute timing accuracy of DSN equipment to 1 microsecond [7].

After our analysis of the in-flight Ka-up/Ka-down data from Juno's engineering tracks, it is clear the station phase delay was stable prior to the installation of the Ka-band Block 6 Exciter and consistent with the ground measurement conducted in November 2018. The station delay after the installation of the Ka-band Block 6 Exciter is reduced by 22 microseconds as measured but has remained stable between the two in-flight test tests conducted after. The change in downlink receivers from WVSR to OLR did not change the delay by more than measurable with in-flight testing, which is consistent with the expected delay of the DSN common platform. We recommend users of Juno gravity science data use delays as shown in Table 2.

Table 2. Recommended DSS-25 Ka-up/Ka-down phase delays for Juno Gravity Science analysis.

Date Range	Path	Round Trip Delay	Uplink Delay	Downlink Delay
Before 23-NOV-2020	Ka/Ka	175	99.5	75.5
After 25-NOV-2020	Ka/Ka	157	78.5	78.5

Prior to the installation of the Ka-band Block 6 Exciter, we recommend users of Juno gravity science data use station delays as measured with ground testing in November 2018 [5]. Because no propagation noise was introduced, the ground testing was able to measure the delay with formal uncertainties much lower than the in-flight testing presented in this report. Therefore, after the installation of the Ka-band Block 6 Exciter and the new OLR receiver used, we recommend users simply remove the additional Ka-band uplink delay and split the measured delay equally into uplink and downlink components.

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