Extraction of Doppler Observables from Open-Loop Recordings for the Juno Radio Science Investigation

Dustin R. Buccino, Daniel S. Kahan, Oscar Yang, Kamal Oudrhiri
Radio Science Systems Group
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA, USA

Abstract—**The goal of the Juno Gravity Science investigation is to estimate the gravitational field of Jupiter by measurement of the spacecraft velocity during periods of closest approach. Velocity is measured by the Doppler shift of dual X- and Ka-band radio links between the Juno spacecraft, in orbit around Jupiter, and the DSS-25 antenna of the Deep Space Network (DSN). During times of closest-approach, Juno experiences large dynamic ranges caused by the orbital dynamics and spin signatures caused by the spin-stabilized spacecraft that are detectable by the receivers at DSS-25. Open-loop recordings of received voltages are processed to compute Doppler observables utilized in the estimation of the gravity field. Presented is a method to process open-loop data collected by the DSN to compensate for the spin signature of the spacecraft, removal of artifacts from Doppler observables caused by the high dynamic environment, and improve performance of the digital phase-locked loop utilized in the data processing.**

I. INTRODUCTION

Juno is a NASA New Frontiers-class mission to explore Jupiter. Juno was launched in August 2011 with an arrival date at Jupiter in July 2016, entering a highly elliptical, polar orbit with a period of 53-days. Juno's science goals are to examine atmospheric composition and structure, map the magnetic and gravitational fields, and explore the magnetosphere. Since entering orbit around Jupiter in a highly elliptical, polar orbit, Juno has had several close-approach passes (called perijove) where a majority of the science data are collected.

Each time the spacecraft approaches Jupiter, small changes in the gravitational field impart an acceleration onto the spacecraft. The Juno radio science investigation will map the gravitational field of Jupiter by tracking the changes in spacecraft velocity through Doppler shift on the radio signal between the spacecraft and Earth-based ground stations of NASA's Deep Space Network (DSN).

II. INSTRUMENTATION

On the spacecraft, the telecommunications system's [1] Small Deep Space Transponder (SDST) and Ka-band Translator (KaT) provide dual X-band (8404 MHz) and Ka-band (32085 MHz) links for Doppler. The KaT is a radio science instrument designed and built by Thales Alenia Space [2]. Ka-band uplink and downlink are included for radio science purposes to calibrate out charged particle effects [3]. On the ground, the DSN's Deep Space Station 25 (DSS-25) antenna, located in Goldstone, CA, provides simultaneous uplink and downlink at X- and Ka-band.

Radiometric tracking data are simultaneously collected by both closed-loop (DSN Block V Receiver) and open-loop (DSN Radio Science Receiver) receivers [4]. While the closed-loop receivers provide measurements of Doppler shift in addition to real-time extraction of embedded telemetry in the X-band signal, the open-loop receivers provide superior noise characteristics tracking the carrier at both X- and Ka-band.

DSS-25 down-converts the received radio frequency (RF) to an intermediate frequency (IF). A numerically controlled oscillator in the open-loop receiver tunes to the expected Doppler profile ('predicted frequency') computed from the predicted spacecraft motion. A recording is created in 16-bit digitized in-phase and quadrature (IQ) values of the received antenna voltages at a given sampling rate f_s. Errors in the expected Doppler profile are referred to as 'residual frequencies' and are primarily due to uncertainties in the predicted spacecraft motion.

III. SIGNAL PROCESSING

The Jet Propulsion Lab's Radio Science Systems Group's (RSSG) Radio Science Visualization and Processing (RSVP) toolkit is a set of software programs to process tracking data from NASA's Deep Space Network. RSVP is an updated version of the STBLTY program set [5].

A. Phase-Locked Loop

The phase-locked loop developed for radio science use in the RSSG performs signal tracking using a digital second-order phase-locked loop (PLL) derived from Densmore 1988 [6]. The phase-locked loop computes wrapped phase from the recorded IQ-values through a phase low-pass filter, phase loop filter, and amplitude low-pass filter given a specified carrier loop bandwidth (B_L) and count time (T_c). These phase values are collected over an output interval and individual frequency estimates are computed as the difference between each phase point.

The carrier loop bandwidth is a key controlling component of the PLL. Low loop bandwidths are desired to reduce the Doppler noise. Additionally, to optimize the thermal noise, the loop bandwidth and count time are related by $B_L = 1/(2T_c)$ [7]. However, the dynamics experienced by Juno do not allow low loop bandwidths to be used reliably in processing of data. A counter-rotation technique allows the dynamics to be compensated to reprocess with lower loop bandwidths.

B. *Counter-Rotation*

Counter-rotation mixes the measured IQ voltages as if a different predicted frequency set were used when the IQ data were recorded. Fundamentally, the new IQ values (z_{new}) are mixed from the old IQ values (z_{old}) as in (1).

$$z_{new}(t) = z_{old}(t)\, e^{2\pi i \phi} \tag{1}$$

where the phase φ is advanced from the previous phase by the difference between the new predicted frequency (f_{new}) and old (f_{old}) predicted frequency:

$$\phi(t) = \phi(t-1) - \frac{f_{new}(t) - f_{old}(t)}{f_s} \tag{2}$$

The new predicted frequency is computed from the reconstructed spacecraft motion based the actual Doppler profile with the noiser closed-loop data.

After counter-rotation of the open-loop data, the PLL is run over the new IQ values to generate the final Doppler observables with lower loop bandwidths, nominally B_L = 0.5 Hz for 1-second count time or B_L = 5 Hz for 0.1-second count time.

IV. RESULTS AND CONCLUSION

One case (the sixth perijove pass, PJ-06 at Ka-band) is to be presented as an example. First, the PLL was run over the original recorded data with a loop bandwidth of 3 Hz and count time of 1-second to get initial frequency estimates for computation of the reconstructed spacecraft motion. The residual frequency of the PLL is shown in Fig. 1. Note that due to the error it was not possible to maintain lock with the ideal setting of B_L = 0.5 Hz for 1-second count time. Second, the original open-loop IQ values were counter-rotated to the Doppler profile computed from the reconstructed spacecraft motion and the spacecraft spin signature. Finally, the PLL was run again over the counter-rotated IQ values at the optimal settings for thermal noise, i.e. B_L = 0.5 Hz for 1-second count time. The final residual frequencies are shown in Fig. 2. The Doppler observables generated in this method are of better quality than the observables generated with a single pass of the PLL. Table I shows the residual root-mean square (RMS) of the frequency residuals after removal of spacecraft motion.

TABLE I. ROOT-MEAN SQUARE OF FREQUENCY RESIDUALS.

Data Processing	**Residual RMS**
First-run (B_L = 3 Hz, T_c = 1s)	25.1 mHz
Post counter-rotation (B_L = 0.5 Hz, T_c = 1s)	12.9 mHz

The processing technique presented has be applied to each perijove radio science dataset.

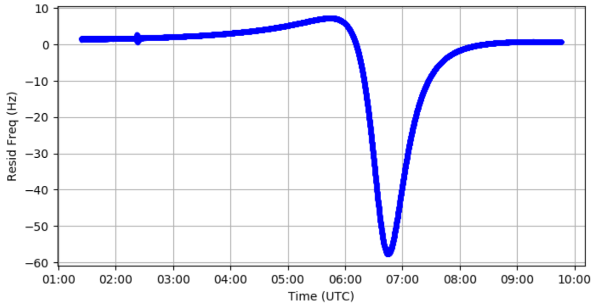

Fig. 1. PJ-06 residual frequencies as originally recorded by the open-loop receiver. The shape is primarily due to the uncertainty in predicted spacecraft motion.

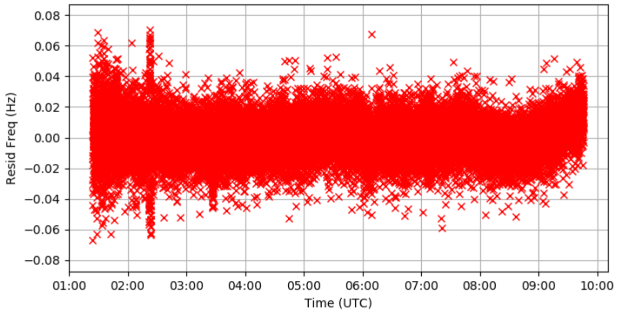

Fig. 2. PJ-06 residual frequencies after counter-rotation, which are mostly Gaussian white noise

ACKNOWLEDGEMENT

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors would like to thank Bill Folkner, the Juno radio science lead Co-Investigator.

REFERENCES

[1] Mukai, Ryan, Hansen, David, Mittskus, Anthony, Taylor, Jim, and Monika Danos. *Juno Telecommunications*. Vol. 16. Pasadena: Jet Propulsion Laboratory, 2012. DESCANSO Design and Performance Summary Series.

[2] Ciarcia, S., Simone, L., Gelfusa, D., Colucci, P., DeAngelis, G., Argentieri, F., Iess, L., and R. Formaro. *MORE and Juno Ka-band Transponder Design*, Performance, Qualification, and In-Flight Validation. 6th ESA International Workshop on Tracking, Telemetry, and Command Systems for Space Applications. ESA, 2013.

[3] Bertotti, B., Comoretto, G., and Iess, L.: 1993, Astron. Astrophys. 269, 608.

[4] *DSN Telecommunications Link Design Handbook*, DSN No. 810-005, Rev. F, Jet Propulsion Laboratory, Pasadena, CA. http://deepspace.jpl.nasa.gov/dsndocs/810-005/

[5] Morabito, D.D. and Asmar, S.W., *Radio Science Performance Analysis Software*. TDA Progress Report 42-120, 1995.

[6] Densmore, A.C., *A Digitally Implemented Phase-Locked Loop Detection Scheme for Analysis of the Phase and Power Stability of a Calibration Tone*. TDA Progress Report 42-93, 1988.

[7] Border, J. and W. Folkner. *Thermal Noise Contribution to Doppler Measurement Error*, JPL Interoffice Memorandum, Sept 18, 2013.