

Determination of the MESSENGER Spacecraft Orbit by Processing Doppler Data in the X-band

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Abstract. High-precision interplanetary range points, particularly Earth-Mercury range points, are essential for constructing modern planetary ephemerides. These range points enable precise orbital determination of Mercury and investigations into the Sun's physical properties and General Relativity tests [1]. This study presents an independent analysis of MESSENGER mission radio science observations, unlike publicly accessible JPL-derived Earth-Mercury range points [2, 3].

Introduction

In modern solar system research, high-precision astrometric observations — particularly radio tracking of orbital spacecraft — play a crucial role in developing highly accurate ephemerides for the Sun and planets. These ephemerides serve as a unique tool for rigorously testing the general theory of relativity and investigating the gravitational characteristics of the Sun. By building upon and integrating findings from previous national studies, this work aims to refine the precision of earlier estimations and potentially unlock novel scientific insights.

The MESSENGER spacecraft [4] was launched into space on August 3, 2004, from the Cape Canaveral Air Force Station in Florida, USA. It became the first spacecraft to achieve orbit around Mercury. Initially designed for an eight-year mission, its operational lifespan was extended multiple times, ultimately concluding in April 2015.

1. Objective and Tasks

The primary objective of this study is to compute and refine the orbital trajectory of the MESSENGER spacecraft. To achieve this, the following tasks were addressed:

1. **Processing radio tracking data** — including Doppler frequency shifts — incorporating calibration adjustments and relativistic corrections for signal propagation.
2. **Numerical integration of the spacecraft’s equations of motion**, accounting for Mercury’s high-resolution gravitational field model and gravitational perturbations induced by the Sun, Moon, and other planets.
3. **Orbital parameter estimation** for the MESSENGER spacecraft using observational data on radio Doppler frequency shifts.

The following section will provide a brief overview of the observed data.

2. Processing of radio tracking data

The X-band raw radio data, including Doppler delay measurements, were analyzed. These data, provided in Orbit Data File (ODF) format by NASA’s Deep Space Network (DSN) Radio Metric Data Conditioning Team (RMDCT), underwent processing to account for solar plasma effects, calibration adjustments, and relativistic signal propagation models.

The Doppler frequency shift delay can be classified into three distinct types based on signal transmission geometry. In the *one-way* configuration, a signal originates from DSN Station A at time t_1 and is detected by the spacecraft at t_2 . For the *two-way* configuration, the same station transmits a signal at t_1 , the spacecraft receives it at t_2 , and immediately echoes it back, with Station A capturing the returned signal at t_3 . The *three-way* variant involves an additional DSN station: Station A sends a signal at t_1 , the spacecraft receives it at t_2 , and relays it to DSN Station B, which records the signal at t_3 .

Doppler observables are derived from the change in the number of Doppler cycles, N , accumulated over the integration time $T_c = t_j - t_i$ at the receiving station. The observed Doppler shift is calculated using the Equation 1:

$$\text{Obs} = \frac{B}{|B|} \cdot \left[\frac{N_j - N_i}{t_j - t_i} - |F_b \cdot K + B| \right], \quad (1)$$

where B denotes the receiver offset (instrumental bias correction), N_i and N_j represent the measured Doppler cycle counts at times t_i and t_j , t_i and t_j are the start and end times of the measurement interval, F_b refers to the frequency offset (carrier frequency deviation), and K is the turnaround ratio (signal amplification factor). For the X-band, the value of K is fixed at $\frac{11}{3}$.

The theoretical expression for the model two-way and three-way Doppler frequency shift is given by Equation 2:

$$F_{2,3} = M_2 f_T(t_3) - \frac{M_2}{T_c} \int_{t_1^s}^{t_1^e} f_T(t_1) dt_1, \quad (2)$$

where M_2 denotes the turnaround ratio (signal amplification factor), f_T is the transmitter frequency, t_1^s and t_1^e represent the start and end times of the integration interval, and T_c is the compression time. The integral in Equation 2 is evaluated using the numerical procedure outlined in [5].

3. Modeling and refinement of the MESSENGER spacecraft orbit

The dynamic model of the MESSENGER spacecraft motion incorporates both gravitational and non-gravitational forces. Gravitational contributions include: Mercury’s gravitational potential, solid-body tidal effects, perturbations caused by the Sun, Moon, and other planets and relativistic corrections.

Non-gravitational forces, primarily solar radiation pressure and thermal radiation, were modeled using a spacecraft macro-model known as the *Box-Wing configuration* [6]. This approach represents the spacecraft as a central cuboid (main body) with two extended solar panels on either side, enabling precise estimation of radiation-induced accelerations.

To numerically integrate the equations of motion, the ABMD integrator [7] was employed. A least-squares fitting procedure was then applied to align the computed model-derived Doppler frequency shifts and range measurements with the observed data. Within this optimization framework, the initial position and velocity vectors of the MESSENGER spacecraft served as adjustable free parameters, allowing for iterative refinement of the orbital solution.

The inverse problem was solved using six initial parameters: $[x_0, y_0, z_0, v_{0x}, v_{0y}, v_{0z}]$. The refined orbital solution for the MESSENGER spacecraft achieved a root mean square (RMS) residual of **0.552 Hz** for Doppler shift observations at DSN Station 26. As shown in Figure 1, the Doppler residuals are plotted for three orbital models. The preliminary JPL MESSENGER orbit (publicly available ephemeris)

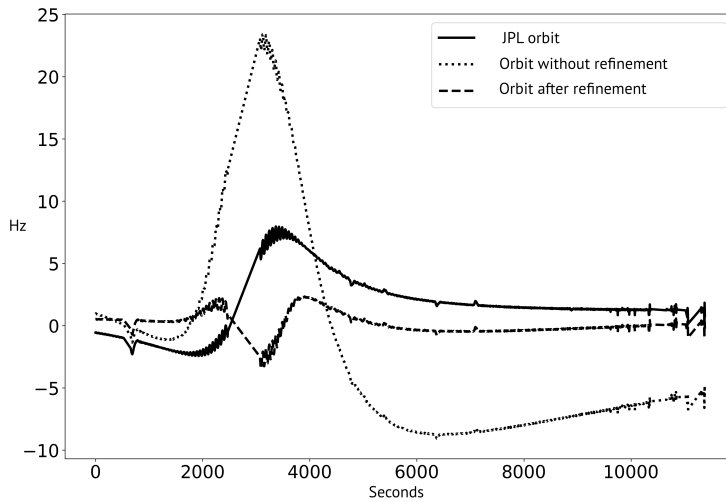


FIGURE 1. Plot of Doppler Shift Residuals (DSN Station 26)

exhibits a residual amplitude of **10 Hz**. In contrast, our initial unrefined orbital model (prior to parameter optimization) shows a significantly larger amplitude of

34 Hz. The refined orbital solution presented here reduces the residual amplitude to **5 Hz**, demonstrating substantial improvement in data-model consistency.

Conclusion

This work presents the first independent analysis of MESSENGER radio tracking data, conducted entirely without reliance on foreign research teams. A high-precision orbital model for MESSENGER was developed, incorporating gravitational perturbations from the Sun, Moon, planets, and Mercury's detailed gravitational field, including tidal effects. Refinement of initial orbital parameters significantly reduced Doppler frequency residuals, improving data-model agreement. Future efforts will focus on enhancing Solar System dynamical models—particularly Mercury's orbit—to advance understanding of the Sun's gravitational influence and fundamental spacetime properties.

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