The flyby anomaly: an investigation into potential causes

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To reach planets and other objects in our solar system, spacecraft typically use gravity assists around intermediate planets to gain energy. For long, such flybys were thought to be known quite accurately and no significant difference between theory and reality was observed.

However, a gravity assist maneuver around Earth, performed by the Galileo spacecraft in 1992, exhibited a small, but still unexplained difference between prediction and reality: the energy increase of the spacecraft was surprisingly higher than expected. In fact, the Doppler tracking data collected by NASA's Deep Space Network during the flyby did not allow to achieve a good orbital fit using normal processing methods. When fitting the data acquired before closest approach in a least-square sense and then trying to pass the result through the entire flyby trajectory (thus post closest-approach data are zero weighted), a strange discontinuity appeared in the residuals at the time of closest approach. In fact, the pre-perigee fit produced residuals which are distributed about a zero mean with a low standard deviation, but a clear asymptotic bias showed up when fitting post-perigee data. If we assume the estimation and the modeling of the spacecraft trajectory to be correct, the residuals should remain flat throughout the encounter. The amplitude of the discontinuity for Galileo is around 60 mHz, which corresponds to an instantaneous velocity change of 2.56 mm/s. Following this observation, other spacecraft, like NEAR or Rosetta, later experienced a similar unexpected energy discrepancy. This phenomenon was named "the flyby anomaly" and is now considered as a major unsolved problem in orbital mechanics.

In order to determine potential causes of this anomaly, this study follows two different approaches.

First, a statistical study is carried out, in which the correlation between the observed anomaly and different parameters of all flybys performed around Earth since Galileo is computed. This enables one to determine which parameters appear related to the anomaly. This constitutes a hint on what phenomenon could be responsible for it and is thus worth deeper investigation. This approach is not new: in 2008, Anderson, Campbell, Ekelund, Ellis and Jordan did a similar study which resulted in an empirical formula that was based on a total of six flybys in the period 1992 – 2005. In our study, we have added another six flybys and extended the observation interval to 2009. Based on this data, a modification of the original empirical formula has been derived, which is able to describe previous and current flybys with and without an anomaly, and which could be used to predict the anomaly of upcoming flybys.

As mentioned before, the anomaly can be interpreted as an unexplained ΔV at perigee. From the observation data available, the sensitivity of this ΔV with respect to various parameters is assessed for each flyby maneuver thanks to the following method. Two state vectors of the considered spacecraft (one when the spacecraft enters and leaves the Earth's sphere of influence, respectively) are propagated toward perigee, which implies that the second propagation is done backward in time. The state vectors are obtained from JPL's Horizon ephemeris system, and propagated using NASA's GEODYN software. For both propagations the subsequent velocity at perigee is computed, which, subtracted, leads to a velocity difference that is related to the anomaly. Therefore, repeating this operation while varying one parameter (like spacecraft attitude, drag coefficient, solar radiation pressure coefficient, etc.) allows for the computation of the sensitivity of this ΔV with respect to the considered parameter(s). In particular, we focus on the anomaly observed for NEAR in January 1998, because it is the largest one seen so far, and on the ones observed during the two flybys of Galileo in December 1990 and 1992, since this is the only possibility to observe the phenomenon on a single vehicle twice (although Rosetta flew by the Earth three times, only the first one exhibits a tiny anomaly). From this sensitivity analysis, it appears that uncertainties of specific parameter values could account for the observed anomalies. This holds in particular for the reflection coefficients of the various surface materials.