The Puzzle of the Flyby Anomaly

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Abstract Close planetary flybys are frequently employed as a technique to place spacecraft on extreme solar system trajectories that would otherwise require much larger booster vehicles or may not even be feasible when relying solely on chemical propulsion. The theoretical description of the flybys, referred to as gravity assists, is well established. However, there seems to be a lack of understanding of the physical processes occurring during these dynamical events. Radio-metric tracking data received from a number of spacecraft that experienced an Earth gravity assist indicate the presence of an unexpected energy change that happened during the flyby and cannot be explained by the standard methods of modern astrodynamics. This puzzling behavior of several spacecraft has become known as the flyby anomaly. We present the summary of the recent anomalous observations and discuss possible ways to resolve this puzzle.

Keywords Flyby anomaly · Gravitational experiments · Spacecraft navigation

1 Introduction

Significant changes to a spacecraft’s trajectory require a substantial mass of propellant. In particular, placing a spacecraft on a highly elliptical or hyperbolic orbit, such as the orbit required for an encounter with another planet, requires the use of a large booster vehicle, substantially increasing mission costs. An alternative approach is to utilize a gravitational assist from an intermediate planet that can change the direction of the velocity vector. Although such an indirect trajectory can increase the duration of the cruise phase of a mission,
the technique nevertheless allowed several interplanetary spacecraft to reach their target destinations economically (Anderson 1997; Van Allen 2003).

Notable missions that relied on an Earth gravity assist maneuver and are relevant to the main topic of this paper include Galileo, which had two encounters with the Earth and one each with Venus and an asteroid to reach Jupiter more quickly; the Near Earth Asteroid Rendezvous (NEAR Shoemaker) mission; the Cassini mission with encounters with Venus, Earth, and Jupiter to speed it on its way to Saturn; and the European Space Agency’s Rosetta mission en route to an encounter with the comet 67P/Churyumov-Gerasimenko.

However, during the Earth flybys, these missions experienced an unexpected navigational anomaly. In the following, we discuss the nature of gravity assist maneuvers, characterize the flyby anomalies experienced by these spacecraft, and discuss the challenges that one faces in attempting to find an explanation of this effect.

2 Gravity Assist Maneuvers

A gravity assist maneuver is a specific application of the restricted three body problem, in which an effectively massless test particle (such as a spacecraft) moves in the combined gravitational field of two larger bodies. When the larger bodies move in circular orbits, the problem is known as the circular restricted three-body problem, or Euler’s three-body problem (Euler 1760a, 1760b, 1760c), among other names. In this problem, the energy and momentum of the test particle are not conserved, although other conserved quantities exist. The energy gain or loss by the test particle is offset by a corresponding loss (gain) in energy by the two larger bodies in the system, however, due to the differences in mass, the corresponding changes in the larger bodies’ velocities are not perceptible.

The circular restricted three-body problem is exactly solvable: after a suitable set of generalized coordinates are chosen, the solution can be expressed in the form of elliptic integrals (Whittaker 1937). The problem has also been analyzed by use of the method of patched conics (Breakwell et al. 1961; Battin 1987), which notionally patches two conics together at the trajectory’s intersection with the sphere of influence surrounding the smaller mass. As well, the problem can be addressed by numerically integrating the equations of motion using a suitably chosen integration method of sufficient accuracy.

However, precision calculation of the trajectory of a spacecraft in the vicinity of a planet requires detailed analysis that takes into account all the effects including a complicated gravitational potential (usually represented in the form of spherical harmonics), perturbations due to the gravitational influence of the planet’s moons, if any, the pressure of light and thermal radiation received from the Sun and the planet, drag forces that may be present.

1 Several additional missions have used planetary assists to reach their target destinations, including Mariner 10 (Venus and Mercury), Pioneer 10 and 11 (Jupiter and Saturn), and also Voyager 1 and 2, which used gravity assists from Jupiter to reach Saturn. Voyager 2 continued to Uranus and Neptune, using the gravity assist of each planetary encounter to target the spacecraft to the next planet. The most feasible plans of space missions inward toward the Sun (such as the Ulysses mission that used a Jupiter flyby to form a trajectory outside the ecliptic plane) and outward to Pluto (such as the New Horizons mission that used a Jupiter flyby to increase significantly the craft’s velocity) depend on gravitational assists from Jupiter.

2 http://www2.jpl.nasa.gov/galileo/.

3 http://near.jhuapl.edu/.

4 http://saturn.jpl.nasa.gov/.

5 http://sci.esa.int/science-e/www/area/index.cfm?fareaid=13.