Anomalous Orbital-Energy Changes Observed during Spacecraft Flybys of Earth

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We report and characterize anomalous orbital-energy changes observed during six Earth flybys by the Galileo, NEAR, Cassini, Rosetta, and MESSENGER spacecraft. These anomalous energy changes are consistent with an empirical prediction formula which is proportional to the total orbital energy per unit mass and which involves the incoming and outgoing geocentric latitudes of the asymptotic spacecraft velocity vectors. We use this formula to predict a potentially detectable flyby velocity increase of less than 1 mm/s for a second Rosetta flyby on November 13, 2007.

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Introduction.—Between December 1990 and September 2005, deep-space missions were launched to Jupiter (Galileo mission), to an asteroid (NEAR mission), to a comet (Rosetta mission), to Saturn (Cassini mission), and to Mercury (MESSENGER mission). During flight, each of these missions was targeted to one or more flybys of Earth for purposes of either gaining or losing heliocentric orbital energy in order to reach their eventual target body [1]. When the first of these flybys, Galileo I, occurred on 8 December 1990, mission engineers at the Jet Propulsion Laboratory (JPL) noticed an unexpected frequency increase in the postencounter radio Doppler data generated by stations of the NASA Deep Space Network. Three of us (JDA, JKC, JFJ) studied this anomalous frequency shift during 1990–1993, but no explanation was found. A second flyby by the Galileo spacecraft exactly two years later (Galileo II) passed through the Earth’s upper atmosphere at an altitude of about 300 km. Atmospheric drag prevented an unambiguous detection of a flyby anomaly [2]. Subsequently however, NEAR mission navigators at JPL [3] and Rosetta mission navigators at the European Space Operations Center (ESOC) in Darmstadt Germany [4] noticed anomalous frequency increases in the postencounter Doppler signals for those two flybys. The Cassini spacecraft also provided an Earth flyby. However, small thrusting maneuvers at the time of its closest approach obscured any immediate detection of an anomalous Doppler shift [5]. Finally, in August 2005, the MESSENGER spacecraft flew past Earth, but no anomaly was detected by the mission navigators [6].

We report here on results from a recent study involving the data analysis and interpretation of radio Doppler data from all six flybys. We find that there is indeed an anomalous energy change during Earth flybys on the order of $10^{-6}$, although we have been unable to find a physical cause or systematic error source for the anomaly. However, we have found an empirical prediction formula that fits all six flybys successfully. Its latitude dependence suggests that the Earth’s rotation may be generating an effect much larger than the frame dragging effect of General Relativity, the Lense-Thirring effect [7]. Among all solar-system bodies, the Earth provides the best natural laboratory for revealing anomalous effects, having both a relatively rapid rotation and a gravitational field well determined from artificial satellites [8].

Analysis and empirical formula.—The anomaly is most evident in Doppler and ranging data for the 1998 NEAR flyby, which was also the most asymmetrical about the equator. The X-band Doppler frequency data before closest approach can be fit to within the noise level of about 0.1 mm/s with a single numerically integrated trajectory (Fig. 1). The trajectory is well determined by 88 h of almost continuous Doppler data at a sample interval of

![Equatorial view of the NEAR flyby, the most asymmetrical flyby with respect to the Equator and the flyby with the largest energy change. The extent of the bending in the Earth’s gravitational field, the geometry of the flyby and its time scale are illustrated. The tick marks are at 10-min intervals as measured from closest approach. Views of the five other flybys are similar and are not shown.](image-url)
Doppler frequency shift is approximately 0.760 Hz, consistent with an increase of the respective fits and demonstrate the impossibility of fitting both pre- and postencounter data with a single fit. The difference in encounter.

The resulting osculating elements for the osculating orbital elements. In particular, the hyperbolic excess velocity \( V_\infty \), represents the postencounter orbital conditions minus the preencounter conditions, which according to conventional physics should agree. We observe that the proportionality coefficient \( K \) in the formula can be

\[
V_\infty^2 = v \cdot v - \frac{2\mu}{r},
\]

\( \mu \) (398 600.4 km\(^3\)/s\(^2\)) is the gravitational constant times the mass of the Earth and \( r \) is the magnitude of \( r \). The osculating \( V_\infty \) varies from about 6.87 km/s to about 6.83 km/s over the entire data interval, largely because of trajectory perturbations by the sun and moon. However, the variation in the difference of the two values of the \( V_\infty \) between the postencounter Doppler-fitted trajectory and the preencounter Doppler-fitted trajectory is only about 0.05 mm/s, as shown in Fig. 3(b). We determine the value of \( \Delta V_\infty \) for NEAR at closest approach with a standard error of \( \pm 0.01 \) mm/s, as shown in Table I, where the error is determined by the accuracy of the pre- and postencounter fitted trajectories, not by the time variability of \( \Delta V_\infty \) over the total Doppler data interval.

Our prediction formula can be expressed in its simplest form in terms of the respective declinations \( \delta_i \) and \( \delta_o \) of the incoming and outgoing osculating asymptotic velocity vectors, or effectively in terms of the geocentric latitudes. The arcane difference between geocentric latitude and inertial declination is not statistically significant. The prediction formula can be written as

\[
\frac{\Delta V_\infty}{V_\infty} = \frac{1}{2} \frac{\Delta E}{E} = K(\cos \delta_i - \cos \delta_o).
\]

The change represented by \( \Delta V_\infty \), or, equivalently, total specific energy \( \Delta E \), represents the postencounter orbital conditions minus the preencounter conditions, which according to conventional physics should agree. We observe that the proportionality coefficient \( K \) in the formula can be

\[
\frac{\Delta V_\infty}{V_\infty} = \frac{1}{2} \frac{\Delta E}{E} = K(\cos \delta_i - \cos \delta_o).
\]
expressed in terms of the Earth’s angular rotational velocity \( \omega_E \) of \( 7.292 \times 10^{-5} \text{ rad/s} [9] \), its mean radius \( R_E \) of 6371 km [9] and speed of light \( c \) by

\[
K = \frac{2 \omega_E R_E}{c} = 3.099 \times 10^{-6}
\]  

Data processing.—Our results were produced at JPL using the Orbit Determination Program (ODP). Calculations using ODP for analysis of the Galileo I Doppler data were duplicated in 1991 by software at the Goddard Space Flight Center and at the University of Texas. The ODP results reported here for Rosetta match those produced at ESA by navigators using their software. Doppler frequency shift is defined as the difference of cycle count at a predetermined Doppler integration time \( TC \) divided by \( TC \) and referenced to a time-variable uplink frequency, as recorded by the transmitting station [10].

Lämmerzahl et al. [11] studied and dismissed a number of possible explanations for the Earth flyby anomalies, including Earth atmosphere, ocean tides, solid Earth tides, and possible deflection due to solar radiation pressure.

Table I. Earth flyby parameters at closest approach for Galileo, NEAR, Cassini, Rosetta, and MESSENGER (M’GER) spacecraft.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GLL-I</th>
<th>GLL-II</th>
<th>NEAR</th>
<th>Cassini</th>
<th>Rosetta</th>
<th>M’GER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>12/8/90</td>
<td>12/8/92</td>
<td>1/23/98</td>
<td>8/18/99</td>
<td>3/4/05</td>
<td>8/2/05</td>
</tr>
<tr>
<td>( H ) (km)</td>
<td>960</td>
<td>303</td>
<td>539</td>
<td>1175</td>
<td>1956</td>
<td>2347</td>
</tr>
<tr>
<td>( \phi ) (deg)</td>
<td>25.2</td>
<td>33.8</td>
<td>33.0</td>
<td>-23.5</td>
<td>20.20</td>
<td>46.95</td>
</tr>
<tr>
<td>( \lambda ) (deg)</td>
<td>296.5</td>
<td>354.4</td>
<td>47.2</td>
<td>231.4</td>
<td>246.8</td>
<td>107.5</td>
</tr>
<tr>
<td>( V_f ) (km/s)</td>
<td>13.740</td>
<td>14.080</td>
<td>12.739</td>
<td>19.026</td>
<td>10.517</td>
<td>10.389</td>
</tr>
<tr>
<td>( V_\infty ) (km/s)</td>
<td>8.949</td>
<td>8.877</td>
<td>6.851</td>
<td>16.010</td>
<td>3.863</td>
<td>4.056</td>
</tr>
<tr>
<td>DA (deg)</td>
<td>47.7</td>
<td>51.1</td>
<td>66.9</td>
<td>19.7</td>
<td>99.3</td>
<td>94.7</td>
</tr>
<tr>
<td>( I ) (deg)</td>
<td>142.9</td>
<td>138.7</td>
<td>108.0</td>
<td>25.4</td>
<td>144.9</td>
<td>133.1</td>
</tr>
<tr>
<td>( \alpha_i ) (deg)</td>
<td>266.76</td>
<td>219.35</td>
<td>261.17</td>
<td>334.31</td>
<td>346.12</td>
<td>292.61</td>
</tr>
<tr>
<td>( \delta_i ) (deg)</td>
<td>-12.52</td>
<td>-34.26</td>
<td>-20.76</td>
<td>-12.92</td>
<td>-2.81</td>
<td>31.44</td>
</tr>
<tr>
<td>( \alpha_o ) (deg)</td>
<td>219.97</td>
<td>174.35</td>
<td>183.49</td>
<td>352.54</td>
<td>246.51</td>
<td>227.17</td>
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<td>( \delta_o ) (deg)</td>
<td>-34.15</td>
<td>-4.87</td>
<td>-71.96</td>
<td>-4.99</td>
<td>-34.29</td>
<td>-31.92</td>
</tr>
<tr>
<td>( M_{sc} ) (kg)</td>
<td>2497</td>
<td>2497</td>
<td>730</td>
<td>4612</td>
<td>2895</td>
<td>1086</td>
</tr>
<tr>
<td>( \Delta V_\infty ) (mm/s)</td>
<td>3.92</td>
<td>-4.6</td>
<td>13.46</td>
<td>-2</td>
<td>1.80</td>
<td>0.02</td>
</tr>
<tr>
<td>( \sigma_{V_\infty} ) (mm/s)</td>
<td>0.3</td>
<td>1.0</td>
<td>0.01</td>
<td>1</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Equation (1) (mm/s)</td>
<td>4.12</td>
<td>-4.67</td>
<td>13.28</td>
<td>-1.07</td>
<td>2.07</td>
<td>0.06</td>
</tr>
</tbody>
</table>

FIG. 3. Panel (a) shows the osculating hyperbolic excess velocity \( V_\infty \) for the NEAR flyby. Panel (b) shows the difference in osculating \( V_\infty \) between the best-fit trajectory for Doppler data taken after closest approach minus the best-fit trajectory for Doppler data taken before closest approach. The osculating parameters are evaluated over the entire data interval from minus 88.4 h to plus 95.6 h.
spacecraft charging, magnetic moments, Earth albedo, solar wind, coupling of Earth’s spin with rotation of the radio wave, Earth gravity, and relativistic effects predicted by Einstein’s theory. All these potential sources of systematic error, and more, are modeled in the ODP. None can account for the observed anomalies.

Conclusions.—Like the Pioneer anomaly [12], and perhaps even more surprising, the Earth flyby anomaly is a real effect inherent to the tracking of spacecraft. Its source is unknown. We expect to continue efforts to understand the anomaly by characterizing the behavior of other orbital parameters of the flybys, including the 2007 Rosetta flyby. For example, the specific orbital angular momentum of the flybys and the angular deflection of $V_\infty$ will be included in our future work.

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