Spacecraft Anomalies: An Update

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Basel, May 15, 2008
Overview

1. Interplanetary Spaceflight
   - Swing-by
   - Deep Space Network
   - Spacecraft Navigation

2. Prehistory
   - The Pioneer Anomaly

3. Flyby Anomalies in EGAs
   - First Observation
   - Flyby data set

4. Search for Explanations
   - Origin of the Flyby Anomaly
   - Origin of the Pioneer Anomaly

5. Outlook
Swing-By

Swing-by (or flyby, slingshot, gravity assist): A method in interplanetary spaceflight to alter the path (and the speed) of a spacecraft by the use of a planet or other heavy celestial body.

- First planned gravity assist (1973): Deceleration of Mariner 10 by Venus in order to reach a stable orbit around Mercury.
Interplanetary Spaceflight

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Main advantages

- Higher velocities $\rightarrow$ distant targets can be reached
- Saves fuel, time and expense
- Easy access to orbits far from the ecliptic
- Can be repeated several times

Trajectories of Pioneer 10 & 11
Pioneer Trajectories
Interplanetary Spaceflight

Deep Space Network: Spacecraft Navigation

DSN: International network of communication facilities (large radio antennas) for the support of interplanetary spacecraft missions & radio- and radar astronomy.

3 facilities (distance ~ 120 degrees)

- Goldstone DSN Complex, Mojave Desert, California, USA
- Madrid DSN Complex, Robledo (Madrid), Spain
- Canberra DSN Complex, Tidbinbilla (Canberra), Australia
Deep Space Network

Deep Space Network

Goldstone, California

Canberra, Australia

Goldstone, California

Madrid, Spain

Deep Space Network
Main method for measuring the **longitudinal** velocity of spacecraft: **DOPPLER EFFECT**

**Basic strategy (Pioneer)**

DSN reference frequency: $$\nu_R = \frac{\nu_E}{\sqrt{\frac{c-v_P}{c+v_P} \nu_E}}$$

Receive frequency: $$\nu_R = \frac{240}{221} \nu_R$$

Response signal from Pioneer: $$\nu'_R = (240/221)\nu_R$$

DSN receive frequency: $$\nu' = \frac{2}{221} \nu_E$$
Spacecraft Navigation

Main method for measuring the **longitudinal** velocity of spacecraft:  
**DOPPLER EFFECT**

**Basic strategy** (Pioneer)

- **DSN reference frequency:**
  \[ \nu_E \]

- **Receive frequency:**
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- **Response signal from Pioneer:**
  \[ \nu'_R = \frac{240}{221} \nu_R \]

- **DSN receive frequency:**
  \[ \nu'_E = \sqrt{\frac{c-v_P}{c+v_P}} \nu_R \]

\[ \rightarrow \nu_P = \frac{19}{221} - \Delta \nu_E \text{, mit } \Delta \nu_E = \frac{\nu'_E - \nu_E}{\nu_E} \]

\[ \text{bzw. } \nu_P = \frac{\nu_E - \nu'_E}{\nu_E + \nu'_E} c \approx \frac{1}{2} \frac{\nu_E - \nu'_{E'}}{\nu_E} c \text{ without frequency turnaround ratio (hard coded).} \]
Mysterious Deceleration of the Pioneer Probes

John Anderson ¹ (Jet propulsion laboratory, Pasadena, Kalifornien):
Anomalous deceleration of Pioneer spacecraft since ∼ 1980 towards the sun (or the earth?).


¹J. D. Anderson, July 1992 Quarterly Report to NASA
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Pioneer 10:
Launch March 2, 1972 / Jupiter flyby Dec 3, 1973
→ hyperbolic orbit, radio contact till Feb 2003.

Pioneer 11:
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Pioneer anomaly

\[ \alpha_{\text{Pioneer}} = -(8.74 \pm 1.33) \cdot 10^{-10} \text{ m/s}^2 \]

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Reliable Doppler telemetry data now available for

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Comments

- Anomalies of Pioneer 10/11 coincide within a range of ∼ 3%.
- \( a_{\text{Sun}}(20 \text{ AU}) = 1.48 \cdot 10^{-5} \text{m/s}^2 \).
- Remains a mystery... \( cH_0 \simeq 6.8 \cdot 10^{-10} \text{m/s}^2, \ a_0(MOND) \simeq 1.2 \cdot 10^{-10} \text{m/s}^2. \)

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Velocity anomaly

![Graph showing Doppler velocity over time]

Days from 1 Jan 1987 00:00:00

Doppler Velocity (m/s)
Pioneer probe design

Weight: 258 kg
Energy source: $4 \times 40$ Watt RGT's
(RGT: Radioisotope thermoelectric generator)

Pioneer 10 (final construction stage)
Plutonium 238
RTG Radiation Measurement (Cassini-Huygens)
Soviet RTGs
December 1990: J.D. Anderson and other engineers at JPL observe an anomalous velocity increase of space probe GALILEO by $\Delta v = 3.92$ mm/s during an Earth flyby (EGA, earth gravity assist).

Further EGAs were investigated in the following:

- NEAR ('92): $\Delta v = 13.46$ mm/s
- Cassini ('99): $\Delta v = -2.0$ mm/s
- Rosetta ('05): $\Delta v = 1.8$ mm/s
- MESSENGER ('05): $\Delta v = 0.02$ mm/s
- GALILEO ('92): $\Delta v = -4.6$ mm/s

The accuracy of the DSN velocity measurement is $\sim 0.01$ mm/s.
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**The Hyperbolic Trajectory: Only an Approximation**

**Orbit determination** of probes is a non-trivial task. Currently, four independent codes are in use:

- JPL Orbit determination Program (various versions from 1970-2001)
- Goddard Space Flight Center: A study in 2003
- Orbit determination code from the University of Oslo
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These programs, e.g., take into account:

- Parametrized post-Newtonian gravity effects of the Sun/Moon/Planets/large asteroids/ terrestrial and lunar figure (multipole) effects/earth tides/lunar librations
- Solar radiation, Solar wind pressure, interplanetary dust
- Spacecraft: Thermal radiation, gas leakage (after correction maneuvers), torques
- Observation stations: Precession, nutation, sidereal rotation, polar motion, tidal effects, tectonic plate drift, models of DSN antennae.
- Signal propagation: Dispersion effects due to Solar wind and interplanetary dust.
TABLE I. Earth flyby parameters at closest approach for Galileo, NEAR, Cassini, Rosetta, and MESSENGER (M'GER) spacecraft. The altitude $H$ is referenced to an Earth geoid, the geocentric latitude $\phi$ and longitude $\lambda$ are listed for the closest approach location, $V_f$ is the inertial spacecraft velocity at closest approach, $V_\infty$ is the osculating hyperbolic excess velocity, the deflection angle (DA) is the angle between the incoming and outgoing asymptotic velocity vectors, the angle $I$ is the inclination of the orbital plane on the Earth's equator, the next four rows represent the right ascension $\alpha$ and declination $\delta$ of the incoming (i) and outgoing (o) osculating asymptotic velocity vectors, and $M_{SC}$ is a best estimate of the total mass of the spacecraft during the encounter. The last three rows of the table give the measured change in $V_\infty$, the estimated realistic error in $V_\infty$, and the prediction of $\Delta V_\infty$ by Eq. (1). The measured $\Delta V_\infty$ for GLL-II is actually $-8 \text{ mm/s}$, but it is reduced in magnitude after subtracting out an estimated atmospheric drag of $-3.4 \text{ mm/s}$.

<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>$V_\infty$ (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>9.7</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>
</tr>
<tr>
<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>$\sigma_{\Delta V_\infty}$ (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>


(J. D. Anderson, J. K. Campbell, J. E. Eklund, J. Ellis, J. F. Jordan @ JPL)
Anderson’s collaborator James Jordan conjectured a connection between the rotation of the earth and the velocity increase.

The ansatz is

$$v = \frac{1}{2} E = K (\cos \delta_i - \cos \delta_0),$$

$$K = 2 \omega ERc = 3 \cdot 10^{-6}.$$
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The ansatz is

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Now the JPL engineers await the next Rosetta flyby in 2009...
A strange behavior

- The anomalous acceleration occurring in Earth flybys is of the order of $10^{-4} \, m/s^2$ - much larger than the Pioneer anomaly.
- Acceleration phase seems to last only some few minutes.
- Standard error analysis (atmosphere / ocean tides / solid earth tides / charging of the spacecraft / magnetic moment / earth albedo / solar wind ...) gives no hint to the origin of the anomaly.
- No consistent explanations from "new physics" (modifications of relativity etc) yet.

Modeled anomalous acceleration
Flyby acceleration mismatch

![Graph](image.png)
Search for Explanations: Pioneer Anomaly

THE STUDY OF THE PIONEER ANOMALY
Focus of the 1995-2002 Analysis

- On-board systematic & other hardware-related mechanisms:
  - Precessional attitude control maneuvers and associated "gas leaks"
  - Nominal thermal radiation due to $^{238}\text{Pu}$ decay [half life 87.75 years]
  - Heat rejection mechanisms from within the spacecraft
  - Hardware problems at the DSN tracking stations

- Examples of the external effects (used GLL, ULY, and Cassini):
  - Solar radiation pressure, solar wind, interplanetary medium, dust
  - Viscous drag force due to mass distribution in the outer solar system
  - Gravity from the Kuiper belt; gravity from the Galaxy
  - Gravity from Dark Matter distributed in halo around the solar system
  - Errors in the planetary ephemeris, in the Earth’s Orientation, precession, polar motion, and nutation parameters

- Phenomenological time models:
  - Drifting clocks, quadratic time augmentation, uniform carrier frequency drift, effect due to finite speed of gravity, and many others

- All the above were rejected as explanations

Most of the systematics are time or/and space dependent!
### Sources of Systematic Error: External

<table>
<thead>
<tr>
<th>Error budget constituents</th>
<th>Bias $10^{-10}$ m/s²</th>
<th>Uncertainty $10^{-10}$ m/s²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 Sources of external systematic error:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>➤ Solar radiation pressure</td>
<td></td>
<td>± 0.001</td>
</tr>
<tr>
<td>➤ From the mass uncertainty</td>
<td>+0.03</td>
<td>± 0.01</td>
</tr>
<tr>
<td>➤ Solar wind contribution</td>
<td>± &lt; $10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>➤ Effects of the solar corona</td>
<td>± 0.02</td>
<td></td>
</tr>
<tr>
<td>➤ Electro-magnetic Lorentz forces</td>
<td>± &lt; $10^{-1}$</td>
<td></td>
</tr>
<tr>
<td>➤ Influence of the Kuiper belt’s gravity</td>
<td>± 0.03</td>
<td></td>
</tr>
<tr>
<td>➤ Influence of the Earth orientation</td>
<td>± 0.001</td>
<td></td>
</tr>
<tr>
<td>➤ DSN Antennae: mechanical/phase stability</td>
<td>± &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>➤ Phase stability and clocks</td>
<td>± &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>➤ DSN station location</td>
<td>± &lt; $10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>➤ Effects of troposphere and ionosphere</td>
<td>± &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td><strong>2 Computational systematics:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>➤ Numerical stability of least-squares estimation</td>
<td>± 0.02</td>
<td></td>
</tr>
<tr>
<td>➤ Accuracy of consistency/model tests</td>
<td>± 0.13</td>
<td></td>
</tr>
<tr>
<td>➤ Mismodeling of maneuvers</td>
<td>± 0.01</td>
<td></td>
</tr>
<tr>
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<td>± 0.02</td>
<td></td>
</tr>
<tr>
<td>➤ Annual/diurnal terms</td>
<td>± 0.32</td>
<td></td>
</tr>
</tbody>
</table>

IJMP A 17 (2002) 875-885, gr-qc/0107022

An interesting set of error sources, but not of a major concern!
### Sources of Systematic Error: On-board

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</thead>
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<tr>
<td>Radio beam reaction force</td>
<td>+1.10</td>
<td>± 0.11</td>
</tr>
<tr>
<td>Thermal/propulsion effects from RTGs:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTG heat reflected off the craft</td>
<td>-0.55</td>
<td>± 0.55</td>
</tr>
<tr>
<td>Differential emissivity of the RTGs</td>
<td></td>
<td>± 0.85</td>
</tr>
<tr>
<td>Non-isotropic radiative cooling of s/c</td>
<td></td>
<td>± 0.16</td>
</tr>
<tr>
<td>Expelled He produced within the RTGs</td>
<td>+0.15</td>
<td>± 0.16</td>
</tr>
<tr>
<td>Propulsive mass expulsion: gas leakage</td>
<td></td>
<td>± 0.56</td>
</tr>
<tr>
<td>Variation between s/c determinations</td>
<td>+0.17</td>
<td>± 0.17</td>
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</tbody>
</table>

#### SNAP-19 RTG

**Heat is an important source, but:**
- It is NOT strong enough to explain the anomaly;
- Exponential decay or linear decrease – NOT seen

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**Graph**

- **1987 [97 W]**
- **1998.8 [65 W]**
- **2001**

**Legend**

- **SNAP-19 RTG**
- **Years**
  - 1975
  - 1980
  - 1985
  - 1990
  - 1995

**Note**

- **~32.8% reduction**
Four Main Objectives:

- Analysis of the early trajectory:
  - Direction of the anomaly: origin
- Analysis of planetary encounters:
  - Should tell more about the onset of the anomaly (e.g. Pioneer 11)
- Analysis of the entire dataset:
  - Temporal evolution of the anomaly
- Focus on on-board systematics:
  - Thermal modeling using telemetry

- Towards the Sun: gravitational models?
- Towards the Earth: frequency standards?
- Along the velocity vector: drag or inertia?
- Along the spin axis: internal systematics?
In **2006**, Slava Turyshhev (a codiscoverer of the Pioneer anomaly) and Victor Toth (programmer at JPL) started a data recovery program.

**Statistics:** ~400 tapes... 90 minutes / tape
Preliminary result Turyshev & Toth: The thermal recoil force may explain 28-36% of the Pioneer anomaly...
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Turyshev: "It's like being on CSI".
Outlook

A MISSION TO EXPLORE THE PIONEER ANOMALY
Measurement Concept: Formation-flying

- Active spacecraft and passive test-mass
- Objective: accurate tracking of the test-mass
- 2-step tracking: common-mode noise rejection
  - Radio: Earth → spacecraft
  - Laser: spacecraft → test-mass
- Flexible formation: distance may vary
- The test mass is at an environmentally quiet distance from the craft, > 250 m
- Occasional maneuvers to maintain formation
Anomaly mission
Interplanetary Spaceflight  Prehistory  Flyby Anomalies in EGAs  Search for Explanations  Outlook

John Anderson

Spacecraft Anomalies: An Update