AIAA 98-4287

INVESTIGATIONS INTO THE UNEXPECTED DELTA-V INCREASES DURING THE EARTH GRAVITY ASSISTS OF GALILEO AND NEAR

Peter G. Antreasian* and Joseph R. Guinn†

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California

Abstract

Unexpected energy increases during Earth flybys of both the Galileo and Near Earth Asteroid Rendezvous (NEAR) spacecraft have drawn evidence of spacecraft trajectory modeling errors, an unknown perturbing force or failure of Newtonian gravity. This paper will investigate the gravity field of Earth as a possible source of these anomalous ΔV's. Other possible sources of errors have been considered including: the mathematical models representing the perturbing forces acting on the spacecrafts while in the sphere of influence of Earth such as relativistic effects, tidal effects, Earth radiation pressure and atmospheric drag. However, most of these perturbations such as atmospheric drag can be ruled out because the imparted acceleration upon the spacecraft is several orders of magnitude less than observed. Since the oblateness effect is several orders of magnitude greater than the non-gravitational perturbations, errors in the spherical harmonic representation of Earth's gravity field will be examined. Other sources that have already been examined and tentatively dismissed include numerical round-off, integration errors, spacecraft antenna phase center offset and spacecraft antenna switching during encounter.

INTRODUCTION

Because of the limited propulsive systems available today for interplanetary trajectories to the outer planets and other solar system bodies, mission designers are utilizing the free exchange of potential energy from the planets such as Venus, Earth and Jupiter to spacecraft kinetic energy during gravity assists. During the first of two Earth gravity assists (referred to as GEGA1), the Galileo spacecraft experienced an unexplained net velocity gain of approximately 4.3 mm/s in December of 1990.

Figure 1 illustrates the nature of the discrepancy for GEGA1; this gain is evident by the ~66 mHz shift between the pre- and post-encounter coherent (2-way) S-Band Doppler data acquired from the Deep Space Network (DSN). The Doppler residuals in Figure 1 were created by fitting the spacecraft trajectory to the pre-encounter data in a least square sense and passing through the post-encounter data. Provided that there are no discrepancies in the estimation and modeling of the spacecraft trajectory, the residuals should remain flat through the encounter and beyond. Instead a 66 mHz shift remained after the encounter with Earth. For Galileo's S-Band frequency this translates to ~4.3 mm/s (1 mm/s = 15.4 mHz). As shown in Figure 2, the range data acquired during this time also exhibited similar behavior (i.e. slope of ~4.3 mm/s). In operations, the Galileo Navigation Team fit the trajectory through the post-encounter by estimating an hypothetical 3-axis instantaneous impulsive maneuver of nearly the same magnitude at perigee (~3.8 mm/s)[1]. Figure 3 shows that the discontinuity in the Doppler residuals can be removed by estimation of this anomalous ΔV.

This event prompted an investigation of both the navigation software of the Navigation and Flight Mechanics section at the Jet Propulsion Laboratory (JPL) and the mathematical models used for deep space navigation. Other agencies such as the Goddard Space Flight Center (GSFC) and University of Texas Center for Space Research (UTCSR) have also investigated this discrepancy, but found no definitive explanation to the source of the ΔV. When Galileo returned to Earth in December 1992 for its second and final Earth gravity assist (GEGA2), special tracking arrangements were made with the Tracking and Data Relay Satellite System (TDRSS), but no anomalous ΔV was apparent [1]. Drag acceleration

*Navigation and Flight Mechanics Section (818) 354-4381
†Navigation and Flight Mechanics Section (818) 354-0425, AIAA Member

most likely masked any anomaly due to the low flyby altitude. An anomalous gravity-like signature did appear in the Doppler residuals; however, the signature waslater found to be caused by the ionospheric interaction upon the tracking signal which was being acquired by the TDRSS system [3]. Since at the lower altitude of the GEGA2 flyby, drag was determined to be on the same order of magnitude as the GEGA1 ΔV, and the level of uncertainty in the drag modeling was of the same order of the magnitude, *Edwards et al.* [2] couldn't rule the ΔV out completely.

Interest in solving this curious puzzle had waned over the years, until the recent Near Earth Asteroid Rendezvous (NEAR) spacecraft's Earth gravity assist (NEGA) on January 23, 1998. Like Galileo's first Earth gravity assist, NEAR also experienced a net gain of kinetic energy. This time as shown in Figure 4, the shift in the 2-way Doppler X-Band signal was approximately 730 mHz. The data prior to the time of closest approach was used in the estimation of NEAR's orbit. Evidence of the net gain in energy is shown by the discontinuity between this data and the post-encounter data which were not included in this orbit estimation. For NEAR's X-Band frequency this translates to ~13.0 mm/s (1 mm/s = 56 mHz). The NEAR range data (shown in Figure 5) too exhibited a similar slope (~13 mm/s) as the GEGA1 case.

After the NEAR encounter, the Doppler residuals exhibited a sinusoidal diurnal signature with an amplitude of approximately 0.05 Hz. This is especially evident because Canberra tracked the spacecraft continuously for several days after the flyby. Like the GEGA1 case, a 3-axis instantaneous impulsive ΔV adjustment (with magnitude of ~9 mm/s) was needed at perigee to adequately fit through the encounter (as shown in Figure 6).

Figure 7. compares the ground tracks of GEGA1, GEGA2 and NEGA from 4 hours before closest approach (C/A) to 4 hours after C/A. The tick marks are spaced at 1 minute intervals and all trajectories are retrograde (westward) with respect to the Earth-Mean-Equator (EME) frame. The locations of the perigees for each encounter are also indicated in this figure.

Table 1 compares the reconstructed hyperbolic orbit parameters relative to the Earth for each of the three Earth flyby cases. Because the tracking data in

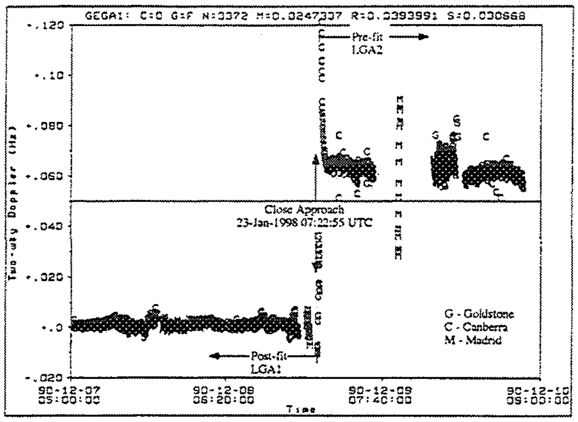

Figure 1: Two-way S-Band Doppler residuals during GEGA1.

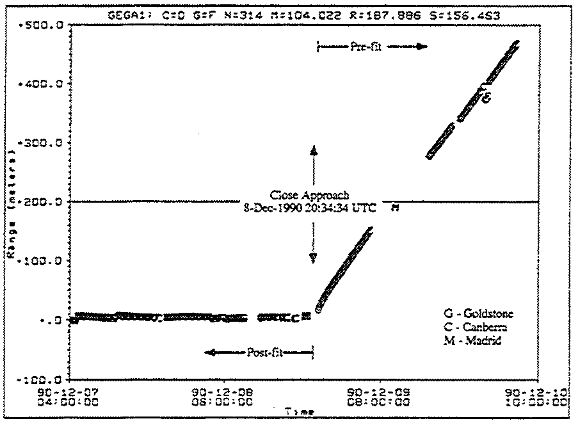

Figure 2: Range residuals during GEGA1.

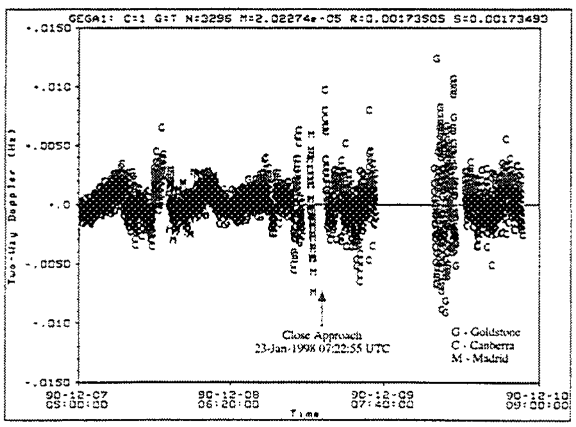

Figure 3: The discontinuity in the Doppler residuals during GEGA1 removed by anomalous ΔV estimation.

the GEGA1 case cannot confirm that an anomalous ΔV event occurred, this analysis will further investigate the GEGA1 and NEGA cases. Figures 8and 9 compare the GEGA1 and NEGA trajectories relative to Earth from the North pole view. Aside from having retrograde orbits and their passage on the sun side of the Earth as shown in these figures, no obvious similarities between GEGA1 and NEGA can be realized. It should be noted that the Cassini spacecraft will have an Earth gravity assist in August of 1999 in order to reach Saturn.

BACKGROUND

Various sources of error were examined for GEGA1. Since it is possible that anomalous thruster activity can occur upon a spacecraft due to sequencing errors or other causes, it is prudent to first suspect the spacecraft's activities as the cause of the apparent energy gain. However, Flight Teams for both Galileo and NEAR have found no evidence of thruster activity nor unusual behavior in their telemetry during their respected encounters[1,4]. Other possible causes for the anomalous ΔV during the GEGA1 flyby such as flaws in the integration of the spacecraft trajectory or in the computation of the observations were first investigated by *Kallemeyn*[5].

Kallemeyn[5] dismissed, to some extent, these possibilities as well as the necessary adjustments made to the Doppler observables such as media (troposphere and ionosphere) affects on the Doppler signal. He also dismissed the switching of Galileo's prime onboard antenna from the front Low Gain Antenna (LGA-1) to the rear LGA-2 during this flyby as the cause. Another possible source of error was thought to lie in the modeling effect of the spacecraft antenna spin upon the Doppler signal. But as *Campbell* [1] notes, *"the ranging data is not subject to the effects of polarization"*. According to *Campbell* [1] on the GEGA1 ΔV, *"The result of analyses to date, based on our current knowledge of the dynamics of the flyby do not allow us to adequately fit an orbit to the Doppler data, without invoking extraordinary dynamics."* Likewise is the case for NEAR, as will be discovered later.

Software Investigations

The Orbit Determination Program (ODP) developed at the Jet Propulsion Laboratory (JPL) is the primary trajectory propagator and estimation filter

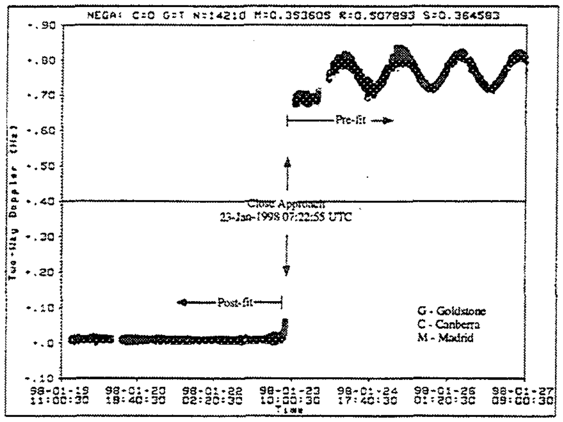

Figure 4: Two-way X-Band Doppler residuals during NEGA.

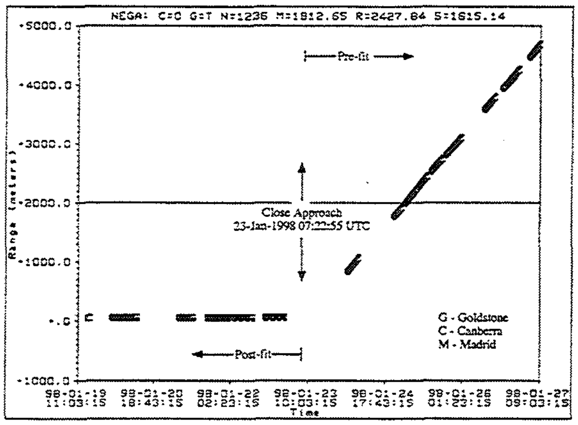

Figure 5: Range residuals during NEGA.

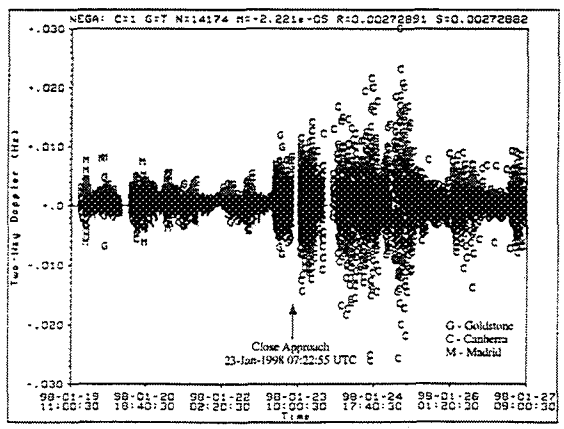

Figure 6: The discontinuity in the Doppler residuals during NEGA removed by anomalous ΔV estimation.

Table 1: Earth Flyby Parameters

	GEGA1‡	*GEGA2*‡	*NEGA*†
TCA (UTC)	8-DEC-1990	8-DEC-1992	23-JAN-1998
	20:34:34.4	15:09:24.9	07:22:55.6
Altitude (km)	959.947	303.108	538.833
Longitude (East)	296.5 E	354.42° E	47.21° E
Latitude	25.2° N	-33.76° S	32.96° N
V_∞ (km/s)	8.949	8.877	6.851
Semi-major Axis (km)	-4977.034	-5057.776	-8493.326
Inclination	143.215°	138.657°	107.97°
Eccentricity	2.47	2.32	1.81
Deflection	47.69°	51.07°	66.92°
B•R (km)	6440.680	4474.826	-12133.305
B•T (km)	-9236.501	-9593.956	-4234.030
Anomalous ΔV (mm/s)	+4.3	0.0	+13.0

‡ With respect to EME 1950
† With respect to EME 2000

used for deep space flight projects [6]. This was indeed the software used by the Galileo Navigation Team during both Galileo Earth encounters. The magnitude of the task of checking the ODP code would be a tremendous undertaking. Because the Galileo trajectory had suffered no ill effect, only a cursory examination of the ODP software was performed by *Stavert*[7], but no obvious errors were found. To further acquit the possibility that errors in the numerical integration of Galileo's trajectory or gravity modeling in the ODP computations as the source of the discrepancy, the tracking data was given to GSFC and UTCSR for analysis with their orbit determination programs and gravity models. Fitting the observations using GSFC's GEODYN II orbit determination software was found by *Nerem*[8] to agree to the ODP's results at the 1 mHz level (0.1 mm/s): Likewise, *Shum*[9] compared the University of Texas Orbit Processor (UTOPIA) orbit determination program and found negligible differences in the residuals. Another independent orbit determination program, the PCODP developed by *Miller*[10] also found no major differences from the ODP computation.

The NEAR Navigation Team used *Miller's* PCODP program as the primary estimation filter during NEAR's Earth encounter while the ODP was used simultaneously for back-up. Both software sets displayed the same behaviour of the frequency shift in the post-encounter data .

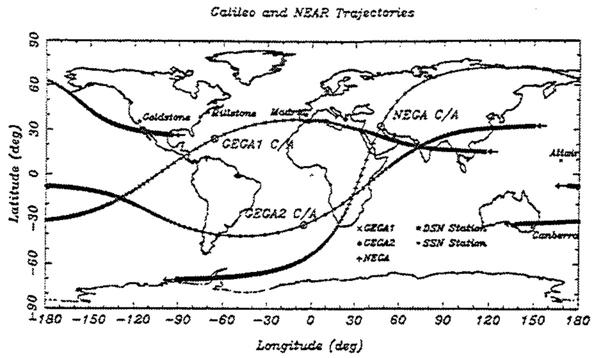

Figure 7: Ground tracks of GEGA1, GEGA2 and NEGA

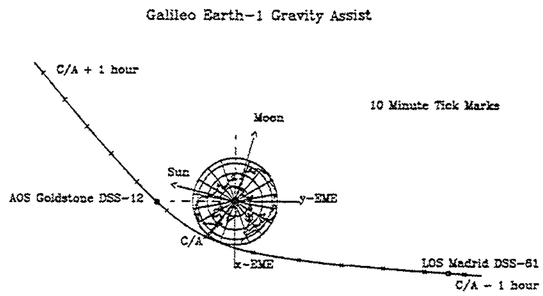

Figure 8: North pole trajectory view of GEGA1

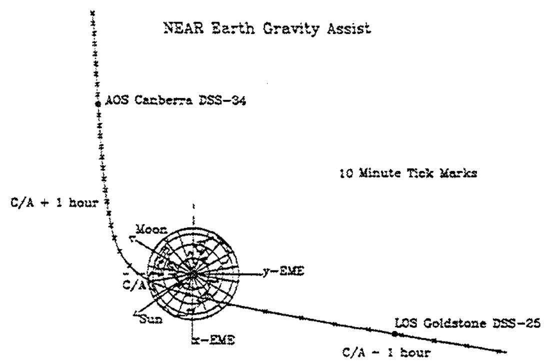

Figure 9: North pole trajectory view of NEGA

Because independent orbit determination /trajectory modeling programs such as GSFC's GEODYN, UTCSR's UTOPIA and *Miller's* PCODP programs have reproduced essentially the same result,it indicates that since the ODP software is not alone in this enigma, the possibility remains small that this is a result of software programming errors. But as *Miller*[10] states, that all these OD programs are not really independent because the developers for such programs "*probably would obtain the formulation from the same source, namely Newton.*"

Advanced Theoretical Investigations

J.K. Campbell of JPL was able to obtain a fit of the encounter data for GEGA1 by estimating Earth's oblateness term, J2, and the harmonics associated with the orientation of Earth and the solid Earth tide, C21 and S21[11, 12]. Although the solved-for values were unreasonable, *Anderson & Krisher*[11] determined that the anomalous acceleration magnitude for the adjusted gravity field at perigee was, $\delta a = 2 \times 10^{-7}$ km/s^2. This appears to be a plausible way of determining the magnitude of the anomalous acceleration that produced the observed ΔV. Because the acceleration that may have produced the ΔV is dependent upon the unknown time span on which it acted, it is otherwise difficult if not impossible to determine either this time span or the magnitude of the acceleration.

Krisher, and *Anderson* have investigated various advanced analytical theories that could explain the observed result of the unaccounted gain in energy during GEGA1 through derivation and sometimes through implementation into the ODP. These theories include: non-conservative or unmodeled potential energy[13, 14], non-Newtonian gravity[12], ocean tides[15], and modifications to relativity[16].

Anderson[13] considered but dismissed the possibility that any nonconservative force contributions caused by gravitational harmonics, C21 and S21 since they are dependent upon the orientation of Earth, would be nearly 2 magnitudes less than that which would be required to produce the desired acceleration. *Anderson*[12] looked at the possibility that Newtonian gravity didn't hold true for a zone at a small fraction of the body radius, but determined that the effect would be too small for GEGA1 and too large for GEGA2. *Krisher*[16,17] considered various nonstandard force models to explain the anomaly such as combining the Moffat theory of gravity with the Yukawa potential, the parameterized post-Newtonian (PPN) formalism of metric theories of gravity, and gravitomagnetism, which is predicted by general relativity for massive spinning bodies. *Krisher*[17] determined that none of these could fully account for the observed acceleration, however two *ad hoc* models (not based on any existing theories) were found to fit the GEGA1 data [17]. Krisher attempted to provide a possible theoretical basis such as the modification of general relativity involving torsion, for one of these models referred to as the '*eps2 model*.' The model appeared to be consistent with other spacecraft planetary flybys, but was later found inconsistent with the stability of planetary orbits [18].

Non-gravitational forces that have also been considered include outgassing of trapped air[19], and those associated with possible spacecraft interaction with Earth's geomagnetic field[20, 21, 22]. Possible electromagnetic interactions during GEGA1 include the force induced upon a spacecraft carrying a net charge[20, 21], a magnetic dipole[21, 22], and ion plasma drag[20]. Kobele[19] gives the odds at "*less than a zillion to one that the unexplained ΔV could be caused by outgassing*" since an equivalent force to that observed would require a substantial amount of air. Wang [20] dismisses the electromagnetic interactions as being orders of magnitude less than the observed acceleration on GEGA1.

Radio Metric Tracking Data Types

Both the Galileo and NEAR spacecraft were tracked from the DSN Deep Space Station (DSS) antennas in Goldstone, California, Madrid, Spain and Canberra, Australia. The radio metric data obtained for Galileo consists of 2-way (coherent) and 1-way non-coherent S-Band Doppler (2.3 GHz) and range. The radio metric data collected for NEAR consists of 2-way and 3-way X-Band Doppler (8.4 GHz) and range.

Besides a few interruptions, radio metric data for Galileo was acquired continuously by the DSN's 34 m High Efficiency (HEF) and Hour Angle-Declination (HD) and 70 m Azimuth-Elevation (AE) antennas from November 2, to December 13, 1990. Due to thermal constraints, the Galileo spacecraft maintained a Sun-pointing attitude through the Earth encounter. To remain in contact with the ground, a switch of the spacecraft antennas was performed from the sun-facing LGA-1 to the aft LGA-2 antenna at 19 minutes before C/A. As noted in [5], in preparation for the antenna switch, the onboard sequence changed the telecom link to non-coherent during the end of Madrid 34 m track at 55 minutes before encounter. As a result, both Madrid and Goldstone's 34 m HD antennas acquired 1-way Doppler data during the time of C/A. The 2-way coverage resumed at 14 minutes after encounter with the Goldstone 34m antenna. Canberra's 34 m antenna acquired lock a few minutes after the short 30 minute Goldstone track. This Goldstone data was obtained at very low elevations (5.8° - 12.7°). In operations, data acquired during elevations lower than 15° are generally discarded because the media (ionosphere and troposphere) have a pronounced effect on the signal. One-way Doppler data is dependent upon the spacecraft's Ultra Stable Oscillator (USO). This clock is known to exhibit biases and drifts in frequency making it very unreliable for orbit determination during dynamical events.

NEAR was tracked continuously from 10 days to 1 hour and 8 minutes before C/A using mainly DSN's newer 34 m Beam-wave guide (BWG) antennas. No onboard antenna switching was performed immediately before or after the encounter. During this time, NEAR's fan-beam antenna was the primary antenna A gap of approximately 3 hours and 39 minutes in tracking coverage occurred during the encounter because of the lack of DSN tracking stations geographically located during the flyby. Goldstone's 34 m BWG antenna was the last DSN station to track NEAR before encounter. Tracking resumed with the Canberra 34 m BWG antenna at 2 hours and 31 minutes after encounter. Since the NEGA altered NEAR's trajectory such that the heliocentric inclination was changed to target for encounter with the asteroid 433 Eros (whose orbit is inclined to the ecliptic plane) in January of 1999, the spacecraft's trajectory flew to the south as viewed from Earth, so that it could only be tracked from the southern Canberra DSN complex. In fact, the spacecraft was tracked continuously for nearly a month after encounter using mainly the 34 m BWG, but also the 34 m HEF. It should also be mentioned that 3-way Doppler was acquired during this time.

The Space Surveillance Network's (SSN) Millstone and Altair tracking stations also tracked both Galileo and NEAR spacecraft a short while just before C/A. As of this report, the authors haven't examined the SSN data for Galileo. Millstone tracked NEAR from 06:12:22 to 06:44:27 UTC on the 23rd of January while Altair tracked from 06:14:28 to 06:51:08 UTC on the same day, approximately 36 minutes after the last Goldstone track and 32 minutes before C/A. The SSN observables included both range and angle data types of azimuth and elevation. Because of a 0.02 deg pointing accuracy, the angle data could only give kilometer level accuracy in the cross-line of sight direction. However, as of this writing, the NEAR SSN range data which should have meter level accuracy, was found to be in disagreement with the DSN data when estimating the NEAR orbit. Apart from this disagreement, the SSN range data from both stations exhibit an intriguing slope shown in Figure 10 when the data were passed through a trajectory estimated with pre-encounter DSN data. This slope as yet cannot be reduced through estimation.

Figures 8 and 9 show the approximate spacecraft locations when the Loss of Signal (LOS) and Acquisition of Signal (AOS) occurred for the 2-way Doppler coverage of both Galileo and NEAR.

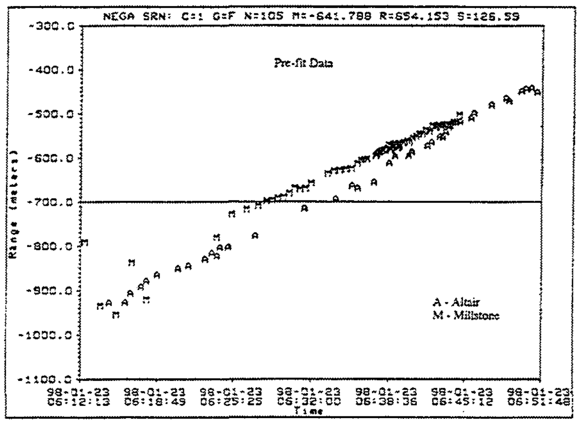

Figure 10: Pre-fit range residuals of NEAR's trajectory acquired by the Space Surveillance Network (this data was 'passed-through' an estimated trajectory based on the DSN pre-encounter data).

Dynamic Models

For each of the flybys a complete set of dynamic models was used. These are listed in table 2. The International Earth Rotation Service (IERS) technical note 18[23] is the basis for the terrestrial reference frame used.

The solar and Earth radiation pressure models for Galileo consist of a flat plate with attitude according to the commanded sun-pointing position. For NEAR it consists of modeling the High Gain Antenna, the fore and aft sides of the solar arrays and the back as flat plates, and the bus as a cylinder with appropriate specular and diffuse reflectivities. Telemetry of the attitude data in quaternions at 15 minute resolution is used to position the components for NEAR.

Measurement Modelling

The 1993 versions of the International Earth

Rotation Service (IERS) Terrestrial and Celestial Reference Frames (ITRF93 and ICRF93) [23] describe the Earth-fixed and inertial radio frames which are used for deep space navigation. The third body gravitational perturbations caused by the sun and planets are determined from the positions derived from the JPL Development Ephemeris, DE403, which is aligned with ICRF93 [24].

Table 2. - Dynamic Models

Model:	*Description:*
N-Body:	All Planets, Sun, Moon
Earth Geopotential:	70 x 70 truncated JGM-3
Indirect Oblateness:	2 x 2 Lunar Model
Solid Earth Tides:	IERS (8 Constituents + Permanent Tide)
Ocean Tides:	IERS (14 Constituents)
Rotational Deformation:	IERS
Relativity:	Point Mass Earth + Lense-Thirring
Solar Radiation Pressure:	Umbra/Penumbra Shadow
Atmospheric Drag:	DTM Model
Albedo Earth Radiation:	2nd Degree Zonal Model
Infrared Earth Radiation:	2nd Degree Zonal Model

Table 3. - Measurement Models

Model:	*Description:*
Solid Earth Tides:	IERS (0th, 1st and 2nd Order Corrections)
Ocean Loading:	IERS (11 Constituents)
Pole Tide:	IERS
Earth Rotation:	Daily Values
Polar Motion:	Daily Values
Plate Motion:	Linear Velocities
S/C Attitude:	Quaternion Inputs

The latest timing and polar motion data delivered as the Earth Orientation Parameter (EOP) file from the Time and Earth Motion Precision Observation (TEMPO) group at JPL are used to relate the Earth-fixed frame to the inertial radio frame. This data set includes daily differences in Universal Time 1 (UT1) which accounts for polar motion, International Atomic Time (TAI), and geodetic pole motion. The DSN station locations are measured in the Earth-fixed frame and have errors less than 10 cm in each coordinate direction [25], and linear plate motion is applied. Table 3 lists the measurement models used.

Filter Methods

All estimation analyses and trajectory propagation in this study used the ODP which is a pseudo-epoch state batch sequential filter. As not to allow stochastics to have influence on the solutions in this study, the single batch filter is preferred and used as the nominal filter. For comparison in a few of the NEAR cases, stochastic station biases and accelerations are included in the filter. In these cases, station range and Doppler biases are modeled as white noise processes with *a priori* uncertainties of 140 Range Units (20 m), and 0.1 mm/s. Stochastic 3-axis accelerations are estimated as a 'colored noise' process with a batch length of 7.5 days, an 1.25 day time correlation and process noise equal to the *a priori* uncertainty of 1. x 10^{-13} km/s^2.

The *a priori* uncertainties applied to the spacecraft state at epoch were on the order of 1000 km, 10 m/s. Ten percent *a priori* uncertainties for the surface reflectivities in the solar radiation model also applied. For ΔV estimation in the NEGA case, *a priori* a 3-axis spherical uncertainty of 100 mm/s was used.

Data Arc & Weights

Galileo's data arc consisted of data from approximately 2 days before to 1.4 days after encounter. The 2-way S-Band Doppler exhibited noise from 2 - 6 mHz, and the range data showed noise less than 4 m. The Doppler was conservatively weighted from 0.5 - 1 mm/s while the range data was weighted at approximately 2 - 10 m.

The data arc for the NEAR case consisted of near continuous DSN range and Doppler observables from approximately 4 days before encounter to 4 days after encounter. NEAR's X-Band range was found to have meter level accuracy, while the Doppler data exhibited errors of less than 5.6 mHz, as such the data weights of 5.6 mHz and 10 meters were applied in the following analyses.

RESULTS

Spacecraft Perturbations

Aside from the central body gravity of the sun (modeled as a point mass), the major perturbations affecting spacecraft motion beyond the sphere of the Earth's influence (2.5 million km) include solar radiation pressure and the third-body perturbations from the planets and moon. Within the Earth's sphere of influence, Earth's point mass gravity becomes the dominate force upon the spacecraft's orbit, and the sun's gravity becomes a third-body force. As the spacecraft flies closer to Earth, the third-body effects decrease and the Earth's oblateness becomes the dominant perturbation. Other major perturbations affecting the spacecraft's trajectory within the sphere of influence of the Earth include relativity, solid and ocean tides, radiation pressure from the sun, and Earth's albedo and infrared radiation. Figures 11 and 12 compare the acceleration magnitude signatures of the major perturbations affecting the orbits of Galileo (GEGA1) and NEAR within ± 4 hours from C/A of Earth. The maximum magnitudes of these and other smaller perturbing forces during this same time span are compared to the central body force of Earth in Table 4.

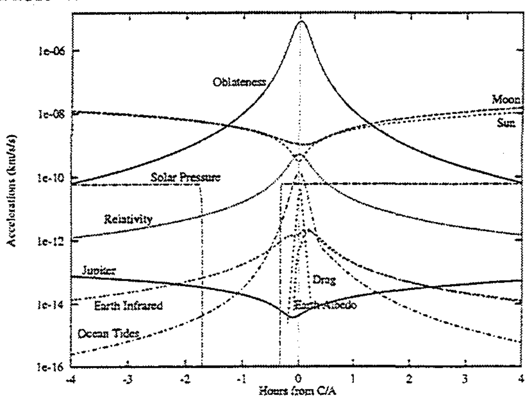

Figure 11: The major perturbations affecting the orbit of Galileo (GEGA1)within ± 4 hours from C/A of Earth.

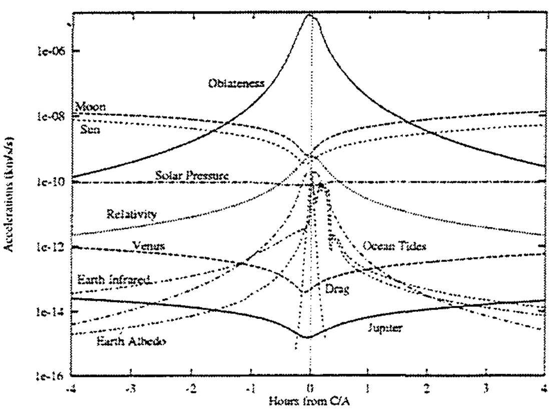

Figure 12: The major perturbations affecting the orbit of NEAR within ± 4 hours from C/A of Earth.

Possible non-gravitational effects from outgassing, thermal radiation emission have been found to be orders of magnitude below the observed amount. Drag forces upon both spacecraft orbits can be ruled out as the source of the anomalous ΔV because the resultant acceleration and thus the integrated velocity are very small in comparison. The integrated effect of Earth's albedo, infrared radiation forces upon the both spacecraft also appears to be a couple magnitudes lower than observed.

Table 4: Comparison of maximum acceleration magnitudes during GEGA1 and NEGA (km/s^2)

Accelerations	*GEGA1*	*NEGA*
Earth Central Body	7.4×10^{-3}	8.3×10^{-3}
Oblateness	8.1×10^{-6}	1.3×10^{-5}
δa*	2.0×10^{-7}	6.0×10^{-7}
Moon	1.5×10^{-8}	1.3×10^{-8}
Sun	1.2×10^{-8}	7.7×10^{-9}
Relativity	5.3×10^{-10}	5.6×10^{-10}
Drag	3.9×10^{-11}	2.5×10^{-10}
Earth Albedo	1.9×10^{-12}	2.0×10^{-10}
Earth Infrared	2.3×10^{-12}	1.5×10^{-10}
Ocean Tides	1.4×10^{-10}	1.9×10^{-10}
Solar Pressure	5.9×10^{-11}	9.2×10^{-11}
Indirect Oblateness	1.5×10^{-14}	1.3×10^{-14}
Moon Oblateness	4.5×10^{-16}	3.0×10^{-16}
Mercury	2.1×10^{-15}	7.0×10^{-16}
Venus	5.7×10^{-15}	1.0×10^{-12}
Mars	2.0×10^{-14}	1.6×10^{-16}
Jupiter	7.8×10^{-14}	2.6×10^{-14}
Saturn	2.3×10^{-15}	1.8×10^{-15}
other planets	$< 1 \times 10^{-16}$	$< 1 \times 10^{-16}$

* Hypothetical acceleration

Anomalous ΔV Estimation

Various filtering methods were used to estimate the anomalous ΔV during and NEGA. These methods included adding stochastic Doppler and range biases per tracking station pass and stochastic 3-axis accelerations. In addition, to the nominal Doppler and range weights, both Doppler-only and range-only solutions were computed. Despite different data weighting schemes, or including stochastic station biases or stochastic accelerations in the filter, the estimated anomalous ΔV for NEAR as shown in Table 5 had a consistent 7.3 mm/s component in the positive along-track direction. This component was well determined to the 2 - 8 μm/s level in all cases as is evident by the 1-σ uncertainties. The radial component was the determined at 2 orders of magnitude less than the along-track component; these values ranged from 3 - 6 mm/s. The cross-track component was least determined at the 1 mm/s level with values ranging from 0 to 14 mm/s. Magnitudes for the ΔV were found to be mostly at the 8.4 - 8.9 mm/s level with a few exceptions.

Table 5: Anomalous ΔV (mm/s) values for NEGA

Filter Method	Radial	Along-track	Cross-track	Magnitude
No stochastics				
Nominal Weight	4.77 ± 0.24	7.27 ± 0.003	5.69 ± 0.98	10.40 ± 0.59
Doppler Only	4.93 ± 0.15	7.25 ± 0.002	0.01 ± 0.74	8.77 ± 0.08
RAnge only	6.52 ± 0.15	7.24 ± 0.003	14.30 ± 0.94	17.30 ± 0.79
Station biases				
Nominal Weight	4.03 ± 0.31	7.30 ± 0.008	2.52 ± 1.85	8.71 ± 0.60
Doppler Only	4.04 ± 0.18	7.30 ± 0.007	2.43 ± 1.05	8.69 ± 0.33
Range only	3.91 ± 0.36	7.28 ± 0.006	1.92 ± 2.15	8.48 ± 0.56
Stochastic accels.				
Nominal Weight	3.56 ± 0.32	7.29 ± 0.008	2.17 ± 1.86	8.40 ± 0.54
Doppler Only	3.69 ± 0.18	7.29 ± 0.007	3.58 ± 1.06	8.92 ± 0.45
Range only	3.27 ± 0.44	7.29 ± 0.008	0.72 ± 2.15	8.02 ±0.35

Table 6: Estimated values to hypothetical normalized gravity field

Term	Nominal	Estimate	Sigma	Δ NEGA	Δ GEGA1[11]*
J2	4.8416955e-04	4.94e-04	± 4.1e-07	9.84e-06	-1.84e-06
C21	-1.8698764e-10	1.38e-05	± 6.1e-07	13.80e-06	4.69e-06
S21	1.1952801e-09	-1.12e-05	± 2.3e-07	-11.20e-06	9.25e-06
C22	2.4392607e-06	-6.53e-06	± 2.5e-07	-8.97e-06	--
S22	-1.4002664e-06	11.10e-06	± 1.1e-07	12.50e-06	--

*Earth GM estimated also.

Earth Gravity Field Estimation

Estimation of the gravity field to degree and order 30 was performed for both the GEGA1 and NEGA trajectories. This estimation included constraining the solution by using the correlated 30 X 30 covariance of JGM-3. The estimation in both cases failed to account for the Doppler frequency shifts observed. The solved-for values in the Galileo case showed reasonable shifts in the spherical harmonic coefficients as show in Figure 13, yet the solution for the NEAR gave erroneous results (not shown). However, it should be noted that in these studies, the Solid Earth Tide harmonics, C21 and S21 were not estimated since these harmonics were considered to be very accurate and provide the basis of the Earth-fixed frame. Figure 13a compares the estimated changes of the coefficients up to degree and order 10 to their *a priori* values for GEGA1. Figure 13b compares these estimated changes against their *a priori* uncertainties. The estimated changes to the coefficients are well within the possibilities, however, these changes were not enough to remove the observed discrepancy in the encounter data. The changes in the gravity coefficients for NEGA case were found to be up to 7 - 12 times their associated values and up to 300 times their associated uncertainties. Even these changes were unable to remove the NEAR discontinuity in the residuals.

Hypothetical Gravity Estimation

Since the above method of using the constrained *a priori* was unable to account for the observed phenomena for Galileo and NEAR, it may be instructive to allow the gravity parameters (by loosening the *a priori* uncertainties ~1000 σ) to 'absorb' the effect for the NEGA case like *J.K. Campbell* did for the GEGA1[11].

NEAR's trajectory and thus, the Doppler data, was found to be sensitive to the 2nd degree and order harmonics, J2, C21, S21, C22 and S22. Like *Campbell*, the estimation of the J2, C21 and S21 gravity harmonics for the NEAR case were also found to reduce both the Doppler and range post-fit residuals analogously to the anomalous ΔV estimation. The estimation of C22 and S22 along with J2, C21 and S21 was found to have a slight advantage over fitting J2, C21 and S21 alone. Although the solved-for values as shown in Table 6 were found to be several magnitudes higher than their *a priori* values (i.e. unreasonable), their combined spatial effect could provide clues to a yet unexplained force. Also listed in Table 6 for comparisons, are the estimated changes (Δ) from *Campbell's* hypothetical gravity estimation. Aside from the J2 and S21 having opposite signs, the changes are nearly of the same magnitude as for the NEAR case.

Figure 14 compares the nominal JGM-3 70 X 70 combined oblateness acceleration effect upon the

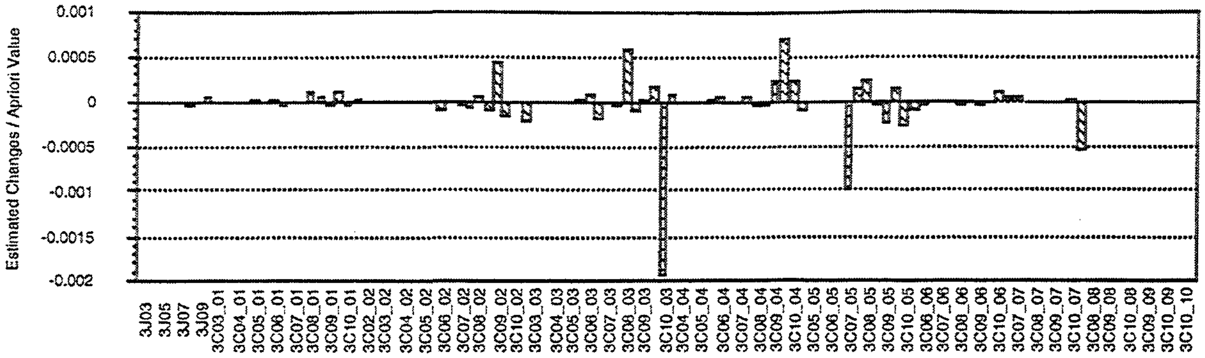

Fig. 8a - Galileo Earth-1 Gravity Field Estimates / Apriori Value

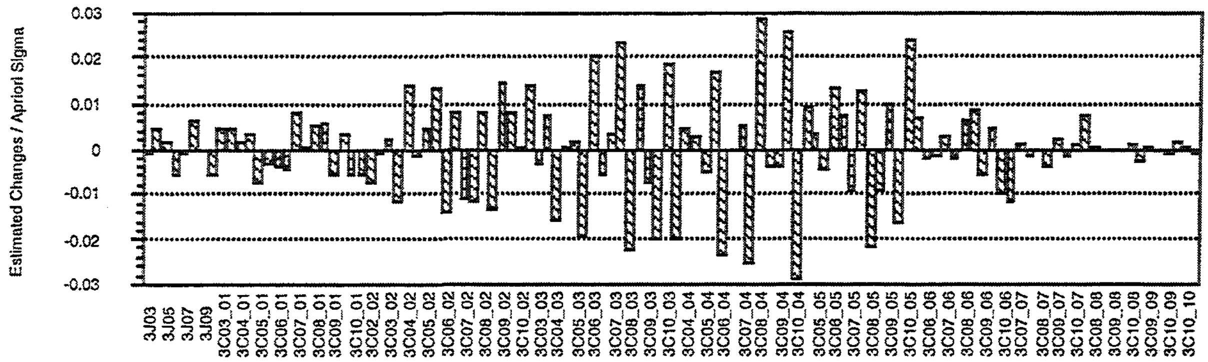

Fig. 8b - Galileo Earth-1 Gravity Field Estimates / Apriori Sigma

Figure 13: GEGA1 gravity field estimates for the 10 x 10 gravity field (the changes to the coefficients are compared to the *a priori* values in (a) and the *a priori* sigmas (b))

NEAR trajectory to that of this adjusted 2 X 2 hypothetical gravity field. Displayed in Figure 14 are the differences between this hypothetical and the nominal gravity accelerations in the orbit-fixed radial, transverse, and normal directions, and the magnitude of the acceleration difference as a function of time ± 33 minutes from C/A. If only 2-way Doppler data was obtained during ± 20 minutes of C/A, could the true spatial resolution of this mysterious effect be realized. The maximum acceleration difference, δa, (in Figure 14) is approximately ~6 x 10^{-7} km/s^2 which is two orders of magnitude lower than that of the overall oblateness. This difference was of the same order of the GEGA1 apparent acceleration (2 x 10^{-7} km/s^2) in which *Campbell* computed.

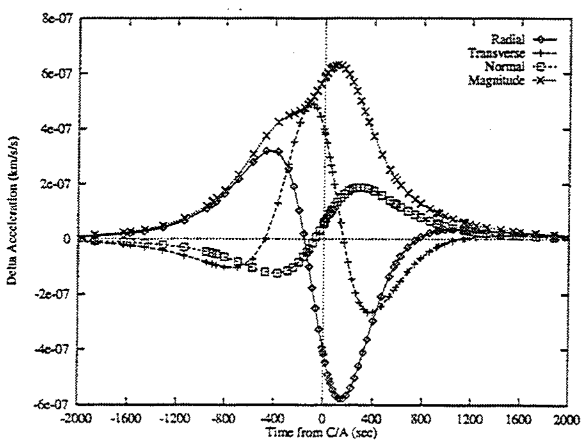

Figure 14: Differences between the hypothetical and the nominal JGM-3 gravity accelerations for NEGA.

CONCLUSIONS

It has become obvious from the gravity field estimations (using the nominal JGM-3 covariance) above, that the conservative laws of gravity can't account for either the GEGA1 or the NEGA case. Instead of trying to find flaws in the existing models, an hypothetical gravity model was estimated to provide clues to the nature of a possible unknown perturbing force. In order to remove the radio metric data discontinuity at C/A, the C21 and S21 terms of the gravity field, which are associated with the timing of the Earth-fixed reference frame relative to the inertial radio frame, had to be grossly adjusted. This suggests that this force may have a spatiotemporal or relativistic nature. Another clue to the nature of this force could be the fact that the estimated ΔV at perigee for NEAR exhibited a well determined along-track component of 7.3 mm/s.

Furthermore, the fact that the data can be fit with an approximation of the geopotential suggests that the force may follow an inverse square relation to the spacecraft position with respect to the Earth. The comparison of the force magnitude against the JGM-3 magnitude leads one to think perhaps (as a last resort) that this is evidence for *antigravity*. If *antigravity* played a role, why hasn't Earth orbiters observed it? Maybe there's a temporal component to this force that can't be sensed from Earth orbiters. The diurnal signature in the post-encounter residuals for NEAR clearly indicates some type of timing mismatch between the observable and the computed observable. Could the Earth orientation parameters be in error? By fitting the data with a spacecraft state epoch begun after the encounter, this diurnal signature for the most part is eliminated. So for whatever occurred during encounter, the effect can be removed by adjusting the epoch state after encounter. It will be interesting to see if the aforementioned anomaly appears during the Cassini Earth gravity assist in August of 1999, or the Stardust's Earth passage in January of 2001.

ACKNOWLEDGMENT

The authors would like to thank George Lewis for obtaining the SSN data for NEAR and the folks at Millstone and Altair for tracking both Galileo and NEAR. Thanks also go to Peter Wolff for assistance in manipulating the 50 x 50 gravity covariance.

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