Comment on ‘Evidence of the gravitomagnetic field of Mars’

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Abstract

In a recent analysis of orbital data from the Mars Global Surveyor spacecraft, Iorio (2006 Class. Quantum Grav. 23 5451) found compelling evidence of general relativity’s gravitomagnetic frame dragging effect. (A subsequent paper (Iorio L 2007 Preprint gr-qc/0701042v5) using the same data and equations claims agreement within 0.5% accuracy, exceeding that expected from NASA’s Gravity Probe B.) However, this confirmation of general relativity was obtained by misinterpreting the MGS data and then altering a key time period.

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1. Introduction

The Mars Global Surveyor (MGS) reached Mars in September 1997. While the main mission was imaging and mapping its surface, its magnetic and gravitational fields were also mapped. The latter began after aerobraking in the Mars atmosphere put the probe in an approximately circular polar orbit, at an altitude of 400 km, in February 1999. The gravitational field data were obtained by observing its orbital motion, via line-of-sight microwave Doppler and range measurements between the probe and Earth stations.

As first described by Lens and Thirring [3], general relativity predicts a rotating massive body would cause a rotational dragging of nearby spacetime. A recent paper by Iorio [1] argued this subtle effect can be detected in the MGS orbit. Previous measurements using the Earth-orbiting LAGEOS and LAGEOS II satellites have been reported by Ciufolini and coauthors [4, 5]. However, the accuracies of those have been questioned [6, 7].

A more definitive finding is expected by year’s end, with the announcement of final results from NASA’s Gravity Probe B. That experiment is an Earth-orbiting gyroscope, designed specifically to measure frame dragging to an accuracy of 1%. Iorio has claimed observation
of this effect already in the MGS orbit. (A subsequent paper \cite{2}\ finds confirmation of general relativity to a 0.5% accuracy.) This has been well publicised. (For example, see \cite{8}.) Here we will review the methods and calculations used to arrive at this extraordinary claim.

2. Analysis of the MGS orbital data

Iorio’s Mars Global Surveyor paper \cite{1} is based on analysis of the MGS orbit by Konopliv \textit{et al} \cite{9}. Discussing their data, he writes

Here we are interested, in particular, in the out-of-plane portion of its orbit. The root-sum-square out-of-plane residuals over a five-year time interval spanning from 10 February 2000 to 14 January 2005 are shown in figure 1. They have been determined in a Mars-centered coordinate system. . . . Due to improved modeling (orientation, gravity, angular momentum wheel de-saturations and atmospheric drag), the average of such residuals amounts to 1.6 m.

This result can be well explained with the action of the gravitomagnetic field of Mars on the orbit of MGS.

The figure referred to was reproduced from Konopliv \textit{et al}. The original is shown as figure 1 here. (Unlike Iorio’s version, it shows six years of data.) To compare the average residual error in the MGS orbit with the action of the gravitomagnetic field of Mars, he started with the gravitomagnetic Lens–Thirring precession of a satellite orbit due a rotating central body:

\[ \dot{\Omega}_{LT} = \frac{2GS}{c^2a^3(1-e^2)^{3/2}} \]  

(See Ciufolini and Wheeler \cite{10} for a derivation.) \( \dot{\Omega}_{LT} \) refers to the secular rate of change in the longitude of the orbit’s ascending node, \( G \) is the gravitational constant, \( S \) is the rotating body’s angular momentum, \( c \) is the speed of light, \( a \) and \( e \) are the orbit’s semi-major axis and eccentricity, respectively.

Referencing Christodoulidis \cite{11}, Iorio expressed a change in \( \dot{\Omega}_{LT} \) as a change in the position of the orbit’s ascending node \( \Delta N_{LT} \) as

\[ \Delta N_{LT} = a \sqrt{1 + \frac{e^2}{2}} \sin i \Delta \Omega_{LT} \]  

(2)

where \( i \) is the orbital plane’s inclination with respect to the central body’s equatorial plane. With \( \Delta P \) representing a time interval (notation introduced in Iorio’s second MGS paper \cite{2}), these expressions can be combined as,

\[ \langle \Delta N_{LT} \rangle = \frac{GS\Delta P \sin i \sqrt{1 + \frac{e^2}{2}}}{c^2a^2(1-e^2)^{3/2}}, \]  

(3)

to show how they were used. The factor of 2 in equation (1) is lost because \( \langle \Delta N_{LT} \rangle \) represents the average change in the position of the orbit’s ascending node over this time interval. Using a value of five years for \( \Delta P \), he obtained a predicted average precession of 1.5 m. Comparing this to the 1.6 m average out-of-plane residual error from Konopliv \textit{et al}, he found that agrees with general relativity’s prediction to within 6%.

\[ \text{1 Here we respond to versions v1–v5 of that ArXiv paper. Note the unattributed changes in v6 which followed the initial posting of this review to Arxiv: ‘root-sum-square’ becomes ‘RMS,’ residuals are now described as ‘overlap differences’, and the precise quantity 1.6 m becomes 1.613 m—giving even closer agreement with general relativity.} \]
Figure 1. RMS orbit overlap differences from Konopliv et al. [9]. Reprinted with permission from Elsevier.
An even more compelling result is obtained in Iorio’s second MGS paper, using the same data and equations. With the exception of a small change in the Mars angular momentum $S$, the only difference in values used is in $\Delta P$, which increases from five years to five years and two months. There the result is presented as a ratio $\mu_{\text{meas}} \equiv (\Delta N_{\text{res}})/(\Delta N_{\text{LT}})$, where $(\Delta N_{\text{res}})$ represents the 1.6 m residual error. The predicted Lens–Thirring precession $(\Delta N_{\text{LT}})$ is not given explicitly, but becomes 1.610 m. Where $\mu_{\text{meas}}$ would be 1 for a perfect agreement with general relativity, this is found to be $0.9937 \pm 0.0053$. Of the uncertainty, he attributes $\pm 0.0052$ to that in the Mars angular momentum, $\pm 0.0001$ to uncertainty in the constant $G$, and none to the residual $(\Delta N_{\text{res}})$ from observations of the MGS trajectory.

What information is actually shown in figure 1 from Konopliv et al? The number of data points are related to a spacecraft trajectory model generated by the JPL Orbit Determination Program [12]. While data from the entire mission are processed to give a global best fit, the output is a sequence of separate trajectory segments, ‘data arcs’, four to six (Earth) days in length. Each plotted datum point corresponds to the intersection of two data arcs.

Ideally, the modeled segments would fit together as a smooth, continuous trajectory. Since the modeling cannot be perfect, there are mismatches. The orbital period of MGS is 2 h, so a single data arc consists of many orbits. As Konopliv et al [9] described, to gauge and minimize mismatches between successive data arcs, each is extended to overlap the next by a full orbit. The RMS difference in the spacecraft positions is then computed over that orbit. (Iorio refers to these as root-sum-square residuals, although RMS indicates root-mean-square.)

These position differences are taken in three directions: radial, along track (the direction the spacecraft is moving) and normal to the orbit plane. Konopliv et al plotted these residual modeling errors in a three-part figure. Part (c), the ‘normal orbit difference’, is the basis of Iorio’s analysis. The original point made was that, as modeling of the Mars gravity field and various perturbations have improved, the errors have declined. In this case, the normal average orbit error has decreased from a previous 3 to 1.6 m.

This does not suggest a net precession of the orbit averaging 1.6 m over a five or six year period of observations $(\Delta P)$. It refers to the average mismatch between successive data arcs. Over the complete trajectory, 442 data arcs, the underlying directed errors could cancel, or accumulate to a large number of meters. Even individually, these error values do not specify orbital precessions.

The normal mismatch between overlapped orbits can be treated as having two parts: an angular tilt of the orbit plane around some axis through the Mars center of mass, plus a normal translation of the orbit plane. (The latter effect would not be expected in a rotationally symmetric system. For a rotating planet with an irregular gravitational field, it may be significant.) Alone, a 1 m normal translation of the orbit would give a 1 m RMS difference, with no angular precession of the orbit.

Assuming the normal orbit difference is exclusively due to Lens–Thirring precession, there would be no translation, and the corresponding orbital tilt would be around the Mars rotation axis. In this case, the overlapped orbits would cross near the poles and separate at the Mars equatorial plane. If the ascending node positions differ there by 1 m, the resulting RMS residual will be less, still not corresponding to what is assumed in Iorio’s calculation. Also, these numbers have no sign to indicate a direction of precession.

Moreover, there is no reason to expect that the value 1.6 is unique. Lemoine et al [13] and Yaun et al [14] described repeated decreases in the MGS orbit residuals as the accuracy of Mars gravity maps and perturbation modeling have improved. Nowhere in Konopliv et al is it suggested that the present 1.6 m normal average orbit error could not be reduced by further refinement of the existing orbit model.
Another crucial element of Iorio’s analysis is his choice of the time period $\Delta P$. According to him, the measured out-of-plane orbit error corresponds to a cumulative precession, increasing with time. The 1.6 m error value from Konopliv et al is based on six years of data, shown in figure 1. Without explanation, his paper takes the same error to apply to a five-year period. (His figure omits the data prior to 2000 to agree with that.) With the predicted Lense–Thirring precession proportional to $\Delta P$, this change brings the difference between his predicted and ‘measured’ values down to 6%.

(Again, in Iorio’s second MGS paper [2] the value becomes five years + two months, with no specific justification given. In this case the result agrees with general relativity to 0.5% accuracy. A slightly different $\Delta P$ would also make perfect agreement possible.)

3. Discussion

It would be very surprising if any test of frame dragging could be obtained from the Mars Global Surveyor trajectory. Unlike some spacecraft, it was not designed for measurement of its undisturbed inertial motion. That was possible, for example, with the Pioneer 10 and 11 space probes [15]. Those encountered no planetary atmospheres, and were spin stabilized, such that the frequent use of thrusters was not required.

In this case, AMD (angular momentum wheel desaturation) thrusters were fired four or five times per day until September 2001, when that was reduced to 1 or 2. Velocity uncertainties due to imprecision of the thrust are partially corrected from observations of the spacecraft motion, but that is limited by the one-dimensional nature of the Doppler velocity measurements.

(In his second paper, Iorio mentioned his value of $\Delta P$ was chosen ‘so to remove the first months of the mission more affected by orbital maneuvers and non-gravitational perturbations’. However, there was no change in orbital maneuvers which would justify a time period starting in November 1999. Also, Konopliv et al pointed out that noise in the Doppler velocity signal was least during the first one and three quarters months, referred to as the ‘Gravity Calibration Orbit’. This preceded deployment of the large high-gain antenna, which increased atmospheric drag.)

Konopliv et al also noted ‘normal orbit error is the greatest, and along track is the least when the orbit plane is near edge-on as viewed from Earth (e.g., January 2001). For this geometry, the signature in the Doppler (which measures the velocity of the spacecraft in the Earth–Mars direction) is greatest for the motion in the orbit plane, but is minimal for the motion normal to the orbit plane.’

Referring to figure 1, note the dips in the radial and along-track differences centered around January 2001, and the corresponding large hump in the normal orbit difference, where it increases by a factor of ten. This obviously contributes to the 1.6 m average normal orbit difference. We could agree with Konopliv et al that this is due to the measurement error. Certainly, it cannot be attributed to a larger general relativistic precession occurring at that time.

Another significant factor at the relatively low altitude of MGS is the Martian atmosphere. From the spacecraft’s asymmetric shape, drag due to its forward motion would be expected to cause out-of-plane forces. For a satellite in polar orbit, rotation of the upper atmosphere would also tend to produce a force causing an orbital precession. Solar heating of the spacecraft on emergence from the Mars’ shadow may be an additional influence.

None of the possible errors due to these or other orbital perturbations are estimated by Iorio, or included in his calculations. (Following initial publication of this review on arXiv, another by Sindoni, Paris and Ialongo [16] has found the uncertainty of the orbit’s precession...
exceeds that claimed in Iorio’s second paper by at least a factor of 10,000. Also see Felici [17].

4. Conclusions

Iorio finds that a certain measure of error in the previously modeled trajectory of the Mars Global Surveyor can be well accounted for by the Lense–Thirring effect of general relativity. Where the residual error is 1.6 m, he finds all but 6% of that is predicted. (In his second MGS paper, he finds the same error is predicted to 0.5% accuracy.) However, this result was obtained by calculating the Lense–Thirring precession with a time period different than the actual period of observations.

Also, where he assumes 1.6 m represents the average of a cumulative effect arising over 5 or 6 years, it actually describes RMS orbital mismatches between pairs of ‘data arcs’—with total spans in the range of 8 to 12 days. The effects are generally not cumulative. Finally, this quantity is not a specific measure of the movement of the orbit’s ascending node, as assumed in Iorio’s calculations.

Other approaches to measure the Lens–Thirring effect are promising. In addition to the pending result from Gravity Probe B, a new experiment has been proposed by Turyshiev et al [18]. This would observe gravitational bending of laser light by the Sun, using two small, relatively inexpensive satellites positioned on the far side of the Sun, and the International Space Station. Second-order bending would be measured for the first time, as well as that due to frame dragging caused by the Sun’s rotation. The latter would be measured to 1% accuracy.

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References

[1] Iorio L 2006 Class. Quantum Grav. 23 5451 (Preprint gr-qc/0606092)
[2] Iorio L 2007 High-precision measurement of frame-dragging with the Mars Global Surveyor spacecraft in the gravitational field of Mars. Preprint gr-qc/0701042 versions v1-v5.
[3] Lense J and Thirring H 1918 Phys. Z. 19 156
[4] Ciufolini I et al 1998 Science 279 2100
[5] Ciufolini I and Pavlis E C 2004 Nature 431 958
[6] Ries J C, Eanes R J and Tapley B D 2003 Lense–Thirring precession determination from laser ranging to artificial satellites Nonlinear Gravitodynamics ed R Ruffini and C Sigismondi (Singapore: World Scientific) pp 201–11
[7] Iorio L 2005 New Astron. 10 603 (Preprint gr-qc/0411024)
[8] Clark S 2007 New Sci. 2587 14
[9] Konopliv A S, Yoder C F, Standish E M, Yuan D N and Sjogren W L 2006 Icarus 182 23
[10] Ciufolini I and Wheeler J A 1995 Gravitation and Inertia (Princeton, NJ: Princeton University Press)
[11] Christodoulidis D C et al 1988 J. Geophys. Res. 93 6216
[12] Moyer T D 2003 Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation (New York: Wiley-Interscience)
[13] Lemoine F G et al 2001 J. Geophys. Res. 106 23359
[14] Yuan D N et al 2001 J. Geophys. Res. 106 23377
[15] Anderson J D et al 2002 Phys. Rev. D 65 082004 (Preprint gr-qc/0104064)
[16] Sindoni G, Paris C and Ialongo P 2007 On the systematic errors in the detection of the Lense–Thirring effect with a Mars Orbiter Preprint gr-qc/0701141

[17] Felici G 2007 The meaning of systematic errors, a comment to “Reply to On the Systematic Errors in the Detection of the Lense–Thirring Effect with a Mars Orbiter,” by Lorenzo Iorio Preprint gr-qc/0703020

[18] Turyshev S G et al 2005 Fundamental physics with the laser astrometric test of general relativity ESA Spec. Publ. 588 11 (Preprint gr-qc/0506104)