Pioneer 10 data analysis: Investigation on periodic anomalies

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PIONEER 10 DATA ANALYSIS: INVESTIGATION ON PERIODIC ANOMALIES

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Abstract. The Pioneer Anomaly refers to the difference between the expected theoretical trajectory of the Pioneer 10 and 11 spacecrafts and the observed trajectory through Doppler measurements. It has been interpreted by the Jet Propulsion Laboratory (JPL) as a constant anomalous acceleration (Anderson et al. 2002). For this analysis, the Groupe Anomalie Pioneer (GAP) composed of several french laboratories has developped a specific trajectography software, ODYSSEY, which enables to test different anomaly models.

The paper will present, after a brief description of the software and the implemented models, the last results obtained: in addition to the constant anomaly, time dependent signatures of the anomaly have been noticed which can be described geometrically. The fit of the Pioneer 10 data with these new models yields a reduction of the standard deviation of the residual by a factor 2 with respect to the simple constant anomaly.

1 Introduction

The Pioneer Anomaly refers to the observed deviation from expectations of the trajectory of the Pioneer 10 and 11 spacecrafts, as observed through Doppler tracking. Precisely, the analysis performed at the Jet Propulsion Laboratory (JPL) have shown that the deviation can be described as a nearly constant and Sunward acceleration with a similar magnitude $(8.74 \pm 1.33)10^{-10}\text{ms}^{-2}$ for the two spacecraft (Anderson et al. 2002).

The presence of this anomaly and its magnitude have been confirmed by different analysis software (Marwardt 2002, Olsen 2007). A number of mechanisms have been considered as attempts of explanations of the anomaly as a systematic effect generated by the spacecraft itself or its environment (see as an example (Nieto et al. 2005) but they have not led to a satisfactory understanding to date. If confirmed, the Pioneer signal might reveal an anomalous behaviour of gravity at scales of the order of the size of the solar system and thus have a strong impact on fundamental physics, astrophysics and cosmology.

An international collaboration has been built recently, within the frame of International Space Science Institute (ISSI), in order to re-analyse the Pioneer data. The Pioneer data which had been analysed by the Anderson team (Anderson 2002) have been made available by Slava Turyshev (JPL) in the framework of this collaboration. They consist in Orbit Data Files (ODF) which contain in particular Pioneer 10 Doppler data from November 30th, 1986 to July 20th, 1998.

The aim of the present paper is to report some results of the analysis of these data performed by a collaboration between three groups at Onera, OCA and LKB within the "Groupe Anomalie Pioneer". A dedicated software called ODYSSEY has been developed to this purpose. The first result is to confirm the existence and magnitude of the anomalous secular acceleration reported by Anderson et al. (2002), using different and as independent as possible tools. The main motivation of the present paper is to study the periodic variations of the anomaly, which are known to exist besides the constant anomaly. Especially, we will show here that this periodic anomaly can be at least partly represented in terms of a modulation of the Doppler signal as a function of a unique azimuthal angle having a physical meaning.

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2 Development of the ODYSSEY software

The Pioneer 10/11 spacecrafts were tracked by the Deep Space Network (DSN) antennas. A S-Band signal at about 2.11 GHz is emitted at time t_1 by a DSN antenna and received onboard the spacecraft at time t_2. The frequency is multiplied by a constant ratio of 240/221 by a transponder and sent back to a ground antenna where it was received at time t_3. The Doppler shift is the difference between the up- and down- frequencies. In fact, the ODF observable is the average of the Doppler shift over a time span called compression interval (Moyer 2000). The ODF format, described in (Wackley 2000), also contains the compression time, the date of the middle of the compression interval, the emitted frequency and the receiving and transmitting DSN antenna identifiers.

To analyse the ODF data, a software called ODYSSEY has been developed at OCA within a collaboration with Onera. It is basically an interplanetary trajectory determination software. It performs numerical integration in rectangular coordinates of dynamical equations to propagate the position and velocity of the spacecraft and variational equations to propagate the sensitivity of the position and velocity with respect to the initial conditions of position and velocity and other parameters to be fitted. The values of the parameters to be estimated are obtained through a best fit procedure using the iterative least-squares method.

Maneuvers are taken into account as increments of velocity along the three directions. The dates of the maneuvers are provided by JPL and their amplitudes estimated as parameters in the best fit analysis.

The dynamical model to compute the motion of the spacecraft includes gravitational attraction by the main bodies of the solar system and direct radiation pressure. The motion of the spacecraft is computed using non relativistic gravitational equations. For the solar radiation pressure we use the same model as in (Anderson 2002).

The dynamical equations are integrated in the Barycentric Celestial Reference System (BCRS); The reference time scale is the Barycentric Coordinate Time (TCB). Positions of terrestrial stations are expressed in the International Terrestrial Reference System (ITRS); the reference time scale is the Coordinated Universal Time (UTC). The transition between ITRS and BCRS on the one hand, and TCB and UTC on the other hand, are performed according to 2003 International Earth Rotation Service (IERS) conventions. The positions of celestial bodies are obtained from DE 405 ephemeris from JPL in BCRS with a reference time scale is similar to the Barycentric Dynamical Time.

Special efforts have been devoted in the development of ODYSSEY for handling the calculation of the ODF observable. In a first step, the perturbations of the round-trip light time are not taken into account. The ODF observable, that is the average of the Doppler shift over the compression time, is computed through a numerical approximation using the 4-points Simpson method.

The instantaneous Doppler shift is calculated in terms of velocities of the endpoints, evaluated at the event times t_1, t_2 and t_3 (Markwardt 2002). As only t_3 is provided in ODF, t_2 and t_1 have to be determined, which is done iteratively using the relativistic light time equation.

In the second step of the computation of the observable, the perturbations which affect the propagation of the tracking signal are taken into account. The Shapiro time delay and the solar corona effect are modeled as in (Anderson 2002). For the determination of the electron density necessary to compute ionospheric effect, the International Reference Ionosphere (IRI) 2007 (Bilitza 2001) has been implemented. For the mapping functions of the tropospheric effect, the Global Mapping Functions (GMF) (Boehm 2006) have been implemented. All these perturbations are modeled as delays affecting the signal (except for the Shapiro delay, their effect in the light time equation is however negligible).

3 Confirmation of the existence of a constant anomaly

Our first aim was to study the secular Pioneer anomaly reported by Anderson et al. (2002). To this aim, we performed a best-fit with a constant anomalous acceleration a_P exerted on the probe and centered on the Sun.

The initial conditions as well as the three components of each maneuver are also fitted. Points with an elevation inferior to 20° are rejected so as to limit the effect of imperfections of atmospherical models. Outliers are also rejected when their difference with the expectation exceeds 100 Hz at the first iteration and 6σ at the following iterations with σ the standard deviation of the residuals at this iteration.

The analysis performed with the software ODYSSEY confirms that a better fit is obtained with a constant sunward acceleration. The value estimated by ODYSSEY for the anomalous acceleration is $a_P = 0.84 \pm$

0.01 nms^{-2} with the formal error given at 1σ. This magnitude is compatible with that reported by Anderson et al.

The postfit residuals show a standard deviation of 9.8 mHz, which is largely improved with respect to a fit without a_P.

4 Study of the periodic variations of the Pioneer Anomaly

It can be emphasized that the level of the residuals is higher than the measurement noise. In order to highlight the potential existence of systematic structures in the residuals, we performed a spectral analysis of the residuals using the SparSpec software (Bourguignon et al. 2007). The result of this spectral analysis is shown on Fig. 1.

The presence of significant periodic terms is clear at the periods measured with respect to a day = 86400 s: $f_1 = 0.9974 \pm 0.0004$ day, $f_2 = \frac{1}{2}(09972 \pm 0.0004)$, and $f_3 = 189 \pm 32$ day. As 0.9972 day = 1.0 sidereal day, these periods are consistent with variations on one sidereal day, half a sidereal day, and half a year.

The presence of diurnal and seasonal variations in the residuals has also been reported by Anderson et al. (Anderson et al. 2002). Anderson et al. (2002) proposes modeling errors such as errors in the Earth's ephemeris, the orientation of the Earth's spin axis or the station's coordinates. However, these parameters are strongly constrained by other observational methods and it seems difficult to change them enough to explain the periodic anomaly.

The main motivation of the present paper is to test an alternative explanation where some perturbation would modify the propagation of the tracking signal along the path from the Earth antenna and the spacecraft. The idea is to represent such a perturbation, whatever its origin, as a function of the angle φ defined as the difference between the Earth Antenna (A) azimuthal angle and the Pioneer (P) azimuthal angle : $\varphi = \varphi_P - \varphi_A$. The main interest of this geometrical model is that it should simultaneously account for the orbital movement of the Earth around the Sun and the diurnal rotation of the Earth.

As this perturbation is supposed to be periodic, it will be represented by a few Fourier coefficients υ_n and υ'_n. The spectral analysis information led us to test the following model :

$$\begin{aligned}\Delta f = &\upsilon_1(\cos(\varphi_u) + \cos(\varphi_d)) + \upsilon'_1(\sin(\varphi_u) + \sin(\varphi_d)) \\ &+\upsilon_2(\cos(2\varphi_u) + \cos(2\varphi_d)) + \upsilon'_2(\sin(2\varphi_u) + \sin(2\varphi_d))\end{aligned} \tag{4.1}$$

Here φ_u and φ_d are the angles φ evaluated on the up- and down-links.

This model results in a spectacular improvement of the best fit residuals, with the standard deviation reduced to 5.5 mHz. The values of the fitted anomalous parameters are reported in table 1.

Table 1. Results of the best fit with periodic terms in the signal, with two different ionospheric models.

a_P (nms^{-2})	υ_1 (mHz)	υ'_1 (mHz)	υ_2 (mHz)	υ'_2
-0.836±0.001	124.3±9.3	-125.3±0.6	2.7±0.2	-4.8±0.1

The best fit with modulated terms shows that when these terms are looked for in a dedicated best fit procedure, they are unambiguously found to differ from zero. Especially, the yearly period corresponds to a large potential amplitude while it was not detected in the spectral analysis of the best fit residuals with only a secular anomaly. This can be explained by the fact that the fit of the initial conditions also induces terms at the at the daily and yearly periods. In particular, a change of the initial conditions may easily produce variations masking modulated terms (Reynaud & Jaekel 2005, Courty 2008).

An even more impressive demonstration of the improvement of the data analysis drawn by the inclusion of modulated terms comes from the spectral analysis of the residuals. This spectral analysis is represented on Fig. 2 for the best fit with modulated terms. It is drawn intentionnally at the same scale as Fig. 1 so that one can easily notice the global reduction of the main peaks in the spectrum as well as all the secondary peaks.

5 Conclusion

In the present paper, we have reported the first results of our re-analysis of the Pioneer 10 Doppler data for the 1986 to 1998 time span. The improvement of the data fit with a constant anomalous acceleration exerted on Pioneer 10 has been confirmed by this new data analysis.

The paper has then been focused on the study of periodic terms in the residuals. The main new result of the paper is that a large part of these diurnal and seasonal anomalies may be captured in a simple geometrical model where the light time on the tracking path is modified in a manner depending only on the azimuthal angle φ between the Sun-Earth and Sun-probe lines. This geometrical model could represent in a simple way the physical effects expected on light propagation in some metric extensions of general relativity which have been studied as potential candidates for the explanation of the secular Pioneer anomaly (Reynaud & Jaekel 2005). Nevertheless, the results of the paper cannot be considered as pointing to a particular possible explanation of the anomaly and similar effects could for example be obtained through a mismodeling of the solar corona model.

However, considering the modulated anomalies has allowed us to reduce by a factor of the order of two the standard deviation of the residuals. This suggests that the new analysis constitutes a richer characterization of the Pioneer data, now involving not only a secular acceleration but also modulated terms, which will have to be compared with any, existing as well as future, possible explanation of the anomaly.

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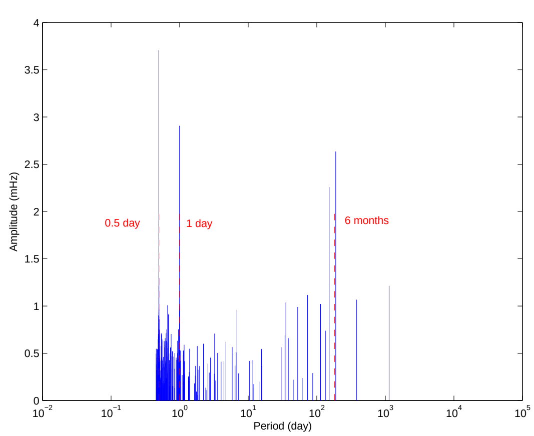

Fig. 1. SparSpec analysis of the residuals from the fit with a constant acceleration.

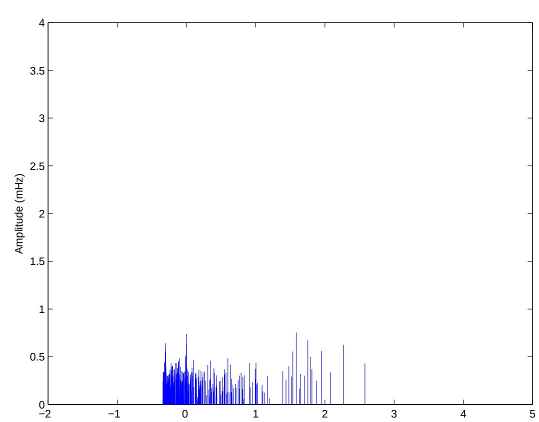

Fig. 2. SparSpec analysis of the residuals from the fit with a constant acceleration and periodic terms.