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THE PIONEER ANOMALY: DATA ANALYSIS AND MISSION PROPOSAL

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Abstract. The Pioneer 10 and 11 spacecrafts show an anomalous Sun-ward acceleration with a nearly constant value.
This paper reports the work of the french teams which have formed the Groupe Anomalie Pioneer (GAP) to study this anomaly.
A new orbit determination software has been developped which has already led to an independant confirmation of the existence of an anomaly.
Missions have been proposed in the framework of the ESA Cosmic Vision process. The mission named Odyssey aims at testing General Relativity at heliocentric distances up to 50 AU.
The principle of the test is to compare the range using DSN techniques to the prediction of General Relativity.
A crucial instrument is the accelerometer embarked on board to measure the non geodesic acceleration and account for it in the navigation software.

1 Introduction

The Pioneer 10 and 11 spacecrafts were launched on March 2, 1972 and April 5, 1973.
Their goal was to explore the solar system beyond Mars orbit with Pioneer 10 going to Jupiter and Pioneer 11 going to Saturn.
Since their rendezvous with the giant planets the two spacecraft have followed escape orbits to opposite ends of the solar system with roughly the same speed which is now about 12 km/s.
The Pioneer Anomaly refers to the fact that their trajectories observed through Doppler tracking by the NASA Deep Space Network (DSN) do not meet the expectations drawn from standard gravitation theory. 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 $(8.74\pm1.33)10^{-10}\mathrm{ms}^{-2}$ for the two spacecraft (Anderson et al. 2002).
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 inability to explain the anomalous behavior of the Pioneer spacecraft with conventional physics has motivated an interest in proposing new space missions aimed at testing General Relativity at large scale and especially at the distance where the anomaly was first observed, that is beyond the Saturn orbit.
Several French laboratories have formed the Groupe Anomalie Pioneer (GAP) to study the various aspects of the Pioneer Anomaly. In particular, Laboratoire Kastler Brossel (LKB), Observatoire de la Côte d'Azur (OCA) and Office National de Recherche Aéronautique et Spatiale (ONERA) have set up a collaboration for performing a new analysis of the Doppler data set used by the JPL team (Anderson et al. 2002). The objective of the new analysis is to confirm (or not) the existence of the anomaly, using different and as independent as possible tools, and then, if possible, to get more information in order to better characterize it. Data types available for analysis are the original ODF, used in 2002 analysis and provided by JPL, and also the ATDF which can be found on the NASA web site. After a rapid description of these data types, this article will present the orbit determination software that has been developed at OCA and discuss the first results obtained with it. In a last part of this article, the ODYSSEY mission general profile and payload will be described.

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2 Description of the data files

2.1 Measurement principle

The measurement principle for the Pioneer mission is the following: deep space spacecraft are tracked from Deep Space Network (DSN) stations on ground. The DSN frequency and timing system generates a 5 MHz and 10 MHz reference frequency which is then sent through the local area network to the Digitally Controlled Oscillator (DCO). Then this signal is multiplied by the DCO and transformed into a Track Synthesizer Frequency (TSF) of about 22 MHz. Then the Exciter Assembly multiplies the TSF by the factor 96 to produce the S-band carrier signal at about 2.2 GHz. This S-band frequency is sent to the antenna where it is amplified and transmitted to the spacecraft at the time t_1. The signal is received by the spacecraft at the time t_2. Onboard the spacecraft, a transponder multiplies the received frequency by a constant ratio of 240/221 and sends it back to Earth where it is received at time t_3 by the same or another DSN station. The observable is the frequency integrated over a given compression time which is obtained from the measured Doppler counts.

2.2 ATDF

Archival Tracking Data File (ATDF) are binary files which can be read thanks to the Trk-2-25 document. They contain the reception time t_3, the emitted frequency at the time t_3, the detection antenna identifier, the Doppler count and the compression time (elapsed time between two Doppler count). The difference between two successive Doppler count divided by the compression time is an averaged frequency. Data are available for Pioneer 10 from 1987 to 1989 and from 1992 to 1994.

2.3 ODF

Orbit Data Files (ODF) are derived from ATDF through a complex process. They can be read thanks to the Trk-2-18 document. They contain the reception time t_3, the reference frequency, the detection and emission antenna identifier, the compression time and the ODF observable. This observable corresponds to the Doppler shift that is to say the difference between the received and emitted frequencies, averaged on the compression time. The availabe ODF are one file for Pioneer 10 from 1987 to 1998 and one file for Pioneer 11 from 1986 to 1990.

3 The orbit determination software

3.1 General description

In order to analyse the data, an orbital simulation software has been developped at OCA in collaboration with ONERA. The name of the software ODYSSEY stands for Orbit Determination and phYsical Studies in the Solar Environment Yonder. The software performs the following operations.

- Numerical integration of dynamical and variational equations in rectangular coordinates,
- Extrapolation of trajectories in the solar system,
- Estimation of initial conditions and physical parameters when using tracking data (Doppler or range) by iterative least squares method.

The dynamical model contains gravity from Sun and planets, solar radiation, manoeuvers and anomalous accelerations.

The measure function implemented is the Doppler observable corresponding to ATDF or ODF observable and the range (useful only for future missions). The Shapiro delay is taken into account and a model of tropospheric and ionospheric effects is implemented.

3.2 Anomaly models

Several models are implemented which could account for the recorded anomaly on the measure. A first model corresponds to a constant acceleration:

$$\vec{a} = a_0 * \begin{cases} \vec{u}_{\text{Sun/sat}} \\ \vec{u}_{\text{Earth/sat}} \end{cases}$$

it can be extended to an acceleration varying quadratically with respect to time to modelise the effect of a gas leak:

$$\vec{a} = (a_0 + a_1 * t + a_2 * t^2) * \begin{cases} \vec{u}_{\text{Sun/sat}} \\ \vec{u}_{\text{Earth/sat}} \end{cases}$$

we have also implemented a modulated acceleration:

$$\vec{a} = (a_0 * \cos \omega t + b_0 * \sin \omega t) * \begin{cases} \vec{u}_{\text{Sun/sat}} \\ \vec{u}_{\text{Earth/sat}} \end{cases}$$

as well as a modulated perturbation on the measure:

$$\Delta f = (a_0 * \cos \omega t + b_0 * \sin \omega t)$$

For a given model, the best values of the parameters are estimated by the software. For the modulated models, the frequency ω is fixed by the user and the amplitudes a_0, b_0 can be estimated.

4 Results

4.1 Results with ATDF data and ODF data

We first present the results obtained with the ODYSSEY software and ATDF data. The figure (figs. 1) shows the residuals - ATDF observable computed by ODYSSEY minus the measured one - obtained after the estimation of some parameters.

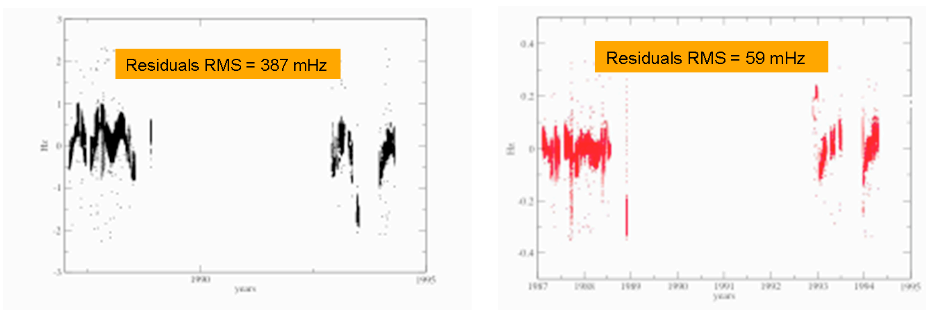

Fig. 1. On the left: residuals with Pioneer 10 ATDF when only the initial conditions are fitted; on the right: residuals when the manoeuvers' amplitudes are also fitted

In the figure 2 a constant anomalous acceleration is also estimated; The results are presented for ATDF and ODF and found to be quite similar with the two data types.

These results are still preliminary but they enable us to give an independent confirmation of the existence of an anomaly. A constant acceleration reduce the residuals on ATDF and ODF data. Our estimations of the anomalous acceleration $(8.4{\pm}0.03)10^{-10}\text{ms}^{-2}$ for ATDF and $(8.35{\pm}0.02)10^{-10}\text{ms}^{-2}$ for the ODF are quite close to the JPL value reported above. It has to be noted that the JPL uncertainty $1.33\ 10^{-10}\text{ms}^{-2}$ corresponds to the systematics generated outside the spacecraft, onboard it, and to the computational systematics. In contrast, our uncertainty $0.02\ 10^{-10}\text{ms}^{-2}$ corresponds only to the accuracy of the best fit estimation.
Different possibilities have been tested for the direction of the anomaly : the direction has no effects on the residuals or the fitted value of the anomaly.

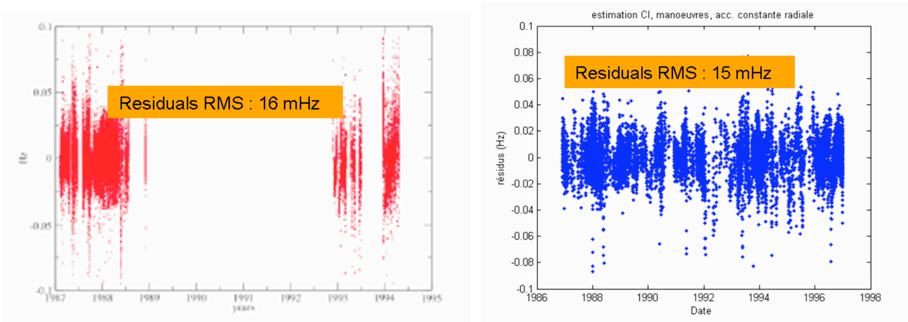

Fig. 2. On the left: residuals with Pioneer 10 ATDF when the initial conditions, the maneuvers and a constant acceleration are fitted. On the right: same estimation but with Pioneer 10 ODF

4.2 Following steps

These results enable us to confirm independently from JPL the existence of an anomaly which can be considered as a constant acceleration on both ATDF and ODF data.

Table 1. Value of the fitted Anomalous acceleration

Aderson et al.: Pioneer 10 ODF	GAP: Pioneer 10 ODF	GAP: Pioneer 10 ATDF
$8.74\ 10^{-10}\mathrm{ms}^{-2}$	$8.35\ 10^{-10}\mathrm{ms}^{-2}$	$8.4\ 10^{-10}\mathrm{ms}^{-2}$

Other independant confirmations of the existence of an anomaly have been obtained by C. Markwardt (2002) and O. Olsen (2007).

Our next steps will be to implement a solar coronna model and to improve of the tropospheric and ionospheric models. We will undertake a study of the modulated models discussed above with the aim of reaching a better characterisation of the nature of the anomaly. We will also compare these empirical models with available physical theories which predict the existence of some Pioneer Anomaly. In particular, we will test the metric extensions to General Relativity (Jaekel and Reynaud 2006).

5 The Odyssey space mission

5.1 Scientific goals

The Solar System Odyssey mission has been proposed in the class M (cost at completion $<$ 300 Meuros) of the ESA Cosmic Vision process (Christophe et al. 2007). It has been designed with four major scientific objectives testing different aspects of gravitation in the solar system. These objectives address the test of deep space gravity, the investigation of planetary fly-bys, a new test of General Relativity at solar conjunctions and a mapping of the gravity field in the outer regions of the solar system. They are achieved thanks to the presence onboard of radio-science and VLBI instruments giving unambiguous information on the position of the spacecraft. Laser ranging is also considered as an option. A crucial feature of the proposal is an accelerometer measuring the non gravitationnal forces experienced by the spacecraft. Its presence is mandatory to determine whether or not the observed anomaly has a gravitational origin. As the energy collected by the solar panels will be insufficient after 13 AU, the spacecraft also contains a radio-beacon with a small Radioisotope Thermoelectric Generator (RTG) enabling the mission to go to distances up to 50-80 AU. The scientific requirements are summarized in the following table:

Table 2. Scientific objectives

Instruments	Deep space gravity	Fly-by investigation	Solar conjunctions	Outer solar system
Accelerometer Radio science VLBI Laser ranging	$\lvert\delta a\rvert < 40\,\mathrm{pm/s}^2$ (3-axes) up to 13 AU	$\lvert\delta \Delta V\rvert < 10\,\mu\mathrm{m/s}$ (3-axes)	Largely better than Cassini $\lvert\delta\gamma\rvert < 10^{-7}$	-
Radio beacon with VLBI	$\lvert\delta a\rvert < 8\,\mathrm{pm/s}^2$ (3-axes) from 10 AU	-	-	$\lvert\delta a\rvert <$ a few pm/s^2

5.2 Mission profile

The different steps of the mission will be : beginning of the mission at 1 AU ; extinction of the laser ranging at 7.5 AU ; release of the radio-beacon planned to happen at 10 AU ; end of the mission for the mothercraft expected at 13 AU ; end of the mission for the radio-beacon expected at 50-80 AU.
The spacecraft will be launched by VEGA on a low Earth orbit. Earth escape will be achieved by means of a bi-propellant propulsion module based on the Astrium Eurostar/LisaPathfinder propulsion module series. For the apogee raising sequence, lunar gravity assist is considered to increase escape performance. After Earth escape, one possibility for the trajectory is to have the following fly-bys : Earth-Mars-Earth-Earth-Jupiter-Saturn. This would mean a launch date in 2017. The different, fly-bys which will be analysed, will put the spacecraft on a highly energetic trajectory toward the outer solar system. The time span to reach Saturn is 7 years.

5.3 Spacecraft design

The design of the spacecraft with its payload is sketched on fig. 3. The total mass of the spacecraft with the radio-beacon is planned to be 422 Kg. The solar panels are designed to provide 56 W at 13 AU. Concerning the attitude control, the spacecraft will be 3-axis stabilized up to 7.5 AU with reaction wheels and then spin stabilized in order to decrease the power consumption.

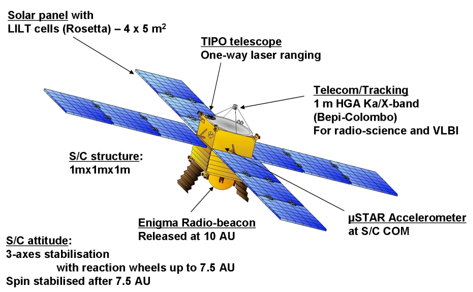

Fig. 3. Spacecraft for the ODYSSEY mission

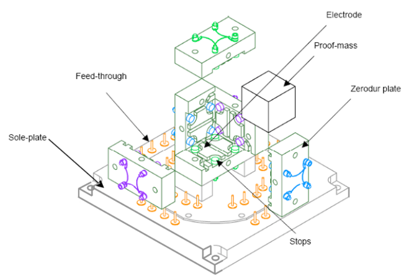

Fig. 4. Mechanical core of the μstar accelerometer

5.4 μSTAR accelerometer

The accelerometer package is composed of an electrostatic accelerometer (fig. 4), with its electronics and a bias calibration system. The core of the instrument is an electrostatic accelerometer based on ONERA expertise in the field of accelerometry and gravimetry (CHAMP, GRACE, GOCE missions). Ready-to-fly technology is used with original improvements aimed at reducing power consumption, size and weight. The ONERA electrostatic accelerometers are accurate enough but the problem is their bias of about $10^{-6}\mathrm{ms}^{-2}$. As this is too large, calibration methods are being considered to measure the bias on board. The bias calibration system consists in a flip mechanism which allows a 180° rotation of the accelerometer to be carried out at regularly spaced times. The flip allows the calibration of the instrument bias along two directions, by comparing the acceleration measurement in the two positions. The instrument can thus measure all the non gravitational forces with an accuracy of 4 10^{-11}ms^{-2} which is largely sufficient to confirm (or not) the presence of an anomaly at the Pioneer level of 8 10^{-10}ms^{-2}.

6 Conclusion

The existence of the Pioneer anomaly has been confirmed by our independent analysis on the ODF as well as ATDF data.
To characterise this anomaly some empirical models have been implemented and are currently being tested.
A physical model corresponding to metric extensions of General Relativity is also being explored.
A new investigation of gravity at the large distances where the Pioneer Anomaly has been detected appears to be necessary.
This is why new space missions have been proposed at ESA during the Cosmic Vision process. The ODYSSEY concept mainly based on radio-science and accelerometer allows one to have this ambitious objective made compatible with the budgets of a class M mission.

7 Acknowledgement

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