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## THE PIONEER ANOMALY : DATA ANALYSIS AND MISSION PROPOSAL

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**Abstract.** The Pioneer 10 and 11 spacecraft are subject to an unexplained acceleration which has a constant value of  $(8.74 \pm 1.33)10^{-10} \text{ms}^{-2}$  and seems to be directed toward the Sun. In 2006, five french laboratories formed the Groupe Anomalie Pioneer (GAP) in order to analyse a set of the Doppler data received from the Pioneer spacecraft. To perform this analysis, a specific orbit determination software has been developed which lead to the independant confirmation of the existence of an anomaly. This software has also been developed to study some aspects of the anomaly : nature, direction... This Pioneer anomaly which may be seen as challenging General Relativity has motivated an interest in flying new probes to the distances where the anomaly was first discovered, that is beyond the Saturn orbit, and studying gravity with modern techniques. A mission named Odyssey has been proposed for the ESA Cosmic Vision 2015-2025. The mission has the objective to verify General Relativity up to 50 AU. The main tracking observable is the range measured between Earth Deep Space Network stations. The principle of the test is to compare this measured value to the prediction of General Relativity. The motion of the probe is calculated by a navigation software with the non geodesic acceleration provided by an accelerometer.

### 1 Introduction

The Pioneer 10 and 11 spacecraft were launched on March 2, 1972 and April 5, 1973. Their goal was to help us explore the solar system beyond Mars orbit with Pioneer 10 going to Jupiter and Pioneer 11 going to Saturn. After these two planetary rendezvous the two spacecraft followed orbits to opposite ends of the solar system with roughly the same speed which is now about  $12 \text{kms}^{-1}$ . Furthermore, it is of note that Pioneer 10 and Pioneer 11 are identical in design. The Pioneer Anomaly refers to their deviations from the expected trajectories as first observed via Doppler radio signals by Jet Propulsion Laboratory (JPL). The deviation is a constant sunward acceleration whose magnitude is  $(8.74 \pm 1.33)10^{-10} \text{ms}^{-2}$  for both spacecraft (Anderson et al. 2002). An international collaboration was built, within the frame of International Space Science Institute (ISSI), in order to analyse the Pioneer data. In this frame, five French laboratories formed the Groupe Anomalie Pioneer (GAP) to study all the aspect of this anomaly. Concerning the Doppler data, Laboratoire Kastler Brossel (LKB), Observatoire de la Côte d'Azur (OCA) and Office National de Recherche Aéronautique et Spatiale (ONERA) performed, through a great collaboration, a new analysis of the data presented in 2002. The objective of the analysis was to confirm or not its existence, by analysing the same data set as JPL, but with different tools and then to possibly characterise it. The type of data that were available for analysis was the original ODF, used in 2002 analysis, and gently provided by JPL and also the ATDF which could be found on the NASA internet site; these data will be described in the first part of this article. The second part of this article will be dedicated to the specific orbit determination software that was developed at the OCA in order to analyse the data. The results obtained will then be detailed. The inability to explain the anomalous behavior of the Pioneer spacecraft with conventional physics has motivated an interest in proposing a new space mission aimed at verifying General Relativity at large scale and especially to the distance where the anomaly was first noticed, that is beyond the Saturn orbit. The mission general profile and payload will be described in the last part of this article.

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## 2 Description of the data files

### 2.1 Measurement principle

The measurement principle for the Pioneer mission is the following : The ground stations employed to track interplanetary spacecraft belong to the Deep Space Network (DSN). 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 then the signal is re-emitted to Earth. At time  $t_3$  a ground station receives the downlink frequency. Actually, frequency are average frequency defined as the number of cycles or Doppler counts per unit times. What is measured is the Doppler count.

### 2.2 ATDF

ATDF are Archival Tracking Data File. They 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. The available data concern Pioneer 10 from 1987 to 1991.

### 2.3 ODF

ODF are Orbit Data Files. They were based on ATDF. They are binary files which 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. We know that the ODF observable has been computed using the following formula and the Doppler counts.

$$Observable = (B/|B|) * [(N_j - N_i)/(t_j - t_i) - |F_b + B|]$$

where:

B = Bias placed on receiver

$N_j$  = Doppler count at time  $t_j$

$N_i$  = Doppler count at time  $t_i$

$[t_i ; t_j]$  = compression interval

$F_b$  = frequency bias

$$F_b = (240/221) * (96 * F_r) - F_{sc} \text{ for 1 way data}$$

$$F_b = (240/221) * (96 * F_r) - (240/221) * (96 * F_t) \text{ for 2 and 3 way data}$$

where :

$F_r$  = Receiver frequency at reception time

$F_{sc}$  = Spacecraft frequency

$F_t$  = Transmitter frequency at emission time

This observable corresponds to the Doppler shift that is to say the difference between the received frequency on the ground and the emitted frequency, averaged on the compression time. Therefore this observable is modulated by the annual and daily movement of the Earth. The available 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 previously described data, an orbital simulation software has been developed at the OCA in collaboration with ONERA. The software is named ODYSSEY which stands for Orbit Determination and phYsical Studies in the Solar Environment Yonder. ODYSSEY performs:

- 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 consists of: gravity from Sun and planets, solar radiation, manoeuvres and anomalous accelerations. The measure function implemented is the Doppler observable corresponding to ATDF or ODF observable and the range (for future missions). To compute the measure function, the Shapiro delay is taken into account and a model of tropospheric and ionospheric effects is implemented.

#### 3.2 Anomaly models

The anomaly models may be as well anomalous acceleration as a perturbation on the measure. The models of anomalous acceleration are :

Constant acceleration :

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

Quadratic acceleration with respect to time to modelise a gas leak:

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

Modulated acceleration :

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

A modulated perturbation on the measure is also implemented :

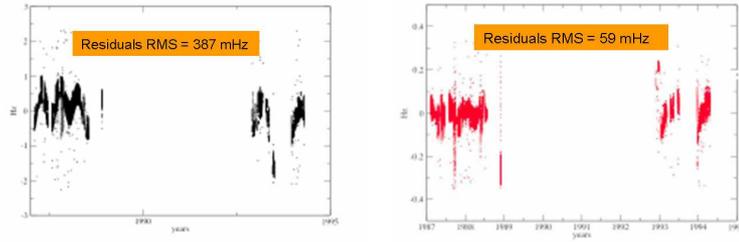
$$\Delta f = (a_0 * \cos \omega t + b_0 * \sin \omega t)$$

To test a model, the values of its parameters are estimated. For the modulated model, the frequency  $\omega$  has to be fixed by the user;  $a_0$  and  $b_0$  are estimated. Several anomaly models may be simultaneously estimated.

## 4 Results

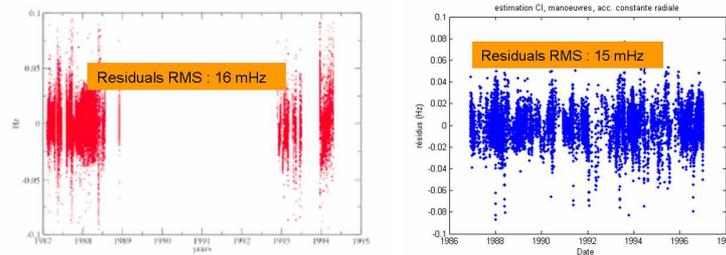
#### 4.1 Results with ATDF data and ODF data

Here are the results obtained with the ODYSSEY software and ATDF data. The following figures (figs. 1) show the residuals between the theoretical ATDF observable computed by ODYSSEY and 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 manoeuvres' amplitudes are also fitted

In the figure 2 a constant anomalous acceleration is also estimated; the results are quite similar for ATDF and ODF.



**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

We infer that an anomalous term is necessary to reduce the residuals. The estimated value of the anomalous acceleration is  $(8.4 \pm 0.03)10^{-10} \text{ms}^{-2}$  for ATDF and  $(8.35 \pm 0.02)10^{-10} \text{ms}^{-2}$  for the ODF which is quite close to the JPL value of  $(8.74 \pm 1.33)10^{-10} \text{ms}^{-2}$ . It should be noted that in the JPL value  $1.33 \cdot 10^{-10} \text{ms}^{-2}$  corresponds to the uncertainties on the systematics generated external to the spacecraft, the onboard generated systematics and the computational systematics while for the GAP value  $0.02 \cdot 10^{-10} \text{ms}^{-2}$  only corresponds to the accuracy of the best fit value. The different possibility implemented for the direction of the anomaly have been tested: the direction has no effects on the residuals or the fitted value of the anomaly.

#### 4.2 Following steps

These results enables 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
$8.74 \cdot 10^{-10} \text{ms}^{-2}$	$8.35 \cdot 10^{-10} \text{ms}^{-2}$	$8.4 \cdot 10^{-10} \text{ms}^{-2}$

The following steps consist in the implementation of a solar corona model to take into account its effects on the Doppler signal and the improvement of the tropospheric and ionospheric models. The study will go on with the characterisation of the nature of the anomaly. More tests have to be done with the different empirical models implemented and with the existing physic theories which predict the existence of a Pioneer Anomaly. In particular, the metric extensions to General Relativity (Reynaud and Jaekel 2006) is being tested.

## 5 The Odyssey space mission

### 5.1 Scientific goals

The Solar System Odyssey is a class M mission ( $< 300$  Meuros) which has been proposed to the ESA Cosmic Vision 2015-2025 (Christophe et al. 2007). It is planning to perform different gravitationnal tests in the solar system. Specifically, the mission will achieve four major scientific objectives: test deep space gravity, investigate planetary fly-bys, test General Relativity at solar conjunctions and map gravity in the outer regions of the solar system. This will be possible thanks to the presence onboard of radio-science (for range and VLBI measurement), of laser ranging and of an accelerometer to measure the non gravitationnal forces undergone by the spacecraft. The range and VLBI measurements will make it possible to know unambiguously the position of the spacecraft ; the accelerometer is mandatory to determine whether the origin of the Pioneer Anomaly is gravitationnal or not. As the energy collected by the solar panels will be insufficient after 13 AU, the spacecraft is composed of a mothercraft and a radio-beacon which contain a little RTG which enables the radio-beacon to continue the mission up to 50-80 AU. The scientific requirements are sumerized in the following table:

**Table 2.** Scientific objectives

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

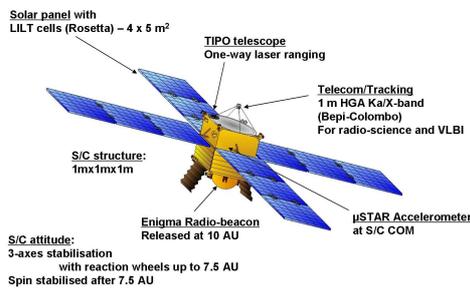
### 5.2 Mission profile

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.

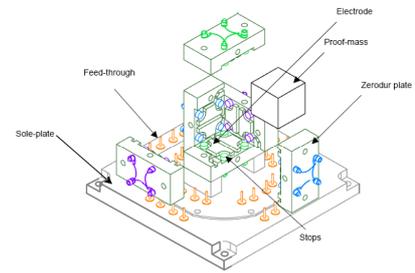
The spacecraft will be launched by VEGA on a low Earth orbit. Earth escape will be achieved by means of a bi-propellant propulsion module based on the Astrium Eurostar/LisaPathfinder propulsion module series. For the apogee raising sequence, lunar gravity assist is considered to increase escape performance. 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

Hereafter is the design of the spacecraft with its payload (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  $\mu$ star accelerometer

#### 5.4 $\mu$ STAR 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 too high bias of about  $10^{-6} \text{ms}^{-2}$ ; that is why calibration methods are being considered to measure the bias on flight. The bias calibration system consists in a flip mechanism which allows a  $180^\circ$  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  $4 \cdot 10^{-11} \text{ms}^{-2}$  which is largely sufficient to confirm/disprove the presence of an anomaly at the Pioneer level of  $8 \cdot 10^{-10} \text{ms}^{-2}$ .

## 6 Conclusion

The existence of an anomaly which can be considered as a constant acceleration has been confirmed with an independant tool from JPL on the ODF data as well as on the ATDF data. To characterise this anomaly some empirical models have already been implemented and are being tested. A physical model corresponding to the theory developed by S. Reynaud and M-T. Jaekel is also being tested; first results are expected soon. Therefore, an investigation of gravity at the distance explored by the Pioneer spacecraft is necessary. The consequence is the proposition of the space mission Odyssey at the ESA Cosmic Vision programme 2015-2025. To test accurately gravity at large scale, there will be a range instrument and an accelerometer onboard the Odyssey spacecraft which are being designed.

## 7 Acknowledgement

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