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TESTING FOR THE PIONEER ANOMALY ON A PLUTO EXPLORATION MISSION

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Abstract

The Doppler-tracking data of the Pioneer 10 and 11 spacecraft show an unmodelled constant acceleration in the direction of the inner Solar System. An overview of the phenomenon, commonly dubbed the Pioneer anomaly, is given and the possibility for an experimental test of the anomaly as a secondary goal of an upcoming space mission is discussed using a putative Pluto orbiter probe as a paradigm.

1 Introduction

The orbit reconstruction from the Doppler tracking data of the hyperbolic trajectory away from the Sun of the Pioneer 10 and 11 probes shows an anomalous deceleration of both spacecraft of the order of $10^{-9}\,\mathrm{m/s^2}$. Even before the Jupiter swing-by, an unmodelled acceleration of that order [2] had been noticed for Pioneer 10. It had however been attributed to gas leaks and a mismodelling of the solar radiation force. Such patterns of explanation became unsatisfactory for the post swing-by hyperbolic arc due to the decrease of the solar radiation pressure inversely proportional to the square of the distance from the Sun and the quiet state of the spacecraft,

Figure 1: View of POP.

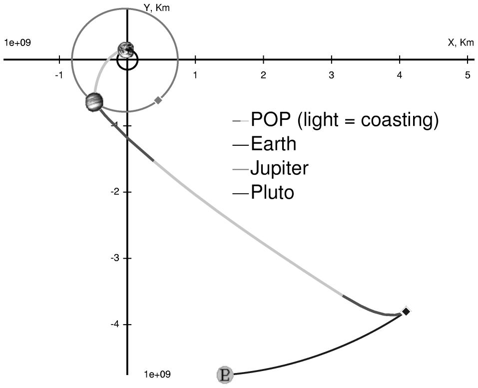

Figure 2: The trajectory of POP.

which should reduce any gas leaks. The anomaly on both probes has been subject to three independent analyses [1, 3]. The result of all investigations is that an anomalous Doppler blueshift is present in the data from both craft of approximately 1.1×10^{-8} Hz/s corresponding to an apparent deceleration of the spacecraft of approximately $8 \times 10^{-10}\,\mathrm{m/s^2}$. From Doppler data alone, it is not possible to distinguish between an anomalous frequency shift of the radio signal or a real deceleration of the spacecraft.

The principle investigators of the anomaly have conducted a thorough investigation of possible biases and concluded that no conventional effect is likely to have caused the anomaly [1]. Meanwhile, there exists an ample body of literature discussing various aspects of possible systematic effects, without definitive conclusion.

Although the Pioneer anomaly (PA) is an effect at the edge of what is detectable with radiometric tracking of a deep-space probe, it is huge in physical terms: The anomaly exceeds the general-relativistic corrections to Newtonian motion by five orders of magnitude (at 50 AU). A gravitational origin of the deceleration of the Pioneer probes is however hard to imagine, since no corresponding anomaly is seen in the orbits of Uranus and Neptune. Hence, a gravitational anomalous deceleration would indicate a violation of the weak equivalence principle.

Considering the efforts that have been undertaken to find a conventional explanation of the PA, it seems likely that only an experiment will finally be able to determine the nature of the effect. A mission to perform an investigation of the PA has to exceed the navigational accuracy of the Pioneers. In particular, the systematic errors in the modelling of onboard generated forces must not exceed a few percent of the Pioneers' anomalous deceleration and the test should take place in the outer part of the Solar system so that external disturbances are minimised.

The spacecraft currently in operation or in design are not capable to fulfil these requirements. Hence, a PA test will have to be performed by a mission which takes into account the experiment already in an early stage of its design process. We discuss in the following how the test requirements can be achieved on a mission which has a test of the PA only as a secondary goal. Considering a non-dedicated mission as a first choice seems reasonable in view of the high cost of a mission to the outer Solar system.

2 The Pluto orbiter probe

To make our considerations about the implementation of a PA test as tangible as possible we consider its realisation onboard of a low-mass, low-thrust mission to Pluto. A study of such a mission has been undertaken recently in ESA's Advanced Concepts Team and detailed results of the system design and trajectory design have been presented in [4].

The goal of the Pluto-orbiter-probe (POP) study was to design a spacecraft that would reach a low circular orbit around Pluto, 1000 km above its surface, using only hardware that will already be space-qualified by the launch date. The capability of entering a Pluto orbit is provided by a nuclear electric propulsion system. The trajectory will incorporate a Jupiter gravity assist. The envisaged launch date is in 2016, arrival at Pluto would be 18 years later in 2034. The spacecraft's wet mass is 837 kg, and the dry mass 516 kg. This would enable a launch with a heavy launcher with an Earth escape velocity of 10 km/s. The science payload will have a mass of 20 kg and will feature a multi-spectral imaging camera, a near-infrared spectrometer, an X-ray spectrometer, a bolometer and the provision to use the communication antenna also as a synthetic-aperture RADAR.

The central part of POP (Fig. 1) is a cylindrical spacecraft bus of 1.85 m length and 1.2 m diameter. The 2.5 m diameter Ka-band (32 GHz) high-gain antenna is located at one end of the bus. The other end of the spacecraft bus houses the propulsion system. It consists of four radioisotope thermoelectric generators (RTG's) on short booms inclined 45° to the axis of the bus, a toroidal tank for the Xenon propellant and the four QinetiQ T5 ion thruster main engines. Attitude control is provided by 10 hollow-cathode thrusters, which use the same power-processing unit and propellant supply as the main engines.

The trajectory of POP (Fig. 2) has a hyperbolic coast phase of 18 AU length before the braking burn for the Pluto orbit capture begins. This coast phase will last 7.4 years. During this time the spacecraft will transverse a radial distance between 13.4 AU and 30.4 AU from the Sun. The mass of POP will then be about 760 kg.

POP is envisaged to employ two different attitude-control modes during different parts of its journey. When the main engines of POP are thrusting and during the swing-by the craft will be three-axis stabilised in order improve pointing accuracy. The same is the case in Pluto orbit where re-orientation requirements demand three-axis control. During long coasts, however, spin stabilisation will be employed. This has the practical benefit of enhancing the lifetime of the momentum wheels and, thus, saves mass. The rotational speed will be very low during the coast, ca. 0.5 rpm, so that attitude acquisition can still be preformed by the star trackers to be used in 3-axis stabilised mode. Hence, no additional attitude acquisition hardware will be necessary during the spinning mode and it can be realised at no additional spacecraft mass. Spin stabilisation during the coast is a crucial factor to enable a test of the PA as it reduces the number of attitude control manoeuvres to one every few weeks and hence minimises onboard generated accelerations.

3 Measurement strategy

With a new mission, the search for a PA-like effect will still rely on radio-tracking. Nevertheless, considerable advances over the precision of the Pioneer data are achievable with present-day telecommunication hardware. The major improvement comes from the use of sequential ranging in addition to Doppler tracking. The information from sequential ranging relies on the group velocity of the signal, whereas the information from Doppler tracking relies on the phase velocity. Sequential ranging is hence insensitive to a gravitational effect on the radio signal, which would be non-dispersive. The usage of both methods allows an anomalous blueshift of the radio signal to be detected which would affect the Doppler signal only. Another advantage of sequential ranging is that it allows a considerably more precise orbit determination than Doppler tracking. Interestingly, Delta differential one-way ranging does not add to the performance of a PA test [5].

For the POP trajectory, the tracking will be precise enough to distinguish between a “drag force” in the direction opposite to the velocity vector, and a force pointing towards the centre of the Solar system. However, despite the high accuracy of tracking techniques, a discrimination between an Earth and Sun pointing deceleration does not seem possible with POP. The distinction would be made by the search for an annual modulation of the Earth-pointing component of the acceleration, revealing that the force on the spacecraft originates from the Sun. For the POP trajectory, the modulation of a Sun-pointing anomaly would be $\lesssim 0.3\%$. Whereas this is still detectable, the modulation is too low to show up in the background noise caused by onboard generated systematics (see next section). Nevertheless the most plausible origins of an anomaly can be discriminated by the combination of Doppler-tracking and sequential ranging because an Earth-pointing anomaly should always be caused by a blueshift and not by an acceleration of the spacecraft.

4 Overcoming systematics

For a new mission the magnitude of the anomaly will in general not coincide with the value from the Pioneer probes but will most likely be influenced by the spacecraft design. Most importantly, the magnitude of the putative anomaly depends on the mass of the satellite for a real acceleration.

For a conventional force, the anomalous acceleration will be inversely proportional to the mass of the satellite, in accordance with Newton's second principle. For POP, which is roughly three times as heavy as the Pioneer probes during the coast, this would reduce a putative anomaly to $3 \times 10^{-10}\,\mathrm{m/s^2}$. A mass dependence should be present for a gravitational force as well, because an explanation in terms of modified gravitation requires a violation of the weak equivalence principle. If the PA is a blueshift of light, the spacecraft mass will not influence the magnitude of the anomaly.

Lacking a conclusive theoretical model of the anomaly, no firm prediction for the magnitude of the anomaly, that one should expect, can be given. Thus the spacecraft design has to reduce acceleration systematics as far as possible or provide means to precisely determine the systematics. With this goal in mind, we review the major potential sources of systematics and how they are controlled on POP.

Fuel leakage is much easier to reduce for an electric propulsion system than a chemical one. The reason is that the propellant for all engines, both main and attitude control, is taken from the same tank through the same pressure regulator. Low leakage rates can easily (and for a moderate mass budget) be achieved by stacking several regulators in a row. In this way the maximal acceleration of POP due to fuel leakage can be reduced to $\sim 0.1\%$ of the PA.

Whereas electric propulsion systems have a considerable advantage concerning fuel leakage, they have the major drawback of requiring high electrical power. For POP, this results in 17,000 W of heat, which has to be dissipated by the radiator fins on the RTG's. Reflection of RTG thermal radiation by the spacecraft bus and antenna will generate a deceleration of $8.5 \times 10^{-10}\,\mathrm{m/s^2}$, the magnitude of the PA. This force can, however, be discriminated from other effects because it will decay with the half-life of the Pu in the RTG's by an amount of 6% during the measurement coast.

The radiation force by the 55 W antenna beam would lead to an acceleration of $2.5 \times 10^{-10}\,\mathrm{m/s^2}$. This force can be controlled by changing the transmission power during the coast and measuring the change in the acceleration of the craft. The reduction in data transmission rate, which accompanies a reduction of the power is not a problem as only a small amount of housekeeping data needs to be sent during the cruise.

The Solar radiation force is less important on POP than it was on the Pioneers and reduces to 1 % of the PA at the end of the coast.

Overall the systematic accelerations of POP can be controlled or modelled to $10^{-11}\,\mathrm{m/s^2}$. With this level of systematics it becomes possible to unambiguously detect an anomalous force or blueshift of PA magnitude.

5 Summary and conclusions

With the current status of our knowledge it would be premature to consider the PA as a manifestation of a new physics. Rather, an incorrectly modelled conventional force seems the most likely origin for the anomaly. Most lines of “explanations” of the PA in terms of “new physics” are not stringent, e. g. it is not at all clear how to circumvent the constraints from planet orbits if a real force is present. Even without a satisfactory model of the anomaly at hand, we found that a test for all currently discussed causes of the PA is possible. The test can be incorporated in a planetary exploration mission to Pluto at practically no cost in launch mass, if the objective of the PA test is taken into account during the design of the spacecraft right from the beginning. Other non-dedicated options for a PA test will be discussed elsewhere [5].

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