PIONEER ANOMALY: WHAT CAN WE LEARN FROM FUTURE PLANETARY EXPLORATION MISSIONS?

Andreas Rathke
EADS Astrium GmbH, Dept. AED41,
88039 Friedrichshafen, Germany.
Email: andreas.rathke@astrium.eads.net

Dario Izzo
ESA Advanced Concepts Team, ESTEC, Keplerlaan 1,
2200 AG Noordwijk, The Netherlands.
Email: dario.izzo@esa.int

The Doppler-tracking data of the Pioneer 10 and 11 spacecraft show an unmodelled constant acceleration in the direction of the inner Solar System. Serious efforts have been undertaken to find a conventional explanation for this effect, all without success at the time of writing. Hence the effect, commonly dubbed the Pioneer anomaly, is attracting considerable attention. Unfortunately, no other space mission has reached the long-term navigation accuracy to yield an independent test of the effect. To fill this gap we discuss strategies for an experimental verification of the anomaly via an upcoming space mission. Emphasis is put on two plausible scenarios: non-dedicated concepts employing either a planetary exploration mission to the outer Solar System or a piggybacked micro-spacecraft to be launched from an exploration spacecraft travelling to Saturn or Jupiter. The study analyses the impact of a Pioneer anomaly test on the system and trajectory design for these two paradigms. Both paradigms are capable of verifying the Pioneer anomaly and determine its magnitude at 10% level. Moreover they can discriminate between the most plausible classes of models of the anomaly. The necessary adaptions of the system and mission design do not impair the planetary exploration goals of the missions.

I. INTRODUCTION

Doppler tracking data of the Pioneer 10 and 11 deep-space probes show a deviation between the orbit reconstruction of the spacecraft and their Doppler tracking signals.[1,2] This discrepancy, that has become known as the Pioneer anomaly, can correspond either to a small constant deceleration of the spacecraft of roughly $9 \times 10^{-10}\,\mathrm{m/s^2}$ or to an anomalous blueshift of the radio signal at a rate of $6 \times 10^{-9}\,\mathrm{Hz/s}$. Since no unambiguous conventional mechanism to explain the anomaly, such as an onboard force, has been identified there is a growing number of studies, which consider an explanation in terms of a novel physical effect.

In April 2004 the European Space Agency (ESA) invited the scientific community to participate in a Call for Themes for Cosmic Vision 2015-2025, to assist in developing the future plans of the Cosmic Vision programme of the ESA Directorate of Science. Among the 32 proposals received in the field of Fundamental Physics, five were proposing a space experiment to investigate the Pioneer anomaly. In its recommendation for the Cosmic Vision programme, the Fundamental Physics Advisory Group (FPAG) of ESA considered these proposals as interesting for further investigation.[3] In view of the controversial discussion still surrounding the effect on the one hand and its high potential relevance for our understanding of the laws of physics on the other hand, the FPAG recommended that ESA should study the possibility to investigate the putative anomaly on board of a non-dedicated exploration mission.

Motivated by this important discussion we provide a preliminary assessment of the capabilities of missions to the outer Solar System to investigate the Pioneer anomaly. We identify two classes of mission that could well represent a future exploration mission. The first class is that of low-mass low-thrust orbiter missions to the outer planets. The second class is that of a heavy, nuclear-reactor powered spacecraft, as formerly proposed by NASA's Prometheus Programme, to explore the giant planets. Within these two paradigms we analyse missions to all planets from Jupiter outward and consider to what extent a verification and characterisation of the Pioneer anomaly is possible. Here we restrict ourselves to an outline of the key issues for a non-dedicated test. For more detailed considerations the reader is refered to the full presentation of our study.[4]

The layout of our considerations is the following: We begin with a review of the Pioneer anomaly in Sec. II. After a description of the observed anomaly in the Pioneer tracking in Sec. II A we turn to the considerations that have been put forward to explain the anomaly and discuss its potential significance for fundamental physics. This review leads us to the formulation of the experimental requirements, that a mission to test the Pioneer anomaly has to fulfil, in Sec. II C. In Sec. II D we discuss the navigational accuracy of present deep-space missions and explain why none of these mission is likely to decide the issue if the Pioneer anomaly is indeed of physical significance. Sec. III turns to the discussion of non-dedicated mission concepts for a test of the Pioneer anomaly. We start by discussing the major design drivers for missions to the outer Solar System in Sec. III A. Then Sec. III B and III C give an overview of the two scenarios that we consider. Sec. III D outlines the necessary design considerations to reduce the systematic accelerations onboard a deep-space probe to a tolerable amount for a test of the Pioneer anomaly. It also summaries the estimated error budget. The measurement strategy for the test is developed in Sec. IV. It is found that the test will have to rely on radio tracking. Consequently we discuss the capabilities of radio tracking in Sec. IV B. Based on the design and mission requirements obtained, the space of trajectory options is explored in Sec. V. This is done separately for the two mission paradigms in Sec. V A and V B. The conclusions of our analysis are summarised in Sec. VI.

II. THE PIONEER ANOMALY

A. The tracking-data anomaly

The Pioneer 10 and 11 spacecraft, launched on 2 March 1972 and 5 April 1973, respectively, were the first to explore the outer Solar System (see Lasher and Dyer[5] for an overview of the Pioneer 10 and 11 missions). Since its Jupiter gravity assist on 4 December 1973 Pioneer 10 is on a hyperbolic coast. Pioneer 11 used a Saturn swingby on 1 September 1979 to reach a hyperbola. The orbit determination for both craft relied entirely on Doppler tracking.

Already before the Jupiter swingby, the orbit reconstruction for Pioneer 10 indicated an unmodelled deceleration of the order of $10^{-9}\,\mathrm{m/s^2}$ as first reported by Null.[6] This effect was, at that time, attributed to on-board generated systematics (i.e. unmodelled behaviours of the spacecraft systems), in particular to fuel leaks. However an unmodelled deceleration remained also during the hyperbolic coast, although the number of attitude-control manoeuvres was reduced to approximately one every five months. Hence fuel leakage, triggered by thruster activity, could no longer be considered as an explanation. Even more surprising, the Doppler tracking of Pioneer 11 also shows an unmodelled deceleration of a similar magnitude.

The anomaly on both probes has been subject to three independent analyses that used different orbit determination programs.[1,2,7] The conclusion of all these investigations was that an anomalous Doppler blueshift is present in the tracking data of both craft, and that the magnitude of the blueshift is approximately 6×10^{-9} Hz/s, corresponding to an apparent deceleration of the spacecraft of approximately $9 \times 10^{-10}\,\mathrm{m/s^2}$. From the Doppler data alone it is not possible to distinguish between an anomalous frequency shift of the radio signal – in conventional terms this could also indicate a drift of the Deep Space Network clocks – and a real deceleration of the spacecraft (cf. Sec. IV B below).

B. Systematics or new physics?

Many attempts[8−−12] have been made to interpret the anomaly as an effect of on-board systematics ranging from fuel leakage to heat radiating from the spacecraft. Unfortunately, the conclusions of the various studies are far from unanimous. In the work of Anderson et al.[2] it is concluded that none of the effects considered is likely to have caused the anomaly. They argue that a heat-generated anomaly would be mainly due to the heat of the radioisotope thermoelectric generators (RTGs), and that this can be excluded because the heat decay from the Plutonium half-life of 87.7 years, would have shown up as a decrease of the deceleration in the longest analysed data interval for Pioneer 10, ranging from January 1987 to July 1998.

They note that gas leaks can be excluded as the cause of the anomalous deceleration, under the sole assumption that the amount of fuel leakage is uncorrelated between Pioneer 10 and 11. However, since both spacecraft designs are identical, two identical gas leaks can ultimately not be excluded.

The inability to explain the Pioneer anomaly with conventional physics has contributed to the growing discussion about its origin. Although the Pioneer anomaly is an effect at the border of what is detectable with radiometric tracking of a deep-space probe, it is huge in physical terms. The anomaly exceeds by five orders of magnitude the corrections to Newtonian motion predicted by general relativity (at 50 AU solar distance). Hence, if the effect is not due to systematics, it would have a considerable impact on our models of fundamental forces, regardless of whether the anomaly was due to a deceleration of the spacecraft or a blueshift of the radio signal.

Several promising models have been put forward to explain the anomaly as a novel physical phenomenon and several papers give an overview of the theoretical aproaches.[2,4,13,14] Up to now all the models to explain the Pioneer anomaly in terms of new physics still have to be considered as incomplete. In view of the current rapid development of the field one can however expect considerable progress in the next few years.

C. Experimental requirements for a new test

From the analysis of the Pioneer tracking data one can deduce the requirements for a new test of the anomaly. For a verification of the anomaly one would need a spacecraft with an acceleration systematics below the magnitude of the anomaly. A long lasting ballistic phase in the trajectory is mandatory so that the search for the anomaly is not overwhelmed by thruster activity. Furthermore since it is unknown if the anomaly is generated by a force or by an anomalous blueshift of the radio signal the experiment has to be sensitive to both possibilities.

These generic requirements may be amended by model dependent requirements stemming from the theoretical analysis of the anomaly. If the anomaly is caused by a modification of the gravitational laws it would require a violation of the weak equivalence principle. The most plausible realisation of this would be via a momentum dependence of the gravitational attraction. To be sensitive to such a "drag force" effect one requires a high radial velocity of the spacecraft with respect to the Sun. This corresponds to a highly eccentric, preferably hyperbolic, trajectory of the spacecraft.

An explicit dependence of the anomalous force on the position of the spacecraft within the Solar System is highly improbable because the trajectories of the two Pioneers are heading away from the Sun in approximately opposite directions and at considerably different inclinations. Thus if such a dependence exists, then it has to be so small as to be undetectable from study of the Pioneer data.

One might want to augment the above requirements for a verification of the anomaly by requirements that would allow a further characterisation of the anomaly. In particular it would be of great interest to test if the anomaly is caused by a force gravitational type, i. e. "new physics", or non-gravitational type, "systematics". Of course an improved acceleration sensitivity of the spacecraft might allow a determination of the force-law that generates the anomaly, e. g. its gradient.

Before we turn to the implementation of high acceleration sensitivity in the design an exploration spacecraft in Sec. III we consider the performance of present deep-space mission for a test of the Pioneer anomaly.

D. Other spacecraft

It stands to reason that if the anomaly detected in the tracking data of the Pioneers, were due to some unknown fundamental physical phenomenon, the anomaly should be observed in the data from other missions as well. For various reasons, up to now no other mission has reached the long-term navigational accuracy of the Pioneer 10 and 11 spacecraft. Here we identify the design characteristics that led to the lower navigational performance of the other past missions to the outer Solar System and discuss the performance expectations for current missions, which have not been designed with a test of the Pioneer anomaly as a (secondary) mission goal. This issue has already been analysed in detail for the Voyager spacecraft and for Galileo, Ulysses and Cassini.[2,15] The basic conclusion is that the 3-axis stabilisation system of the Voyager probes and of Cassini performs so many attitude-control manoeuvres that it is impossible to detect the anomaly on these spacecraft. For Galileo and Ulysses the large systematic errors due to solar radiation pressure and malfunctions of part of the attitude control systems prohibited any reliable result.

Amongst the current missions, ESA's Rosetta mission[16] to the comet Churymov-Gerasimenko has a trajectory to the outer Solar System, that would seem suited for verifying the Pioneer anomaly. The Rosetta trajectory has a long elliptical coast arc from July 2011 to January 2014, during which the distance from the Sun will increase from 4.5 to 5.4 AU. Unfortunately the system design and operations of the spacecraft will not allow a successful test of the Pioneer anomaly. During the coast arc, the Rosetta craft will enter a so-called hibernation mode, when the power generated by the solar arrays drops below a certain value. In this mode the spacecraft will be spin-stabilised with a rotational velocity of approximately 1 rpm. Most on-board instruments, including the attitude control and radio transmission system, will be switched-off. During the hibernation no tracking can be performed, hence the presence of a force can only be inferred from the trajectory evolution between the entry and exit of hibernation. The large $68\,\mathrm{m}^2$ solar arrays on the craft will cause an acceleration bias of approximately $10^{-8}\,\mathrm{m/s}^2$, one order of magnitude larger than the Pioneer anomaly. Since the orientation of the solar arrays during the hibernation phase is not actively maintained, a large uncertainty in the solar radiation force on the spacecraft, $\sim 10^{-9}\,\mathrm{m/s}^2$, will result. Hence both, the large unknown acceleration systematics and the lack of regular tracking passes, will prohibit a test of the anomaly with Rosetta.

Close to the class of exploration missions discussed in this work, is NASA's New Horizons mission.[17] The destination of this mission is Pluto and the launch is scheduled for 2006. Also for this mission no test of the Pioneer anomaly is foreseen. On the contrary, the mission baseline foresees that the spacecraft will be in a spin-stabilised mode with little onboard activity and infrequent tracking passes during most of the journey, similar to Rosetta. In contrast to Rosetta this mode is not required by power constraints and was mainly chosen to increase component lifetime and reduce operation costs. Hence an enhanced tracking of the mission for a test of the Pioneer anomaly would be possible in principle. However doubts remain that a sufficient knowledge of onboard acceleration biases can be achieved to render such a test reliable. The system design of the mission is far from ideal for a test of the Pioneer anomaly. The RTG of New Horizons is directly attached to the spacecraft bus. This design will lead to a considerable back-scattering of RTG heat from the back of the antenna causing a large acceleration bias – most likely one order of magnitude bigger than the Pioneer anomaly – along the spin axis of the spacecraft. The determination of this acceleration bias to sufficient accuracy in order to disentangle it from a putative anomaly would most likely require a purpose made high-accuracy thermal radiation model. The difficulties in the determination of the bias are aggravated by a possible degradation of the surface properties of the RTG and the back of the antenna during the flight. Hence, even with an enhanced tracking coverage, the system design of the New Horizons spacecraft will be a considerable obstacle for any attempt to verify the Pioneer anomaly with this mission.

The inability of various missions to achieve a long-term navigational accuracy comparable to that of Pioneer 10 and 11 demonstrates that both the system design and the trajectory design will need careful consideration to accomplish a test of the Pioneer anomaly. From the failure of Galileo and Ulysses and the deficits of New Horizons it is clear that simply requiring a spin stabilised spacecraft on a mission to the outer Solar System will not be sufficient. Detailed considerations are necessary to reduce the acceleration systematics on the test spacecraft to a sufficient level. In the next section we will turn to the system design challenges posed by a Pioneer anomaly test and we will present design solutions to reduce the acceleration uncertainty that are feasible in non-dedicated scenarios.

III. NON-DEDICATED MISSION CONCEPTS

A. The capabilities of exploration missions

Dedicated missions to verify and characterise the Pioneer anomaly are presently being intensively considered and at least two promising concepts have been identified, that could reach acceleration sensitivities down to $10^{-12}\,\mathrm{m/s}^2$.[18] A non-dedicated mission is not expected to reach the full performance of the dedicated concepts. It has however the major advantage of coming at considerably reduced costs provided a suitable mission can be identified to host the experiment without interfering with the primary mission goals.

We will first consider a class of low-mass, low-thrust missions inspired by the study of a Pluto orbiter probe, POP,[19,20] and demonstrate the feasibility of a Pioneer anomaly test on such a mission. We then consider large spacecraft with electric propulsion powered by nuclear reactors to explore the moons of the giant planets Jupiter and Saturn. One such spacecraft was until recently considered by NASA under the name of Jupiter Icy Moons Orbiter, JIMO. While the large amount of heat radiated from the nuclear reactor on the craft would prohibit a test of the Pioneer anomaly on the main spacecraft, this class of missions could accommodate a small daughter spacecraft of less than 200 kg mass (Compared with the 1500 kg of payload envisaged for JIMO). This spacecraft could then be jettisoned during the approach of the mothercraft to the target planet, and could use the planet for a powered gravity-assist to achieve a ballistic hyperbolic trajectory. The Pioneer anomaly test would then be performed by the daughter spacecraft.

B. The POP spacecraft

Pluto Orbiter Probe (POP) is an advanced spacecraft designed within the Advanced Concepts Team of ESA,[19--22] that is capable of putting a 20 kg payload into a low-altitude Pluto orbit. The preliminary design has a dry mass of 516 kg and a wet mass of 837 kg. The spacecraft is powered by four RTGs. The original mission profile envisages a launch in 2016 and arrival at Pluto after 18 years of travel time, including a Jupiter gravity assist in 2018. A suitable launch vehicle would be an Ariane 5 Initiative 2010. The preliminary design of POP consists of a cylindrical bus, of 1.85 m length and 1.2 m diameter. The 2.5 m diameter Ka-band antenna is mounted on one end of the main structure. The four general-purpose-heat-source (GPHS) RTGs are placed at the other end of the main structure, inclined 45 deg to the symmetry axis of the craft. The 4 QinetiQ T5 main engines are as well placed at this end of the main structure. Next to the main engines in the main structure is the propellant tank accommodating 270 kg of Xenon propellant. POP is a good example of what an advanced spacecraft to the outer Solar System may look like and we therefore take it as a paradigm for this kind of mission.

C. The piggyback micro spacecraft

In the framework of NASA's Prometheus Program, JIMO was proposed by NASA as the first mission to demonstrate the capabilities of electric propulsion powered by a nuclear reactor. The mission, recently cancelled in view of the new NASA priorities, is still a plausible architecture for other future exploration mission. Due to its high payload capabilities, a JIMO type of mission could carry a micro (μ-) spacecraft to test the Pioneer anomaly. The spacecraft would be jettisoned at some point on the trajectory, and put into hyperbolic heliocentric trajectory via a planetary gravity assist. This would allow the spacecraft to perform a Pioneer anomaly test after its swingby.

A possible baseline design for the piggyback spacecraft, resulting from the design-driver of reducing on-board generated systematics, is that of a spin-stabilised craft. A preliminary mass estimate and power budget can be based on the results of ESA's study of an Interstellar Heliopause Probe,[23] which has a similar baseline. The result yields a mass of 150 kg. The spacecraft would use ion thrusters (e. g. hollow-cathode thrusters) for attitude-control, and carry only a minimal scientific payload. Since only a small data rate would be required, a 1.5 m high-gain antenna would be sufficient even in the outer Solar System. The required 80 W of power to operate the payload, the communication subsystem and the attitude control system would be provided by two RTGs weighing 12.5 kg each. Heat pipes from the RTGs to the main structure of the spacecraft would be used for thermal control.

In addition, a chemical propulsion module would be necessary to provide a moderate ΔV before and during the swingby. This propulsion stage would be jettisoned after the swingby, to eliminate the danger that residual fuel might leak from the module and spoil the Pioneer anomaly test. The dry mass of the module is estimated to be 16 kg. A detailed design is beyond the scope of this study. We apply a 20% mass margin and a 20% margin on the required power. Accelerations due to on-board generated systematic errors are inversely proportional to the mass of the spacecraft. Hence for the calculation of the error budget, the conservative estimate will arise from assuming the lower mass for the spacecraft but the higher power consumption.

D. Spacecraft design

From our review of missions to the outer Solar System we saw that a major obstacle for a test of the Pioneer anomaly is a lack of knowledge about the onboard generated forces, which are typically one order of magnitude larger than the Pioneer anomaly (cf. Longuski et al.[24]). The aim of this section is to review possible design solutions to reduce the overall on-board generated systematics to less than $10^{-10}\,\mathrm{m/s^2}$, i. e. less than 10% of the Pioneer anomaly by adopting, at the early design phase, some spacecraft design expedients that do not spoil the planetary-science mission objectives.

From the goal to minimise the uncertainties in conventional accelerations, one can deduce several design requirements for our spacecraft that are summarized in Table I: Spin stabilisation of the spacecraft seems mandatory in order to reduce the number of attitude control manoeuvres of the spacecraft. Furthermore it ensures that all onboard-generated accelerations are pointing along the spin axis of the craft. This effectively eliminates the effect of systematics on the determination of the direction of a putative anomaly. For the exploration scenario spin stabilisation is most practically only chosen during the coast phases of the mission.

An electric propulsion system is the most promising option to reduce the amount of acceleration systematics from propellant leakage, although an electric propulsion system has the disadvantage, that due to its high power consumption it considerably increases the amount of heat generated on board the spacecraft. The major source of asymmetric thermal radiation from the craft are the RTGs. The heat systematics can be constrained to a sufficient degree by monitoring the temperature of the RTGs at 0.1 K level. Furthermore the view factor of the RTGs from the spacecraft bus and the antenna should be made as small as possible in order to reduce radiation back-scattering and simplify the modelling. In order to constrain the systematics induced by the radio transmission beam the transmission power during the measurement phase can be reduced to a few Watts.

While the requirements imposed on the spacecraft make it necessary that the spacecraft is already designed with the goal of testing the Pioneer anomaly under consideration, the modifications suggested come at no increase in launch mass and at no increase in risk. In particular, the goal of testing the Pioneer anomaly is compatible with the constraints of a planetary exploration mission.

Source of acceleration uncertainty	Suggested counter measure
Thrust history uncertainty	Spin stabilisation
Fuel leaks	Electric propulsion
Heat from spacecraft bus	Placement of radiators, spin stabilisation
Heat from RTGs	Reconstruction from monitoring of RTG temperature
RTG helium outgassing	Orientation of pressure relief valves on RTG's
Radio beam force	Low transmission power during test
Solar radiation pressure	Sufficient heliocentric distance

TABLE I: Sources of acceleration uncertainties and possible design solutions.

	POP paradigm Δa $/(10^{-11}\,\frac{\mathrm{m}}{\mathrm{s}^2})$	μ-spacecraft Δa $/(10^{-11}\,\frac{\mathrm{m}}{\mathrm{s}^2})$
Fuel leaks	0.4	0.2
Heat from bus	1.0	1.0
Heat from RTG	2.8	1.4
RTG helium outgassing	2.7	2.0
Radio beam	0.5	2.2
Solar radiation pressure	$149\,(\frac{R_\oplus}{r})^2$	$268\,(\frac{R_\oplus}{r})^2$
Total	$7.4+$ $149\,(\frac{R_\oplus}{r})^2$	$6.8+$ $268\,(\frac{R_\oplus}{r})^2$

TABLE II: Acceleration uncertainties for the two mission paradigms.

For the major acceleration uncertainties the numerical values, that were found achieveable in the study[4] by the above design solutions, are given in Table II. The sources of acceleration, which were identified are uncorrelated – at least to the level of the modelling performed – and the overall acceleration due to systematics is therefore bounded by the value $\Delta a = \sum_i \Delta a_i$. This returns $\Delta a = [7.4 + 149\,(R_\oplus/r)^2] \times 10^{-11}\mathrm{m/s}^2$ for the exploration mission and $\Delta a = [6.8 + 268\,(R_\oplus/r)^2] \times 10^{-11}\mathrm{m/s}^2$ for the piggyback micro spacecraft, where $R_\oplus$ denotes the Earth orbit's semimajor axis. This would, when sufficiently far from the Sun, allow the determination of the anomaly to a precision of 10 %.

The accuracy to which an anomalous acceleration can be determined will also strongly depend on its direction. Since all error sources will cause an acceleration purely along the spin axis of the spacecraft, they will be competing with an Earth-pointing anomaly, which would most likely be an effect on the radio signal. When studying the capabilities of the mission to discriminate the direction of the anomaly, the systematic errors do not influence the result because their direction does not change and their magnitude has a gradient, which cannot be confused with a direction-dependent modulation.

IV. MEASUREMENT STRATEGIES

A. Instrumentation options

A mission to test the Pioneer anomaly has to provide three types of information. It must monitor the behaviour of the tracking signal for an anomalous blueshift; it must be able to detect an anomalous gravitational force acting on the spacecraft; and it must also be capable of detecting an anomalous non-gravitational force on the spacecraft. From these three tasks it is obvious that radio tracking is the experimental method of choice because it is sensitive to all three of the possible sources of the Pioneer anomaly.

However the orbit reconstruction from radio tracking data does not discriminate between a non-gravitational "systematics" and a gravitational "new physics" origin of the anomaly. Such conclusions can only be drawn from a statistical test of a specific candidate model against the observed deviation from the nominal orbit. Hence a model-independent discrimination between a gravitational and non-gravitational anomaly would be highly desirable. Such a distinction could in principle be accomplished with an accelerometer on board the spacecraft, because deviations of the spacecraft from a geodesic motion will be induced by non-gravitational forces only. Unfortunately the use of accelerometers reaching the sensitivity level of the Pioneer anomaly is excluded by weight constraints: high-precision accelerometer assemblies weigh typically in the order of 100 kg (cf. e. g. ESA's GOCE mission[25]). Concludingly, the discrimination between a gravitational and non-gravitational anomaly will rely on the interpretation of the tracking data.

B. Tracking observables for the Pioneer anomaly test

The suitability of an interplanetary trajectory for a test of the Pioneer anomaly may be influenced by a dependence of the Pioneer anomaly on the orbital parameters of the trajectory, as already discussed in Sec. II C above. The second important criterion for the choice of trajectory is if it enable a precise measurement of the properties of the anomaly. For the purpose of a general survey of trajectory options for a broad class of missions a simulation of the tracking performance for each trajectory becomes unfeasible due to the large computational effort involved. Hence we resort to the opposite route: In this section we derive a linearised tracking model for the anomaly that neglects the back-reaction of the anomaly on the orbital parameters of the trajectory. This model allows to express the performance of the tracking techniques for a specific trajectory as a function of the heliocentric distance of the spacecraft and the flight angle only.

The capabilities of the radio tracking techniques are evaluated by determining after which time a detectable deviation from the trajectory has accumulated. The perturbation on the position vector is well described, for our purposes, by the simple equation

$$\ddot{\mathbf{s}}^* = \mathbf{a}^* \,. \tag{1}$$

where $\mathbf{s}^* = \mathbf{r} - \boldsymbol{\rho}$ is the difference between the position $\mathbf{r}$ of a spacecraft not affected by the anomaly and the position $\boldsymbol{\rho}$ of a spacecraft affected by the anomalous acceleration $\mathbf{a}^*$. In fact we may write the full equation of motion in the form:

$$\ddot{\mathbf{s}}^* + \frac{\mu_\odot}{r^3}\left[\left(\frac{r}{\rho}\right)^3 - 1\right]\mathbf{r} + \mu_\odot \frac{\mathbf{s}^*}{\rho^3} = \mathbf{a}^* \,. \tag{2}$$

Note that this holds also for non-Keplerian $\mathbf{r}$ whenever the non-gravitational modelled forces may be considered state-independent (as is the case for the systematic accelerations considered in Sec. III D). At Jupiter distance, it takes roughly three months for the second and third terms of Eq. (2) to grow within two orders of magnitude of $\mathbf{a}^*$. The smallness of the back-reaction on the orbital parameters is also the reason why it is not possible to decide from the Pioneer Doppler data if the observed anomaly is caused by an effect on the radio signal or a real acceleration.

Without loss of generality we consider our spacecraft as lying in the ecliptic plane. Direct connection to the tracking observations in the geocentric frame, in which the measurements are actually conducted, can be established by projecting the anomalous velocity change and position change onto the Earth–spacecraft vector. The projected anomalous velocity then corresponds to the Doppler observable and the anomalous difference in the Earth–spacecraft distance to the sequential ranging observable. The change in the geocentric angular position of the spacecraft in the sky, $\alpha^*_\oplus$ corresponds to the information obtained by Δ-differential one-way ranging or other differential very large baseline techniques. It is obtained from the component of $\mathbf{s}^*$ perpendicular to the Earth–spacecraft direction through the relation $\alpha^*_\oplus \simeq s^*_\perp / s$. We get

$$v^*_\parallel = |v^*(t_1)| \cos\beta(t_1) - |v^*(t_0)| \cos\beta(t_0) \,, \tag{3}$$

$$s^*_\parallel = |s^*(t_1)| \cos\beta(t_1) - |s^*(t_0)| \cos\beta(t_0) \,, \tag{4}$$

$$\alpha^*_\oplus \simeq \frac{\left[|s^*(t_1)| \sin\beta(t_1) - |s^*(t_0)| \sin\beta(t_0)\right]}{s(t_0)} \,, \tag{5}$$

where β is the angle between the anomaly direction and the Earth–spacecraft vector. The equations (3)–(5) estimate the effect an anomalous acceleration on the tracking observables.

It is convenient to express the angle β as the sum of the angle between $\mathbf{a}^*$ and the Sun–spacecraft vector $\beta_\odot$, and the angle between the Earth–spacecraft vector and the Sun–spacecraft vector $\beta_\oplus$, $\beta = \beta_\odot + \beta_\oplus$. With this decomposition several relevant cases can easily be treated:

- Sun pointing acceleration from a central force, $\beta_\odot \equiv 0$
- Inertially fixed acceleration $\beta_\odot =$ const. This case also yields insights into the case of a drag-force type deceleration along the trajectory because the change of $\beta_\odot(t)$ stays typically within the same magnitude as that of $\beta_\oplus(t)$.
- A blueshift of light. It leads only to a change of the *apparent* velocity along the line of sight of the spacecraft, $v^*_\parallel$, but not of the position, i. e. $\mathbf{s}^* \equiv 0$. From the direction of the effect we have immediately $\beta \equiv 0$.

Both the rate of change $\dot{\beta}_\odot$ and the angle $\beta_\oplus$ are small quantities for trajectories in the outer Solar System. Hence analytical expressions for $\cos\beta$ and $\sin\beta$ are conveniently obtained by expanding β around the angle at the begin of the tracking interval $\beta(t_0)$ in the quantities $\dot{\beta}_\odot$ and the mean motion of the Earth. After these steps the magnitude of the anomalous contributions to the tracking observables in the above cases of special interest depends on the heliocentric distance r and the direction of the anomaly in the heliocentric frame $\beta_\odot$, only.

Expressions analogous to Eqs. (3)–(5) and the expansions described above hold for the systematic acceleration uncertainties. Combining the expressions for the effect of the anomaly and the systematic accelerations, one can determine the sensitivity of a tracking technique to one of the three generic classes of the Pioneer anomaly.

The result is that sequential ranging is capable of distinguishing between the candidate directions of the anomaly for heliocentric distances beyond Pluto if $\beta_\odot$ is not too small. Doppler and very large baseline techniques are inferior in performance. However the additional use of Doppler tracking is mandatory since it is the only technique that is sensitive to a blueshift of the radio signal. For a drag-force type anomaly one would have $\beta_\odot = 90\,\mathrm{deg} - \gamma$, where γ is the flight angle. Hence in order to be able to discriminate between a drag force and a central force γ must no be too large. Consequently in the next section we require $\gamma < 75\,\mathrm{deg}$ for the trajectory design.

V. TRAJECTORY DESIGN

A. Orbiter missions to Pluto, Neptune and Uranus

The Cosmic-Vision Programme of the European Space Agency refers to the decade 2015-2025. Hence this timespan will be used as a baseline launch date for the trajectories, that we consider. Missions to Pluto, Neptune and Uranus are discussed separately from those to Jupiter and Saturn, as the distances of the former planets allow for a Pioneer anomaly test to be conducted by the exploration spacecraft during its long trip. For the latter two targets one has to resort to using a special μ-spacecraft piggybacked to the exploration spacecraft (cf. Sec. III C).

In this section we discuss the possibility of using putative exploration missions to Pluto, Neptune and Uranus to perform the Pioneer anomaly test. Since the scientific return of a planetary flyby is quite limited and has already been exploited in several past interplanetary missions we will consider *orbiter* missions exploiting Nuclear Electric Propulsion (NEP) for a final orbital capture. The trajectory baseline is that of one sole unpowered gravity-assist around Jupiter. Many trajectory options and missions are of course possible for exploring these far planets but a single Jupiter swingby is probably the most plausible baseline in terms of risk and mission time. The purpose is to show that a Pioneer anomaly test would in general be possible, on these missions, on the vast majority of the possible trajectories. In the considered mission scenario the Pioneer anomaly test would be performed during the ballistic coast phase after Jupiter. A good trajectory from the point of view of the Pioneer anomaly test has the following characteristics (cf. Sec. II C):

- Hyperbolic trajectory.
- Reduced flight angle γ (we will allow at maximum 75 deg) during the test (allowing easy distinction between the velocity direction and the spacecraft–Earth direction).
- Long ballistic phase.
- Large Sun–spacecraft–Earth angle during the test (allowing distinction between the Earth direction and the Sun direction).

We briefly touch upon the implications of these requirements. From standard astrodynamics we know that along a Keplerian trajectory we have the following relation for the flight angle $\cos\gamma = \sqrt{p}/(r\sqrt{2/r - 1/a})$, where p is the semilatus rectum and a the semi-major axis of the spacecraft orbit. It is therefore possible to evaluate the flight angle γ at any distance from the Sun by knowing the Keplerian osculating elements along the trajectory after Jupiter. In particular we note that highly-energetic orbits (i. e. fast transfers) lead to larger values of the angle γ. This leads to prefer a slower transfer orbit. However, a low velocity results also in a longer trip and might cause a smaller value of the anomaly. The requirement on the length of the ballistic arc (an issue for orbiter mission baselines) also tends to increase the transfer time. In fact the on-board propulsion (assumed to be some form of low thrust) could start to brake the spacecraft much later in a slower trajectory (the square of the hyperbolic velocity, C3, at arrival on a Lambert arc gets smaller in these missions for longer transfer times). To have a large Sun–spacecraft–Earth angle during the test phase implies that the test has to start as soon as possible after the Jupiter swingby not allowing for a long thrust phase immediately after the swingby as would be required by optimising some highly constrained trajectory for low-thrust orbiter missions.

To assess the impact of the requirements on the trajectory design we conduct a multi-objective optimisation of an Earth-Jupiter-Planet flyby mission assuming pure ballistic arcs and an unpowered swingby. We evaluate the solutions using the Paretian notion of optimality, that is, a solution is considered as optimal if no other solution is better with respect to at least one of the objectives. We optimise the C3 at Earth departure as well as the mission duration (as discussed this parameter is directly related to the flight angle γ and to the ballistic arc length). The Earth departure date t_e, the Jupiter swingby date t_j, and the Planet arrival date t_p were the decision variables, the departure date being constrained to be within the Cosmic Vision launch window, and the arrival date being forced to lie before 2100.

The optimisation was performed using a beta version of DiGMO[26] (Distributed Global Multi-objective Optimiser), a tool being developed within the European Space Agency by the Advanced Concepts Team. The software is able to perform distributed multi-objective optimisations with a self-learning allocation strategy for the client tasks. Differential evolution[27] was used as a global optimisation algorithm to build the Pareto sets. Constraints were placed on the Jupiter swingby altitude ($r_p > 600,000\,\mathrm{km}$). Planet ephemerides were JPL DE405.

Target Planet	Departure Date	Mission Duration / years	Departure C3 / (km^2/s^2)
Pluto	2015-Nov	17-27	89-88
Pluto	2016-Dec	11-15	92-100
Neptune	2018-Jan	14-40	74-75
Neptune	2019-Feb	10-12	90-95
Uranus	2020-March	9	81
Uranus	2021-April	7	96
Uranus	(2015-2016)-Dec	12-14	79
Uranus	(2015-2016)-Dec	28-33	79

TABLE III: Pareto-optimal launch windows for missions to the various outer planets in the considered decade.

Each of the trajectories belonging to the Pareto fronts might be modified to allow an orbiter mission. Starting from one of the trajectories of the Pareto-Front, if the launcher is able to provide all the C3 that is required and we do not apply heavy constraints, the optimal trajectory will be ballistic up to the very last phase, and a braking manoeuvre would start just before the arrival to the planet. If the problem is more constrained, for example if we add a departure C3 upper limit, then the ion engines would need to be fired also before and after Jupiter. The firing immediately after Jupiter is necessary to assure that the planet orbit is reached at the right time (this was the case for the POP trajectory to Pluto[19]). In this case a Pioneer anomaly test would return less scientific data because the thrusting phases could not be used for the characterisation of the putative anomaly. Adding a constraint not to use the engines immediately after Jupiter, on the other hand, would introduce an increase in the propellant mass needed due to the late trajectory correction. This would hardly be accepted by the system designers, and the Pioneer anomaly test would anyway be possible during the subsequent coast phase of several years.

The resulting launch windows, mission durations and C3s are displayed in Table III. All the Pareto optimal missions feature a coast arc of several years after the Jupiter swingby. With the exception of some very fast Pluto transfers their flight angles are low enough during the whole coast to allow a discrimination between the candidate directions of the anomaly. We may conclude that any trajectory of a flyby or of an orbiter mission to the outer planets Pluto, Neptune and Uranus is likely to be suitable for a Pioneer anomaly test with no modifications, meaning that the three main requirements discussed would be fulfilled during a trajectory arc long enough to gain significant insight into the anomaly.

B. μ-spacecraft on Jupiter and Saturn missions

A different situation occurs if we try to test the Pioneer anomaly by exploiting a putative mission to Jupiter or Saturn. In these cases the proximity of the planets to the Sun and the likely low energy of the transfer orbit would not allow for the test to be performed during the travel to the planet. A possible solution is that of designing a piggyback μ-spacecraft to be added as a payload to the main mission. As a guideline for the mother-spacecraft trajectory, we consider the JIMO baseline and perform an optimisation of a 2016 launch opportunity. This was done to obtain information on the switching structure of the thrust so that possible strategies of jettisoning could be envisaged. The thrust is considered to be fixed and equal to 2 N for a spacecraft weighing 18000 kg. Final conditions at Jupiter do not take into account its sphere of influence. The optimised trajectory (visualised in Fig. 1) foresees a June 2016 injection into a zero C3 heliocentric trajectory and a rendezvous with Jupiter in May 2023. We demand that the μ-spacecraft secondary mission does not affect the mothercraft trajectory, optimised for the main mission goals. A feasible solution is a spacecraft detaching from the mother spacecraft at the border of the arrival-planet's sphere of influence, navigating towards a powered swingby of the target planet, and putting itself autonomously into a hyperbola of as high as possible energy. We assume that the μ-spacecraft is at the border of Jupiter's sphere of influence with zero C3. The gravity assist has to allow it to gain enough energy to have, in the heliocentric frame, a hyperbolic trajectory. We also allow for a non-zero flight angle γ at Jupiter. Under the assumption of a tangential burn at the periapsis

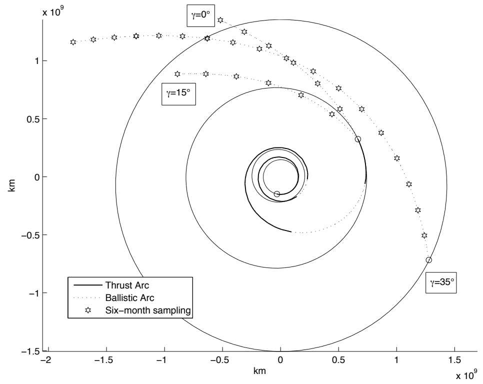

FIG. 1: Piggyback micro spacecraft trajectory options.

we find for the required ΔV the expression

$$\Delta V = \sqrt{V_P^2(3 - 2\sqrt{2}\cos\gamma) + 2\frac{\mu_P}{r_p}} - \sqrt{2\frac{\mu_P}{r_p}}. \quad (6)$$

Here V_P is the heliocentric velocity of the planet, μ_P its gravitational parameter and r_p the pericentre of the hyperbolas. Once the required ΔV is obtained from Eq. (6) it is easy to work out the ratio between the propellant mass and the spacecraft dry mass using the Tsiolkovsky equation. Assuming the use of chemical propulsion for the powered gravity-assist ($I_{sp} = 260\,\mathrm{s}$) and putting a constraint on the gravity assist altitude of $600,000\,\mathrm{km}$ in the Jupiter case and $40,000\,\mathrm{km}$ in the Saturn case, one finds the ΔV and fuel-to-dry-mass ratio in dependence of the flight angle as displayed in Table IV. Due to the high pericentre and the greater velocity of the planet, the Jupiter case requires a higher propellant mass.

Target	γ / deg	0	15	30	45	60
Jupiter	ΔV / (km/s)	.7	1.1	2.2	3.8	5.8
	$\Delta M/M_0$	.32	.53	1.3	3.5	8.9
Saturn	ΔV / (km/s)	.17	.27	.55	1	1.6
	$\Delta M/M_0$	.071	.11	.24	.48	.86

TABLE IV: μ-spacecraft thrust requirements

As a consequence, the same spacecraft designed for a $|\gamma| = 15\,\mathrm{deg}$ Jupiter case is capable, in the Saturn scenario, to go into a $|\gamma| = 35\,\mathrm{deg}$ trajectory. Figure 1 displays example hyperbolic trajectories that first go to decreasing heliocentric distances and have good performances with respect to the Pioneer anomaly test. They allow for long periods, in which the direction of the anomaly could be precisely measured, since the modulations in the tracking signal due to the motion of the Earth, which enable the determination of the direction of the anomaly, are enhanced for low heliocentric distances.

VI. CONCLUSIONS

We have considered two plausible mission architectures for the exploration of the outer Solar System that may also be used to test the Pioneer anomaly. Firstly a class of low-mass low-thrust missions to Pluto, Neptune or Uranus. For this mission type the Pioneer anomaly investigation can be performed by radio-tracking of the exploration spacecraft. The other mission paradigm considered is that of a μ-spacecraft piggybacked on a large nuclear-reactor-powered spacecraft sent to explore Jupiter or Saturn. The small spacecraft would be jettisoned from the mother spacecraft on the approach to its destination, would use the target planet of the mother spacecraft for a powered swingby, and subsequently performs the Pioneer anomaly investigation by radio tracking on a hyperbolic coast arc. Starting from a review of our knowledge of the effect, we have derived a set of minimal requirements for the spacecraft design and trajectory.

For both mission paradigms the detection of the anomaly is found to be possible during the whole measurement phase, which extends over several years. On-board systematics would still limit the precision in the determination of the magnitude of the anomaly to approximately 10%. This does not seem much of an improvement compared to the 15% error margin of the original determination from Pioneer 10 and 11 tracking data. However by suitable system-design solutions a non-dedicated test would be able to rule out the last candidate onboard sources of the anomaly. Furthermore a simple upper limit on the flight angle for the trajectories enables the discrimination between the most plausible classes of candidate models for the anomaly. The attainable acceleration sensitivity of $\sim 8 \times 10^{-11}\,\mathrm{m/s^2}$ will be insufficient for a precise characterisation of the anomaly. In particular, a slope of the anomaly would most likely only be determined to the first order – if at all. This would hardly be sufficient to determine unambiguously the physical law that might underlie the Pioneer anomaly. Hence the quality of the scientific return of non-dedicated missions cannot compete with a dedicated mission, for which acceleration sensitivities down to $10^{-12}\,\mathrm{m/s^2}$ would be attainable. In view of the ongoing controversial discussion about the origin of the Pioneer anomaly and the extraordinary costs of a dedicated deep-space mission to the outer Solar System it seems however more appropriate to consider the more modest approach of using a non-dedicated mission to verify if the Pioneer anomaly is indeed an indication of a novel physical effect.

[1] Anderson, J. D., Laing, P. A., Lau, E. L., Liu, A. S., Nieto, M. M., and Turyshev, S. G., "Indication, from Pioneer 10/11, Galileo, and Ulysses data, of an apparent anomalous, weak, long-range acceleration," *Physical Review Letters*, Vol. 81, 1998, pp. 2858–2861, http://arxiv.org/abs/gr-qc/9808081.

[2] Anderson, J. D., Laing, P. A., Lau, E. L., Liu, A. S., Nieto, M. M., and Turyshev, S. G., "Study of the anomalous acceleration of Pioneer 10 and 11," *Phys. Rev.*, Vol. D65, 2002, pp. 082004–1–082004–50, http://arxiv.org/abs/gr-qc/0104064.

[3] European Space Agency Fundamental Physics Advisory Group, "Recommendation on the 'Cosmic Vision' Programme," Tech. Rep. FPAG(2004)10, European Space Agency, 2004.

[4] Rathke, A. and Izzo, D., "Options for a non-dedicated test of the Pioneer anomaly," 2005, http://arxiv.org/abs/astro-ph/0504634.

[5] Lasher, L. and Dyer, J., "Pioneer Missions," *Encyclopedia of Astronomy and Astrophysics*, edited by P. Murdin, Institute of Physics Publishing, Bristol, UK, 2002, http://eaa.iop.org/abstract/0333750888/2187.

[6] Null, G. W., "Gravity field of Jupiter and its satellites from Pioneer 10 and Pioneer 11 tracking data," *Astronomical Journal*, Vol. 81, 1976, pp. 1153–1161.

[7] Markwardt, C. B., "Independent confirmation of the Pioneer 10 anomalous acceleration," 2002, http://arxiv.org/abs/gr-qc/0208046.

[8] Katz, J. I., "Comment on "Indication, from Pioneer 10/11, Galileo, and Ulysses data, of an apparent anomalous, weak, long-range acceleration"," *Physical Review Letters*, Vol. 83, 1999, pp. 1892, http://arxiv.org/abs/gr-qc/9809070.

[9] Murphy, E. M., "A prosaic explanation for the anomalous accelerations seen in distant spacecraft," *Physical Review Letters*, Vol. 83, 1999, pp. 1890, http://arxiv.org/abs/gr-qc/9810015.

[10] Scheffer, L. K., "Conventional forces can explain the anomalous acceleration of Pioneer 10," *Physical Review*, Vol. D67, 2003, pp. 084021–1–084021–11, http://arxiv.org/abs/gr-qc/0107092.

[11] Anderson, J. D., Laing, P. A., Lau, E. L., Nieto, M. M., and Turyshev, S. G., "The search for a standard explanation of the Pioneer anomaly," *Modern Physics Letters*, Vol. A17, 2002, pp. 875–886, http://arxiv.org/abs/gr-qc/0107022.

[12] Anderson, J. D. and Mashhoon, B., "Pioneer anomaly and the helicity-rotation coupling," *Physics Letters*, Vol. A315, 2003, pp. 199–202, http://arxiv.org/abs/gr-qc/0306024.

[13] Bertolami, O. and Paramos, J., "The Pioneer anomaly in a bimetric theory of gravity on the brane," *Classical and Quantum Gravity*, Vol. 21, 2004, pp. 3309–3321, http://arxiv.org/abs/gr-qc/0310101.

[14] Defrere, D. and Rathke, A., "Pioneer anomaly: What can we learn from LISA?" 2005, http://arxiv.org/abs/gr-qc/0509021.

[15] Nieto, M. M. and Turyshev, S. G., "Finding the origin of the Pioneer anomaly," *Classical and Quantum Gravity*, Vol. 21, 2004, pp. 4005–4024.

[16] Verdant, M. and Schwehm, G. H., "The international Rosetta mission," *ESA Bulletin*, Vol. 93, Feb. 2002, pp. 12–24.

[17] Stern, A. and Spencer, J., "New Horizons: The first reconnaissance mission to bodies in the Kuiper belt," *Earth, Moon and Planets*, Vol. 92, 2003, pp. 477–482.

[18] Dittus, H. et al., "A mission to explore the Pioneer anomaly," *39th ESLAB Symposium: Trends in Space Science and Cosmic Vision 2020, Noordwijk, The Netherlands*, Apr. 2005, http://arxiv.org/abs/gr-qc/0506139.

[19] Bondo, T., Walker, R., Willig, A., Rathke, A., Izzo, D., and Ayre, M., "Preliminary design of an advanced mission to Pluto," *24th International Symposium on Space Technology and Science, Miyazaki, Japan*, June 2004, ISTS 2004-r-49.

[20] Rathke, A., "Testing for the Pioneer anomaly on a Pluto exploration mission," *International Workshop on Frontier Science: Physics and Astrophysics in Space*, Jun. 2004, http://arxiv.org/abs/astro-ph/0409373.

[21] Vasile, M., Summerer, L., Linder, N., Saive, G., and Silvestri, C., "Advanced trajectory options for the exploration of the outer Solar System," *24th International Symposium on Space Technology and Science, Miyazaki, Japan*, June 2004, ISTS 2004-k-10.

[22] Izzo, D., Bevilacqua, R., and Valente, C., "Optimal large reorientation manoeuvre of a spinning gyrostat," *6th Cranfield Conference on Dynamics and Control of Systems and Structures in Space: 2004*, 2004, pp. 607–616.

[23] Lyngvi, A., Falkner, P., Kemble, S., Leipold, M., and Peacock, A., "The Interstellar Heliopause Probe," *55th International Astronautical Congress – Vancouver, Canada*, Oct. 2004, IAC-04-Q.2.A.06.

[24] Longuski, J., Todd, R., and König, W., "A survey of nongravitational forces and space environmental torques with applications to the Galileo spacecraft," *Journal of Guidance and Control*, Vol. 15, No. 3, 1982, pp. 545–553.

[25] Mui, D. and Allasio, A., "GOCE: the first core Earth explorer of ESA's Earth observation programm," *Acta Astronautica*, Vol. 54, 2003, pp. 167–175.

[26] Izzo, D., Markot, M. C., and Nann, I., "A distributed global optimiser applied to the design of a constellation performing radio-occultation measurements," *AAS/AIAA Space Flight Mechanics Con-*

ference, Jan. 2005, AAS 05-150.

[27] Storn, R. and Price, K., "Differential evolution - a simple efficient heuristic for global optimisation over continuous space," *Journal of Global Optimisation*, Vol. 11, 1997, pp. 341–359.