ISTS 2004-k-10

PRELIMINARY DESIGN OF AN ADVANCED MISSION TO PLUTO

Torsten Bondo, Roger Walker, Andrew Willig*, Andreas Rathke, Dario Izzo and Mark Ayre

ESA/ESTEC Advanced Concepts Team,
*ESA/ESTEC Earth Observation Department
Keplerlaan 1 2200 AZ, Nordwijk ZH, The Netherlands
www.esa.int/act
(E-mail: torsten.bondo@esa.int, roger.walker@esa.int)

Abstract
A technology assessment and feasibility study is being performed within the ESA Advanced Concepts Team on sending a small-to-medium (700-900 kg) Nuclear Electric Propulsion spacecraft into orbit around Pluto with a mission launch in 2016 using existing or emerging space technology. The objective of the study is to examine which technologies are needed to achieve this objective and to understand how current technology trends can modify this scenario in the future.

It is found that a feasible mission, that includes a pioneer anomaly test on the cruise phase, can be accomplished if technologies such as gridded ion engines coupled to multiple Radioisotope Thermal Generators, composite structures and miniaturised avionics/payload are considered.

1. Introduction

Currently most of our knowledge about Pluto and its moon Charon comes from indirect clues. No spacecraft has ever visited either of them, and from the Earth the angular size of Pluto is close to the resolving limit of the most capable ground and space-based observatories. However, there is consensus in the scientific community that a mission to the Pluto-Charon system will considerably increase our knowledge of the formation and evolution of the Solar System as well as the origin of volatiles and organic molecules that enabled the appearance of life on our own planet.

The New Horizons mission with planned launch in 2006 will perform a quick fly-by (10-13 km/s) of the Pluto-Charon system in 2015 and continue on to encounter a KBO (Kuiber Belt Object) [1]. This mission indeed promises great scientific return. However, the image mapping of Pluto and Charon would naturally be improved if the fly-by could occur at a smaller relative velocity or if the spacecraft could go into orbit around the Pluto/Charon system. Furthermore, an orbiting spacecraft would not only increase the surface coverage and resolution substantially, but also allow for detailed investigation of atmosphere composition and dust particles.

From a technological point of view, inserting a probe in orbit around such a distant planet at a reasonable propellant expenditure poses considerable challenges in terms of all aspects of system engineering.

In this paper we present a system engineering study of POP (Pluto Orbiter Probe) a spacecraft of 830 kg that requires ~1 kW of nuclear power to feed its electric propulsion system. The preliminary spacecraft system design, example payload and overall mission design is presented in detail. This includes a low thrust capture at Pluto and spiral down to low altitude orbit via Charon. Furthermore it is pointed out that at no cost in ΔV tracking data on the coast phase towards Pluto can investigate the anomalous deceleration reported from Pioneer 10 and 11.

2. POP Mission Analysis - Cruise Phase and orbit insertion at Pluto

For a spacecraft below 1000 kg a direct transfer to Pluto requires C3 values of over 200 km^2/s^2 [2]. Since no current launcher is able to provide this C3, a gravity assist manoeuvre at Jupiter can be used to lower the C3 requirements for the launcher. The proposed launch date of 17-Dec-2016 is within the next launch window to Jupiter and imposes a C3 capability of 100 km^2/s^2 for the launcher for a direct insertion of a S/C mass of up to 900 kg. This can be achieved with an Ariane 5 initiative 2010 launcher that is expected to be available at 2015 [2]. Other existing launchers can also provide this capability.

The gravity assist will take place on 29-Jun-18 at a distance of approx 540.000 km from Jupiter, followed by an approx 15 year transfer phase until Pluto's Sphere of influence is reached at 03-Jun-33 (see Fig 1). The propellant mass required for the transfer is 220 kg, which is mainly used to accelerate POP after Jupiter swing-by and decelerate it to approach Pluto's sphere of influence with a low relative velocity of 200 m/s.

The final orbit insertion phase from the Sphere of influence (see Fig 1) includes a low-thrust capture of the spacecraft into an initial orbit around Pluto using electric propulsion and subsequent spiral down to a final low altitude orbit for surface imaging science operations[1].

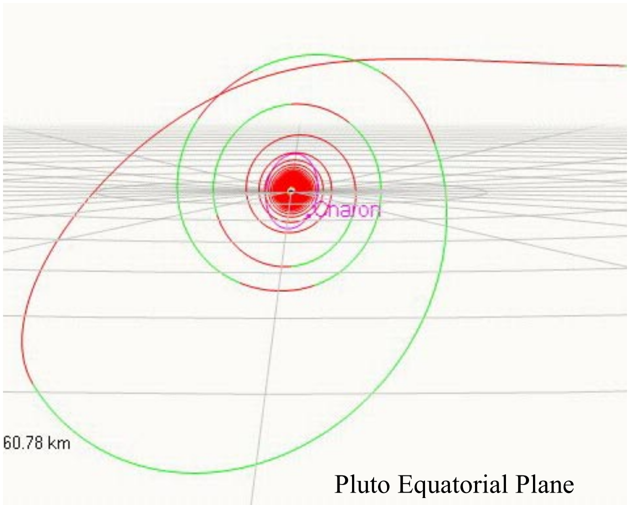
[1] The trajectory optimization has been performed by DITAN [2] for the cruise phase and STK's Astrogator for the orbit insertion phase. The effect of Charon has been included in the model of the capture

Approach periapsis and start time of the insertion burn were varied in order to assess the resulting semi-major axis and eccentricity. Generally, it was found that periapsis could be lowered to 50,000 km. Below this value, progressively higher elliptical capture orbits were observed, which was undesirable for spiral down time. Above this value, higher semi-major axis values were obtained leading to longer initial orbital periods and extended time to spiral down. Likewise, capture burn initiation before or after 200,000 km radius on approach resulted in higher eccentricity capture orbits. Hence, these conditions were considered the best to satisfy the objective of minimising capture semi-major axis and eccentricity. Additionally, it was found that small burns of the order of a few days well in advance of periapsis could be used to target a wide range of variation in the orbit plane of the capture orbit.

3. POP payload and viewing strategy

It is assumed that even a limited payload mass value of approximately 20 kg is sufficient to meet a significant part of the scientific requirements. This should be achievable even with current technology considering the heritage of other planetary exploration missions like SMART-1 [3]. The payload and viewing strategy has not been a driving factor in the present study since the focus is on trajectory and system design. Nevertheless a strategy has been outlined to get important estimates on the requirements posed by the payload on the other subsystems.

The instrument payload is shown in Table 1, and is based upon a measurement strategy that operates in two phases, Pluto approach and Pluto orbit.



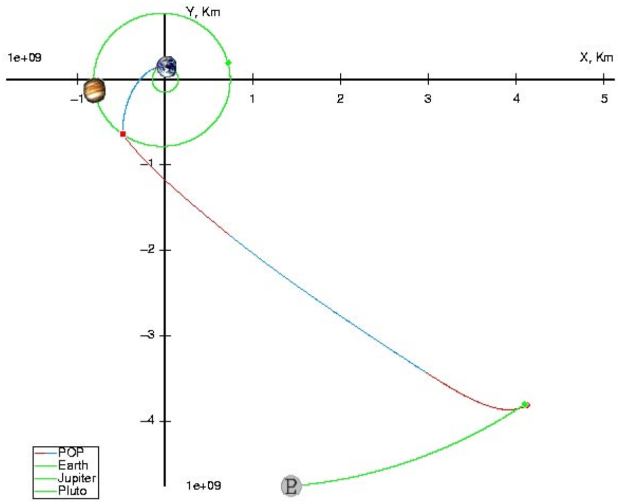


Fig 1. Left. Spiral down and Orbit Capture around Pluto. Thrust Phase: red. Coast phase: green. Approach from 1.5 Mkm. Right: Cruise phase to Pluto including Jupiter swing-by. Launch Dec 2016 Gravity assist date June 2018. Arrival at Pluto's Sphere of influence June 2033. Thrust Phase: red. Coast phase: blue.

Overall, starting at 1.5 million km from Pluto on approach, the whole capture orbit and spiral down process (including a close approach of Charon) to the final 1000 km altitude imaging orbit was attained after 316 days using only 11 kg of Xe propellant. This was deemed to be within the mission duration and mass budget constraints imposed.

The desired final orbit for POP was chosen according to the primary imaging requirements and optimal illumination conditions of the planets surface. In practical terms, this meant a 1000km altitude circular orbit for maximum image resolution and a solar aspect angle of 22.5° wrt. The orbit plane (analogous to a 10:30 polar orbit in Earth orbit for obtaining shadow from surface topography. The orbital parameters for the final target orbit were:

a = 2150 km, e = 0.001, i = 99°, Ω = 127 °, ω = 0°, θ = 20°, P = 328 minwhere a is semi major axis, e, eccentricity, Ω Ascending node, ω argument of perihelion, θ true anomaly, P orbit period

In the approach phase Doppler tracking must provide exact positioning during final approach and orbit insertion. During this period the multi spectral imaging camera (VISCAM) will operate in Mode 1 (Staring) to produce observational imagery of Pluto and Charon. The Near Infrared Spectrometer (NIS) and radiation counter may also be used during this period for initial data acquisitions. Finally, wide area bolometry of Pluto and possibly Charon will be collected.

Once in orbit the first goal is to establish as precisely as possible the satellite orbit around Pluto using Doppler techniques. Once the orbit has a nominal definition, Radar Science will establish an initial Geoid for Pluto, and VISCAM will operate in MODE 2 (push-broom) to provide high-resolution imagery (100 m per pixel at 1000 km altitude) of the visible part of Pluto's surface (due to the orientation of Pluto's North pole, parts of Pluto's surface is in permanent night). During this time it is also proposed to collect bolometry, X-ray spectroscopy, and NIS (if light levels allow).

The collection of VISCAM coverage of Pluto will take around 100 days with 10 day data collection periods where imagery is collected to an optimised coverage schedule, and then followed by a ten day transmission period to Earth.

Once the Pluto Geoid/nominal orbit has been established this allows the Synthetic Aperture Radar (SAR) programme to start. This instrument will provide global mapping (approx 300 days) for Pluto, and will produce a Digital Elevation Model, over which imagery from VISCAM can be draped to enable science data products that clearly illustrate the surface morphology.

The science output of POP should be a Geoid model, global Digital Elevation Model, X-ray characterisation of surface elemental compositions, global surface roughness, high resolution imagery of illuminated side of planet, NIS characterisation of atmospheric species, surface temperature maps and radiation environments.

Instruments	Mass (kg)	Operational Mode
VISCAM (AMIE Camera)	2.2	Mode 1: fully staring system for long exposures. Mode 2: TDI central band on CCD array for push-broom operation.
Near Infrared Spectrometer	4.6	Used to view atmosphere via limb sounding against sun background.
X-ray Spectrometer	3.0	Used to characterise surface types.
Radiation Experiment	1.0	Investigates Pluto's radiation environment.
SAR Electronic Modules (not including antenna)	7.0	Provide high resolution imagery, Pluto geoid, Digital Elevation Model, and possible interferrometric data.
Bolometer	1.5	Provides point measurements of surface temperature for global mapping.

Table 1 Payload Overview

If additional fuel is available (approx 2 kg) it will be possible to spiral up to Charon to increase the coverage and resolution of the initial images taken of Charon.

4. Spacecraft System Design

A trade-off analysis of the subsystems composing the spacecraft has been carried out in order to minimize S/C + propellant mass.

Critical technologies for the POP subsystems have been identified and miniaturized reliable components selected where possible.

In the following sections these trade-offs and selections for each S/C sub system are explained.

4.1 Propulsion and Power

Due to the high ΔV and launcher constraints a fuel efficient and low-mass ion-engine is an excellent choice for a mission to Pluto. In this paper 4 QinetiQ T5 ion engines are considered. The engines are operated in a 2/2 active/redundant configuration using 1 kW of power and producing a thrust of 36 mN with an Isp of 4500 s. The ISP engine performance has been upgraded slightly to include expected improvements in the operating grid voltage over the next few years. This engine is space qualified and has been selected for the future ESA GOCE mission [4] and has lifetime and specific power performances that make it ideal for Deep Space missions. Furthermore, the AOCS (comprising 10 Hollow Cathode Thruster) and the main thrusters use the same propellant and can be operated by same Power Processing Unit which simplifies the S/C configuration and reduces mass.

The total propellant mass budget is 270 kg of Xe. This includes the propellant for AOCS in orbit and cruise and the propellant for spiral down and cruise phase. An additional 15% propellant is added for redundancy. This propellant can be contained in a toroidal tank of 150 litres under ~80 bars of pressure with dimensions that fit in the lower deck of the S/C.

With the lifetime and thermal issues demanded for a Pluto mission the 1kW of power can only be provided by 4 US GPHS RTGs that weigh 56 kg per unit and provide approx 225 Watts after 16 years[2]. The reason for this is that solar power would require large arrays beyond Jupiter and that nuclear reactors are inherently more complex and massive systems that currently cannot operate for periods extending to decades without human intervention.

The current version of US-GPHS RTGs are planned to be phased out in 2008 and be replaced by Stirling Radioisotope Generators (SRGs) and Multi Mission Radioisotope Generators (MMRTGs). These RTGs are currently being tested by the US Department of Energy and NASA [5]. Available data indicate no improvements in their specific power compared to the current ones. Therefore it was sufficient for our purpose to base our analysis on the current RTGs where more data, thermal implications and safety issues are well understood having flown at missions like Cassini/Hyugens and Ulysses.

4.2. Communication and data handling

The proposed TT&C system implements Ka-band technology, which is already used in flying ESA missions like SMART-1 and will be implemented in future ESA missions like BepiColombo. This choice is supported by the fact that already in 2008-2010 ESA

[2] The End Of Life value for the power is calculated by the radioactive decay of Plutonium.

will begin ground station operations with a 35 m Ka-band antenna. For redundancy purposes and to support tracking experiments a X-band system has also been chosen to give a dual-band capability.

The TTC subsystem is therefore based on 2 Deep Space Transponders (DST) and 2 TWTA (50W Tx power for the Ka-band). A 2.5 m High Gain Antenna and 2 Low Gain antenna as well as the Radio Frequency Distribution Unit + other passive components make out the rest of the communication system which has a total mass of 33 kg.

The down link rate from S/C at Pluto to a 35 m ESA ground station using Ka–band (max distance 38.2 AU at arrival) leads to a bit rate of 380 bps using modern coding techniques. The pointing requirements to the antenna for Earth communication at Pluto is ~0.1degree, a value that is significantly higher than the 10 arcsec posed by the payload and therefore easily achievable.

4.3 Thermal design

A steady state thermal analysis has been done by dividing POP into 39 thermal nodes and investigating hot and cold cases. The analysis has drawn general design level conclusions that are summarised below:

First, it seems unlikely that there is a requirement for additional modular heating units to maintain the temperatures of the payload and fuel tanks within an acceptable temperature range. The RTGs produce a very large amount of heat, and intelligent selection of the conductance value between the RTGs and the main spacecraft bus would easily provide enough heat to pass to the rest of the spacecraft.

Second, from a power and thermal perspective there are basically two operating modes – (i) engines on and (ii) engines off. The thermal conductances must then be designed to allow passive maintenance of tank and payload temperatures during thrust periods (through selection of conductive paths to tap waste heat produced by the T5s PPU to maintain tank and payload temperature). During engine off phases the vehicle will either be using the optical payload to map Pluto or SAR mapping Pluto (solar radiation negligible) or transmitting to Earth (antenna as sunshield). In either case there will be a large surplus of electrical power being produced by the RTGs. Use of resisitive shunts located at or near to the RTGs, thermally isolated from the main s/c structure, can be used to convert the electrical energy into thermal energy and dump this excessive heat. The temperature difference that operation of these shunts induces in the RTGs is small (allowing them to stay close to ideal operating temperature), and the analysis suggests there could be problems incorporating these shunts into the T5 PPUs as this is closer to the tank and could cause excessive heating.

Finally, an amount of the unused electrical energy can be diverted to a resistive coil heater integrated with the tank if heating is required – this could be the case when operating the science payload as this produces a comparatively small amount of heat. When the RF payload is operating, heat dissipated from the TWTAs could be directed to maintain the toroidal tank temperature.

4.4 AOCS

The choice of the AOCS subsystem has been driven partly by the payload requirement of a pointing stability of 10 arcsec for 10 sec for imaging and by the test for the Pioneer Anomaly (see section 5) requiring a long coast phase with only rare use of the AOCS thrusters.

3-axis stabilisation is chosen during most parts of the cruise phase and in operation at Pluto. However, on the ballistic part of the cruise, with the antenna pointed towards Earth, a spin-stabilised configuration is chosen with a spin rate of 0.5 rpm.

Due to the lack of disturbances in deep space the speed of rotation could be as low as 0.005 rpm without violating the pointing requirements of the antenna. The higher speed is chosen as a compromise between the wish for a margin in case of the impact of a small body and the requirement to maintain attitude acquisition in spinning mode still using a star tracker instead of the usual star scanner. Due the use of the same attitude acquisition hardware the spinning mode comes essentially at no ΔV. In contrast to this it even saves mass because the momentum wheels will be switched off during the three years of spinning mode and thus their lifetime will be enhanced reducing the level of redundancy required.

Ten Hollow cathode Thruster using Xenon fuel, 4 momentum wheels and 1 gyro make up the AOCS that amounts to 6.4 kg. The total propellant consumption due for 1 years of operations and the cruise and spiral down phase is 2.12 kg.

4.5 POP Mass budget and overview

In table 2 the total mass budget, including subsystem as well as system margins, is presented. The subsystem margins are either 10% or 20% depending on the level of maturity of the technology. Included in the mass budget is the launch margin which is given by the launch capability of 900 kg with a C3 of 100 km^2/s^2 (Ariane 5 launcher initiative 2010).

The mass budget shows that the propellant takes up 32% of the overall mass.

Total Mass Budget	Without Margin kg	Margin %	% of total mass
Structure	65.0	20	9.32
Thermal Control	5.0	20	0.72
Communications	33.0	10	4.34
Data Handling	5.0	10	0.66
AOCS	6.4	10	0.85
Propulsion	88.2	10	11.59
Power	224.0	10	29.44
Harness	10.0	20	1.43
Payload	19.3	10	2.54
Total Dry Mass			510 kg
System Margin			10%
Total Dry Mass with System Margin			560 kg
Total Propellant incl. 15% redundancy			270 kg
Total Wet Mass			830kg
Launch margin			70 kg

Table 2 Mass budget

In Table 3 an overview of POP is provided and in Figure 2 a sketch of the POP S/C is illustrated. The main structure, the thrust tube, is a 1.85m long cylinder with a 1.2m diameter. This thrust tube is divided into an upper observation deck with the RF and payload and a lower deck with the power processing unit for the engine, the fuel tank and where the 4 RTG are mounted with an angle of 45 degrees. This configuration was chosen after a calculation of the radiated heat from the RTG to the antenna showed that operation conditions could be fulfilled. The 4 T5 engines are mounted in the base of the cylinder.

Fig 2 Sketch of POP

Characteristics	Summary
Launch	December 2016 with an Ariane 5 initiative 2010 available 2015. POP wet mass of 830 kg in hyperbola towards Jupiter . Gravity assists takes place in 2018.
Arrival at Pluto	June 2034 after a 1 year long circular spiral down phase. Final orbit circular with an inclination of 99° in 1000 kilometer altitude. Charon visited on spiral-down phase.
Propellant	270 kg Xenon. Stored in toroidal tank with a 154 litre volume.
Propulsion	A 2 active/2 redundant system of QinetiQ T5 carbon-gridded engines.
Power	4 RTGs providing 1.05 kW at Pluto.
TT&C	X-band/Ka-band system with a 2.5 m HGA and 2 LGA. Downlink rate of 380 bps with ESA 35 meter ground station at Ka-band.
AOCS	3-axis during operations and spinning on ballistic part of cruise. Stabilized by 4 momentum wheels, 10 Hollow Cathode Thrusters. 1 gyro, 1 sun sensor and 2 star trackers. Pointing stability 10 arc sec for 10 sec.
Structure	Cylinder - thrust tube 1.85 meter long - 1.2 wide - antenna on top. Composite material thrust tube, CFRP struts, Al/honeycomb panels
Thermal	Passive heating using resistive coil heaters for the tank and shunts for the RTG when excess electrical power must be dumped.
Payload	20 kg multi-band imaging system,spectrometor and SAR experiment.

Table 3 S/C Overview

The POP thrust tube should be made of composite materials and the decking of aluminium honeycomb. It is estimated that a structure of 60 kg (see Table 2) can support the heavy part of the S/C, namely the tank, RTGs and propulsion equipment. The additional 5 kg in the structure budget is from an adaptor ring to mount POP to the launcher adaptor cone and separation device.

5. Pioneer Anomaly

There is a growing interest in the so called Pioneer Anomaly (PA), an unexplained constant deceleration of 0.9 ± 0.1 nm/s^2 observed in the trajectories of the Pioneer 10, Pioneer 11 spacecraft and, less conclusive, in that of Galileo and Ulysses [6]. A thorough investigation of possible conventional causes for the anomaly has yielded no satisfactory explanation. Hence it cannot be excluded that the observed deceleration is due to a new-long range force. In particular the numerical coincidence between the PA and the so-called Hubble acceleration, the acceleration scale related to cosmic expansion, may indicate a connection between the long-range properties of gravitation and the PA. Even if the PA has a more conventional explanation its understanding will be important for the upcoming formation-flying missions like LISA which have increasingly high demands on navigational accuracy. Up to now the suggestions for a verification of the anomaly have focused on dedicated missions [7,8]. This is not a very attractive approach taking into account the exceedingly high costs of space missions and the possibility that the PA might have a trivial explanation. It thus seems worthwhile to consider a non-dedicated alternative. Due to the tiny magnitude of the PA a verification of the effect is only possible in the outer part of the Solar system where the disturbing force of Solar radiation pressure no longer swamps the tracking data.

The long coast arc of 15 AU length between the spacecraft's thrusting after Jupiter swing-by and the thrust deceleration phase in Pluto approach make POP an ideal mission for a PA test. Whereas the acceleration induced by Solar radiation pressure will be below 0.25 nm/s^2 during the whole coast phase and tracking capabilities have reached a level of 0.003 nm/s^2 [8] the high requirements on the knowledge of on-board generated accelerations pose a challenge. A spin stabilization of POP during the cruise phase is mandatory in order to avoid blurring of the acceleration data with the regular unloading of the momentum wheels by AOCS thrusters. The major onboard forces to take into account will be propellant leakage, RTG heat reflected from the back of the antenna and the force generated by the antenna beam.

The effect of Xenon leakage is at least an order of magnitude below the expected PA because the piping system is at only 2 bar pressure resulting in a very low outflow velocity of leaking Xenon. The force from the antenna beam will cause an acceleration of about 0.25 nm/s^2. This effect is however easily separated from a putative PA by changing the transmission power of the communication system during the coast phase and thus determining the acceleration induced by the antenna beam at 5% level or better. This is possible because he data transmission rate required during the coast phase is by far smaller than that required at Pluto. The major systematic problem is the amount of RTG heat reflected from the back of the antenna. This will result in a deceleration of approximately 0.5 nm/s^2 which is hard to model precisely and which can be distinguished from other effects only by its exponential decrease caused by the decay of the Plutonium in the RTGs, which amounts to only 5% during the coast arc.

A detailed discussion of the on-board systematics will be presented elsewhere [9]. The general conclusion is however that a test for the existence of the PA is possible on the POP mission at no cost in ΔV. Even a discrimination between an Earth-pointing deceleration (indicating an error in the tracking system) and a Sun-pointing deceleration (indicating new physics) seems within reach of POP.

6. Conclusion

A feasible system and mission design of a Pluto Orbiter Probe has been produced that includes definitions at subsystem level and the optimisation of the s/c trajectory. The study illustrates that it is feasible as well as scientifically rewarding to send a small spacecraft of a mass of 800-900 kg to orbit Pluto using nuclear electric propulsion methods and miniaturised payload and avionics equipment.

Finally, it has been shown that a verification of the possible new long-range force, the Pioneer Anomaly, can be performed during the coast phase to Pluto adding further scientific value to the mission concept.

Thanks

The authors would like to thank Peter Holsters, Ben Fallis, Robin Biesbroek, Massimiliano Vasile, Gregory Saive, Natascha Linder, Tiziana Pipoli, Leopold Summerer and Andres Galvez.

References

[1] Gou Y., Farquhar W. New Horizons Mission Design for the Pluto-Kupier Belt Mission. AIAA 2002-4722, AIAA/AAS Astrodynamics Specilaist Cenference and Exhibit, 5-8 August 2002, Monterey, California.

[2] Massimiliano Vasile, Robin Biesbroek, Leopold Summerer, Andres Galvez and Gerhard Kminek, Options for a mission to Pluto and beyond, Paper AAS 03-210, 13th AAS/AIAA Space Flight Mechanics Meeting, Ponce, Puerto Rico 9-13 February 2003 AAS Publications Office

[1] A. E. Marini, G. D. Racca, B. H. Foing, "SMART-1 Technology Preparation for Future Planetary Missions",

[4] Lanny G. Thieme and Jeffrey G. Schreiber, NASA GRC Technology Development Project for a Stirling Radioisotope Power System, NASA/TM—2000-210246, Glenn Research Center, Cleveland, Ohio, AIAA–2000–2840

[5] C. H. Edwards, R.J. Blott, Optimisation of the T5 Ion Extraction Grids for the GOCE Application, paper IAC-03-S.4.09, 54th International Astronautical Congress, 29 September - 3 October 2003, Bremen, Germany.

[6] J. D. Anderson, P. A. Laing, E. L. Lau, A. S. Liu, M. M. Nieto and S. G. Turyshev, Study of the anomalous acceleration of Pioneer 10 and 11, Phys. Rev. D 65, 2002, 082004 [gr-qc/0104064].

[7] O. Bertolami, M. Tajmar, Gravity control and possible influence on space propulsion: a scientific study, ESA CR(P)4365 (2002), available at www.esa.int/gsp/ACT/Assets/Fund/gravity_control.pdf

[8] M. M. Nieto, S. G. Turyshev, Finding the origin of the Pioneer anomaly, gr-qc/0308017.

[9] A. Rathke, Testing for the Pioneer anomaly on a Pluto-exploration mission, in: Proceedings of the 3rd international congress on frontier science - physics and astrophysics in space (Rome, June2004), in preparation.