ORBIT DETERMINATION OF THE SMART-1 MISSION

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ABSTRACT

This paper describes the operational orbit determination of the first Small Mission for Advanced Research and Technology, SMART-1, emphasising the experiences gained navigating a spacecraft with solar electric propulsion (SEP).

Since launch, interruptions to planned thrust arcs by unforeseen platform events and both long and short term small variations of the SEP performance have had an impact on the spacecraft navigation. These impacts are discussed and in particular the evolution of the SEP performance throughout the mission and the response of the navigation team is analysed. Finally the operational orbit determination is presented in some detail, including illustrative examples.

1. INTRODUCTION

SMART-1 is the first ESA lunar mission and the first ESA mission whose primary source of propulsion is SEP [1]. It was launched from Kourou into geostationary transfer orbit on 27th September 2003 and is expected to be in lunar orbit on 15th November 2004 after a complex transfer orbit.

The orbit determination requirements of the early part of the mission were relatively modest. The primary function of the orbit team at ESOC has been to ensure accurate enough station pointing predicts and pointing of the SEP motor to allow the mission to proceed and to provide up to date orbital events. For the Lunar resonances currently taking place the navigation demands are greater, nevertheless the challenge of this mission has been that it is a new form of propulsion for ESA and new experience is gained as a result.

After launch the immediate objective was to raise the perigee to 20000 km as quickly as possible to avoid prolonged exposure of the solar arrays to harmful effects of the Earth’s radiation belts. This was achieved with near continuous SEP thrusting except for unavoidable breaks during eclipses and unexpected SEP switch off due to both SEP and platform events [2]. The desired perigee height was reached by the end of January 2004 by which time 26.4 kg of Xenon had been used by the SEP, very close to the expected usage at this point in the mission [3].

Before continuing, a pause in thrusting of around 25 days was inserted to delay the apogee raising phase and hence reduce the length of upcoming eclipses to below an acceptable level. The apogee was then raised to a distance of 230000 km by the middle of august. This has involved SEP thrusting around perigee followed by coast arcs around apogee. During this phase the thrusting arcs were arranged to rotate simultaneously the orbital plane. After this phase of the mission the orbit was prepared for the Lunar resonances.

The three Lunar resonances are about 27 days apart, the first took place on 19th August 2004. Their effect is to raise the perigee and to rotate the orbit both in inclination and argument of perigee with successively increasing effect to help prepare for Lunar capture.

A major issue in the navigation has been the avoidance of thrusting during eclipses. The SEP subsystem consumes a large fraction of platform power (up to 1.4178 kW from a total available of 1.850 kW) and cannot be supported by battery power. In addition battery capacity limits any eclipses to 135 minutes duration for platform loads only.

For orbit determination the main issue has been the SEP performance. Slight variations in the SEP thrust level with respect to the expected value and the behaviour of the thruster on-off times have had a significant impact on orbit predictions. During the perigee raising phase unexpected shut downs were a problem. During the apogee raising phase both long and short term variations in the SEP thrust level have been observed.

2. SMART-1 PROPULSION SYSTEM

SMART-1 is a three axis stabilised spacecraft propelled using a stationary plasma Hall-effect type thruster (PPS-1350-G) developed by SNECMA, primarily for north south station keeping of geostationary satellites. For SMART-1 the thruster design is similar to that on the Stentor spacecraft, with some changes to limit peak inrush power and to be able to operate over a range of power levels [4]. The variable power feature is important for SMART-1 to use efficiently the solar array power over the mission lifetime. Koppel and Estublier describe the SEP flight model for SMART-1 in detail in [5].

The motor’s nominal thrust and mass flow rate are modelled as quadratic polynomials in the SEP nominal power set parameter P_{PPU}, the coefficients of the polynomials being determined before launch during motor ground tests [3]. The value of P_{PPU} can be set to one of

117 levels with a maximum value of 1.4178kW and is used to command the SEP subsystem units to desired thrust and specific impulse values. At maximum power the SEP has a nominal thrust of 70.1 mN. For a spacecraft mass of 350 kg this translates to a nominal acceleration of ca. 0.2 mm/s^2 against the direction of the SEP firing.

SMART-1 angular momentum management can be performed during thrusting using the SEP mechanism. The mechanism is mounted on a gimble and the reaction wheel levels are reduced by the spacecraft autonomously pointing the thruster away from the spacecraft centre of mass thereby inducing a torque on the spacecraft. The attitude of the spacecraft compensates for the motion of the SEP mechanism to ensure the direction of thrusting is as commanded.

Wheel off loading manoeuvres (WOLs) using the hydrazine thrusters were not required in the early phase of the mission because the SEP was on during a large proportion of the orbit. Later in the mission the SEP was thrusting during a smaller proportion of the orbit and hence more WOLs have been necessary, including during SEP firing. Compared to the SEP firing for a few hours the effect of the WOLs (typical ΔV a few mm/s) on the orbit are very small and are not an important issue for orbit determination.

3. ORBIT DETERMINATION SOFTWARE

The orbit determination software used for SMART-1 is based on the AMFIN (Advanced Modular Facility for Interplanetary Navigation) libraries [6] and therefore has much in common with the software used for Rosetta and Mars Express. The AMFIN software has been rigorously cross-verified with respect to JPL software [7]. All three missions use the same main program, which links AMFIN libraries and a single spacecraft specific library. The SMART-1 library selects AMFIN dynamic modelling routines and deals with interfaces with other sub systems to access information on commanded attitude and SEP and WOL manoeuvre accelerations.

4. SEP PERFORMANCE

The SMART-1 SEP system has performed well and as a result the mission is proceeding successfully. SEP performance issues such as deviations in planned thrust arcs and small variations from nominal performance are important to spacecraft navigation and are discussed here.

4.1 Interruptions in SEP

Responding to deviations in planned thrust arcs is an important task performed by the orbit determination team in ensuring the reliability of the orbit predictions produced by flight dynamics. This section describes this in detail.

To date there have been 44 unscheduled SEP shutdowns for a variety of reasons. The main reasons have now been corrected in flight [2]. For example, some unexpected SEP switch-offs originated within the SEP subsystem, mainly during the passage through the Earth's radiation belts. Subsequent analysis and correlation with the 2003 Halloween Solar Flare has shown that these events are related to high-energy proton collisions with a device on the spacecraft called the optocoupler. Such events are known as optocoupler single event transients (OSETs). In early 2004 a software patch was installed on the spacecraft which ensures that if an OSET occurs the SEP motor is autonomously restarted after 30 minutes. Since this time OSETs have a much reduced impact on the spacecraft orbit.

If the star trackers are temporarily unavailable during SEP the spacecraft attitude is controlled by reaction wheel rate integration. This is less accurate than star tracker control and mispointing of the spacecraft can build up as a result. This mispointing results in the spacecraft acceleration deviating from that which is modelled by the manoeuvre optimisation team. If the mispointing grows too large the SEP will switch off.

The SEP off time (and autonomous restart time if applicable) is usually available from telemetry at the next pass.

If the SEP motor burn is interrupted the orbit predictions can be seriously degraded. The normal response to an SEP interruption is that the manoeuvre optimisation team generates a new predicted orbit and acceleration profile including the switch off and restart if appropriate. Thereafter, accurate station pointing predicts and other orbit products can be generated by the orbit determination team.

It is possible that the switch-off time is not available. This could occur if the station pointing predict inaccuracies resulting from the SEP interruption cause the spacecraft signal acquisition to fail at a future pass before telemetry can be downloaded.

This scenario occurred for SMART-1 at the end of November 2003. An interruption to the SEP due to an OSET had occurred during a weekend, the station pointing predicts becoming more and more inaccurate until the station could not acquire the spacecraft the following Monday morning. In this case there was a pass of data available after the OSET. The situation was dealt with by the orbit determination team. A number of trial and error solutions were obtained varying the SEP switch off time and setting all SEP accelerations after this time to zero. The result which best fit the available data arc was chosen and station predicts produced from which the spacecraft signal was immediately acquired. An investigation later discovered and corrected a misunderstanding in the definition of error values given with the pointing predicts which affected the station's search for the spacecraft. The problem has not recurred.

4.2 Variation in Nominal Performance

One of the responsibilities of the orbit determination team is to calibrate the performance of the SEP motor. The calibration results improve the future SEP performance predictions and provide data for analysis of the motor performance.

The manoeuvre optimisation team regularly optimises the SEP thrusting into the future. In these optimisations the nominal acceleration is multiplied by the SEP scale factor k_{SEP}, set to 1 at launch, to obtain the spacecraft SEP acceleration modelled at any given time,

If consistent estimates of the SEP performance are obtained for a period of time then the manoeuvre optimisation team are informed of an update to the value of k_{SEP}. In this way the motor performance used to plan the mission is based on recent SEP performance history.

Under normal circumstances the SEP motor switches on and off at the correct times and the SEP motor is pointed accurately in the nominal direction. Unmodelled small variations in the SEP performance then become the primary source of error for orbit determination and orbit prediction. In the following we distinguish between long and short term variations in the SEP performance.

Long-Term Performance Trends

The thruster exhibits slight variations in performance over its lifetime as part of its normal behaviour. This was seen in long-term data available from pre-launch ground tests.

Based on regular routine orbit determinations, small long-term variations in engine performance have been observed. Fig. 1 shows SEP performance with respect to nominal and the performance applied by manoeuvre optimisation (expressed as a k_{SEP} percentage deviation from unity) from launch until September 2004.

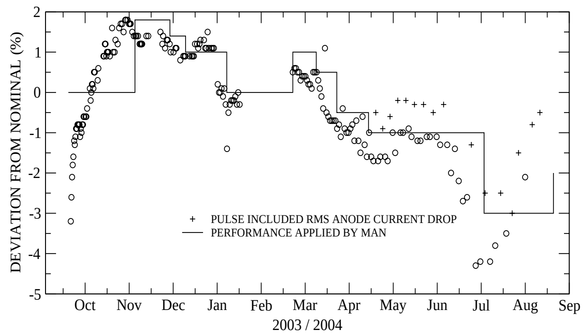

Fig. 1. Long term SEP performance variation.

After some initial variability, early over performance gradually gave way to nominal then small under performances as thruster lifetime increased. A slight increase was noticed after the month long SEP break and then in mid April the behaviour began to exhibit short term variations, referred to in Fig. 1 as 'pulse included rms anode current drop'. These are discussed later.

The k_{SEP} lags behind the performance values due to the fact that the value used by the manoeuvre optimisation team is not changed unless a few orbit determinations show consistent results.

By varying the value of k_{SEP} to keep close to the latest SEP performances, the orbit predictions produced can be improved. However, short-term variability cannot be modelled in this way.

Short Term Performance Variability

From around April 2004 the quality of routine orbit determinations - as observed in post fit residuals - was sometimes seen to vary significantly from solution to solution as the orbit determination window moved forward in time. The residuals would occasionally show a degraded fit and large-scale features. An example of such an orbit determination result is given in section 5.4.

The poor fits seemed to correspond to particular SEP manoeuvres. When the manoeuvre in question was no longer within the data window the fits improved. It was suspected that performance variations within a thrust arc were responsible for this solution degradation.

There is information available from telemetry which is thought to relate to thruster performance. For example the high frequency component of the discharge current between the thruster's anode and cathode (rms anode current). There were indications pre-launch that when the rms anode current is low the thruster performs more efficiently. During the manoeuvres thought to be responsible for the degraded fits, transitions occurred between high and low values of the rms anode current. After this correlation was found a new working practice was introduced into the routine orbit determination. The calibration of the SEP manoeuvres is now performed based on the behaviour of the rms anode current.

In order to take into account performance variations within a single SEP arc, multiple scale factor are estimated for the SEP accelerations whose durations are based on rms anode current plots provided by the flight control team.

An example is given in Fig. 2 where the rms anode current is seen to drop sharply at 21:30 on 10th August and then rise sharply to the original level 12 hours later.

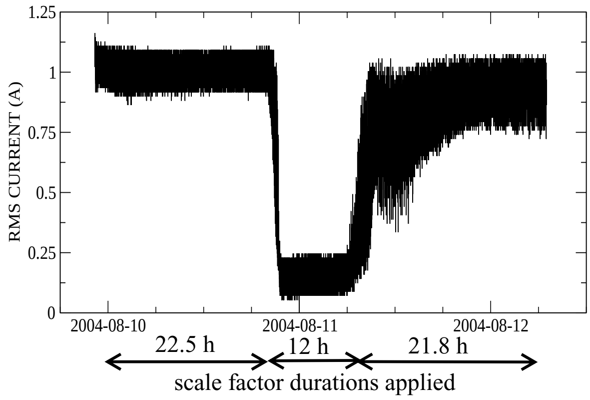

Fig. 2. Rms anode current and scale factor splitting.

Three scale factors were estimated for this manoeuvre, corresponding to the time periods indicated

These rms anode current drops have been seen to occur rather frequently (see Fig. 1). This behaviour of the motor is now the main cause of orbit prediction uncertainties. In Fig. 1 the average performances over the whole of each SEP arc are shown. The scatter in the SEP performance figures increases when rms anode current drops appear, degrading the fit of k_{SEP} to the data obtained since.

Performance variations related to rms anode current drops have had impacts on the spacecraft operations, e.g. they been known to cause commanded SEP switch on times to move within an eclipse period, necessitating new commands to be generated and sent to the spacecraft.

5. OPERATIONAL ORBIT DETERMINATION

Orbit determination on SMART-1 has been routinely performed two or three times per week depending on the phase of the mission. In addition it has often been necessary to perform extra orbit determinations in response to an unexpected event. In this section, the orbit determination set up and two routine orbit determinations in different phases of the mission are described.

5.1. Tracking Data

Pre-launch, it was optimistically intended to track the spacecraft only twice per week but due to the near constant thrusting and SEP performance variations it was soon realised that more station passes were required. SMART-1 is a test mission and it has lowest priority when allocating station time. Passes have therefore been scheduled when station time was not required by other missions. Passes of several hours each day are the norm with coverage varying between data arcs.

Two way S-band range and Doppler data have been available from frequent passes of a number of ESA ground stations. Until August, Villafranca II had tracked most frequently (125 passes) followed by Perth (109), Maspalomas (93), Kourou (58) Villafranca I (3) and New Norcia (1). Meteorological data are obtained at all stations.

Standard deviations of 20 m for the range and 1 mm/s for the Doppler measurements compressed to 60 s count time are assumed. Observations below 10^{o} elevation are excluded.

5.2 Orbit Determination Set-Up

The length of the data arc has varied during the mission, from 2 days (4 revolutions) early in the mission to 7 days (1 revolution) more recently.

Throughout the mission, the dynamic model for the orbit determination of SMART-1 has consisted of:

- Central potentials of the Earth, the Moon, the Sun and all planets based on JPL DE405 ephemerides plus relativistic perturbations due to the Sun.
- Earth gravity field model JGM3 and NASA Goddard Lunar gravity model GLGM-2. The degree and order of each depending on the mission phase.
- A flat plate model of the solar radiation pressure (SRP) assuming 15.076 m^2 effective surface area and spacecraft mass constant over a data arc but updated as required.
- SEP manoeuvre modelling as described in section 2.
- Finite duration WOL manoeuvres.

In order to calibrate the SEP thrusting, scale factors in 3 orthogonal directions fixed with respect to the SEP mechanism are estimated. A priori uncertainties equivalent to 10% in the acceleration magnitude and circa 3^{o} in direction are applied. In the following, only the magnitude scale factor is discussed.

The orbit determination involves estimating the spacecraft state at an epoch close to apogee and calibrating the SEP manoeuvres, individually if possible. Whether each manoeuvre can be individually calibrated depends on the data distribution for the observation interval and the length of the SEP arcs calibrated. Early in the mission, when manoeuvres were more frequent, it was often necessary to group several manoeuvres together for the purposes of calibration

A scale factor for the simple SRP model was estimated during the month long manoeuvre free period after the perigee raising phase. This calibrated SRP model has been used since.

Troposphere corrections have used real time weather data and the Klobuchar ionosphere model has been applied.

The following are treated as consider parameters within the estimation (with a priori standard deviations given): station location component uncertainties (10 cm standard deviation), range bias per station (20m), wet troposphere correction (4 cm), dry troposphere correction (1 cm), ionosphere correction (10 cm) and transponder delay (10 nsecs).

5.3 Early Orbit Determination

This is an example of an orbit determination during the perigee raising phase. At apogee, in the middle of the observation interval, the orbital period was 14.9 hours and the perigee and apogee distances were 12713.2 km and 48753.5 km respectively

The observation interval covers four revolutions and contains two Kourou passes and one Maspalomas pass. The SEP is on at all times except for a short time around each perigee.

There is more than a full revolution between adjacent passes and therefore the manoeuvres cannot be entirely separated using the available tracking data. The post fit Doppler residuals, Fig. 3, show the manoeuvre distribution (SEP on times indicated as horizontal lines and apogees as crosses) relative to the data available. The first and last manoeuvres covered by the tracking data were treated separately and the two central manoeuvres calibrated together.

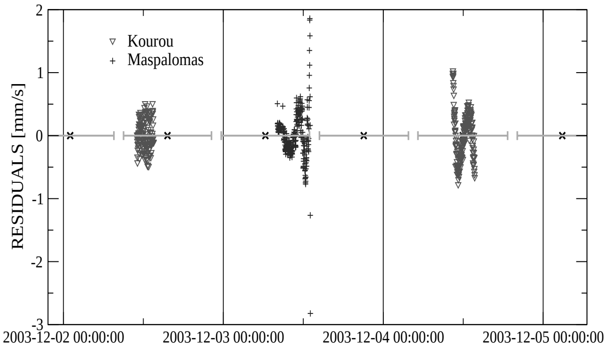

Fig. 3. Doppler residuals of an early orbit determination.

The estimated manoeuvre magnitude corrections relative to the nominal acceleration, modelled by the manoeuvre optimisation team at that time with $k_{SEP} = 1.018$, were: $-0.30 \pm 0.06\,\%$ for the first SEP arc, $-0.61 \pm 0.01\,\%$ for the second and third arcs and $-0.23 \pm 0.09\,\%$ for the final arc. These formal errors are over optimistic because of the limitations in the fidelity of the SEP modelling.

These results represent a consistent over performance with respect to the pre-launch acceleration model for the motor of 1.2-1.6%. What is important for orbit propagation however is that the performance with respect to the currently modelled acceleration at that time had been observed consistently for over two weeks and as a result the k_{SEP} value was updated to 1.014.

5.4 Recent Orbit Determination

As the orbit period has increased the orbit determination window has contained fewer revolutions and therefore fewer SEP arcs. The frequency of passes has not changed substantially so it has become possible to calibrate each SEP arc separately.

An example of an orbit determination from August 2004, shortly before the first moon resonance is given. A single SEP arc lasting 56 hours was calibrated with an observation interval spanning around one week. Seven passes of Villafranca II, four of Perth and one from New Norcia are included.

In Fig. 4, the post-fit Doppler residuals are presented for a solution estimating only a single set of calibration factors over the whole of the thrusting arc. A poor fit is seen with residuals of over 100 mm/s. The estimated manoeuvre magnitude correction is $2.39 \pm 0.0003\,\%$ of the optimised nominal at the time ($k_{SEP} = 0.970$).

This SEP arc corresponds to the rms anode current plot in Fig. 2, which indicates an expected variation in thrust level. Therefore, for the purposes of calibration, the manoeuvre was split as described in section 4.2. The resulting post-fit Doppler residuals given in Fig. 5 are greatly improved.

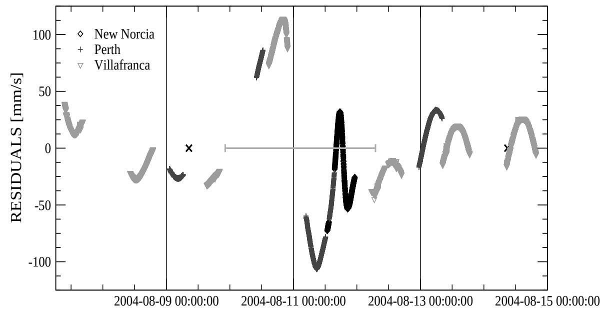

Fig. 4. Doppler residuals using a single calibration factor.

The estimated manoeuvre magnitudes relative to the optimised nominal were: $1.27 \pm 0.01\,\%$ for the first section, $5.10 \pm 0.01\,\%$ for the central section, corresponding to the rms anode current drop, and $1.80 \pm 0.003\,\%$ for the final section. As a result of consistent over-performance, the value of k_{SEP} was raised to 0.980 shortly afterwards. This over performance of the SEP during periods of low rms anode current has been observed consistently

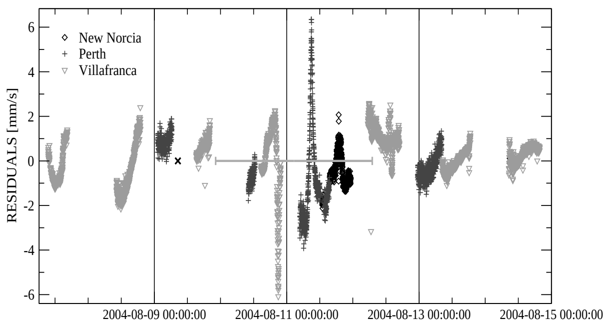

Fig. 5. Doppler residuals using three calibration factors.

Propagated orbits based on the two orbit determinations were compared and the orbit differences shown in Fig. 6.

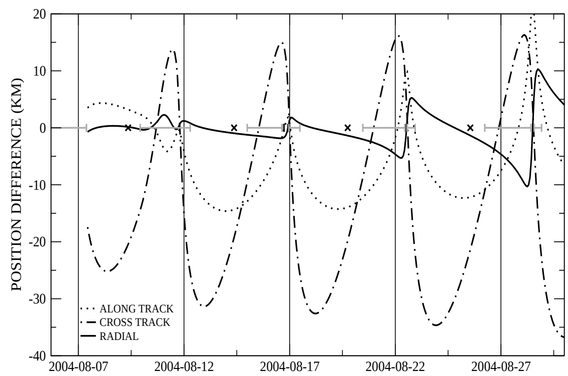

Fig. 6. Propagated orbit comparison

The differences in the non radial components are nearly periodic with maxima of around 35 km in the cross-track and 20 km in the along track directions. The periodic nature indicates that the mean effect of the manoeuvre on the orbit is well calibrated with a single set of scale factors.

A typical estimate of the orbit determination accuracy achieved during this part of the mission, based on comparing overlapping data arcs is 4km in position and 40 mm/s in velocity, mainly in the cross track direction

5.5 Effect of Performance Variations on Pointing Predicts

As a result of the orbit determination described in the previous section new station pointing predicts are produced. In Fig. 7 the difference in the latest determined orbit and the previous determined orbit is shown in the form of station pointing predicts differences. The previous determined orbit was used for the pointing predicts currently at the stations and applied $k_{SEP} = 0.970$ to predict the performance of the manoeuvre.

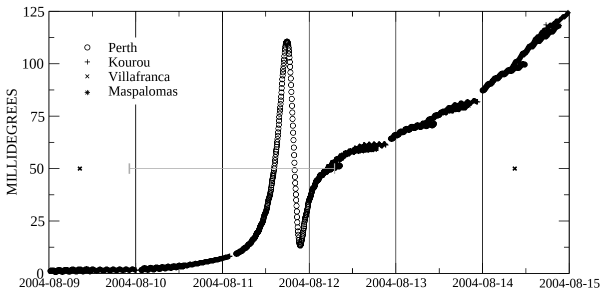

Fig. 7. Build up of errors in station pointing predicts due to manoeuvre performance variation nominal

After a peak at perigee the pointing errors build up in the stations due to the variation in the SEP performance from the predicted nominal. At apogee after the manoeuvre the pointing error is 100 millidegrees. It is therefore recommended to send the new pointing predicts to the stations to replace the current ones. Once the value of k_{SEP} is updated to 0.980 one may expect the predicted nominal performance to be more accurate and the pointing errors after the manoeuvre to be smaller.

6. CONCLUDING REMARKS

The process of calibrating the frequent SEP manoeuvres for SMART-1 in order to keep track of SEP performance has been discussed. Operational methods are in place to absorb the long-term changes in manoeuvre performance into future SEP planning but short-term variations in thrust level cannot be accounted for in this way.

For the next few months SMART-1 must be kept close enough to the planned orbit such that any orbit dispersions due to navigation errors at a Lunar resonance can be compensated for before the next resonance or Lunar capture. A serious SEP disturbance, due to an unexpected, non-recovered SEP shut-down for example, could necessitate an additional resonance to be inserted before capture. SEP performance variations will affect the efficiency of the resonances and must be monitored closely and the value of k_{SEP} kept as up to date as possible. Once in Lunar orbit the transition to the selected operation orbit will require frequent thrusting for a two month period.

The experiences gained in navigating SMART-1 will be applied to future ESA low thrust missions such as Bepi-Columbo.

Acknowledgement

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