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The impact of advanced platform and ion propulsion technologies on small, low-cost interplanetary spacecraft

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Abstract

This paper assesses the application of small ion-propelled spacecraft of about 200 kg launch mass to low-cost interplanetary missions, for which very high velocity increments (ΔV) are required. Here, the "low-cost" criterion eliminates the utilisation of the launcher for the attainment of escape velocity, thereby implying the use of an ion propulsion system for orbit-raising from an initial low Earth orbit or from the geostationary transfer orbit. The sample missions considered were to rendezvous with a wide range of asteroids; they require a total ΔV of the order of 10–12 km/s. Although the performance of the solar array is critical, recent advances in solar cell technology have enabled considerable progress to be made in this area. Other relevant advances include improved batteries, attitude and orbit control sensors, and communication systems. Gridded ion thrusters are essential, owing to the need for very high values of specific impulse. They allow a very large number of target bodies to be accessible within a launch mass of 200–250 kg.

1. Introduction

Deep space missions with significant scientific objectives usually require a very large velocity increment ΔV). Although some of this can often be provided by planetary swing-bys, until recently, the only options available to achieve this were to launch on a very large and costly rocket or to supply the necessary ΔV by use of an on-board propulsion system. The latter approach led to a large propellant load, and thus to a heavy spacecraft and the need for an expensive launcher. The advent of the operational ion propulsion system (IPS), as demonstrated so convincingly by the Deep Space 1 (DS-1) [1] mission, has permitted a complete re-evaluation of this situation. Moreover, a more ambitious mission is now underway; this is Muses-C [2], which is to take a sample from an asteroid and return it to Earth for laboratory examination.

Owing to the high specific impulse (SI) available from an IPS, which can be a factor of 10–20 greater than that from a conventional chemical propulsion system, the propellant load required in the second option mentioned above can be reduced by the same factor. This very large gain can be further enhanced by

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utilising an even less costly launch vehicle to deploy the spacecraft initially into a low Earth orbit (LEO) or to geostationary transfer orbit (GTO). Earth escape can then be achieved via a spiral orbit-raising manoeuvre, as recently undertaken by the Artemis communications satellite [3]. A similar transfer from GTO will soon be demonstrated during the SMART-1 [4] lunar mission.

The potential mass reductions and associated financial gains available from the use of an IPS has led to several studies which have explored the minimum spacecraft mass that could provide a viable deep space mission [5–8]. Such an objective is assisted substantially by significant advances in other technological fields [9], notably lightweight solar arrays and batteries and high temperature semiconductors.

This progress recently led to the conclusion [5] that a 10 km/s mission to an asteroid could be launched as an Ariane 5 auxiliary payload into GTO, which has a mass limit of 120 kg. This mission would commence with an orbit-raising manoeuvre to escape from the Earth's gravitational field, but could not accommodate redundancy. This earlier work has thus been extended to examine the impact of increasing the launch mass to about 200 kg, with the aim of carrying redundant thrusters and a larger payload, whilst simultaneously raising the total velocity increment available.

2. Asteroid missions

There has, for many years, been great interest in deep space missions, heightened by the need to understand better the origin and evolution of the solar system, and also by the possibility of finding evidence of past or present life elsewhere. This interest extends to the asteroids and comets orbiting the Sun, mainly because they are considered to be remnants of the material from which the solar system was formed. However, a major problem associated with missions to these bodies is the substantial cost involved. This is due largely to the very high ΔV required for escape from the Earth's gravitational field and then to reach the target in a reasonable time. A rendezvous with the target adds further to this requirement, which totals many km/s.

The initial objective of the present study was to select suitable targets, taking into account the need to minimise launch cost. Although a very large ΔV was deemed mandatory, preliminary calculations suggested that 12–14 km/s might be achieved by a 200 kg spacecraft carrying a reasonable payload. A list of accessible asteroids [10] was examined, together with their orbital parameters and the values of ΔV required to rendezvous with them following Earth escape. These were between 4.5 and 8 km/s, so are feasible using the spacecraft envisaged in this study. Indeed, it was found to be possible to target up to three such bodies in a single mission. Three asteroids can be visited for a total ΔV of below 10 km/s in at least 14 combinations and all multiple-targets studied require less than 12 km/s.

From this examination of possible targets, it was clear that most represent desirable scientific objectives. It was also evident that special expertise and extensive discussion within the science community will be required to select the asteroids giving the best scientific return. Since none of them require a total value of ΔV exceeding 12 km/s, they are all accessible and there was thus no need to be specific at this stage.

3. Propulsion requirements

3.1. Primary propulsion

A preliminary assessment indicated that it is necessary to achieve values of SI of the order of 5000 s to realise the above objectives. Thus, gridded ion thrusters are essential, since no other developed technologies provide an adequate SI, coupled with a thrust of the order of tens of mN and long life. While the absolute performance of such thrusters has almost reached a plateau, significant improvements have been reported in life expectancy, partly through the use of carbon ion extraction grids and also through the attainment of higher values of propellant utilisation efficiency.

As regards the overall mass of an IPS, important advances are being made in the propellant feed and power conditioning fields. In the former, there have been moves towards microminiaturisation, although the early promise of micro-electronic mechanical systems (MEMS) has not yet been realised. In the latter, SiC semiconductor technology will permit high-temperature operation of power conditioning circuits, allowing thermal design constraints to be relaxed and leading to substantial mass and volume reductions.