Near Earth asteroid resource utilisation for large in-orbit reflectors

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Abstract

The resources offered by the family of near Earth asteroids could provide bulk materials to support future space science ventures, both crewed missions and space-based astronomy. Using low-energy transfer trajectories small near Earth asteroids could be captured directly, or their material resources returned to Earth orbit or the Lagrange points. With novel fabrication methods, such as additive layer manufacturing, large-scale space structures including optical and radio telescopes could in principle be assembled from such resources. Indeed, with bulk materials readily available, very large numbers of structures could be fabricated in-situ for interferometry applications.

Key words: near Earth asteroid; space resources; space reflectors

1. Introduction

The inherent cost of large science missions (whether robotic or crewed exploration) is in part due to the cost of lifting material from the bottom of the Earth's deep gravity well. However, emerging technologies offer the possibility of sourcing material from in-situ resources, including the Moon and the family of near Earth asteroids [1]. Such resources include water from C-type asteroids, either for logistic support or to be electrolytically cracked into hydrogen and oxygen for propellant. Metals from M-type asteroids offer a wider range of in-situ resources for manufacturing.

While the Moon provides an important potential resource [2], it also requires material to be lifted from its own gravity well, while asteroid resources are arguably more accessible. This can be seen by estimating the near Earth asteroid resources available with an energy investment equivalent to lunar escape speed. For example, with a Δv investment of 2.73 kms^{-1} (lunar escape speed) approximately 10^{13} kg of near Earth asteroid material is in principle available [3]. Importantly, while lunar escape speed represents the minimum energy investment required to lift material from the Moon to escape, asteroid resources can be accessed across a spectrum of energy investments, starting from a relatively low threshold. With a Δv investment of only 100 ms^{-1} approximately 10^{10} kg of asteroid material is in principle available, given the orbit and size distribution of the near Earth asteroid population [3]. Indeed the most easily accessible known target (2006 RH120, with a diameter of a few meters) can be captured with a Δv investment of order 60 ms^{-1} [4].

While near Earth asteroid resources are often seen as enabling future human space ventures, they could also provide exciting new opportunities for space science; for example, by providing bulk material for large-scale reflectors for optical or radio astronomy. Combined with new technologies, such as additive layer manufacturing, the convergence of in-situ resources and new fabrication methods could enable entirely new ways of delivering space science in future [5]. Moreover, with additive layer manufacturing, multiple reflectors could be fabricated at low marginal cost to enable interferometry with very large numbers of elements. In-situ resources from near Earth asteroids would provide bulk material for reflectors, while specialised subsystems, such as instruments and detectors, would be launched from Earth.

In this Viewpoint some recent work on near Earth asteroid capture, material processing and the deployment of large-scale reflectors will be synthesised and discussed. Possibilities for the fabrication of multiple large-scale reflectors for space-based astronomy and interferometry will then be speculated upon.

2. Asteroid capture

While the family of near Earth asteroids represent a vast potential wealth of material, the accessibility of that material for space science or other purposes is constrained by orbital dynamics. While some target objects have orbital elements similar to those of the Earth, others move along eccentric and/or high inclination orbits which require significant energy to reach and return from.

Recent work has shown that the stable invariant manifolds of the L_1 and L_2 Lagrange points of the Sun-Earth system could be used as efficient routes to capture small near Earth asteroids, or return material processed from them [4,6]. The stable manifolds represent families of trajectories which naturally wind onto periodic orbits at the L_1 or L_2 Lagrange points, either in-plane Lyapunov orbits or North/South halo orbits.

First, a spacecraft with an efficient, high specific impulse propulsion system (likely solar electric propulsion) would rendezvous with a target body and mechanically grapple the asteroid. A burn from the low thrust propulsion system would then push the asteroid onto a ballistic trajectory which intersects the desired stable invariant manifold. A subsequent burn would then push the asteroid onto the manifold itself, after which it would naturally wind onto a periodic orbit about either the L_1 or L_2 Lagrange point. While the co-linear Lagrange points are unstable, active control of captured bodies at such locations appears possible [7], while the Lagrange points themselves represent potential staging posts for future human space activities, or locations for space-based astronomy [8]. Returning material directly to the L_1 or L_2 Lagrange points could therefore provide resources to support such ventures.

In addition to Lagrange point capture, recent work has also shown that low-energy capture is possible using so-called Kolmogorov-Arnold-Moser (KAM) tori [9]. In this strategy an asteroid moving on an initially chaotic orbit in the Sun-Earth system is manoeuvred, again likely using an efficient, high specific impulse solar electric propulsion system. The manoeuvre pushes the asteroid inside a so-called KAM torus which traps it on a periodic orbit about the Earth. Remarkably, the asteroid still has sufficient energy to escape, but doesn't (the zero velocity surfaces at the L_1 and/or L_2 Lagrange points remain open). In principle the asteroid can escape through so-called Arnold diffusion, but the diffusion timescale is so long that the asteroid remains trapped for practical engineering purposes [9].

Using insights into orbital dynamics it appears that capturing or returning material from near Earth asteroids could be efficiently achieved, although the total time integrated impulse required is still large. Moreover, some asteroids are in relatively easily accessible orbits representing the lowest costs targets, so-called Easily Retrievable Objects (EROS), with a capture Δv of less than 500 ms^{-1} [4]. While the near Earth asteroid resource is vast, it will clearly be harvested in the most efficient manner, leading to competition for the most easily accessible resources.

3. Material sorting

Aside from capturing or returning material from near Earth asteroids, another key challenge is material sorting. This is particularly acute since most terrestrial mining processes often rely on gravity to sort ground materials. Clearly, direct gravitational sorting is not feasible in the weak gravity of near Earth asteroids. However, material can in principle be sorted using light pressure as an effective sieve to sort grains by density [10]. In this strategy grains of material are lofted from the asteroid surface with light pressure perturbing the lowest density grains more strongly than dense metallic grains, since the acceleration due to light pressure scales with area-to-mass ratio. As the lofted grains slowly sink back to the asteroid surface lighter grains such as olivine (density of order 3.5 gcm^{-3}) will have been perturbed more strongly than dense metallic Fe-Ni grains (density of order 7.5 gcm^{-3}). In this manner bulk sorting of material could be achieved. Practically, a rover could move across the asteroid surface gathering and lofting material while other rovers move synchronously to collect separated grains. The entire group of rovers can move across the asteroid surface at a suitable speed to ensure that the Sun-asteroid-grain geometry is optimised to maximise the relative displacement of dense grains and lighter grains [10].

4. Large gossamer reflectors

Assuming a source of metallic grains is available from processed near Earth asteroid resources, thin film metallic reflectors can in principle be fabricated. Vapour deposition of aluminium from metallic powder feedstock has been considered for the fabrication of large solar sails [11]. The vapour is deposited onto a cold roller and then the thin metallic film separated to be seamed to form larger structures. Modern additive manufacturing technology can also be envisaged to fabricate large thin films with a load bearing structure manufactured directly on top of the film [5].

For a parabolic collector to be used for space-based optical or radio astronomy the parabolic form could be generated via a rigid load-bearing structure. However, recent work has shown that light pressure can be used to deform a large slack membrane into a parabolic shape [12]. A disk membrane supported by an outer hoop structure in envisaged. It can be shown that for a membrane of uniform reflectivity the deformed shape is not parabolic. But requiring a parabolic form a priori, the required surface reflectivity profile required to generate such a shape via light pressure can be determined. The required azimuthally symmetric variation in reflectivity from the centre to the edge of the disk can in principle be manufactured during fabrication of the reflector, while active control appears possible using patches of electrochromic coatings. For example, a 100 m radius spinning disk with a slack length of order 105% of the disk radius can generate a parabola with a focal length of the same order as the disk radius itself, where the disk is perfectly reflective at its centre and absorbing at its edge [12]. In principle then, ultra-large but lightweight parabolic reflectors could be fabricated from in-situ resources. While requirements on the accuracy of the surface profile of optical reflectors are clearly demanding, radio frequency applications are less stringent.

For space-based astronomy the axis of the reflector clearly needs to be pointed in arbitrary directions. However, using light pressure to deform the membrane into a parabolic shape implies that the reflector needs to be Sun-pointing. This is suitable for applications in power generation but not for astronomy. Work is currently underway to determine how a non-azimuthally symmetric reflectivity profile across the membrane could be used to generate a parabola with an axis which is directed away from the Sun-line. It can also be envisaged that near Earth asteroid resources could be used to provide the bulk materials required to fabricate large numbers of ultra-large reflectors for interferometry. Indeed, if the manufacturing infrastructure is in place and bulk material is readily available then the marginal cost of each new reflector may be modest.

5. Accelerated manufacturing

If large parabolic reflectors could be fabricated using near Earth asteroid resources it also opens up the possibility of the reflectors being used to accelerate the processing of asteroid material itself. For example, a 500 m radius aluminium reflector with a thickness of 0.5 μm has a mass of order 1 tonne and collects 1 GW of total power at the Earth's distance from the Sun. It appears then that industrial-scale power can in principle be generated via a relatively modest mass which could be delivered to Earth escape on a conventional launch vehicle.

After deployment the reflector could then use light pressure for propulsion (solar sailing) to reach a suitable M-type metal rich near Earth asteroid. With 1 GW of total power available the reflector could then liberate metals which could be manufactured into additional reflectors, thereby accelerating the processing of the asteroid. In principle this accelerated processing is exponential, however due to the transport delay in turning metal into reflectors the total reflector area, and hence total processed mass, increases as a polynomial rather than exponential function of time. It could even be anticipated that the reflectors could spiral back to Earth orbit or the Lagrange points using light pressure. Here they would be collected and re-processed into other products for new applications. In this way the production and transport of bulk metals back to Earth orbit could be achieved using a modest initial investment in mass delivered to Earth escape. Other scenarios for bootstrapping large-scale industrialisation of space using robotics and automation have been considered with an initial seed mass as low as 12 tonnes [13].

6. Conclusions

It is clear that near Earth asteroids represent a vast potential resource of in-situ material, although the material resource has a spectrum of accessibility starting from the most easy to reach targets. Bulk materials can therefore be sourced from near Earth asteroids, reducing the launch cost of future science missions. Such bulk material could in principle be used, with novel fabrication methods such as additive layer manufacturing, to assemble large reflectors for optical or radio astronomy. Indeed, very large numbers of reflectors could be assembled for interferometry. While near Earth asteroid resources could provide bulk material, specialised components such as instruments and detectors would be launched from Earth. Clearly, such ventures are speculative, but the development of the infrastructure to capture and process near Earth asteroid resources could offer significant and exciting new opportunities for space science in future.

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