A Space-based Laser System for the Deflection and Manipulation of Near Earth Asteroids

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Abstract Analysis gained from a series of experiments has demonstrated the effectiveness of laser ablation for the low thrust, contactless deflection and manipulation of Near Earth Asteroids. In vacuum, a 90 W continuous wave laser beam has been used to ablate a magnesium-iron silicate sample (olivine). The laser operated at a wavelength of 808 nm and provided intensities that were below the threshold of plasma formation. Olivine was use to represent a rocky and solid asteroidal body. Assessed parameters included the average mass flow rate, divergence, temperature and velocity of the ejecta plume, and the height, density and absorptivity of the deposited ejecta. Experimental data was used to verify an improved ablation model. The improved model combined the energy balance of sublimation with the energy absorption within the Knudsen layer, the variation of flow with local pressure, the temperature of the target material and the partial re-condensation of the ablated material. It also enabled the performance of a space-based laser system to be reassessed. The capability of a moderately sized, conventional solar powered spacecraft was evaluated by its ability to deflect a small and irregular 4 m diameter asteroid by at least 1 m/s. Deflection had to be achieved with a total mission lifetime of three years. It was found to be an achievable and measurable objective. The laser (and its associated optical control) was designed using a simple combined beam expansion and focusing telescope. The mission study therefore verified the laser's proof-of-concept, technology readiness and feasibility of its mission and subsystem design. It also explored the additional opportunistic potential of the ablation process. The same technique can be used for the removal of space debris.

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INTRODUCTION

Laser ablation is being investigated as a possible low thrust technique for the contactless deflection and manipulation of Near Earth Asteroids (NEAs). It is achieved by irradiating the surface of an asteroid with a laser light source. Heat from the laser beam is absorbed, enabling the illuminated material to sublimate directly from a solid to a gas. The sublimated material then forms into a plume of ablated ejecta. Similar to the rocket exhaust, the flow of ablated material produces a continuously controlled low thrust. This low thrust can be used to push the asteroid away from an Earth threatening impact; modifying the asteroid's trajectory and tumbling motion. Other techniques of low thrust, contactless deflection also include the gravitiy tractor [31, 65] and ion beaming [7].

Previous analysis performed by Sanchez et al. 2009 [62] demonstrated the theoretical capability of surface ablation. With a relatively low mass into space, and a short warning time, ablation can provide a controllable deflection action. Here, the energy input is provided by concentrated solar energy. A large space-based solar concentrator can collect, focus and sublimate a small portion of the asteroid's surface [37, 38]. However launching and operating a large spacecraft is a significant technological challenge. The solar concentrator needs to be manoeuvred at close proximity to the asteroid, under the asteroid's irregular gravity field. The contaminating effects of the ejecta plume are also unknown.

A simpler and more adaptable solution could be to split the single spacecraft into multiple units. A swarm of small scale, low power spacecraft could fly in formation with the asteroid. Their overlapping beams of light would be used to increase the surface power density, enabling its sublimation [33, 34, 68]. This second approach provides a far more flexible solution, with built in redundancy that can be easily scaled. The number of spacecraft would depend on the size and composition of the asteroid and the warning time before impact. Multiple spacecraft also permit the delivery of a much more powerful system. It reduces the required time needed to achieve a suitable deflection distance and the occurrence of any single point failure. A highly redundant mission scenario is preferable as it accounts for large observational uncertainties in the asteroid's material and structural composition, and in the mission design parameters [79].

Alternatively a collimated or focused laser beam could be used to increase the operating distance between the asteroid and the spacecraft. Lasers provide a convenient, versatile and predictable method of transporting energy. They can propagate over an extended distance, with very little loss of energy, dispersion and beam quality. Each spacecraft could be equipped with an identical kilo-watt class, solar powered laser [69]. The swarm would be less affected by the asteroid's irregular gravity field and the contaminating effects of the ejecta plume. Larger mega-watt or giga-watt space-based lasers could also be used. Powered by a nuclear reactor, the laser could be mounted onto a single spacecraft, the International Space Station (ISS) or the Moon [19, 35, 45, 66, 78]. It would however require developing a high-power, space-based laser system and overcoming the significant political ramifications of launching, controlling and operating a nuclear reactor in space. A swarm of low power, but highly efficient space-based lasers, powered by conventional solar arrays is therefore a far more attractive solution.

Further research is still required to advance the current understanding of laser ablation as a viable method of asteroid deflection. The ablation model is based on the energy balance of sublimation and was developed from three fundamental assumptions. These assumptions defined the physical formation of the ejecta plume, the composition of a dense and homogeneous target asteroid (with a one-dimensional transfer of heat) and the potential of the ejecta to contaminate any exposed surface [20, 62]. To examine the viability of these assumptions and the general applicability of the ablation and contamination models, a series of laser ablation experiments were performed by the authors [15, 17]. In vacuum, a 90 W continuous wave laser beam was used to ablate a magnesium-iron silicate (olivine) rock. The laser operated at a wavelength of 808 nm and provided intensities that were below the threshold of plasma formation. Olivine was used to represent a rocky and solid asteroidal body. The experiment measured the average mass flow rate, dispersion and temperature of the ejecta plume and the contaminating effects - height, density and absorptivity - of the deposited ejecta. Results were used to improve the ablation and contamination models. Degradation caused by the deposited ejecta is a critical factor. It will affect the performance of the laser beam, its operational lifetime and the overall endurance of the ablation technique. The system performance of the spacecraft will also be affected. The ejection of material will affect the stability and directionality of the resultant thrust vector.

The experiments demonstrated how laser ablation is dominated by the volumetric removal of gaseous material. It is similar in shape and formation to the exhaust in standard methods of rocket propulsion, although the absorptive properties of the deposited material were considerably different. Reported in Gibbings et al, 2013 [17], the absorptivity of the deposited ejecta was 10^4 m^{-1} (two orders of magnitude smaller than previously assumed in [20]) and had a deposited density of 250 kg/m^3 (previously assumed to be 1000 kg/m^3 in [20]). There was also no immediate saturation of the exposed surface, nor the formation of a permanently attached opaque surface layer. The deposited material was loosely bound to the underlying substrate and could be easily removed. The laser beam also provided a self-cleaning action. There was no apparent deposition along the path length of the laser beam. The initial model was found to be overly conservative in an unexpectedly benign environment. It also excluded the additional optical-thermal effects between the laser beam and the ejecta plume, and the occurrence of incoherent ablation from the target's surface. The improved model, verified through the experimental results, therefore combined the energy balance of sublimation with the energy absorption within the Knudsen layer, the variation of sublimation temperature with local pressure, the temperature dependent thermal conductivity of the target material and the partial re-condensation of the ablated material. These improvements were developed from previous research papers given in Knight, 1979; Bulgakov et al, 1999; Robbie et al, 1982, Ketren et al, 2010; O'Keefe et al, 1971 [10, 22, 23, 42, 57]. They detail laser ablation for non-space applications.

The revised model was then used to size and demonstrate the capabilities of a space-based ablation system. The performance of the spacecraft was evaluated by its ability to deflect a small and irregular 4 m diameter asteroid by at least 1 m/s. Deflection had to be achieved with a total mission lifetime of three years. It was found to be an achievable and measurable objective. Mission mass and complexity is saved by the direct ablation of the asteroid's surface. The same technique can also be applied to the de-orbiting of space debris [47, 48, 52, 54, 56, 70, 71].

The paper will therefore report on the results and analysis gained from the laser ablation experiments. It includes a presentation of the recently advanced ablation model and its overall effect on the design of a space-based ablation system. The laser system was sized from an assessment of the minimal input power, spot size radius, shooting distance (including the degrading effects of the ablated ejecta) and momentum coupling. The size of the laser will directly affect the configuration and subsystem design of the spacecraft. Analysis also explored the additional scientific, exploration an exploitation potential of the ablation process. The necessary technological development needed to fully develop laser ablation into a viable space-based application is also addressed. Work therefore supports the general diversity and durability of using space-based lasers and the applicability of the model's experimental verification.

LASER ABLATION MODEL

The laser ablation model is based on the energy balance of sublimation. It combines the absorption of the laser beam, the latent heat of complete sublimation and the heat loss through conduction and radiation [20, 51, 62]. Improvements include the energy absorption within the Knudsen layer, the variation of sublimation temperature with local pressure, the temperature dependent thermal conductivity of the target material and the partial re-condensation of the ablated material. Ablation occurs without any ionisation or ejection of solid particles. The target asteroid is also assumed to be a dense, homogeneous structure, which behaves as a black body with an infinite heat sink. Degradation caused by the deposited ejecta is based on the Beer-Lambert-Bougier law. The text below provides a short summary of the ablation and contamination models. It is however given in more detail in Gibbings 2013; Vasile et al, 2014 [15, 74]

Using a one-dimensional energy balance at the illuminated spot, the ablation model derives the mass flow rate per unit area of the sublimation material $\dot{\mu}$. This is given by:

$$\dot{\mu}\left[E_v + \frac{1}{2}\bar{v}^2 + C_P\left(T_{SUB} - T_0\right) + C_V\left(T_{SUB} - T_0\right)\right] = P_I - Q_R - Q_C \tag{1}$$

where E_v is the latent heat of complete sublimation, $\bar{v}$ is the velocity of the ejecta plume, C_P is the specific heat capacity of the ejected gas at constant pressure, T_{SUB} is the sublimation temperature, T_0 is the temperature of the material prior to sublimation, C_V is the specific heat capacity of the asteroid at a constant volume and P_I is the absorbed laser beam per unit area. Q_R and Q_C are the heat loss per unit area through radiation and conduction respectively.

The term $C_V\left(T_{SUB} - T_0\right)$ accounts for the energy needed to increase a layer of the target material from its initial temperature T_0 to the sublimation temperature T_{SUB}. The term $\frac{1}{2}\bar{v}^2 + C_P\left(T_{SUB} - T_0\right)$ accounts for the energy that is absorbed by the vapour in the Knudsen layer from the solid-gas interphase (later in the sublimation it is the liquid-gas interface) and the accelerated gas phase [23]. C_V is considered to be constant and equal to the maximum heat capacity according to the Debye-Einstein asymptotic heat capacity for solids [57]. C_P is the maximum expected heat capacity value given the range of sublimation temperatures of the target material [41]

The heat loss, per unit area, through radiation and conduction are:

$$Q_R = \sigma_{SB}\varepsilon\left(T_{SUB}^4 - T_{AMB}^4\right) \tag{2}$$

$$Q_C = \left(T_{SUB} - T_o\right)\sqrt{\frac{C_V \rho_A \kappa_A}{\pi t}} \tag{3}$$

σ_{SB} is the Stefan-Boltzmann constant, T_{AMB} is the ambient surrounding temperature and t is the time that the surface of the asteroid is illuminated under the spot light. ε, ρ_A and κ_A are the black body emissivity, density and thermal conductivity of the asteroid respectively. The thermal conductivity from the sublimated material to the inner core is assumed to be a function of the sublimation temperature. It is achieve through the power law relation:

$$k_A = k_{A_0}\left(\frac{298}{T_{SUB}}\right)^{0.5} \tag{4}$$

The average velocity of the ejecta plume $\bar{v}$ is calculated by assuming Maxwell's distribution of an ideal gas. It is defined by the sublimation temperature, the molar mass of the ablated material M_a and Boltzmanns constant k_b. This is given by:

$$\bar{v} = \sqrt{\frac{8 k_b T_{SUB}}{\pi M_a}} \tag{5}$$

The experimental result shows that the olivine sample will ablate and dissociate into diatomic oxides. This has a prevalence of magnesium (Mg) and silicon oxide (SiO), where its molar mass was considered to be 0.06 kg/mol [15, 17]. The force F_{SUB} acting on the asteroid is therefore given by a product of the ejecta velocity and the mass flow rate of the ablated material. It is expressed as:

$$F_{SUB} = \lambda \bar{v} \dot{m}_{SUB} \tag{6}$$

A constant scatter factor λ is used to account for the hemispheric, rather than the linear expansion of the ejecta plume. It is the integral of the trigonometric part in equation (10). The ablation temperature is related to the local pressure through the Clausius-Clapeyron equation:

$$ln\frac{p_s}{p_{ref}} = \frac{E_V}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T_{SUB}}\right) \tag{7}$$

p_s is the pressure corresponding to the temperature T_{SUB} and p_{ref} is the pressure corresponding to the reference temperature T_{ref} [10, 22]. R is the universal gas constant. The vapour pressure will increase with the temperature of the irradiated asteroid. The reference temperature was taken to be 3800 K (at 1 atmosphere). Previous research has shown that the sublimation temperature for a range of Mg-Fe and Si-Fe oxides can vary between 3175-3800 K. [42, 77]. A lower sublimation temperature can also be caused by the transparency of pure minerals [40]. The enthalpy of complete sublimation is considered to be constant in the range of temperatures in which equation (7) is valid.

The mass flow rate is also dependent on the local pressure at the interface between the Knudsen layer and the ablated material through the Hertz-Knudsen equation [24]. This is expressed as:

$$\dot{\mu} = (1-k)\, p_s \left(\frac{1}{2\pi R_S T_{SUB}} \right)^{\frac{1}{2}} \tag{8}$$

where k is the fraction of molecules that re-condense at the interphase. (1-k) is therefore the fraction of vapour molecules that contributes to the pressure of sublimation, but not the sublimated flux. p_s is the vapour pressure and R_S is the specific gas constant. R_S can be expressed as a function of the molecular mass M_a and the universal gas constant, R = 8.3144 J/molK, where $R_S = \frac{R}{M_a}$. The maximum rate of evaporation not only depends on the supply of heat (and therefore its temperature), but must also be accompanied with an increase in the vapour pressure that is caused by the sublimation action. The fraction of molecules that re-condense is expected to increase with the local pressure. However the change in the thrust due to the recondensation is limited. Figure 1 plots the resulting thrust against a wide range of recondensation fractions. The maximum variation in thrust is only 4 %. This can therefore be considered negligible.

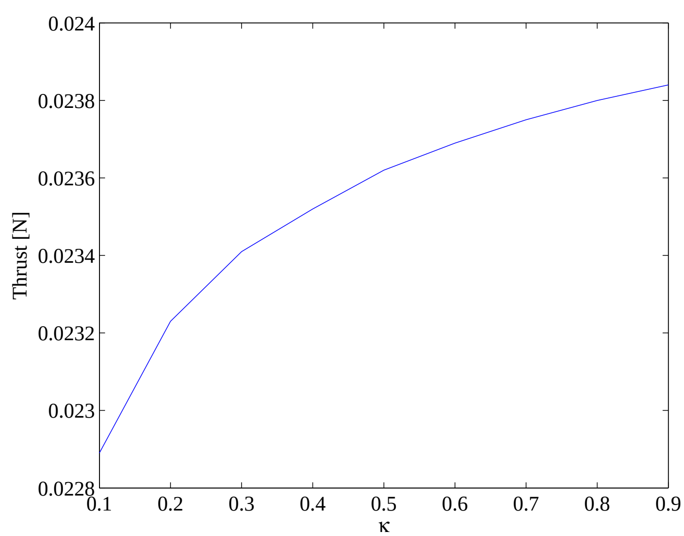

Fig. 1. Thrust Sensitivity to the Recondensation Ratio

The absorbed laser power per unit area P_I can be defined as:

$$P_I = \frac{\tau \tau_g \alpha_M \eta_L P_L}{A_{SPOT}} \tag{9}$$

η_L is the efficiency of the laser system, A_{SPOT} is the area of the surface spot and P_L is the input power to the laser. $\alpha_M = (1 - \varepsilon_a \alpha_s)$ is the absorption at the spot. This is dependent on the albedo α_s of the asteroid multiplied by the increment in reflectively ε_a at the wavelength of the laser beam. For a S class (silicates - olivine, pyroxene - and metals) asteroid the albedo is between 0.1 and 0.3. It has a 20 % reflectively peak increment between 750 and 800 nm with respect to the central wavelength at 505 nm [11]. A standard NEA has an average albedo of 0.154 [12]. The reflectivity of an asteroid is dependent on its mineral composition, chemistry, particle size and temperature. Each reflectance spectrum is characterised with wavelength-dependent absorption features, which also varies with the different classes of asteroids (S, C, M and E class). S and C class asteroids are the most common classification within the NEA population. Equation (9) also accounts for the absorption of the laser beam τ_g within the rapidly expanding and absorbing plume of ejecta. From the experimental results, it is expected that the ejecta plume will absorb 10-15 % of the incoming laser beam. The input power of the laser beam is also multiplied by a degradation factor τ. This accounts for the degrading effects caused by the re-condensed deposited ejecta material. The re-condensed material does not directly affect the laser beam, but it can reduce the power input generated by the solar array, or any other power source that uses sunlight. The degradation caused by the ablated ejecta is computed using the model developed by Kahel el al, 2006 [20].

The expected level of degradation is defined by first calculating the plume density ρ at a given distance r from the spot location and local elevation angle θ from the surface normal (as shown in Figure 2). It is expressed as [20]:

$$\rho(r, \theta) = \rho^* k_P \frac{d_{SPOT}^2}{(2r + d_{SPOT})^2} \left[cos \left(\frac{\pi \theta}{2 \theta_{MAX}} \right) \right]^{\frac{2}{k_I - 1}} \tag{10}$$

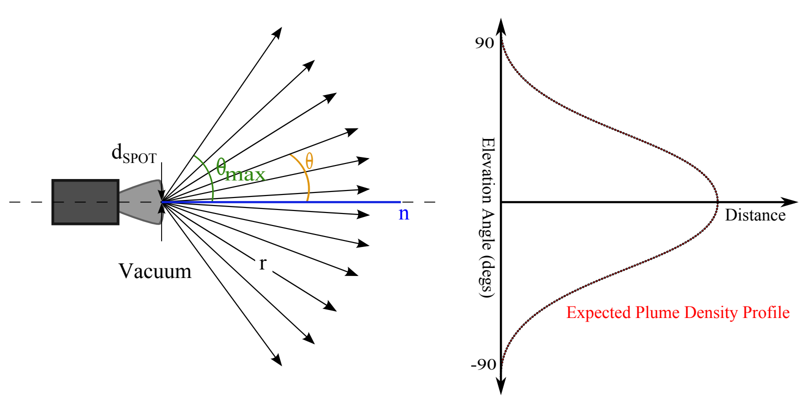

Fig. 2. Local Reference Frame and Geometry of the Ejecta Plume

d_{SPOT} is the surface spot diameter, k_I the adiabatic index (for diatomic molecules this is 1.44), k_P is the jet constant (for diatomic molecules this is 0.345) and θ_{MAX} is limited to 130.45 degs [20, 28]. The density at the nozzle (at the sublimation point) ρ^* is given by:

$$\rho^* = \frac{\dot{m}_{SUB}}{A_{SPOT}\bar{v}} \tag{11}$$

On any exposed surface, located within the ablation volume, the variation in the cumulative ejecta thickness can be expressed as:

$$\left[\frac{dh}{dt}\right]_{layer} = \frac{2\bar{v}\rho}{\rho_{layer}} cos\Psi_{vf} \tag{12}$$

ρ_{layer} is the layer density of the deposited material and Ψ_{vf} is the geometric view factor. A factor of two accounts for the increase in velocity due to expansion of gas into a vacuum. From this, the degradation factor τ given by the Beer-Lambert-Bougier-Law can be expressed as:

$$\tau = e^{-\eta h} \tag{13}$$

η is the absorptivity of the deposited ejecta (absorbance per unit length) and h is the thickness of the deposited material. In the experiments reported in Gibbings 2013; Gibbings et al, 2013 [15, 17], for the ablation of an olivine sample, the absorptivity and layer density of the deposited ejecta was found to be 10^4 m^{-1} and 250 kg/m^3 respectively.

The mass flow rate of the ablated material can then be computed by integrating $\dot{\mu}$ over the surface area illuminated by the laser beam. This is in accordance to the model initially developed by Sanchez et al, 2009 [62], given by:

$$\dot{m}_{SUB} = 2V_{rot}\int_{y_{min}}^{y_{max}}\int_{t_{in}}^{t_{out}} \frac{1}{E_v^*}\left(P_I - Q_R - Q_C\right)\, dt\, dy \tag{14}$$

The new term E_v^* is the augmented enthalpy and is equal to:

$$E_v^* = \left[E_v + \frac{1}{2}\bar{v}^2 + C_P\left(T_{SUB} - T_0\right) + C_V\left(T_{SUB} - T_0\right)\right] \tag{15}$$

The limits [y_{min}, y_{max}] and [t_{in}, t_{out}] define the location and duration for which the surface spot is illuminated respectively. V_{rot} is the velocity of rotation of the asteroid's surface as it travels under the illuminated spot area.

TECHNOLOGY DEMONSTRATION MISSION

Using the revised ablation model, it was possible to assess the preliminary mission feasibility and spacecraft design of a small, laser ablation deflection system. The system aimed to demonstrate the technological capabilities of laser ablation in providing a sufficiently high and measurable deflection action. The mission objective, to which the performance of the deflection action was compared, was to deflect a small and irregular 4 m diameter asteroid (2006 RH120, S class) by at least 1 m/s. Deflection had to be completed with a total mission lifetime of less than three years, and be developed from highly innovative, yet achievable technologies within the 2025+ timeframe. The mission concept was called LightTouch[2] and the spacecraft was called AdAM (Asteroid Ablation Mission).

Deflection was assessed by either measuring the integral of acceleration imparted onto the asteroid or through the variation in the asteroid's orbital position and velocity [72]. Variation is with respect to the nominal, pre-ablated orbit. Each method gives a measure of the imparted Δv. The following sections detail the specifications of the space-based laser system and how it was integrated into the subsystem design of the spacecraft. Please see the publications by Vasile et al 2013; Vetrisano et al 2013 [72, 73, 75] for further information on the mission architecture, asteroid selection, orbital analysis, and the guidance, navigation and control (GNC) of the mission. Papers by Gibbings 2013; Vasile et al 2013 [15, 72] detail further information on the secondary payload selection (impact sensor and LIBS) and subsystem design.

Sizing the Laser System

The design of the spacecraft was developed by first considering the performance and specifications of the laser (as its primary payload) and impact sensor. A diode pumped fibre laser was selected to initiate the ablation process. An impact sensor (similar to the instrument flying on the ESA Rosetta mission) would also be used to measure the momentum and deposition effects of the ablated ejecta.

Critical parameters for sizing the laser system included the minimal input power, spot size radius and shooting distance. These factors will affect the overall thrust time of the mission and the required optical alignment, stability and control of the laser system. Power, beam quality and the focusing requirements are other important parameters. Reported in Vasile et al, 2013 [72] the accumulative thrust time required to achieved the necessary deflection of 1 m/s was evaluated at different input powers (850-1000 W), spot side radius (0.8-1 mm) and shooting distances (20-50 m). Analysis included the degrading effects of the ablated ejected.

As expected contamination caused by the ejecta plume is considerable lower at greater shooting distances. At 50 m the contamination of the solar arrays only results in a 5 % reduction of power. The laser beam will also have a self-cleaning effect on the impinging ejecta plume. A small spot can lower the laser input power. At 50 m from the asteroid, a 860 W laser (input power) with a spot size radius of 0.8-1 mm would require an accumulative thrust time of 165-200 days. It would result in a surface power density between 428-274 MW/m^2. Combined with a fast interplanetary transfer (with one deep space manoeuvre) of 306.5 days, the mission objective can be achieved in just over two years. The total thrust time will be divided into several ablation phases, each lasting 30 days and be followed by orbital determination. The sequential ablation of the asteroid's surface is used to improve the robustness and reliability of the deflection action. New procedures can be tested and verified. The ablation response can also be monitored throughout. The remaining mission year of operations can be used to increase the robustness (by providing a large contingency margin) of the mission and to perform additional opportunistic science objectives. The latter can be achieved with the inclusion of a combined Raman/Laser Induced Breakdown Spectrometer (LIBS). LIBS can examine the chemical, mineralogical and isotopic composition of the ejecta plume. It will also be supported with the operations of the narrow and wide angle cameras. Both cameras are needed for GNC.

The laser system was therefore assumed to operate with an input power of 860 W (increasing to 1032 W with a 20 % design margin), a temperature of 10 °C (based on the diodes), a wavelength of 1070 nm, an overall plug-in efficiency of 55 % and a system mass of 24 kg. Efficiency was based on the performance of electrically pumped, high power ($\sim$ 1.5 kW) fiber laser systems. Here, high power semiconductor lasers are coupled with a length of doped fibre that is placed in a laser resonator. The efficiency of the diodes ($\sim$ 75 % state-of-the-art) and fibre laser (>70 %), at an output wavelength of 1070 nm (based on existing industrial kilo-watt class lasers), results in a laser with an electrical-to-optical efficiency of 55 %. These values are based on the current and perceived near-future advancement in fibre technology and system efficiencies. For example, recent advancement by nLIGHT Photonics demonstrated, through the DARPA Super Efficiency Diode Sources and Architecture for Diode High Energy Laser Systems programmes, a diode laser pumped efficiency greater than 75 %. These pumped lasers represent the most compact, efficient and highest power currently available for a continuous wave light source. The system mass was based on the performance of existing kilo-watt class industrial lasers, perceived technological development, and the heritage gained from previously flown and therefore space qualified reflective telescopes (for example, the HiRISE instrument on the Mars Reconnaissance Orbiter).

Shown in Figure 3 the laser (and associated optical control) was designed using a simple, combined beam expansion and focusing telescope. With a nominal focus length of 50 m, a collimated beam (that appears as a point source) will be expanded and refocused onto the desired point on the surface of the asteroid. A telescope will expand the collimated output of a high-power fibre laser to about 75 mm in diameter. The laser beam will then be focused by a highly reflective and metallic off-axis parabolic or aspheric mirror, with an approximate diameter of 100 mm. The focusing laser beam will then be reflected from a right-angle, half-cube reflector. This will allow for the final position and orientation of the output laser beam. For repositioning of the exit laser beam, the end optic could be placed in a domed window. Beam steering will be provided by motorised actuators on the focusing optics. This can improve the pointing and stability of the laser beam, and so minimises any focusing errors.

The laser output is fed from the fibre enclosure via a fibre umbillical to a collimated unit. The couples the output to free-space. The use of off-axis reflective optics will provide the maximum transmission of the optical system, with minimal component heating and loss. The system provides a m-squared factor of 1.1. The smaller the value the better the quality - focus and depth-of-field - of the laser system. Figure 4 shows the relationship between

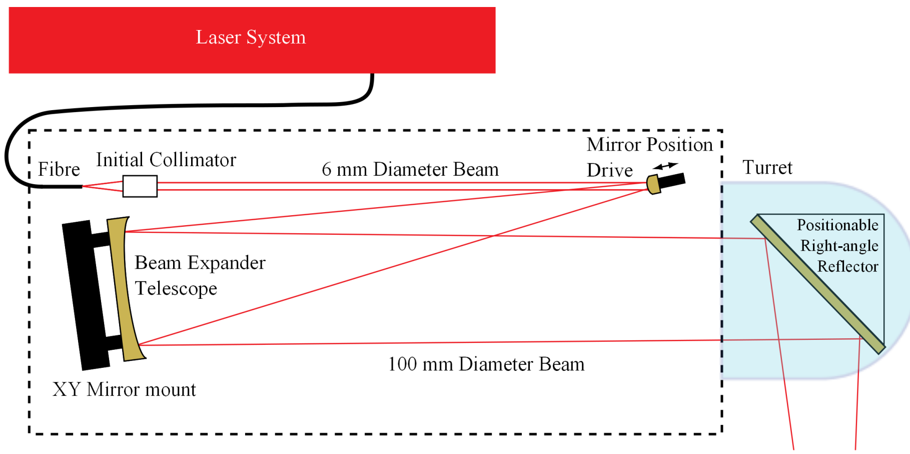

Fig. 3. Laser System and Telescope Beam Expander. Image reproduced from [72]

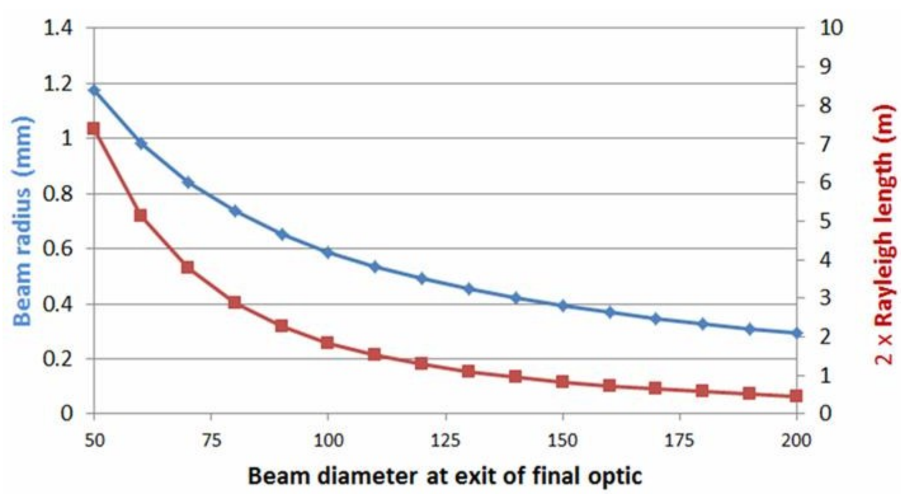

Fig. 4. Beam Behaviour of a 1070 nm Fibre and a f = 50 m Optic. Data reproduced from [72]

the beam diameter at the exit of the focusing mirror and the focused spot radius at 50 m from the surface of the asteroid. For a 100 mm beam diameter the $2Z_R$ value is 2 m. Therefore, either side of the focus, the beam intensity will not change appreciably over 1 m. Ablation can still occur with a de-focused laser beam. For a 70 mm beam diameter and a 0.8 m spot radius, the $2Z_R$ value is over 3 m.

The $2Z_R$ value provides a degree of operational flexibility and control in the focusing of the laser beam. It can be used to account for any irregularities in the asteroid's shape, rotational velocity and surface features. A precise, distance measurement, between the spacecraft and the spinning asteroid may be difficult to achieve. It also reduces the control and size requirements of the optics. With the active alignment of the telescope's optical separation, the focus point of the system can be easily manipulated. This can occur over many meters. The focus point of the laser beam on the surface of the asteroid can also be tracked with an onboard laser range finder, or similar instrument.

Spacecraft Configuration

The AdAM spacecraft was designed to operate in two orbital configurations; either trailing the asteroid or in a radial direction. The two different approaches correspond to the two operational strategies for ablation. It is important to understand how the close proximity operations of the spacecraft would affect the design of the GNC system and the overall performance of the deflection action.

Shown in Figure 5, in the trailing configuration the spacecraft is flying in formation with the asteroid's along track, trailing or leading by 50 m. This limits the contamination effects of the ejecta plume on the performance of the optics, radiators, multi-layering insulation and solar arrays. In the radial configuration, as shown in Figure 6, the spacecraft is located between the asteroid and the Sun. This reduces the number of actuators by balancing the forces acting on the spacecraft, while still providing a measurable deflection action [73, 75]. Here, the laser beam operates perpendicular to the spacecraft's solar arrays, from the umbra side. The laser system is located on the top face of the spacecraft; fully exposed to the full formation of the ejecta plume. Any ejecta that does deposit, will do so on the rear of the solar arrays. This poses a negligible risk to the power generating ability of the solar arrays. The two optical cameras point towards the asteroid.

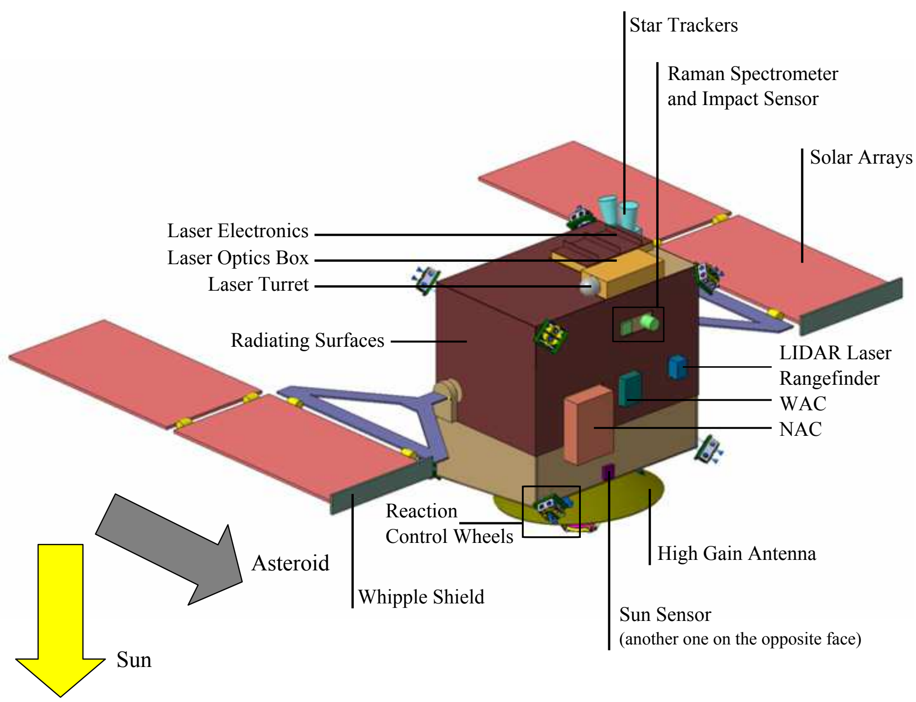

Fig. 5. AdAM in the Trailing Configuration - All Externally Mounted Instruments and Units

In the trailing configuration the laser is again located on the top face of the spacecraft. However the laser beam is directed across, towards the asteroid. To reduce the deposition effects of the ejecta on the solar arrays, the solar arrays have been rotated. This provides a smaller frontal area to the incoming ejecta plume. Two Whipple Shields have also been included. Each shield is mounted on the front edge of the solar array and can protect the

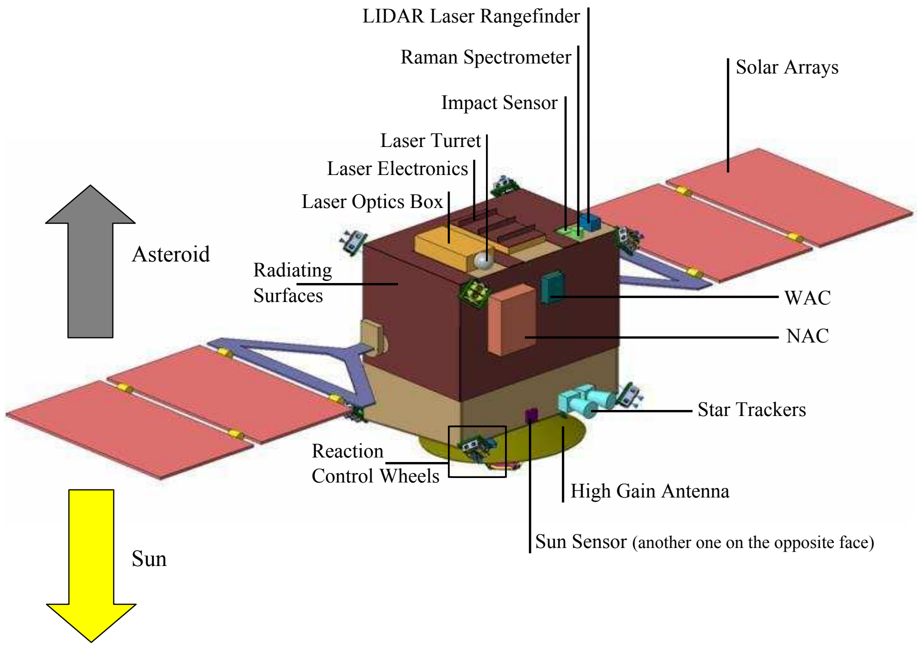

Fig. 6. AdAM in the Radial Configuration - All Externally Mounted Instruments and Units

spacecraft (and its system performance) from the abrasive effects of the ablated ejecta. A similar solution was implemented on the NASA Stardust mission to comet Wild2 and is currently flying on both the ISS and the Automated Transfer Vehicle. The Whipple Shields provide an innovative and relatively low mass shielding solution. It consists of a thin, multi-layer structure of mylar and kapton that acts as a sacrificial bumper shield.

In both configurations the laser and radiators are always in the shadow cone of the spacecraft. This allows maximum heat dissipation. Radiators (4.3 m^2) face into deep space, a high gain antenna (1.3 m) points towards the Earth and the solar arrays (7.5 m^2) are orientated towards the Sun. Low cost telemetry, tracking and command is provided by an 12 m X-band telecommunication link (planned upgrade from S-band) with the ESA ground station site at Harwell, England (Malindi, Kenya as the back-up). The spacecraft is 3-axis stabilised with four reaction wheels and sixteen reaction control thrusters. Acquisition and navigation to the asteroid is provided by two star trackers, sun sensors, an inertial measurement unit, a laser range finder and two optical cameras. The GNC subsystem, as reported further in Vertrisano et al 2013; Vasile et al 2013 [72, 73, 75], has been designed to account for the forces of the laser recoil, the gravity of the asteroid, the gravity gradient of the Sun, solar radiation pressure, plume impingement and the induced deflection action. These factors will be used to estimate the spacecraft's trajectory and the response to the ablation process [75]. Further details on the subsystem analysis and design of the AdAM spacecraft can be found in Vasile et al 2013; Gibbings 2013 [15, 72, 73].

Table 1 summarised the mass budget for the AdAM spacecraft. This is for a nominal laser input power of 860 W. The design of the spacecraft was based on a conservative and robust design approach. It therefore included a 5 % mass margin for existing off-the-shelf components, a 10 % margin when small modifications are required and a larger 20 %

margin for new design units. Each subsystem also included a conservative 20 % mass margin. A 20 % margin was also added onto the nominal dry mass. The allocation of the mass margin is in accordance with ESA standards. Shown in Table 1, the largest proportion of the spacecraft's mass is the structure, followed by the power and GNC subsystems.

Table 1. Spacecraft Mass Allocation - 860 W Laser Launched by the PSLV XL into GTO

	Current Mass (kg)	Maturity Margin (%)	Maximum Mass (kg)
Payload	2	3	4
Data Handling	2	3	4
Power	66.5	16.3	77.3
Communication	37.7	8.8	41
GNC & AOCS	31.5	9.5	34.4
Thermal	12.9	20	15.5
Propulsion	59.9	12.3	67.3
Harness	28.2	20	33.9
Structure & Mechanisms	100	20	120
Spacecraft Dry Mass			**524.9**
Subsystem Mass Margin		20	87.5
Dry Mass with Margin			**524.9**
Propellant			442.2
Spacecraft Wet Mass			**967.1**
Launch Vehicle Capability			1074
Launch Vehicle Margin			10.69
Mass Margin (%)			**10**

A second iteration was also performed. Shown in Table 2, this investigated whether a reduction in the laser input power to 480 W would be possible. Analysis presented in Gibbings 2013; Vasile et al 2014; Vasiel et al 2013 [15, 72, 74] showed this to be the minimum possible input power of the laser. To remain a competitive deflection technique, laser ablation must always provide a higher momentum coupling value than other forms of low thrust, contactless deflection methods (for example, the gravity tractor and ion beaming that uses electric propulsion). A 480 W laser corresponded with a 0.65 mm spot size radius, a peak thrust of 5.5 mN and a momentum coupling value of $1.15{\cdot}10^{-5}$ N/W. The momentum coupling relates the achievable thrust delivered by the ablation process to the input power installed onto the spacecraft. The definition is slightly different than previously defined in Phipps et a, 1988, 1997, 2000, 2011 [49, 51, 53, 55]. The modification was essential to compare the performance of the laser to the other forms of electric propulsion. The interest here was to size the power system onboard the spacecraft.

If the spot size can be controlled down to a fraction of a millimeter, then the momentum coupling of the system can be extremely large. This translates directly into requiring a smaller sized laser system with a much lower input power. For example, a 300 W laser can deliver almost $2{\cdot}10^{-5}$ N/W at a thrust level of 5 mN, if the spot size can be reduced to 0.2 mm. However a 0.2 mm spot size is a very demanding requirement in the optical system. Shown in Figure 4, controlling the beam radius to 0.2 mm (or smaller) is possible, but would require precise control as the $2Z_R$ value drops rapidly below 1 m. A spot size between 0.6-1 mm is far more reasonable and enables the requirements on the focusing distance to be relaxed.

Another improvement was to replace the LIDAR range finder with a low-mass and low-power range finder. Shown in Figure 4, the Rayleigh range can also be increased to 3 m. This was used to reduce the navigation requirement of the spacecraft. The spacecraft's mass was also optimised. This included improvements in the propellant mass, and the thermal, structural and power subsystem mass. It will have a cascade effect on the rest of the spacecraft design. The same margin philosophy was used throughout.

Table 2. Spacecraft Mass Allocation - 480 W Laser Launched by the PSLV XL into GTO

	Current Mass (kg)	Maturity Margin (%)	Maximum Mass (kg)
Payload	20	19	23.8
Data Handling	17.1	10.9	18.9
Power	46	14.6	52.8
Communication	37.7	8.8	41
GNC & AOCS	44.5	12.6	50
Thermal	12.4	20	14.8
Propulsion	59.9	12.3	67.3
Harness	25.3	20	30.9
Structure & Mechanisms	83	20	99.6
Spacecraft Dry Mass			**399.2**
Subsystem Mass Margin		20	79.8
Dry Mass with Margin			**479**
Propellant			351.9
Spacecraft Wet Mass			**831**
Launch Vehicle Capability			1074
Launch Vehicle Margin			243
Mass Margin (%)			**22.6**

Reducing the laser input power decreased the size (and therefore the mass) of the solar arrays, radiators, PCDU and the laser itself. A solar array area reduced to 4.25 m^2. The mass of the laser could also be reduced to 5.6 kg. In the previous analysis, over 50 % of the laser mass was a thermal heat sink. This had already been included in the mass of the spacecraft's thermal subsystem (including radiators, heat pipes and multi-layering insulation). The mass of the optics remained the same.

The reduction in the input power was only possible because of the fast transfer time of the baseline trajectory and an reassessment of the accumulative push time. Figure 7 and 8 shows the thrust history and the imparted Δv of the reduced power solution. The thick red line represents the accumulative push time needed to reach a deflection of 1 m/s.

In practice this would be divided into a series of ablation periods, followed by an orbit determination campaign. The push time plotted on the x-axis is measured as a fraction of the orbital period of the asteroid.

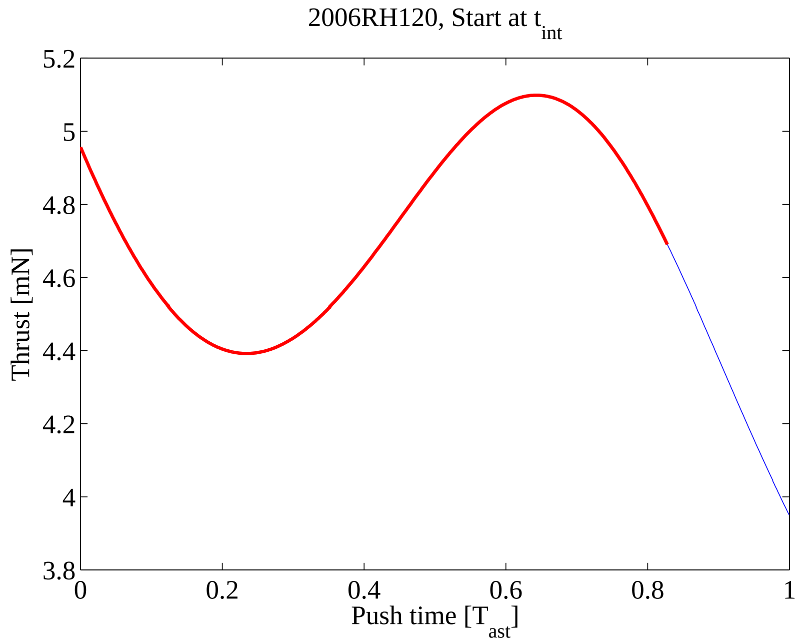

Fig. 7. Thrust Level for the Reduced 480 W Laser Input

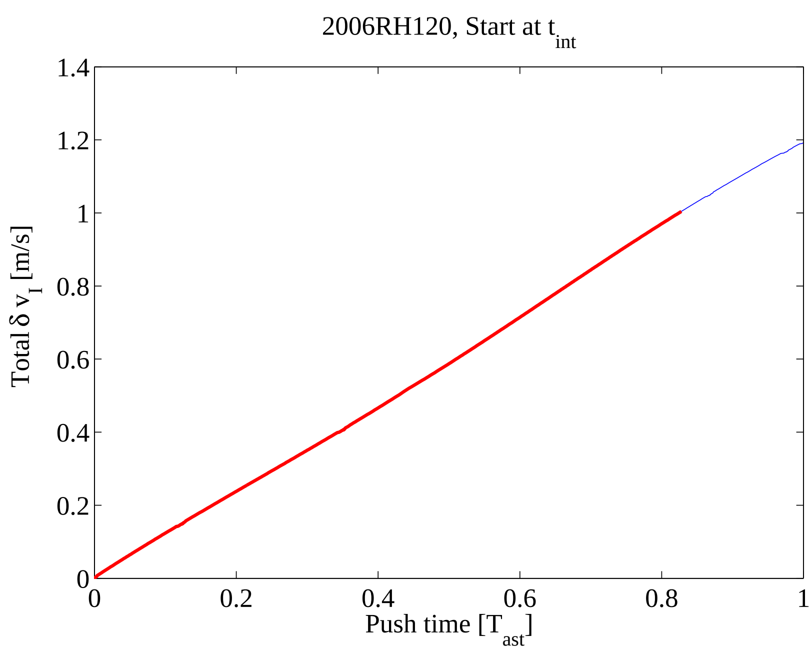

Fig. 8. Thrust Level for the Reduced 480 W Laser Input

If the peak thrust is reduced to 5.5 mN and the input power to the laser is 480 W, the push time increases to 83 % of the orbital period of the asteroid [72, 73]. The accumulative thrust time almost doubles to 302-403 accumulative days. Despite this increase, the time to achieve the 1 m/s deflection action is still achievable within the mission duration of three years.

It should also be noted that the substantial reduction in the laser's input power does not significantly affect the mass of the spacecraft. Only 136 kg is saved. This relates to a reduction of about 0.12 kg/W of laser power. The dry mass is dominated by the structural mass. Here, for reliability reasons a 20 % mass margin was applied. A 20 % margin was also added to existing flight proven components and industry standard hardware. It included the solar array mechanism, impact sensor and thermal components. A more relaxed 10 % mass margin would lower the spacecraft's total wet mass to 779 kg and the dry mass to 445 kg. The result is comparable with the NEAR Shoemaker mission.

OPPORTUNISTIC POTENTIAL

Work also demonstrated the additional scientific, exploration and exploitation potential of laser ablation. Experiments performed by the authors showed how laser ablation results in the subsurface tunnelling and volumetric removal of deeply situated and previously inaccessible material [15, 17]. This is due to the formation of a subsurface groove and the ejection of highly volatile material within the ejecta plume. The ablated material is elementally identical to the original source material. However the absorptive properties - deposited ejecta height, density and absorptivity - are considerably different. Deposition results in a fine, powder-like material that can be easily removed.

The exposure, interaction and possible collection of this newly ablated material can maximise the scientific capability of any contactless deflection-based mission. It can also be used to enhance any remote sensing, in-situ or sample return mission. Deep, subsurface material extraction is not currently possible through conventional exploration techniques. Nor is it being considered in any future asteroid missions (i.e. Marco Polo-R). Sample depth (for an asteroid mission), using current state-of-the-art drilling techniques is limited to a few centimetres below the surface [39]. Laser ablation could therefore be used to advance the scientific return of any planetary, exploration or deflection-based mission. This includes detailed elemental, structural, mineralogical and isotopic analysis.

Mounted onboard a rendezvousing spacecraft, the spectra response of the ablation event could be examined through optical cameras, a laser range finder or a suite of visual-infrared and mid-infrared spectrometers [25]. Data from optical cameras and a laser range finder can determine the shape model, albedo and surface roughness of the asteroid. Spectrometers can perform spectral-thermal analysis, and secondary global mineralogical and compositional analysis. A spacecraft passing through the plume can also be used to collect the ablated ejecta. Material could then be examined in-situ or as part of a sample return mission. The composition and velocity of the ablated material could be assessed by an interstellar dust analyser, microwave spectroscopy or ion mass spectroscopy. An externally mounted sticky-pad mechanism (or similar) could also be used to retrieve the ablated ejecta [26]. This currently provides a passive collection method for loose surface regolith, but could be developed to collect the ablated ejecta [27]. The spacecraft would use the sticky-pad to skim the exposed, ablated surface. Similarly the Stardust mission successfully collected and returned cometary and interstellar material to Earth. Material was captured in aerogel and secured within a sample return capsule.

Laser ablation could also be extended to include the commercial extraction and exploration of resources. The ablation process could be used to mine the extra-terrestrial subsurface material. Any prospecting resource mission would depend on the accessibility of the asteroid, its telescopic spectral analysis, the feasibility of the resource extraction technique and the concentration of material being sought [13]. Analysis performed by Sanchez et al, 2011; Sanchez et al 2012 [58, 60] demonstrated that a substantially large amount of resources (in the order of 10^{14} kg) can be accessed at a relatively low energy level. Using current technologies, neighbouring asteroids ranging from 2-30 m in diameter can be returned for scientific, exploration and resource utilisation purposes [14]. This can occur across a wide spectrum of energy levels. Some are, in fact, more accessible than the Moon. For example, with only 100 m/s of Δv, approximately $8.5 \cdot 10^9$ kg of asteroid material could be exploited [61, 76]. This is significantly lower than any lunar exploration activity, which (due to the presence of a gravity well) is limited to a minimum threshold of 2.37 km/s [6, 63].

It is estimated that a C class asteroid contains 60 % of extractable, useful material. This includes a rich mixture of volatile substances (for example, carbon dioxide, nitrogen, ammonia, water, carbon and sulphur), complex organic molecules, dry rocks and metals (for example, iron, nickel, cobalt, platinum group metals, magnesium and titanium) [8, 29, 30, 43]. Other exotic material, with new and unknown properties, might also form in space [5, 32]. Platinum group metals are siderophiles as they dissolve readily in molten iron. This makes them rare, and therefore expensive, as they are mostly trapped in the Earth's core [21]. The iron content in M class asteroids can be as high as 88 % [44]. They are also believed to be rich in platinum group metals [21]. The iron content for a S class asteroid is reduced to 22 %. It is dominated with silicon dioxide (38 % by mass), magnesium-oxide (24 % by mass) and ion-oxide (10 % by mass) [44]. Extracted material could provide radiation shielding against galactic cosmic rays, distilled for fuel extraction, provide thermal control, space structures, manufacturing and continued life support [16, 18, 36, 50].

Material could either be processed at the in-situ locations, or returned to Earth. Laser ablation could slice the asteroid into multiple, smaller and more manageable segments. Engineering and scientific precursor missions could also be used to test new surface science and extraction techniques. Laser ablation, as a low thrust orbit modification system, could gravitationally capture an asteroid within an Earth or cis-lunar orbit, or around the liberation points of L_1 and L_2 [14, 18, 59, 63, 64]. Here, the asteroid could act as a platform for testing and developing future deep-space operational experience. This would enable manned and robotic missions to extend their reach across the solar system. Asteroids could act as staging posts and life support units for future space exploration activities. It could also kick-start an entirely new in-situ resource utilisation industry [9] or be used for geo-engineering related purposes. Material extracted from a much larger ($>$ 500 m diameter) captured asteroid could create a solar insulating dust ring around the Earth [3, 4, 46, 67]. A cloud of ejected and unprocessed material would become gravitationally anchored at, or around, the L_1 point [1–3]. By preventing, and controlling how much sunlight is absorbed into the Earth's atmosphere, the effects of global warning could be reduced.

TECHNOLOGY DEVELOPMENT

In order to translate the theoretically perceived benefits of laser ablation into a viable space-based application, certain technologies and system design approaches would need to be developed. The most critical component in the design of the AdAM spacecraft (or any other ablation based activity) is the laser system, its associated optics and the cascade effect it has on the design of the power, thermal, GNC and structural subsystems. All other subsystems have a relatively high level of technology readiness. For example, the development of solar arrays and narrow angle cameras are already included in ESA's technology roadmap for general space missions. Further information on the technology readiness of the AdAM spacecraft and the LightTouch^2 mission opportunity can be found in Gibbings 2013; Vasile et al 2013 [15, 72].

The development of a highly reliable and efficient (> 80 %), high power laser will also have a significant impact on a range of terrestrial applications. This includes, but is not limited to: cleaning, mining, cutting, surgery and wireless power transmission. The ablation system (including the laser and the optics) must be capable of focusing and steering the beam onto the surface of the asteroid. It must therefore include control algorithms with in-situ dialogistic integration for adaptive control, and an advanced thermal management system for cooling the laser. The system will also have to be space qualified against the effects of radiation, launch loads, thermal cycling, vacuum and electromagnetic compatibility.

The space-based detection, tracking and ablation of small asteroids could be demonstrated through simple precursor missions. This would support the development of a fully developed deflection mission. It could be achieved in low Earth orbit with a dummy asteroid, a piece of space debris or combining it into a rendezvous mission with multiple themes. The mission opportunity could test the integration of the attitude motion's reconstruction strategy and the in-situ measurement of the asteroid's rotational state. Alternatively a science dominated precursor mission could test the ability of the laser system to analyse the material properties of an illuminated sample. The opportunistic potential of the laser payload would serve as a technology demonstration of an ablation deflection system. Either option would improve the technology readiness level of the laser, optics and ablation process.

CONCLUSION

Results from a series of laser ablation experiments have been used to examine the effectiveness of laser ablation for the deflection and manipulation of NEAs. The experiments studied the development of the ejecta plume and the potential of the deposited ejecta to contaminate any exposed surface. Results were used to validate an improved ablation model and reassessed the performance of laser ablation in providing a deflection action. It has enhanced the current understanding and modelling of the ablation and contamination process for a dense and rocky body. The improved ablation model combined the energy balance of sublimation with the absorption within the Knudsen layer, the variation of sublimation temperature with local pressure, the temperature dependent thermal conductivity of the target material and the partial re-condensation of the ablated material. The momentum coupling was also found to be a key parameter to assessing performance. Together with the expected level of contamination and the minimum power requirement, it will affect the size of the laser system.

The size of the laser system will then drive the surface spot size radius, the onboard optical control and the shooting distance of the laser. The specifications of the laser will also govern the size and mass of the spacecraft's solar arrays and radiators, the physical configuration and accommodation of all payload, hardware and supporting units, and its close proximity operations. Analysis has shown how a space-based laser ablation system can be easily integrated into a conventional solar-powered spacecraft. The design maximised the use of near-term technologies and embraced a robust design philosophy of simplicity, reliability and mission heritage. Laser ablation could be used to explore the further scientific, exploration and exploitation of asteroids. The same technology can also be applied to the active removal of space debris.

Future work is still required to fully develop the ablation model and improve the technology readiness level of critical systems. Described in Gibbings 2013 [15] this includes more detailed, inclusive experiments and theoretical modelling. It is important to understand the three dimensional energy balance of sublimation, the inclusion of solid particles within the ejecta plume and the model's applicability to a greater range of asteroid analogue target material. The scalability of the optical control and the beam quality required to achieve the necessary spot size is also an open issue. It requires further investigation.

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