# INITIAL RESULTS FROM HYDROCODE MODELLING OF THE IMPACT OF SMART–1 ON THE LUNAR SURFACE

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## Abstract

ESA's SMART–1 lunar orbiter impacted the Moon on 3 September 2006. The impact was predicted to occur into a horizontal or shallow sloping surface at approximately 2 km/s; however, observations combined with further imaging of the proposed impact site suggest the spacecraft could have impacted into the side of a hill, therefore representing a 45° to even 90° impact. A brief impact flash was observed, as well as a debris cloud. In support of the end–of–mission campaign, questions remain as to the shape of the crater that might be observable by future orbiters, either by direct observation or indirectly via visibility of a freshly generated ejecta field. Challenges of modelling the impact include: possibly highly grazing incidence and the contrasting effects of the horizontal hypervelocity component and the subsonic vertical component; compaction of the regolith due to porosity; the change in porosity over the upper few metres, and the complex response of the spacecraft structure (e.g. torque effects generated by solar arrays). It may be that the solar arrays broke off, imparting a rotation to the spacecraft platform. We present initial results of hydrocode modelling, performed to understand the cratering process and ejecta production for a hollow cube projectile for a range of impact angles.

## 1 Introduction

The European Space Agency's (ESA) SMART–1 (*Small Missions in Advanced Research Technology*) lunar orbiter was launched in September 2003 on an Ariane 5, with a launch mass of 367 kg. The primary aim of the mission was to test new technologies, including a number of miniaturized instruments. Scientific observation of the Moon was also carried out, to investigate lunar geochemistry and to aid the understanding of the evolution of the

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Earth–Moon system. This highly successful mission culminated in a spectacular 'crash–down' into the *Lacus Excellentiae* region, at 05:42 GMT on 3 September 2006. Preliminary analysis of the topographic stereo and SMART–1 maps suggest that the satellite impacted the Moon in the ascending slope of a mountain, at a height of approximately 1.5 km above *Lacus Excellentiae* (http://sci.esa.int/science-e/www/area/index.cfm?fareaid=10)

Observations of the impact event were carried out by a number of telescopes worldwide, including the Canada–France–Hawaii Telescope (CFHT); early analysis of the period immediately after the impact flash estimated that the cloud of ejecta or debris travelled some 80 km in 130 s (http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=39969). This suggests that some of the ejecta travelled across the mountain that the spacecraft supposedly hit; evidence of the ejecta blanket may provide an imaging target for future missions. It is also possible that the spacecraft ricocheted (perhaps over the hill) on impact with the lunar surface; attempts to observe any remnants of the spacecraft could also be made in future missions. For example, the Lunar Reconnaissance Orbiter (planned for launch in 2008) will have a camera with a resolution of 0.5 m. This may be sufficient to identify any large fragments of SMART–1's solar arrays, should they have survived the impact, given that they measure approximately 6 m each in length.

## 2 Motivation for modelling the impact

Modelling the impact can aid the reconstruction of the impact event, and enable predictions of the crater size and morphology to be made that future spacecraft observations will be able to confirm. We can also compare such a highly oblique impact with normal incidence impact events. Moreover, we can compare and contrast differences in the equally unique impact of the Deep Impact spacecraft into comet Tempel–1 in July 2005. Despite the differences in target materials, we can still learn from the experience gained from these two large scale experiments to aid us in interpreting the data and planning for future spacecraft impact experiments (such as Don Quijote; http://www.esa.int/SPECIALS/NEO/SEMZRZNVGJE_0.html).

Modelling is also beneficial to spacecraft engineers and designers, in understanding how materials respond to such high energy events. For this purpose, we used both AUTODYN–2D and AUTODYN–3D (from Century Dynamics, now ANSYS) and focused primarily on the very early stages of the impact event — that is, the initial stages of impact crater formation and associated ejecta distribution. The response of the spacecraft in the initial stages of the impact event will also be commented on.

## 3 Challenges and assumptions

There are many challenges associated with modelling such a unique event. While we are able to characterise and represent the spacecraft with well–known materials (e.g. aluminium), it is with less familiarity that we can represent the lunar regolith. While we are currently developing a lunar regolith model to implement in AUTODYN, we initially

use the standard sand material data available within the AUTODYN material library. The sand is defined using a compaction equation of state derived from tri–axial compression experiments on sand from Sjobo, which takes into account porosity effects for that specific sand (Laine and Sandvik, 2001). Sand has also been used by other authors to represent the lunar regolith (Burchell and Cole (2006).

We perform vertical impacts (i.e. 90°) using AUTODYN–2D to provide an upper limit of crater dimensions for this impact event, should the spacecraft have impacted face on into a hill or crater wall for example. This is achieved using a 2D version of the code to significantly reduce processing time. We also focus on the predicted highly grazing incidence of $1° − 2°$ from the horizontal, of which there is little modelling experience reported on in the literature. We will also investigate 45° impacts, running at the time of submission of this paper.

The response of the spacecraft to the impact is also important from an engineering point of view; will the solar arrays break off, will the spacecraft body crumple or be melted, and so on. Our results presented here ignore the solar arrays, and focus solely on the effect of the aluminium body impacting into the lunar surface. Determining the spatial resolution of the spacecraft presents some challenges as the geometry of the modelled spacecraft has to be consistent with the actual spacecraft mass. We have emphasized the importance of representing the correct mass of the spacecraft, given that the kinetic energy of the impact will depend upon this. We initially represent our spacecraft as a hollow aluminium block, defined by a Lagrange solver, which is favoured for the description of deformation to solids. An erosion factor is applied to the Lagrange elements to reduce unphysical deformation of the cells. The block is first defined as a solid cube, and then filled with 'unused'. This requires a high level of resolution in order to remove the appropriate amount of material to concur with the mass limit of 285 kg (at present, neglecting solar arrays). So, the higher the resolution, the more accurate the mass is to the real–life situation, but at a greater cost to the processing time, given that a higher resolution results in more cells and therefore more calculations per computational cycle. Our early findings (presented at the workshop, Sept 2006) were built for speed of result production, and so were based on a 700 kg spacecraft, which are presented here for comparison. Subsequent refinement has allowed us to define a $\sim 300$ kg spacecraft.

## 4 Model

We represent the lunar regolith as sand, and model an area of 'regolith' appropriate for the angle of impact, i.e. for a vertical impact a deep cube like area of sand is required (Figure 1a), for grazing incidence impacts a longer, shallower area of material is required (Figure 1b). The target is defined using the *Smooth Particle Hydrodynamics* (SPH) solver, with particle sizes of $\sim 10$ cm. SPH originates from an application in astrophysics and is typically used for modelling intense deformations, such as asteroid collisions (e.g. Asphaug et al., 1998). The main advantage of SPH is to bypass the requirement for a numerical grid to calculate spatial derivatives, thus avoiding grid tangling problems. The SPH particles are 'packed' into the target using an algorithm that places the particles one smoothing length from their nearest neighbours, based on statistical calculations. The aluminium
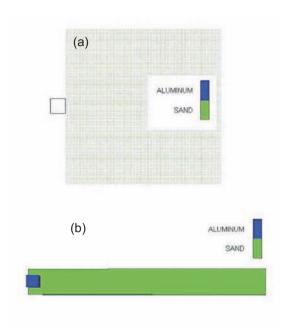
Figure 1: (a) setup for a 90°, vertical impact; impact direction is from left to right and (b) set–up for a highly grazing incidence impact.

spacecraft is defined using the Lagrange solver, as described in the previous section, and in models discussed here has a mass of approximately 300 kg, which equates to 50 cells along each length of the spacecraft. In all models the impact occurs at 2 km/s, which is broken down into horizontal and vertical components according to the angle of impact.

## 5 Results & discussion

Our models are in the very elementary stages of the wider work frame, but it is necessary to complete these before adding more complicated components to the setup. The model output presented here is based on the very first few milliseconds to seconds of the impact event.

### 5.1 90°, vertical impact

Our simple 2D–vertical impact was run for 2 weeks real time, which modelled 369 ms of the impact event. In that time, a transient crater 7.12 m wide and 4.88 m deep was produced. Given that a vertical impact was modelled, the crater is circular. This provides an order of magnitude estimate for the upper limit on the depth of the crater produced on the
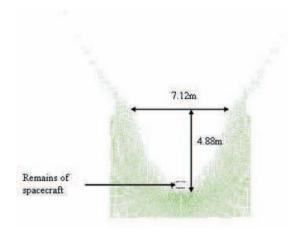
Figure 2: Model output for 90° vertical impact after 369 ms

Moon. The spacecraft itself crumples very quickly upon contact with the lunar surface, presumably due to its hollow construction, combined with the high energy imparted in one direction in a vertical impact.

## 5.2 2°, grazing incidence impact

Given the more complicated nature of a 3D simulation, and the greater number of calculations required per computational cycle in comparison to a similar 2D model, only a few milliseconds of the impact were modelled in the time frame assigned to the project. However, we can still make useful observations based on the model output. Our output shows the initial development of the ejecta curtain, and illustrates clearly the 'butterfly effect' that is a classic signature of oblique impacts, and is not observed in 2D planar impacts. The crater continues to develop after the spacecraft has bounced away, indeed Figure 3 shows the development of the ejecta curtain less than 0.1 s after the initial impact (for the heavy SMART–1 model). At this time, the ejecta is travelling at 400 m/s, and has extended to at least 20 m wide and 5 m high. The lighter SMART–1 model has not yet been run to a comparable time. In both simulations, the spacecraft appears to bounce after the initial impact with the lunar surface (Figure 4). For the 700 kg spacecraft, this occurs at around 8 m; for the lighter, more realistic SMART-1, this bounce occurs at about 10 m. The spacecraft remains largely intact in both simulations (Fig. 5), although the model was not run for as long as the 90° impact.

## 6 Comparisons with Deep Impact

In July 2005, the Deep Impact (DI) spacecraft released a $\sim$ 360 kg probe that collided with Comet 9P/Tempel 1 at $\sim$ 10.2 km/s. The impact revealed the comet to be dustier
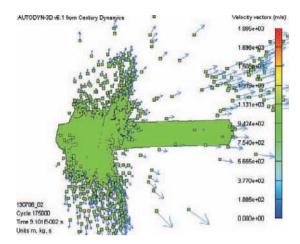
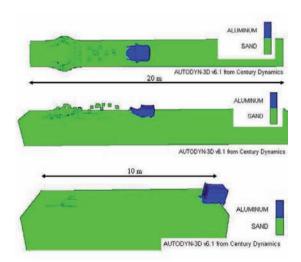Figure 3: Development of the butterfly–shaped ejecta seen in the 700 kg spacecraft simulation.



Figure 4: Top and middle: overhead and side view respectively of the 700 kg spacecraft impact. Bottom: side view of the 300 kg SMART–1 impact. Both images are taken after 4.5 ms and show that the spacecraft bounces after the initial impact with the lunar surface.
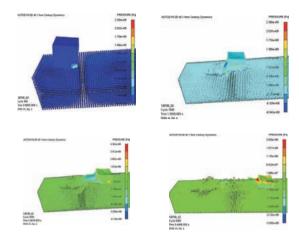
*Figure 5: These images show the propagation and decay of peak pressures within the spacecraft itself for the very early stages of the impact event. The deformation of the spacecraft is due to the numerical 'erosion' factor that is applied to avoid extreme distortion of the cells and subsequent failure of the model.*

and less icy than expected and the impact generated a large, bright dust cloud that obscured the hoped–for view of the impact crater. However, predictions based on laboratory experiments and analytical scaling suggested the crater should be a few hundred metres in diameter, a few tens of metres in depth and would form in a few minutes. In analyzing the images from the impact, Schultz (http://deepimpact.jpl.nasa.gov) was able to identify several stages of crater formation that are characteristic of an oblique impact. The first sequence revealed a double flash: a faint initial flash at contact and then a delay before a brilliant flash saturated the images. A bright plume left the comet at high speed and formed an arc; this represents the vapour phase and is very similar to that observed in experiments at the NASA Ames Vertical Gun Range (AVGR). A conical curtain of ejecta that gradually expanded was visible in images as the camera looked back at the impact.

Although the mass of the spacecraft is comparable to the SMART–1 impact, the velocity of the Deep Impact event is five times higher. Indeed, the kinetic energy of the Deep Impact event was almost 20 GJ, while the SMART–1 impact was less than 1 GJ. The output of these two impact events cannot be compared directly, but the lessons learned from using spacecraft as planetary penetrometers can certainly be used to direct future penetrometry missions.

## 7    Comparisons with lab impacts

Laboratory simulations of the SMART–1 impact performed by Burchell and Cole (2006) at the University of Kent accelerated 2 mm aluminium spheres at 2 km/s into fine grained sand, used as an analogue for lunar soil. The target tray was tilted to 2º to represent

the grazing incidence of the SMART–1 impact. The experiment produced a non-circular crater, with material spreading out forward and sideward from the crater. Based solely on these laboratory results and ignoring issues of scaling, Burchell et al. (2006) estimated the SMART–1 impact crater to be 7 m long and 4.5 m wide. Our 90º impact produces a circular crater approximately 7 m in diameter; however our oblique incidence simulations were not run to a comparable time. A ricochet of the projectile was also observed in experiments, suggesting a bounce of the projectile; simulations of our grazing incidence impact also suggest a bounce at about 8–10 m. Issues arise in direct scaling from experimental to planetary–sized impacts due to the difference in physical regime between small (lab scale) and large (planetary scale) impact crater formation; lab scale impact craters are primarily governed by the strength of the materials, whereas large planetary impacts are controlled by gravitational forces. While the speed of the SMART–1 impact was comparable to speeds attainable in the lab, the size of the impact is not. In addition, laboratory craters generally predict the size of the transient crater, while those observed in a gravity-dominated environment will have been modified accordingly. However, due to the low–velocity nature of the SMART–1 impact, the laboratory experiments provide a useful estimate of the order of magnitude of the resulting crater, which are indeed comparable to our predictions using AUTODYN.

# 8   Future work

Modelling the impact of SMART–1 into the lunar surface is challenging and requires many assumptions and simplifications to be made. Indeed, our model output presented here is based upon the simplest representation of the impact event. For future attempts, we intend to consider the following:

1. Solar arrays: our model currently represents the impact of a hollow aluminium cube; the inclusion of arrays will likely alter the impact dynamics of the spacecraft upon impact with the lunar surface, particularly if the spacecraft strikes at an angle at varying degrees of pitch and/or yaw.

2. Resolution: the resolution of the current model results in a mass of  300 kg, of the aluminium cube alone. When considering the other components of the spacecraft (i.e. the solar arrays), the resolution of the model will have to be increased, in order to resolve a smaller mass.

3. Lunar regolith: current models substitute lunar regolith for sand, a well defined material in the AUTODYN material library. Data from various sources (e.g. the Lunar Sourcebook) will be projected onto the Sand equation of state (Laine and Sandvik, 2001) for initial comparison of the two materials. More advanced work will focus on the experimental derivation of lunar simulant properties, through analysis of shock propagation through the material, which will then be implemented into AUTODYN as a new material. The effects of porosity should also be considered, as in Wünnemann et al. (2006).

4. Equation of State: other equations of state will be investigated, including the Porter-Gould EoS as implemented by Church et al. (2006).

We will also compare our predictions with future observations of the impact site, taking into account post–transient crater slump. Lessons learnt from this modelling exercise could be used in the future to apply to other planetary penetrators, including Europa penetrators into porous, cryogenic ice.

**Acknowledgements**

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