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Proposal Title : **IMPACT CRATERING: THE EFFECTS OF TARGET TOPOGRAPHY AND HETEROGENEITY**

SECTION VII - Project Summary

INTRODUCTION: Impact cratering has been and continues to be the dominant macroscopic surface process on the majority of solid bodies in the solar system. Impacts form craters that act as subsurface probes, excavating subsurface material and depositing it outside of the crater, generating and mixing the regolith, and launching future meteorites. Current knowledge of the excavation and modification of impact craters from experiments and numerical models is limited primarily to cases of flat, homogeneous, and uniformly layered targets. Thus, existing experimentation and numerical modeling provide only first-order guidance when considering the effects of impact in a realistic environment: rough terrain that can be as heterogeneous in structure at depth as it is irregular at the surface.

SCIENCE GOALS AND OBJECTIVES: The goal of this proposed work is to take the next logical step in experimental impact-cratering studies by investigating the effects of regional target topography and strength heterogeneity on the impact process. In particular, we will identify how these variables affect the excavation of materials from a growing impact crater, the growth and modification of the crater shape, and the final crater morphometry. We will use these results to adapt and modify existing crater-scaling relationships to describe the behavior of such complex targets.

METHODOLOGY: Impact-cratering experiments will be performed at the Experimental Impact Laboratory at NASA Johnson Space Center. Two non-invasive experimental techniques will be used to observe the cratering process in real time – the Ejection-Velocity Measurement System (EVMS) and a Real-Time Profiling System (RTPS). The EVMS projects a vertical laser plane through the impact point and perpendicular to the target surface. This laser plane is strobed at a known rate while a CCD camera images the event, which allows individual ejecta particles to be tracked along their ballistic trajectories to determine the particle's ejection position, speed, and angle. The RTPS projects a laser plane vertically onto the target surface to illuminate a cross-section through the growing impact crater, which is then imaged by a video camera. This allows the crater profile to be traced during crater excavation, growth, and modification. Both of these techniques will provide insight into the effects of target topography and heterogeneity on the highly dynamic process of crater excavation, growth, and modification. A 3D laser scanner will be used to determine crater shapes and dimensions with submillimeter precision.

RELEVANCE: Impact cratering is a major process affecting planetary surfaces at all scales and throughout time in the solar system. The experimental studies of the dependence of impact cratering on target topography and heterogeneity proposed here are relevant to Solar System Workings in terms of the "evolution and modification of surfaces." (Appendix C.3).

IMPACT CRATERING: THE EFFECTS OF TARGET TOPOGRAPHY AND HETEROGENEITY

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CONTENTS

1 SCIENTIFIC/TECHNICAL/MANAGEMENT

1.1 Introduction and Implications

Impact cratering is a fundamental physical process that has dominated the evolution and modification of every planetary surface in the Solar System. Impact craters act as probes of a planetary surface, excavating subsurface material and depositing it outside of the crater, generating and mixing the regolith on airless bodies, and launching future meteorites off a surface. In order to capitalize on the utility of impact craters as a means of probing a planet's surface, it is important to improve our understanding of the impact-cratering process itself. High-speed accelerators have been used for decades to investigate the impact process in a controlled laboratory environment. New experimental methods allow more quantitative and higher-resolution studies than ever before, illuminating the dynamics of the excavation and modification of growing impact craters in real time [Cintala *et al.*, 1999; Anderson *et al.*, 2003; Barnouin-Jha *et al.*, 2007]. The work proposed here seeks to expand our understanding of the impact cratering process by using these quantitative experimental methods to examine more realistic models of planetary surfaces in the laboratory. Well-defined scaling relationships [*e.g.*, Chabai, 1965; Holsapple and Schmidt, 1982; Housen *et al.*, 1983; Housen and Holsapple, 2011] can then be used to extrapolate the laboratory results to planetary surfaces allowing the application of experimental results to crater morphology on the Moon, Mercury, and asteroids.

Current knowledge of the excavation and modification of impact craters from experiments and numerical models is limited primarily to cases of flat, homogeneous, and uniformly layered targets. The only experiments in granular material with any kind of topography known to us were intended to examine the effects of target curvature during very large impacts on spherical bodies [Schultz *et al.*, 1986; Schultz, 1988]. Recently, the first preliminary report of numerically modeled impacts into sloped topography has concluded that the distribution of material ejected during impacts is significantly affected by topography [Elbeshausen and Wünnemann, 2011]. Impact crater morphology and morphometry have been linked to the thickness of a clastic layer (the regolith) on top of a more competent rock unit (typically basalts) on the lunar surface by Oberbeck and Quaide [1968]. Gault *et al.* [1968] experimentally investigated the effects of interbedded competent and incompetent strata on subsurface crater structure. Numerical simulations have explored layered targets [Senft & Stewart, 2007] and Bart et al. [2011] and Bart [2014] have tested these models using lunar craters. Schultz [2000, 2007] performed experiments into low-impedance layers on top of solid targets to investigate the extent to which such layers can minimize the damage in the underlying competent substrate; similar experiments were performed by Dohi et al. [2012]. Beyond these examples, the added complexities of heterogeneous targets or targets with regional surface topography have not yet been investigated with the goal of applying results to crater-scaling relationships. Thus, existing experimental data and numerical modeling results provide only first-order guidance when considering the effects of impact in a realistic planetary context: rough terrain that can be as heterogeneous in structure at depth as it is irregular at the surface.

The goal of the proposed work is to take the next logical step in experimental cratering studies by investigating the effects of target topography and subsurface heterogeneity on the impact process. In particular, we will identify how these variables affect the excavation of material from a growing impact crater, the growth and modification of the crater shape, and the redistribution of ejected material. We will use a combination of laser illumination and high-speed photography of impact experiments in targets with topographic or subsurface structures similar to those expected on actual planetary surfaces to follow the excavation and modification of growing craters in real time. Experimental data will be used to establish criteria that will guide the interpretation of a cratered surface, specifically those on airless bodies such as the Moon, Mercury, and asteroids with topographic terrains and strength-layered substrates.

1.2 Objectives

- To design a variety of simple targets for use in impact experiments that more realistically approximate sloping topography and strength-layered subsurface heterogeneities as expected on planetary surfaces.
- To use these targets in impact experiments to examine the effects of topography and target heterogeneity on impact-crater excavation, growth, and modification through the use of a high-resolution ejecta-particle tracking system, a real-time crater-cavity profiling system, and three-dimensional measurements of final crater morphometries.
- To modify existing scaling relationships to accommodate the effects of regional topography and subsurface layering and to apply our findings to the interpretation of simple craters on planetary surfaces, specifically the Moon.

1.3 Background

Studying the impact-cratering process is challenging for a number of reasons. The events in question are very large, energetic, and (luckily) not common in recent times on the Earth's surface, so we have very little experience in observing the natural process itself. The Moon has been an enormous resource for morphological and morphometric data about impact craters and has guided our current best understanding of their formation. Field geology at terrestrial craters has allowed us to examine the three-dimensional structure of impact craters and further illuminate the cratering process. The use of accelerators in the laboratory has allowed variables affecting the impact-cratering process to be controlled and the mechanics of formation to be studied in detail at small scales. These experimental results can be scaled to planetary-sized impacts using well-developed, non-dimensional relationships. Mathematical models using first principles have become easier to run as computers have become faster, providing a look at the impact process at larger scales. Experiments, numerical models, and observations have led to the current understanding of the impact cratering process and final crater properties (Fig. 1).

While both experiments and computational models have produced great insights into the impact-cratering process over the past few decades, they typically treat the original target surface as horizontal with a homogeneous to relatively simple subsurface structure. This is a realistic target scenario for some craters, most notably Meteor Crater, with its distinctive layering and ejecta deposits [*e.g.*, Shoemaker, 1963; Grant and Schultz, 1993; Kring, 2007; and references therein]. Meteor Crater was emplaced in a locality that has, in contrast to the Moon, simplified target stratigraphy, subsurface structure, and topography. A more realistic target has a more rugged

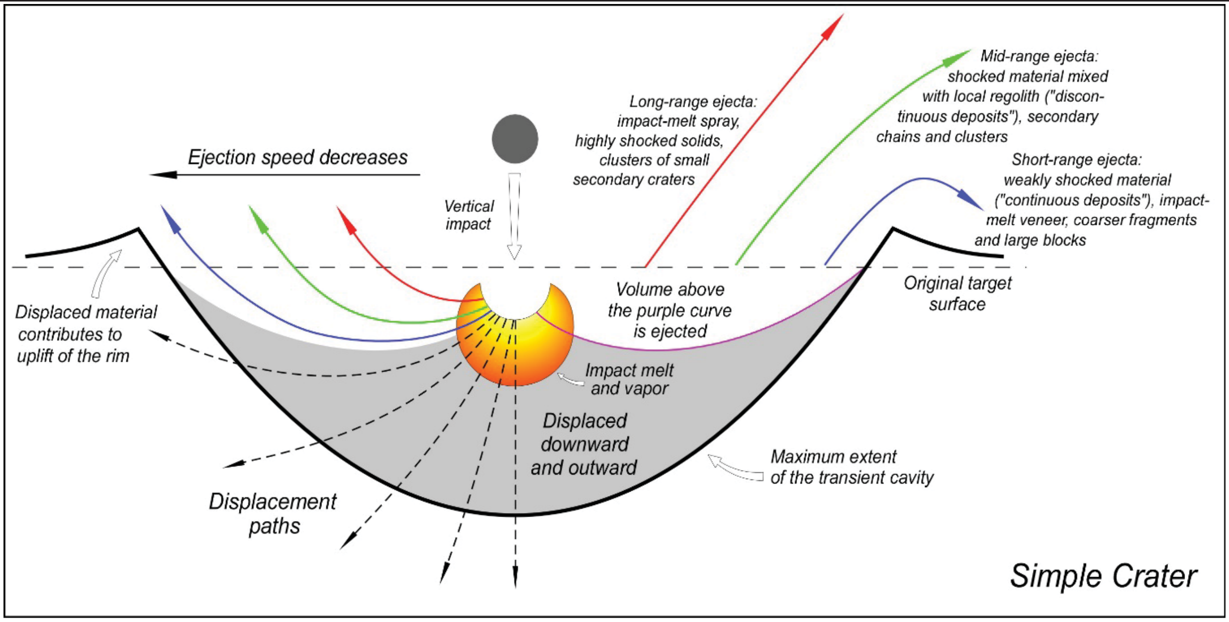

Figure 1. Highly schematic version of the excavation flow-field generated by an impact. The left side shows possible flow lines, although their exact shape is not known for impact events. The right side summarizes the characteristics of ejecta from each of the example trajectories on the left (colored arrows). Note that all of the affected material is forced away from the impact site; some is ejected, while most is compressed downward and radially outward, resulting in "plastic deformation" of the target. This component typically composes more than half of the cavity's volume. Material excavated early in the event originates near the impact point at shallow depths, suffers the most intense shock effects, is ejected at higher speeds, and travels farther compared to material excavated at later times.

topography and is potentially layered. These complexities appear to affect crater excavation and modification [for example, see Plescia & Spudis, 2014], although the exact differences from impacts into flat targets is not yet understood. Numerous examples on the lunar surface exist that demonstrate the effects of heterogeneities in the target surface on a final crater's form.

Craters in Sloping Targets: For example, Fig. 2 shows the simple lunar crater Lowell H which formed on the rim of the larger Lowell crater [Plescia and Spudis, 2014]. The continuous slope of the crater rim affected the final shape of the smaller crater, resulting in half of Lowell H looking "normal" on the eastern side and the downslope half appearing smaller and deformed. The only experiments of which we are aware that varied the topography of the surface used a hemispherical target to investigate the effect of impact onto a spherical planet [Schultz *et al.*, 1986; Schultz, 1988] and were not looking at small-scale details of simple craters in targets with regionally sloping topography.

Craters in Layered Targets: Quaide and Oberbeck [1968, 1975; see also Oberbeck and Quaide, 1968] first proposed that small, flat-floored craters and craters with concentric interior structures (Fig. 3) might be formed in targets that are strength-layered. In particular, they invoked a more friable layer above a more competent layer as one might expect in the maria, with a regolith a

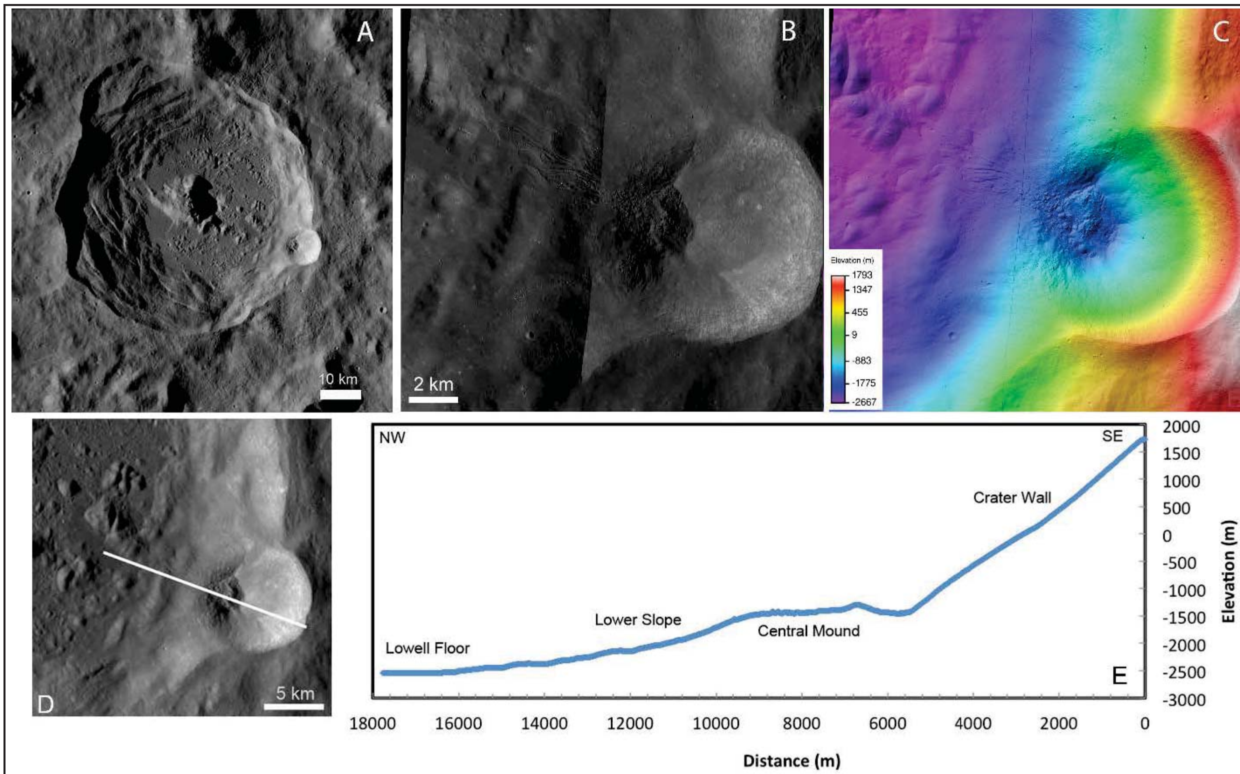

Figure 2. Example of a crater in a target with topography. North is to the top in all images. (A) Lowell crater, Orientale Basin, the Moon, with Lowell H superimposed on the east-southeast crater rim. (B) Close-up of Lowell H showing asymmetric interior morphology. (C) Topographic map of Lowell H. (D) Topographic profile location across Lowell H. (E) Topographic profile from Lowell crater's rim through Lowell H and onto the floor of Lowell crater. [Modified from Plescia & Spudis, 2014].

few meters thick atop a basalt flow. By performing impact experiments with such layered targets, Quaide and Oberbeck were able to reproduce the general morphology of these small craters, determining a quantitative relationship between crater morphology and the thickness of the regolith. That relationship, in turn, could be used to estimate the thickness of a regolith on any lunar mare from observations of such craters, as was completed by Bart *et al.* [2011] and further quantified by Bart [2014] using numerical modeling of impacts into layered targets by Senft & Stewart [2007]. With the advent of new quantitative imaging techniques in the laboratory, we can investigate how the excavation flow, crater growth, and modification of the crater are further affected by the subsurface layering and examine the distribution of ejected material inside and beyond the crater.

1.4 Technical Approach and Methodology

The work proposed herein is divided into two primary tasks that will examine the effects of target topography and subsurface heterogeneity on the excavation, growth, and modification of experimental impact craters. The descriptions of the tasks refer to the three main laboratory techniques that will be used, so it is appropriate to describe those methods first.

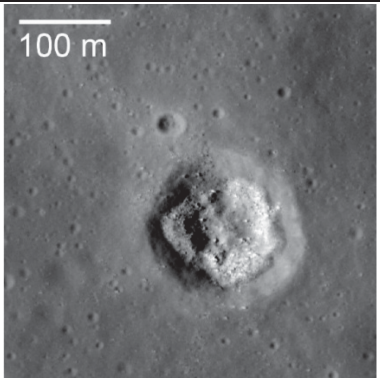

Figure 3. Example of a crater into an inferred strength-layered target. This 170-m crater is located on the mare near the Apollo 12 site and displays concentric morphology. Within the crater is a concentric bench, 90–100 m in diameter, formed by rocky debris. Such craters are typically found on the maria, where the regolith is a few to perhaps a few tens of meters thick and overlies a more competent rock unit. [-3.297 / 336.708E, M104661862RE]

1.4.1 Laboratory Techniques

At the moment of impact, a projectile begins to transfer its energy and momentum to the target material, establishing a subsurface flow-field (Fig. 1) that acts to enlarge the growing crater cavity by initially compressing target material downward and outward, and then subsequently ejecting material upward and outward in an expanding ejecta curtain as the target decompresses [Gault *et al.*, 1968]. The angles and speeds at which particles are ejected from the target's surface can be used to track the evolution of the sub-surface flow-field [Anderson *et al.,* 2004; Anderson and Schultz, 2006]. Current analytical models (such as the Z Model [Maxwell 1973, 1977; Orphal, 1977]), the majority of numerical models, and non-dimensional crater-scaling relationships assume flat, homogeneous targets. The extent to which surface topography and subsurface structure affect the excavation flow of a growing crater or its subsequent modification is critical to assessing the distribution of materials around and within the final crater. To do this, we will conduct impact experiments using techniques that allow us to track individual particles in the ejecta, monitor the crater's growth as a function of time, and obtain a three-dimensional map of the final crater morphometry.

Ejection Velocity Measurement System (EVMS)

Quantitatively observing the ejection speeds and angles of individual particles during laboratory-scale impacts is possible using the laser-based Ejection Velocity Measurement System [EVMS; Cintala *et al.*, 1999]. A vertical laser plane, passing through the impact point, is oriented at a known angle to the viewing direction of a CCD camera (Fig. 4A). Laser illumination is triggered by the impacting projectile and strobed at a known frequency while the camera shutter stays open. The resultant image allows individual ejecta particles to be tracked along their ballistic trajectories (Fig. 4B) to determine the particle's ejection position, speed, and angle (Fig. 4C). These data can then be compared to ejection-speed scaling relationships.

The EVMS offers a unique window into the removal of material from the growing cavity during its excavation. The effects of target topography and layering on crater excavation can be tracked quantitatively and compared to ejecta kinematics during impacts into flat, homogeneous targets [Cintala *et al.*, 1999; Anderson *et al.*, 2007, 2010, 2014]. The distribution of ejection velocities leads to the final ejecta distributions outside of the impact crater; insight into the dependence of

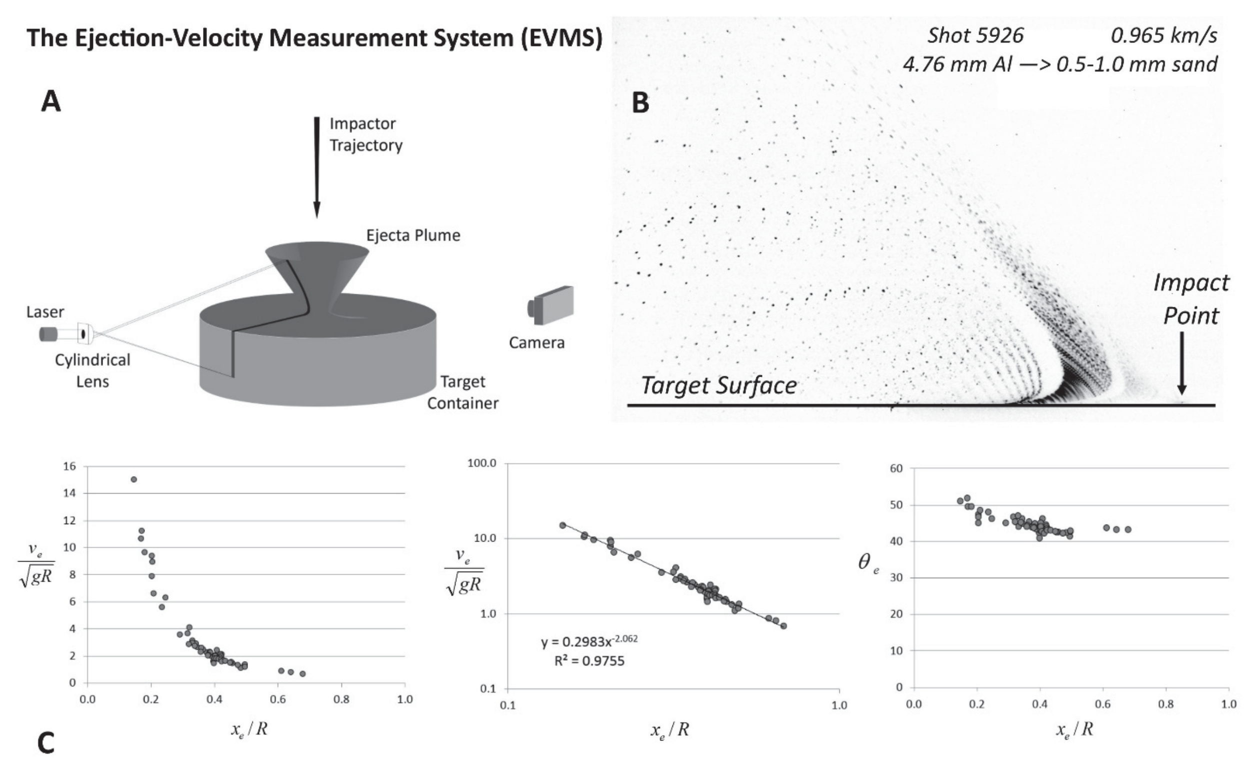

Figure 4. (A) Schematic of the Ejection-Velocity Measurement System (EVMS). (B) EVMS image showing the ballistic trajectories of individual ejecta particles. (C) Image analysis results in quantitative data on ejection speed (v_e), position (x_e), and angle *(θ_e)* as the crater grows that can be compared to those predicted by scaling relationships. (Gravitational acceleration, *g*, and final crater radius, *R*. Fit to the ejection-speed scaling relationship is shown in center graph; for more discussion see Section 1.4.5.)

these distributions on target topography and heterogeneity can assist in interpretation of crater geomorphology and ejecta deposition on planetary surfaces.

Real-Time Profiling System (RTPS)

Throughout the excavation stage, target material moves downward and outward around the expanding crater cavity (Fig. 1). Near the end of crater expansion, target material in the center of the crater cavity may rebound upward and material may slump downward off the crater walls [Gault *et al.*, 1968]. A real-time profiling system (RTPS) has been developed at the JSC Experimental Impact Facility (EIL) which allows for the quantitative observation of these modifications to a growing crater (see similar method described by Barnouin-Jha *et al.* [2007]).

A laser plane is projected into the growing cavity and observed using a high-speed digital video camera via a first-surface mirror mounted on the opposite side of the impact chamber (Fig. 5). In this case, however, the laser line projected onto the target surface is on continuously, illuminating the profile of the growing cavity. The video camera, framing at a known rate, images the crater interior as it grows; use of the video camera will preclude overexposure of the early stages of crater growth by the impact flash (as would occur with a time exposure and a strobing

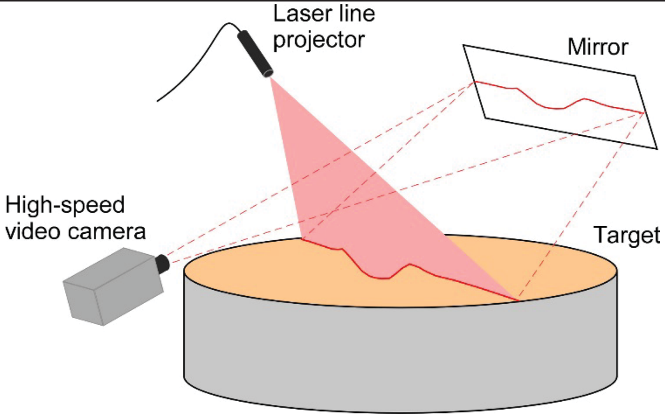

Figure 5. Real-time profiling system (RTPS). A laser line illuminates the profile of a growing impact crater which, in turn, is imaged by a high-speed video camera.

laser), permitting data to be collected very near the impact site. This geometry also illuminates the trailing edge of the ejecta curtain, unlike the EVMS system which illuminates the leading edge. The rate of growth of the transient cavity and the time required to form the crater can then be determined directly from the scale of the photographs and the framing rate of the video camera.

This technique will provide insight into the effects of target topography and heterogeneity on the highly dynamic process of crater growth and modification. This system and the EVMS will provide fundamental new information to be used in refining scaling relationships, tuning numerical models, and examining impact craters and their deposits on Earth, the Moon, and other planets.

Three-Dimensional Crater Scanner

In the past, the final crater was removed from the impact chamber and a simple profilometer was used to measure a profile across the crater (Fig. 6A). A major update to the techniques available at the Vertical Gun is the addition of a NextEngine 3D laser scanner that will record final crater topography. The scanner is inserted into the impact chamber above the target container. For each shot, the target surface will be scanned prior to and after the impact, resulting in three-dimensional maps of the original target topography and the final crater morphometry. There are three substantial benefits to this new system. First, the final crater does not have to be moved outside of the chamber, minimizing the risk of any slumping or other modification to the crater prior to measuring its morphometry. Second, the three-dimensional map of the final crater morphometry contains far more information than a simple linear profile through the crater (Fig. 6B). Third, the original target topography can be subtracted from the final crater morphometry to examine exactly how the target surface has been modified by the impact. This will result in very accurate measurements of the shape of the crater in all azimuths around the impact point and with respect to any topography or subsurface heterogeneity in the original target. This is a substantial advance in quantifying the final crater morphometry in these experiments.

1.4.2 Experiment Design

For consistency, all of the proposed experiments will be performed under conditions as similar as possible, changing only the target characteristics of interest. We will use 5 mm glass projectiles with a density near 2.6 g cm^{-3}, similar to the intrinsic density of the target material which, for all of the topography experiments, will be a fine-grained sand that is sufficiently coarse (>0.25 mm) to permit photography of individual grains by the laser-based systems. This same sand will be used as the bulk target in the heterogeneity experiments, modified to examine layered targets as discussed below. We have built larger target containers out of PVC to maximize the volume

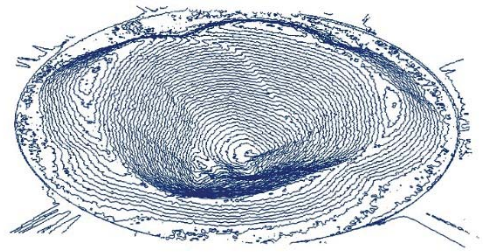

Figure 6. The new three-dimensional crater scanner digitizes the entire crater's surface rendering a three-dimensional map of the final crater as shown by this example of a test depression made in the target container.

of our target while still allowing the buckets to be moved by a single person. The new small and large target containers are 12.1 cm high and 26.1 and 31.3 cm in diameter, respectively. In this way, we can minimize any boundary effects from a shock wave hitting the edge of the container, although it should be noted that the shock energy decays as distance squared at a minimum and the sand targets would attenuate shock and stress waves even further. In our EVMS work up to this point, we have not seen any alteration of the ejecta that we might ascribe to a reflecting shock wave. However, in the interest of moving up to denser projectiles and higher speeds, new containers were needed.

All impacts will be vertical, meaning that the projectile momentum vector will be parallel to the gravitational acceleration vector, which is fixed by the design of the Vertical Gun itself. The impact speed will be held constant throughout all experiments at 1.5 km s^{-1}. (The vertical gun is capable of speeds close to 3 km s^{-1} that are reproducible to <1%.) We note that these impact speeds are well below those occurring on the Moon which is why standard scaling relationships will be used to extrapolate our findings to planetary scales (see Sect. 1.4.5). Pressures in the impact chamber will be held to ~1 torr to minimize drag forces on the ejecta. Note that four experiments per work day is typical, but the number may decrease to two or three per day based on the complexity of target construction.

Experimental Series 0: Impacts into Flat, Homogenous Targets

Our first (3-5) experiments will be control shots under the conditions described above, using a homogeneous target with no topography. This will allow us to examine a "normal" impact using our two laser-based techniques; investigate the excavation, growth, and modification of the growing crater; determine the three-dimensional morphometry of the final crater; and obtain a dataset that we can use to compare to future experiments in this proposal.

1.4.3 Task 1: Effects of Regional Topography

There is very little in the archives of experimental impact cratering that can be used as a guide for this task. Therefore, we will start our examination of the general effects of topography by conducting a series of experiments into targets with *regional topography* where an impact occurs into a target whose entire surface is at a constant slope. In this case, the topography's length scale is much larger than the final crater's diameter. Future work will include investigation of targets with local topography, such as slopes on the order of the crater diameter, ridges, and valleys. We anticipate little difficulty in constructing the simple topographic elements described in this proposal (see our proof-of-concept example in section 1.4.7). Maximum slopes will be limited by the angle of repose of the target sand, fortuitously differing little from the maximum slopes observed over most of the Moon.

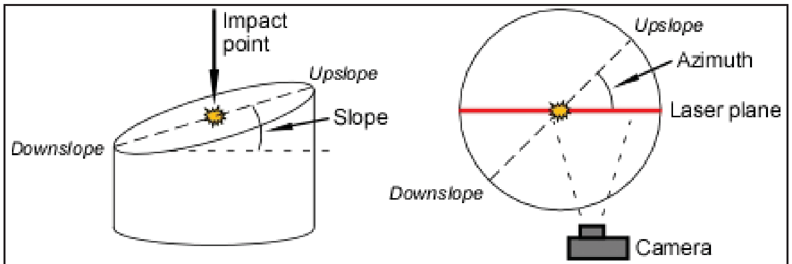

Figure 7. Side (left) and top views of the experimental target with a regional-slope dimension >> crater diameter. By rotating the target container, we can image different azimuths of the growing crater and ejecta, resulting in a three-dimensional characterization of the cratering process under these conditions. Laser illumination can occur optionally from the side or from above the target.

Experimental Series 1: Regional Topography (Fig. 7) will be examined by simply varying the slope of the target surface from zero in 5^{o} increments up to the maximum angle of repose (~35°). In order to fully characterize the effect of slope in all directions of azimuth around the impact point, we will also vary the azimuth (the angle between the upslope direction and the laser plane) from 0° (upslope direction parallel to and illuminated by the laser plane) to 45°, 90°, 135°, and 180° (downslope direction parallel to and illuminated by the laser plane), resulting in 35-40 impact experiments total. An impact-flash detector will be used to trigger the main EVMS illumination laser, assuring that event illumination will begin at or within microseconds of projectile contact with the target.

It is important to note here that a vertical impact into a sloping target surface is not the same as an oblique impact into a flat surface (Fig. 8). The subsurface flow-field set up by the impact should intersect the target surface differently in the upslope versus downslope direction, assuming a traditional flow-field such as that predicted by the Z-Model [Maxwell, 1973, 1977; Orphal, 1977], affecting the angle and speed of the ejected particle; this hypothesis will be testable using the EVMS data. When material is ejected from the sloped surface, the gravitational-acceleration vector defines the ballistic trajectories of the particles. In the case of a vertical impact into a sloped surface, the gravity vector is parallel to the momentum of the projectile, whereas it is different from that of the projectile momentum in oblique impacts. This will affect the subsurface flow-field of the particles, leading to differences in the excavation of the crater from upslope to downslope. Finally, gravity and friction takes over near the end of transient-cavity formation to end crater growth and modify the final crater shape, which will be different in the upslope and downslope directions (see Fig. 2). Direct comparison will be possible between our excavation-flow data for impacts into sloped surfaces and earlier work that examined excavation-stage flow during oblique impacts [Anderson *et al.,* 2003, 2004].

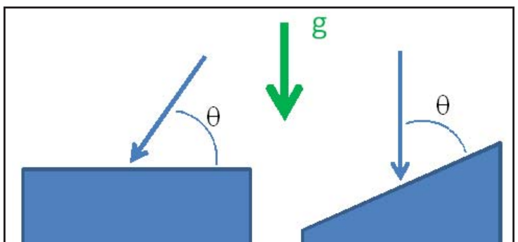

Figure 8. The momentum vector of an incoming projectile is not parallel to the gravity vector during an oblique impact (left) as compared to a sloped target in these experiments (right).

1.4.4 Task 2: Effects of Target Heterogeneity

Target heterogeneity, in this context, means any notable deviation from a target with homogeneous properties throughout its volume. For this proposal, we will focus on the type of target heterogeneity expected within the lunar maria: *strength-layered targets*.

Future work will include investigation of targets with other heterogeneities such as buried block populations.

Experimental Series 2: Strength-Layered Targets (Maria): The subsurface structure in the maria is a consequence of their sporadic volcanic histories, in which regoliths could have developed on exposed flow surfaces between eruptions. The result could have been an intercalated unit, alternating between relatively coherent basalts and immature, fragmental regoliths. Depending on the specific eruption history, any number of such layered sets could have formed.

The proposed experiments in this series will require materials to simulate the regolith (the same sand used in the topographic experiments) and the basalt flows (Fig. 9). Recently, we have had success creating stronger layers with sodium-silicate bonded sand. A dilute Na-silicate solution is mixed with the sand and then allowed to dry, resulting in a solidified material whose strength can be varied by varying the weight percent of Na-silicate in solution. A Chatillon TCD-1100 force-measuring stand has been purchased for the EIL allowing us to quantify the strength of the bonded sand for comparison to other experiments and numerical models.

Because these represent a new type of experiment and the nature of the results is somewhat uncertain, we will restrict most of the layered-target experiments to a single layer of "basalt." We will then vary the thickness of the "regolith" sand systematically, observing the ejecta and transient cavity with the laser-illuminated photography. At 1.5 km s^{-1}, craters formed from 4.76-mm aluminum projectiles in sand with the vertical gun are typically about 17 cm in diameter. Oberbeck and Quaide [1968] first observed flat-floored craters when the ratio of the crater diameter to "regolith" thickness in their experiments was approximately 4.25. Bart [2014] further quantified this relationship by comparison with numerical models of impacts into layered targets [Senft & Stewart, 2007]. These studies imply that we will begin to observe this morphometric change in our experiments when the "regolith" (or sand) layer is ~4 cm thick. Therefore, we will start with a thick regolith layer of 6 cm and compare the results to our control craters as we thin the regolith until we see differences in ejection kinematics and final crater morphometry/morphology; we estimate that ~6 different regolith thicknesses will be needed to characterize the transition. In addition, we can further test the quantitative relationship derived by Bart [2014] by identifying the morphologic transitions from central mounds to flat floors to concentric craters in these experiments. We note that the effects of spallation in targets with tensile strength can lead to notable shot-to-shot variations, even for identical, vertical impacts [*e.g.,* Gault, 1973]. Therefore, once we observe the effect of the substrate, we will perform a set of three control experiments using identical target configurations for each new regolith thickness to document the variances in ejection speeds and angles; this will avoid generalizing from a single, possibly unrepresentative event.

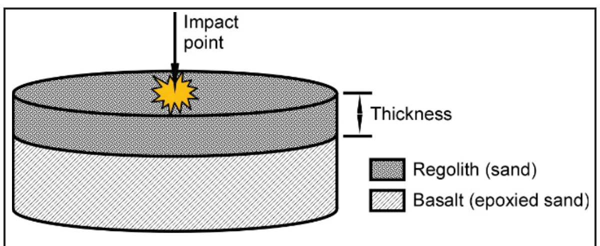

Figure 9. Strength-layered target. The lighter layer represents a more coherent basalt below a regolith, as is characteristic of the mare. The "basalt" layer will be a mix of sand and sodium-silicate that has been dried to result in a stronger material.

We estimate that it will take approximately 20 experiments to characterize the effect of a stronger layer beneath a regolith of varying thickness on the excavation, growth, and modification of an impact crater.

1.4.5 Dimensionless Scaling Relationships

The initial conditions of an impact can be related to the excavation flow and the final crater's size through what are now standard, dimensionless scaling relationships [*e.g.*, Chabai, 1965; Holsapple and Schmidt, 1982; Housen *et al.*, 1983; Housen and Holsapple, 2011]; they have proven very useful in aiding our understanding of the various processes that lead to the formation of planetary-scale craters. In fixing the initial conditions and by providing direct measurements of ejecta kinematics and final crater morphometries [*e.g.*, Cintala *et al.*, 1999; Anderson *et al.*, 2003], laboratory experiments, in turn, provide valuable constraints important to the further development of scaling relationships, while lending additional insight into the impact process at planetary scales.

Very briefly, final crater dimensions can been tied to the initial impact conditions through dimensionless groups ("Π-groups," [Buckingham, 1914]) of relevant variables (such as projectile and target properties, projectile size, impact speed, and gravitational acceleration); these relationships point to a single parameter α governing the slope of a power-law form relating the scaled crater dimensions to the scaled projectile energy (eq. 1) [Holsapple and Schmidt, 1982]. Using a similar approach, it can be shown that the scaled ejection speed is related to the scaled ejection location (as measured from the impact point) through a different exponent that is also, however, a function of α (eq. 2) [Housen *et al.*, 1983]. Determined from least-squares fits to the results of impact experiments (Fig. 4c), α can, in theory, be used to scale the laboratory craters to planetary scales. Such scaling can then be used, for example, to assist in the interpretation of surface features or to infer the original impact parameters from final crater dimensions.

For example, in the strength-layering experiments proposed here, it is possible that the scaling relationship between ejection speed and location is not one simple power-law but rather the parameter α differs when the crater is primarily excavating within the “regolith” or the stronger subsurface unit. This would indicate that the flow-field is being affected by the strength of the underlying unit and would have implications for the excavation of material from that lower unit when compared to the “standard” scaling expectations for impacts into homogeneous targets. Similarly, the experiments into a sloped target might show an azimuthal dependence on the scaling parameter depending on whether the subsurface flow-field is excavating in the upslope or downslope direction. When utilizing the scaling relationships to extrapolate to planetary scales, effects such as subsurface layering and regional topography may have significant effects on the redistribution of surface materials during impacts; the work proposed herein will allow us

$$\frac{R}{a} = k_2 \left(\frac{ga}{U^2}\right)^{-\alpha/3} \qquad Eq.1$$

$$\frac{v_e}{\sqrt{gR}} = k_1 \left(\frac{x_e}{R}\right)^{-\left(\frac{3-\alpha}{2\alpha}\right)} \qquad Eq.2$$

where *R* is final crater radius; *a,* projectile radius; *g,* gravitational acceleration; *U,* impact speed; v_e and x_e , ejection speed and position, respectively; k_1 and k_2, constants; and α, the scaling parameter.

to test these ideas and gain more insight into the physical process of impact cratering on more realistic planetary surfaces.

1.4.6 Application to Lunar-Crater Morphology

The experimental objective is not to reproduce a specific crater, but rather to identify and understand the *controls* on classes of craters. LROC images [Robinson *et al.*, 2010] will serve as "ground truth" and a proxy for both the experimental and operational tasks providing a reference for evaluating the experimental results (*e.g.*, Figs. 2, 3). For example, impact craters having diameters of a few to hundreds of meters on the lunar maria have a range of morphologies related to the thickness of the regolith [*e.g.*, Quaide and Oberbeck, 1968; Bart, 2014]. Specific morphologic attributes to be examined are the transitions from simple bowl-shaped craters to those having central mounds, thence to flat floors and concentric geometries (Fig. 3). LROC stereo and LROC WAC digital-elevation models, as well as LOLA profiles, can provide the vertical component of the morphometric data.

With the advent of very high-resolution LROC imagery, more and more morphological detail is being observed in lunar craters (see Figs. 2, 3). While numerical models are useful and important, the complexities of the real lunar system are too intricate and fine-scaled to model mathematically. By attempting to reproduce the *general* features that we observe in the LROC images, the experiments proposed herein will lead us to a better understanding of the various small-scale details that we see on the lunar surface.

1.4.7 Proof-of-Concept: Target Topography

We anticipated that the targets for the topography experiments might be difficult to create, since we need to devise some way of creating a slope within the standard target containers. After a bit of experimentation, we created a "template" out of thick plastic that was cut in a curve such that, when wrapped around the inside of the standard target bucket, it resulted in a target surface with a predetermined slope. We filled this container with sand to the top of the template and smoothed the surface. As a proof-of-concept, we impacted a 4.76-mm aluminum sphere into this target at 0.935 km/s and imaged the ejecta with the EVMS (Fig. 10). During a later experiment under similar conditions (with a higher velocity of 1.977 km/s), the Real-Time Profiling System was used to image the growth and modification of a crater into a sloped target (Fig 11). Both the EVMS and RTPS worked well in imaging these craters; we have begun analyzing these images and anticipate that our regional topography experiments will go smoothly.

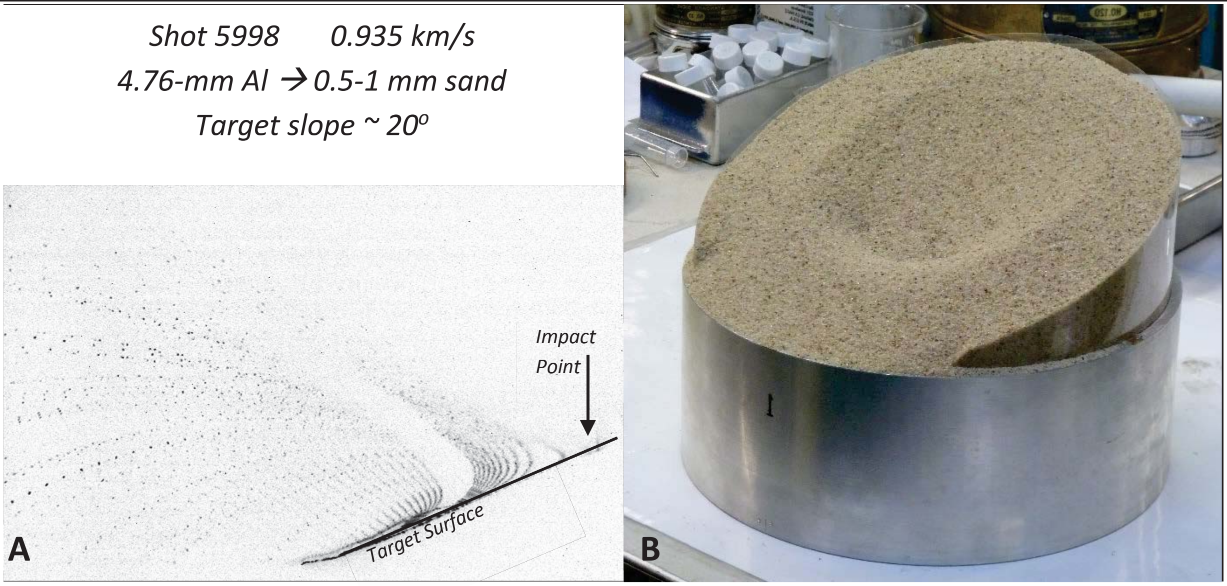

Figure 10. An impact into a sloped target, approximately 20 deg. (A) The EVMS image obtained during this impact. (B) The final crater formed; unfortunately, the target container was bumped as it was set down on the measurement table resulting in the collapse of the downslope part of the crater. The 3D Crater Scanner will obviate this possibility by imaging the crater before it is moved at all. The clear plastic template used to extend the surface of the target upward and create the sloped target is readily visible in this photograph.

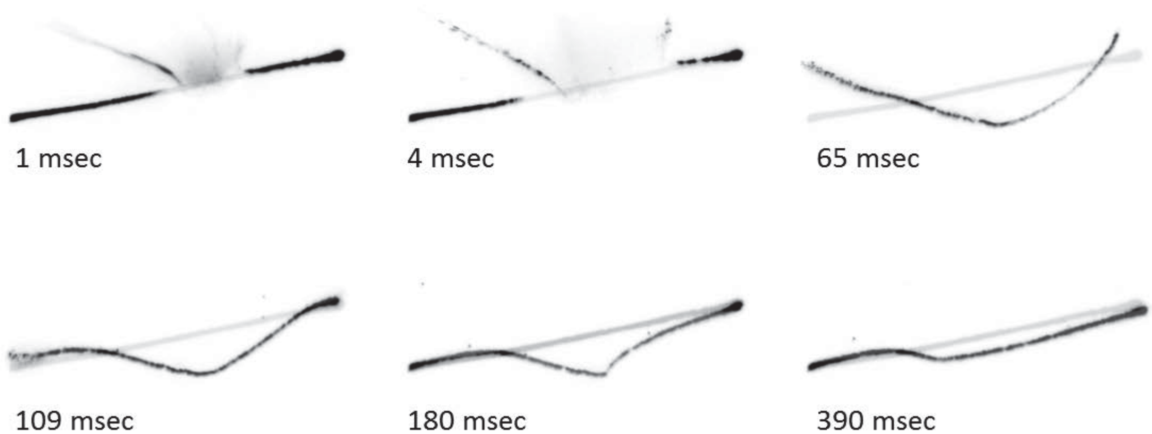

Figure 11. The RTPS images of a crater into a sloped target surface. Time after impact is given. The original target topography, sloped at 20°, is indicated on each image. The crater has essentially finished forming by 109 msec. Note the slumping of the upslope rim by 180 msec which acts to significantly infill and smooth out the final crater shape (390 msec). This view was at ~45° to the target plane and is uncorrected, so it is foreshortened in the vertical axis.

1.5 Relevance to NASA and the Solar System Workings Program

This proposed experimental research is relevant to NASA's Solar System Workings program and ROSES-2015 as an investigation of impact cratering, one of the primary physical processes affecting the evolution and modification of planetary surfaces throughout the solar system. Our laboratory-based results will be relevant to questions about the growth and development of regoliths on airless bodies and geomorphological analysis of impact craters and their ejecta deposits on bodies such as the Moon, Mercury, and asteroids.

1.6 Work Plan and Schedule

Ideally, given the complexities of some of the targets that we will be constructing for these experiments, we estimate that we will be able to complete 2-3 shots per day at the Experimental Impact Laboratory. We plan to front-load the majority of the proposed experiments to the first two years allowing for additional, repeat, or "gap-filling" shots during year three. Therefore, we have allotted four weeks of active shooting each of the first two years and two weeks of shooting in year three. This conservative estimate incorporates the various unforeseen events which may occur during our experimental runs.

Once the images from the EVMS and Real-Time Profiling System are obtained in the laboratory, we estimate that each shot will require 10 hours of digitizing, processing, and analysis by PI Anderson, Co-I Cintala, and/or the undergraduate research assistant.

	Year 1	**Year 2**	**Year 3**
Series 0: Controls (~5 shots)			
Experiments			
Data analysis			
Series 1: Regional Topography (~35 shots)			
Experiments			
Data analysis & comparison with lunar craters			
Manuscript preparation			
Series 3: Strength-Layered Targets (~20 shots)			
Experiments			
Data analysis & comparison with lunar craters			
Manuscript preparation			

1.7 Roles and Responsibilities

Dr. Jennifer L. B. Anderson (Principal Investigator) is a Professor of Geoscience at Winona State University (WSU). Anderson will be responsible for the overall direction and much of the work of the proposed project, including experiment design, data analysis, and interpretation. Anderson has requested a total of five weeks of travel support to Houston, TX – four weeks of experiments throughout the year and a week at the Lunar and Planetary Science Conference. The bulk of the data processing, analysis, and interpretation will be done from WSU.

Dr. Mark J. Cintala (Co-Investigator) is the Manager of the JSC Experimental Impact Laboratory (EIL) in the Astromaterials Research and Exploration Science Directorate (ARES). He will be responsible for target design and preparation, scheduling and completing the various experiments, and assisting in data processing, analysis, and interpretation.

Dr. Jeffrey B. Plescia (Collaborator) is a Principal Professional Staff member at the Johns Hopkins University Applied Physics Laboratory and is a Co-I on the LRO LROC experiment. He will be primarily responsible for LROC image analysis of the morphology and morphometry of craters affected by target topography and heterogeneity. As a member of the LROC team, Plescia's work outlined here is already funded as part of the JHU/APL Lunar Science Institute Node. He will provide data and examples for this project as needed.

Mr. Francisco Cardenas (Gunner/machinist), along with Roland Montes, is responsible for smooth operation and maintenance of all three accelerators, vacuum systems, and machine tools in the EIL. He will participate in virtually every phase of experimentation, from target preparation through post-shot safing.

Mr. Roland Montes (Gunner/machinist), along with Frank Cardenas, is responsible for smooth operation and maintenance of all three accelerators, vacuum systems, and machine tools in the EIL. He will participate in virtually every phase of experimentation, from target preparation through post-shot safing.

Funds are requested for PI Anderson to hire an ***Undergraduate Student Assistant*** from WSU for each year of the project to assist in the image processing and digitization of the EVMS and Cavity-Growth Profile images. Anderson will train the student(s) and supervise them as they use simple software to digitize the ballistic trajectories and cavity profiles. They will then transfer these data to pre-existing processing spreadsheets to calculate ejection parameters such as speed, angle, and position and track the cavity growth in time. Anderson has had success in the past engaging students in these activities and producing high-quality work that has been presented at the Lunar and Planetary Science Conference [undergraduate students were co-authors on EVMS abstracts by Anderson *et al.* 2007, 2010, and 2014] and will be submitted for publication in a peer-reviewed journal.

1.8 Data Management Plan

The data collected in the proposed tasks will be included in the papers published in peer-reviewed journals and associated supplementary materials. Large data blocks, such as the high-speed video imagery, will be available from the PI or Co-I by request. The results of the proposed tasks will also be disseminated through oral presentations and posters at major conferences.

Update to Proposal No. 15-SSW15_2-0266
August 28, 2016
Principal Investigator: Jennifer L. B. Anderson

IMPACT CRATERING: THE EFFECTS OF TARGET TOPOGRAPHY AND HETEROGENEITY

Submitted to NASA Research Announcement NNH15ZDA001N-SSW, Solar System Workings

Principal Investigator: Jennifer L. B. Anderson (Winona State University)
Co-Investigator: Mark J. Cintala (NASA Johnson Space Center)
Collaborator: Jeffrey Plescia (Johns Hopkins Applied Physics Lab)

This document replaces the original Section 1.8 Data Management Plan from the above proposal.

1.8 Data Management Plan

1.8.1 Description of data types, volume, formats, and standards

Data produced in the course of the proposed work will include initial impact conditions and the following files for each of the ~65 impact experiments: (1) JPG and TIF files of the raw and processed ejection-velocity measurement system (EVMS) images, (2) JPG and TIF files of the 3D NextEngine laser scanner images of the pre- and post- target surface topography, and (3) AVI video files of the growing impact crater profiles as imaged with the Real-Time Profiling System (RTPS). Analysis is primarily completed in Microsoft Excel and Origin software. Most data formats will consist of tabular numerical information (e.g., in Microsoft Excel format), large image files (in TIF format), and video files (in AVI format).

1.8.2 Description of the schedule for data archiving and sharing

Data will be archived in peer-reviewed scientific journals in the form of tables and/or figures, including associated online supplementary information, depending on journal policies and the volume of data; this data archiving will occur upon submission of our anticipated journal articles, expected to be within a year of data generation. Data too detailed for publication will be recorded in hard-copy laboratory notebooks or in dedicated laboratory databases (e.g., EIL maintains a database of all initial impact conditions for every experiment). Interested parties are welcome to peruse these informal databases and notebooks.

1.8.3 Description of the intended repositories for archival data, including mechanisms for public access and distribution

Our long-term archiving plan is to upload journal articles, including supplementary information discussed above, to NASA's Scientific and Technical Information Center (STIC). This is a publicly accessible, taxpayer-funded, long-term storage solution.

1.8.4 Discussion of how the plan enables long-term preservation of data

Journal articles will be maintained by the respective journals as per the policies of their publishers. Also, once uploaded onto the NASA STIC storage site, the data will be archived and accessible indefinitely.

1.8.5 Discussion of roles and responsibilities of team members in accomplishing the DMP

Each team member will comply with this DMP and assure that the scientific community has access to all data. This includes the responsibility to provide and prepare the data for journal-publication and inclusion into the journals' supplementary information. Once published, it will be the PI's responsibility to have the entire journal article archived at STIC.