HIGH-SPEED OPTICAL TRACKING OF INDIVIDUAL EJECTA PARTICLES FROM HYPERVELOCITY IMPACTS. Lukas Kortmann[1], Erkai Watson[1], Matthias Ebert[2], and Frank Schäfer[1,2,] Max Gulde1*, [1]Fraunhofer Institute for High-Speed Dynamics, Ernst Mach-Institut, EMI, 79104 Freiburg, Germany, [2]Intitute of Earth and Environmental Sciences – Geology, Albert-Ludwigs-Universität Freiburg, 79104 Freiburg, Germany.
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Introduction:

Faces of solid planetary bodies including those in our solar system are subjected to countless impacts from meteoroids and asteroids, continuously altering their surfaces. Material ejected during such high-velocity collisions can provide deep insights into the crater formation process as well as the physical and chemical properties of the impactor and target.

To access ejecta characteristics such as velocity and mass distributions, several mechanical and optical techniques have been developed to analyze transient impact events in the laboratory [1]. Perhaps most prominently, a light sheet perpendicular to the impact surface has been used to record the trajectories of particles within a single plane of the ejecta plume [2] (Fig. 1). In subsequent years, this Laser Light Sheet (LLS) technique has been improved on, e.g. by the use of fast charge-coupled device cameras [3] and optical flow-field techniques [4], [5].

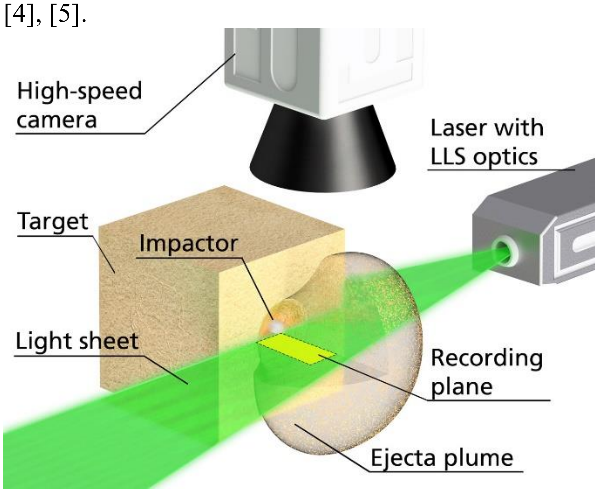

Fig. 1 Schematic of the experimental setup: light sheet from continuous wave laser (green) illuminates thin plane within ejecta plume during impact event. Ejecta traversing field of view (yellow) are recorded by high-speed camera.

However, identifying and tracking individual particles over several recorded pictures still poses a challenge, especially when particles are partially obstructed or tumbling. Here, we present a novel approach for the robust identification and characterization of individual ejecta particles. Specifically, we do not rely on cross-correlation as in optical flow methods and can track even very small particles with high accuracy.

In the following, we sketch the applied methodology and present the results from a 2 mm Al sphere impacting perpendicularly on Carrara marble [6] at 6.3 km/s. The experiment was conducted using a two stage light-gas gun at Fraunhofer EMI [7].

Methodology:

In a first step, the particle positions are determined for every recorded frame. Additionally, a timestamp is saved so that each detected particle occurence has a unique coordinate triple in position-time (XYT) space, as depicted in Fig. 2 (blue dots). Notably, in the current experiment, we focused on the fast ejecta and excluded frame volumes displaying spallation. To correlate individual particles in different frames, we make the following assumptions about their propagation:

(i) particles experience very little deceleration, which would present itself as slight upward bends in XYT space. Particle deceleration is mainly caused by atmospheric braking and amounts to a maximum of about 5 % at the test chamber pressure of 10^4 Pa.

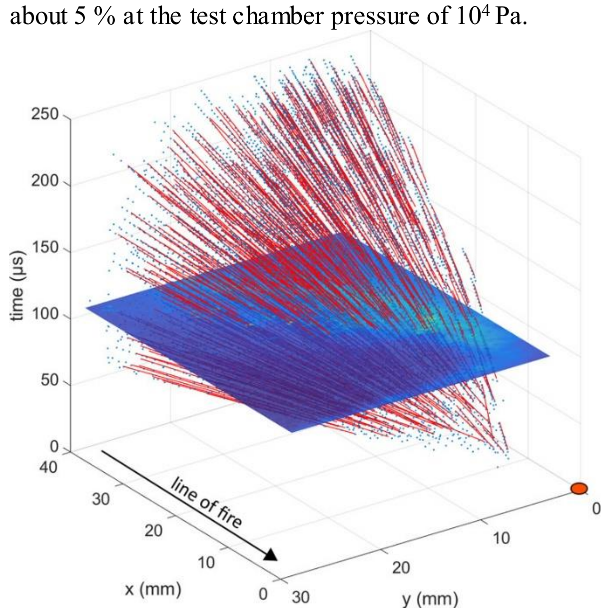

Fig. 2 XYT point cloud with detected particle occurrences (blue dots) and calculated particle trajectories (red lines). Exemplary frame displayed for t = 105 µs. Red dot marks impact position.

(ii) particles travel in straight lines in the recording plane, which we verified by multiframe integration. This behavior is to be expected since particles move at very high velocities through the camera's field of view. During this time, gravity acts perpendicularly to the plane of observation and will move the particle at most few tens of microns, not enough to be removed from the 1 mm thick LLS volume.

With particles moving in straight lines in the xy-plane as well as the absence of strong deceleration effects, particle trajectories will also be straight lines in XYT space. Individual particles are correlated by finding these lines in the XYT point cloud (Fig. 2, red lines).

Specifically, we employ a GPU-accelerated iterative RAndom SAmple Consensus (RANSAC) algorithm [8]: Pairs of randomly selected points in XYT space are used to generate lines within the point cloud. If in a sequence of frames a large amount of detected particle occurences lies within a given radius of such a line, they are considered to stem from the same particle. The found trajectories are then tested against some basic physical assumptions, including homogeneity of inter-frame velocities and directionality compared to the immediate neighborhood. In the current experiment, this results in the exclusion of around 2 % of all trajectories.

Results & Discussion:

We find the particles launch time and position by backpropagation assuming a uniform atmospheric deceleration (Fig. 3). Particles with negative starting positions or times in relation to the impact were removed (around 5 % of total trajectories).

The majority of the particles are launched within a narrow window of about 20 µs (Fig. 3A). This result fits well with the formation time of the transient crater, which is estimated to be on a comparable time scale.

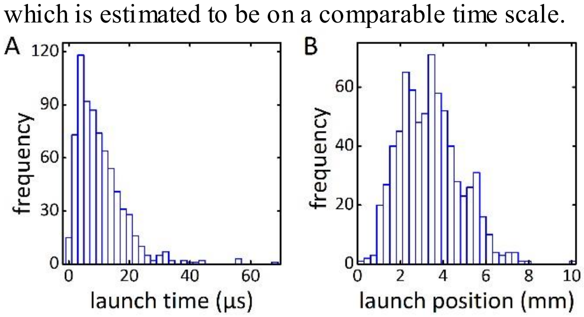

Fig. 3: Computed launch times (A) and positions (B) with respect to the impact time and point. N = 734.

Launch positions range from the impact point (x = 0) to around 10 mm with a maximum between 2 and 4 mm (Fig. 3B). This result is consistent with the final crater radius, which is determined to be 12 mm.

Assuming spherical particles with homogeneous density, we can calculate the cumulative ejected mass within the LLS from the visible area of the detected particles. Figure 4 displays the relation between particle velocity and cumulative mass of particles faster than this velocity. The functional relationship is well described by a power law with an exponent of -3µ and µ = 0.57. This result is consistent with theoretical and experimental oberservations for similar experiments on rocks with low porosity [1].

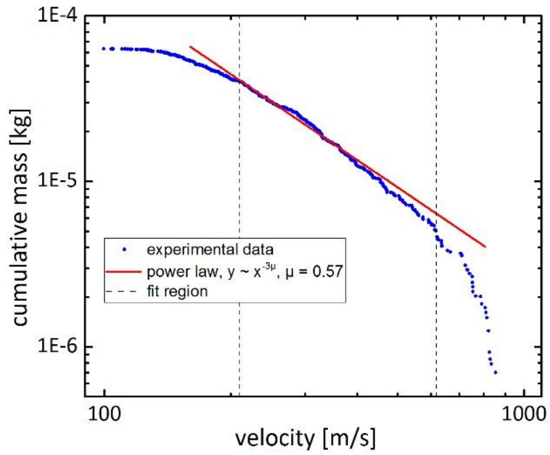

Fig. 4 Cumulative mass of particles in LLS with velocities larger than v. The functional relation between 200 m/s < v < 600 m/s is well described by a power law (fitted by red line).

Conclusions:

We have developed a novel methodology to accurately determine the trajectories of individual particles ejected after hypervelocity impacts. Making only very basic assumptions, the approach allows for a robust analysis even for partially obstructed and strongly tumbling particles.

The knowledge of the trajectory, velocity, and size of each individual particle allows us to comprehensively describe the ejection dynamics with unprecedented precision. Results were thoroughly tested against available data as well as theoretical considerations and found to be in excellent agreement.

More generally, we believe that the ability to reliably identify the dynamical key characteristics of fast moving particles will serve as an important enhancement in the experimental analysis of cratering processes as well as the validation of numerical impact models.

References:

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