Analysis of Darkened Fragments Resulting from Laboratory Hypervelocity Experiments

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ABSTRACT

NASA's Orbital Debris Program Office (ODPO) relies on measurements from optical, radar, and *in situ* measurements to facilitate the development of data-driven orbital debris environmental engineering models such as the NASA Orbital Debris Engineering Model (ORDEM). For optical measurements, the ODPO relies on ground-based optical telescopes to statistically assess objects in geosynchronous orbit and, in the future, low Earth orbit (LEO). The data collected include the detected object's orbital parameters, time of observation, and optical magnitude. The latter parameter can be converted to a size using NASA's optical Size Estimation Model (oSEM). It is well known that the observed magnitude of orbital debris can vary based on an object's material constituents, observational geometry, and the effects of space weathering.

To assess these magnitude variations, the ODPO uses the Optical Measurement Center (OMC) at NASA Johnson Space Center to characterize a variety of materials and fragments from laboratory impact tests representative of fragments that constitute the orbital debris population. One experiment was DebriSat: a 56 kg spacecraft was built to incorporate structural elements of a modern LEO spacecraft and was subjected to a hypervelocity impact test at the U.S. Air Force's Arnold Engineering Development Complex using test parameters that may be encountered in LEO. The DebriSat project has provided an abundance of information for assessing fragmentation debris in terms of material, color, shape, size, density, mass, and other derived parameters. Prior to the impact test, the ODPO collected spectral measurements on a subset of the materials used to construct DebriSat for a "ground-truth" of their optical properties. After the successful hypervelocity impact test, the DebriSat team observed a fine, dark dust coating all the fragments. Prior research has suggested that this came from ablated material deposited on the fragments during the impact test, causing a change in the reflective properties [1]. Given that this lower reflectivity on the DebriSat fragments will influence the laboratory-acquired magnitudes used to calculate size and inform potential updates to the oSEM, it is critical to assess if this darkening effect on the DebriSat fragments is a laboratory bias or something that could occur in on-orbit breakup events.

This paper will provide a brief overview of the OMC and DebriSat experiment, focused on the optical characterization of a subset of materials using broadband photometric measurements and spectroscopic measurements. In addition, elemental analysis of various DebriSat fragments and the soft-catch foam used in the hypervelocity experiment compared with pristine foam will be examined to further evaluate the source of the dark material coating all fragments. Finally, the authors will present a twofold plan 1) for assessing potential biases in laboratory impact experiments that could affect laboratory optical characterization and 2) for mitigating biases when compared with ground-based optical telescopic measurements of the orbital debris environment.

1. INTRODUCTION/BACKGROUND

One of the primary motivations for designing the Optical Measurement Center (OMC) at NASA Johnson Space Center (JSC) was to establish a laboratory that could simulate telescopic measurements to further characterize targets representative of orbital debris. OMC laboratory characterization can be done via broadband filter photometry and spectroscopy for material characterization, lightcurve measurements, bidirectional reflectance measurements (BRDF), and phase angle investigations. Each of these research investigations have been used in pursuit of supporting updates to the optical Size Estimation Model (oSEM). The oSEM defines a simple model to compare direct telescopic measurement data via calibrated magnitudes to a size – or (d) diameter [2] as shown in Equation 1.

$$d = \frac{2 \cdot R}{\left[\pi \cdot A_g \cdot \Psi(\alpha)\right]^{0.5}} \cdot 10^{\left[\frac{Mabs(v)+Msun(v)}{-5.0}\right]} \tag{1}$$

The diameter equation requires the absolute magnitude of the object, $M_{abs}(v)$, in a filter (in this case *v* – visible) and the absolute magnitude of the illumination source, M_{sun}. For objects in geosynchronous orbit, the range, R, is assumed to be 36,000 km. The next parameters are based on empirical data and research as best fits for telescopic measurements, specifically the geometrical albedo $A_g = 0.175$ [3] and Lambertian phase function Ψ (α), where α represents the phase angle. For size estimates, α is set to 0 as a standard measure and agreed to within the Inter-Agency Debris Coordination Committee.

Recently, the OMC has focused on evaluating albedo variations and phase functions using simple geometric shapes with known material compositions and homogenous coatings. The intent is to characterize the most simplistic approach to the oSEM and to analyze the data before proceeding into more complex, realistic targets one would observe in orbit. To expand on this research and the complexity associated with albedo, it is well known that various on-orbit factors can affect the surface composition of spacecraft materials and their optical response, including space weathering exposure (ultraviolet, atomic oxygen, electron, and proton bombardment), impacts from micrometeoroids and orbital debris and the event by which an orbital debris object was generated: explosions or collisions. The latter is the focus for this paper, specifically objects generated from hypervelocity impacts/collisions. Considering the most recent ground-based hypervelocity impact test that was conducted on a high-fidelity representation of a low Earth orbit (LEO) spacecraft, DebriSat, the majority of ~300,000 recovered fragments have all displayed a surface darkening or coating.

The following paper will highlight the details of the DebriSat experiment and test parameters, provide an overview of observed darkening from other hypervelocity impact (HVI) laboratory tests, present laboratory measurements from laser-induced breakdown spectroscopy (LIBS) and reflectance spectroscopy, exhibit simulation analysis using ray-tracing software, and provide a conclusion on the cause of this material darkening and whether it is a real-world effect one may observe on-orbit. The goal is to inform the space situational awareness community of a new factor that can influence magnitude-to-size models when comparing laboratory experiments with telescopic data. Understanding these parameter variations will directly show how optical telescopic data used in building environmental models, such as the NASA Orbital Debris Engineering Model (ORDEM), may need to be reassessed based on new knowledge of the orbital debris environment and the updates that are currently being investigated for improving the oSEM.

2. DEBRISAT and other HVI TESTS

Data-driven models such as ORDEM depend upon ground-based testing, *in situ* measurements, and ground-based optical and radar measurements of the orbital debris environment for component models and measurements. One component model is the NASA Standard Satellite Breakup Model, which models the debris produced by an explosion or HVI. The Satellite Orbital debris Characterization Impact Test (SOCIT), conducted by the Department of Defense (DOD) and NASA at Air Force Arnold Engineering Development Complex (AEDC) in 1992, supported the development of satellite breakup models using a (then) near-contemporary satellite bus as a target. Spacecraft construction has evolved in the interim decades, and the accidental collision of Cosmos 2251 and Iridium 33 in 2009 demonstrated that the latter spacecraft was not correctly modeled by a SOCIT-based breakup model. As a result, the DebriSat experiment was designed in 2013 with the intent to construct a modern-day LEO spacecraft that would be used to update breakups models used by NASA and the DOD for catastrophic fragmentation events.

The DebriSat experiment is a collaboration between the ODPO, the Space Force Space Systems Command (SSC), The Aerospace Corporation, and the University of Florida (UF). DebriSat was the third of three HVI tests conducted at AEDC in 2014. The first set was conducted by NASA’s Hypervelocity Impact Technology (HVIT) team as a pre-test using a multi-shock shield. The second test, DebrisLV (launch vehicle), was constructed by The Aerospace Corporation as a lower-fidelity target for the “dress rehearsal” test using shot parameters similar to the HVIT pre-test but incorporating the soft-catch system to mitigate secondary damage to the fragments as was used in DebriSat. This section summarizes the test parameters and general overview of the HVI tests to investigate commonalities and differences that may lead to the resultant fragmentation darkening identified in the DebriSat experiment. Special attention to test target composition, organics versus more metallic components, and energy to target mass ratio (EMR) is of interest to isolate contributing factors to fragment darkening. The constant between these four tests is the commonality in the test chamber. The impact chambers were prepped with soft catch foams prior to DebrisLV and DebriSat, and all fragmentation material was removed after each test, minimizing any prior testing contamination. Details of the four HVI tests and their associated test parameters are presented in Tab. 1, with details on the HVI pre-test noted in [4].

Table 1. Test parameters for the SOCIT4 HVI pre-test, DebrisLV, and DebriSat test campaigns.

	SOCIT4/ Transit	**HVIT pre-test**	**DebrisLV**	**DebriSat**
Target body dimensions	46 cm (dia) × 30 cm (ht)	2.65 m (length) multi-shock shield	35 cm (dia) × 88 cm (ht)	60 cm (dia) × 50 cm (ht)
Target mass	34.5 kg	56 kg* *multi-shock blankets only*	17.1 kg	56 kg
Projectile material	Al sphere	Hollow Al cylinder with attached nylon bore-rider	Hollow Al cylinder with attached nylon bore-rider	Hollow Al cylinder with attached nylon bore-rider
Projectile dimension/mass	4.7 cm diameter, 150 g	8.6 cm × 9 cm, 598 g	8.6 cm × 9 cm, 598 g	8.6 cm × 9 cm, 570 g
Impact speed	6.1 km/sec	6.9 km/sec	6.9 km/sec	6.8 km/sec
Impact Energy to Target Mass ratio (EMR)	2.8 MJ	14.2 MJ	14.2 MJ	13.2 MJ
Soft-Catch System: Polyurethane foam stacks	3 densities: 0.06, 0.096, and 0.192 g/cm^3; 25 cm thick	none	3 densities: 0.048, 0.096, and 0.192 g/cm^3; ≤ 51 cm thick	3 densities: 0.048, 0.096, and 0.192 g/cm^3; ≤ 61 cm thick
Pressure in tank	2.4 Torr	1.5 Torr	1.3 Torr	1.8 Torr

2.1. SOCIT4

The SOCIT series were conducted to characterize fragmentation debris resulting from HVI on various test articles to at AEDC between 1991 and 1992. SOCIT4 utilized a flight-ready 1960s era U.S. Transit navigation satellite, which was suspended from cabling in the test chamber and partially surrounded with multi-density polyurethane foam stacks, as shown in Fig. 1. SOCIT4 used a Transit - O (operational series, sometimes denoted by the phonetic alphabet's "Oscar") satellite core, without solar panel attachments. The satellite bus consisted of transmitter, receiver, and power electronics attached to a central aluminum and fiberglass column; the exterior was composed of fiberglass and glass phenolic honeycomb skin [5]. After the test, the polyurethane catch panels were sprayed with high pressure water to dislodge the fragments from the foam stacks, thus reducing the foam to small residue particulates. A subset on the order of at least 100 of the largest fragments were collected that were not embedded in foam and not effected by the water-spray foam removal process, thus maintaining the surface properties for further characterization.

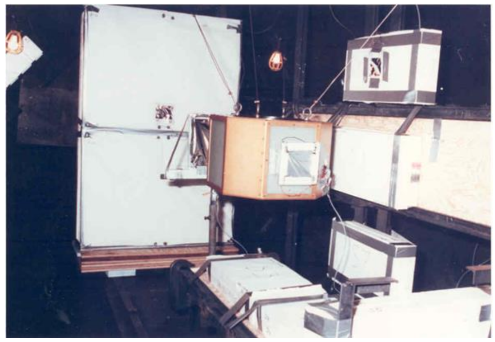


Figure 1. SOCIT4 prior to impact, showing the OSCAR core bus and surrounding catch panels.

The results of the impact test generated over 4700 fragments larger than 3 cm in the longest dimension [6]. Dominant recovered materials aluminum in all size regimes, copper, phenolics/plastic, fiberglass, and steel contributed to various size bins as presented in [6]. These fragments did not display a darkening effect, although they included organic materials such as phenolics and fiberglass. Two representative fragments from SOCIT4 are presented in Fig. 2, showing no indication of darkening; additionally, no darkening was observed on any of the SOCIT4 fragment collection.

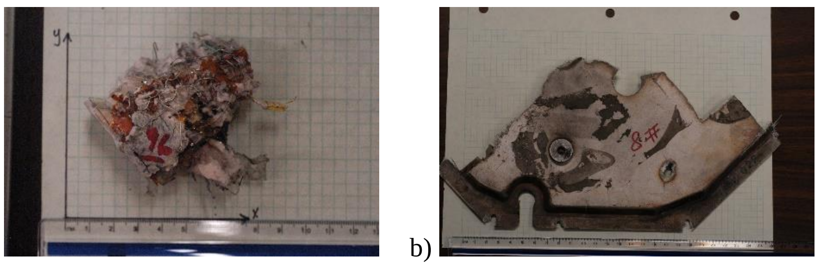
a)  b)

Figure 2. Fragments from SOCIT4 test series: a) #96, potted electronics, composed of aluminum, phenolic/plastic, and other materials; b) #8, exterior panel, composed of aluminum and phenolic/plastic.

2.2. HVIT pre-test

Prior to the DebriSat and DebrisLV impact experiments at AEDC in 2014, NASA's HVIT and ODPO agreed that a pre-test experiment would be beneficial to not only evaluate the test parameters planned for the following test series, but also to provide an opportunity to test a multi-shock shield at a high energy to target mass ratio (EMR). The multi-shock shield used in this test campaign consisted of four walls of 22 layers of fiberglass 3784 blankets and a seven-layer steel mesh in front of a double rear wall made of two sets of 45-layer Kevlar® blankets [7]. A photo of the test target is shown in Fig. 3.

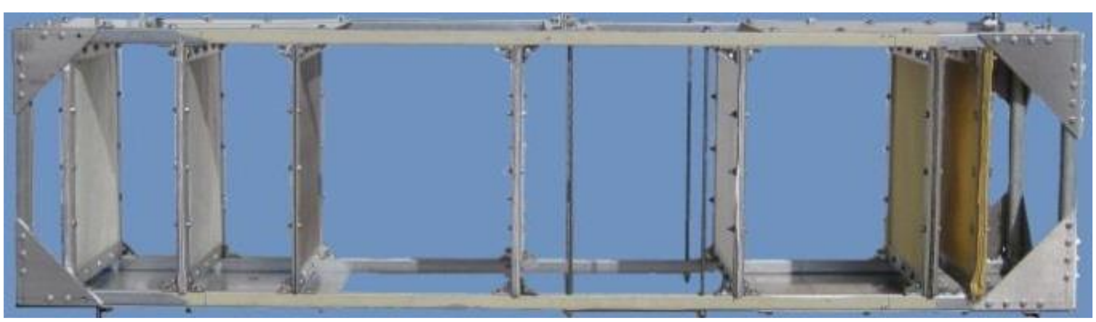


Figure 3. HVI pre-test conducted at AEDC prior to DebrisLV and DebriSAt to evaluate multi-shock shield at high EMR [7]. The length of the multi-shock shield is 2.65 m.

This specific test was focused on characterizing multi-shock shield for HVI analysis, thus no fragments were collected or analyzed. The results were deemed successful as the shield did stop the projectile and the HVIT team inspected the various layers to analyze the penetration characteristics. Beyond the scope of this this test, it also provided a fortuitous opportunity for insight on material darkening – without any soft catch polyurethane panels but at the same EMR as DebrisLV and DebriSat. In addition, this test used organic materials in the shielding design. Post-impact images are shown in Fig. 4. Witness samples were placed in the test and were analyzed to assess the cloud of debris/dust that is generating during these high-speed impact tests. The analysis showed solidified molten droplets of (Fe-Cr-Ni) and oxide/silicate that were attributed to the darkened matter that adhered to the witness samples, discussed in detail regarding the phases that contributes to this material assessment [8]. The analysis pointed to various components from the target that were correlated to these findings, as well as indications of aluminum from the projectile. One of the metal supports from this pre-test was also used for analysis in the NASA LIBS spectroscopy to better characterize the darkening residue observed on the materials, discussed in Section 3.0.

a) b) c)

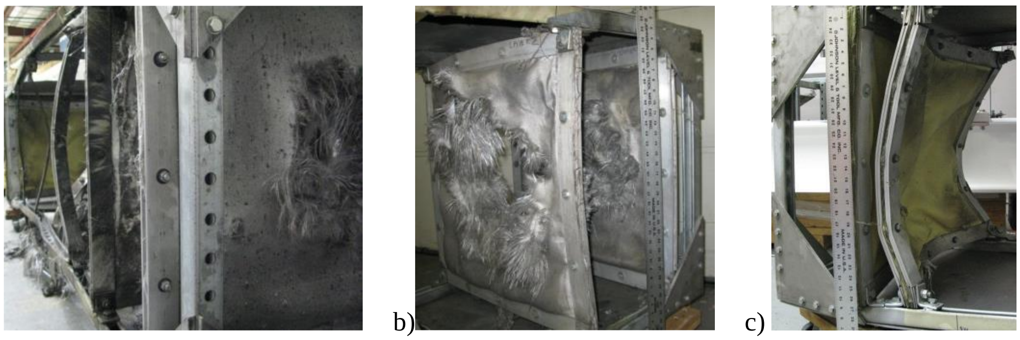


Figure 4. Post-impact images from HVI pre-test: a) view down velocity vector of projectile path (fiberglass front layers), b) back of first two fiberglass layers, c) rear Kevlar® walls [7].

Two-stage light-gas guns employ sabots to encapsulate the projectile during the rapid acceleration phase. Sabots are generally made of differ types of thermoplastics, such as Lexan, isoplast, Zytel, and others, where the composition can be tuned for the desired performance/properties. Example choices may include incorporating fiber reinforcement to increase sabot strength when using a dense projectile or the selection of a softer material to help cushion the extreme g-forces felt by a lower density projectile. During a nominal experiment with a two-stage light-gas gun, the entire sabot, or fragments, are separated from the projectile before impact with the target, generally through impact onto a plate that is placed up-range of the target. Depending on the specifics of the range being used, this plate may also be made of thermoplastic, or metal, but the impact of these fragments generates high enough shock stresses to melt/vaporize the sabot fragments. The energetic and fast-moving propelling gasses (generally H_2), can then drive these hot organic-rich vapors downrange towards the cold target and impact chamber walls, offering a possibility to vapor deposit fine organic powder on relatively colder surfaces.

Figure 5. Al plates used for alignment tests in a two-stage light-gas gun. All targets were impacted ~5.5 km/s, at a chamber pressure of ~40 mtorr. From left to right, projectiles used in each test were as follows: pre-test blank, Lexan cylinder (no sabot), Lexan cylinder (no sabot), Al sphere, Lexan cylinder (no sabot, projectile partially impacted sabot catcher), Al sphere, stainless steel sphere.

Fig. 5 includes pictures of post-test Al target plates used for calibration of the two-stage light-gas gun in the Experimental Impact Laboratory (EIL) at NASA Johnson Space Center. In this sequence of images, some targets used Lexan cylinders as projectiles (no sabot), while others used Al or stainless-steel spheres (requiring a sabot). Two of the cleanest, or brightest, targets were the tests with sabot-less Lexan cylinder projectiles. A noticeably darker appearance is observed when either sabots were used and could act as a source for vaporized organic materials or the

Lexan projectile partially impacted the sabot catcher, thus producing a cloud of highly shocked thermoplastic vapor in the chamber. The general darkening on these target plates can only be consequence of the sabot and projectile since no other materials were impacted during these tests.

The presence of this organic vapor has been prohibitive to some shock studies using C-bearing rocks. Hörz *et al.*, [9] developed a catcher system using multiple layers or steel wool, fiberglass insulation, and Al foil to decelerate the sabot fragments before impact was made the solid surface of the sabot catcher. Decreasing the impact speeds of these fragments decreases the ultimate shock pressure and prevents the phase transformation to a vapor phase. It is important to note that while the AEDC range does not use a sabot design that that allows separation from the projectile during free-flight, the presence of the Nylon bore-rider that ultimately impacts the target provide another possibility to introduce highly shocked/vaporized thermoplastic into the test chamber. The tests shown in Fig. 5 were not originally intended or designed to directly compare darkening of the target plates. Among similar testing configurations, such as the Al spheres, smaller variations in the magnitude accumulated soot would be expected due to common variations in chamber cleanliness.

2.3. DebrisLV

The DebrisLV (launch vehicle) was constructed by The Aerospace Corporation as a lower-fidelity target than DebriSat that would be used to test all test parameters, similar to the HVI pre-test, but this test would utilize the foam encapsulating the test chamber to ensure the thicknesses and positioning of the soft-catch foam would be sufficient. DebrisLV impact test also provided an opportunity to study the hypervelocity impact effects on derelict launch vehicle upper stages. The target was composed of mostly metals, including aluminum, stainless steel, copper, and titanium as shown in Fig. 6 [10]. The test was conducted two weeks after the HVI pre-test also at AEDC, and all resultant fragments were collected and shipped to UF for processing and characterization. As this was intended to be a pre-test for DebrisLV, the thorough characterization of these fragments will be done after the DebriSat fragment characterization, starting with x-ray imaging of the soft catch foam panels to commence late in 2024.

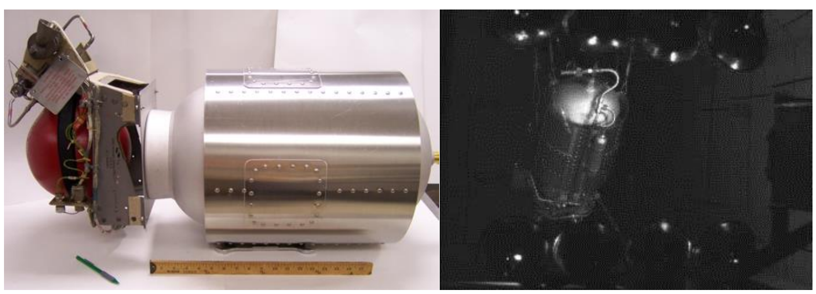
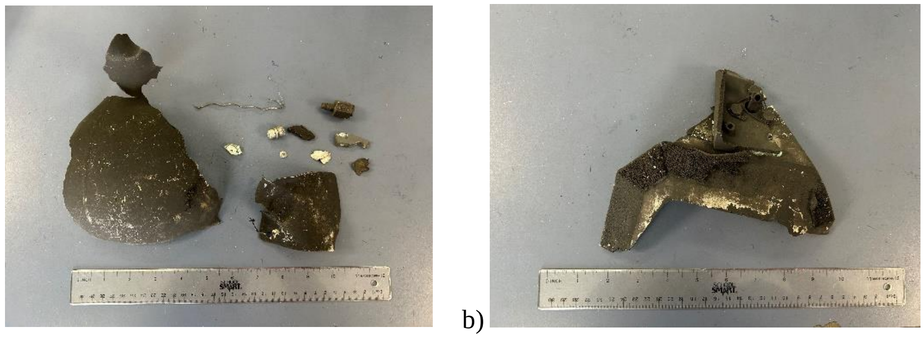


Figure 6. DebrisLV, left as built and right within AEDC chamber.
Images courtesy of Aerospace (left) and AEDC (right).

The DebrisLV fragments, subset shown in Fig. 7, also displayed a darkening and were subject to various studies led by The Aerospace Corporation to characterize the plasma/vapor blast during the hypervelocity impact test [10]. The analysis suggested that the high-energy impact test generated a highly turbulent aluminum vapor cloud that left condensed metal deposits on the fragments. This report also states that the physical effects found on the DebrisLV fragments (metal pitting) are similar to observations noted on the exterior of reentered space debris [10]. Additional analysis identified the reflectance dropped from 95% to 6% for DebrisLV fragments and highlighted the variability in albedo estimates that are used for in orbital debris to apply size estimations [8]. Lastly, the presence of sputtered aluminum oxide identified on the fragment samples was analyzed, specifically using laser ablation of aluminum to isolate the presence of oxygen. After ablating aluminum in a range of air (0.5 -2 Torr) it was summarized the aluminum oxide that was identified in DebrisLV and DebriSat could be attributed to the tank pressure held at 2 Torr, and thus not likely an element that would be detected in orbit [11].



a) b)

Figure 7. DebrisLV fragments, a) metallic with small components, b) metallic with Velcro. Images provided by UF.

2.4. DebriSat

DebriSat was constructed using modern-day materials and construction techniques based on research and advisement from aerospace subject matter experts. The spacecraft was developed to represent a low Earth orbit (LEO) spacecraft with many flight-like materials as well as emulated components to save cost on the design of DebriSat. Unlike DebrisLV and the previous impact test, SOCIT, DebriSat incorporated multilayer insulation (MLI), solar panels, and carbon fiber reinforced polymer (CFRP) – the latter being a widely used material in modern spacecraft construction – adding to a significant increase in the low-density material construction. DebriSat did use various metals similar to previous impact tests, as well as optical and other sensors as expected for a LEO spacecraft. Images and details on the DebriSat target are shown in Fig. 8. Using the NASA Standard Satellite Breakup Model (SSBM), the original estimate for the total number of fragments generated was calculated to be approximate 85,000 for fragments 2 mm and larger. To date, the team at UF continues to characterize the over 294,000 fragments collected that will be used to support updates to the NASA SSBM and optical and radar SEMs; details on the SSBM and overall DebriSat project can be found in [12]. This is a direct consequence of the target construction and is primarily attributable to the larger number of CFRP fragments that dominate the smaller fragment population below 5 cm.

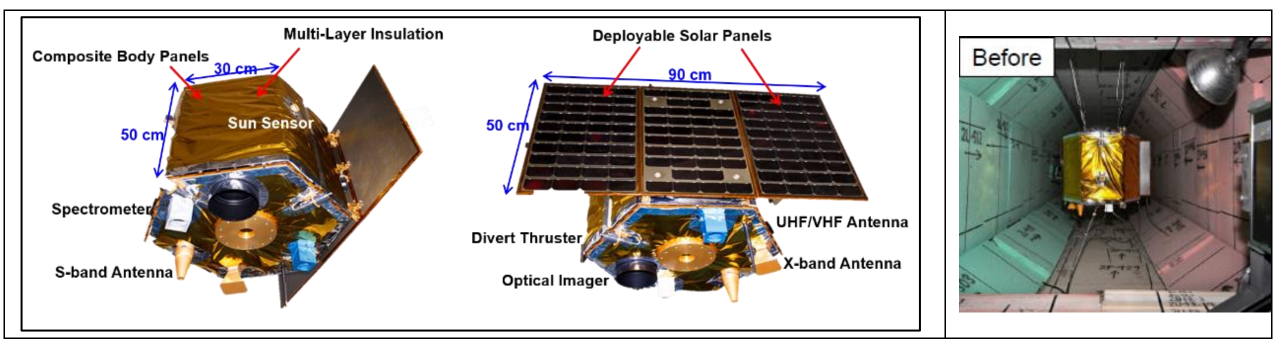


Figure 8. Left: DebriSat digital image pre-impact showing various components. Right: DebriSat pre-impact at AEDC.

A striking difference between previous impact tests and DebriSat identified during the fragment collection prior to be shipping to UF and during the characterization process was the visible darkening on all fragments, as shown in Fig. 9. This impact test has the same energy to mass ratio as DebriLV and the HVI pre-test, but it was unlike previous tests used CFRP in the target construction. Initial theories suggested the darkening could be attributed to CFRP powder/dust, the foam panels, or metal vapor, as discussed in DebrisLV. The metal droplets seen in DebrisLV and DebriSat were mostly associated with target material and small percentages of the projectile [8]. Adams, *et al.*, also correlated the Carbon to composite honeycomb structures, MLI, and possibly the soft catch foam panels [8]. This latter association was the motivation to determine if the soft catch foam panels would bias laboratory experiments in comparison to on-orbit break up events. In addition, further analysis conducted with laser ablation experiments also helped identify an area to investigate that leads to debris darkening. It was determined that the deposition of carbon from ablation of a composite target, specifically over highly reflective metallic aluminum leads to the darkening effect, as observed visually and supported by a significant decrease in optical reflectance of the aluminum surface [1].

a) DS142245 | b) DS160713 | c) DS152194

Figure 9. Fragments from DebriSat: a) a composite honeycomb panel, b) telescope outer shell, and c) multilayered insulation

3. LABORATORY MEASUREMENTS/ SIMULATIONS

One of the motivations for developing the OMC was to support updates to the optical SEM. Due to the generous amount of fragments from DebriSat as well as previous impact tests, the data can be further scrutinized to focus on specific aspects of the parameters that are used to estimate size, such as variations in materials via LIBS characterization/spectroscopy that effect albedo and phase function analysis, that could be conducted experimentally in the OMC or via ray-tracing simulations. To further evaluate the previous research studies on what contributes to this darkening effect and if it is a laboratory bias/effect that can/should be removed from measurements conducted with ground-based sensors, the following analysis will be presented. Section 3.1 will offer an overview on the LIBS characterization conducted to identify the various elements in and on various fragments from the previously mentioned impact tests. Section 3.2 will discuss a case study of one of the larger recovered DebriSat fragments for spectral analysis in comparison to pre-impact spectral results. Section 3.3 will provide a ray-tracing assessment on simple shapes with different reflective coatings and how they compare with known phase functions used on the optical SEM (*i.e.*, Lambertian).

3.1. LIBS Characterization

NASA uses a suite of Keyence® instruments for detailed inspections in ODPO's Fragment Analysis Facility, details in [13], specifically for this paper, the KEYENCE EA-300 Element Analyzer (EA). The EA-300 uses LIBS with a Class 1 laser that can be adjusted in different user selected laser power settings on the target surface generating a plasma while a broadband, high-resolution spectrometer simultaneously conducts atomic emission spectroscopy. For this analysis, a subset of fragments from DebriSat (21 in total), samples from pre-HVIT test (8), samples of the soft catch foam (pristine and retrieved from the DebriSat test), and calibration materials were used to assess the various elements on the materials, but more specifically to isolate common elements that could contribute to the debris darkening. In addition, fragments from a previous impact test that used CFRP and glass fiber reinforced polymer (GFRP) were analyzed; details on this previous test conducted by Kyushu University are available in [14]. GFRP is also a common material used in the DebriSat construction, commonly associated with printed circuit boards.

The DebriSat fragments analyzed included both metals, glass, and organic materials. Of the metal fragments analyzed, the predominant elements included Zn, Al, Fe, Cu, and Ag. This analysis is consistent with previous findings by [8] and also highlights Zn as one of the elements that at the time was unable to be correlated to a specific material in the DebriSat construction. The analysis, completed via LIBS analysis, correlated the Zn to Zn-Al coated screws, gaskets, and specific components in the material build. Also present throughout all analyses was the presence of carbon and oxygen. The telescope sunshade fragment (DS#160713) presented in Fig. 9b, responded with the highest abundance of O over Al, Zn, and H.

To assess the elements contributing to the darkened foam, samples of foam, CFRP, GFRP, and other carbon-based materials were analyzed from various impact tests and calibration materials. A summary of the findings is presented in Tab. 2. As presented, the foam panels do constitute C elements, but the dominant C elements were associated with CFRP. Additionally, the HVI-pre-test also indicted presence of C, which did not include CFRP or foam panels, pointing to the fact that C is associated with the organic materials used in the multi-shock shield, specifically Kevlar® blankets, with prominent carbon bonds.

Table 2. LIBS analysis of materials by elemental abundance

Material Class	Material Type/ Fragment (DS) or foam (DSF) association	Predominant element by abundance	Other elements in descending order of abundance
Control Foams	FR-3730	C 95%	H
Control Foams	FR-4510	C 65%	O, H
Control Foams	FR-4515	C 75%	O, H
Control Foams	FR-4550	C 69%	O, K, H
Med Density foam	N/A	C 77%	O, H
DebriSat recovered foam	DSF274	C 54%	Al, O, Cu, H
DebriSat recovered foam	DSF647	C 68%	O, Zn, H
DebriSat recovered foam	DSF652	C 76%	O, H
DebriSat recovered foam	DSF660	C 76%	O, H
DebriSat recovered foam	DSF174	C 70%	O, H, Zn
DebriSat MLI	DS174472	C 79%	O, H
DebriSat CFRP	DS197042	C 91%	O, H
CFRP Face Sheet + Al S250 core	N/A	C 81%	O, H
CFRP	Kyushu University	C 85%	O, H, K
GFRP	Kyushu University	C 76%	O, H, Si, K
HVI pre-test	Sample retrieved via glove swipe on metal	C 62%	Fe, H, Na, O, Zn
HVI pre-test	Sample retrieved via tape pull on metal	C 55%	O, Al, Fe, H, Na

Lastly, several darkened foam and non-metal DebriSat fragments were inspected and found to be dominated by Al, see Tab. 3. This is also consistent with previous reports suggesting molten metals adhered fragments during this highly energetic impact experiment.

Table 3. LIBS analysis of material with likely molten metal presence

Material Class	Fragment (DS) or foam (DSF) association	Predominant element by abundance	Other elements in descending order of abundance
DebriSat foam	DSF652	Al 54%	Fe, Cu
Epoxy, Green	DS173880	Al 41%	Cu, Fe
Epoxy, black	DS197303	Al 65%	Fe, Cu, Zn, H, O, Si, Ni

In summary, based on the recent LIBS characterization in addition to previous studies, it appears the foam is not a contributor to this darkening effect, and it is instead a result of the small particulates of CFRP/GFRP and molten metal. The presence of O may be partitioned into an abundance attributable to residual tank pressure as well as the O-bonds in the compensational makeup of the organic target materials. Therefore, this physical darkening effect does appear to be a reasonable effect for on-orbit breakup events and would lead to decreased albedo of observed targets.

3.2. Spectral Measurements

To further evaluate the significance of this darkening effect and characterize albedo for various materials, spectral analysis of DebriSat fragments has been ongoing. A subset of fragments was measured pre-test as presented in [15]. The following will showcase one of the retrieved fragments in comparison to the pre-test measurements. The spectrometer used is an Analytical Spectral Device (ASD) FieldSpec Pro Spectrometer®, which is used to acquire spectral reflectance measurements over a broad range of 350 nm to 2500 nm as ground-truth to compare with *in situ* and optical measurement telescopic data. The goal is to assess reflectance data that can compared with photometric data and the reflectance data can change due to various factors, such as impact experiments, space weathering (*in situ* or via laboratory experiments), and physical changes (*i.e.*, surface changes or material construction variability). To compare pre-impact and post-impact spectral measurements of a Celestron™ telescope used in the DebriSat build, spectral measurements were acquired on various parts of the telescope housing. The retrieved telescope housing pictured in Fig. 10, shows how the darkened areas vary after minimal cleaning (via wipes or alcohol) was performed to determine if this darkened matter can be easily removed and to access the surface as close to pre-impact nature as possible.

Figure 10. Digital images of the recovered DebriSat telescope housing

Fig. 11 shows the pre-impact and post-impact spectral measurements of a Celestron™ telescope used in the DebriSat build. The spectral data measurements are presented as averaged over difference areas on the telescope. As shown the pre-impact telescope has a clear absorption feature near 450-500 nm associated with the orange paint, followed by a steep reflectance near 100% from 1000-2500 nm. The absorption feature centered near 800 nm is indicative of aluminum. The two dark data points (data 1 and data 2) are associated with darker areas measured on the telescope, and the post-impact telescope is an area that was wiped down to provide a better comparison to the pre-impact spectra. The darker areas (dark 1 and dark 2) indicate a 10-30% reflectance across all wavelengths, maintaining the orange color absorption feature, but aluminum absorption feature is harder to identify. For the post-impact telescope, the orange color absorption feature near 450-500 nm is still visible as well as the 800 nm aluminum absorption band, but overall, the reflectance is closer to 55%, thus an overall decrease of 30-40% in the visible regime and 40-45% beyond 1000 nm. From the standpoint of ground-based telescopes observations, which typically utilize sensors that cover 350-1100 nm, a decrease of 40%, especially for small objects, may result in undetectability by ground-based optical sensors.

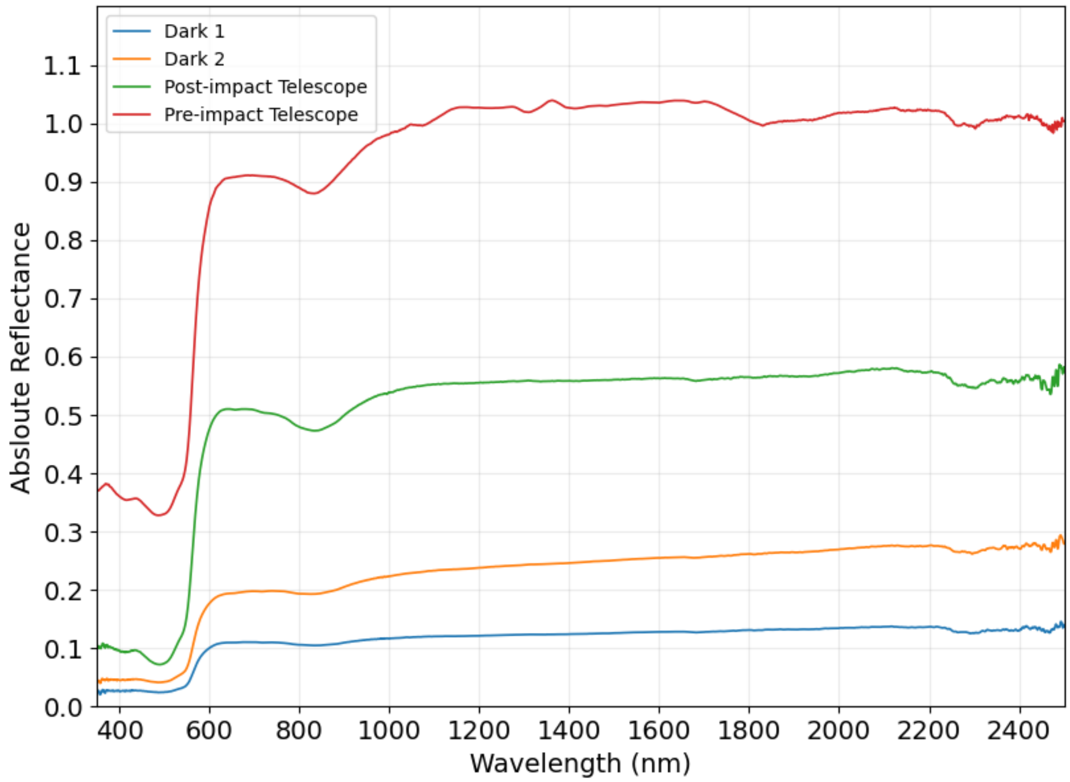


Figure 11. Spectral measurements of same telescope fragment pre- and post-DebriSat.

3.3. Simulation

The last component of this characterization report to inspect what was causing the darkening, assessing the decrease in reflectivity via spectroscopy, was conducting simulations of simple targets of known material/shape to investigate how phase functions vary in comparison to the standard Lambertian model used in the optical SEM. The software used to conduct these ray-tracing simulations is Photon Engineering's FRED Optical Engineering Software. The software allows the user to recreate the optical throughput with the specific instrument and optical configurations and use predefined materials or upload user specific reflectance spectra for material coatings; definitions used for these simulations are presented in Tab. 4.

Table 4. FRED simulation definitions

Scatter-type	Definition
Lambertian	Lambertian with 100% reflectivity
Matte White	Lambertian with 80% reflectivity
Matte Gray	Lambertian with 40% reflectivity
Matte Black	Lambertian with 4% reflectivity
Flat Black Paint	As defined by FRED, with 2% reflectivity
Lambertian Orange Fragment	Aluminum base material, with coating applied to surface matching reflectivity data from DebriSat sample, Lambertian with 100% reflectivity.

The Lambertian Orange Fragment component requires further explanation when using the OMC acquired spectra as discussed in Section 3.2. The spectral data is typically acquired over a series of phase angles (angle defined by the illumination source-target-detector) that are maximized to collect the most reflected light without saturating the detector, then averaged to present a single reflectance spectrum as shown in Fig. 11 in Section 3.2. Provided this information, when the spectra are uploaded to the FRED software, it forces the user to associate that data to a phase function unless a use defined phase function is provided (*i.e.*, one would need to measure the reflectance from 0-180 degrees phase angle to generate a user-defined phase function). For the purposes of this research, the spectral data collected in the OMC used a Lambertian phase function, as used with the OSEM for this comparative analysis. Note: The Lambertian Orange fragment uses the pre-test Celestron™ telescope spectral measurements as discussed in in Section 3.2

In Figs. 12 and 13, the results from a simulation using a cylinder with length-to-diameter ratio of 3:1 and a sphere, respectively, using different scattering properties is presented. The value for each datapoint was scaled using min-max scaling presented in Equation 2:

$$\frac{datapoint - minimum}{maximum - minimum} \tag{2}$$

This scaling was chosen to amplify the differences in the absolute values of the different results while preserving their curves as much as possible. Other scaling methods caused the results to be overlayed on top of each other, which do not lend themselves to meaningful visual analyses. The FRED software computes the bidirectional reflectance distribution (BRDF) for each phase angle, thus when comparing between the two shapes, there is no notable differences in the phase function comparison. Additionally, it was no surprise that the reflectance fell off appropriately from matte white, matte gray, matte black, and black paint. The second objective was to determine, what one would expect when comparing the pre-impact test samples to the post-test. From this simulation, theoretically, the reflectance could drop from near 100% to somewhere between 0-40% depending on the amount of darkening on each fragment, assuming matte gray or darker surface coatings. Recall, the estimates from the DebrisLV analysis suggested a reflectance decrease from 95% to 6% for the DebrisLV fragments [8]. Future work will include taking these shapes with the associated coating (minus Lambertian orange) and acquiring BRDF photometric measurements in the OMC to compare with this simulation data. This will further refine the expected decrease in reflectively one may expect from on-orbit breakup events.

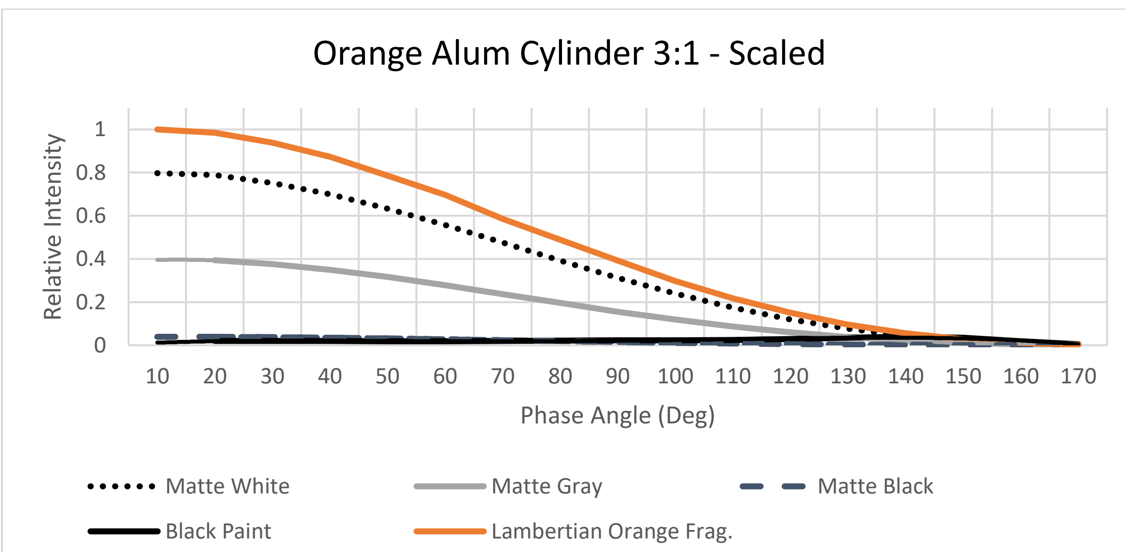


Figure 12. FRED simulation using a cylinder with length to diameter ratio of 3:1.

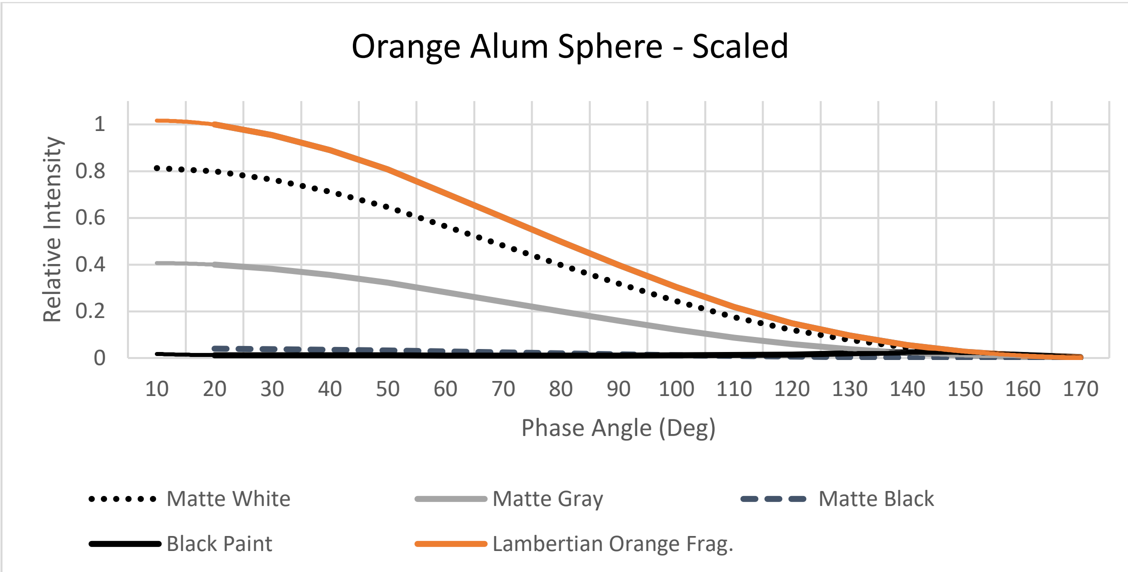


Figure 13. FRED simulation using an aluminum sphere.

4. SUMMARY

This paper provided an overview of various laboratory HVI tests with the goal to characterize the darkening that appears on fragments resulting from the DebriSat impact experiment. The objective was to further assess if on-orbit breakup events would also incur this darkening, which could affect the overall brightness and thus lead to erroneous size estimates using NASA's oSEM or make detectability from ground-based optical sensors more challenging. The analysis presented comparisons from SOCIT, HVIT pre-test, DebrisLV, and DebriSat, all conducted at AEDC, all of which were similar in test parameters except the EMR with SOCIT was much lower than that of the following HVI tests. Also presented were calibration tests conducted in NASA's EIL to provide additional visualization on how darkened targets organic sabot (or "launch package components") contribute to target darkening. The fragments/test targets from these tests do show a darkening that could be contributed to various test parameters, including but not limited to EMR, organic material in the target, test chamber pressure (presence of oxygen), melted metal, organic-rich vapors from the projectile, and the cleanliness of the chamber between test shots.

To address the specific parameters used in the oSEM, specifically magnitude, albedo, and phase functions, laboratory analyses and simulation were conducted. The findings from this research investigation are as follows:

- A thorough analysis of DebriSat fragments, the soft-catch foam, and materials from other HVI tests was presented to determine if the darkening was due to the soft-catch foam. The analysis determined this was not the case; although carbon is present, it is also present in HVI tests that did not use the soft catch foam.
- In common with previous research studies, the darkened material appears to be traceable to molten metal and the presence of fiber reinforced polymers.
- A portion of the darkening may be attributable to the projectile's bore-rider, though its relative contribution cannot be estimated at this point. This motivates further research in this regard to isolate the magnitude of this effect, if any.
- Spectral measurements of a DebriSat fragment pre- and post-test were assessed to determine how the overall reflectance could be affected. Looking at the peak reflectance for most sensors near 700 nm, the reflectance decreases 40% when compared to the pre-test fragment, and even more to 70-80% in areas that were not cleaned and represents the worst-case scenario for reflectance.
- Optical ray-tracing simulations were completed on two simple targets (cylinder and sphere) using the same reflectance coatings. The objective for the simulations was to determine if shape contributes to phase function variations when using BRDF measurements and to complement the spectra data to assess expected reflectance decreases for different coatings on simple targets. The results presented suggest a reflectance decrease of 100% if the resultant fragment has a surface coating that is black, a 60% decrease if gray, and 20% if white. The shape of the target did not introduce any notable differences with this initial simulation for phase functions. This

reflectance decrease is consistent with previous studies that showed a decrease of 95% to 6% using witness samples from DebrisLV.

In summary, this paper has presented research and characterization into ground-based HVI tests used to simulate break-up events in orbit to determine reflectance degradation and how that could lead to further uncertainty in the size estimates. Although this paper provides quantitative results using laboratory data, the results are qualitative when compared to real-world events.

One physical parameter not discussed but well-known to effect reflectance properties of on-orbit materials is space-weathering. Additional laboratory experiments are welcome to further characterize this effect, but perhaps with fully purging impact test chambers to remove the presence of oxygen. Opportunities to observe spacecraft with *a priori* information on spacecraft materials directly before and after a break-up event would also be informative, but would take resources, photometric observing campaigns, and repeat observations of the same target over time. Even with this rare observing opportunity, objects that are tumbling or are viewed with different aspect angles can also lead to variations in reflected brightness. In conclusion, the authors summarize with a note that break-up "objects in mirror are darker/larger than they appear."

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