

NASA/TM-2018-219802



Full-Scale Passive Earth Entry Vehicle Landing Tests: Methods and Measurements

Justin D. Littell and Sotiris Kellas
Langley Research Center, Hampton, Virginia

January 2018

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question to help@sti.nasa.gov
- Phone the NASA STI Information Desk at 757-864-9658
- Write to:
NASA STI Information Desk
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

NASA/TM-2018-219802



Full-Scale Passive Earth Entry Vehicle Landing Tests: Methods and Measurements

Justin D. Littell and Sotiris Kellas
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

January 2018

The use of trademarks or names of manufacturers in this report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

Table of Contents

1. Introduction	4
2. Test Vehicles.....	4
3. Test Setup	6
4. Test Results	8
4.1. Test 1 Results	9
4.2. Test 2 Results	17
4.3. Test 3 Results	23
5. Summary	28
6. Recommendations.....	29
7. References	32

List of Figures

Figure 1 - EEV test vehicle schematic	5
Figure 2 - Iso view of the painted ring pattern used for all test vehicles	6
Figure 3 - UTTR test area	6
Figure 4 - Test vehicle shown with release hook (in orange) attached to vehicle's three point harness.	7
Figure 5 - Test vehicle attached to helicopter via a 33 m long lanyard	7
Figure 6 - Drop penetrometer used for practice testing. Side view on cradle (left) and top view (right)....	9
Figure 7 - Test 1 overhead view.....	10
Figure 8 - Test 1 release. Hook opening (left) and angle immediately after release (right)	11
Figure 9 - Test 1 free flight tracking. UHD-4k view (left) and high speed view (right).....	11
Figure 10 - Test 1 zoom 3x high speed view at impact (left) and exaggerated view (right).....	12
Figure 11 - Test 1 post impact orientation (left) and crater (right)	12
Figure 12 - Test 1 position tracking. Camera view (left) and resolved position (right).....	13
Figure 13 - GPS analysis for Test 1	13
Figure 14 - Test 1 low-g accelerometer data.....	15
Figure 15 - Test 1 free flight acceleration.....	16
Figure 16 - Test 1 angle position	17
Figure 17 - Test 2 overhead view.....	18
Figure 18 - Test 2 release 4 image sequence	19
Figure 19 - Test 2 free flight sequence as captured by the south high speed camera	20
Figure 20 - Test 2 zoom 3x high speed view at impact	21
Figure 21 - Test 2 impact location and crater	22
Figure 22 - Test 2 position tracking. Camera view (left) and resolved position (right).....	22
Figure 23 - GPS analysis for Test 2	23
Figure 24 - Test 3 release. Before (left) and after (right) release hook open	24
Figure 25 - Test 3 free flight sequence as captured by the North high speed camera.....	25
Figure 26 - Test 3 impact location and crater	26
Figure 27 - Test 3 position tracking. Camera view (left) and resolved position (right).....	26
Figure 28 - GPS analysis for Test 3	27
Figure 29 - Test 3 free flight acceleration.....	28
Figure 30 - Sample camera coverage array.....	30

List of Tables

Table 1 - Testing summary	9
---------------------------------	---

List of Acronyms

AGL – Above Ground Level

ATV – All Terrain Vehicle

CG – Center of Gravity

EEV – Earth Entry Vehicle

GPS – Global Positioning System

HD – High Definition

ICoSS – Integrated Composite Stiffened Structure

MDU – Manufacturing Demonstration Unit

MMEEV – Multi-Mission Earth Entry Vehicle

MP – Mega Pixel

MSR – Mars Sample Return

PSS – Payload Support Structure

SC – Sample Container

TPS – Thermal Protection System

UHD-4k – Ultra-High Definition, 4K

UTTR – Utah Test and Training Range

VFR – Visual Flight Rules

1. Introduction

A passive Earth Entry Vehicle (EEV) concept was developed in the late 1990's for the Mars Sample Return (MSR) program [1] as the most reliable means of delivering Mars samples back to Earth. Passive EEVs differ from EEVs using active systems such as parachutes or other external landing systems [2-4] because they rely solely on vehicle aerodynamics for kinetic energy dissipation and on vehicle structure for impact attenuation upon landing. Original aerodynamic and landing load attenuation systems for the MSR EEV were tested in the early 2000's timeframe [1,5]. Those tests were conducted at the intended landing site at the Utah Test and Training Range (UTTR). Afterward, the MSR program was postponed and the development of the passive EEV for the MSR mission was halted. It was resurrected in 2008 as a Multi-Mission Earth Entry Vehicle (MMEEV) concept [6].

The aerodynamic shape of test vehicles described in this report is based on the original passive MSR design developed in the 2000s; however, a more efficient structural design was introduced using the Integrated Composite Stiffened Structure (ICoSS) concept. The ICoSS structure is uniquely suited for the passive Multi-Mission EEV as it can be configured to accommodate different energy absorbing methods as well as offer fabrication flexibility [7].

Following a developmental period between 2014 and 2016 which included Manufacturing Demonstration Unit (MDU) fabrication, materials characterization and full-scale forward shell pressure tests [7], two full-scale EEVs were fabricated using the ICoSS design and tested at UTTR. Three full scale impact tests were conducted on two test vehicles at UTTR during the summer of 2016. While the objectives of the full-scale tests were to verify the structural design, this report will cover the attempt to precisely measure parameters such as impact velocity, attitude at impact, vehicle stability, and other parameters required to ensure a successful final portion of free flight and landing. This report will document the test setup and procedures, instrumentation used and free flight characteristics of the three tests conducted. Additional information documenting the impact performance of the test vehicles can be found in reference [8].

2. Test Vehicles

A schematic of the test vehicle is shown in Figure 1. The test article's forward shell utilizes the ICoSS structural concept and it is fitted with surrogate Thermal Protection System (TPS). The sample canister (SC), is securely attached to the Payload Support Structure (PSS). The PSS is a rigid structure and in addition to cradling the SC, it also integrates the vehicle's forward shell to the back shell. Ballast mass and the instrumentation were housed in the SC as shown in the schematic.

While the two test vehicles used in the impact tests were very similar in shape and design, they contained subtle structural differences. One important difference was in the surrogate TPS material used on the forward shell. Test Vehicle 1 used stronger polyurethane foam than Test Vehicle 2. The test vehicle diameter was 1.2 m and each weighed approximately 22 kg.

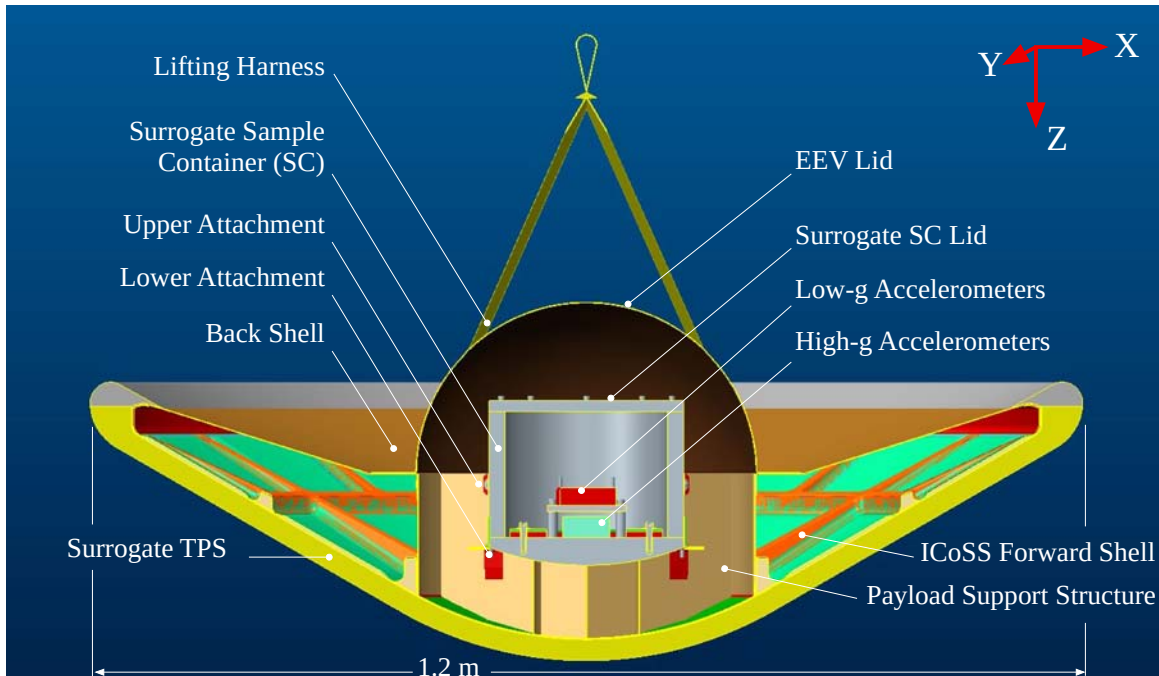


Figure 1 - EEV test vehicle schematic

Onboard instrumentation included two accelerometer packs, located inside the SC. The first was a 20-g (herein referred to as “low-g”), three axis accelerometer pack, located at the vehicle center of gravity (CG), and the second was a 6000-g (herein referred to as “high-g”), three axis accelerometer pack. The high-g accelerometer pack contained three piezoelectric sensors and three angular rate sensors and was rigidly attached to the SC base. This accelerometer pack was triggered at ground impact via a sensed g-threshold limit, and was capable of recording 3 seconds of data at a rate of 75 kHz in a circular buffer.

The low-g accelerometer pack contained three piezoresistive sensors, capable of measuring DC (i.e. gravitational) accelerations, and was located at the test vehicle CG. The low-g acceleration pack was intended to record the free flight accelerations, including acceleration due to aerodynamic drag and other flight characteristics. The low-g accelerometer pack had the capability of recording three-axis accelerations for 30 minutes at 1 kHz. It was triggered well in advance of the impact while the test vehicle was on the ground via an external trigger, initiated by a test team member.

Each test vehicle was painted with a black-and-white striped coded pattern in order to help determine orientation during free flight when examining ground video data. The code was unique for each quadrant of the test vehicle by using a three-concentric-ring painted pattern – an inner and outer on the bottom and one on the shoulder of the test vehicle. The coded stripes painted on the bottom would help determine orientation while viewing the test vehicle from underneath, while the code on the shoulder of the test vehicle would help determine orientation when viewing from the side. Since it was expected that cameras would first see the bottom of the test vehicle as it entered their view, and then see the side as the test vehicle became level with the camera position right before impact, viewing the two codes in conjunction would give an accurate view of the orientation during the final portion of free flight and at impact. The EEV lid was also painted using two concentric coded rings, in case the test vehicle should drop or impact in an off-nominal condition. Figure 2 shows the painted ring pattern that was used on the bottom and shoulder of the test vehicles. The EEV lid is not shown.

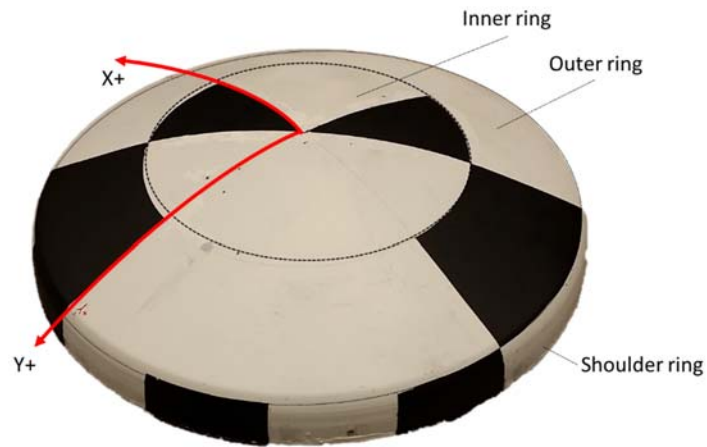


Figure 2 - Isometric view of the painted ring pattern used for all test vehicles

3. Test Setup

UTTR was the landing site for many past sample return missions and anticipated to be the landing site for future sample return missions. Following a survey of a large portion of the lake bed conducted during the original MSR project, the surveying team concluded that the ground morphology was relatively uniform and testing anywhere on the dry lake bed would be representative of the entire area. The specific test area for the 2016 tests was chosen primarily for practical reasons as it was adjacent to one of the few access roads through the test range. Figure 3 shows a general view of the test area.



Figure 3 - UTTR test area

Drop tests were performed with the aid of a helicopter. Test vehicles were attached to the helicopter release hook through a three point harness, as shown in Figure 4. The hook was suspended from the helicopter at the end of a 33 m long lanyard, as shown in Figure 5. The test plan called for the test vehicles to be dropped from a height of approximately 400 m above ground level (AGL) to achieve at least 98% terminal velocity.

The center of a 61 m diameter area was identified as the target impact spot, and the helicopter drop position was estimated based on ground wind speed. For each test, wind direction and speed was taken into consideration for the helicopter hover positioning, and the helicopter was in contact with ground personnel for guidance throughout each test, should the ground winds abruptly change. All further test setup assumes impact will occur in the 61 m diameter impact zone.



Figure 4 - Test vehicle shown with release hook (in orange) attached to vehicle's three point harness.



Figure 5 - Test vehicle attached to helicopter via a 33 m long lanyard

An onboard high definition (HD) camera was mounted to the helicopter nose, pointing down. This camera was present to record the test vehicle release and initial portion of flight, while also available to capture any anomaly during release, should one occur.

Two four-megapixel (MP), monochrome, high speed cameras filming at 500 Hz were positioned on the ground in order to capture vehicle orientation and speed during the last portion of free flight and at impact. Cameras used 60 mm lenses and were stationed 142 m apart. The center of the impact zone was 200 m from each camera position, and each camera field of view was a 61m horizontal length at the center. These parameters were chosen based on the camera pixel density, lenses and practical camera communication cable lengths available and test range safety. The camera positions made a right angle between each other. A right angle setup was critical to determine vehicle orientation from two perpendicular directions, giving a full three-dimensional solution obtained from the camera data. Both cameras were pitched up to achieve an approximate 3° angle. At the center of the impact zone distance, the cameras were able to see up to approximately 65 m above the ground.

Three ground ultra-high definition (UHD-4K) camcorders filming at 29.97 Hz were also present for each test. Two were stationed next to the high speed cameras, approximating the high speed view, while the third was hand held by a team member for each test.

Portable GPS units were used on the ground and in the helicopter to capture both the drop position and impact position from each test, and a portable weather station capable of measuring wind speed and direction was set up in the staging area to assist with helicopter drop positioning.

All tests followed the same general procedure. The test vehicle was first placed on a foam cradle and leveled and adjusted to be horizontal. After leveling, both accelerometer packs were armed and the low-g accelerometer pack was then triggered and allowed to collect data for up to two minutes while the SC lid was closed and the EEV lid was installed. The test vehicle was removed from the cradle, placed on the ground and the release hook was carefully attached to the lifting harness. The helicopter lifted the test vehicle such that it was hanging just above the ground. After inspection by the ground personnel ensured the test vehicle was correctly secured to the release hook, an all-clear was communicated and the helicopter began its ascent to its predetermined altitude and position. After clearance was given to drop, the helicopter released the test vehicle and began to descend back to the staging area for landing. After landing the test vehicle was retrieved using an all terrain vehicle (ATV) and brought back to the staging area for data download. Concurrently, video was also reviewed and downloaded. At the impact site, post-impact pictures were taken, GPS coordinates were recorded, and crater depth and diameter were measured.

4. Test Results

Prior to conducting drop tests using the actual test vehicles, a rigid hemispherical penetrometer was used to practice the helicopter positioning, release, data collection methods, and communication between ground and helicopter. The penetrometer had a diameter of 66 cm and weighed approximately 39.7 kg, which, compared to the test vehicles, was a higher ballistic coefficient. It was also painted with the three concentric circle black and white coded striped pattern for aid in camera tracking. Two views of the penetrometer are shown in Figure 6.



Figure 6 - Drop penetrometer used for practice testing. Side view on cradle (left) and top view (right)

A total of five preliminary drop tests were completed on the penetrometer. The first two contained the onboard instrumentation, while the final three were used for helicopter positioning and drop location checkouts only. The successful completion of the fifth preliminary test satisfied the test team that drop positioning, data collection methods, and communication protocols were all sufficient.

All tests were conducted on July 21st, 2016. Table 1 shows the parameters recorded for all three drop tests, including drop and impact positions, altitude at release, flight time and impact notes. Drop altitude AGL was found by subtracting elevation at impact from drop elevation, while also taking into account the 33 m of lanyard from which each test vehicle was attached. Free flight time was determined by examining the low-g accelerometer free flight timestamp data between release and ground impact.

Table 1 - Testing summary

Test	Test Vehicle	Drop Position	Impact Position	Drop altitude AGL (m)	Sustained winds, m/s (knots-kts) from direction	Free flight time (s)	Notes
1	Test Vehicle 1	40°21.140'N 113°16.017'W	40°21.163'N 113°16.030' W	401.3	2.57 (5) from S	17.8	
2	Test Vehicle 1	40°21.015'N 113°16.017' W	40°21.095'N 113°16.078' W	420.8	2.06 (4) from S	21.1	Large amounts of tumbling during free flight
3	Test Vehicle 2	40°21.093'N 113°15.928' W	40°21.116'N 113°15.932' W	409.6	5.66 (11) from SSE	16.9	Large amounts of rotation at impact

4.1. Test 1 Results

Test 1 consisted of Test Vehicle 1 with the sample canister ballasted to a total mass of 12.5 kg, leading to a total test vehicle mass of 34.3 kg. The low-g accelerometer pack was triggered at 7:11 am local time, and the impact occurred at 7:26 am local time. Winds at the time of impact were 2.57 m/s (5 kts) sustained

from the south, measured at ground level. Figure 7 shows an overhead map view of the drop (green pin) and impact (red pin) positions of the test vehicle with respect to the camera field of view and impact zone. The access road is located on the left side of the image, along with the ground camera positions next to the road (yellow pins) and field of view edges (blue lines). The 61 m impact zone is identified by the green circle.

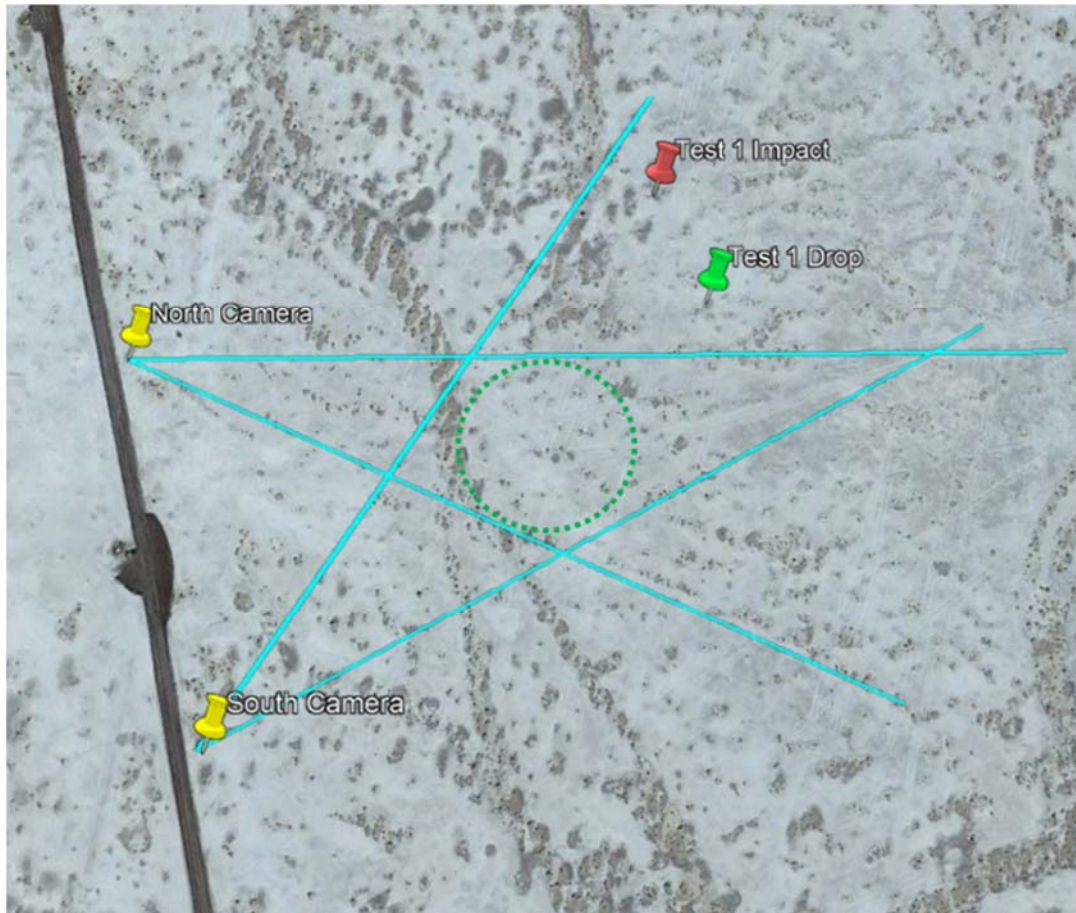


Figure 7 - Test 1 overhead view

The test vehicle was dropped approximately 68.6 m NNE from the center of the drop zone at an altitude of 401.3 m AGL and the test vehicle traveled approximately 46.3 m NNW further away from the center of the drop zone. Because the impact position was further to the north and east of the middle of the drop zone, only the south ground cameras (both high speed and UHD-4K) were able to image the impact event. The test vehicle fell out of view of the north cameras. The test vehicle released from the hook at a nominal condition, but immediately after release the test vehicle rotated (as viewed relative to the helicopter orientation) nearly 90° from the horizontal. Fortunately, there was enough altitude to allow for the test vehicle to stabilize and the oscillations to damp out, and the test vehicle impacted the ground at 4.8° to the vertical. Figure 8 shows views from the onboard camera, both immediately upon release hook opening (left), and the test vehicle pitch angle at the beginning of free flight (right).

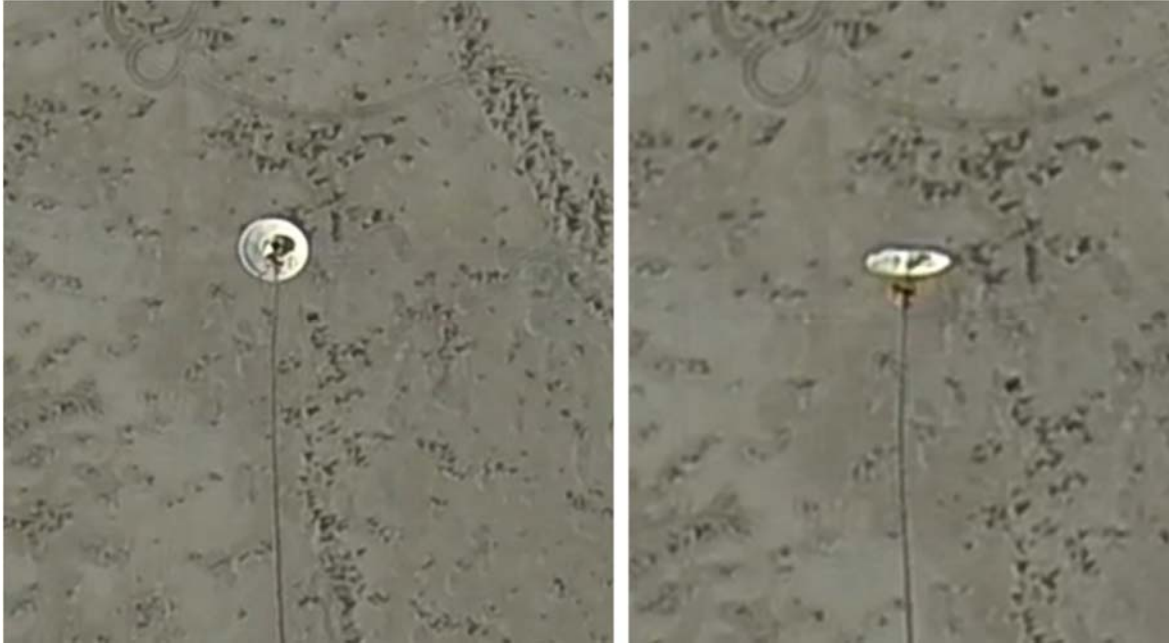


Figure 8 - Test 1 release. Hook opening (left) and angle immediately after release (right)

Figure 9 shows the test vehicle during the last portion of free flight as imaged by both the UHD-4K and high speed camera. Each image also has a zoomed view of the test vehicle to show detail captured, along with the flight path projection. The test vehicle did not exhibit any spinning throughout the free flight sequence.

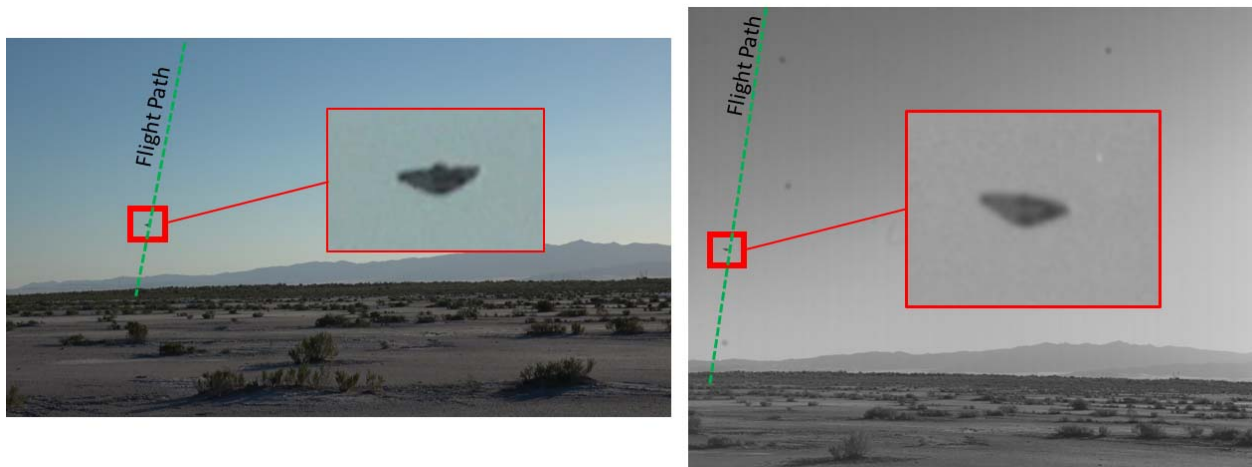


Figure 9 - Test 1 free flight tracking. UHD-4k view (left) and high speed view (right)

The impact occurred near the north edge of the high speed camera field of view; however there was adequate resolution present to track the test vehicle both during free flight and at impact. Figure 10 shows the test vehicle at impact, as viewed from the south high speed camera zoomed to 3x, with an exaggerated view of the painted striped pattern used for impact orientation analysis.

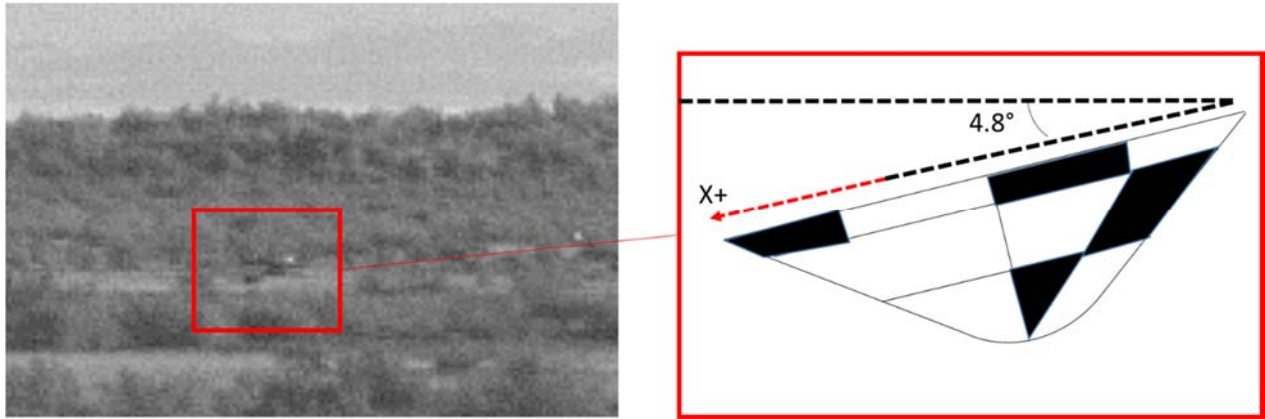


Figure 10 - Test 1 zoom 3x high speed view at impact (left) and exaggerated view (right)

By carefully examining the striped pattern and recreating an exaggerated view, the tracking data showed the $x+$ direction pointed downward at a 4.8° angle at impact. There also appeared to be some angle tilt toward the $y+$ direction (away from the camera); however, the video data from the south camera could not definitively confirm the magnitude of this response. Had the test vehicle impacted within the 61 m field of view, the north camera could have aided in determining the angle for this instance. The post-impact position of the test vehicle, along with crater at impact is shown in Figure 11.



Figure 11 - Test 1 post impact orientation (left) and crater (right)

In general, in order to be able to use video data for engineering analysis, the scaling of the camera's pixel units into engineering units (i.e. meters or feet) must be accomplished. Typical scaling involves the selection of points of interest at known distances apart within the camera field of view and assigning them a known value in engineering units. In this test series, points of interest were selected and measured at the mid-plane of the impact zone prior to all testing, making scaling known for locations inside the impact zone. However, because the test vehicle impacted much further away from the impact zone than anticipated, the pre-test measured scaling factors could not be used due to the camera's inability to perceive differences in depth perspective. Instead, the scaling issue was resolved by using the known size of 1.2 m of the test vehicle itself. A more robust solution would have been to conduct a post-test calibration by acquiring in-situ scale bar information at the impact position after the video data had been downloaded. However, since this was not performed, Figure 12 shows the tracking results of the vehicle using the vehicle scale bar method from the south high speed camera.

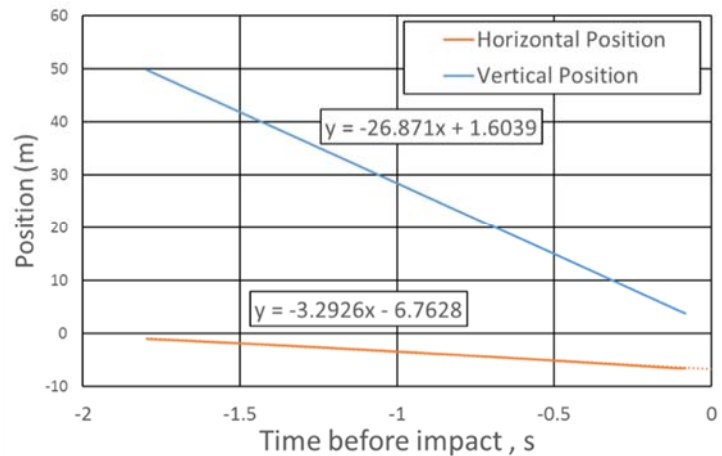
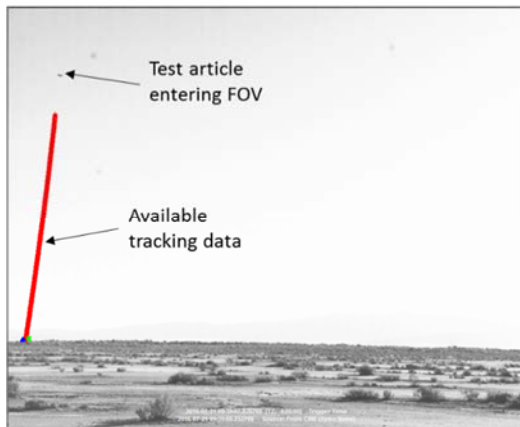


Figure 12 - Test 1 position tracking. Camera view (left) and resolved position (right)

The tracked flight path in red is shown on the left and the tracked position measurements are plotted on the right. Both the vertical and horizontal positions resembled a line with constant slope, indicating a constant velocity and zero acceleration during the final 1.8 s before impact of which camera tracking data were available. Taking the slope of both of the lines, the two-dimensional tracking analysis was computed. It showed a flight path vertical velocity of 26.87 m/s and a horizontal velocity of 3.29 m/s. However, the single south camera view was restricted to viewing the three-dimensional impact event in only the two in-plane dimensions - the horizontal and vertical parallel to the camera sensor plane. To mitigate this deficiency, the velocities were found in the two in-plane dimensions and then scaled using the three-dimensional flight path data obtained from the GPS measurements. Figure 13 shows the GPS analysis using camera, drop and impact locations.

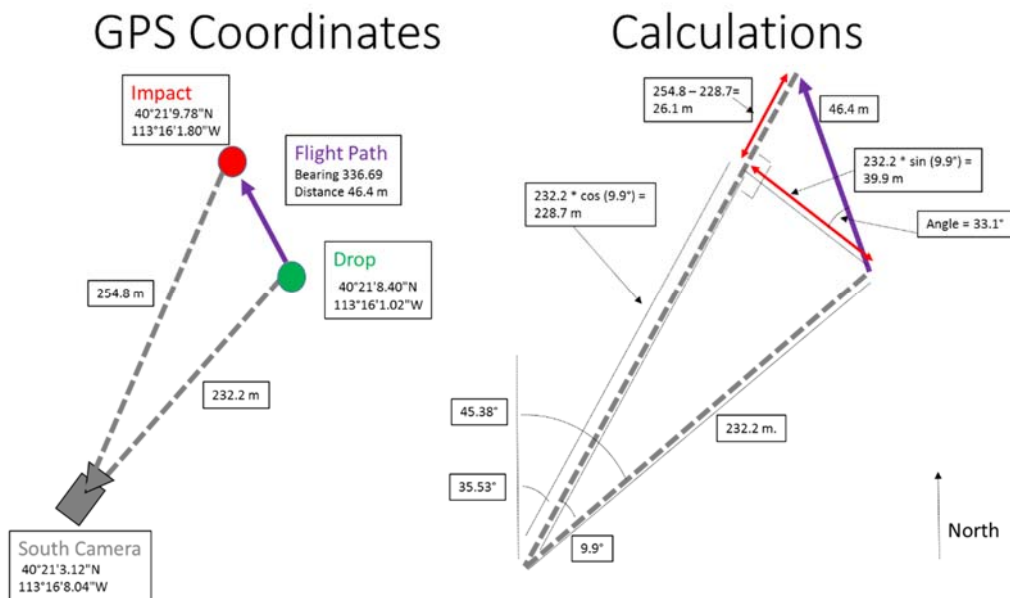


Figure 13 - GPS analysis for Test 1

By using the coordinates for each of the items of interest and the simple geometrical calculations, a full reconstruction of the test vehicle's flight path as viewed from the camera was determined. The main

takeaway from the GPS analysis showed the flight path angle of 33.1° relative to the camera sensor plane. This angle was used in conjunction with the horizontal velocity obtained from the camera tracking analysis to resolve both a lateral in- and out-of-plane velocities for the final 1.5 s of flight. The lateral in-plane velocity was 2.75 m/s, and the lateral out-of-plane velocity was 1.8 m/s as determined from the camera analysis. Taking these results and using a simple distance traveled over the free flight time calculation using the GPS coordinates, an average 2.2 m/s in-plane and an average 1.5 m/s out-of-plane velocities were calculated. The calculated average velocity GPS number differs more than the ratioed velocities obtained from the camera tracking because the GPS average assumes a constant acceleration in the lateral direction during the entire free flight, which may or may not be affected by the wind, test vehicle oscillation, drag, or other external factors. The camera field of view only examined the final 65 m of vertical free flight, of only approximately 50 m of which was tracked.

In addition to the camera tracking and GPS analysis, the velocity at impact was also determined by integration of the high-g accelerometer data. Due to the close-to-nominal impact orientation, the velocities found when integrating the accelerations from the high-g accelerometer pack were 29.6 m/s in the vertical direction and 5.1 m/s in the root-sum-squared horizontal direction, after a correction factor for the slight 4.8° angle in the $x+$ direction was applied. A full analysis of the impact data is presented in reference 8.

When using the three methods of determining the impact conditions, slightly different values were obtained. The differences associated with each of the methods arose from the assumptions made in the processing of the data. Because the test vehicle landed where only one camera could view the impact, the camera tracking analysis presented three-dimensional results based off of a single camera view using scaling factors based from a two dimensional test vehicle assumption. While the GPS analysis used a position difference and flight time to obtain an average flight velocity, it assumed constant acceleration during the entire free flight. The GPS analysis did not consider variations in the wind or test vehicle drag, and was also unable to determine orientation at impact. The high-g accelerometer was a third way to measure the impact velocities and orientation; however, this measurement only occurred upon test vehicle impact and this method assumed that the vehicle motion stopped during the data collection processes, thus ensuring the delta-velocity obtained by integrating the measured accelerations was consistent with the total velocity at impact. The high-g accelerometer would not accurately measure the impact velocities if the test vehicle were to bounce or skim off the ground upon impact. Each test, as it turned out, had various characteristics which made a particular method best suited to obtain the impact conditions. For Test 1, the impact condition numbers were ultimately determined and reported using the high-g accelerometer data. However it was useful to have all three methods as potential options, such that the reported flight characteristics and impact velocities could be verified to some degree. Additionally, if one method proved to be unavailable, the others could be used to obtain the necessary measurements.

The low-g accelerometer data were examined next. A full time history trace of the low-g acceleration data is presented in Figure 14.

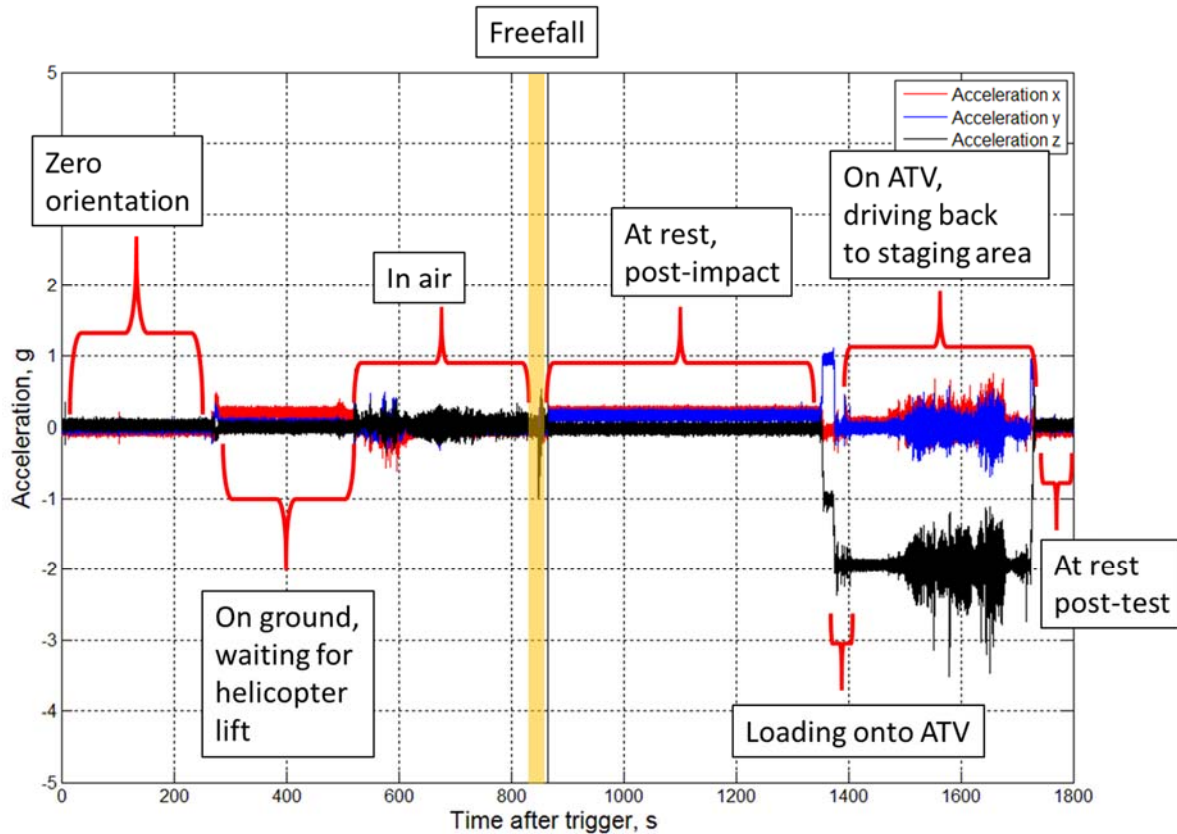


Figure 14 - Test 1 low-g accelerometer data

A full sequence of test events can be reconstructed by examining the onboard acceleration data from the low-g accelerometer pack. For the first 273 seconds, the test vehicle was in its cradle, at rest, leveled in the xz- and yz- planes. During this time, the sample canister and EEV lids were also installed. The test vehicle was then placed on the ground and attached to the release hook. For the next 225 seconds (between times 273 and 503 seconds), the test vehicle was stationary on the ground while the helicopter began its lift-off and climb. At the 503 second mark, the test vehicle was lifted off the ground, and for the next 344 seconds (between times 503 and 847.7 seconds), the helicopter and test vehicle climbed to the release position. Free flight occurred for 17.8 seconds; which started at 847.7 seconds and ended with ground impact at 865.5 seconds. The test vehicle was stationary and oriented in its post-impact position, which occurred between times 865.5 and 1352 seconds while the test team travelled to the impact site. The test article was loaded onto the ATV between times 1352 and 1378 seconds, driven back to the impact site between 1378 and 1724 seconds and placed on the ground for data download after 1724 seconds until data recoding stopped at 1800 seconds.

A close-up view of only the free flight acceleration is presented in Figure 15. The free flight began once the acceleration in the z direction abruptly changed at approximately 847.7 seconds, and ended when the test vehicle impacted the ground, which was defined by a large spike recorded in the acceleration at approximately 865.5 seconds. The data in between these two times revealed the test vehicle behavior while in free flight.

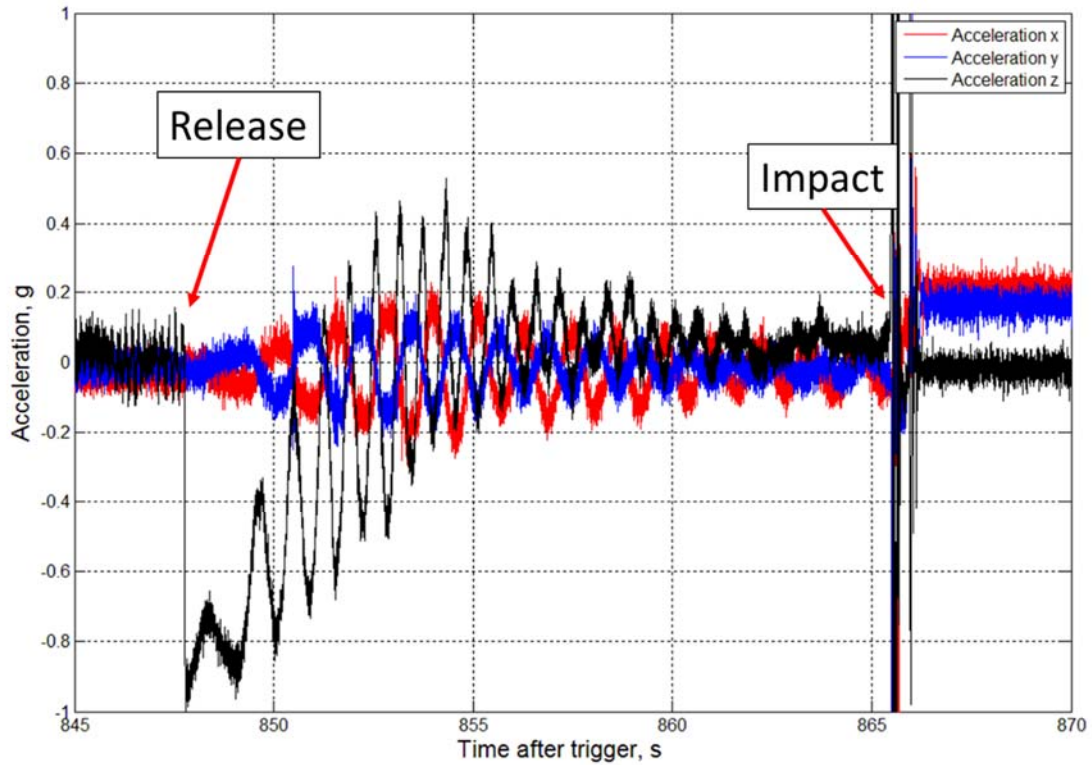


Figure 15 - Test 1 free flight acceleration

The data showed an 0.8 Hz oscillation behavior in all three axes. These oscillations were also confirmed by the high speed video during the last portion of free flight. A frame of video of the angle of the test vehicle is plotted at five different times before impact, using the extreme left tilt and right tilt (as viewed from the camera position) as normalized maximum and minimum values of a sine wave, respectively. A half sine wave is formed when plotting these numbers versus time. The time between subsequent angle measurements in the sine wave was approximately 1.2 s, leading to a frequency of 0.83 Hz, which confirmed the accelerometer data during free flight. A graphical representation of the video tracking is shown in Figure 16.

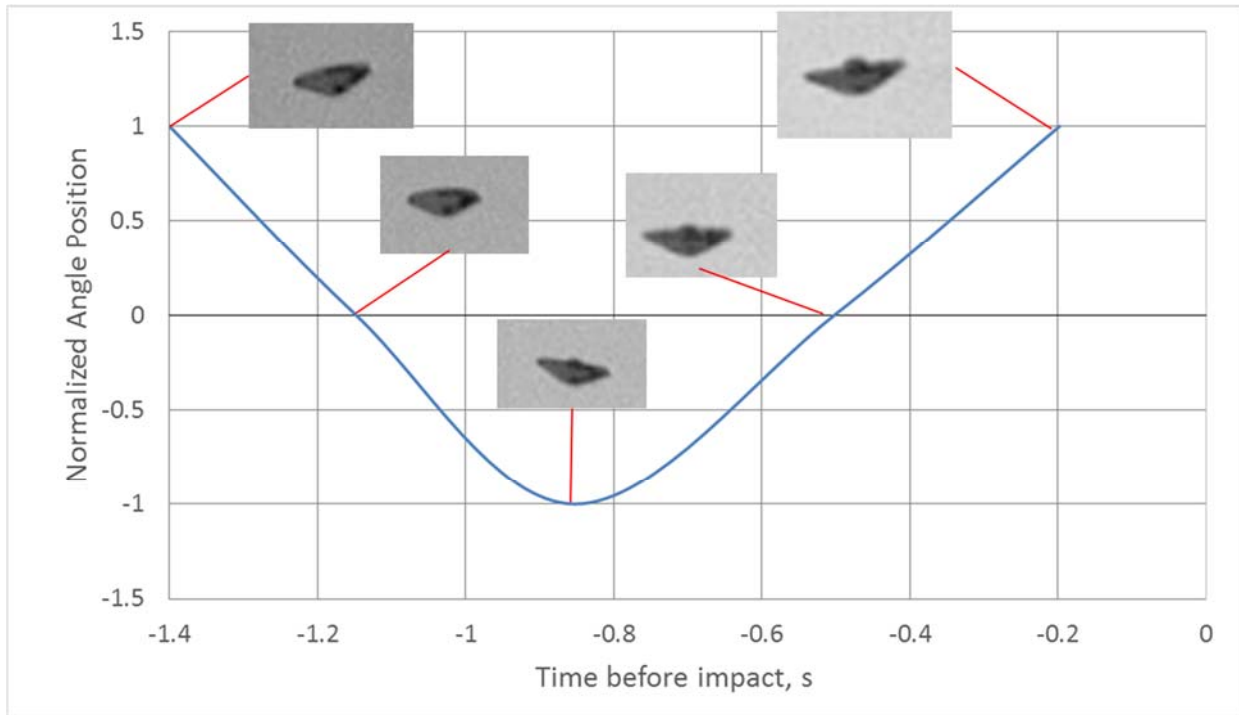


Figure 16 - Test 1 angle position

Additionally, the acceleration data in the vertical (z) direction exhibited an abrupt change between approximately 0 g and -1 g at release, then slowly approached 0 g at about the 860 s mark. This approaching of 0 g during flight indicated that the terminal velocity condition had been reached, and verified the 0 g acceleration result obtained in the velocity tracking data by the camera. Finally, the oscillation magnitudes experienced in all three axes of the vehicle decreased from their maximums which occurred at around the 854 s mark to minimal (but not exactly zero) values immediately before impact. This behavior suggested that the vehicle oscillation stabilized toward the end of the free flight, which allowed it to land at a close-to-nominal impact condition.

However, the free flight acceleration data were limited to oscillation, flight time, and terminal velocity determinations only. Other potential uses for the free flight data would have been to determine quantitative vehicle dynamics such as free flight stability and global damping values. These characteristics proved difficult because the complete six degree-of-freedom (i.e. three axis accelerations along with three axis angular rotational rates) data were not available in the low-g instrumentation package. Schemes using only the three axis collected acceleration data were proposed, but ultimately dismissed due to large potential errors associated with needed assumptions related to vehicle aerodynamics.

The vehicle impact produced dynamic loads of around 560 g [8]; however, post-test inspections revealed that the test vehicle was largely undamaged, with only minor damage in localized areas of the epoxy-fillet between the forward shell and the payload support structure. Therefore the test vehicle was prepared for a second drop test, providing a second attempt to land the vehicle within the predetermined landing zone.

4.2. Test 2 Results

The test vehicle used for Test 1 was cleaned up and reused for Test 2. The low-g accelerometer pack was triggered at 7:55 am local time, and the impact occurred at 8:07 am local time. Winds at the time of impact

were 2.06 m/s (4 kts) sustained from the south, and occasionally gusting to near 5.14 m/s (10 kts) measured at ground level.

Upon release from the helicopter, the test vehicle experienced a perturbation which caused it to tumble. This tumbling led the vehicle to travel approximately 181 m horizontally at a bearing of 332.2 degrees while in free flight. Figure 17 shows the drop (green pin) and impact (red pin) positions of the vehicle, overlaid onto an overhead map. The access road, camera positions (yellow pins), field of view edges (blue lines) and impact zone (green circle) are all identified for reference, and were unchanged from Test 1.

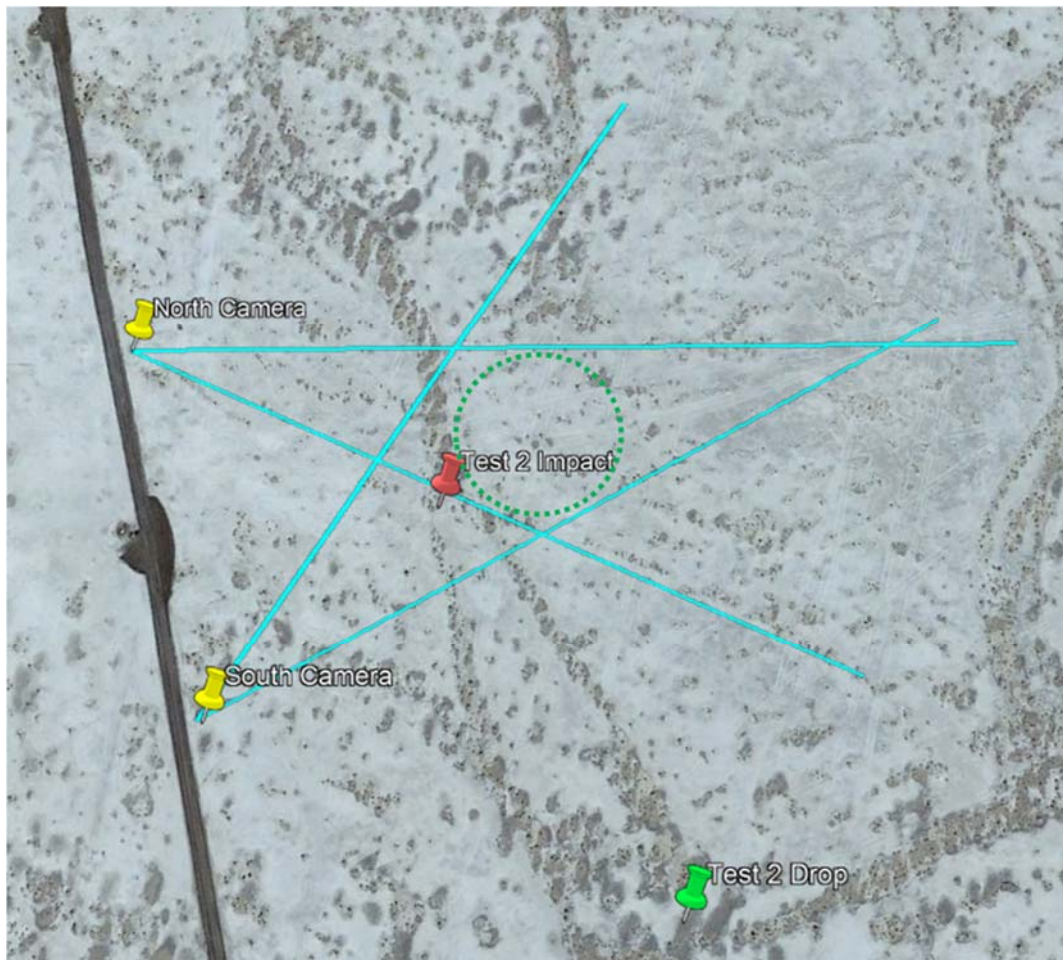


Figure 17 - Test 2 overhead view

At release, the test vehicle was undergoing a large port-starboard oscillation, along with the beginnings of a pitch rotation, as viewed from the onboard camera mounted on the helicopter. Unfortunately, due to the combination of a) sideways velocity caused by the lanyard oscillation, b) the angle of the test vehicle from the pitch rotation, and c) potential winds aloft, end-over-end tumbling occurred during the free flight. Figure 18 shows the release sequence, as imaged from the onboard camera. The white object in the foreground is the helicopter wire strike protection system mounted just below the camera.

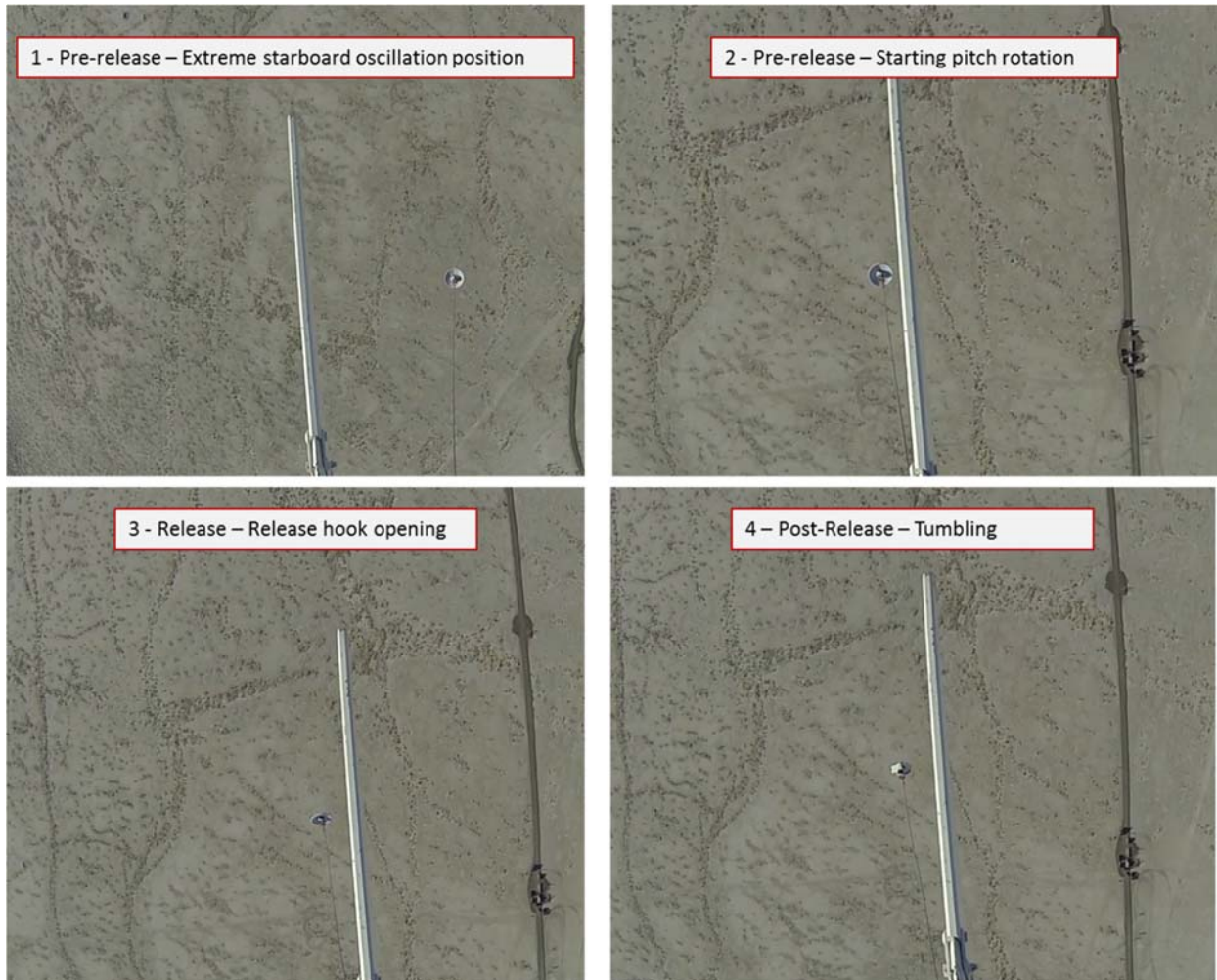


Figure 18 - Test 2 release 4 image sequence

The end-over-end tumbling behavior continued throughout the entire free flight. The test vehicle impacted the soil immediately in front of the designated impact zone. As with Test 1, the impact was only captured by the south high speed and the UHD-4K cameras. Figure 19 shows the test vehicle flight path as captured by the high speed camera. The test vehicle was exhibiting a clockwise rotation, as viewed from the camera location, with four major positions highlighted: right side-up (1), sideways, pointed (approximately) to the north (2), upside-down (3), and pointed (approximately) to the south (4).

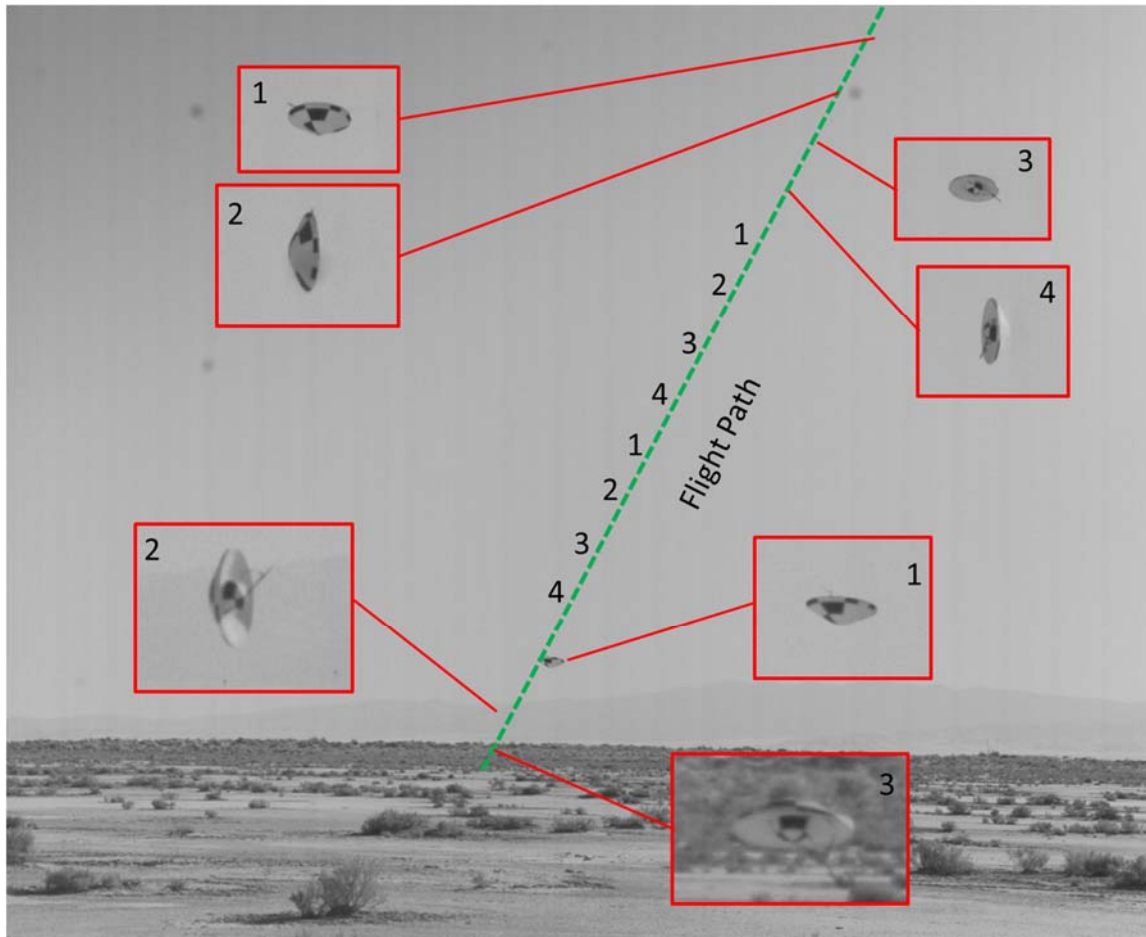


Figure 19 - Test 2 free flight sequence as captured by the south high speed camera

The south high speed camera was able to capture the last four rotations of the test article from the tumbling. A rotation frequency of 2.7 Hz was determined from an analysis by using the images obtained and frame rate of the camera. Additionally, the camera data showed the vehicle did appear not to be spinning about its z-axis. Next, Figure 20 shows the test vehicle orientation at impact. Note the image is much more detailed due to the test vehicle position being much closer to the camera at impact. .



Figure 20 - Test 2 – 3x zoom high speed view at impact

The test vehicle came to rest upside-down, near the original impact position. Figure 21 shows the post-test orientation of the test vehicle, along with the crater made at impact. The crater is comprised of two “C” shaped indentations on either side of a round indentation from the EEV lid. The three distinct imprints on the ground was due to the rotation of the test vehicle at impact.



Figure 21 - Test 2 impact location and crater

Because of the unwated tumbling, the test was declared a “no-test”, or invalid with regard to a vehicle stability measurement and impact attenuation standpoint. Therefore, impact and free flight accelerations were not further analyzed. However, the effect of the tumbling on the free flight position was examined only using the high speed camera tracking methodology. This analysis is shown in Figure 22.

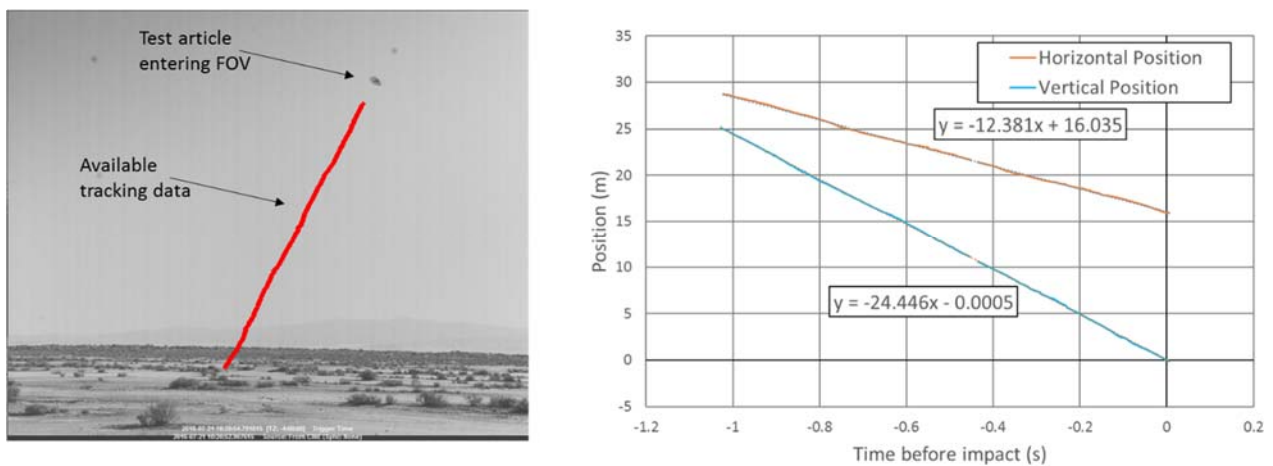


Figure 22 - Test 2 position tracking. Camera view (left) and resolved position (right)

Taking the slope of both of the lines in Figure 22, the two-dimensional tracking analysis shows a vertical velocity of 24.45 m/s and a horizontal velocity of 12.38 m/s. The large amounts of tumbling gave the test vehicle its large horizontal velocity. A similar GPS measurement analysis was completed to resolve the velocities found in the two projected camera sensor in-plane dimensions to dimensions both in- and out-of-plane of the camera sensor. Figure 23 shows the GPS analysis using camera, drop and impact locations.

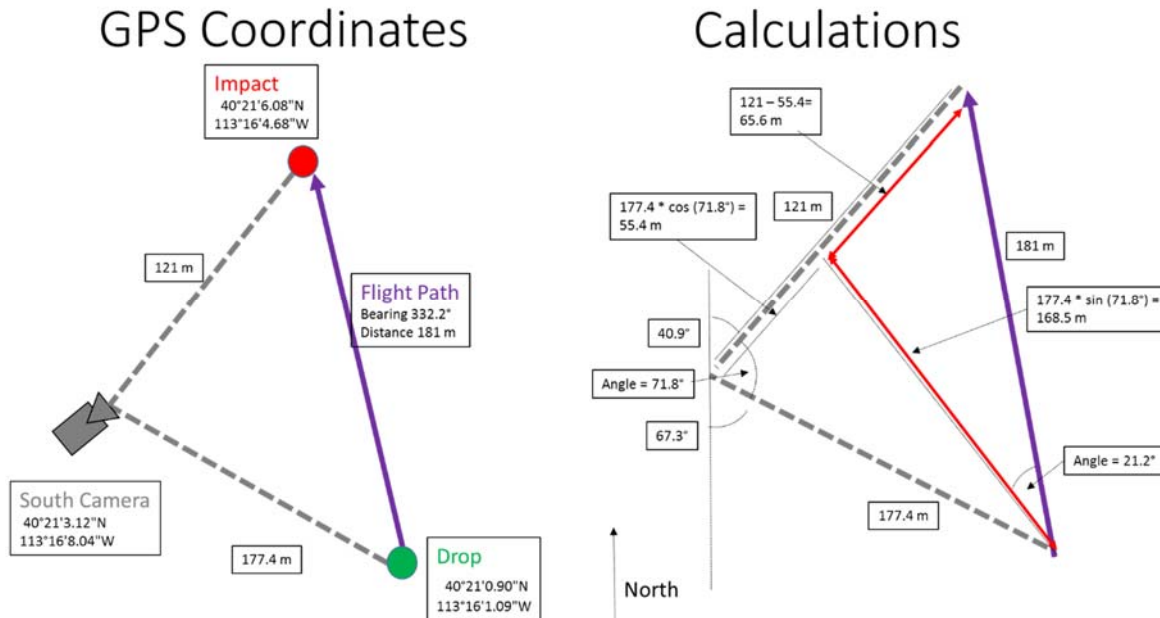


Figure 23 - GPS analysis for Test 2

A full reconstruction of the test vehicle's flight path, similar to what was computed for Test 1, was completed for Test 2 and showed a flight path angle of 21.2° relative to the camera sensor plane. This angle was used in conjunction with the horizontal velocity obtained from the camera tracking analysis to give both a 11.5 m/s lateral in- and 4.5 m/s out-of-plane velocities for the final second of flight. Using a simple distance traveled over the free flight time calculation, an in-plane 8.0 m/s velocity and 3.1 m/s out-of-plane velocity were calculated. The calculated average velocity numbers differed from the proportional velocities obtained from the camera tracking because the averages assumed a constant acceleration in the lateral direction during the entire free flight, which could have been affected by the wind, test vehicle tumble, drag, or other external factors. Further analysis on the impact or damping was not completed due to the tumbling condition of the free flight, and thus no other free flight or impact parameters were calculated. Furthermore, the test vehicle survived this off-nominal impact event, demonstrating further the robustness of the ICoSS structural design.

4.3. Test 3 Results

Test 3 used Test Vehicle 2 with the payload ballasted to 12.5 kg, which lead to a total test vehicle mass of 34.9 kg. The low-g accelerometer pack was triggered at 9:22 am local time, and the impact occurred at 9:32 am local time. Winds at the time of impact were 5.66 m/s (11 kts) sustained from the SSE, measured at ground level.

Test vehicle release from the helicopter was similar to Test 1. The test vehicle was released while the lanyard exhibited a large oscillatory sway. The test vehicle pitched to approximately 90 degrees just after

release; however, it did not tumble. The handheld UHD-4K camera captured both the time immediately before and after the release, images of which are shown on the left and right, respectively, in Figure 24.

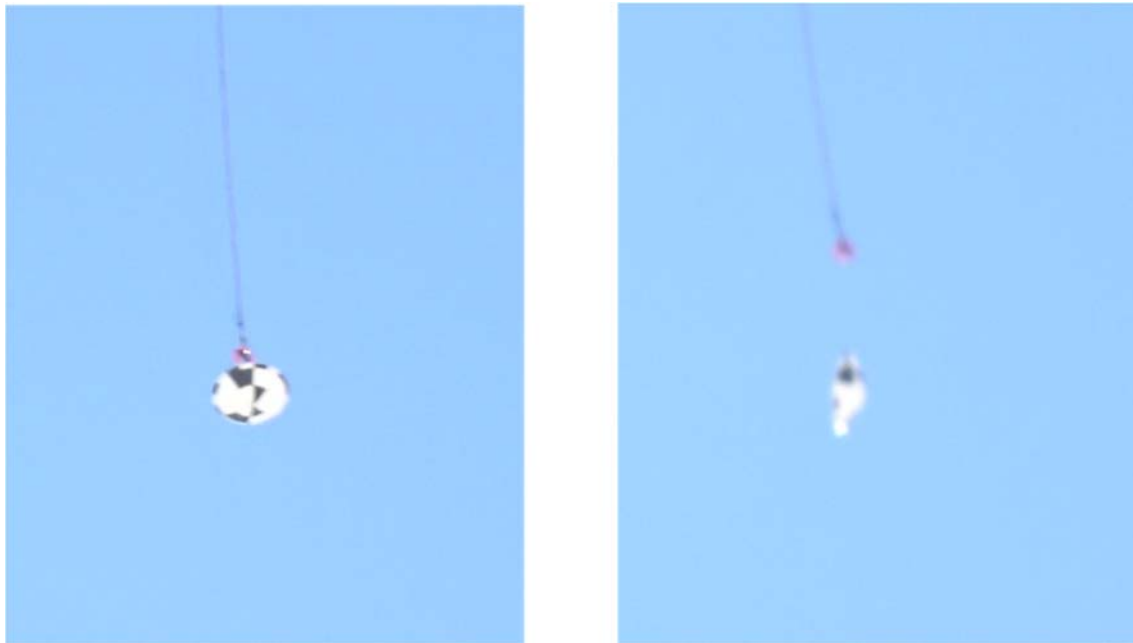


Figure 24 - Test 3 release. Before (left) and after (right) release hook open

Unlike tests 1 and 2, the final impact position of Test 3 was only captured by the north high speed and UHD-4k cameras. The test vehicle was released from a height of 409.6 m AGL. The test vehicle fell with a bearing of 352.5° and impacted the ground 321.3 m away from the north camera's position. Due to the extreme distance between the camera and impact location, detailed analysis of the test vehicle behavior throughout the last portion of the free flight proved difficult. To further complicate the analysis, the test vehicle appeared to be noticeably oscillating in two axes when examining the camera data, having both in-plane left-to-right sway, along with an out-of-plane forward-to-backward sway. This type of oscillation was expected for this vehicle shape and resembled the motion of a conical pendulum. The oscillation was similar to that observed in Test 1, however more complex as it occurred in two axes. Figure 25 shows the flight path and tracking results from the north high speed camera. The test vehicle at various angles is highlighted.

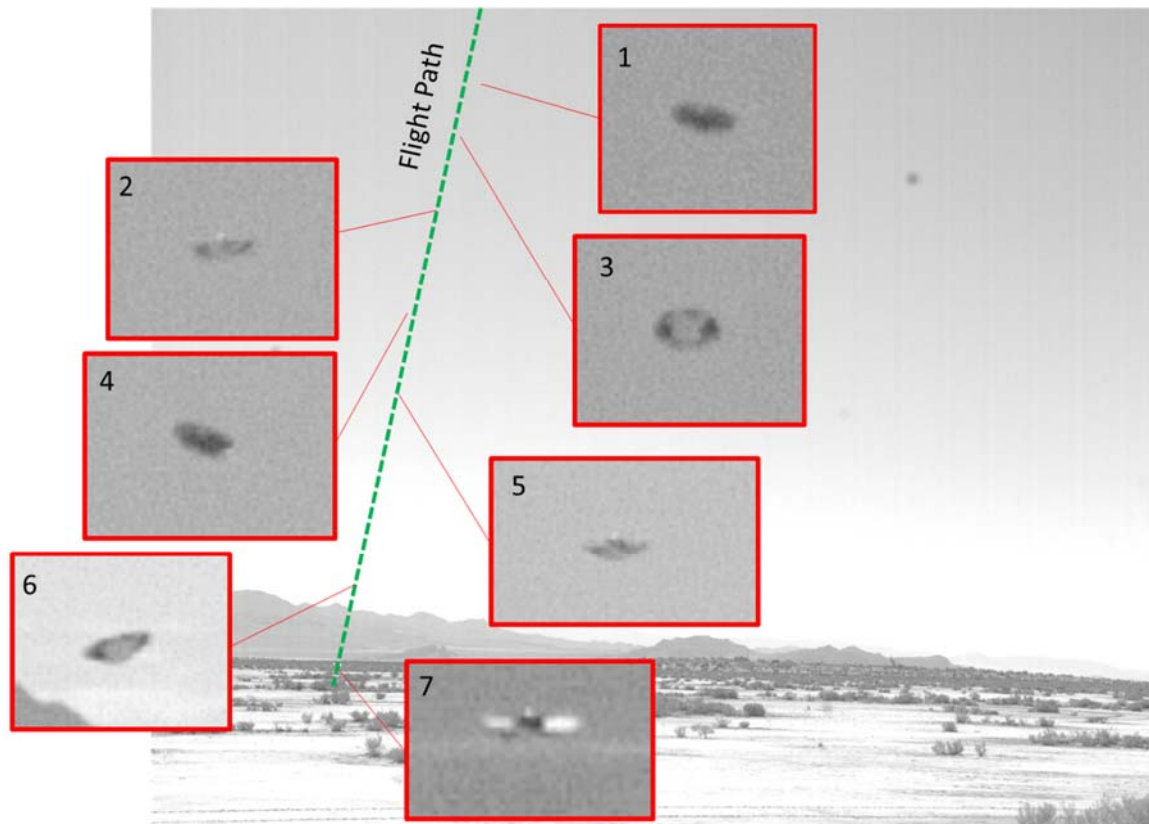


Figure 25 - Test 3 free flight sequence as captured by the north high speed camera

The seven frames of video in Figure 25 show the test vehicle at various states during the final seconds of free flight. Each frame represents a unique orientation of the test vehicle. As viewed from the camera perspective, some frames show an in- to out-of-plane oscillation, such as in frame three, while others show a left-to-right oscillation, as in frame six. Others frames such as two and five, show a flat, nominal orientation. With all frames taken together, a conical pendulum pattern emerged. As with tests 1 and 2, it did not appear to be spinning about its z axis. Shortly after frame seven, the test vehicle impacted the ground. Figure 26 shows a close-up of the impact.



Figure 26 - Test 3 impact location and crater

It is unclear from the high speed video the exact orientation in which the test vehicle impacted the ground due to the extreme distance between the camera and test vehicle. However, the likely impact scenario was reconstructed by examining the crater and the surrogate TPS foam at the impact site. The test vehicle impacted the ground on its shoulder at the 135° radial with high horizontal and rotational velocities. The large rotational velocities caused the test vehicle to slide off the ground, leading to the surrogate TPS between the 45° and 225° radials to separate from the aeroshell. The separation left pieces of the surrogate TPS material scattered around the impact site, as shown in Figure 26.

This test was also invalidated with regard to impact attenuation because the vehicle did not have enough free fall height to allow for the extreme oscillation (caused by perturbation at release) to damp out. Therefore impact loads were not further analyzed. However, the free flight characteristics were examined using both the high speed camera tracking methodology, along with the onboard low-g accelerometer pack. The high speed camera tracking analysis is first shown in Figure 27.

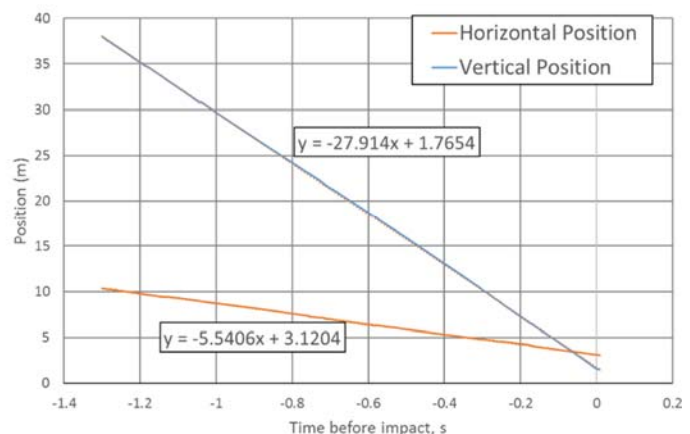
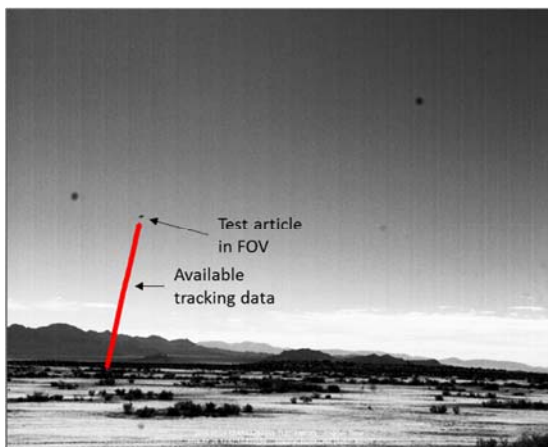


Figure 27 - Test 3 position tracking. Camera view (left) and resolved position (right)

After tracking was completed, the results show the test vehicle impacted with vertical velocity of 27.91 m/s and a horizontal velocity of 5.54 m/s. These velocities were closer to the velocities seen in Test 1, further suggesting that the test vehicle - at least during the free flight - behaved similar enough to Test 1 to be able to be analyzed using the GPS analysis. A similar GPS measurement analysis was completed which resolved the velocities to both the in- and out-of-plane dimensions. Figure 28 shows the GPS analysis using camera, drop and impact locations.

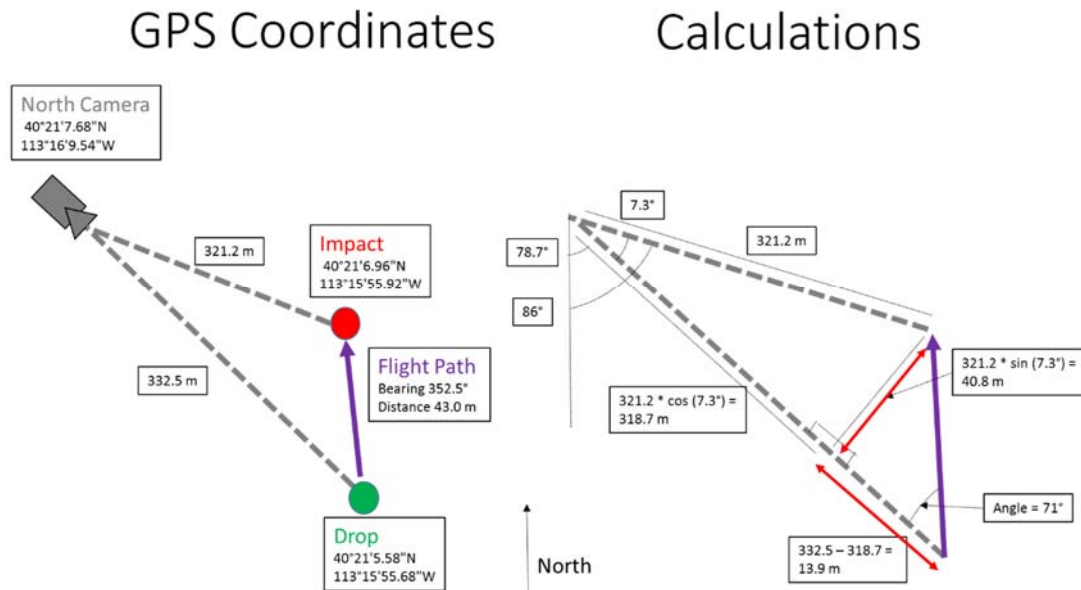


Figure 28 - GPS analysis for Test 3

Using GPS data and resolving the coordinates into in- and out-of plane positions, average impact velocities were found. Total lateral velocity was approximately 2.5 m/s, with an in-plane component of 2.4 m/s and an out-of-plane component of 0.8 m/s. The vertical velocity was resolved through the camera tracking. As with the first two tests, since the vehicle was out of the range of the original scaling bars, the test vehicle itself was used as the scale factor, and checked at various positions throughout the camera view. The velocities measured, using the endpoints of the scaling factors obtained, showed a range between 27.9 m/s and 28.5 m/s vertical velocity. Horizontal velocity was determined to be 5.5 m/s. Resolving this velocity into in- and out-of-plane measurements showed an in-plane velocity of 5.2 m/s and an out-of-plane velocity of 1.8 m/s. These measurements are in general agreement with the free flight characteristics seen in Test 1.

A close-up view of only the free flight acceleration is presented in Figure 29. The free flight began once the acceleration in the z direction abruptly changed from zero g to approximately -1 g at 614.5 s, and the test vehicle impacted the ground when a large spike was recorded in the acceleration at approximately 631.4 s. The data in between these two times revealed the test vehicle behavior while in free flight.

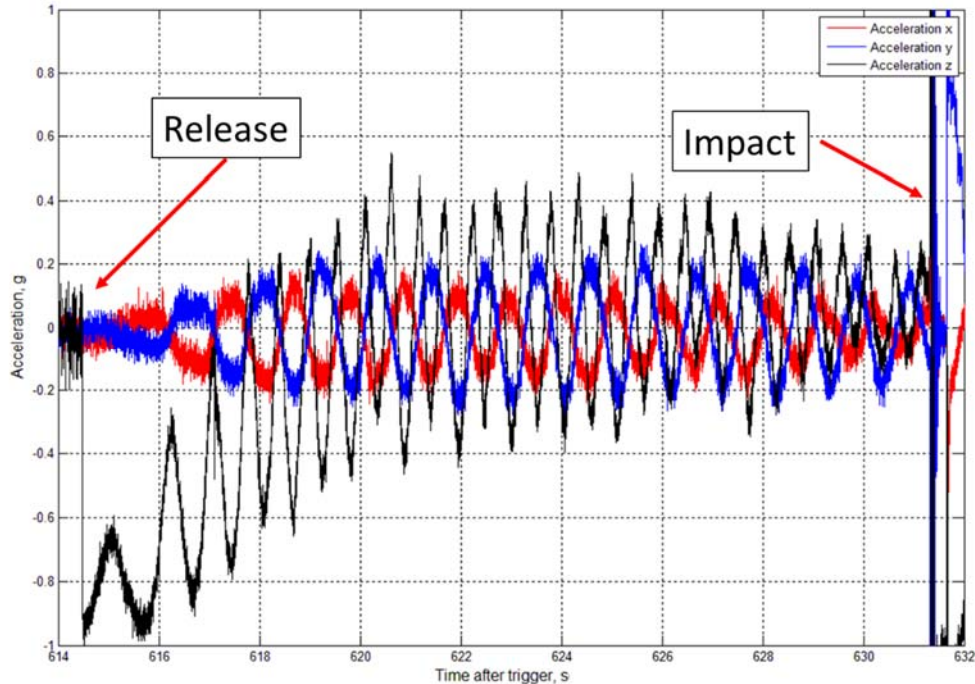


Figure 29 - Test 3 free flight acceleration

The free flight acceleration resembled the general trends in the free flight acceleration from Test 1. An oscillation of 0.95 Hz was observed for all three directions. Additionally, shape of the acceleration data in the vertical (z) direction resembled the general shape from Test 1. The trend of an abrupt 0 to -1 g change at 614.5 s, then the zero approach at approximately 620 s was all consistent with Test 1 performance. However, unlike Test 1, where the oscillatory magnitudes decayed toward the end of the free flight, during Test 3, there was still noticeable oscillation motion throughout and leading up to impact. These oscillations lead to rotational motion which caused the vehicle to impact the ground off-nominally. The test vehicle impacted the ground while on its shoulder with the large rotational motion, causing it to skim off of the ground and to release much of the TPS surrogate foam on the impact side. Because of the foam loss, the test vehicle was unable to be reused. However, Test 3 did provide additional confirmation of the ICoSS design, providing further evidence of the structural robustness during nominal and extreme off-nominal impact orientations.

Even though the vehicle behaved in a similar manner to Test 1, the most significant difference between Test 1 and 3 is that the initial perturbation in Test 3 was much higher than Test 1. The higher perturbation combined with higher winds aloft (not directly measured but can be assumed due to higher ground winds) caused the vehicle to both travel a longer horizontal distance during free-flight, and experience higher rotational oscillations. From these results, it can be determined the conditions from Test 3 are on the margin, and should be taken into consideration when attempting a future test series. Future considerations are described in the *Recommendations* section of this report.

5. Summary

A series of three tests were conducted on a passive Earth Entry Vehicle (EEV) during the summer of 2016. Two test vehicles were dropped at the Utah Test and Training Range (UTTR) from an altitude of

approximately 400 m to test vehicle structural integrity and vehicle impact response. Both free flight and impact accelerations were successfully recorded for each of the three tests. Free flight data from onboard instrumentation and ground cameras have been extensively analyzed and presented. Although helicopter positioning and winds caused the test vehicle to impact outside of the nominal 61 m impact zone, both the high speed and ultra high definition cameras in one of the camera locations were able to image each impact event. Cameras were also present both on the helicopter and on the ground to successfully capture the test vehicle release.

In all three drop tests test vehicles exhibited an unexpected large perturbation during release which caused one of the test vehicles to tumble and a second to enter a large oscillation and land at an unrealistically high off-axis angles. Only one test was deemed successful where, despite large initial oscillations, the test vehicle reached a stable condition just before landing.

Despite large initial perturbation at release, Test 1 saw a successful drop and impact event. The test vehicle impacted the ground at 29.6 m/s at a 4.8° impact angle. For Test 2, outside influence lead to the test vehicle to tumble immediately after release and, therefore the free flight and impact data were unable to be used. Test 2 was considered a non-test. Test 3 was also released with initial perturbation higher than Test 1, and did not have enough time to reach a stable free fall and impact, like what was seen in Test 1. Test 3 impacted the surface on its shoulder with a large rotational velocity. Due to the off-nominal condition at impact, Test 3 was also considered a non-test from a structural attenuation standpoint. However, the free flight characteristics were analyzed and showed similar free flight characteristics to that of Test 1. It impacted at 27.9 m/s vertical and 5.5 m/s horizontal velocities using the camera tracking analysis method developed.

Based on video evidence, it is believed that the initial perturbation which was observed in all three drops, was a result of high head wind in combination with the use of the three point lifting harness. The three point harness was able to resist vehicle rotations while the vehicle remained suspended from the helicopter; however, the lift force generated by the head wind caused the vehicle to suddenly pitch up the moment it was released. In general, there were competing requirements that both needed to be considered when designing the tests. The first was to make sure the vehicles were released at a low enough altitude in order to give the best possible chance of landing within the designated impact zone. The second was to attempt to release the vehicles from a high enough altitude to ensure the free flight oscillations would have enough flight time to damp out. The result was a balancing act that achieved both requirements, but led to problems in achieving each to the fullest extent.

6. Recommendations

This report discusses the equipment, procedures and results obtained from a successful test series conducted on EEV test articles in the remote Utah desert at UTTR. The test series was highly successful from a test conduct and data collection standpoint; however, the results obtained spurred ideas for possible changes which could be implemented for future testing programs. There are four major recommendations encompassing the four major portions of the test: the data system, the camera array, the test vehicle rigging system, and the test vehicle release positioning technique.

The data collection system onboard each test article consisted of two different physical accelerometer packages which required two distinct setups, primarily due to the differences between the high-g and low-g collection requirements. All parameters associated with data collection (pre-test data collection parameters, buffering, arming, triggering, and data download) were then required to be completed twice – once for each system. While these deficiencies were accounted for in the test procedure, a more robust

solution of only using one data collection system is recommended. A small, ruggedized self-contained data system consisting of an onboard controller, communication, power and storage, along with the capability of collecting external inputs such as a voltage readings from bridged based sensors would simplify pre-test, triggering and post-test data download procedures. It is also recommended that a spare data collection system be available, as one of the accelerometer packages used for this test series failed, and a spare had to be used.

The camera setup for this test series was optimized for an assumed circular landing zone 61m in diameter based on equipment availability and constraints. The results presented show that the attempts to achieve impact in the landing zone proved difficult for the practice hemispherical tests, and impossible for the tests conducted with the actual test articles. And, while each test conducted in this test series did have video coverage from one camera, it is recommended that for future tests, the camera coverage be expanded to encompass at a minimum of four times the size of the nominal landing zone. To extend this coverage, an array of cameras and scaling objects must be utilized. An example array of cameras could be positioned in a similar fashion to what is presented in Figure 30. The camera array can be extended to add more cameras to extend the array as much as practical to encompass more area if needed. Other parameters such as physical positioning to allow for communication, personnel access and range safety must also be considered when determining the final camera array configuration. Additionally, as previously described, post-test scale bar calibrations should be performed at the actual impact site to achieve the highest resolution data needed for camera tracking purposes.

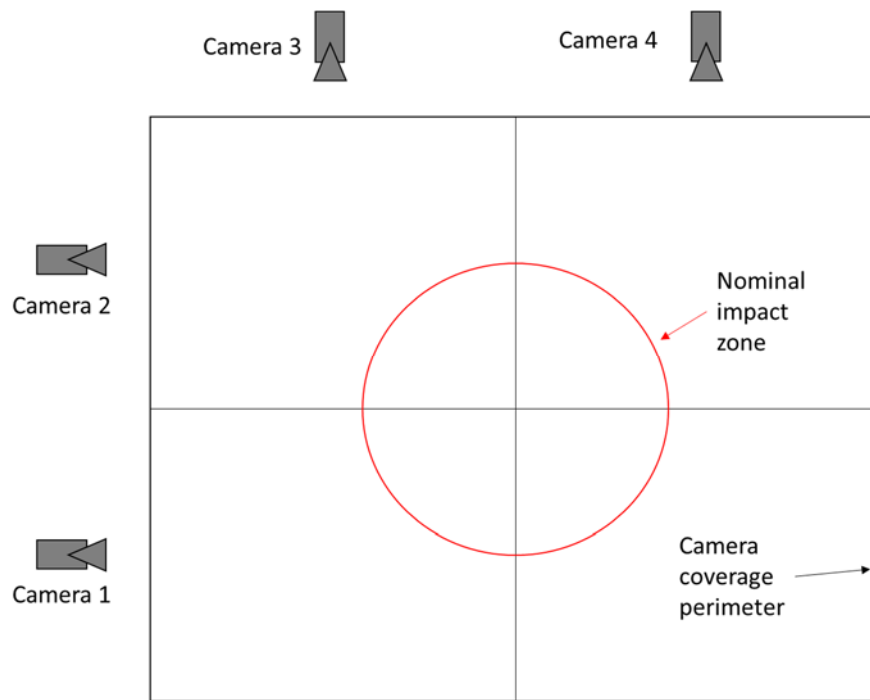


Figure 30 - Sample camera coverage array

The third parameter is associated with the camera setup and involves determining a method to better position the helicopter when locating the nominal drop location. Portable GPS devices were present on the ground, in the cabin of the helicopter and on the helicopter's instrument panel. Problems communicating GPS position coordinates between the ground to pilot and the crew to pilot resulted in large amounts of time and effort in conducting helicopter flybys and circling to accurately locate the drop location. Future

tests should include visual markers such as flags or other temporary structure that could be placed on the ground such that the helicopter pilot can easily track to the required nominal impact position using projected intersection lines of the ground markers. These types of techniques are routine for pilots flying under Visual Flight Rules (VFR) conditions, for which all pilots are certified. After locating the nominal drop position, the pilot can then make corrections for wind or other conditions as needed. GPS coordinates in this situation would simply act as a backup positioning device.

Finally, all three tests showed the test vehicle being perturbed immediately upon release hook opening. This perturbation was the main cause for the invalidated “no-test” determinations obtained in tests 2 and 3. The perturbation was caused from an imbalance of force on the test vehicle due to the three point harness resisting the swaying motion from the test article prior to release. The original MSR testing utilized a single point harness design. While the perturbation from the release was not present for those tests using the single point harness design, oscillations from the lanyard due to the helicopter climb caused an inadvertent release of the first test attempt of the MSR test articles. It was because of this inadvertent release that the three point harness was employed in this test series. Test results now show that neither harness is ideal. A potential solution to the three point harness is to have the helicopter approach the drop zone from downwind instead of upwind. With the helicopter traveling downwind during release, the lift force acting on the vehicle will be minimal.

7. References

1. Mitcheltree, R.A., and Kellas, S. "A Passive Earth-Entry Capsule for Mars Sample Return." American Institute of Aeronautics and Astronautics, Inc. Paper 98-2851. 1998.
2. Desai, P.N. and Cheatwood, F.M. "Entry Dispersion Analysis for the Genesis Sample Return Capsule." *Journal of Spacecraft and Rockets*, Vol. 38, No. 3. May-June 2001.
3. Desai, P.N and Qualls, G.D. "Stardust Entry Reconstruction." American Institute of Aeronautics and Astronautics. AIAA-2008-1198. 2008.
4. Beshore, E. et. al. "The OSIRES-REx Asteroid Sample Return Mission." IEEE Aerospace Conference. Mar 7-14, 2015. Big Sky, MT.
5. Kellas, S. and Mitcheltree, R.A. "Energy Absorber Design, Fabrication and Testing for a Passive Earth Entry Vehicle." 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference. Denver, Colorado. April 22-25, 2002.
6. Maddock, R.W. "Sample Return Challenges Multi-Mission Earth Entry Design Trade Space and Concept Development Strategy." 6th International Planetary Probe Workshop, Atlanta, GA. June 2008.
7. Kellas, S. "Integrated Composite Stiffeners Structure (ICoSS) Concept for Planetary Entry Vehicles." 57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. San Diego, California. January 2016.
8. Kellas, S. "Passive Earth Entry Vehicle Landing Test." IEEE Aerospace Conference. March 4-11, 2017. Big Sky, MT.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 01-01-2018			2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Full-Scale Passive Earth Entry Vehicle Landing Test: Methods and Measurements					5a. CONTRACT NUMBER	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Littell, Justin D.; Kellas, Sotiris					5d. PROJECT NUMBER	
					5e. TASK NUMBER	
					5f. WORK UNIT NUMBER 664817.02.07.03.03	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199					8. PERFORMING ORGANIZATION REPORT NUMBER L-20899	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001					10. SPONSOR/MONITOR'S ACRONYM(S) NASA	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA-TM-2018-219802	
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified Subject Category 39 Availability: NASA STI Program (757) 864-9658						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT During the summer of 2016, a series of drop tests were conducted on two passive earth entry vehicle (EEV) test articles at the Utah Test and Training Range (UTTR). The tests were conducted to evaluate the structural integrity of a realistic EEV vehicle under anticipated landing loads. The test vehicles were lifted to an altitude of approximately 400m via a helicopter and released via release hook into a predesignated 61 m landing zone. Onboard accelerometers were capable of measuring vehicle free flight and impact loads. High-speed cameras on the ground tracked the free-falling vehicles and data was used to calculate critical impact parameters during the final seconds of flight. Additional sets of high definition and ultra-high definition cameras were able to supplement the high-speed data by capturing the release and free flight of the test articles. Three tests were successfully completed and showed that the passive vehicle design was able to withstand the impact loads from nominal and off-nominal impacts at landing velocities of approximately 29 m/s. Two out of three test resulted in off-nominal impacts due to a combination of high winds at altitude and the method used to suspend the vehicle from the helicopter. Both the video and acceleration data captured is examined and discussed. Finally, recommendations for improved release and instrumentation methods are presented.						
15. SUBJECT TERMS Entry Decent and Landing; Impact testing; Measurement techniques; Spacecraft testing						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)	
U	U	U	UU	37	19b. TELEPHONE NUMBER (Include area code) (757) 864-9658	