NASA/CR–2018-219801

Orion Ground Test Article Water Impact Tests

Photogrammetric Evaluation of Impact Conditions

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January 2018

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Prepared for Langley Research Center
under Contract NNL12AA09C

January 2018

Available from:

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Executive Summary

The Ground Test Article (GTA) is an early production version of the Orion Crew Module (CM). The structural design of the Orion CM is being developed based on LS-DYNA water landing simulations. As part of the process of confirming the accuracy of LS-DYNA water landing simulations, the GTA water impact test series was conducted at NASA Langley Research Center (LaRC) to gather data for comparison with simulations.

The simulation of the GTA water impact tests requires the accurate determination of the impact conditions. To accomplish this, the GTA was outfitted with an array of photogrammetry targets. The photogrammetry system utilizes images from two cameras with a specialized tracking software to determine time histories for the 3-D coordinates of each target. The impact conditions can then be determined from the target location data.

Five vertical drop tests (VT1, 2, 3, 4, and 10) and five swing tests (ST5, 6, 7, 8, and 9) were performed. For test ST7, there were technical difficulties with the cameras for the 3-D photogrammetry system. For that test, the impact conditions were determined via 2-D photogrammetric evaluation of images from a single camera.

The photogrammetry data offers several different possible solutions. This report provides four solutions for the angles and angular rates and velocities at each photogrammetry target for each test. At this writing, the solution used for GTA simulation impact conditions is based on Targets 1000, 1005, 1002, & 1008 for angles and angular rates and Target 1006 for velocities. The impact conditions computed from the photogrammetry data in the GTA Global Coordinate System are provided in the following table. The angles follow the Orion convention in which the angles are about the global axes and are imposed in the order yaw, then pitch, then roll. The angles are not Euler angles.

Impact Conditions in GTA Global Coordinate System

Test	Impact Time (s)	Target 1006 Velocities			Targets 1000, 1005, 2002, & 1008 Angles & Angular Rates						
		Vx (in/s)	Vy (in/s)	Vz (in/s)	Roll Angle (deg)	Pitch Angle (deg)	Yaw Angle (deg)	Ang. Rate (rad/s)	Ang. Rate Axis Nx	Ang. Rate Axis Ny	Ang. Rate Axis Nz
VT1	14.050	387.37	9.44	-1.91	1.20	-35.08	2.23	0.01676	-0.2653	0.7473	0.6092
VT2	38.988	401.62	-0.91	0.34	-6.24	-45.91	0.76	0.06373	0.1964	0.9645	-0.1765
VT3	49.382	387.44	0.05	-0.25	-3.19	-24.11	0.45	0.02028	-0.3247	0.8733	0.3631
VT4	57.383	381.29	1.04	-1.27	-1.44	-24.00	0.46	0.01206	-0.4688	0.8021	0.3701
ST5*	16.831	415.91	-0.02	-228.80	-0.92	26.50	-0.05	0.03736	-0.2913	0.9247	-0.2453
ST6	6.126	341.74	2.89	-448.50	-1.56	-18.51	0.07	0.04445	-0.5112	0.8588	0.0321
ST7	NA	499.64	0.00	-687.19	0.00	-43.76	0.00	0.01935	0.0000	-1.0000	0.0000
ST8	30.005	326.41	-2.03	-648.56	28.47	-43.51	0.78	0.08786	-0.5421	0.4934	0.6802
ST9**	23.800	372.87	-1.09	-280.87	0.43	0.82	-24.89	0.04217	0.1491	0.9227	0.3556
VT10	55.588	387.41	1.61	-1.03	-3.19	-16.16	0.75	0.01533	-0.4867	-0.1787	0.8551

* For ST5, a roll angle of 180 degrees is imposed before imposing the listed angles.
** For ST9, a roll angle of 90 degrees is imposed before imposing the listed angles.

The measurement precision tolerances are estimated as follows:

Distance: ~0.1 inches
Velocity: ~2 in/sec
Angle: ~0.3°

The above tolerances are based on evaluations of precision and do not take into account systematic errors that could affect accuracy by producing a bias in the measurements. The distance tolerance is a consequence of noise in the raw photogrammetry position data. The velocity tolerance is based on the deviation of the measured vertical acceleration from 1g. The angle tolerance is dominated by the precision of the alignment of the photogrammetry targets on the GTA. No tolerance has been determined for the rotation rates; however, the effect that rotation rate error has on the rotation angles is judged to be small based on the magnitude of the rotation rates and the time duration from impact to maximum response.

Table of Contents

List of Figures

List of Tables

1. Abstract

The Orion Multi-Purpose Crew Vehicle (MPCV) Ground Test Article (GTA) water impact tests (WIT) were conducted at the NASA Langley Research Center (LaRC) in calendar year 2016. The GTA WIT test series was initially planned to be comprised of eight drop tests. Four tests were planned to be vertical drop tests without horizontal velocity, and four tests were to be swing tests with both vertical and horizontal velocity. As the test program proceeded, a fifth vertical test and a fifth swing test were added to the test matrix. The GTA WIT tests were designed to represent a wide variety of possible Orion nominal and off-nominal ocean landing scenarios. Monte Carlo analysis of these possible landing scenarios was used to derive the planned impact conditions (e.g. velocity, attitude) for each of the ten tests. The actual impact conditions for the tests differed from the planned impact conditions due to a variety of factors including imperfections in the test set-up, dynamics of the test article suspended on its rigging, and aerodynamics of the test article during free fall. The process for using photogrammetry to determine the actual impact conditions (velocities, rotation angles, and rotation rates) for the tests is described, and quality checks of the photogrammetry results with estimates of their precision are provided.

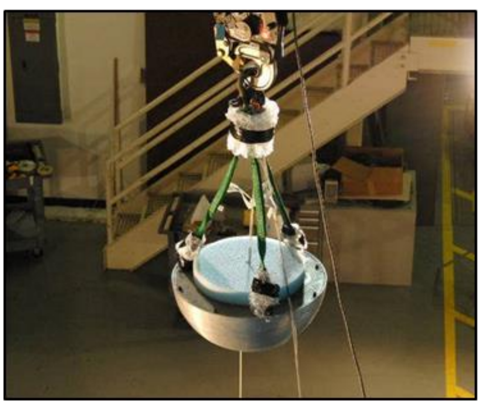
2. Introduction

When the Orion MPCV returns to Earth, the Crew Module (CM) will re-enter the atmosphere, descend under parachutes, and then land in the ocean. For nominal landing scenarios, the CM will descend under three parachutes and land in the Pacific Ocean. Off-nominal landing cases include situations in which one of the three parachutes fails to properly deploy, thereby increasing the CM descent velocity, and also launch abort scenarios that result in the CM landing in the Atlantic Ocean with potentially higher winds than those experienced for nominal landings. These different mission scenarios, combined with a variety of environmental conditions (e.g. surface winds, ocean wave slope and velocity), produce a wide range of possible landings that produce different vehicle dynamics and loads on the vehicle structure and the crew. These vehicle dynamics and crew loads are determined through analysis using water impact simulations with the LS-DYNA® finite element code. The simulations incorporate analytical models of the water, the CM vehicle structure, and parameters that govern the dynamic fluid-structure interaction (FSI) between them. The Orion MPCV Structural Design and Verification Requirements [Ref. 1] requires all analysis tools used for structural loads determination or structural verification, which includes the LS-DYNA water-landing model, to be validated through testing.

The process to validate the Orion CM water-landing model employed several validation approaches aligned with the recommendations set forth in NASA's Standard for Models and Simulation [Ref. 2]. The primary model validation method was a ground test campaign comprised of four separate water impact test programs conducted from 2009 to 2017. The four test programs were designed to incrementally increase the fidelity and complexity of the test article and impact conditions from one set of tests to the next, such that when all tests were completed the CM water-landing model would be validated to the extent required by Orion.

2.1 Elemental Water Impact Tests

The first test program was the Elemental Water Impact Test (EWIT) series conducted at the NASA Langley Research Center (LaRC) in 2009. EWIT was comprised of three phases in which simple test articles of varying sizes and construction were dropped vertically into an indoor pool. The Phase 1 tests used a stiff, 20-inch diameter aluminum hemisphere instrumented with accelerometers and pressure transducers to measure structural rigid-body response and wetted surface pressure distributions [Ref. 3]. The Phase 2 tests used a larger, 36-inch diameter aluminum elliptical tank head with more flexibility than the Phase 1 test article [Ref. 4]. The added flexibility produced local structural responses that were measured and compared to an LS-DYNA model. For Phase 3, a small-scale composite sandwich elliptical tank head was used as a pathfinder for instrumenting and testing similar MPCV CM structures, such as the backshell panels and composite heatshield. A plunge depth study was performed as part of the planning for the Phase 3 tests [Ref. 5]. Examples of the EWIT test article and test set-up are shown in Figure 1.



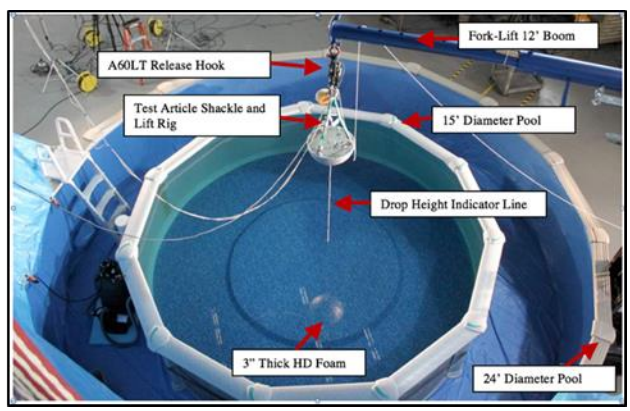


Figure 1. EWIT Phase 1 Test Article and Test Set-up

2.2 Max Launch Abort System Water Impact Tests

The second test program was the Max Launch Abort System (MLAS) WIT series conducted by the NASA Engineering and Safety Center (NESC) at the United States Army Aberdeen Proving Grounds in 2011 [Ref. 6]. The test article was constructed by modifying the capsule used for the MLAS pad abort test conducted by the NESC in 2010. The MLAS capsule was a boilerplate structure with geometry similar to the Orion CM. The MLAS water impact tests were effective in evaluating the capsule's rigid-body dynamics, wetted surface pressures, and the FSI parameters used in the LS-DYNA water model. The MLAS WIT test article was instrumented with accelerometers, an inertial measurement unit, and strain gages. A total of 59 MLAS drop tests were conducted. All of the tests were vertical drop tests without horizontal velocity.

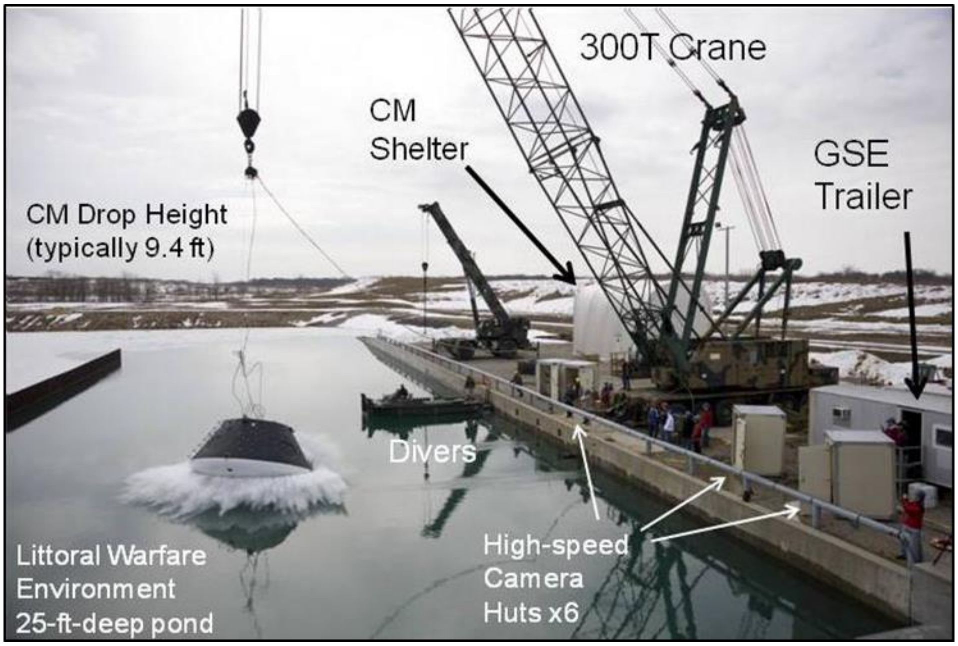


Figure 2. MLAS WIT Vertical Drop Test at Aberdeen Proving Grounds

2.3 Boilerplate Test Article Water Impact Tests

The third test program was the Boilerplate Test Article (BTA) WIT series conducted at NASA LaRC from 2011 to 2013 [Ref. 7]. BTA WIT used a full-scale MPCV CM test article with geometry and mass properties comparable to the actual CM flight vehicle, but with a low-fidelity boilerplate structure and a simple aluminum heatshield with plain hemispherical geometry. The tests were conducted in three phases, with different test objectives and slight modifications to the test article for each phase. The instrumentation for all of the BTA WIT tests included roughly 160 channels of accelerometers, strain gages, water pressure transducers, and rotation rate sensors.

For the Phase 0 tests, the heatshield was stiffened by wooden blocks inserted between the heatshield and the boilerplate structure. The intent of this stiffening was to rigidize the heatshield to prevent structural deformations from changing the geometry of the wetted surface interacting with the water. Three Phase 0 tests were conducted, all of which included both vertical velocity and horizontal velocity. The Phase 1 BTA WIT tests used the same test article as Phase 0, but the wooden blocks between the heatshield and boilerplate structure were removed to increase the heatshield flexibility. Seven Phase 1 tests were conducted with various combinations of impact angles, vertical velocity, and horizontal velocity. BTA WIT Phase 2 was a series of ten vertical drop tests designed to evaluate the repeatability of the test data. Three different combinations of impact conditions were selected, and three or four repeat tests were conducted at each set of conditions to quantify the measurement precision. The BTA WIT test article and set-up for a representative vertical drop test are shown in Figure 3.

Figure 3. Test Sequence for a Representative BTA WIT Phase 2 Vertical Drop Test

2.4 Ground Test Article Water Impact Tests

The fourth and final series of Orion water impact tests used to validate the water-landing model was the Ground Test Article (GTA) WIT conducted at NASA LaRC in 2016. The GTA WIT test article was assembled by integrating the GTA CM structure with the post-flight heatshield from the Orion Exploration Flight Test 1 (EFT-1) mission. The GTA CM structure was an early prototype of the MPCV CM, and incorporated materials and structural design features similar to those being used in the CM for Orion's Exploration Mission 1 (EM-1) and Exploration Mission 2 (EM-2). Combined with the post-flight EFT-1 heatshield, the GTA WIT test article was considered to be similar enough to the EM vehicle that it could be used to accomplish the final series of tests to validate the Orion water-landing model.

GTA WIT consisted of ten tests. Five of the tests were vertical drop tests (i.e. no horizontal velocity), and five tests were swing tests with horizontal velocity combined with vertical velocity. Compared to the BTA WIT test article, the instrumentation for GTA WIT was increased to roughly 530 channels, including accelerometers, strain gages, water pressure transducers, deflection sensors, and rotation rate sensors. GTA WIT was the only test series that included anthropomorphic test devices (i.e. crash test dummies). Two ATDs were included and assembled into flight-like crew seats which were mounted on a single-axis, stroking crew impact attenuation system as shown in Figure 4.

Figure 4. Anthropomorphic Test Devices Installed in the GTA

The GTA WIT tests were conducted in a manner similar to the BTA WIT tests. Vertical tests were accomplished by suspending the test article over the LaRC Hydro-Impact Basin from the gantry winches, and then dropping the test article by opening the release hook attached to the test article. Swing tests were conducted by first assembling the GTA to the swing platform (aka Integration Platform). The GTA/swing platform assembly was then suspended from the gantry winches and pulled back along a pendulum arc to a position pre-determined to produce the desired impact velocities. The GTA test article and set-up for one of the swing tests are shown in Figure 5. For all GTA WIT tests, an array of photogrammetry cameras was set-up to track targets on the test article. The target position data acquired from these cameras was post-processed to derive precise impact conditions (e.g. impact velocities, angles, and angular rates) for each test that were then used to initialize the LS-DYNA landing simulations used for correlation and model validation.

Figure 5. Test Set-up for a Representative GTA WIT Swing Test with Horizontal Velocity

2.5 Integrated Ground Testing Strategy

The four water impact testing programs were sequenced as shown in Figure 6. Each test program, or phases within a test program, were designed to build upon the completed objectives and lessons learned from the preceding tests. The high-level model validation objectives that were accomplished by each test program were as follows.

EWIT: Acquired experience and test data to select the sensors (accelerometers, pressure transducers, rate sensors) to carry forward into the BTA WIT and GTA WIT test programs.

MLAS WIT: Provided rigid-body dynamics data for a relevant CM geometry that enabled Orion to adjust FSI parameters and improve the accuracy of global loads predictions from the LS-DYNA model.

BTA WIT: First tests using a full-scale Orion CM geometry with relevant mass properties and flight-like horizontal velocities. The introduction of horizontal velocity uncovered additional modifications to the LS-DYNA FSI parameters necessary to predict global dynamic behavior for ascent abort landing cases.

GTA WIT: First tests using flight-like, full-scale Orion CM and heatshield structures with impact conditions representing Orion's most stressing water landing scenarios. Test data provided the basis to validate the MPCV water-landing model in accordance with the Orion Structural Design and Verification Requirements [Ref. 1].

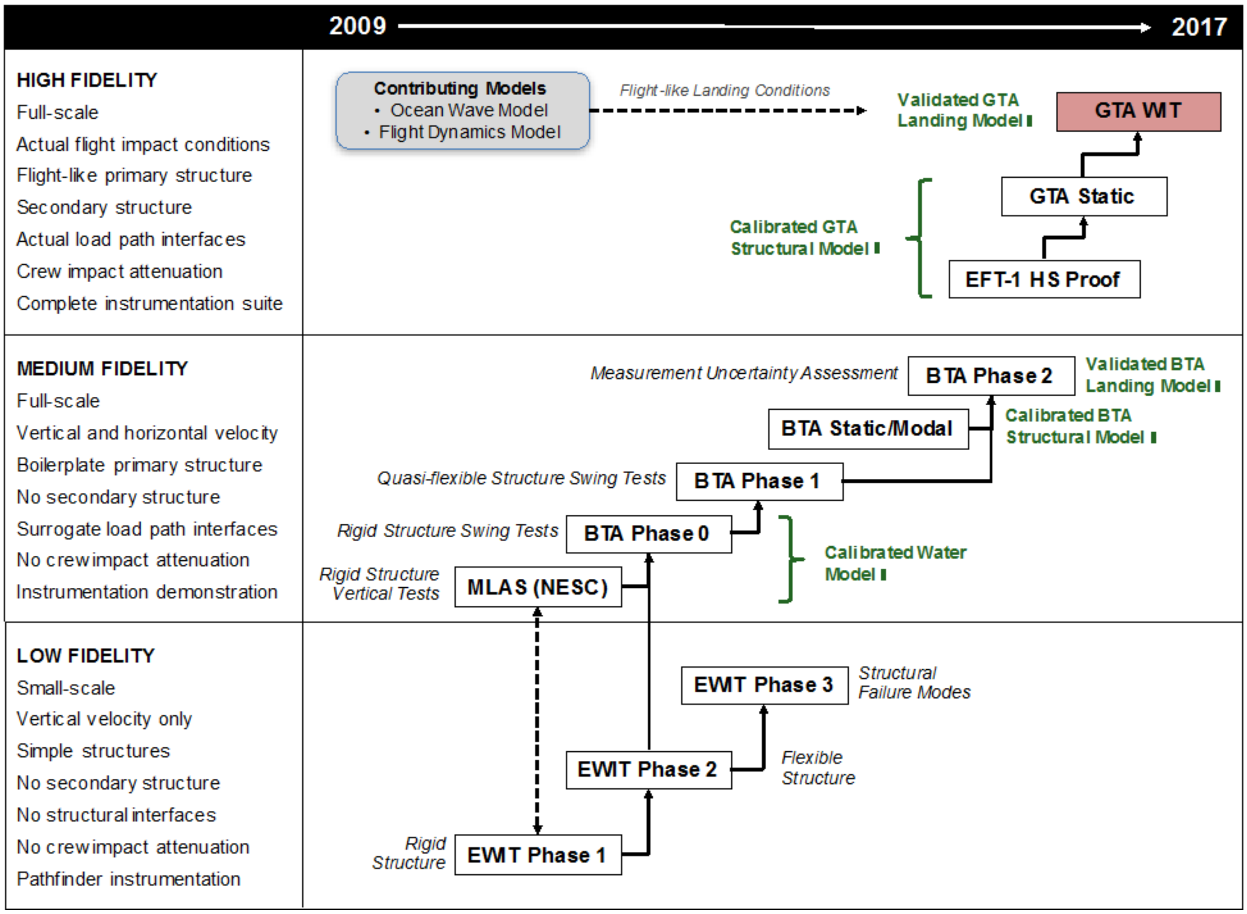


Figure 6. Orion MPCV Water Impact Testing Sequence

3. Coordinate Systems

Multiple coordinate systems have been used for the GTA test and simulation effort, including the following:

1. Photogrammetry Coordinate System
2. GTA Global Coordinate System
3. GTA Local Coordinate System
4. GTA Attitude for LS-DYNA Initial Set-Up Positioning via *DEFINE_TRANSFORMATION

The Photogrammetry Coordinate System and the GTA Global Coordinate System are illustrated in Figure 7. Except where otherwise specified, data provided in this report is in the GTA Global Coordinate System. The GTA Local Coordinate System moves with the GTA and aligns with the GTA Global Coordinate System when the GTA is sitting upright with zero yaw, pitch, and roll angles. The GTA yaw, pitch, and roll angles are defined in the following description of LS-DYNA initial conditions.

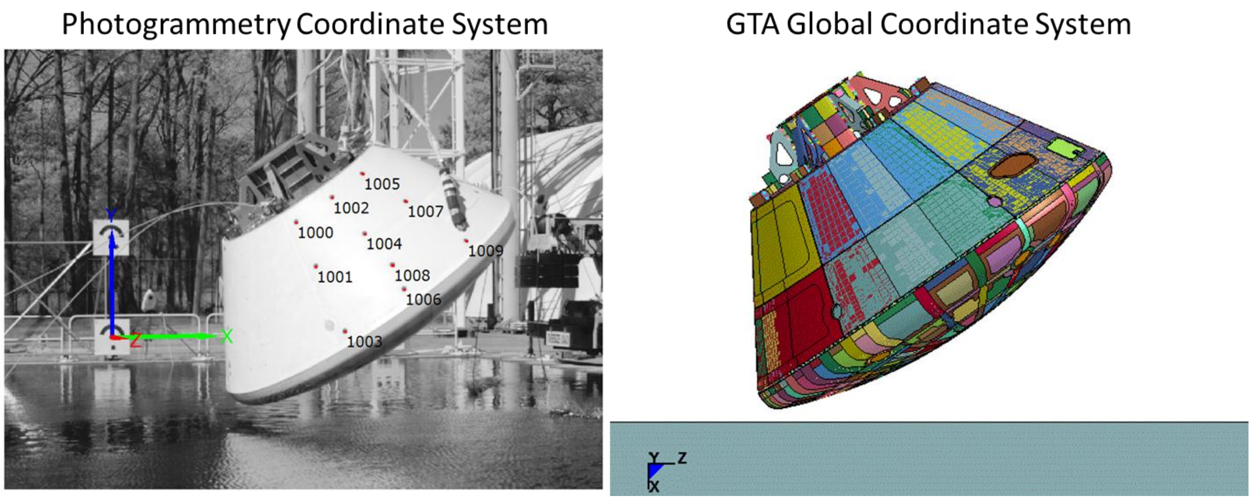


Figure 7. Coordinate Systems

The transformation between the Photogrammetry Coordinate System and the GTA Global Coordinate System is as follows:

Photogrammetry Coordinate System		GTA Global Coordinate System
X-Axis (Positive to the right in Fig. 7)	➔	Positive Z-Axis
Y-Axis (Positive Upward)	➔	Negative X-Axis
Z-Axis (Positive out of page in Fig. 7)	➔	Negative Y-Axis

The set-up for the initial conditions for LS-DYNA simulations of the GTA water impact tests follows the convention used for defining initial conditions for the Orion landing simulations. The rotation angles are imposed in the order 1) Yaw, 2) Pitch, and 3) Roll. Each angle is imposed about the axes of the GTA Global Coordinate System. These are not Euler angles. For the LS-DYNA initial set-up positioning, yaw is a positive rotation about the Z-axis, pitch is a negative rotation about the Y-axis, and roll is a negative rotation about the X-axis. This convention is used only for the LS-DYNA input specified via *DEFINE_TRANSFORMATION, which sets the initial location and attitude for the GTA. For all other purposes, the yaw, pitch, and roll angles are described as positive rotations about their respective axes. Initial velocities and rotation rates are defined via *INITIAL_VELOCITY_GENERATION following the sign conventions of the GTA Global Coordinate System.

4. Processing of Photogrammetry Data

The GTA was outfitted with an array of photogrammetry targets. The photogrammetry system utilizes high-speed video in conjunction with PONTOS [Ref. 8], a specialized tracking software, to determine time histories for the coordinates of each target. The impact conditions can then be determined from the target location data. The photogrammetry set-up featured a bank of cameras located along the southern edge of the Hydro Impact Basin (HIB) at LaRC. An array of targets along the northern edge provided reference points to establish the global coordinate system. Two cameras provided high-speed video for 3-D photogrammetry and one camera provided high-speed video for 2-D photogrammetry. The set-up is illustrated in Figure 8.

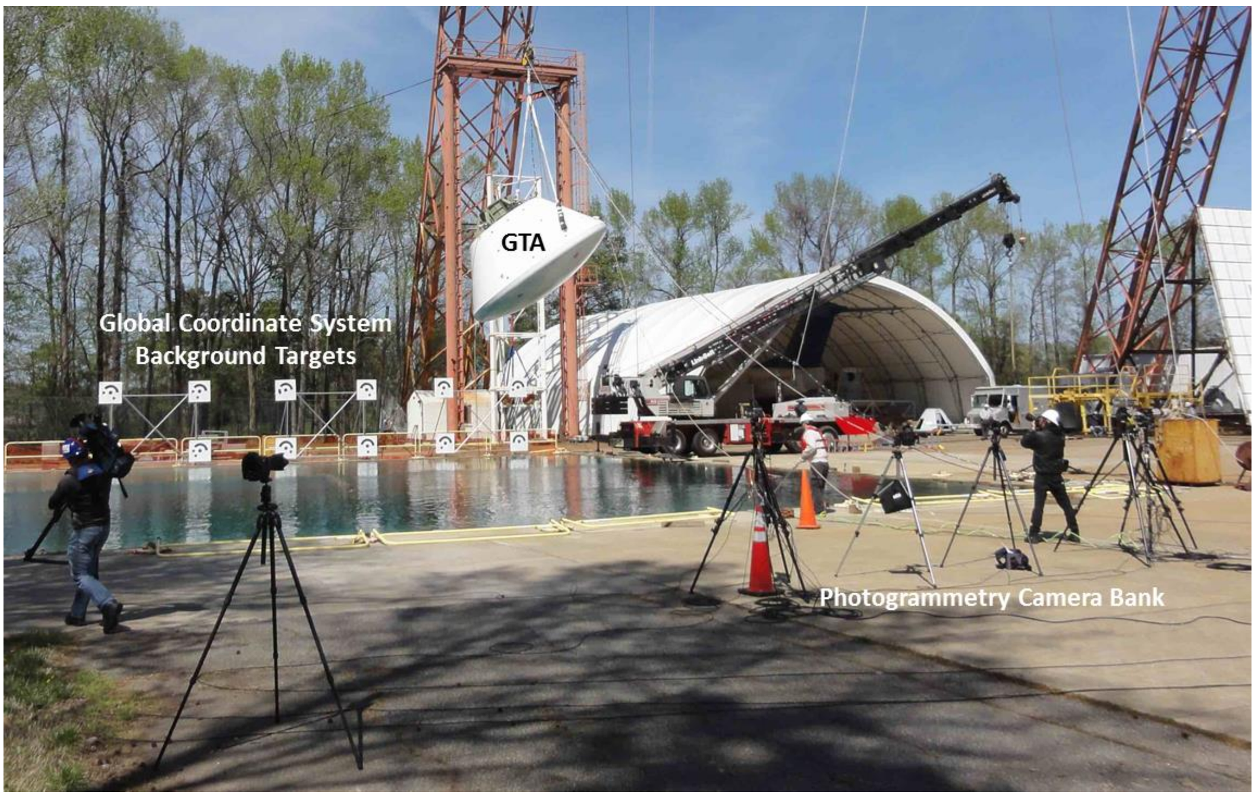


Figure 8. Photogrammetry Set-up

4.1. Photogrammetry Target Locations

The GTA was outfitted with an array of photogrammetry targets as illustrated in Figure 9, which shows the port side of GTA. Similar target arrays existed on the starboard side and the leeward side, which were needed for the 180° and 90° roll tests (ST5 and ST9). The top row of targets (1000, 1002, & 1005) was located eight inches along the slope of the backshell below the top edge, the middle row of targets (1001, 1004, & 1007) was located eight inches along the slope of the backshell above the middle row of fasteners, the bottom outer targets (1003 & 1009) were located eight inches along the slope of the backshell above the lower edge, and the bottom middle target (1008) was located 24 inches along the slope of the backshell above the lower edge. The targets along the vertical edges of the backshell were located six inches from the edge. Targets 1002, 1004, and 1008 lay along a line that represented the GTA Local Coordinate System X-axis rotated by the backshell angle, 32.5°. Targets 1000 and 1005, 1001 and 1007, and 1003 and 1009 defined lines parallel to the GTA Local Coordinate System Z-axis. Target 1006 was located at the approximate location of the GTA center of gravity (CG) projected onto the backshell and is not in line with Targets 1003 and 1009.

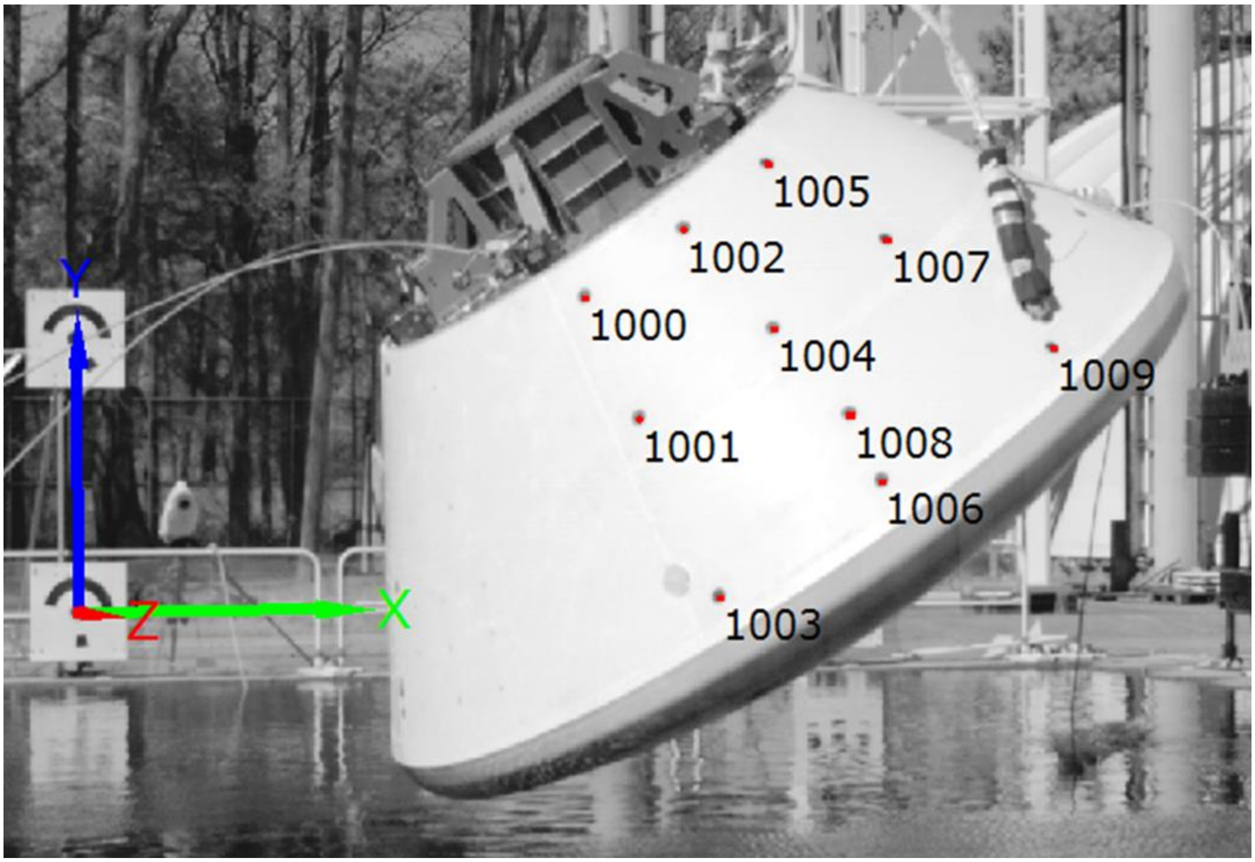


Figure 9. GTA Photogrammetry Targets

The photogrammetry system utilizes images from two cameras to triangulate the 3-D coordinate position time histories for each of the targets. The time step for the data is 1 msec. The target locations are defined in the Photogrammetry Coordinate System, which is defined based on the array of stationary background targets. The target coordinates can be used to define four vectors as shown in Figure 10.

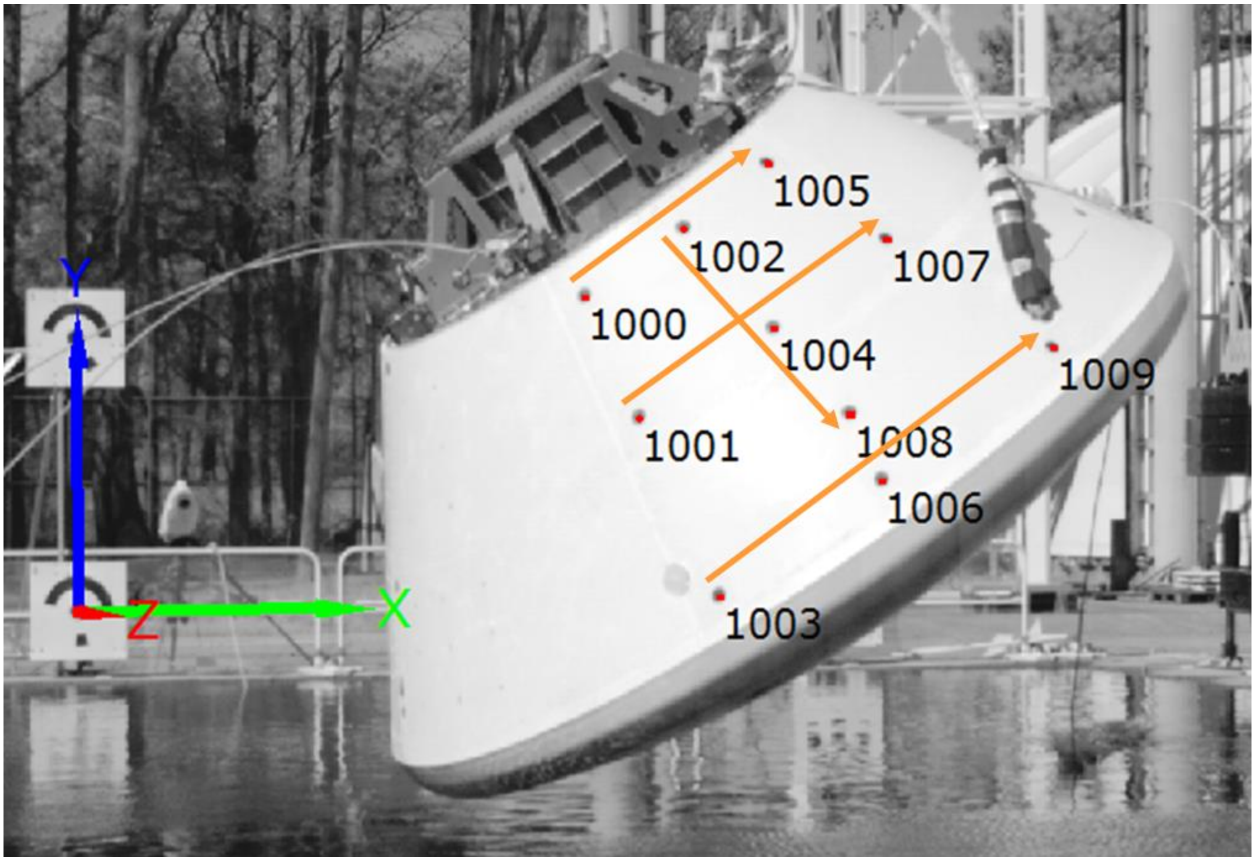


Figure 10. Vectors Formed by Photogrammetry Targets

Vectors $V_{1000\text{-}1005}$, $V_{1001\text{-}1007}$, and $V_{1003\text{-}1009}$ are parallel to the GTA Local Coordinate System Z-axis. Vector $V_{1002\text{-}1008}$ lies on the surface of the backshell in the GTA Local Coordinate System X-Y plane. The angle of the backshell is 32.5° relative to the main axis (GTA Local Coordinate System X-axis).

4.2. GTA Local Coordinate System Vectors

The process for establishing the GTA Local Coordinate System vectors is illustrated in Figure 11. The GTA Local Coordinate System Z-axis (n_Z) is assumed to be represented by any of the vectors $V_{1000\text{-}1005}$, $V_{1001\text{-}1007}$, and $V_{1003\text{-}1009}$. The vector $V_{1002\text{-}1008}$ (n_1), is assumed to lie in the GTA Local Coordinate System X-Y plane. Calculating the cross product of n_Z and n_1 produces n_2. Crossing n_2 with n_Z produces n_3, which should be identical to n_1. The angle between n_3 and n_1 can be considered a quality check on the assumption that $V_{1002\text{-}1008}$ lies in the plane normal to $V_{1003\text{-}1009}$. This process has been repeated using $V_{1000\text{-}1005}$, $V_{1001\text{-}1007}$, and $V_{1003\text{-}1009}$ to represent n_Z. Based on the angle between the main axis and $V_{1002\text{-}1008}$, the GTA Local Coordinate System Y-axis (n_Y) can be calculated as $n_2 \cos(32.5°) – n_3 \sin(32.5°)$. The GTA Local Coordinate System X-axis (n_X) can then be calculated as the cross product of n_Y and n_Z.

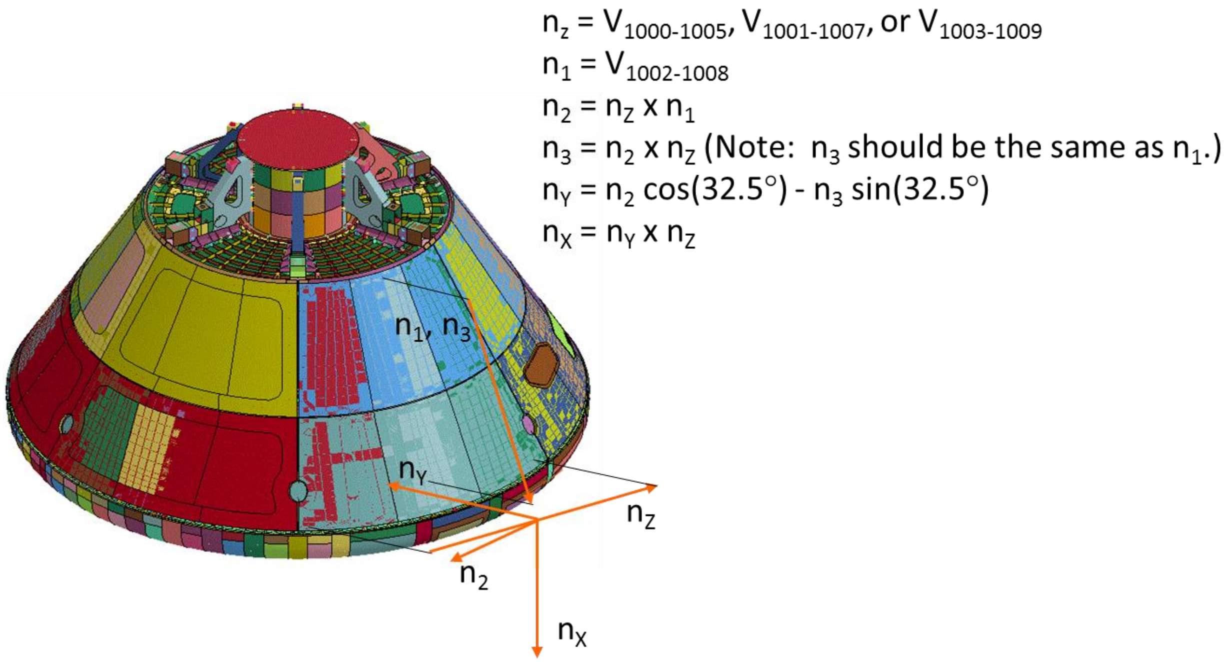


Figure 11. Calculation of GTA Local Coordinate System Axis Vectors

4.3. GTA Yaw, Roll, and Pitch Angles

As noted previously, the angular rotations for the LS-DYNA simulation impact conditions are applied about the global coordinate axes in the order 1) Yaw (ψ), 2) Pitch (θ), and 3) Roll (ϕ). The transformation matrices are as follows:

– Yaw rotation about global Z axis.

- $\langle \mathbf{n_0}' \rangle = \langle \mathbf{n_0} \rangle \begin{bmatrix} \cos(\psi), & \sin(\psi), & 0 \\ -\sin(\psi), & \cos(\psi), & 0 \\ 0, & 0, & 1 \end{bmatrix}$

– Pitch rotation about global Y axis.

- $\langle \mathbf{n_0}'' \rangle = \langle \mathbf{n_0}' \rangle \begin{bmatrix} \cos(\Theta), & 0, & -\sin(\Theta) \\ 0, & 1, & 0 \\ \sin(\Theta), & 0, & \cos(\Theta) \end{bmatrix}$

– Roll rotation about global X axis.

- $\langle \mathbf{n(t=0)} \rangle = \langle \mathbf{n_0}'' \rangle \begin{bmatrix} 1, & 0, & 0 \\ 0, & \cos(\phi), & \sin(\phi) \\ 0, & -\sin(\phi), & \cos(\phi) \end{bmatrix}$

Starting with the vectors <1,0,0>, <0,1,0>, and <0,0,1> representing the GTA Local Coordinate System X-, Y-, and Z-axes, the GTA Global Coordinate System vectors that define the axes of the GTA Local Coordinate System can be computed as follows:

$$n_x = < \cos(\psi)\cos(\theta), \sin(\psi)\cos(\phi)+\cos(\psi)\sin(\theta)\sin(\phi), \sin(\psi)\sin(\phi)-\cos(\psi)\sin(\theta)\cos(\phi) >$$

$$n_y = < \boxed{-\sin(\psi)\cos(\theta)}, \cos(\psi)\cos(\phi)-\sin(\psi)\sin(\theta)\sin(\phi), \cos(\psi)\sin(\phi)+\sin(\psi)\sin(\theta)\cos(\phi) >$$

$$n_z = < \boxed{\sin(\theta)}, \boxed{-\cos(\theta)\sin(\phi)}, \cos(\theta)\cos(\phi) >$$

The terms in the orange boxes allow for the easy determination of the rotation angles based on the GTA Local Coordinate System vectors determined from the photogrammetry data. In the following equations, n_{Z1} refers to the X-component of the GTA Local Coordinate System Z-axis, n_{Z2} the Y-component of the Z-axis, and n_{Y1} the X-component of the Y-axis:

Pitch Angle, $\theta = \arcsin(n_{z1})$

Roll Angle, $\phi = -1 * \arcsin(n_{z2} / \mathrm{sqrt}(1 - n_{z1}^2))$

Yaw Angle, $\psi = -1 * \arcsin(n_{y1} / \mathrm{sqrt}(1 - n_{z1}^2))$

4.4. GTA Velocity

The LS-DYNA *INITIAL_VELOCITY_GENERATION input specifies the velocity vector in the GTA Global Coordinate System at a specified point. Any target can be used provided the corresponding location is specified in the model as the center point for the initial rotation rate.

The velocities are determined by differentiating the photogrammetry data for the GTA Global coordinates of each target; however, this is complicated by noise resulting from small variations in the coordinates between time steps. In order to eliminate the noise, the X, Y, and Z coordinates were curve fit to a quadratic equation that is a function of time. A quadratic equation was chosen because it represents the vertical motion of a body in freefall under constant gravity. An arbitrary decision was made to use the quadratic curve fit for the horizontal coordinates even though there is no reason to believe that any significant forces are acting in those directions during freefall. The curve fit is performed only between the start of the photogrammetry time history, which is after the start of freefall, and the time of impact. The curve fit equations are shown below:

$$x(t) = at^2 + bt + c$$
$$error_i = x_i - at_i^2 - bt_i - c$$
$$error_i^2 = x_i^2 + a^2t_i^4 + b^2t_i^2 + c^2 - 2ax_it_i^2 - 2bx_it_i - 2cx_i + 2abt_i^3 + 2act_i^2 + 2bct_i$$

$$\partial \Sigma error_i^2 / \partial a = 2a \Sigma t_i^4 + 2b \Sigma t_i^3 + 2c \Sigma t_i^2 - 2 \Sigma x_it_i^2$$
$$\partial \Sigma error_i^2 / \partial b = 2a \Sigma t_i^3 + 2b \Sigma t_i^2 + 2c \Sigma t_i - 2 \Sigma x_it_i$$
$$\partial \Sigma error_i^2 / \partial c = 2a \Sigma t_i^2 + 2b \Sigma t_i + 2c \Sigma 1 - 2 \Sigma x_i$$

Perform summations, set derivatives to zero, and solve three simultaneous equations for the coefficients a, b, and c.

Repeat for y_i and z_i.

Figures 12 and 13 illustrate the effect the curve fit has on the coordinates and velocities of Target 1006 for VT3. The curve fit is indistinguishable from the raw photogrammetry data for the position coordinates; however, the curve fit eliminates noise from the differentiated velocities. The noise band for the velocities determined from raw data is on the order of 50 in/sec. The velocities resulting from the curve fit track along the center of the noise band. The curve fit coordinate time histories were used for all impact condition calculations, including rotation angles and rotation rates. For input into the simulations, the impact velocities are simply the derivatives of the curves fits for the coordinate time histories at the time of impact.

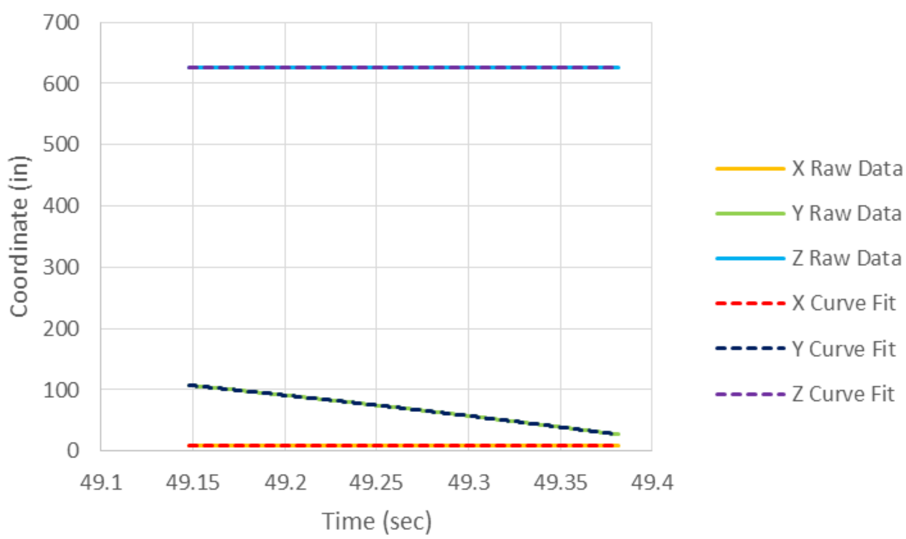


Figure 12. Curve Fit Target 1006 Coordinates for VT3

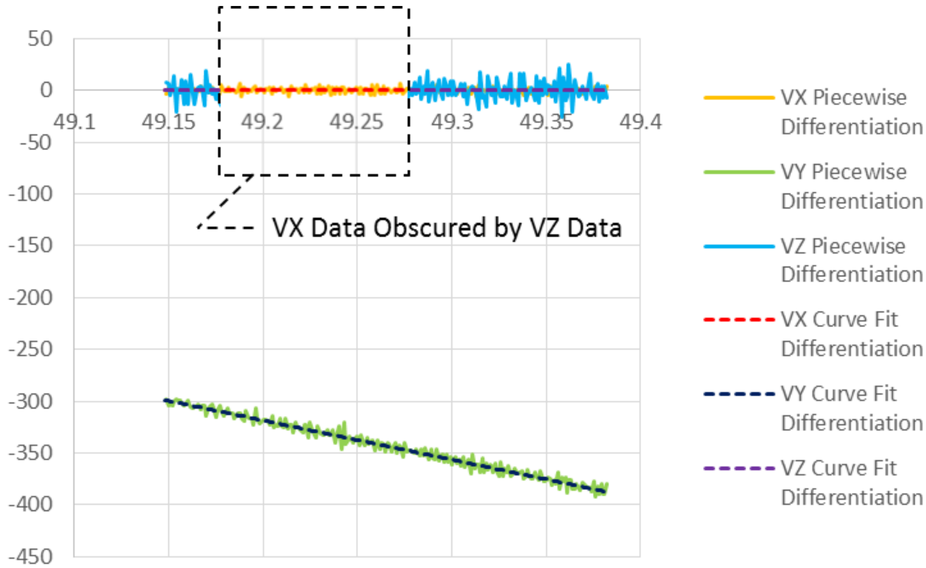


Figure 13. Curve Fit Velocities for Target 1006 for VT3

4.5. GTA Yaw, Roll, and Pitch Rotation Rates

The LS-DYNA *INITIAL_VELOCITY_GENERATION input requires the rotation rate and a vector defining the axis for the rotation rate. Figure 14 illustrates how this was determined from the photogrammetry data. From the steps described above, time histories were determined for the GTA Global Coordinate System vectors that define the axes of the GTA Local Coordinate System. The difference between the axis vectors at two points in time defines vectors representing the rate of change of each axis. Crossing the rate of change vectors for any two axes produces a vector representing the axis of rotation multiplied by the square of the rotation rate scaled by the component of the axis of rotation vector normal to the two rate of change vectors. A quality check of the computation can be performed by comparing the results of the cross product of the three possible pairs of the GTA Local Coordinate System axis vectors to verify that they produce the same axis of rotation vector. The square root of the sum of the squares of the lengths of the three cross product combinations produces the square of the rotation rate. Since the computation produces the square of the rotation rate, engineering judgment must be applied to decide whether to take the positive or negative root. This typically involved the piecewise differentiation of the pitch angle history to verify that it was in approximate agreement with the calculated y-axis rotation rate. For input into the simulations, the two points in time used to determine the impact conditions are the impact time and one millisecond before the impact time.

The direction of ω is given by any of the following:

$$n_\omega = d_X \times d_Y / |d_X \times d_Y|$$
$$= d_Y \times d_Z / |d_Y \times d_Z|$$
$$= d_Z \times d_X / |d_Z \times d_X|$$

The magnitude of ω is given by:

$$|\omega| = 1/dt*[|d_X \times d_Y|^2 + |d_Y \times d_Z|^2 + |d_Z \times d_X|^2]^{1/4}$$

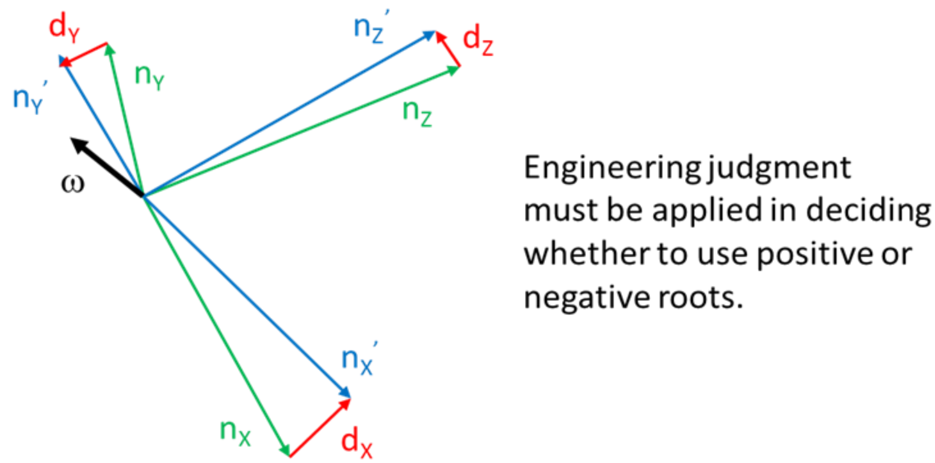


Figure 14. Calculation of Rotation Rate and Rotation Rate Axis

4.6. ST7 2-D Photogrammetry

For test ST7, the 3-D photogrammetry was not available due to technical difficulties with some of the cameras. The only camera footage available for photogrammetry was from a single camera located on the south side of the impact basin, which provided a side view of the impact. For that test, the single camera provided the ability to derive only 2-D photogrammetry data, which permitted the computation of just the horizontal and vertical target positions in the plane of the camera view. No out-of-plane target position data is available, so only the vertical velocity, horizontal velocity, pitch angle, and pitch rate can be determined. The 2-D data for ST7 was processed in the same manner as the 3-D data from the other tests, but with the out-of-plane target positions set to zero.

4.7. Impact Condition Photogrammetry Results

Multiple sets of impact conditions have been computed for each test. For rotation angles and angular rates, four solutions are provided. Three of the solutions are based on using different lines of targets to establish the GTA Local Coordinate System Z-axis vector as shown in Figure 15. The solutions are described based on the targets used to define the vectors. The Target 1000-5-2-8 solution has the Z-axis defined from Target 1000 to

1005, and the vector in the X-Y plane defined from Target 1002 to 1008. The fourth solution is based averaging target locations to establish the vectors that define the GTA Local Coordinate System as shown in Figure 16. The local Z-axis is defined from the average of the locations of Targets 1000, 1001, and 1003 to the average of the locations of Targets 1005, 1007, and 1009. The vector in the local X-Y plane is defined from the average of the locations of Targets 1000, 1002, and 1005 to the average of the locations of Targets 1003, 1008, and 1009. This vector is inclined relative to the main axis at an angle different from the 32.5^0 angle of the backshell. The angle is 29.94^0 for the 0^0 roll target set, 29.81^0 for the 90^0 roll target set (ST9), and 29.87^0 for the 180^0 roll target set (ST5). Note that Target 1006 takes the place of Target 1008 for the 90^0 roll case (ST9). Velocity solutions are provided at each target location.

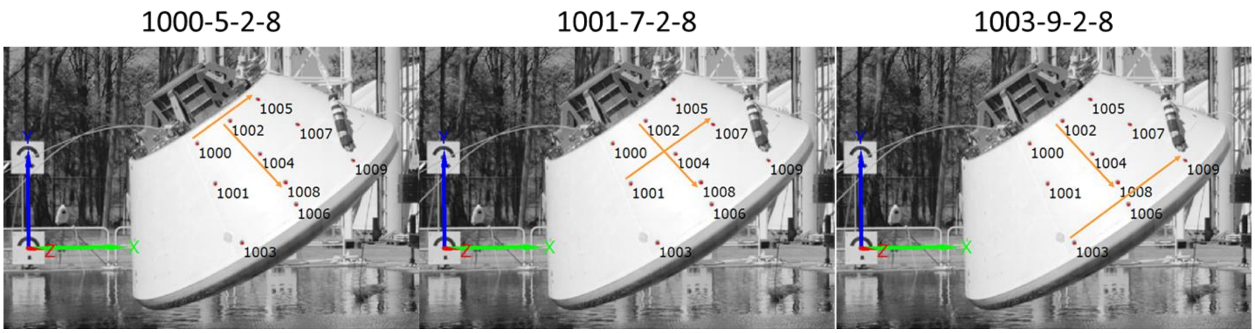


Figure 15. Vectors for Three Photogrammetry Solutions

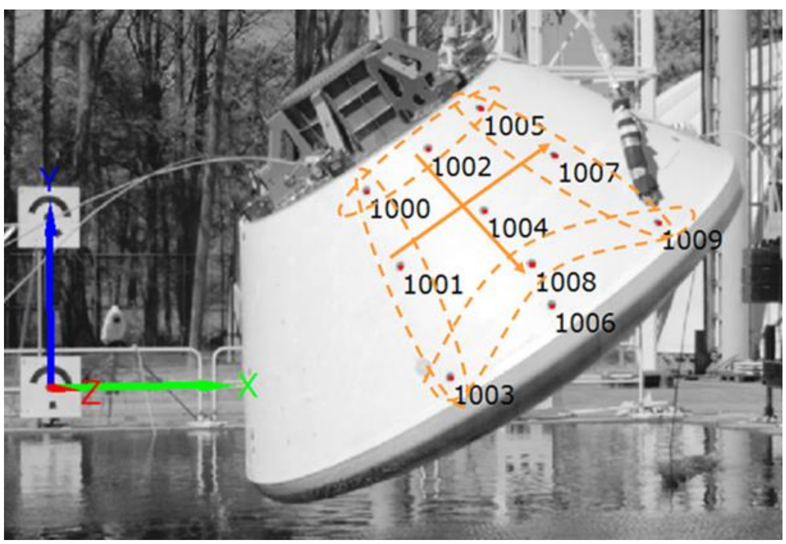


Figure 16. Vectors for Averaged Target Location Photogrammetry Solution

At this writing, the solution used for GTA LS-DYNA simulation impact conditions is based on Targets 1000, 1005, 1002, & 1008 for angles and angular rates and Target 1006 for velocities. This is based on test versus simulation correlation results and the examination of test trajectory reconstructions based on integration of accelerometer and rotation rate sensor data.

The impact conditions determined from the photogrammetry data in the GTA Global Coordinate System are listed in Tables 1 through 20. Aside from the camera problems with ST7, the quality of the photogrammetry data was excellent. There were no lost data points due to shading during the freefall period except for Target 1009 of VT2 and ST7. Angles are in degrees, but angular rates are in radians/second based on the input conventions of LS-DYNA.

Table 1. VT1 Rotation Angles and Angular Rates

Target Set	Roll (deg)	Pitch (deg)	Yaw (deg)	Angular Rate (rad/sec)	Nx	Ny	Nz
1000-5-2-8	1.20	-35.08	2.23	0.01676	-0.2653	0.7473	0.6092
1001-7-2-8	1.37	-34.53	2.33	0.01893	-0.3900	0.8109	0.4363
1003-9-2-8	1.27	-34.83	2.27	0.01758	-0.4299	0.7764	0.4608
Target Avg.	1.28	-34.79	2.25	0.01722	-0.3630	0.8096	0.4614

Table 2. VT1 Velocities

Target	Vx (in/sec)	Vy (in/sec)	Vz (in/sec)
1000	386.70	8.71	-1.59
1001	386.71	8.93	-1.90
1002	386.91	8.59	-1.37
1003	387.02	9.22	-2.23
1004	387.22	9.28	-1.64
1005	387.16	8.61	-1.23
1006	387.37	9.44	-1.91
1007	387.53	9.02	-1.41
1008	387.35	9.15	-1.73
1009	387.94	9.35	-1.57

Table 3. VT2 Rotation Angles and Angular Rates

Target Set	Roll (deg)	Pitch (deg)	Yaw (deg)	Angular Rate (rad/sec)	Nx	Ny	Nz
1000-5-2-8	-6.24	-45.91	0.76	0.06373	0.1964	0.9645	-0.1765
1001-7-2-8	-6.12	-44.58	0.85	0.06994	-0.0941	0.8857	-0.4547
1003-9-2-8	NA	NA	NA	NA	NA	NA	NA
Target Avg.	-6.17	-45.15	0.81	0.06589	0.0256	0.9370	-0.3484

Table 4. VT2 Velocities

Target	Vx (in/sec)	Vy (in/sec)	Vz (in/sec)
1000	384.27	-1.79	0.55
1001	389.23	-2.03	0.10
1002	386.30	-1.37	0.91
1003	387.82	-0.45	0.23
1004	386.16	-2.29	0.72
1005	387.64	-1.97	1.30
1006	401.62	-0.91	0.34
1007	393.73	-0.58	0.93
1008	383.27	-0.84	0.79
1009	NA	NA	NA

Table 5. VT3 Rotation Angles and Angular Rates

Target Set	Roll (deg)	Pitch (deg)	Yaw (deg)	Angular Rate (rad/sec)	Nx	Ny	Nz
1000-5-2-8	-3.19	-24.11	0.45	0.02028	-0.3247	0.8733	0.3631
1001-7-2-8	-3.01	-23.59	0.52	0.01980	-0.2280	0.8792	0.4183
1003-9-2-8	-3.09	-23.88	0.49	0.02151	-0.3190	0.8871	0.3336
Target Avg.	-3.09	-23.84	0.42	0.02151	-0.3123	0.8502	0.4239

Table 6. VT3 Velocities

Target	Vx (in/sec)	Vy (in/sec)	Vz (in/sec)
1000	386.29	-0.58	0.21
1001	386.55	-0.47	-0.14
1002	386.72	-0.28	0.35
1003	386.73	0.02	-0.64
1004	387.10	-0.25	0.13
1005	387.06	-0.45	0.43
1006	387.44	0.05	-0.25
1007	387.54	-0.42	0.19
1008	387.37	0.06	-0.13
1009	388.13	0.29	-0.02

Table 7. VT4 Rotation Angles and Angular Rates

Target Set	Roll (deg)	Pitch (deg)	Yaw (deg)	Angular Rate (rad/sec)	Nx	Ny	Nz
1000-5-2-8	-1.44	-24.00	0.46	0.01206	-0.4688	0.8021	0.3701
1001-7-2-8	-1.25	-23.47	0.54	0.01075	-0.1398	0.7985	0.5856
1003-9-2-8	-1.38	-23.77	0.49	0.01161	-0.1619	0.8347	0.5264
Target Avg.	-1.35	-23.73	0.48	0.01435	-0.3112	0.6570	0.6867

Table 8. VT4 Velocities

Target	Vx (in/sec)	Vy (in/sec)	Vz (in/sec)
1000	380.55	0.33	-1.07
1001	380.74	0.79	-1.27
1002	380.77	0.68	-0.83
1003	380.95	1.20	-1.59
1004	381.03	0.65	-1.04
1005	380.92	0.48	-0.82
1006	381.29	1.04	-1.27
1007	381.16	0.73	-0.91
1008	381.20	0.91	-1.18
1009	381.58	1.14	-1.07

Table 9. ST5 Rotation Angles and Angular Rates

Target Set	Roll (deg)*	Pitch (deg)	Yaw (deg)	Angular Rate (rad/sec)	Nx	Ny	Nz
1000-5-2-8	-0.92	26.50	-0.05	0.03736	-0.2913	0.9247	-0.2453
1001-7-2-8	-0.70	26.48	-0.15	0.03175	-0.3804	0.8853	-0.2673
1003-9-2-8	-0.72	25.93	-0.15	0.04058	-0.3277	-0.9262	-0.1862
Target Avg.	-0.76	26.24	-0.05	0.00750	0.8880	-0.1572	-0.4322

* For ST5, a roll angle of 180 degrees is imposed before imposing the listed angles.

Table 10. ST5 Velocities

Target	Vx (in/sec)	Vy (in/sec)	Vz (in/sec)
1000	415.93	0.66	-227.35
1001	415.51	0.18	-227.75
1002	416.65	0.77	-227.56
1003	419.12	-0.43	-230.89
1004	416.30	0.44	-228.07
1005	417.37	0.91	-228.01
1006	415.91	-0.02	-228.80
1007	417.02	0.61	-228.58
1008	415.86	0.16	-228.48
1009	416.37	0.29	-229.46

Table 11. ST6 Rotation Angles and Angular Rates

Target Set	Roll (deg)	Pitch (deg)	Yaw (deg)	Angular Rate (rad/sec)	Nx	Ny	Nz
1000-5-2-8	-1.56	-18.51	0.07	0.04445	-0.5112	0.8588	0.0321
1001-7-2-8	-1.36	-17.98	0.13	0.04362	-0.4349	0.8985	0.0604
1003-9-2-8	-1.45	-18.29	0.10	0.04307	-0.4250	0.9027	0.0663
Target Avg.	-1.45	-18.24	0.07	0.04326	-0.4427	0.8963	0.0258

Table 12. ST6 Velocities

Target	Vx (in/sec)	Vy (in/sec)	Vz (in/sec)
1000	340.27	2.15	-447.48
1001	340.32	2.24	-448.25
1002	341.03	2.54	-447.01
1003	340.50	2.27	-449.34
1004	341.38	2.80	-447.64
1005	341.84	3.12	-446.73
1006	341.74	2.89	-448.50
1007	342.49	3.30	-447.24
1008	341.72	2.89	-448.15
1009	343.37	3.63	-447.91

Table 13. ST7 Rotation Angles and Angular Rates

Target Set	Roll (deg)	Pitch (deg)	Yaw (deg)	Angular Rate (rad/sec)	Nx	Ny	Nz
1000-5-2-8	0.00	-43.76	0.00	0.01935	0.0000	-1.0000	0.0000
1001-7-2-8	0.00	-42.63	0.00	0.02594	0.0000	1.0000	0.0000
1003-9-2-8	NA	NA	NA	NA	NA	NA	NA
Target Avg.	0.00	-43.11	0.00	0.00638	0.0000	-1.0000	0.0000

Table 14. ST7 Velocities

Target	Vx (in/sec)	Vy (in/sec)	Vz (in/sec)
1000	475.18	0.00	-647.23
1001	481.05	0.00	-658.24
1002	479.13	0.00	-656.51
1003	494.34	0.00	-676.63
1004	489.18	0.00	-666.40
1005	475.79	0.00	-649.12
1006	499.64	0.00	-687.19
1007	486.54	0.00	-661.87
1008	496.46	0.00	-674.95
1009	NA	NA	NA

Table 15. ST8 Rotation Angles and Angular Rates

Target Set	Roll (deg)	Pitch (deg)	Yaw (deg)	Angular Rate (rad/sec)	Nx	Ny	Nz
1000-5-2-8	28.47	-43.51	0.78	0.08786	-0.5421	0.4934	0.6802
1001-7-2-8	28.72	-42.99	0.95	0.08371	-0.6632	0.4660	0.5857
1003-9-2-8	28.61	-43.29	0.87	0.08654	-0.6623	0.4910	0.5659
Target Avg.	28.61	-43.25	0.82	0.07901	-0.5929	0.5748	0.5640

Table 16. ST8 Velocities

Target	Vx (in/sec)	Vy (in/sec)	Vz (in/sec)
1000	321.68	-4.79	-649.90
1001	323.53	-4.51	-650.48
1002	322.06	-5.85	-648.73
1003	324.48	-2.58	-651.07
1004	324.15	-4.60	-648.60
1005	323.60	-5.43	-647.51
1006	326.41	-2.03	-648.56
1007	325.64	-4.60	-647.23
1008	325.66	-3.44	-648.54
1009	327.45	-2.65	-646.42

Table 17. ST9 Rotation Angles and Angular Rates

Target Set	Roll (deg)*	Pitch (deg)	Yaw (deg)	Angular Rate (rad/sec)	Nx	Ny	Nz
1000-5-2-8	0.43	0.82	-24.89	0.04217	0.1491	0.9227	0.3556
1001-7-2-8	0.00	0.85	-24.89	0.05298	-0.6421	0.7084	0.2930
1003-9-2-8	-0.10	1.00	-24.89	0.04495	0.0608	0.9410	0.3329
Target Avg.	0.08	0.90	-24.50	0.05508	-0.1534	0.7216	0.6751

* For ST9, a roll angle of 90 degrees is imposed before imposing the listed angles.

Table 18. ST9 Velocities

Target	Vx (in/sec)	Vy (in/sec)	Vz (in/sec)
1000	369.53	-0.75	-279.99
1001	370.45	-2.44	-280.84
1002	371.19	-0.96	-279.99
1003	370.81	0.07	-281.22
1004	371.74	-1.05	-280.42
1005	371.75	-1.09	-280.18
1006	372.87	-1.09	-280.87
1007	373.15	0.03	-280.72
1008	NA	NA	NA
1009	374.33	-0.14	-281.16
1010	371.00	0.67	-281.79
1011	374.34	0.88	-281.68

Table 19. VT10 Rotation Angles and Angular Rates

Target Set	Roll (deg)	Pitch (deg)	Yaw (deg)	Angular Rate (rad/sec)	Nx	Ny	Nz
1000-5-2-8	-3.19	-16.16	0.75	0.01533	-0.4867	-0.1787	0.8551
1001-7-2-8	-2.97	-15.60	0.81	0.01554	-0.1037	0.3744	0.9214
1003-9-2-8	-3.12	-15.91	0.77	0.01723	-0.5889	0.4220	0.6893
Target Avg.	-3.09	-15.87	0.71	0.00868	-0.5497	0.4612	0.6965

Table 20. VT10 Velocities

Target	Vx (in/sec)	Vy (in/sec)	Vz (in/sec)
1000	386.99	1.22	-0.94
1001	386.98	1.23	-0.98
1002	386.53	1.04	-0.78
1003	386.89	1.25	-1.10
1004	387.07	1.31	-0.91
1005	386.77	1.40	-0.78
1006	387.41	1.61	-1.03
1007	387.27	1.09	-0.84
1008	387.19	1.55	-0.97
1009	387.40	1.79	-0.92

A major component of the variability and uncertainty in the simulations comes from uncertainty in the impact velocity, orientation angles, and angular rates as determined from the photogrammetry data. The largest angular rate is 0.08786 rad/sec for the Target 1000-5-2-8 solution for ST8. This would be enough to change the angles by approximately 0.5^{o} over the first 0.10 seconds during which the primary impact response occurs, which suggests that angular rate is not a major factor.

The actual impact conditions closely mirrored the planned impact conditions in all cases with the exception of ST7, for which the pitch angle was significantly lower than expected (-50.2^{o} planned vs. -43.76^{o} actual) due to pitch oscillation of the swing platform and the GTA being tipped off by the explosive bolts when it was released from the platform. The planned and actual impact conditions are listed in Table 21 and are illustrated in Figure 17. The basis for the comparison is the Target 1000-5-2-8 solution for angles and the Target 1006 solution for velocities.

Table 21. Planned and Actual Impact Conditions

Test	Planned V_X (ft/sec)	Actual V_X (ft/sec)	Planned V_Y (ft/sec)	Actual V_Y (ft/sec)	Planned V_Z (ft/sec)	Actual V_Z (ft/sec)	Planned Roll (deg)	Actual Roll (deg)	Planned Pitch (deg)	Actual Pitch (deg)	Planned Yaw (deg)	Actual Yaw (deg)
VT1	32.20	32.28	0.00	0.79	0.00	-0.16	0.00	1.20	-34.00	-35.08	0.00	2.23
VT2	32.20	33.47	0.00	-0.08	0.00	0.03	0.00	-6.24	-45.00	-45.91	0.00	0.76
VT3	32.20	32.29	0.00	0.00	0.00	-0.02	0.00	-3.19	-23.00	-24.11	0.00	0.45
VT4	32.20	31.77	0.00	0.09	0.00	-0.11	0.00	-1.44	-23.00	-24.00	0.00	0.46
ST5*	35.50	34.66	0.00	0.00	-20.00	-19.07	180.00	179.08	-26.00	-26.50	0.00	0.05
ST6	28.40	28.48	0.00	0.24	-38.10	-37.37	0.00	-1.56	-20.30	-18.51	0.00	0.07
ST7	39.60	41.64	0.00	0.00	-56.20	-57.27	0.00	0.00	-50.20	-43.76	0.00	0.00
ST8	26.00	27.20	0.00	-0.17	-56.20	-54.05	30.00	28.47	-43.80	-43.51	0.00	0.78
ST9*	30.00	31.07	0.00	-0.09	-25.00	-23.41	90.00	0.43	-26.00	-24.89	0.00	0.82
VT10	32.20	32.28	0.00	0.13	0.00	-0.09	0.00	-3.19	-15.00	-16.16	0.00	0.75

* Pitch and yaw angles are switched for 90° roll case and have signs reversed for 180° roll case for consistency with test planning data.

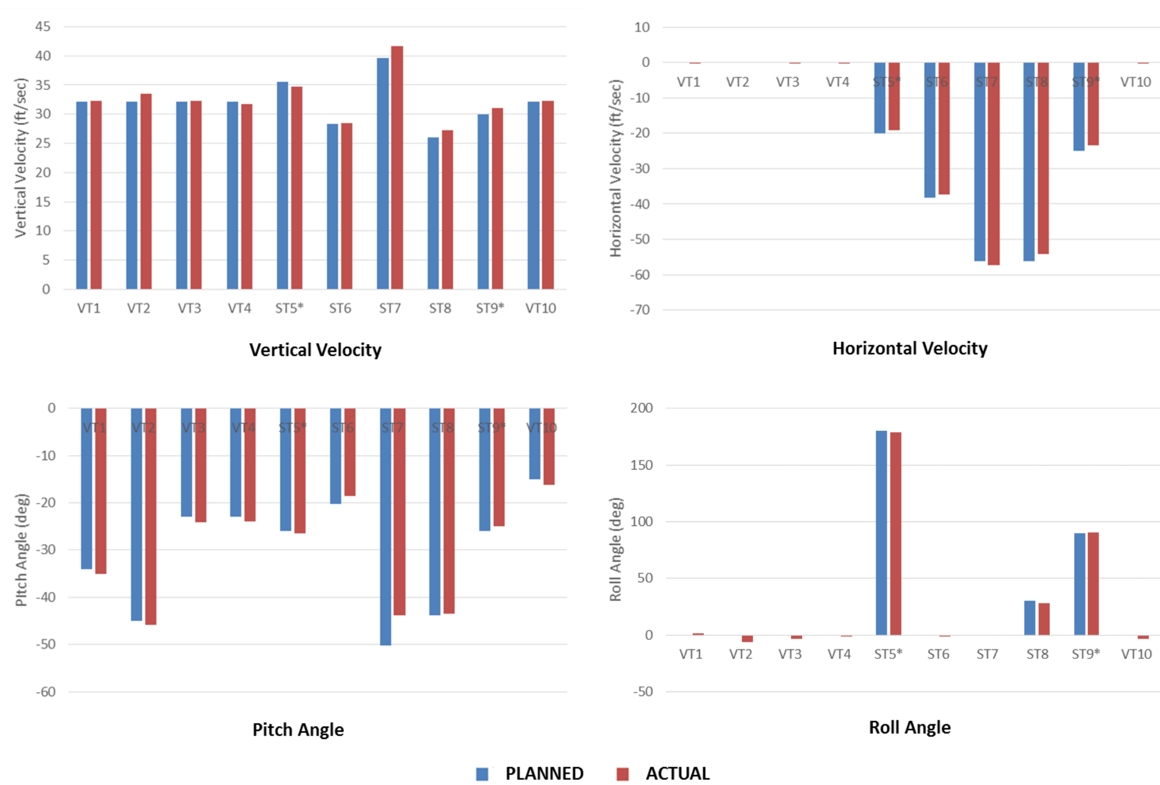


Figure 17. Planned and Actual Impact Conditions

4.8. LS-DYNA Simulation Initial Conditions

The LS-DYNA initial conditions are based on the values in Tables 1 through 20, but with modifications based on the initial height above the water. The water impact in the LS-DYNA models is timed to occur at 0.0155 seconds. To account for the change in velocity due to gravitational acceleration, the vertical velocity (Vx) is reduced by 0.0155 sec x 386.1 in/sec^2 = 5.98 in/sec. The distance between the GTA and the water surface is computed based on the geometry of the heatshield at the centerline. For setting the initial height above the water, it is necessary to account for the effect of the LS-DYNA parameter FRCMIN, which specifies the fluid element volume fraction at which fluid-structure coupling initiates. Changing FRCMIN from the default value of 0.5 changes the effective location of the water surface relative to the actual water mesh geometry. In the Orion water model used for the GTA simulations, FRCMIN is set to 0.45. Through trials with small LS-DYNA test models, it was determined that the impacting object begins to interact with the water at a distance above the nominal surface location equal to 2*(0.5-FRCMIN)*d, where d is the height of the first layer of elements immediately above the water representing the air void. The mesh used for the water impact simulations for compliant models has a first layer of air void elements that is 2 inches tall, which results in an effective water surface location 0.2 inches above the nominal location.

For input to LS-DYNA, the signs are reversed for the roll and pitch angles. This is because pitch is defined about the negative Y-axis so that toe-in is a positive pitch angle. Roll is similarly defined as about the negative X-axis. The impact conditions are defined based on the side of GTA that was visible to the cameras along the south side of the basin. As a consequence, an initial roll angle of 180° must be defined for ST5 and 90° for ST9 before applying the roll, pitch, and yaw angles provided in the tables.

5. Data Quality Checks

5.1. Photogrammetry Coordinate System Check

The targets used to define the axes of the Photogrammetry Coordinate System are illustrated in Figure 18. The alignment of the targets is critical to establishing the photogrammetric measurements of the target location. The target array was measured before the test series began in order to establish scaling. The target arrays were checked for plumb on the day before each test, prior to the photogrammetry system calibration procedures.

Figure 18. Photogrammetry Coordinate System Targets

5.2. GTA Photogrammetry Target Location Check

A set of photogrammetry measurements were performed for each of the three sides of the GTA that had targets while GTA was standing upright on a level floor inside the shop preparation area. The locations for the photogrammetry targets were relative to a reference target array resting on top of the access trunk as shown in Figure 19.

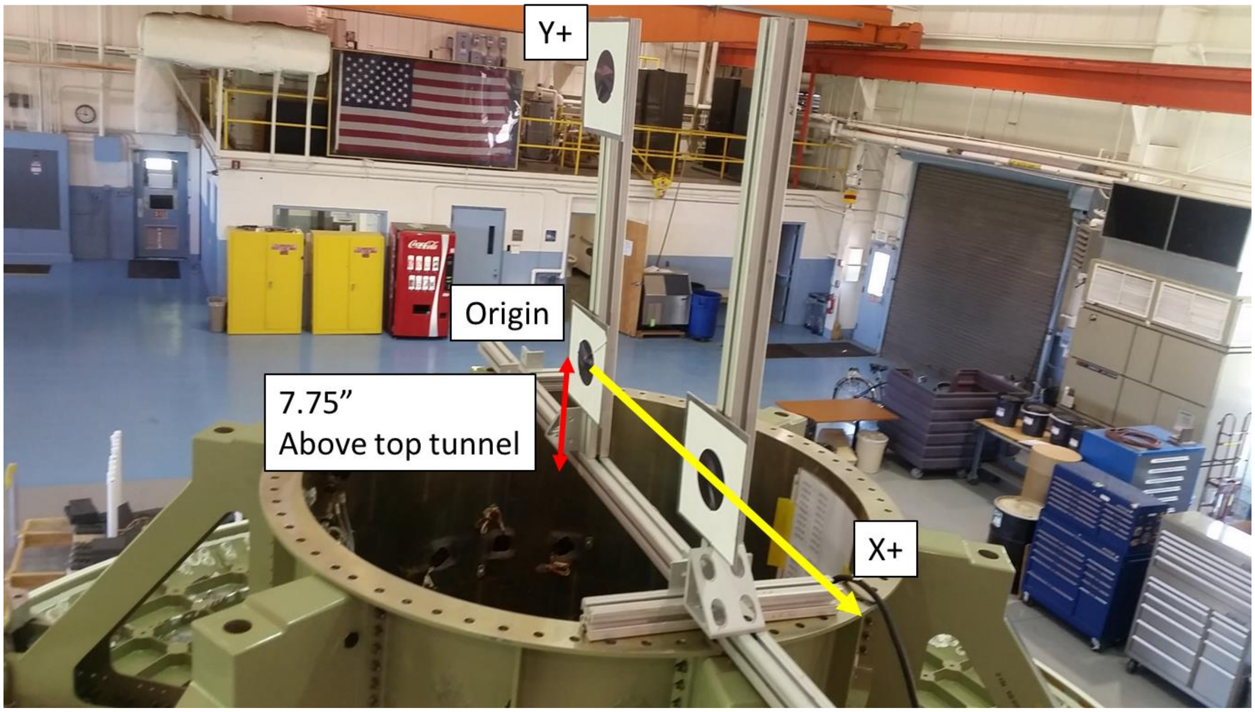


Figure 19. Reference Target Array for Shop Floor Photogrammetry Measurements

Figure 20 shows the targets arrays on the three sides of GTA. Coordinates of the targets in the GTA Global Coordinate System are listed in Tables 22 through 24. The photogrammetry cameras are located on the south side of the basin. For most of the tests, the cameras see the 0° roll target set. For ST5, the cameras see the 180° roll target set, which has a target array similar to the 0° roll target set. For ST9, the cameras see the 90° roll target set.

Target 1006 represents the location of the CG projected onto the backshell. Target 1006 is forward of center for the 0° roll target set, on center for the 90° roll target set (ST9), and aft of center for the 180° roll target set (ST5). Due to interference with other features of GTA, the lower row of targets is moved upward and Target 1006 takes the place of Target 1008 for the 90° roll target set (ST9).

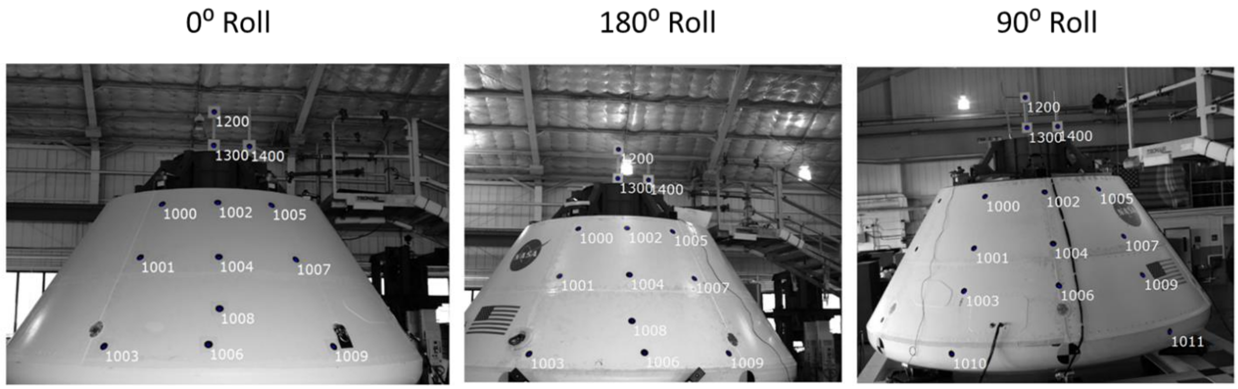


Figure 20. Target Arrays on Three Sides of GTA

Table 22. 0° Roll Target Locations from Shop Floor Measurements

Target	GTA Global X (in)	GTA Global Y (in)	GTA Global Z (in)
1000	37.7378	-52.043	-22.1355
1001	60.8546	-66.1435	-29.2357
1002	37.0902	-56.5528	0.7987
1003	93.7391	-86.1807	-39.3196
1004	60.3391	-72.7357	1.1155
1005	36.913	-51.6217	23.5076
1006	91.8065	-94.5875	-2.5993
1007	60.3179	-65.8023	31.7479
1008	79.6709	-86.2779	1.2568
1009	92.6111	-85.553	42.7131
1200	-17.3141	0	0
1300	0	0	0
1400	0	0	17.9513

Table 23. 180 Roll Target Locations from Shop Floor Measurements

Target	GTA Global X (in)	GTA Global Y (in)	GTA Global Z (in)
1000	37.6453	-52.03191	-22.0379
1001	61.1027	-66.11504	-29.6494
1002	37.0881	-56.63455	0.776379
1003	93.6248	-85.62058	-40.1149
1004	59.9572	-72.55752	0.82834
1005	37.1687	-51.98573	23.47819
1006	91.8437	-94.71133	5.333496
1007	60.444	-66.24037	31.34512
1008	79.7171	-86.37049	0.93105
1009	92.5708	-85.89888	42.2064
1200	-17.3194	0	-0.16947
1300	0	0	0
1400	0	0	17.95672

Table 24. 90 Roll Target Locations from Shop Floor Measurements

Target	GTA Global X (in)	GTA Global Y (in)	GTA Global Z (in)
1000	37.7971	-49.20538	-27.9464
1001	61.3317	-63.72644	-34.947
1002	37.1589	-56.96856	0.531663
1003	79.1129	-74.40896	-40.6858
1004	60.5889	-73.36071	0.900839
1005	37.1292	-49.437	28.8626
1006	77.9552	-85.17098	0.705977
1007	60.3188	-63.53048	36.9222
1009	78.0776	-73.86913	42.42368
1010	103.552	-87.51088	-47.4917
1011	102.43	-87.77833	49.84815
1200	-17.30026	0	-0.17961
1300	0	0	0
1400	0	0	17.96512

The angles of the reference lines formed by the targets are listed in Table 25, and the angle errors between n3 and n1 are listed in Table 26.

Table 25. Angles of Principal Vectors for Shop Floor Measurements

Targets for 0° Roll Tests (Port) - VT1, VT2, VT3, VT4, ST6, ST7, ST8, & VT10			
Target Set	Pitch (deg)	Roll (deg)	Yaw (deg)
1000-5-2-8	-1.03521	-0.52884	-2.42343
1001-7-2-8	-0.50422	-0.32056	-2.41977
1003-9-2-8	-0.78778	-0.43841	-2.42138
Target Average	-0.75600	-0.42220	-2.43203
Targets for 90° Roll Test (Leeward) - ST9			
Target Set	Pitch (deg)	Roll (deg)	Yaw (deg)
1000-5-2-6	-0.67359	0.233603	-2.15477
1001-7-2-6	-0.80745	-0.15622	-2.15816
1003-9-2-6	-0.71369	-0.37215	-2.15871
Target Average	-0.73476	-0.13639	-2.18321
Targets for 180° Roll Test (Starboard) - ST5			
Target Set	Pitch (deg)	Roll (deg)	Yaw (deg)
1000-5-2-8	-0.59992	-0.05813	-2.39855
1001-7-2-8	-0.61873	0.11773	-2.39753
1003-9-2-8	-0.73354	0.193697	-2.39729
Target Average	-0.66425	0.10846	-2.39647

Table 26. n_3 Angle Relative to n_1 for Shop Floor Measurements

Targets for 0° Roll Tests (Port) - VT1, VT2, VT3, VT4, ST6, ST7, ST8, & VT10	
Target Set	n_3 Angle relative to n_1 (deg)
1000-5-2-8	0.64611
1001-7-2-8	0.09152
1003-9-2-8	0.39147
Target Average	0.08686
Targets for 90° Roll Test (Leeward) - ST9	
Target Set	n_3 Angle relative to n_1 (deg)
1000-5-2-6	0.21987
1001-7-2-6	0.55165
1003-9-2-6	0.59730
Target Average	0.14794
Targets for 180° Roll Test (Starboard) - ST5	
Target Set	n_3 Angle relative to n_1 (deg)
1000-5-2-8	0.35480
1001-7-2-8	0.26961
1003-9-2-8	0.32032
Target Average	0.25027

An interesting aside is that the data for all three sides indicates a yaw angle of approximately -2.4°. Had the yaw angle been positive for one side and negative for the opposite side, the explanation would have been that the GTA was not level; however, this was not the case. The angle was approximately the same for all three sides, which indicates that the vertical leg of the reference target array was out of plumb.

5.3. Precision of Photogrammetry Measurements

The photogrammetry data from each test provides a time history of the coordinates of each of the photogrammetry targets. This data can be used to generate time histories for the distances between targets on the test article, which should remain constant. Time histories were developed for the distance from Target 1000 to each of the other targets as shown in Figure 21. The differences between the maximum and minimum lengths from the time histories are tabulated in Table 27. The calculations are based on a least squares fit of the photogrammetry target location time histories, which has the effect of smoothing out any outlying data points. The precision is remarkable considering that the photogrammetry targets are approximately 3 inches in diameter. The results are shown graphically in Figure 22. Based on these results, a precision tolerance on target location of 0.1 inches is expected in the typical case. ST7 is an outlier case due to the 2-D photogrammetry used for that test and is not shown in the figure since it is off the scale relative to the other tests.

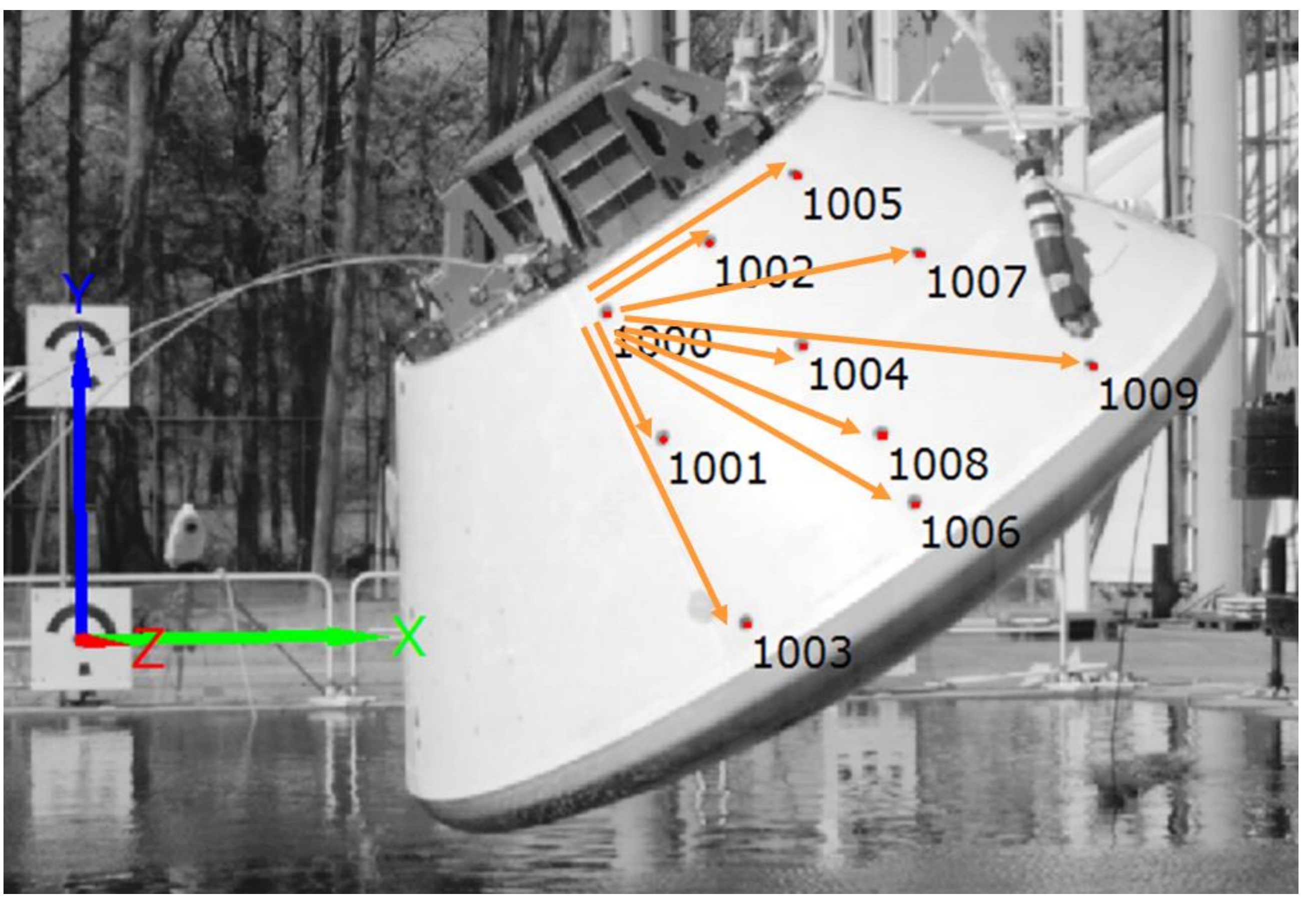


Figure 21. Target-to-Target Photogrammetry Measurements

Table 27. Time History Distance Variation from Target 1000 (in)

Test	Target 1001	Target 1002	Target 1003	Target 1004	Target 1005	Target 1006	Target 1007	Target 1008	Target 1009
VT1	0.0098	0.0061	0.0068	0.0129	0.0074	0.0157	0.0049	0.0148	0.0109
VT2	0.1535	0.0734	1.1469	0.0150	0.0800	0.4835	0.4846	0.1366	NA
VT3	0.0119	0.0079	0.0071	0.0044	0.0073	0.0128	0.0043	0.0109	0.0086
VT4	0.0067	0.0089	0.0090	0.0024	0.0071	0.0031	0.0082	0.0049	0.0070
ST5	0.0188	0.0117	0.4644	0.0252	0.0365	0.0503	0.0596	0.0196	0.0340
ST6	0.0041	0.0246	0.0164	0.0125	0.0537	0.0125	0.0578	0.0154	0.0709
ST7	2.1658	4.0273	4.6498	13.0663	2.2780	20.7682	12.1998	18.5617	NA
ST8	0.0283	0.0251	0.0234	0.0157	0.0389	0.0020	0.0292	0.0131	0.0497
ST9	0.0755	0.0270	0.0187	0.0910	0.0288	0.0242	0.0291	0.0107	0.0288
VT10	0.0068	0.0316	0.0072	0.0021	0.0190	0.0035	0.0253	0.0060	0.0301

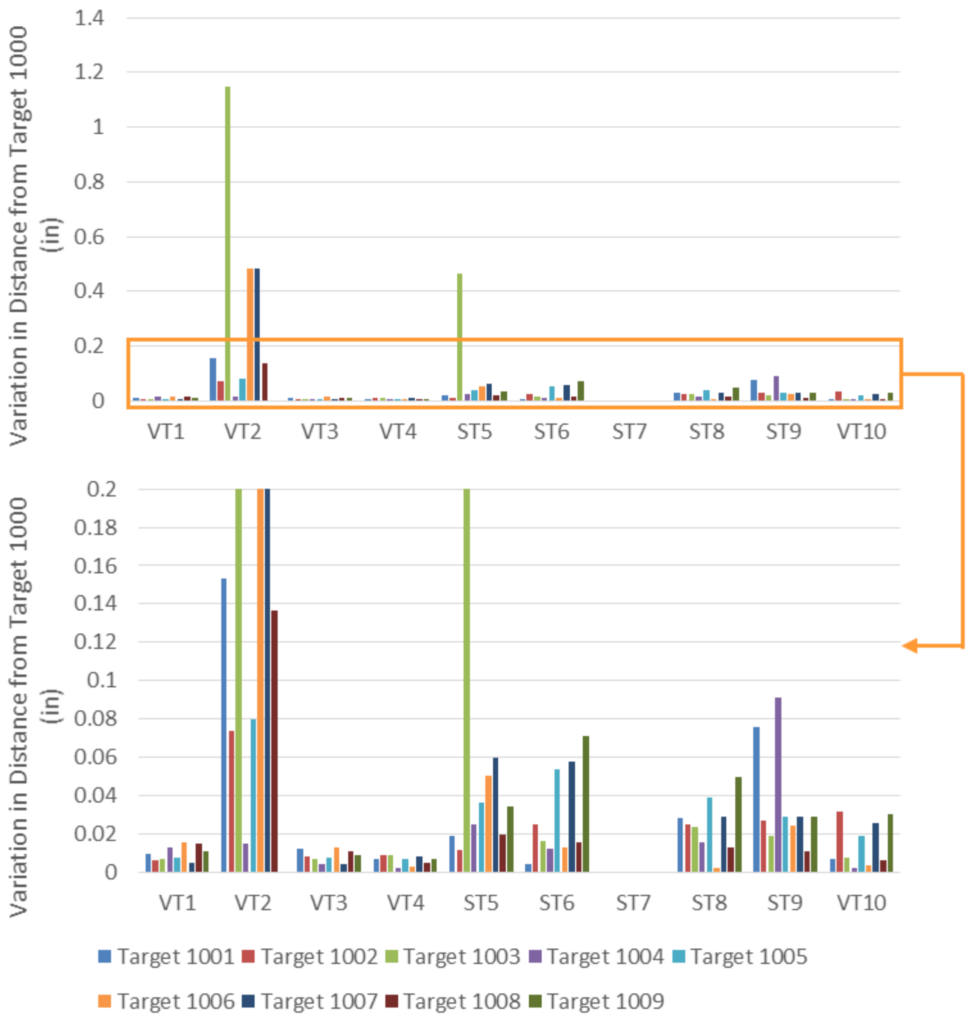


Figure 22. Time History Distance Variation from Target 1000

Time histories for the distance variations for ST7 are shown in Figure 23. The large variation in the distance time histories suggest the possibility of significant errors in the pitch angle and velocity calculations. Note that there was no data for Target 1009.

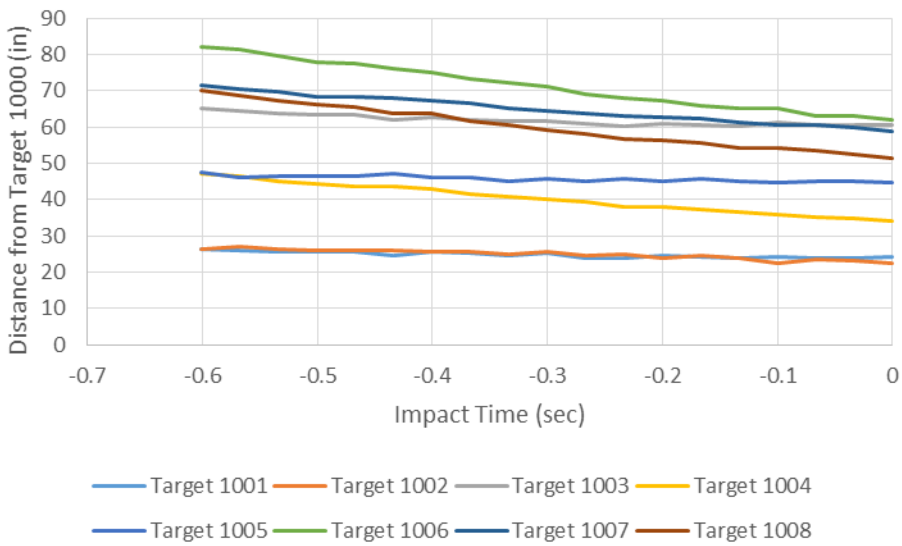


Figure 23. ST7 Time History Distance from Target 1000

The lengths of the key vectors as measured on the shop floor and as recorded at the moment of impact for ST7 are listed in Table 28.

Table 28. Lengths of Key Vectors for ST7

Vector	Length Measured on Shop Floor (in)	Length Measured on Shop Floor Projected to 2D Plane (in)	Distance between Targets at Moment of Impact for ST7 (in)
1000-1005	45.65	45.65	44.82
1001-1007	60.99	60.99	60.67
1003-1009	82.04	82.04	NA
1002-1008	51.93	42.58	45.68

5.4. Orthogonality Check of GTA Local Coordinate System

As noted in Section 4.2, there is an assumption that the vectors $V_{1000-1005}$, $V_{1001-1007}$, and $V_{1003-1009}$ (n_Z) are perpendicular to $V_{1002-1008}$ (n_1). This assumption can be checked by crossing n_Z and n_1 to form n_2, then crossing n_2 with n_Z to form n_3, and then taking the scalar product of n_3 and n_1 to determine the cosine of the angle between them. Ideally, n_3 and n_1 should be parallel. Three variants of the calculation were performed, using $V_{1000-1005}$, $V_{1001-1007}$, and $V_{1003-1009}$ to define n_Z. Table 29 and Figure 24 show the time averages of the error angles computed from the curve fit data for the target positions. ST7 is not included due to differences in the methodology for processing the 2D data for that test.

Table 29. Average Perpendicularity Error (deg) between n_Z and n_1

Test	Targets 1003-9-2-8	Targets 1001-7-2-8	Targets 1000-5-2-8
VT1	0.39	0.09	0.63
VT2	0.33	0.11	1.03
VT3	0.37	0.08	0.61
VT4	0.29	0.03	0.51
ST5	0.46	0.24	0.34
ST6	0.25	0.06	0.49
ST7	NA	NA	NA
ST8	0.29	0.01	0.54
ST9	0.02	0.06	0.36
VT10	0.50	0.17	0.72

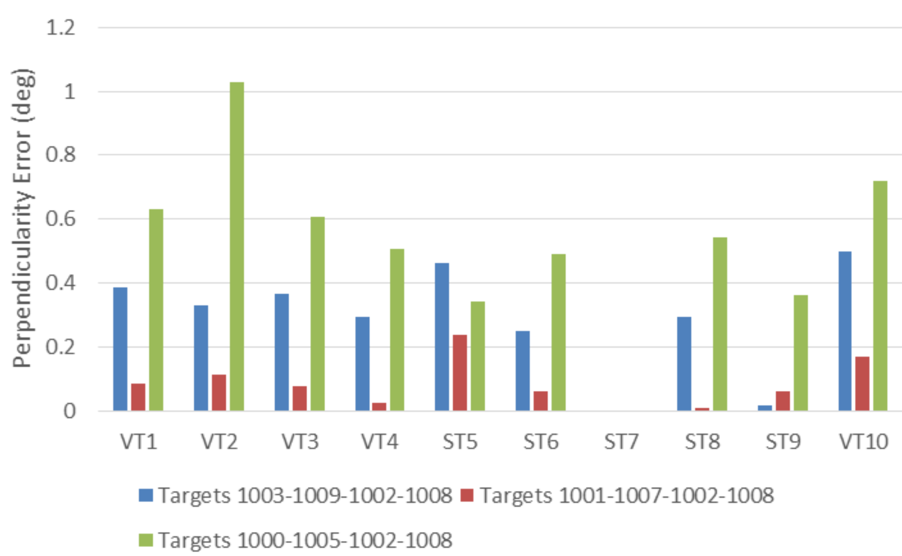


Figure 24. Average Perpendicularity Error between n_Z and n_1

The precision tolerance of 0.1 inches on two targets separated by approximately 60 inches gives an angle measurement tolerance of 2 * 0.1 inches / 60 inches * 57.296 deg/radian = 0.2°; however, looking at the results above suggests the alignment of the targets is a significant factor. The results indicate 0.3° as reasonable estimate for the precision of the angle error in the typical case.

5.5. Curve Fit Gravitational Acceleration Check

For the curve fit of the position data to a quadratic equation, the coefficient that multiplies the time squared term for the vertical position should be half the gravitational acceleration. Table 30 lists the gravitational acceleration values determined this way for each of the targets for each of the tests. Due to aerodynamic drag, the value should be less than or equal to 1g (386.1 in/sec^2). The same data is shown graphically in Figure 25. Some variability in the data is expected, and the results show that the variability is biased below 1g.

Table 30. Gravitational Acceleration (g) from Curve Fit of Target Coordinates

Test	VT1	VT2	VT3	VT4	ST5	ST6	ST7	ST8	ST9	VT10
# Steps	204	144	234	239	325	193	18	78	137	276
Target 1000	0.9697	0.9314	0.9735	0.9718	0.9622	0.9735	0.8858	1.0431	0.9501	0.9722
Target 1001	0.9680	1.0801	0.9751	0.9739	0.9647	0.9730	0.8904	1.0823	0.9661	0.9702
Target 1002	0.9710	0.9762	0.9772	0.9745	0.9659	0.9777	0.8883	0.9972	0.9690	0.9664
Target 1003	0.9701	0.6598	0.9751	0.9751	1.0201	0.9750	0.9244	1.0372	0.9625	0.9676
Target 1004	0.9737	0.9859	0.9798	0.9773	0.9649	0.9793	0.9107	1.0175	0.9674	0.9738
Target 1005	0.9741	1.0249	0.9802	0.9774	0.9652	0.9827	0.8697	1.0383	0.9810	0.9686
Target 1006	0.9724	1.1919	0.9809	0.9795	0.9636	0.9811	0.9060	1.0380	0.9871	0.9771
Target 1007	0.9767	0.8996	0.9840	0.9794	0.9624	0.9864	0.8967	1.0279	1.0055	0.9740
Target 1008	0.9728	0.7274	0.9811	0.9783	0.9636	0.9817	0.9096	1.0395	0.9737	0.9750
Target 1009	0.9789	NA	0.9884	0.9855	0.9585	0.9910	NA	0.9848	0.9692	0.9762

Figure 25. Gravitational Acceleration from Curve Fit of Target Vertical Coordinates

The second row in the table identifies the number of time steps in the photogrammetry histories used for the curve fit. The time increment per step is 0.001 seconds except for the 2-D data used for ST7, which had a time increment per step of 0.033 seconds. The curve fit extends between the start of the photogrammetry history, which occurs when the test article comes fully within camera range during free fall, and the time step identified as the point of impact.

The tests with a shorter duration for the photogrammetry histories show greater variation in the calculated vertical acceleration. The camera setup and the initial conditions for the tests govern the amount of time during which the test article is within the camera view. The velocity error is estimated as follows:

Velocity Error = # Steps x Step Time Increment * (Acceleration – 1g) * 386.1 in/s/s

This calculation has been repeated for each target of each test. The results are shown in Table 31. ST7 is shown in the table as having a much larger error than the other tests, but it is assumed that the accuracy of the 2-D photogrammetry measurements improved as the height above the water decreased and GTA became level with the camera. The same data is shown graphically in Figure 26. Data for ST7 is not shown in the figure since it is off the scale relative to the other tests.

Table 31. Possible Velocity Errors (in/sec) based on Acceleration Measurement Errors

Test	VT1	VT2	VT3	VT4	ST5	ST6	ST7	ST8	ST9	VT10
Target 1000	-2.38	-3.81	-2.40	-2.61	-4.75	-1.97	-26.18	1.30	-2.64	-2.96
Target 1001	-2.52	4.46	-2.25	-2.41	-4.43	-2.01	-25.13	2.48	-1.80	-3.17
Target 1002	-2.29	-1.32	-2.06	-2.35	-4.28	-1.66	-25.62	-0.09	-1.64	-3.58
Target 1003	-2.35	-18.92	-2.25	-2.30	2.52	-1.87	-17.34	1.12	-1.99	-3.45
Target 1004	-2.08	-0.78	-1.82	-2.10	-4.41	-1.54	-20.48	0.53	-1.73	-2.79
Target 1005	-2.04	1.39	-1.79	-2.09	-4.37	-1.29	-29.87	1.15	-1.01	-3.35
Target 1006	-2.17	10.67	-1.73	-1.89	-4.57	-1.41	-21.56	1.14	-0.68	-2.44
Target 1007	-1.84	-5.58	-1.45	-1.90	-4.72	-1.01	-23.70	0.84	0.29	-2.77
Target 1008	-2.15	-15.16	-1.71	-2.00	-4.57	-1.37	-20.73	1.19	-1.39	-2.67
Target 1009	-1.67	NA	-1.05	-1.34	-5.20	-0.67	NA	-0.46	-1.63	-2.54

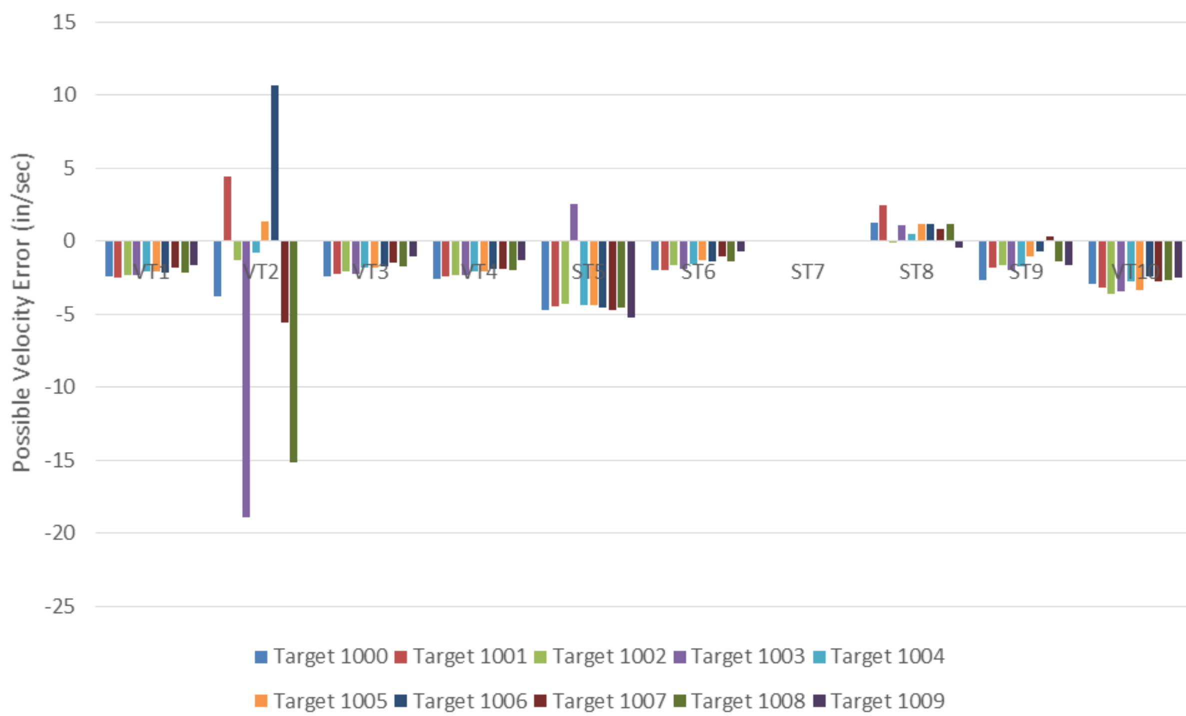


Figure 26. Possible Velocity Errors based on Acceleration Measurement Errors

The above tolerances on velocity are too large given that air drag would be expected to result in a modest reduction in the measured vertical acceleration. Looking at these results, 2 in/sec is a reasonable estimate of the expected precision of the velocity measurement in the typical case.

5.6. Rotation Rate Error Tolerance

The photogrammetry calculations can be compared with data from rotation rate sensors mounted to GTA. The GTA featured three sets of rotation rate sensors. Two were on the lid of the top access trunk, and one was on the backbone inside the pressure vessel. A complication in the use of the rotation rate sensor data is the uncertainty in how the data was zeroed prior to the start of the test. A comparison has been made for ST4. Figure 27 shows the pitch rate from the three rotation rate sensors. Because it features the least noise, the backbone rotation rate sensor is used for comparison to photogrammetry data. Figure 28 shows the rotation rate sensor data compared to the pitch rate from photogrammetry as determined based on the three different sets of targets. Despite the noise in the rotation rate sensor signal, it is evident that the rotation rate is increasing at a rate similar to the photogrammetric data.

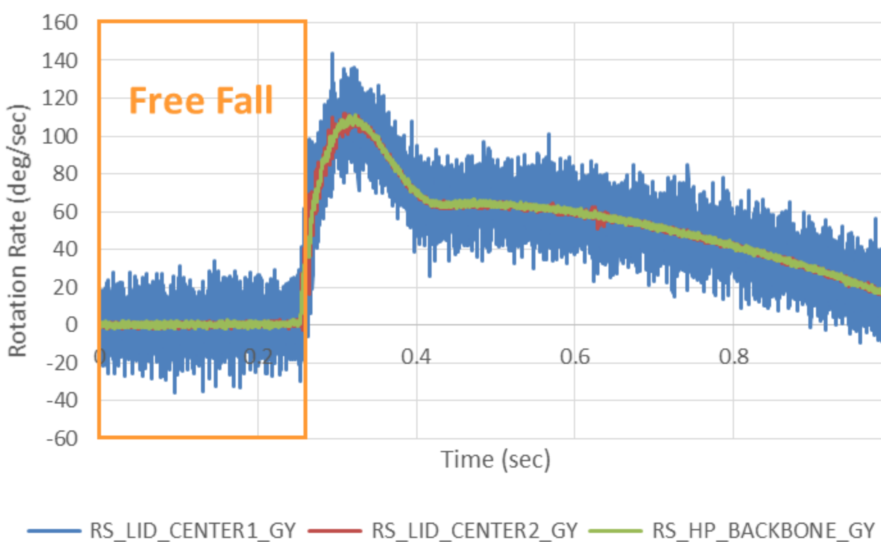


Figure 27. VT4 Rotation Rate Sensor Test Data for Pitch

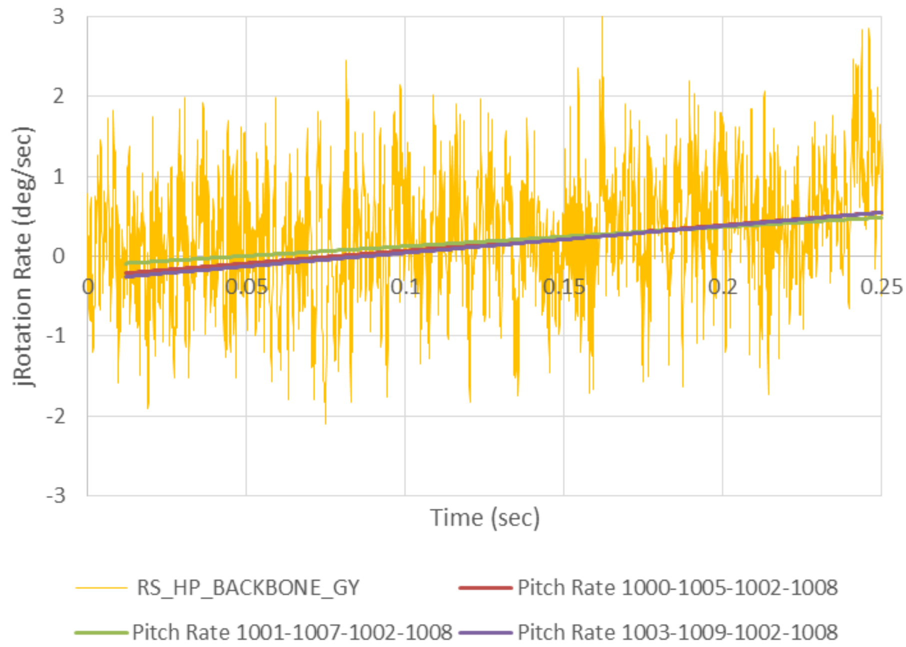


Figure 28. VT4 Rotation Rate Sensor Data and Photogrammetry Data for Pitch Rate

5.7. Yaw Angle and Lateral Velocity Error

The yaw angles, athwartship velocities, and pitch rates determined from the photogrammetry evaluation are listed in Table 32. The values are for the Target 1000-5-2-8 solution for angles and angular rates and Target 1006 solution for velocities. For ST9, the pitch angle is listed rather than the yaw angle. Ideally, these parameters should be zero, especially for the vertical drop tests. VT1 is the only test that shows a yaw angle greater than 2^{o} and the only test that shows an athwartship velocity greater than 6 in/sec. This could be real, or it could be an artifact of crosswind or slight misalignment of the background photogrammetry targets. The pitch rate should also be zero, especially for the vertical drop tests. For the swing test, pitch oscillation of the swing platform was known to occur along with a rotational impulse upon firing of the pyrotechnic bolts that released the GTA from the swing platform.

Table 32. Yaw Angle, Athwartship Velocity, and Pitch Rate Measurements

Test	Yaw (deg)	V_Y (in/sec)	Pitch Rate (deg/sec)
VT1	2.23	9.44	0.72
VT2	0.76	-0.91	3.52
VT3	0.45	0.05	1.01
VT4	0.46	1.04	0.55
ST5	-0.05	-0.02	1.98
ST6	0.07	2.89	2.19
ST7	NA	NA	-1.11
ST8	0.78	-2.03	2.48
ST9	0.82	-1.09	2.23
VT10	0.75	1.61	-0.16

6. Conclusions

The photogrammetry data offers several different possible solutions. This report provides four solutions for the angles and angular rates and velocities at each photogrammetry target for each test. At this writing, the solution used for GTA simulation impact conditions is based on Targets 1000, 1005, 1002, & 1008 for angles and angular rates and Target 1006 for velocities. The impact conditions computed from the photogrammetry data in the GTA Global Coordinate System are provided in Table 33. The angles follow the Orion convention in which the angles are about the global axes and are imposed in the order yaw, then pitch, then roll. The angles are not Euler angles.

Table 33. Impact Conditions in GTA Global Coordinate System

Test	Impact Time (s)	Target 1006 Velocities			Targets 1000, 1005, 2002, & 1008 Angles & Angular Rates						
		Vx (in/s)	Vy (in/s)	Vz (in/s)	Roll Angle (deg)	Pitch Angle (deg)	Yaw Angle (deg)	Ang. Rate (rad/s)	Ang. Rate Axis Nx	Ang. Rate Axis Ny	Ang. Rate Axis Nz
VT1	14.050	387.37	9.44	-1.91	1.20	-35.08	2.23	0.01676	-0.2653	0.7473	0.6092
VT2	38.988	401.62	-0.91	0.34	-6.24	-45.91	0.76	0.06373	0.1964	0.9645	-0.1765
VT3	49.382	387.44	0.05	-0.25	-3.19	-24.11	0.45	0.02028	-0.3247	0.8733	0.3631
VT4	57.383	381.29	1.04	-1.27	-1.44	-24.00	0.46	0.01206	-0.4688	0.8021	0.3701
ST5*	16.831	415.91	-0.02	-228.80	-0.92	26.50	-0.05	0.03736	-0.2913	0.9247	-0.2453
ST6	6.126	341.74	2.89	-448.50	-1.56	-18.51	0.07	0.04445	-0.5112	0.8588	0.0321
ST7	NA	499.64	0.00	-687.19	0.00	-43.76	0.00	0.01935	0.0000	-1.0000	0.0000
ST8	30.005	326.41	-2.03	-648.56	28.47	-43.51	0.78	0.08786	-0.5421	0.4934	0.6802
ST9**	23.800	372.87	-1.09	-280.87	0.43	0.82	-24.89	0.04217	0.1491	0.9227	0.3556
VT10	55.588	387.41	1.61	-1.03	-3.19	-16.16	0.75	0.01533	-0.4867	-0.1787	0.8551

* For ST5, a roll angle of 180 degrees is imposed before imposing the listed angles.
** For ST9, a roll angle of 90 degrees is imposed before imposing the listed angles.

The measurement precision tolerances are estimated as follows:

Distance: ~0.1 inches
Velocity: ~2 in/sec
Angle: ~0.3°

The above tolerances are based on evaluations of precision and do not take into account systematic errors that could affect accuracy by producing a bias in the measurements. The distance tolerance is a consequence of noise in the raw photogrammetry position data. The velocity tolerance is based on the deviation of the measured vertical acceleration from 1g. The angle tolerance is dominated by the precision of the alignment of the photogrammetry targets on the GTA. No tolerance has been determined for the rotation rates; however, the effect that rotation rate error has on the rotation angles is judged to be small based on the magnitude of the rotation rates and the time duration from impact to maximum response.

Acknowledgements

The authors would like to recognize the photogrammetry effort spearheaded by Justin Littell of NASA LaRC, which included arranging the photogrammetry staging and camera set-up, conducting the photogrammetry test operations, and processing the photogrammetry video data to obtain target position time histories. Also, the authors would like to recognize the leadership of James Corliss of the NASA Langley Research Center’s Atmospheric Flight and Entry Systems Branch (D205) in directing the test planning, test performance, simulation modeling, and test versus simulation correlation effort.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01/01/2018

2. REPORT TYPE
Contractor Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Orion Ground Test Article Water Impact Tests_Photogrammetric Evaluation of Impact Conditions

5a. CONTRACT NUMBER
NNL12AA09C

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Vassilakos, Gregory J.; Mark, Stephen D.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
747797.06.13.06.32.04.02

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, Virginia 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
STC Technical Report 3590

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-CR-2018-219801

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified
Subject Category 39
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES
Langley Technical Monitor: Robin C. Hardy

14. ABSTRACT
The Ground Test Article (GTA) is an early production version of the Orion Crew Module (CM). The structural design of the Orion CM is being developed based on LS-DYNA water landing simulations. As part of the process of confirming the accuracy of LS-DYNA water landing simulations, the GTA water impact test series was conducted at NASA Langley Research Center (LaRC) to gather data for comparison with simulations.The simulation of the GTA water impact tests requires the accurate determination of the impact conditions. To accomplish this, the GTA was outfitted with an array of photogrammetry targets. The photogrammetry system utilizes images from two cameras with a specialized tracking software to determine time histories for the 3-D coordinates of each target. The impact conditions can then be determined from the target location data.

15. SUBJECT TERMS
Ground test article; Impact; LS-DYNA; Landing; Orion; Water

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk(email help@sti.nasa.gov
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	53	(757) 864-9658