American Astronautical Society
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AAS 08-068

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31st ANNUAL AAS GUIDANCE AND CONTROL CONFERENCE

February 1-6, 2008
Breckenridge, Colorado

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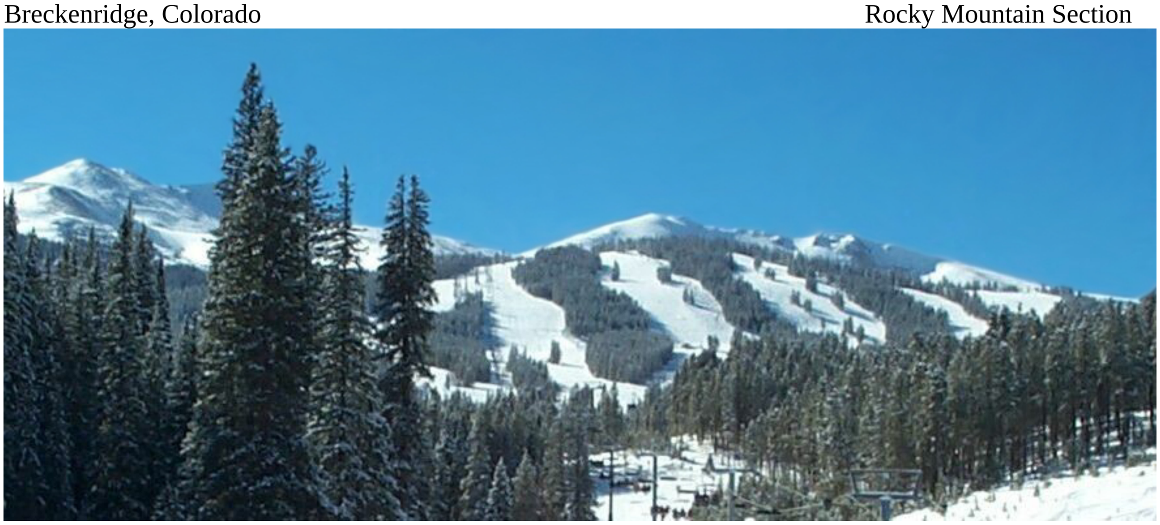
Rocky Mountain Section



AAS Publications Office, P.O. Box 28130 - San Diego, California 92198

CHALLENGES OF ROLL ORIENTATION WITH RESPECT TO VEHICLE HEADING AT TOUCHDOWN FOR THE ORION COMMAND MODULE

Robert S. Gay*   Brian D. Bihari†

Due to mass constraints, the Orion Command Module landing attention system requires that the capsule be oriented in a specific direction with respect to the horizontal surface-relative velocity (Heading) at touchdown in order to keep crew and vehicle loads within specifications. These constraints apply to both land and water landings. In fact, water landings are even more constrained with the addition of impact angle requirements necessary to slice through the water. There are two primary challenges with achieving this touchdown orientation: 1. Navigation knowledge of velocity (needed to determine Heading) with and without GPS, including the effects of the Heading angle itself becoming undefined as horizontal velocity decreases, and 2. Controlling to the desired orientation in the presences of chute torque and wind gusts that may change the Heading just prior to touchdown. This paper will discuss the design and performance of the current Orion navigation and control system used to achieve the desired orientation at touchdown.

INTRODUCTION

The Orion Command Module (CM) is essentially a scaled up Apollo Command Module. It has a base diameter of approximately sixteen and one half feet (16.5 ft) or five and one half meters (5.5m); where Apollo was approximately twelve and five sixths feet (12.8 ft) or approximately four and one quarter meters (4.2). They share the same outer mold line (slope of sides 32.50 degrees). This increase in size will allow for a total crew complement of up to six (6) astronauts for International Space Station (ISS) missions and up to four (4) for Lunar missions. It is an enclosed capsule with a parachute system to control descent rate in the terminal touchdown phase. The Orion Command Module provides a safe and comfortable environment for human habitation and for cargo transfer. These functions include a pressurized volume, crew interaction and support systems, systems required to autonomously dock to Constellation elements, and reentry systems, including parachutes, retro-rockets, and thermal protection. The CM is easily reconfigurable for the three Design Reference Missions, and allows additional cargo to be carried to ISS when fewer crewmembers are flown.[1] The parachute system currently incorporates a set of two (2) drogue chutes, three (3) pilot chutes (to pull out the mains) and three (3) main chutes. The mass properties and Reaction Control System (RCS) used for the analysis presented in this paper are based on the most recent design cycle release: LM606C. The approximate mass of the CM under the main chutes is a little over 18,300 lbm (8300 kg). The Command Module reaction control system (RCS) consists of 2 strings. Each string has 6 thrusters, 2 for yaw control, 2 for roll control, and 2 for pitch control. Nominally only one string will be used at a time.

Originally, the CM was to target land landings on the continental United States (CONUS), but recent weight reduction activities have changed this to targeting US coastal waters as the primary target with land landings in contingency situations only (e.g. Pad Aborts that are blown back onto land by winds on the parachute system). These same weight reduction activities have currently produced a CM vehicle that must be properly oriented with respect to the direction of travel (Heading) at touchdown (for water and land landings). The need for this Heading orientation is driven by structural and crew loading limitations. This study with analyze the capability of the current Orion CM design to achieve the desired orientation at touchdown. Results from this analysis will be used to validate or modify the existing requirement of 30 degrees allowable pointing error for horizontal velocities greater than 10 ft/s. Horizontal velocities less than or equal to 10 ft/s do not require a specific orientation.[2]

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ROLL CONTROL OVERVIEW

Orion Command Module Definitions

The Orion CM body frame coordinate system and associated Euler angle rotations are described below in Figure 1. In order for the CM to slice through the water at touchdown, a "hang angle" is produced by the parachute attachment configuration. A description of this angle is shown in Figure 2.

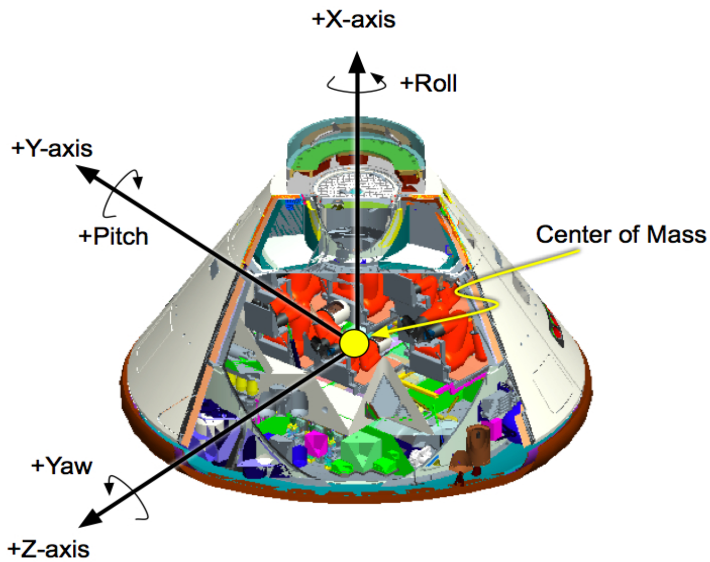


Figure 1 Orion GN&C Body Coordinate System and definition of Euler Angles17[3]

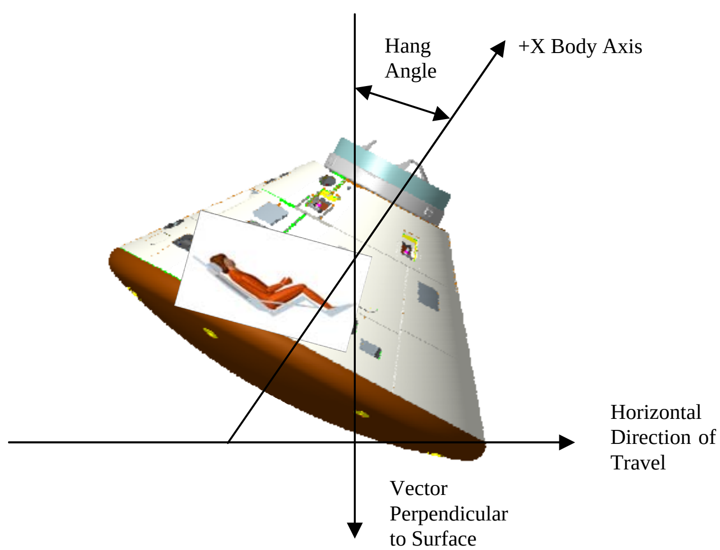


Figure 2 Hang Angle Definition

Why is Roll Control Needed

For water landings the ability to control the roll attitude at impact is necessary to reduce the loads on the vehicle and crew. This is accomplished by impacting the water with a hang angle (currently designing to 28 degrees toes down) and going in the direction of the wind and thus the waves. The hang angle is necessary to achieve a non-zero impact angle (hang angle + wave angle) to allow the vehicle to slice through the water reducing impact loads. No roll control can result in lower relative impact angles which, if coupled with increased normal velocity, will significantly increase X-loads.[4] Figure 3 shows the various combinations of impact angle and normal velocities encountered with and without roll control. Figure 4 describes the vehicle capability for water landing with respect to crew loads. The plot shows the allowable horizontal velocity given the orientation of the vehicle with respect to the direction of travel (Heading).

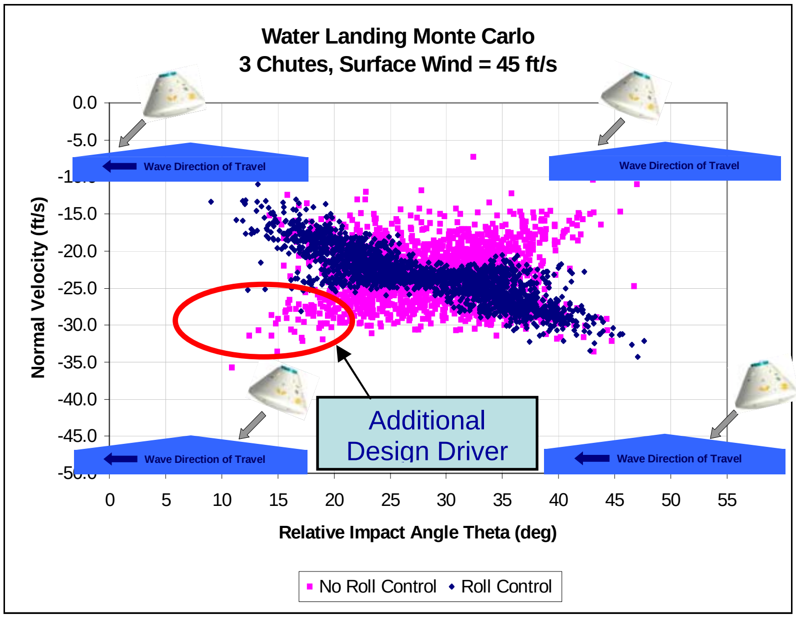


Figure 3 Water-Landing Normal Velocity vs. Impact Angle with and without Roll Control.[4]

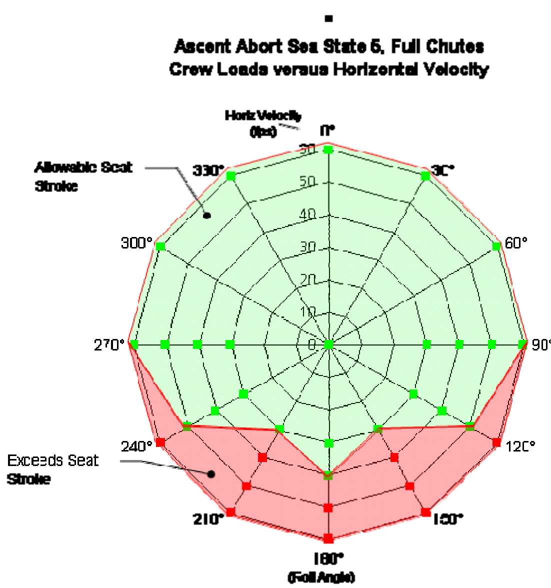


Figure 4 Orion CM Water-Landing Crew Loads Capability.[4]

For land landing (currently only a contingency situation) it was found that for non-zero hang angles, the capsule shape had the propensity to tumble over once the ground was impacted if the vehicle was not pointed in the general direction of motion. Additionally, crew and structural limits require that the vehicle be pointed in the direction of motion. Apollo had similar issues as well. Apollo testing with regard to roll control is summarized by the following text and Figures 5 and 6:

> "Landings with the spacecraft at a roll orientation of 180 degrees were the most unstable and tumbled the vehicle, producing multiple impacts. Higher horizontal velocities produced more violent impacts. The damage to spacecraft structures was extensive and included compartment sidewall cracks and debonding of secondary equipment. However, at horizontal velocities less than 40 fps, the crew has an excellent chance for survival. Potential hazards to the crew were the possible rupture of the fuel and oxidizer tanks and the high accelerations recorded at the crew-couch system. In general, however, the Apollo command module and associated components withstood severe landings better than had been expected." [5]

> "Apollo did not perform a lateral orientation near touchdown. After we (Apollo) went to the heavier Block II configuration, our simulations showed a fairly high percentage of our pad abort cases would drift back on to the beach. (See Figure 8 for impact testing on land) The project removed all the vegetation from the beach area and plowed the beach to make it softer. The program did have a project that performed a design study that would have oriented the capsule prior to impact using a mechanical device in the chute mortar area. The device was in a canister and a gear system rotated the capsule about the main chute risers to the desired orientation."[6]

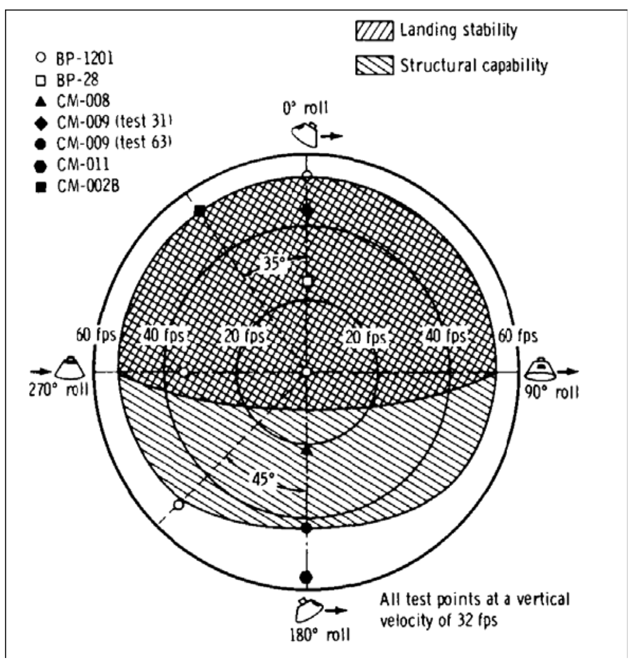


Figure 5 Apollo Land-Landing Capability as a Function of Roll Angle. [5]

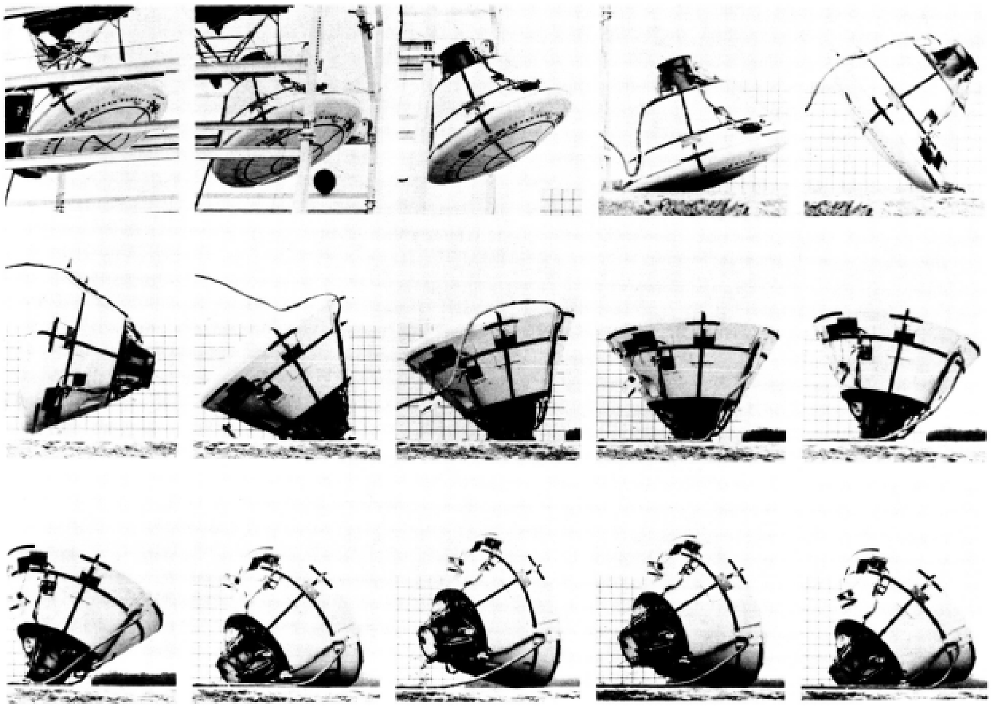


Figure 6 Apollo Testing: Landing Dynamics of CM-008 During Test 28. (Roll 180 deg, Pitch 27.5 deg, Horiz Vel = 25ft/s) [5]

Active vs. Passive

Active control of the vehicle roll is currently being accomplished by the use of the Reaction Control System (RCS) roll jets. This system is being sized to allow for adequate control of the vehicle under the main parachutes to within the boundaries set forth in the design requirement documents and is part of this investigation. Recent changes in the type of propellant being proposed from GO_2/GCH_4 to a Mono-propellant: Anhydrous-Hydrazine (H_2N_4) have raised questions about its impacts on the parachutes and its riser lines. An investigation is under way to examine these affects and determine if the Hydrazine should be used during this phase of flight. This has also resulted in an investigation of alternative active and passive control systems as well as vehicle designs that do not need to be oriented prior to touchdown / surface impact.

Alternate active systems being evaluated include: Steerable parachutes (e.g. parafoils, steerable clusters, etc.), solid propellant roll control system, active aero surfaces, and mechanical devices (e.g. Apollo-style flowerpot). Passive control is being investigated as a means to remove the threat of Hydrazine on both the parachute system and landing with a toxic substance in the tanks. The potential passive systems include but are not limited to the following [4]:

1. A deployable tethered anchor. Deployed panel/structure may provide drag in water/land, and upon tensioning of tether, orient the vehicle in the proper direction. For water landing, deploy part of backshell that is tethered to vehicle (currently need heat shield to protect pressure shell from water impact). For land landing, could tether heat shield to vehicle.
2. Deploy aero surface into vertical air stream. Aero surface could be an inflatable or section of CM outer mold line. Uses vertical velocity to provide drag and orient the vehicle.
3. Selectively cutting suspension lines, or cutting canopy surfaces. Changes drag surface, adds horizontal velocity. Sensing is necessary to cut the “right” lines. May need to remove confluence

fitting – partly acts as swivel. Unable to revert to original state, or modify (re-attach) drag surface if necessary.

The analysis performed in preparation of the paper assumes that the RCS will be used as an active controller in its current format and does not consider the impacts of the propellant on the parachute system.

Why is it Challenging

Along with actually achieving the desired orientation as addressed above, there are several issues that make roll control difficult. First of all, determining the Heading angle is dependent on navigated planet-relative velocity and attitude. Assuming the gyros are performing nominally (there will be at least three on board), the navigated attitude will not be a problem, but the horizontal velocity required for Heading can be an issue, especially at low speeds. The Heading angle is determined by knowing the individual components of the planet-relative velocity vector. As the magnitude of the vector decreases, the percentage of error in the components with respect to the magnitude increases. This is true with or without GPS availability. Furthermore, the Heading angle itself becomes undefined as the magnitude of the horizontal velocity goes to zero. Thus, the smaller the horizontal velocity magnitude is, the more problematic it is to determine the Heading. This would seem beneficial, since lower velocities will produce smaller loads, but depending on vehicle capability, even low velocities with no roll control can be detrimental. Analysis done for this paper will help shape the vehicle requirements.

In addition to problems with determining the Heading angle, wind shifts near touchdown could potentially change the Heading too late for the controller to alter course. This and errors in navigated altitude, make commanding logic for roll control more complicated (i.e when to start and how big does the horizontal velocity have to be before control is activated). Obviously, the vehicle must be able to sustain an impact in any orientation with horizontal velocity within some limit. This study will attempt to establish what the Guidance, Navigation, and Control (GNC) system can accomplish, so that the proper requirements are levied on the Landing and Recovery Systems (LRS) system for crew and structural safety.

KEY SIMULATION MODELS AND PARAMETERS

Simulation Background

The Advanced NASA Technology Architecture for Exploration Studies (ANTARES) [7] simulation was used to conduct the analysis for this report. ANTARES is NASA's primary 6-DOF simulation for Project Orion. This simulation contains the JSC Engineering Orbital Dynamics Package [8] (JEOD) as well as fully integrated prototype Guidance, Navigation, and Control (GNC) flight software and related sensor models. ANTARES has been designed to support a wide variety of requirements assessments, design trades, and operator in the loop evaluations. Much of ANTARES is based on a Common Model Library (CML) architecture, which leverages off the significant simulation development conducted by several organizations across JSC, including the Aeroscience and Flight Mechanics Division (A&FMD), the Automation, Robotics and Simulation Division (ER) and the Mission Operations Directorate (MOD). Additionally, users at other centers working on Constellation tasks are utilizing and enhancing the ANTARES simulation.

Entry Navigation

The Orion entry navigation filter is still under development. The final number of states and measurement types are yet to be determined. Honeywell and NASA are working collaboratively on the final design. Thus, the NASA prototype absolute filter in ANTARES was used for the analysis in this study. The filter is relatively simple with just the essential states: inertial position, inertial velocity, and inertial attitude error (9 states total). The attitude error is modeled as Modified Rodriguez Parameters (MRP). Measurements include GPS position and velocity and barometric altitude. The GPS measurements are computed using a simple truth plus error model and the barometric altitude is generated by converting a pressure measurement to a geodetic altitude via a curve-fit of the Standard 76 atmosphere model. The barometric measurements are only available below 120,000 feet. GPS measurements are generally available except during plasma blackout. A model using curve-fits of Computational Fluid Dynamics (CFD) data determines if the electron density is high enough to attenuate the GPS frequency. GPS measurements may also be prohibited throughout the trajectory if desire to analyze contingency performance. The filter states are propagated with a forth order Runge Kutta integrator using a 2x2 gravity model and IMU accelerometer and gyro data. See reference 9 for more details on the NASA prototype absolute filter and sensor models.

Entry Guidance

The Orion Command Module uses PredGuid skip entry guidance to fly ranges much further than Apollo. This allows the CM to achieve US coastal waters for all possible “anytime” return trajectories from the Moon. PredGuid combines the Apollo entry guidance algorithm with a modified version of the numerical predictor-corrector developed for the Aero-assist Flight Experiment aerocapture fight program. Specifically, PredGuid replaces the Down Control, Up Control, and Kepler phases of the Apollo guidance algorithm with a numerical predictor-corrector. After vehicle velocity has reached subsonic speeds, PredGuid employs a simple terminal guidance scheme to steer out the remaining crossrange error.[10]

Touchdown Roll Control Command Logic

When to Enable Control. A major player in the challenge of roll orientation is in knowing when to start the maneuver. The floor or minimum altitude to start the orientation is dictated by the worst case angle of rotation, 180 deg, the max descent rate of the vehicle which assumes one of the main chutes to have a failure, 35 ft/s (11.5 m/s), and the rate at which the control system can rotate the vehicle (variable depending on jet size and commanded control deadbands).

Example: If the vehicle can achieve a 7 deg/s rotation rate, then the following would be the minimum starting altitude:

180 (deg) / 7 (deg/sec) * 35 (ft/sec) = 900 ft (295 m)

The CEV team selected an initial starting altitude of 1500 ft to allow for margin in control system performance and changes to the rotation rate. This study examined values up to 2300 ft to account for dispersions and navigation errors. Every increase in altitude allows for extended time to orient the vehicle but at the cost of extra propellant to maintain the heading once it is achieved. A current propellant budget of 40 lbm is being book-kept for this maneuver.

When to Activate Control. Additional control command logic was added to only activate the controller if the magnitude of the horizontal velocity was greater than some specified value. Furthermore, once the controller has been activated, even if the horizontal velocity falls below the given threshold, the last valid command will be used. If the horizontal velocity then increases beyond the threshold, a new command will be computed based on the current Heading. So long as the horizontal velocity remains above the threshold, the command orientation will be cyclically updated.

Touchdown Roll Controller Design

Various control system algorithms/schemes for active control using the RCS jets were considered. Since the original focus of the team was to look at land landings and the vehicle was to have a zero degree hang angle (and airbags), the roll jets were the only jets deemed necessary to perform the roll maneuver. Two control algorithms were examined; the first developed by Zach Putnam (Draper Labs) (See Figure 7)[11], and the second by Roger Wacker and Greg Loe of Honeywell (See Figure 8).[12] The second proved to have performed better and was thus selected for continued efforts. Various attitude, rate and maneuver deadbands were examined before the final values were selected.

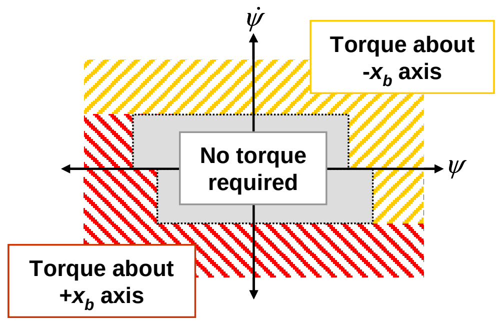
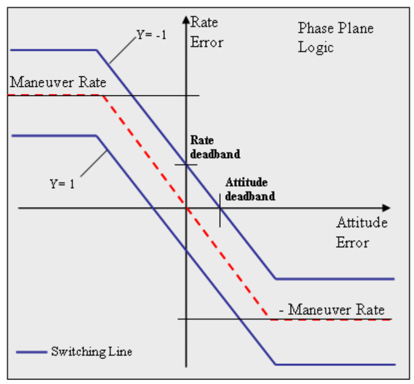


Figure 7 Original ANTARES RCS roll jet thrusting logic in the phase plane. [11]



Attitude Deadband =2.0 deg
Maneuver Rate = 7.0 deg/sec

Figure 8 Honeywell Roll Control Phase Plane Diagram. [12]

With the change to primary landings being in the water and thus the requirement to land with a hang angle to "knife into" the water instead of "belly flop", a control concept of adding in yaw jets to compliment the roll jets was considered. The first step was to see if the land landing concept would work for various hang angles before adding complexity to algorithm. Initial results and analysis (done with LM606B vehicle) showed that there was little degradation in performance (roll orientation) when using the roll jets only so the concept of supplementing them with the yaw jets has not been further examined. However, results from this analysis, which used updated vehicle properties and jet configuration, do show degradation in performance for a 28 degree hang angle. More details on this are given in the results and conclusion sections.

Parachute

The CEV Parachute Assembly System (CPAS) team is responsible for providing the LRS team data on parachute performance. The CPAS team is currently testing "Gen-1" parachutes in drop tests at the Yuma test grounds in New Mexico. They are conducting a series of tests to obtain flight like performance numbers and improve the system design. This results in changes to the parachute system and modeling of that system. The LRS team is then responsible to provide an accurate math model or equations to be used in simulating the chute behavior. A high fidelity 12 degree of freedom (DOF) parachute simulation which uses two 6-DOF Bodies (chute, vehicle), elastic coupling between parachute and vehicle, with slings modeled as off-body riser attach point called the "Decelerator System Simulation (DSS)"[13] is used as a stand alone tool for chute modeling and vehicle attitudes at touchdown/splashdown. DSS is then verified and tuned verses drop test (flight) data. Figure 9 shows how dynamic the parachutes can be in the real world; and illuminates the difficulties in attempting to model this behavior in a simulation.

While the DSS simulation models chute dynamics in a sophisticated manner, it does not contain a high fidelity navigation model or the ability to fly outside the chute box. For integrated systems and trajectories the ANTARES 6-DOF simulation is used and thus a simplified parachute model is desired. The high fidelity modeling in DSS could be replicated in ANTARES, but time and resource constraints prohibited this option. Thus, the ANTARES simulation chute model was adapted from a combination of the Space Shuttle drag chute model, DSS equations, and Apollo drogue chute damping equations.[14] Detailed comparisons between the simplified ANTARES model and the high fidelity DSS simulation showed good matches and thus allow analysis to proceed with the ANTARES implementation.

One of the major effects on the roll orientation provided by the parachute is the twist torque in the chute lines and its impact on the command module. This model is based on testing provide by the CPAS team. Data from this testing is shown in Figure 10. The model implemented in ANTARES is currently turned on when the Main Chute generates forces on the CM. Additionally 75 ft/lb per 360 degrees twist angle was added after the end of the table data since no data was generated for this regime for the No Keeper case. See Figure 11 for a depiction of the "Keeper" and "No Keeper" configuration. The use of a Keeper reduces twist torque substantially, but also adds complexity and increased risk of line abrasion/breaking.

Figure 9 Main Parachute Drop Test [15]

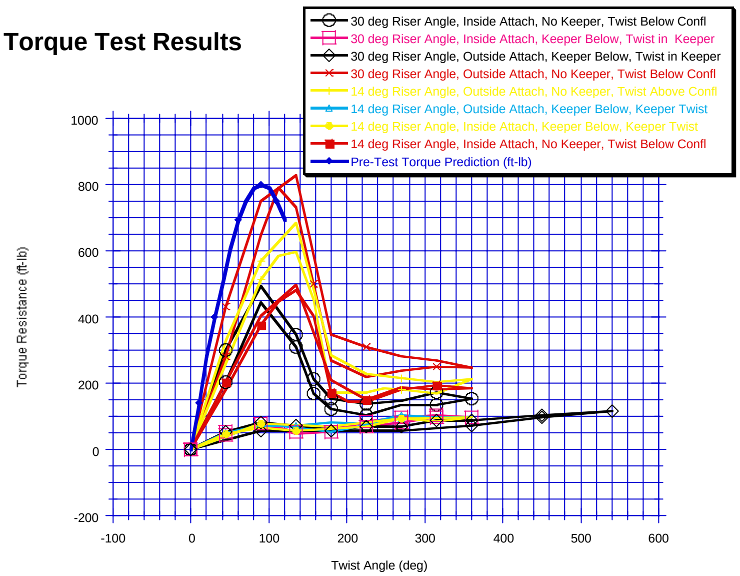


Figure 10 CEV Main Chute Torque Test Results [16]

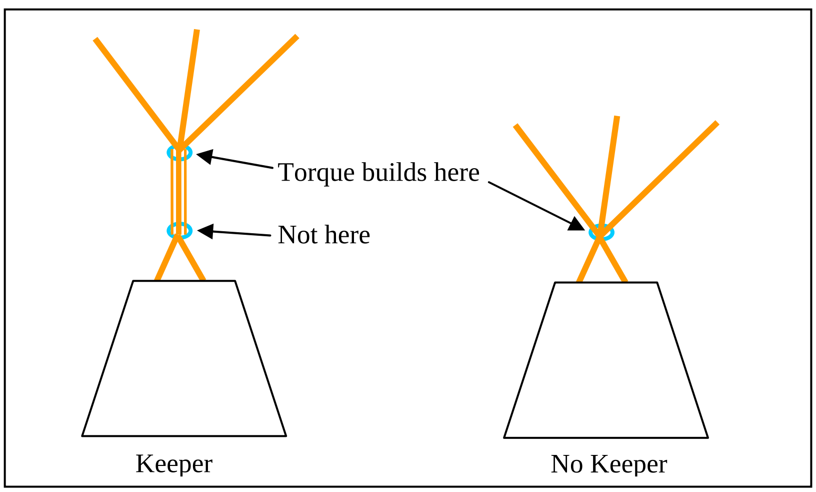


Figure 11 Keeper vs. No Keeper

Atmosphere Model

The Earth environment (pressure, density, temperature) and winds used in the ANTARES simulation is from the Global Reference Atmosphere Model (GRAM) provided by NASA / Marshall Space Flight Center. Current requirements for the Orion vehicle, dictate that this model be used for all analysis. The GRAM model was recently updated (November 2007) from GRAM 1999 Version 3 to GRAM 2007. The new version of GRAM 2007 is being used for this analysis. For a complete rundown of GRAM see Reference 17. To properly use the GRAM model it should not be called more often then it takes the body that the atmosphere is affecting to translate one body length. Calling it more often can result in high frequency noise that may affect results. The winds play a major roll in the ability of the vehicle to control its attitude near touchdown and thus this model and its correct implementation are critical to this analysis.

Aerodynamics

The aerodynamics model in ANTARES uses the official CEV Aerodynamics Panel (CAP) delivery (Version 0.33). The delivery includes the aerodynamic coefficients along with interpolation routines.[18]

RCS System

Assuming that the RCS system is being actively used (main assumption of the paper) to control the vehicle orientation, its main contributors are the amount of torque that can be applied and the direction of that torque. The torque is affected by the type of propellant, size of the jets, orientation of the jets, number of jets and degradation of thrust due to altitude affects[19]. The lag between when the flight control system (FCS) decides to fire a jet and how fast the RCS jets react to that command are important aspects. The minimum on and off times of the jets are also important. RCS build up and tailoff/decay were considered secondary affects and not modeled for this study.

Mass Properties

The Orion Command Module is more then twice as heavy as the Apollo capsule and has significantly greater Moments and Products of Inertia. The larger mass and inertias make the vehicle a lot harder for the control system to compensate for them than on Apollo given that the jet thrust may be at the same level. The center of gravity is controlled via packaging and ballast (if necessary) to provide a reasonable Lift over Drag, currently targeting 0.27 with ranges between 0.25 and 0.35.

ANALYSIS

The current requirement for roll control at touchdown is 30 degrees for horizontal velocities between 10 and 40 ft/s (Ref 2). The analysis in this study will help validate and/or adjust this requirement. Due to the navigation issues at slow speeds, it is likely that the 30 degree requirement should be adjusted with variation in horizontal velocity; i.e. 30 degrees at 40 ft/s, and some larger number at 10 ft/s. The progression between 10 and 40 ft/s is to be determined. Since only velocities greater than 10 ft/s require active orientation of the vehicle, all statistics shown in this report only include runs where the horizontal velocity at touchdown was greater than 10 ft/s. All Monte Carlo sets include a total of 1000 runs with dispersions on all appropriate GNC-related parameters.

Since there are several parameters to vary, a systematic parametric Monte Carlo approach was employed. In other words, a few variables were adjusted, while others were held constant. The intent of this approach was to determine the sensitivities of each of the parameters so that appropriate values could be chosen for the next round of analysis. Thus, the following sections will describe the various Monte Carlo parametric studies and summarize their results.

Reference Trajectory Description

A long range skip entry to US coastal waters (near San Clemente, CA) was chosen as the reference trajectory for all analysis in this study. Specifics on Entry Interface (EI) conditions and targeted landing site are listed below, and Figure 12 shows the ground track. This trajectory heads due north coming from the South Pole and landing off the coast of California.[20]

EI-1 Long range polar: 4800 nmi

Geodetic Latitude	= -46.66992 deg
Longitude	= -115.50 deg
Inertial azimuth	= 0.0 deg
Inertial topocentric flight-path	= -5.90 deg

Target: San Clemente Island (~100 nmi west of island)

Target Geodetic Latitude	= 32.75 deg
Target Longitude	= -120.750 deg

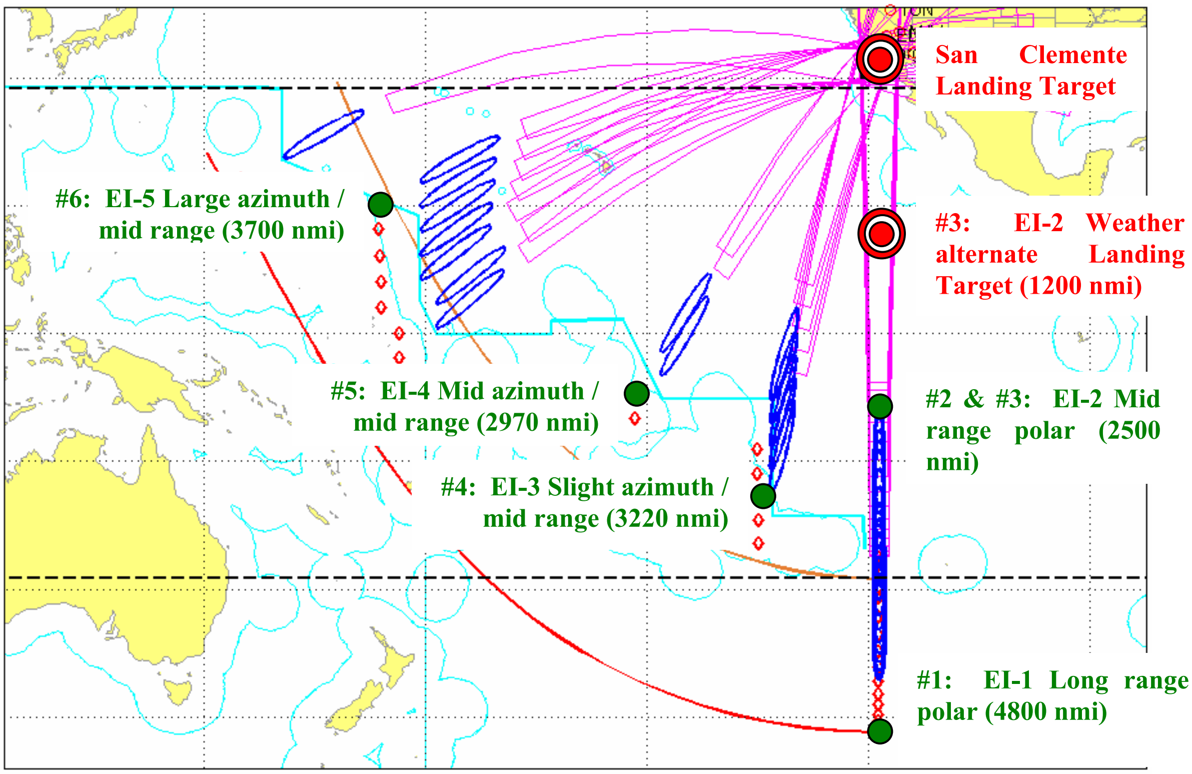


Figure 12 Reference Entry Trajectories for Orion DAC2 CM Vehicle [20]

Velocity Triggers and GPS Velocity Usage During Roll Control

The first two parameters examined were velocity trigger thresholds and the use of GPS velocity measurements during roll control. Recall that once control is enabled (at 2300 ft altitude in this case), it is only activated if the horizontal velocity is above a give threshold. To test performance, three different thresholds were studied: 5, 7, and 10 ft/s. Another variation considered was the usage of GPS velocity measurements during roll control. The idea was to test controllability with a good, but possibly noisy Heading estimate verses a smooth, but less accurate Heading estimated with IMU propagation and GPS position-only update. Furthermore, the nominal GPS errors during the entire entry were also scaled by a factor of three to see if GPS accuracy would have much of an effect. Finally, the parameters held constant for this analysis were: 160lb jets used; No-Keeper on the parachute lines; 28 degree hang angle; and roll control enabled at 2300 ft geodetic altitude above surface level. Table 1 contains a summary of the results.

Table 1
VELOCITY TRIGGERS AND NO GPS VEL DURRING ROLL CONTROL
(GPS On, 160lb Jets, No-Keeper, 28 deg H.A., 2300 ft control start altitude)

Case Description	Total Roll wrt Heading Err		Nav Roll wrt Heading Error		Control Roll wrt Heading Error		Propellant Usage	
	Max	μ+3sig	Max	μ+3sig	Max	μ+3sig	Max	μ+3sig
gps1sig_5_gpsvel	121.39	23.00	3.38	2.46	120.10	24.40	77.03	63.06
gps1sig_5_nogpsvel	121.28	24.23	10.05	6.62	119.80	24.94	77.03	62.95
gps1sig_7_gpsvel	121.39	23.05	3.38	2.46	120.10	24.47	77.03	62.53
gps1sig_10_gpsvel	156.58	31.34	3.50	2.47	156.21	32.09	77.03	62.27

gps3sig_5_gpsvel	**72.26**	**24.60**	**5.94**	**4.56**	**73.59**	**26.03**	**89.10**	**68.98**
gps3sig_5_nogpsvel	**70.20**	**25.16**	**13.54**	**8.33**	**72.08**	**25.74**	**89.16**	**68.87**
gps3sig_7_gpsvel	**89.47**	**24.99**	**5.94**	**4.55**	**90.91**	**26.39**	**89.10**	**68.54**
gps3sig_10_gpsvel	**142.49**	**29.31**	**5.94**	**4.60**	**140.89**	**29.52**	**89.10**	**67.91**

It is clear that the velocity triggers less than 10 ft/s performed better. Activating control prior to reaching the "critical" velocity (10 ft/s) definitely produced better results. It is also clear that prohibiting GPS velocity measurements during roll control only increased Heading error, while providing no noticeable control improvements. In addition, the increase in GPS errors had little effect. Another noticeable fact is that the maximum values for all parameters except navigation were not consistent with the mean+3sigma values. This inconsistency is due to fact that a handful of outliers exists for each case. These outliers are clearly visible in the plots shown in Appendix A. Analysis of these outliers will be the focus of future work.

Velocity Triggers with No GPS

The second round of analysis focused on testing the velocity trigger thresholds if GPS was not available. The same set of constant parameters was used as for the first round of test cases. Table 2 contains the results of this analysis. Because the navigation error in horizontal velocity is over 20 ft/s, the results of varying the velocity trigger thresholds (all of which are well below 20 ft/s) are somewhat mixed and do not tell the same story as if GPS is available. These runs do however provide information on overall performance when is not available. Clearly there as some outliers, but most of the pointing errors are below 70 degrees with only a handful of runs above 90 degrees; and all errors are below 30 degrees near the 40 ft/s limit.

Table 2
VELOCITY TRIGGERS WITH NO GPS
(160lb Jets, No-Keeper, 28 deg H.A., 2300 ft control start altitude)

Case Description	Total Roll wrt Heading Err		Nav Roll wrt Heading Error		Control Roll wrt Heading Error		Propellant Usage	
	Max	μ+3sig	Max	μ+3sig	Max	μ+3sig	Max	μ+3sig
gpsOff_5fps_trigger	**169.34**	**64.98**	**150.78**	**47.14**	**169.66**	**41.17**	**72.05**	**64.16**
gpsOff_7fps_trigger	**168.76**	**63.41**	**150.95**	**47.51**	**164.47**	**39.39**	**72.05**	**63.90**
gpsOff_10fps_trigger	**172.68**	**67.23**	**126.75**	**46.03**	**163.94**	**37.45**	**69.99**	**64.50**

160lb and 100lb Jets with and without a Keeper

The third round of analysis focused on the performance of 160lb jets verses 100lb jets with and without a Keeper on the parachute lines. Given the results of round one, the velocity trigger was chosen to be 5 ft/s. The starting altitude for roll control remained at 2300 ft. Variation in GPS availability as well as hang angle were also tested. Tables 3, 4, 5, and 6 summarize the results.

Table 3
160lb JETS WITH NO-KEEPER
(5ft/s velocity trigger, 2300 ft control start altitude)

Case Description	Total Roll wrt Heading Err		Nav Roll wrt Heading Error		Control Roll wrt Heading Error		Propellant Usage	
	Max	μ+3sig	Max	μ+3sig	Max	μ+3sig	Max	μ+3sig
gpsOn_0_hang_ang	**33.65**	**14.36**	**3.24**	**2.42**	**32.04**	**16.62**	**64.58**	**57.82**
gpsOn_28_hang_ang	**145.51**	**35.88**	**3.89**	**2.52**	**145.28**	**35.52**	**70.39**	**66.55**
gpsOff_0_hang_ang	**142.01**	**56.93**	**121.16**	**48.29**	**92.36**	**20.85**	**70.69**	**60.68**

gpsOff_28_hang_ang	**134.50**	**64.15**	**117.24**	**48.53**	**152.68**	**37.40**	**79.61**	**68.19**

Table 4
160lb JETS WITH KEEPER
(5ft/s velocity trigger, 2300 ft control start altitude)

Case Description	**Total Roll wrt Heading Err**		**Nav Roll wrt Heading Error**		**Control Roll wrt Heading Error**		**Propellant Usage**	
	Max	**μ+3sig**	**Max**	**μ+3sig**	**Max**	**μ+3sig**	**Max**	**μ+3sig**
gpsOn_0_hang_ang	**21.61**	**12.78**	**3.27**	**2.37**	**21.26**	**14.43**	**47.41**	**35.58**
gpsOn_28_hang_ang	**25.41**	**13.40**	**3.87**	**2.47**	**25.02**	**15.20**	**47.47**	**39.19**
gpsOff_0_hang_ang	**145.68**	**57.32**	**124.22**	**48.91**	**88.98**	**21.56**	**37.54**	**34.94**
gpsOff_28_hang_ang	**145.24**	**57.48**	**125.08**	**49.32**	**64.74**	**18.83**	**43.72**	**39.55**

Table 5
100lb JETS WITH NO-KEEPER
(5ft/s velocity trigger, 2300 ft control start altitude)

Case Description	**Total Roll wrt Heading Err**		**Nav Roll wrt Heading Error**		**Control Roll wrt Heading Error**		**Propellant Usage**	
	Max	**μ+3sig**	**Max**	**μ+3sig**	**Max**	**μ+3sig**	**Max**	**μ+3sig**
gpsOn_0_hang_ang	**169.11**	**104.40**	**3.09**	**2.38**	**169.18**	**101.81**	**47.39**	**48.23**
gpsOn_28_hang_ang	**172.71**	**137.63**	**3.12**	**2.38**	**172.54**	**136.55**	**48.78**	**49.45**
gpsOff_0_hang_ang	**171.75**	**109.14**	**107.83**	**45.95**	**166.20**	**97.08**	**51.98**	**49.36**
gpsOff_28_hang_ang	**175.08**	**151.34**	**108.10**	**47.22**	**179.15**	**146.12**	**48.49**	**49.76**

Table 6
100lb JETS WITH KEEPER
(5ft/s velocity trigger, 2300 ft control start altitude)

Case Description	**Total Roll wrt Heading Err**		**Nav Roll wrt Heading Error**		**Control Roll wrt Heading Error**		**Propellant Usage**	
	Max	**μ+3sig**	**Max**	**μ+3sig**	**Max**	**μ+3sig**	**Max**	**μ+3sig**
gpsOn_0_hang_ang	**30.57**	**15.01**	**3.09**	**2.37**	**30.71**	**16.23**	**34.67**	**31.53**
gpsOn_28_hang_ang	**29.14**	**15.15**	**3.08**	**2.38**	**32.14**	**16.59**	**34.85**	**33.92**
gpsOff_0_hang_ang	**160.75**	**54.85**	**101.17**	**45.95**	**127.51**	**24.37**	**32.01**	**30.46**
gpsOff_28_hang_ang	**157.65**	**55.73**	**110.89**	**47.21**	**123.20**	**25.98**	**33.61**	**33.43**

Observations from the third round of analysis are as follows:

- Outliers continued to skew maximum parameters with respect to mean+3sigma values.
- If GPS is available, control performance dominates the total roll with respect to Heading error. If GPS is not available, navigation errors dominate performance except for the No-Keeper scenario where several cases had large control errors as well.
- Control performance is diminished with 28 degree hang angle compared to a 0 degree hang angle if no Keeper is used.
- Adding a Keeper to the parachute lines greatly improves control performance and significantly reduces propellant usage.
- A Keeper must be used for 100lb jets (at least for the gains used in the twist torque model for this analysis). Without a Keeper, the 100lb jets do not have enough control authority over the parachute twist torque.

Control Start Altitude and Velocity Triggers

The forth round of analysis sought to examine the effects of varying the altitude at which roll control was enabled. For completeness, a few velocity triggers were also tested with this new parameter variation. Given the results of round three, 160lb jets were test with and without a Keeper, while 100lb jets were only tested with a Keeper. Tables 7, 8, and 9 contain a summary of the results.

Table 7
CONTROL START ALTITUDE AND VELOCITY TRIGGERS
(GPS On, 160lb Jets, No-Keeper, 28 deg H.A.)

Case Description	Total Roll wrt Heading Err		Nav Roll wrt Heading Error		Control Roll wrt Heading Error		Propellant Usage	
	Max	μ+3sig	Max	μ+3sig	Max	μ+3sig	Max	μ+3sig
5fps_2300ft_start	145.51	35.88	3.89	2.52	145.28	35.52	70.39	66.55
8fps_2300ft_start	145.51	35.64	3.89	2.52	145.28	35.21	70.39	65.89
10fps_2300ft_start	145.51	34.37	3.89	2.49	145.28	34.15	70.39	65.61
5fps_1500ft_start	148.00	41.12	3.89	2.46	148.08	40.37	44.85	44.72
8fps_1500ft_start	148.00	41.07	3.89	2.46	148.08	40.27	44.85	44.65
10fps_1500ft_start	148.00	41.96	3.89	2.46	148.08	41.08	44.85	44.52

Table 8
CONTROL START ALTITUDE AND VELOCITY TRIGGERS
(GPS On, 160lb Jets, Keeper, 28 deg H.A.)

Case Description	Total Roll wrt Heading Err		Nav Roll wrt Heading Error		Control Roll wrt Heading Error		Propellant Usage	
	Max	μ+3sig	Max	μ+3sig	Max	μ+3sig	Max	μ+3sig
5fps_2300ft_start	25.41	13.40	3.87	2.47	25.02	15.20	47.47	39.19
8fps_2300ft_start	25.41	13.41	3.87	2.46	25.02	15.21	47.14	38.54
10fps_2300ft_start	41.17	14.48	3.87	2.47	38.63	15.97	41.11	37.86
5fps_1500ft_start	23.91	13.64	3.85	2.47	23.52	16.14	33.07	29.97
8fps_1500ft_start	23.91	13.53	3.85	2.47	23.52	16.06	31.01	29.54
10fps_1500ft_start	43.05	14.66	3.85	2.48	40.50	16.83	29.58	29.28

Table 9
CONTROL START ALTITUDE AND VELOCITY TRIGGERS
(GPS On, 100lb Jets, Keeper, 28 deg H.A.)

Case Description	Total Roll wrt Heading Err		Nav Roll wrt Heading Error		Control Roll wrt Heading Error		Propellant Usage	
	Max	μ+3sig	Max	μ+3sig	Max	μ+3sig	Max	μ+3sig
5fps_2300ft_start	29.14	15.15	3.08	2.38	32.14	16.59	34.85	33.92
8fps_2300ft_start	29.19	15.23	3.08	2.38	32.19	16.62	34.85	33.61
10fps_2300ft_start	87.29	18.54	3.08	2.37	89.35	19.40	34.92	33.24
5fps_1500ft_start	143.61	37.09	3.08	2.39	142.89	35.97	25.63	25.58
8fps_1500ft_start	143.61	37.30	3.08	2.38	142.89	36.14	25.09	25.37
10fps_1500ft_start	143.61	38.81	3.08	2.39	142.89	37.43	25.09	25.55

It is clear that if 160lb jets are used; lowering the roll control start altitude to 1500 ft significantly reduces propellant usage, while control performance is degraded only a little with no Keeper and hardly at all with a Keeper. However, if 100lb jets are used propellant is saved, but control performance suffers significantly. As seen in round one analysis, thresholds below 10 ft/s performed better with only a slight increase in propellant usage for the lower thresholds. Navigation performance was consistent with previous analysis.

CONCLUSIONS

The following is a list of the primary conclusions of the analysis results:

- Using a Keeper on the parachute lines improves control performance greatly and significantly reduces fuel usage. This benefit is seen with 160lb or 100lb jets. If a Keeper is used and GPS is available, then the 30 degree pointing requirement can be met for horizontal velocities above 10 ft/s.
- Choosing a lower altitude (< 2300 ft) to start control generally saves fuel (especially if no Keeper is used), but has an adverse effect on control for 100lb jets.
- Prohibiting GPS velocity measurements during roll control did not improve control performance, and only increased Heading estimation error. Thus, if available, all GPS measurements should be used for filter state update.
- The horizontal velocity trigger threshold chosen to activate control should be less than the "critical" velocity value; i.e. if roll control is required for velocities above 10 ft/s, then the activation trigger should be less (ex. 5 – 8 ft/s).
- Performance when GPS is not available does not meet the current requirement for pointing. However, the errors improve significantly as the magnitude of horizontal velocity increases. In addition, the use of a Keeper allows the control error to be fairly consistent with the "GPS on" cases. This would suggest that the requirement (at least for a contingency "no GPS" scenario) should be adjusted for velocity magnitude. Structural and crew loading attenuation system requirements will determine the criticality of GPS for roll control.

FUTURE WORK

There are still a few more parameters to analyze for the CM roll control problem. All of the cases covered in this study assumed that all parachutes were performing properly. Analysis needs to be done on the 1-parachute-out case which produces a faster decent rate (~35 ft/s vs. 20 ft/s). This faster decent would likely effect the most desirable control start altitude. Results of this analysis may also be drivers for structural and crew loads due to the higher vertical impact velocity. Other parameters include 120lb jets and possible changes in the parachute modeling parameters. Finally, all of the "outlier" cases need to be study closely to fully understand the root causes. This will hopefully allow of design improvements that can eliminate them all together.

ACKNOWLEDGEMENTS

The authors would like to thank the following people for assistance and invaluable help in preparing this paper: Al Strahan, Chris Madsen, Greg Loe, Roger Wacker, Brian Hoelscher, Joe Gamble, Zachary Putnam, Susan Stachowiak, Jeff Semrau, Andrew Barth, Chris Johnson, Chris Prouty, Mike Frostad, Robert Reitz, and Tim Crain. Also we would like to thank all of the group members on the following teams: Entry Mode Team, Entry Flight Control Team, Entry Navigation Team, Entry Guidance Team, Entry Performance Team, Landing and Recovery Systems Team.

ACRONYMS

ANTARES	Advanced NASA Technology Architecture for Exploration Studies
CM	Command Module
GNC	Guidance, Navigation, and Control
GRAM	Global Reference Atmospheric Model
JSC	Johnson Space Center
LRS	Landing and Recovery Systems
PP	Phase Plane

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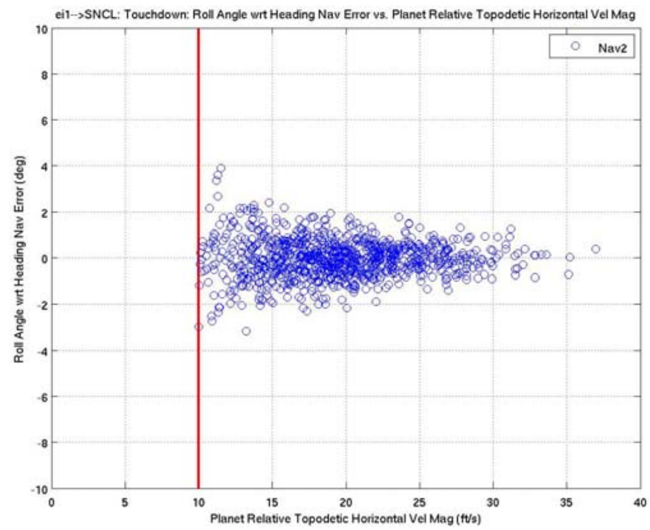
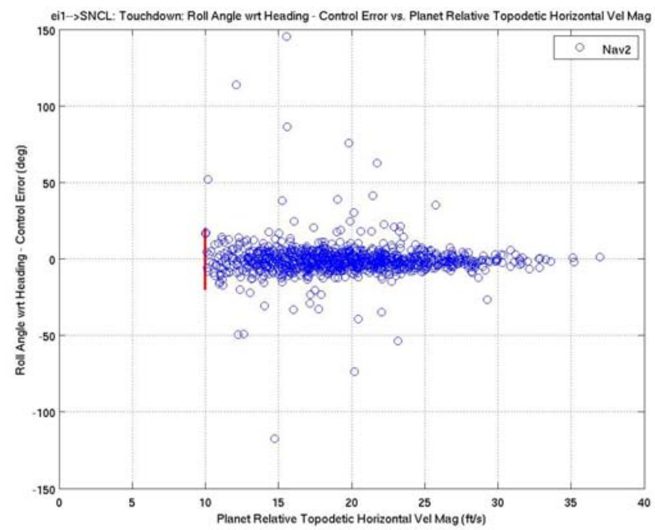
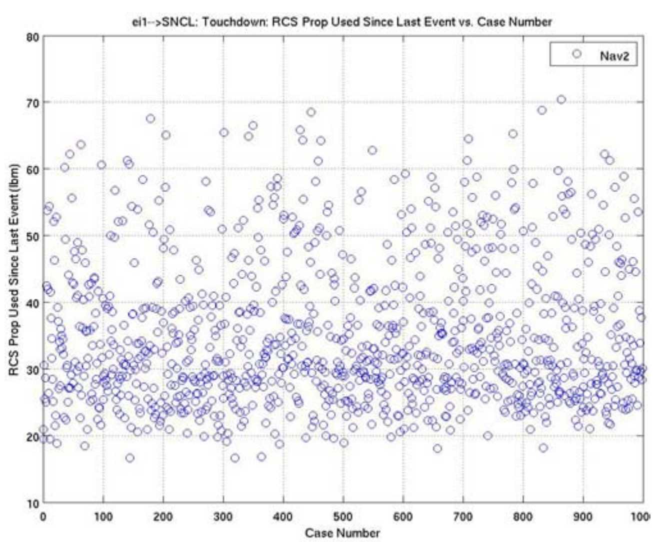
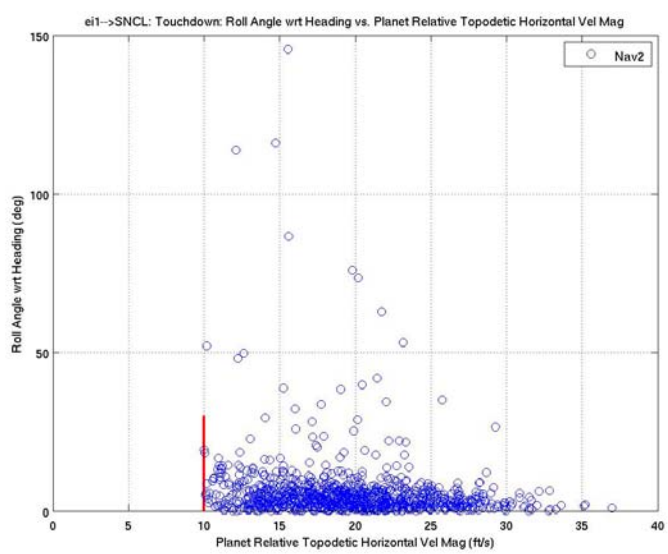
APPENDIX A: Roll Control Performance Plots

GPS On and No-Keeper
(28 deg. H.A., 2300 ft Control Start Altitude, 5 ft/s Vel. Trigger)

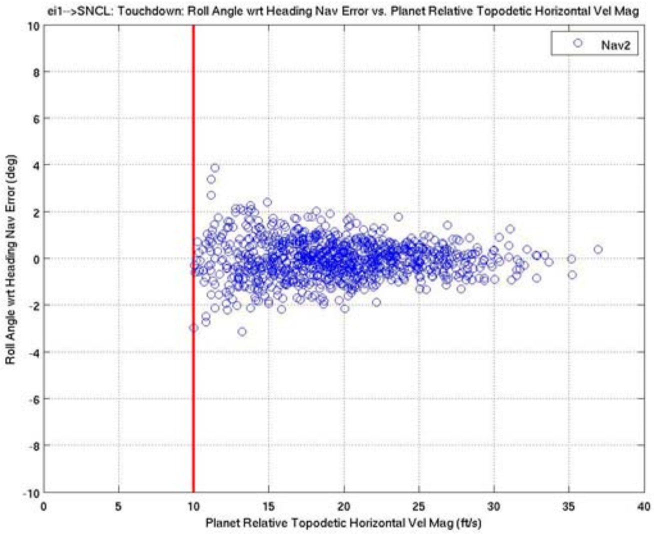


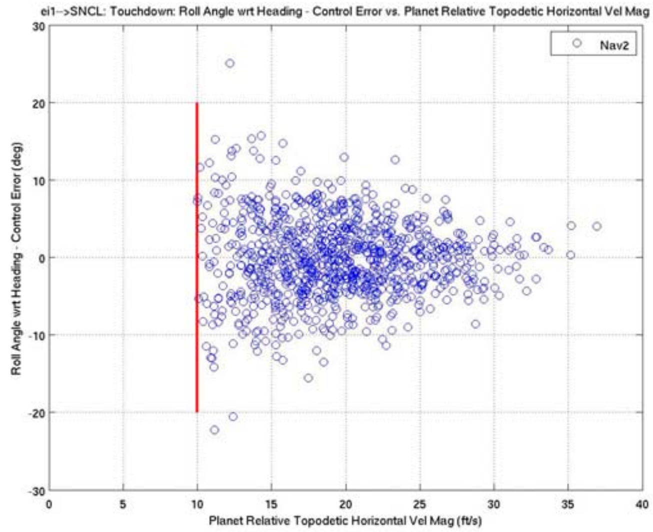


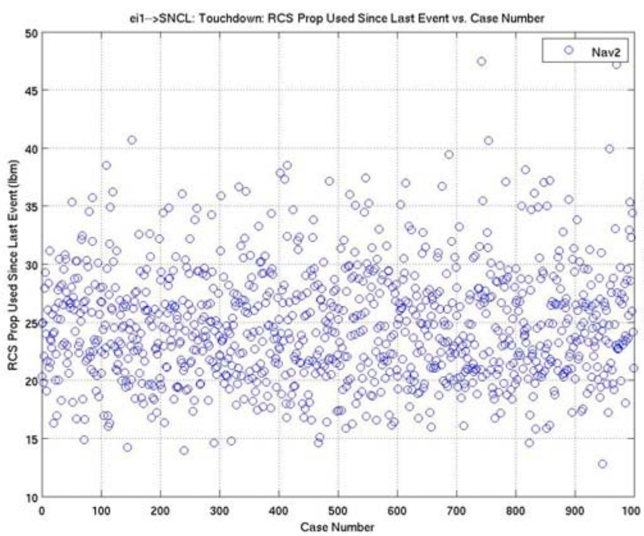


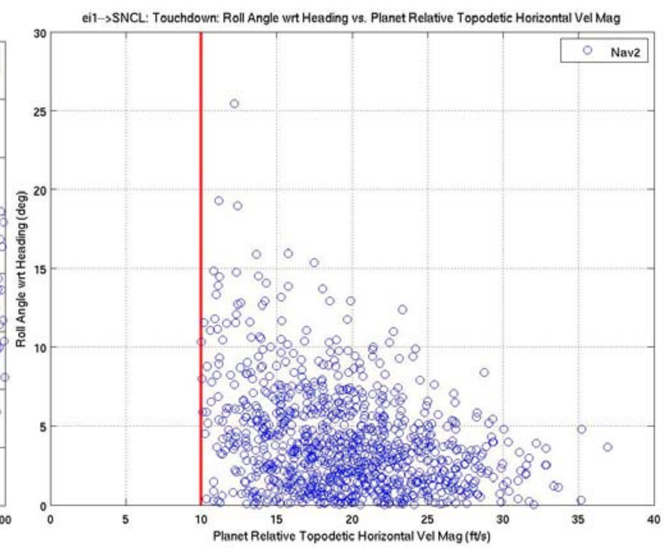


GPS On with Keeper
(28 deg. H.A., 2300 ft Control Start Altitude, 5 ft/s Vel. Trigger)









GPS Off and No-Keeper
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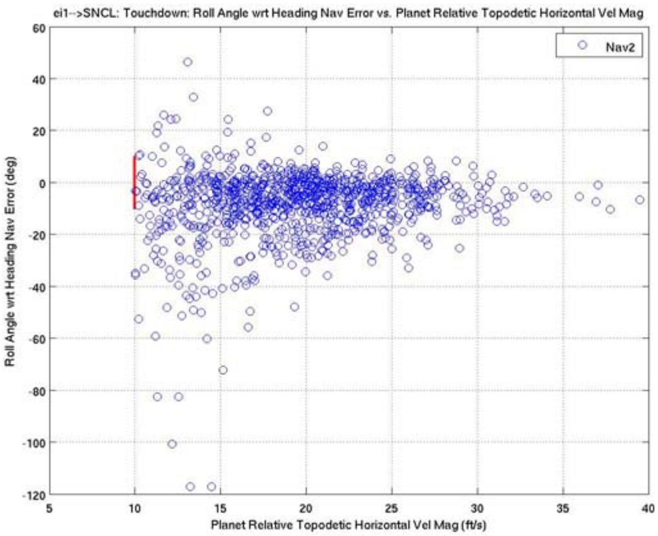

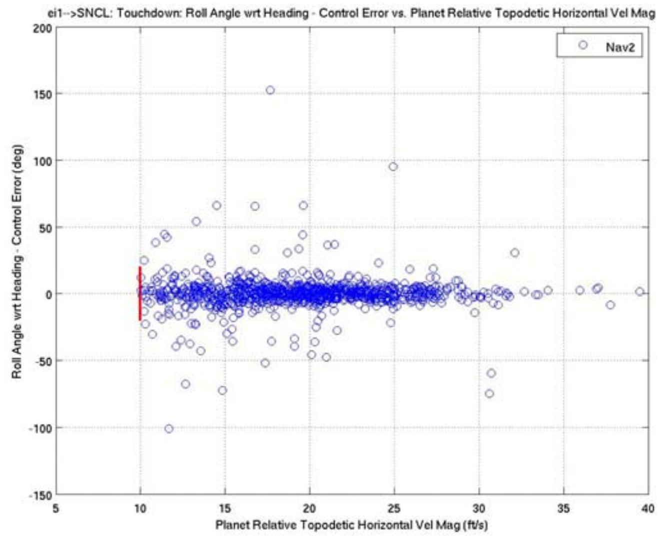

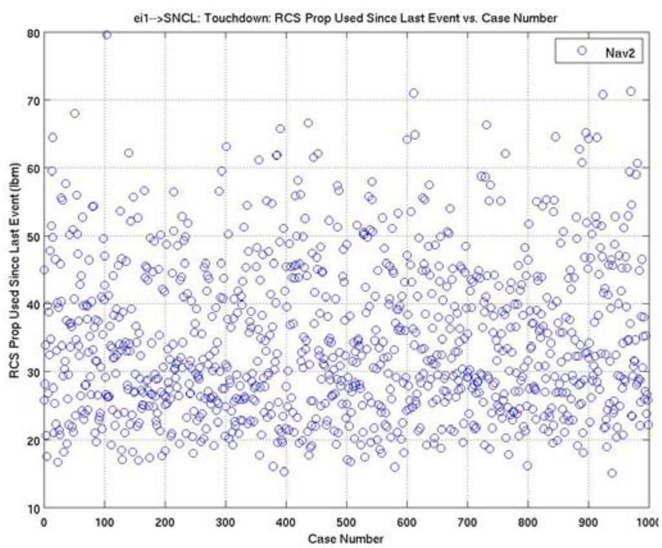

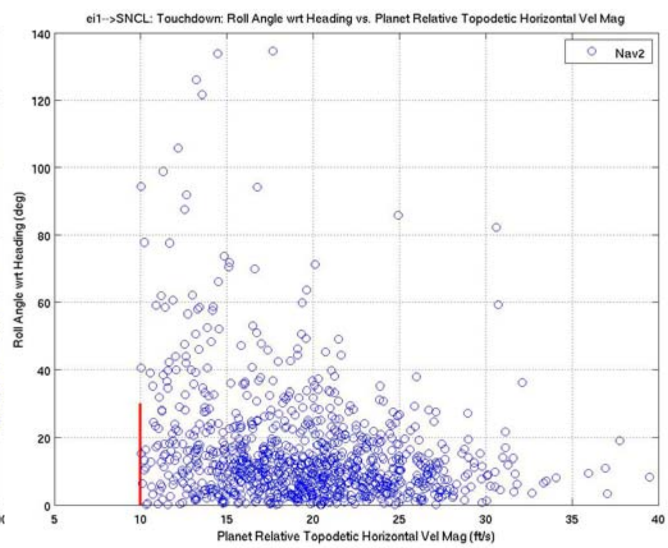

GPS Off with Keeper
(28 deg. H.A., 2300 ft Control Start Altitude, 5 ft/s Vel. Trigger)