Orion GN&C Overview and Architecture

Howard Hu and Tim Straube
NASA Johnson Space Center, Houston, TX 77058, USA

The Crew Exploration Vehicle, named Orion, is a critical element in the Constellation Program to develop the transportation system needed to send humans back to the moon and then beyond. Lockheed Martin is the prime contractor for the Orion spacecraft, which is managed by the Johnson Space Center. The Orion GN&C sub-system is being jointly developed by NASA and Lockheed Martin through a mode team approach. The GN&C is a critical element of the Orion mission to carry astronauts to low earth orbit to service the International Space Station and then on later flights to transfer and return a crew of four to the moon. The Orion GN&C system must perform monitoring and abort functions during ascent, rendezvous and docking in both low earth and lunar orbits, perform uncrewed lunar loiter operations, perform trans earth injection and atmospheric entry and landing. The Orion also must be integrated with the Ares I Crew Launch Vehicle, the Earth Departure Stage of the Ares V and the Lunar Surface Access Module. This paper provides an overview of the Orion GN&C system. The functional capabilities of the Orion GN&C will be provided in the context of Constellation architecture, the key GN&C requirements will be summarized, the GN&C architecture will be presented, the development schedule and plans will summarized and finally conclusions will be presented.

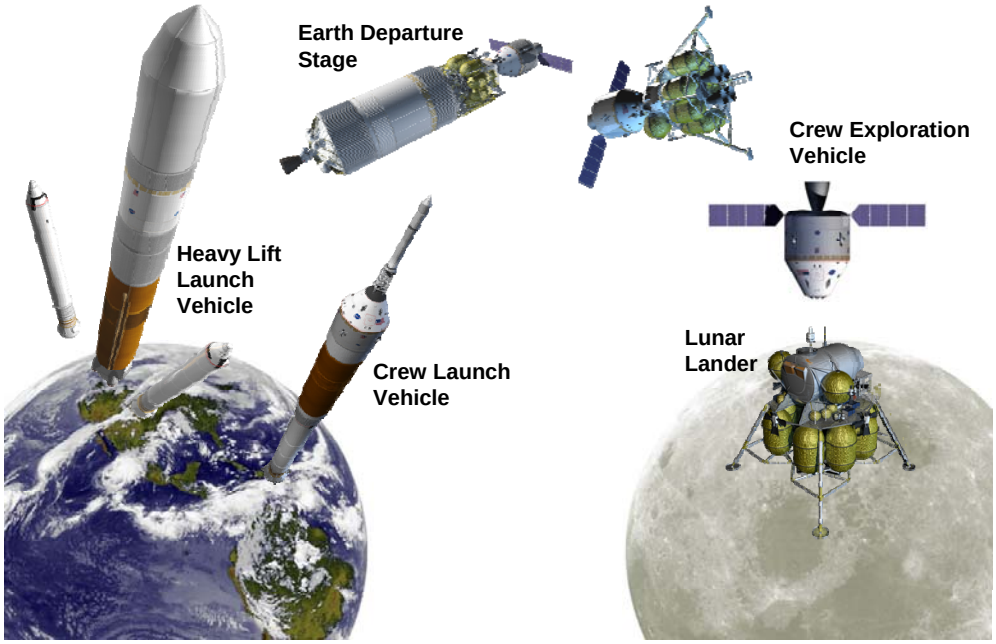
I. Introduction

In January 2004, President Bush announced an exciting new vision for the human exploration of space[1]. The vision called for the completion of assembly of the International Space Station and retirement of the Space by 2010, followed by an aggressive spiral development of transportation capabilities for exploration beyond Low Earth Orbit. This new develop of transportation capabilities included the first flights of the Crew Exploration Vehicle (CEV) (subsequently named "Orion") by 2014 and return of humans to the Moon before 2010. The vision also called for the Moon to be used as a proving ground for the capabilities necessary to explore Mars and beyond. This vision provided NASA a clear directive for the future of human spaceflight.

During the summer of 2005 NASA completed the Exploration Systems Architecture Study (ESAS)[2]. This study defined the architectural concepts for the first steps in developing the transportation system necessary to complete the new exploration vision. The study intended to develop a safe, accelerated, affordable and sustainable approach to human exploration based on the following tenants:

- Meet all US human spaceflight goals
- Significant advancement over Apollo
- Minimum of two lunar missions per year
- Provide a 125 metric ton launch vehicle for lunar and later Mars missions
- Higher ascent crew safety than the Space Shuttle
- Capable of servicing the Space Station
- Order transition of the workforce
- Requirements-driven technology program
- Annual "go-as-you-pay" budget planning.

The key elements of the architecture derived from the ESAS, shown in Figure 1, consist of the Crew Launch Vehicle (CLV) Ares I, the CEV Orion, a Cargo Launch Vehicle (CaLV) Ares V and a Lunar Surface Access Module (LSAM), also called the Lunar Landing Vehicle (LLV). Additionally, critical developments are necessary in Ground Launch Operations, Mission Operations and Lunar Surface elements (such as habitation and rovers) to meet all of the goals of the new exploration missions.



NASA has initiated procurements for the initial elements of the architecture, Orion and Ares I. For Ares I, Allied Technologies (ATK) was selected to develop the Shuttle Solid Rocket Booster derived first stage, Pratt Whitney Rocketdyne was selected to develop the J-2X Upper Stage engine and procurements are currently in progress for selection of Upper Stage and Upper Stage Instrumentation Unit contractors. For Orion, Lockheed Martin was selected in a competition with Northrop Gurmman/Boeing as the prime contractor. These two key systems are being developed differently, the Orion vehicle is a more traditional prime contract with specific elements being jointly developed with NASA, while Ares I is being designed by NASA for production by the winning contractor teams. One of the critical areas being jointly developed for Orion is the Guidance, Navigation and Control (GN&C) system which is utilizing a Multi-Organizational Design Engineering (MODE) team approach. This proven traditional approach was utilized to develop the Space Shuttle GN&C and has been demonstrated to effectively incorporate the best skills of both the government and contractor team.

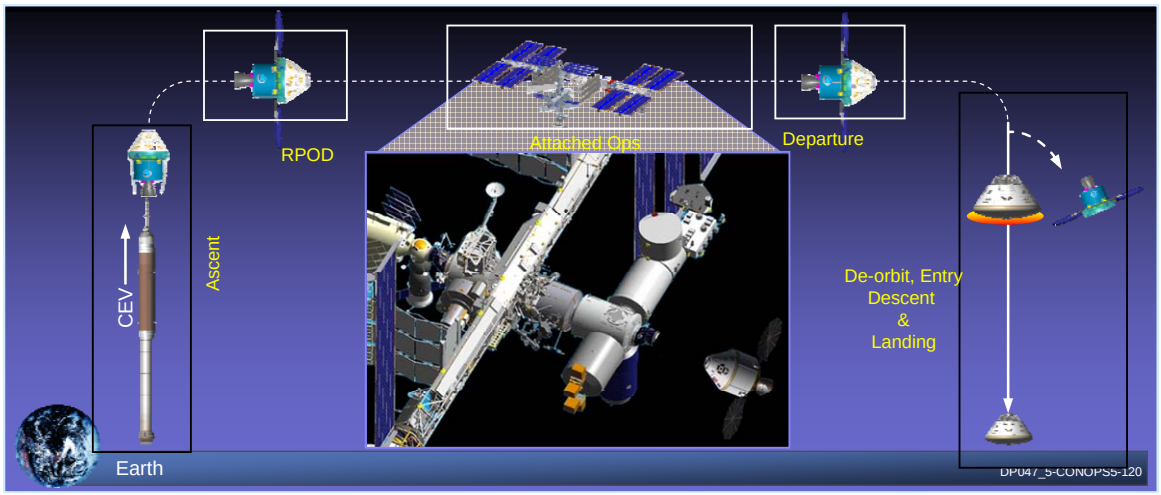
This paper will provide an overview of the GN&C development efforts. The first section will provide background on the Constellation elements and how they are applied to complete the primary design reference missions and provide an overview of the Orion spacecraft design, concepts of operations and the resulting key GN&C requirements. Section III will over the GN&C system architecture and functional elements, while Section IV will discuss the GN&C development and test plans. Finally, some conclusions will be drawn based on the status of the GN&C efforts to date.

II. Orion Background

The Constellation program is responsible for providing the transportation elements necessary in returning humans to the moon. Although the near term expectation is a series of vehicles that can return humans to the moon prior to 2020 and can replace the Space Shuttle in servicing the ISS, each system must also be developed with the long term in mind. The elements are intended to be utilized for the long term in supporting NASA exploration missions and therefore must be evolvable to human exploration of Mars. This long term focus and the stated focus of the vision to provide a sustainable (both in technical and fiscal terms) exploration program result in the systems being developed with the following attributes; affordable, safe and reliable, evolvable, upgradable, reusable, common, modular, flexible and effective.

The Constellation elements were presented in Figure 1. The Ares I is two-stage 22 ton launch vehicle intended to carry Orion to orbit with significantly increased safety over the Space Shuttle[3]. The Ares I first stage consists of a five segment Shuttle-derived solid rocket booster and the upper stage is propelled by a J-2X main engine evolved from the Saturn V J-2 engine. The Ares V is the heavy lift vehicle for NASA's next generation of space exploration. This 130 ton two-stage launch vehicle, consists of a first stage propelled by two five segment Shuttle-derived solid rocket boosters and five RS-68 engines and an upper stage powered by a J-2X engine that is also utilized as the Earth Departure Stage (EDS) for transporting the Orion and LLV to the lunar orbit. The LLV is currently in conceptual design, but it will perform many key functions including insertion into lunar orbit, descent to the lunar

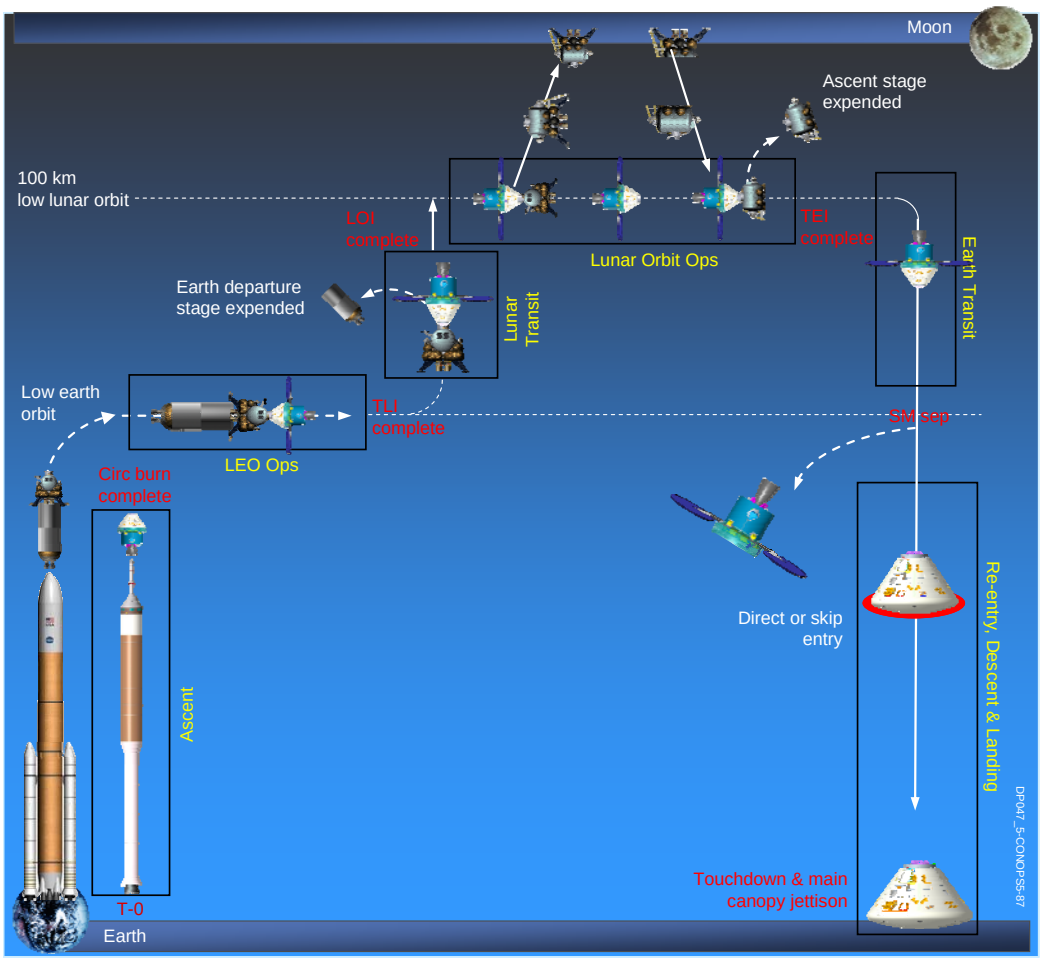
surface and ascent back to low earth orbit. The Orion crew vehicle is based on the capsule designs of past NASA programs, but incorporates many new technologies to provide a vehicle directly tied to the desired attributes. Orion is responsible for providing the necessary crew capabilities for rendezvous with the ISS and flight to and from lunar orbit[4].



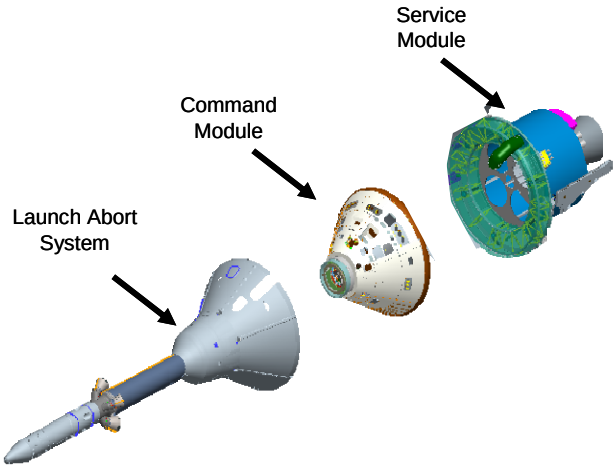
The two primary design reference missions for the Orion vehicle are delivering a crew of six to the ISS and transporting a crew of four to lunar orbit for lunar exploration missions. Figure 2 provides an overview of the ISS servicing reference mission. Orion is launched to low earth orbit atop the Ares I. Once it has separated from the Ares I upper stage, it performs the insertion burn to achieve a safe orbit and performs rendezvous and docking with the ISS. Following an upto 210 day stay at the ISS, Orion completes separation maneuvers and performs entry, descent and landing to a Contiential United States (CONUS) landing site. These critical events drive the driving GN&C requirements in Table 1. The concepts of operations for the lunar mission are provided in Figure 3. Once again, Orion is launched atop the Ares I and inserts itself into a safe orbit. For this mission, Orion performs rendezvous and docking with the EDS/LLV stack which has been place in orbit by the Ares V. The EDS then performs a burn to place the LLV/Orion onto a trans-lunar trajectory. Upon arrival at the moon the LLV will perform the burns necessary for insertion in lunar orbit, separate from Orion and descend to the lunar surface. During the lunar stay the Orion will remain in orbit uncrewed. Following lunar surface operations, the LLV will ascend back to lunar orbit to rendezvous and dock with Orion. Orion must be prepared to perform a safety critical contingency docking with the LLV in the event of failures to the LLV systems. The Orion must then perform the burns to place itself upon the earth return trajectory and perform entry and landing, again nominally to a CONUS landing site. Additionally to satisfy safety requirements, the Orion must be able to safely return the crew from the moon following a communications failure with the ground. This operational concept results in the additional driving GN&C requirements in Table 1.

Table 1 – GN&C Driving Requirements

ISS Reference Mission	Lunar Reference Mission
Independently determine the need for ascent aborts	Rendezvous and dock with EDS/LLV
Provide safe aborts with no black zones	Independently determine the need for EDS burn abort
Perform orbital insertion maneuver	Control the mated LLV/CEV stack
Rendezvous and dock with the ISS	Navigate during translunar and transearth cost
Meet ISS visiting vehicle requirements	Perform orbit maintenance during uncrewed lunar coast
Separate and safely depart from the ISS	Perform contingency docking to LLV
Safely return the crew to a CONUS landing site	Accommodate possible tumbling LLV for docking
Safely dispose of the Service Module	Perform Trans Earth Injection
Perform fault detection and provide health and status to Systems Management	Perform entry and landing to CONUS landing site
Provide GN&C Automatic command execution	Provide safe return following loss of comm
Provide manual control capabilities	

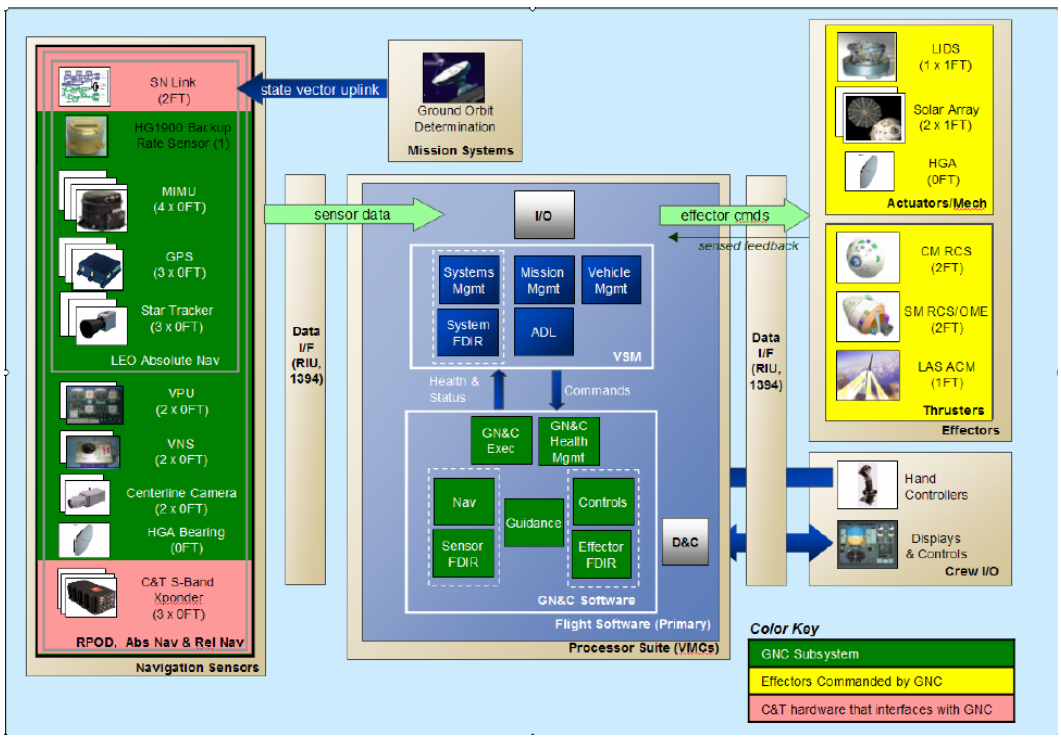


The Orion spacecraft designed to meet these critical driving requirements consists of a Command Module (CM), Service Module (SM) and Launch Abort System (LAS) as shown in Figure 4[5]. The CM consists of the primary structure for crew support, incorporates the bulk of the avionics systems and provides the capability for entry and landing. The service module provides the necessary support elements for the in-space operations including a majority of the consumables, propulsion and main engine for large orbital burns. The LAS perform the functions necessary to safely extract the CM from the launch vehicle in the event of a launch failure. The primary hardware that incorporates and/or supports the GN&C functions is distributed among the elements. The CM hosts the flight computers executing the GN&C software, the displays and controls the crew utilizes and inertial and relative navigation sensors. In addition, the CM contains the necessary thrusters for entry and landing control, as well as the landing and recovery systems such as parachutes and airbags. The SM provides the propulsion systems necessary for in-space flight operations including the main engine for large orbital burns (insertion, rendezvous, trans earth injection and deorbit) and a six-degree of freedom thruster system for attitude and docking control. The LAS provides the necessary actuation systems for safe extraction of the CM in the event of a launch system abort.



III. Orion GN&C System Overview

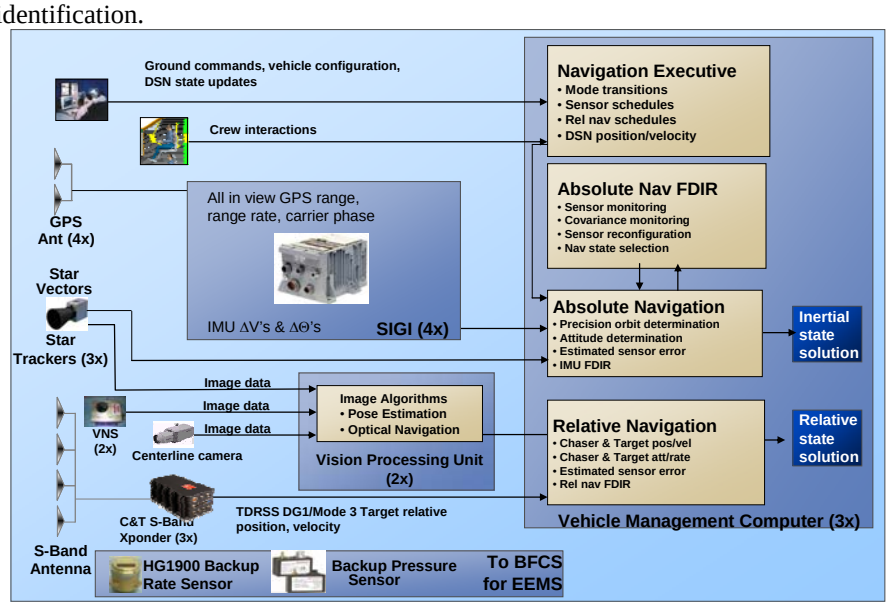
The Orion GN&C sub-system consists of the necessary elements to meet the driving requirements provided in previous section. The GN&C system must execute during all phases of flight and actively control during many critical functions. Additionally, it must monitor the performance the integrated vehicles during all operations and often provide abort and/or backup capabilities in the event of failures to other elements of the Constellation system. Figure 5 provides an overview of the Orion GN&C sub-system.



The Orion GN&C system relies on propulsive systems for control during all flight phases. Additionally, parachutes and attenuation systems are utilized for landing. Four propulsive systems are used for Orion control; the CM entry control thrusters, the SM orbit control thrusters, the SM main engine (SMME) and the LAS abort motor and abort control motors. The CM propulsion system consists of six thruster pods containing three 160 lbf thrusters to provide two fault tolerant 3-axis rotational control of the CM during entry and reorientation for landing. The SM propulsion system provides 6 degree of freedom (rotational and translational) control and propulsion for large ΔV

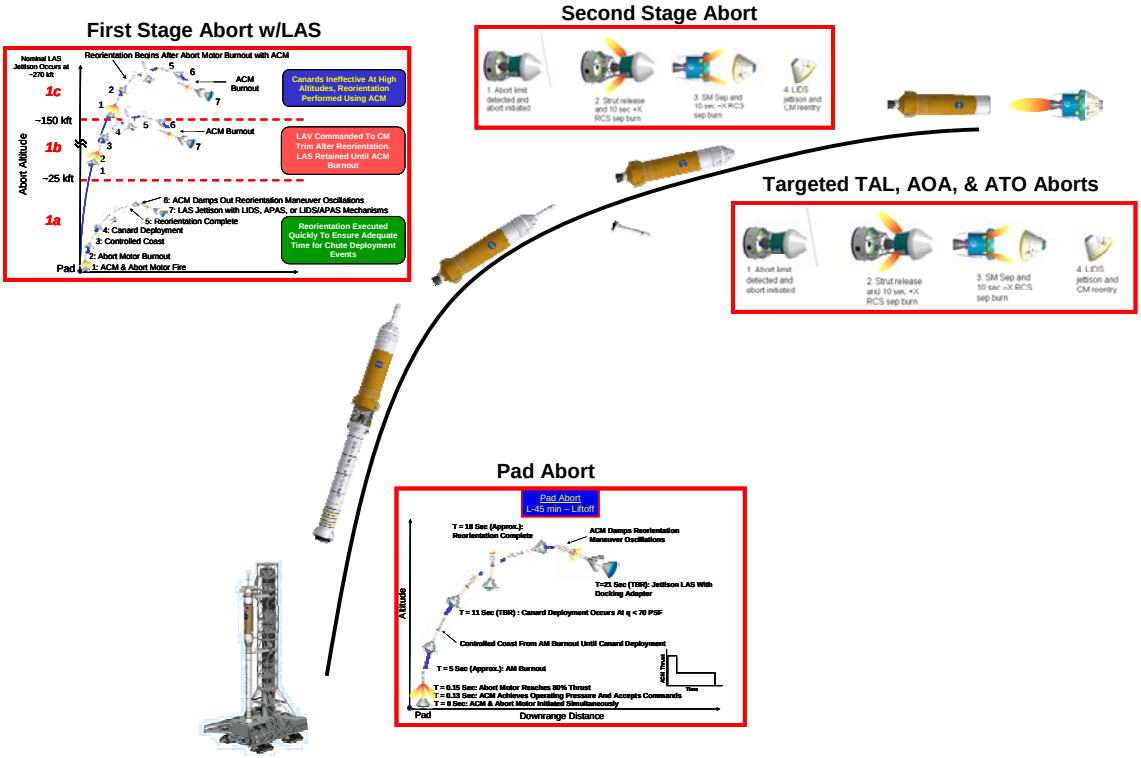
maneuvers. The SM thruster system consists of four pods containing six thrusters each and redundancy is provided through a block swap approach. For the large maneuvers, the SM provides a single gimbaled 7,500 lbf main engine derived from the Shuttle Orbital Maneuvering System engines and an auxiliary translation system consisting of eight axially directed 110 lbf for backup. The LAS provides the control necessary to safely separate from the launch vehicle in the event of a launch abort (primarily during first stage flight) via the abort motor utilized to separate the CM from the launch vehicle and the abort control motors utilized for stabilization during the abort motor burn and to control and reorient the vehicle for chute deployment and landing.

The Orion navigation system provides inertial and relative navigations capabilities. As shown in Figure 6, a centralized approach has been selected for the navigation system that incorporates a series of navigation sensor measurements within the flight computers to estimate the position and attitude states. The inertial navigation sensors consist of ground state updates, GPS, inertial measurement units and star trackers, augmented with a vision based deep-space navigation system lunar missions. Relative navigation measurements are provided by the vision navigation system that will incorporate optical and LIDAR measurements to provide relative range, bearing and orientation combined with range measurements from the onboard communications systems. These measurements are then processed by the Absolute and/or Relative Navigation filters within the software. The GN&C software is also responsible for performing fault detection and health management of the navigation system, including selection filtering and fault identification.



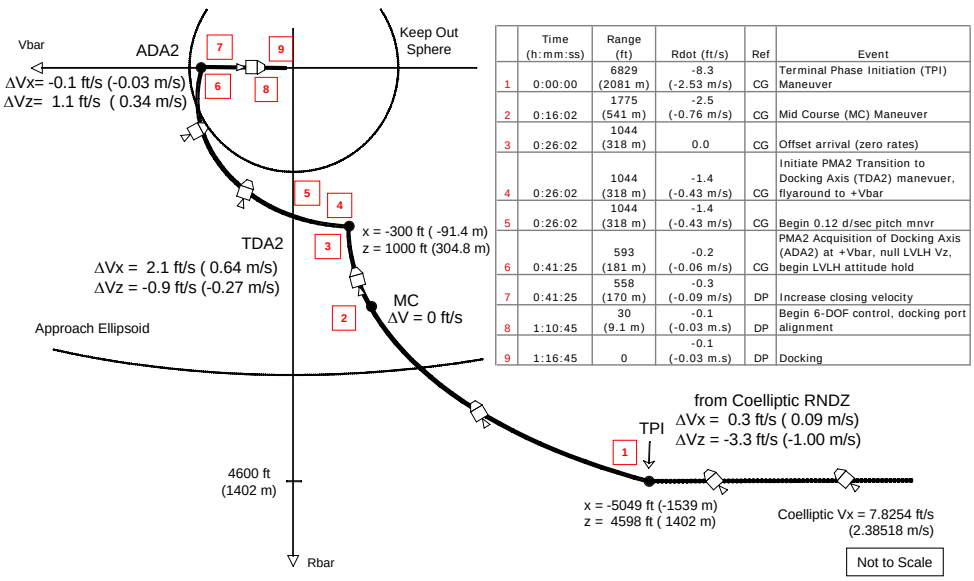
The Orion guidance system must perform several functions including targeting maneuvers for insertion, rendezvous, deorbit and translunar flight and performing entry guidance to CONUS landing sites. The guidance incorporates significantly new capabilities for the Orion mission including onboard translunar targeting, automated docking and skip entry guidance. To meet safety requirements Orion must provide the capabilities necessary to return the crew from the moon without communications with the ground, requiring onboard targeting calculations for the earth return maneuvers. Although, significant capability existed for Apollo, the GN&C team is developing upgrades and evolution to those algorithms for the Orion mission. This requirement also leads to a need for the uncrewed Orion vehicle to perform contingency rendezvous and docking with a disabled LLV necessitating that automated rendezvous and docking be incorporated into the design. The requirement to land at CONUS landing sites has necessitated the application of skip entry guidance to provide adequate down range capabilities for all possible return conditions. The GN&C team is developing and testing algorithms to safely provide these capabilities for the Orion vehicles L/D ratio.

The Orion control systems must provide capabilities for onorbit attitude control, proximity operations and docking control, pointing during large ΔV maneuvers and atmospheric entry control. Automatic closed-loop control laws and jet selection algorithms are being developed to provide all of these capabilities.

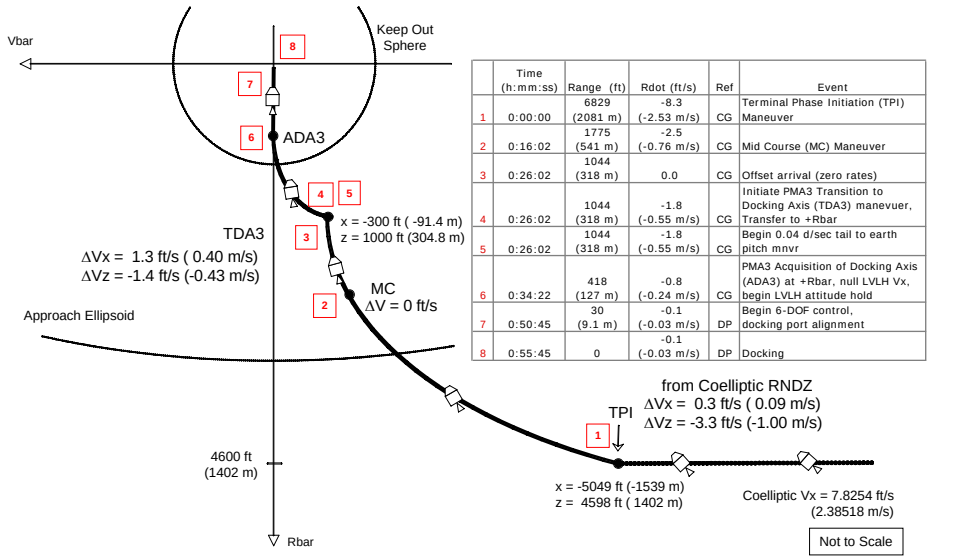


A critical safety function in the Orion GN&C development is providing safe abort modes during all powered flight operations. Figure 7 provides an overview of the Orion abort capabilities. On the pad and during first stage flight the LAS is utilized to power the CM away from the launch tower and/or vehicle, gain adequate altitude and then reorient the vehicle for chute deployment. As the second stage assumes control the LAS is jettisoned and the SM provides abort thrust. For early second stage aborts, the Ares engine is shut down and the SMME propels the Orion to a safe condition for CM/SM separation and a nominal CM landing. Later in second stage more benign abort capabilities are provided that would fly the vehicle to landing sites either across the Atlantic or back to CONUS or if energy exists carry the Orion to a safe orbit.

Both of the Orion mission scenarios require rendezvous and docking. The Orion must provide the capability to perform rendezvous and docking in Low Earth Orbit for both the ISS mission and to the EDS/LLV for the lunar mission. Figures 8 and 9 provide the proximity operations trajectories for the ISS and EDS/LLV missions respectively[6]. The contingency operations for the LLV lunar docking are expected to be very similar to the EDS/LLV docking. Key drivers in the trajectory development were meeting all safety criteria for the ISS visiting vehicle operations, providing common frameworks for the two scenarios and achieving reasonable requirements for the relative navigation sensors.. Additionally, it was desired to provide common algorithms for all rendezvous and docking operations.

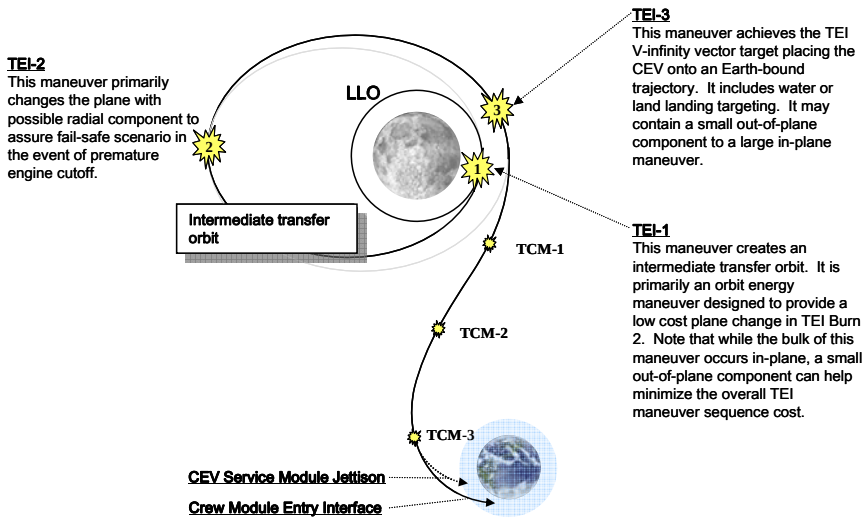


	Time (h:mm:ss)	Range (ft)	Rdot (ft/s)	Ref	Event
1	0:00:00	6829 (2081 m)	-8.3 (-2.53 m/s)	CG	Terminal Phase Initiation (TPI) Maneuver
2	0:16:02	1775 (541 m)	-2.5 (-0.76 m/s)	CG	Mid Course (MC) Maneuver
3	0:26:02	1044 (318 m)	0.0	CG	Offset arrival (zero rates)
4	0:26:02	1044 (318 m)	-1.4 (-0.43 m/s)	CG	Initiate PMA2 Transition to Docking Axis (TDA2) manevuer, flyaround to +Vbar
5	0:26:02	1044 (318 m)	-1.4 (-0.43 m/s)	CG	Begin 0.12 d/sec pitch mnvr
6	0:41:25	593 (181 m)	-0.2 (-0.06 m/s)	CG	PMA2 Acquisition of Docking Axis (ADA2) at +Vbar, null LVLH Vz, begin LVLH attitude hold
7	0:41:25	558 (170 m)	-0.3 (-0.09 m/s)	DP	Increase closing velocity
8	1:10:45	30 (9.1 m)	-0.1 (-0.03 m.s)	DP	Begin 6-DOF control, docking port alignment
9	1:16:45	0	-0.1 (-0.03 m.s)	DP	Docking

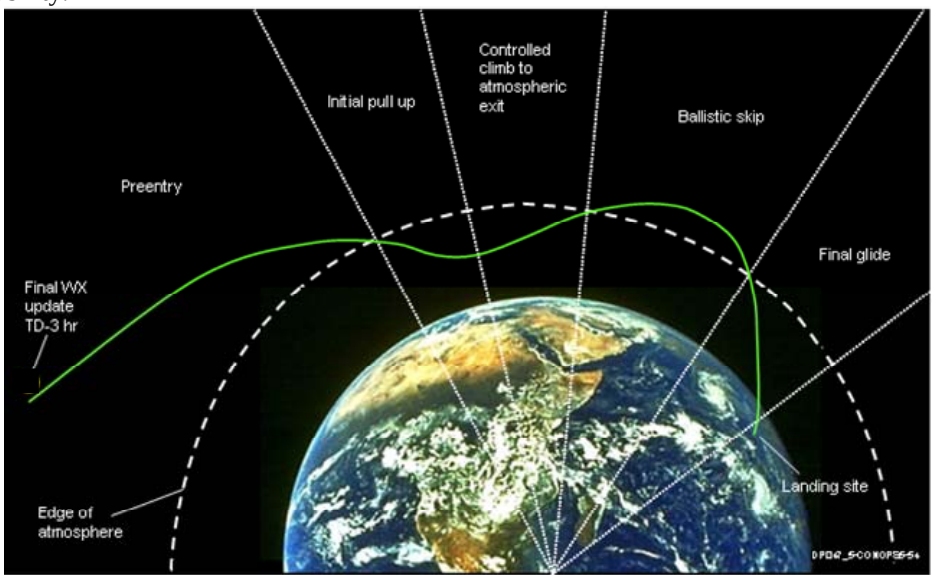


	Time (h:mm:ss)	Range (ft)	Rdot (ft/s)	Ref	Event
1	0:00:00	6829 (2081 m)	-8.3 (-2.53 m/s)	CG	Terminal Phase Initiation (TPI) Maneuver
2	0:16:02	1775 (541 m)	-2.5 (-0.76 m/s)	CG	Mid Course (MC) Maneuver
3	0:26:02	1044 (318 m)	0.0	CG	Offset arrival (zero rates)
4	0:26:02	1044 (318 m)	-1.8 (-0.55 m/s)	CG	Initiate PMA3 Transition to Docking Axis (TDA3) manevuer, Transfer to +Rbar
5	0:26:02	1044 (318 m)	-1.8 (-0.55 m/s)	CG	Begin 0.04 d/sec tail to earth pitch mnvr
6	0:34:22	418 (127 m)	-0.8 (-0.24 m/s)	CG	PMA3 Acquisition of Docking Axis (ADA3) at +Rbar, null LVLH Vx, begin LVLH attitude hold
7	0:50:45	30 (9.1 m)	-0.1 (-0.03 m/s)	DP	Begin 6-DOF control, docking port alignment
8	0:55:45	0	-0.1 (-0.03 m/s)	DP	Docking

Orion's primary role in the lunar exploration mission translunar phase is execution of the Earth Return maneuver. Figure 10 provides an overview of the Earth return maneuver trajectory[7]. A day before the expected LLV liftoff, the Orion will perform a plane change maneuver to align the orbit inclination and LAN for a nominal in-plane LLV ascent. Following the LLV / Orion rendezvous, Orion will perform a day-long series of Trans Earth Injection (TEI) maneuvers placing it on a 3.5 day return flight to Earth.



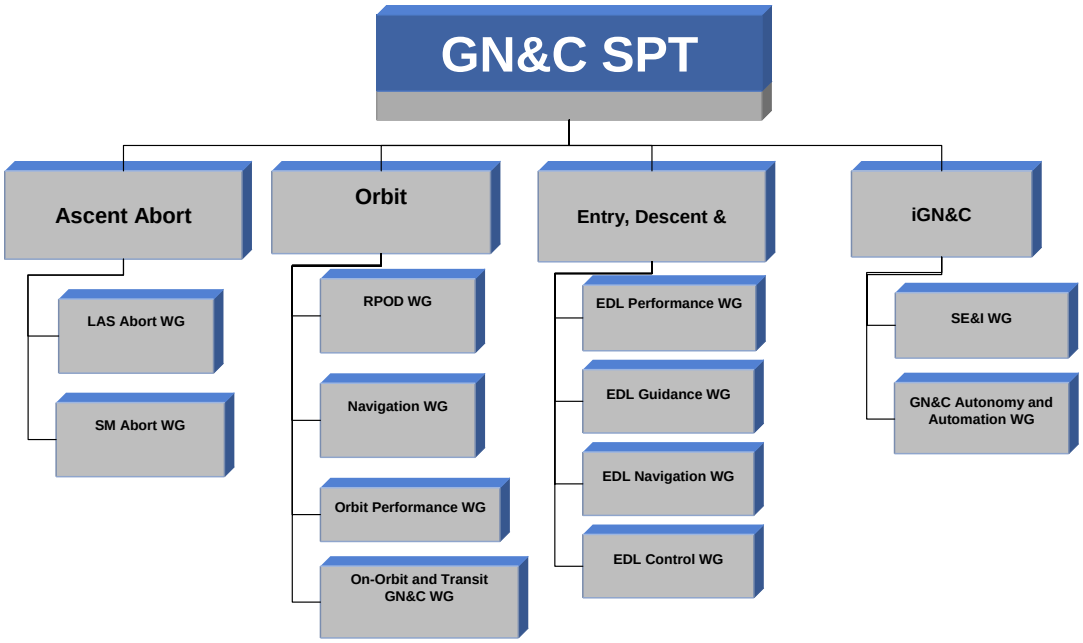
A final key element of the Orion GN&C design is the capability to perform a skip entry return to a CONUS landing site. Skip entry guidance is employed to extend the down range capabilities of the vehicle. Figure 11 shows how a skip maneuver is performed to skip out of the atmosphere following the initial entry extending the landing down range capability.



IV. Orion GN&C Development Plans

Provide a summary of the GN&C mode team approach, provide the GN&C development Schedule, provide a brief summary of the SW development, provide a summary of the test philosophy and end with a few words on test flights and initial operational flights.

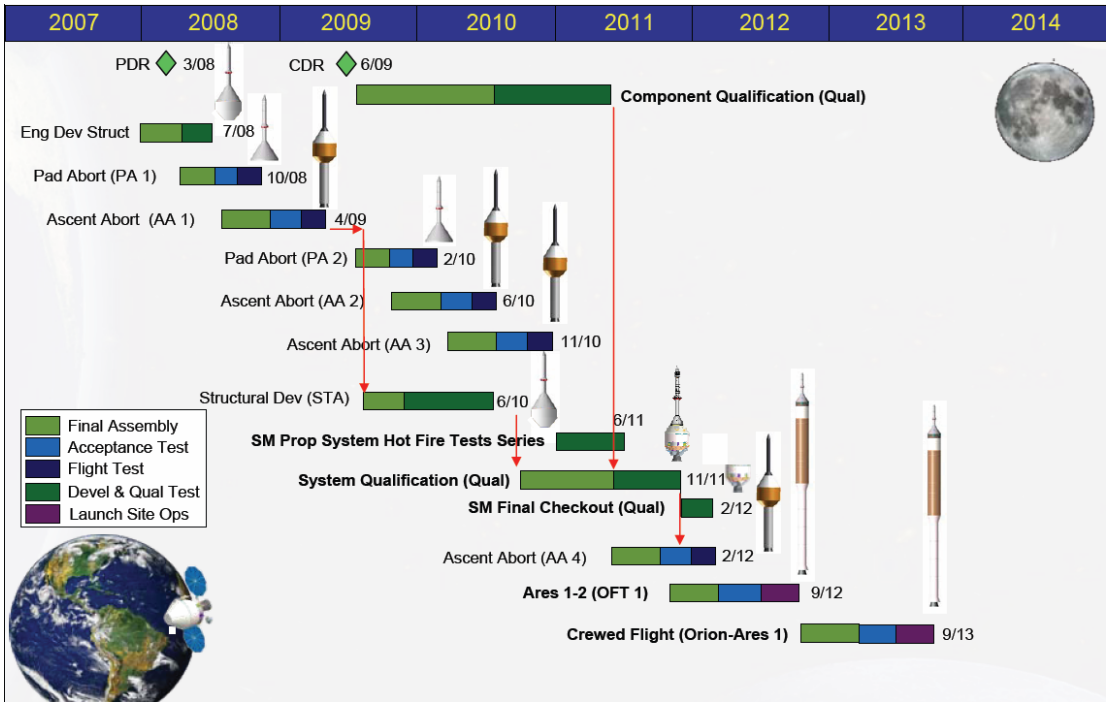
The Orion GN&C is being developed using a Multi-Organizational Design Engineering (MODE) team approach. The MODE team approach employs the best capabilities of the government and the Lockheed Martin prime contractor to jointly develop the GN&C design. Figure 12 provides the overall MODE team structure, where MODE teams have been created for Ascent & Aborts, On-Orbit, Entry and Integrated GN&C that are jointly lead by NASA and LM. In addition Working Groups are created below the MODE teams to allow execution of detailed engineering functions, such as LAS Aborts, Navigation, Rendezvous, Proximity Operations and Docking (RPOD), and GN&C Autonomy and Automation. The flight operations and functional capabilities, as defined by requirements, have been distributed among the MODE teams for development of the Orion GN&C functions. A critical element in the successful execution of the MODE team approach is for the government and its prime to operate in a collaborative environment.



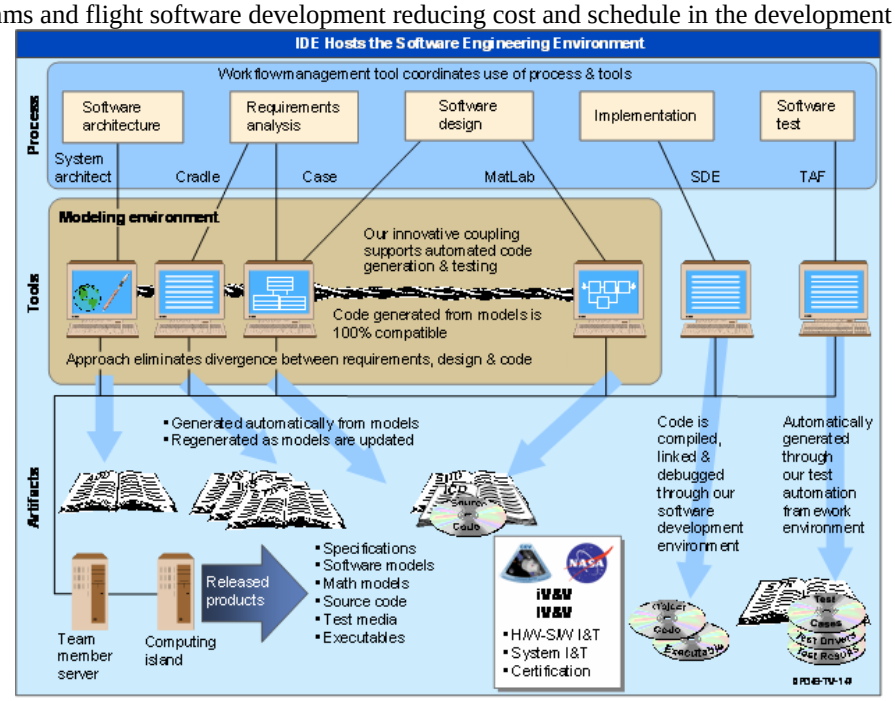
The Orion GN&C development is being conducted under a traditional design schedule (see Figure 13), but significant early development and test efforts are being employed to minimize risks in the design approach. The GN&C algorithms and performance analyses are being jointly conducted by NASA and LM utilizing independently developed simulations and tools. Multiple test and verification efforts are planned. Figure Y shows the test and verification process planned for the GN&C. Early software simulations will be conducted to develop system designs and algorithms, software and hardware will be integrated for early risk mitigation and demonstration in the Exploration Development Lab (EDL) and finally integrated verification is performed in the CEV Integrated Avionics Lab (CAIL).

Add the latest project schedule for GN&C

The Orion development also incorporates a robust flight test program. As seen in Figure 14, the team will conduct a series of Pad Abort (PA) and Ascent Abort (AA) flight tests to demonstrate the abort system. These are followed by a series of integrated Ares I / Orion flight tests to demonstrate acceptable performance prior to human operational flights. The first abort tests will demonstrate the functionality of the LAS. These will be followed by flight tests that demonstrate the performance of the system during various flight phases. As these tests are performed the GN&C software and hardware is evolved to allow integrated demonstration during the final AA tests. The next test integrates the Orion with the Ares I and provide ascent, orbit and entry testing of the Orion GN&C.



Although a traditional waterfall schedule is being executed, the GN&C software will be developed using modern tools and processes being put in place by the Lockheed Martin flight software team. Figure 15 provides an overview of the software development process that incorporates objected oriented design techniques, model based design, automated testing and automatic code generation. The GN&C algorithms will be implemented using Mathworks based products, autocoded and then integrated with moding and sequencing logic developed in the Kennedy Carter Unified Modeling Language toolset. The application of these modern tools are expected to simplify the integration of GN&C algorithms and flight software development reducing cost and schedule in the development of the GN&C.



V. Conclusion

The Orion vehicle is currently in development by NASA and prime contractor Lockheed Martin. Orion plays a critical and challenging role in providing the transportation capabilities necessary to achieve the exploration vision. The design reference missions and concepts of operations require a series of challenging GN&C capabilities.

The Orion GN&C system design has been introduced and several critical capabilities are being developed. A MODE team approach is being utilized to develop the GN&C. The GN&C system is being developed under a classical waterfall schedule, but modern design approaches are being incorporated. A robust series for laboratory tests are being conducted and combined with significant flight tests prior to human operations.

Significant design and development remains for the Orion GN&C, but the NASA and LM teams have demonstrated that the MODE teams can work in a collaborative environment to meet the challenges ahead.

Acknowledgments

The authors would like to acknowledge all members of the Orion GN&C MODE teams. The collaborative environment and attitude of these teams has been extraordinary. Additionally, many members of the Orion systems engineering and other sub-teams have contributed to development of the GN&C sub-system design.

References

1. "The Vision for Space Exploration", *National Aeronautics and Space Administration*, February 2004.
2. NASA Exploration Systems Architecture Study, National Aeronautics and Space Administration, NASA-TM-2005-214062, November 2005.
3. Cook, S., Ares Project Status, *2nd AIAA Space Exploration Conference*, Houston, TX, December 4-6, 2006.
4. Hatfield, S., Orion Project Status, *2nd AIAA Space Exploration Conference*, Houston, TX, December 4-6, 2006.
5. CEV SDR Kickoff, National Aeronautics and Space Administration, Houston, TX, July 11-12, 2007.
6. D' Souza, C., Spehar, P. Hanak, C. and Clark, F.., "Orion Rendezvous, Proximity Operations and Docking Design and Analysis," *AIAA Guidance, Navigation, and Control Conference*, AIAA-07-6683, Hilton Head, S.C., August 2007.
7. Condon, G., Dawn, T., Merriam, R., Sostaric, R., and Westhelle, C., "CEV Trajectory Design Considerations for Lunar Missions," *30th Annual AAS Guidance and Control Conference*, AAS-07-075, Breckenridge, CO., February 2007.