

# Recent Experiences of the NASA Engineering and Safety Center (NESC) Guidance Navigation and Control (GN&C) Technical Discipline Team (TDT)

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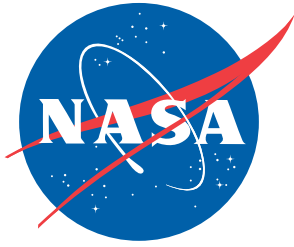
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## **Nomenclature**

AA	Ascent Abort
ACM	Attitude Control Motor
AM	Abort Motor
ATB	Abort Test Booster
CAS	Credibility Assessment Scale
CEV	Crew Exploration Vehicle
CG	Center of Gravity
CM	Crew Module
CxP	Constellation Program
DOF	Degree of Freedom
DSN	Deep Space Network
E2E	End-to-End
ESMD	Exploration Systems Mission Directorate
FCS	Flight Control System
FOT	Flight Operations Team
FTV	Flight Test Vehicle
GN&C	Guidance Navigation and Control
GPS	Global Positioning System
IMU	Inertial Measurement Units
IRMA	Integrated Risk Management Assessment
IRT	Independent Review Team
ISS	International Space Station
JSC	Johnson Space Center
LAS	Launch Abort System
LAV	Launch Abort Vehicle
LC	Launch cycle
LIS	Lost-in-Space
LPF	Low Pass Filter
MAVERIC	Marshall Aerospace VEHICLE Representation In “C”
Max-Q	Maximum Dynamic Pressure
MLAS	Max Launch Abort System
MMH	Monomethylhydrazine
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
NTO	Nitrogen Tetroxide
OS	Objective System
PA	Pad Abort
PDR	Preliminary Design Review
PID	Proportional-Integral-Derivative
PRA	Probabilistic Risk Analysis
RID	Review Item Discrepancies
RoCS	Roll Control system

RRT	RID Review Team
SBD	Smart Buyer Design
SM	Service Module
SR	Separation Ring
TDT	Technical Discipline Team
TVC	Thrust Vector Control



## Abstract

*The NASA Engineering and Safety Center (NESC), initially formed in 2003, is an independently funded NASA Program whose dedicated team of technical experts provides objective engineering and safety assessments of critical, high risk projects. NESC's strength is rooted in the diverse perspectives and broad knowledge base that add value to its products, affording customers a responsive, alternate path for assessing and preventing technical problems while protecting vital human and national resources. The Guidance Navigation and Control (GN&C) Technical Discipline Team (TDT) is one of fifteen such discipline-focused teams within the NESC organization. The TDT membership is composed of GN&C specialists from across NASA and its partner organizations in other government agencies, industry, national laboratories, and universities. This paper will briefly define the vision, mission, and purpose of the NESC organization. The role of the GN&C TDT will then be described in detail along with an overview of how this team operates and engages in its objective engineering and safety assessments of critical NASA projects. This paper will then describe selected recent experiences, over the period 2007 to present, of the GN&C TDT in which they directly performed or supported a wide variety of NESC assessments and consultations.*

## 1.0 Introduction

The National Aeronautics and Space Administration (NASA) Engineering Safety Center (NESC), initially formed in 2003 in the wake of the *Columbia* tragedy, is an example of a One-NASA Program. NESC is an independently funded NASA program whose dedicated team of technical experts coordinates and conducts objective engineering and safety assessments of critical, high-risk projects. The NESC is a strong technical resource for customers and stakeholders seeking responsive service for solving the Agency's difficult problems. NESC's strength is rooted in the diverse perspectives and broad knowledge base that add value to its products, affording customers a responsive, alternate path for assessing and preventing technical problems while protecting vital human and national resources. NESC provides timely technical positions to its customers and stakeholders based on independent test and analysis, not opinion.

By encouraging alternative viewpoints and ensuring objective reporting methods, NESC is able to serve as a uniquely unbiased assessment resource. NESC delivers technical evaluation and consultation products in the form of written reports that include solution-driven, preventative, and corrective recommendations. In July of 2011, the NESC initiated its 370<sup>th</sup> technical assessment. The NESC communicates its lessons learned from each assessment to NASA's leadership through bi-annual briefings and to engineers through both the Agency Lesson Learned system and a series of NESC Technical Bulletins issued periodically. These communication channels function to inform the NASA technical community and, therefore, NESC's customers and stakeholders. NESC's range of services includes testing, analysis, and data review in fifteen engineering disciplines. NESC also engages in proactive discipline advancing activities.

The Guidance, Navigation, and Control (GN&C) Technical Discipline Team (TDT), the primary subject of this paper, is one of fifteen (15) such discipline-focused teams within the NESC organization. The NASA Technical Fellow for GN&C maintains and leads the TDT. The TDT membership is composed of senior GN&C engineers from across NASA's Field Centers as well as from its partner organizations in other government Agencies, industry, national laboratories, and universities.

This paper will briefly define the vision, mission, and purpose of the NESC organization. It contains a detailed description of the role of the GN&C TDT and an overview of how this team operates and engages in its objective engineering and safety assessments of critical NASA projects. Descriptions of several recent, 2007 to present, experiences in which the GN&C TDT performed or supported a wide variety of NESC assessments and consultations are also included in this paper.

## **2.0 NESC Vision, Mission, and Organization**

One of the tenets of an effective safety philosophy is to provide an avenue for independent assessment of the technical aspects and risks of critical systems. NESC offers this alternate reporting path for all NASA programs and projects.

The vision that NESC has for itself is to serve as the independent and objective deep technical resource of choice for NASA Programs and other government Agencies. As its fundamental mission, the NESC strives to set the example for engineering and technical excellence within NASA. The primary purpose of this independent and objective organization is to increase safety through engineering excellence. NESC collaborates with its customers and stakeholders to ensure the safety and success of their programs and projects. A resource for the Agency, the NESC is a unique and valuable asset for the high-risk programs that NASA undertakes.

At the core of the NESC is an established knowledge base of technical specialists pulled from the ten NASA Centers and from a group of partner organizations external to the Agency. This ready group of engineering experts is organized into 15 TDTs. TDT members are drawn from NASA, industry, academia, and other government Agencies. By drawing on the minds of leading engineers from across the country, the NESC consistently solves technical problems, deepens its knowledge base, strengthens its technical capabilities, and broadens its perspectives, thereby further executing its commitment to engineering excellence.

Maintaining a diverse and broad base of knowledge, keeping informed and engaged with each Center and the Agency's major programs, responding efficiently to requests for assistance, and retaining a high degree of independence are the basis of the organizational structure of the NESC. There are some 50+ full-time NESC-badged employees, the majority of which are based at NESC Headquarters located at NASA's Langley Research Center in Hampton, Virginia. NESC employs over 550 other engineers nationwide (part-time) as the members of the 15 TDTs.

To achieve the goals stated above, the NESC is organized into six distinct offices:

**NASA Technical Fellows** assemble, maintain and provide leadership for the TDTs and are stewards for their disciplines. The Technical Fellows serve as the senior technical experts for the Agency in support of the Office of the Chief Engineer and the NESC. They are an independent

resource to the Agency and industry to resolve complex issues in their respective discipline areas. While they all lead their own NESC TDTs, some Technical Fellows may also lead Agency-wide discipline Working Groups. Specifically, the Technical Fellows are responsible for: 1) fostering consistency of Agency-level standards and specifications, 2) promoting discipline stewardship through workshops, conferences and discipline advancing activities, and 3) ensuring identification and incorporation of lessons learned into Agency processes.

**NESC Chief Engineers** provide insight into their Centers' programs and help to coordinate the facilities and resources of each Center when required to support NESC activities. NESC also proactively exploits its network of Center-based Chief Engineers for outreach to and communications with the broad NASA community. The Chief Engineers also coordinate with the NASA Technical Fellows in the process of identifying potential discipline issues and problems to be addressed proactively by the NESC.

**Principal Engineers** use TDT members provided by the NASA Technical Fellows and resources arranged by the NESC Chief Engineers to lead independent technical reviews, assessments, tests, and analyses.

**The Systems Engineering Office** dispositions requests as they come in, performs proactive trending analysis and problem identification, and provides other integration and system engineering support.

**The Management and Technical Support Office** is the business arm of the NESC, taking care of the contracting, budgeting, and management of the NESC's infrastructure.

Under the leadership of the **Director's Office**, these five components come together to form the heart of the NESC — the NESC Review Board (NRB). The life cycle, from initial assessment plans to interim status briefings to final reports, of every formal activity performed by the NESC requires approval of the NRB. The NRB is a vital peer review process for the NESC, which directly supports the development of high quality end products for stakeholders. All NESC reports must be reviewed and approved by the NRB prior to out-briefing the stakeholders. The NRB brings a diversity of thought to the decision-making process. It is an amalgam of people representing different Centers, programs, and engineering backgrounds.

After an activity performed by the NESC has concluded, results are delivered to the stakeholders in the form of written engineering reports that include solution-driven preventative and corrective recommendations. The NESC strives to set the example for the Agency by providing full and appropriate documentation of every activity. Along with each report, lessons learned are communicated to Agency leadership and to engineers through avenues such as the Agency's Lessons Learned system, the reports themselves, and the periodic NESC Technical Bulletins.

In addition to acting on requests from outside of the NESC, another important function of the NESC is to engage in proactive investigations to identify and address potential concerns before they become major problems. To further this goal, the NESC is currently leading NASA's efforts for independent data mining and trend analysis. The NESC has established a Data Mining and Trending Working Group that includes representatives from all NASA Centers as well as external to the Agency.

### 3.0 NESC GN&C TDT

The GN&C TDT is a technical resource that supports the NESC and the NRB-approved independent assessment teams. The primary purpose of the GN&C TDT is to engage in the resolution of GN&C related issues throughout the agency when directed by the NRB or by NESC senior leadership. A secondary purpose of the GN&C TDT is to identify proactively Agency-wide GN&C engineering discipline issues and problems.

The NASA Technical Fellow for GN&C assembles, maintains, and manages the GN&C TDT. The GN&C resources (subject matter experts, tools, and test facilities) required to support the assessment teams and other GN&C-specific NESC activities come from the TDT. The GN&C TDT is cognizant of all GN&C related assessments to ensure adequate and timely GN&C expertise support. This is accomplished via bi-weekly teleconference meetings and with annual face-to-face meetings of the TDT. These and other communication mechanisms (e.g., a NESC-internal GN&C TDT secure website to post team news and other information) are used to unite the TDT members located across NASA.

The GN&C TDT consists of individuals that are experts in a wide range of GN&C sub-disciplines including GN&C systems, GN&C analysis, GN&C components and hardware systems (sensors, actuators, interfacing hardware systems), GN&C software, flight dynamics, mission design, flight operations, launch vehicle flight mechanics analyses, and launch vehicle guidance systems. As mentioned above, this team of experts collectively serves as discipline “think tank” to identify potential GN&C issues and problems to address proactively by the NESC.

Given the wide-breadth and depth required to staff the GN&C TDT adequately as well as to support multiple assessments simultaneously, a staffing model has been developed to recruit and staff the GN&C discipline TDT. This staffing model requires skill sets representing discipline systems experts, sub-discipline specific experts, and technical team support personnel. The GN&C TDT consists of a “core” group of approximately 20–30 discipline systems experts. It also consists of an extended team of about 5–6 specific experts from each of the sub-discipline areas of expertise that encompass the broad scope of the GN&C discipline at NASA. These sub-discipline experts are on call-up to the NASA Technical Fellow and to the core team. Approximately 100 GN&C experts, the majority of them being NASA Civil Service employees from across the Agency, currently comprise the entire NESC GN&C TDT. When the operational function of the GN&C discipline TDT is constrained by limited Agency in-house staffing resources, additional GN&C discipline expertise from outside the NASA community (e.g., industry and academia) are exploited to augment the TDT membership.

The members of the “core” group are senior level individuals from across the Agency that have broad, but expert knowledge. These senior experts have in-depth knowledge of one, or several, GN&C expertise areas, but probably not all the GN&C areas of expertise. The individuals who make up the TDT’s “core” group possess exemplary leadership and teamwork skills since they both represent their Center’s GN&C engineering organization and also serve as the GN&C leadership interface to the NESC’s assessment teams.

The sub-discipline specific experts are individuals that have in-depth experience and expertise in a specific GN&C area. The TDT core group defines these specific areas. For example, on the

GN&C TDT, there will be sub-discipline experts in the following areas: inertial sensors, GPS navigation, spacecraft attitude determination and control, stellar/celestial sensors, formation flying, flight dynamics, aeronautical vehicle flight control, inter-planetary navigation, flight mechanics, reaction wheels, control moment gyros, controls structures interaction, mission design, launch vehicle guidance and control, etc.

The technical support group is the third and last major component of the GN&C TDT. The technical support group is a small (about 3–5 people) contingent of individuals that support the NASA Technical Fellow for GN&C in the day-to-day management and operation of the GN&C TDT. These are typically GN&C engineers with perhaps 5–8 years of professional work experience. They contribute routine administrative and technical support (e.g., recording teleconference meeting minutes, providing logistics for the annual face-to-face meeting, updating the TDT's internal website, etc.) while at the same time benefiting from the mentoring experience of working with the other TDT members. The technical support group, by virtue of their role on the TDT, has exposure to a wide range of GN&C problems from across NASA as well as the opportunity to witness first-hand the problem solving skills of some of the Agency's senior GN&C engineers. This has turned out to be a win-win situation that both benefits the operation of the TDT and the technical support group personnel.

In closing this section of the paper there are some general observations that should be made regarding the multiple benefits of serving as a TDT member. Working as a member of an NESC TDT clearly offers challenging opportunities. Members of the TDT interact with the best of the best in NASA, industry, academia, and other government agencies to address a broad spectrum of discipline technical issues. TDT members also find that working within the NESC organizational structure permits an exposure to other NASA programs, projects, cultures, methods, and business practices from across the Agency. Typically, this allows experiences to be gained outside one's normal work area within a single NASA Center organization. The experience should broaden one's horizons via the wide network of job-related interactions. There will be technically challenging and diverse assignments of a high impact/high feedback/high visibility nature. Serving on a TDT provides an avenue for both professional growth and positive recognition, not only within the discipline Community of Practice but also within the NESC's customer and stakeholder community. The overall TDT experience is one that should provide motivated, tenacious, and intellectually curious team members with a very high degree of job satisfaction.

#### **4.0 Experiences of the NESC GN&C TDT**

The GN&C TDT has engaged in multiple NESC assessments, consultations and reviews since the NESC became an operational organization in November of 2003. Reference 1 provides a description of NESC GN&C TDT activities over the period 2003 to 2007.

Highlighted in this section are several of the most recent TDT experiences. In certain cases, significant relevant technical details are provided as background. These experiences, which occurred over the period from 2007 to present, were selected to illustrate the wide variety of work the GN&C TDT engages in. The reader will see that the GN&C TDT supported both human space flight projects and robotic spacecraft projects. The time durations over which the work was performed varied from durations of a few weeks to a month or two for the smaller

scale quick-reaction peer review tasks to durations of several months to over a year for larger scale efforts. In cases where the task was primarily focused on a specific GN&C discipline issue, the work was performed exclusively by the NASA Technical Fellow for GN&C and/or small contingents of GN&C TDT members. In other cases that required a more multi-disciplinary approach the GN&C TDT members supported the task as part of a larger, integrated NESC team effort under the direction and leadership of an NESC Project Engineer. As with the majority of NESC endeavors, experts from virtually all NASA Centers, other government Agencies, national laboratories, academia, and industry were involved in conducting these activities.

#### **4.1 Max Launch Abort System (MLAS) Flight Test Assessment**

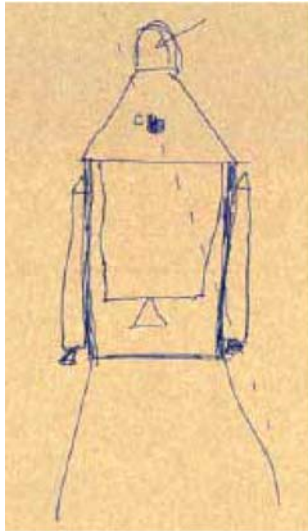
The NESC designed, developed, and flew the alternative MLAS as risk mitigation for the baseline Orion spacecraft launch abort system (LAS) already in development. The NESC was tasked with both formulating a conceptual objective system (OS) design of this alternative MLAS as well as demonstrating this concept with a simulated pad abort (PA) flight test. The goal was to obtain sufficient flight test data to assess performance, validate models/tools, and to reduce the design and development risks for a MLAS OS.

In June 2007, the Associate Administrator for the Exploration Systems Mission Directorate (ESMD) requested the NESC undertake the MLAS Project. The MLAS was named after Maxime (Max) Faget. Dr. Faget was the lead designer of the Mercury space capsule and developed its abort system called the “Aerial Capsule Emergency Separation Device”. It was in his honor that the MLAS was named. His innovative spirit and his team’s rapid development of new technologies formed the inspiration for the MLAS Project.

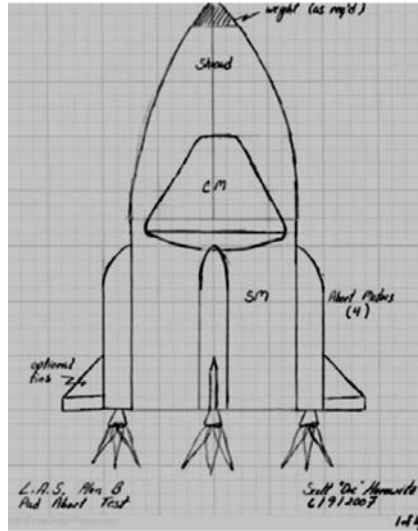
The charter for the MLAS Project was to develop, design, and test an alternate concept for the Orion Crew Exploration Vehicle (CEV) LAS. MLAS would be theoretically capable of extracting the Orion vehicle from the launch vehicle at any time from crew ingress at the launch pad through staging and ignition of the second or upper stage of the Ares-I crew launch vehicle. The MLAS Project would conclude with at least one full-scale unmanned PA test suitable for demonstrating the viability of this alternate LAS concept. The MLAS project would be run independently from the Constellation Program (CxP) and Orion Project in order to minimize impact on in-line program resources. It was dictated that off-the-shelf hardware and existing technology would be used wherever possible on MLAS. Design and development work previously accomplished by the NESC would be leveraged for this project. Previous work includes the CEV smart buyer design (SBD), composite crew module, and the alternate launch abort system. This NESC infrastructure was used to form the NASA-wide MLAS Project team. For example, members of the GN&C TDT (Reference 1) were recruited to serve on the MLAS GN&C team and other members were subsequently recruited to serve as peer reviewers of the GN&C team’s work.

The origins of the tower-less MLAS flight test vehicle (FTV) can be traced to the initial notional ‘back of the napkin’ drawing (see Figure 1a) that was conceived during a CEV SBD study outbrief brainstorming session in March 2006. Subsequently, a refined MLAS drawing (see Figure 1b) was provided to NESC in June 2007 by Scott “Doc” Horowitz, the Associate Administrator for the ESMD at the time MLAS was initiated, as a notional point of departure for the early system level trades and vehicle configuration studies. It is interesting to compare the final MLAS FTV prelaunch physical configuration (see Figure 1c) with the original notional

drawings depicted in Figure 1a and Figure 1b. One can clearly see that the MLAS concept differs from Orion LAS in that it uses side-mounted abort motors instead of a tower-tractor abort motor design that pulls the crew module (CM) from above. The tower abort motor has been designed out of the MLAS concept and the CM fully encapsulated in a forward fairing.



a) First notional conceptual drawing (2006).



b) Refined conceptual drawing (2007).



c) Mounted on launch stool at Wallops Island (2009).

Figure 1. MLAS FTV.

The MLAS GN&C team was formed in July 2007 and was given the responsibility for modeling, simulating and analyzing the trajectory and attitude dynamics of the MLAS FTV during its simulated PA flight. The GN&C team ensured that the flight test occurred within the envelope defined by the requirements, and they constructed the nominal target flight timeline and trajectory. The GN&C team selected all of the MLAS trajectory and attitude flight instrumentation equipment including the inertial measurement units (IMUs) and global positioning system (GPS) receivers. The team chose these navigation sensors to generate flight test data that would permit post-flight reconstruction of MLAS vehicle trajectory and attitude dynamics. Analyses performed by the GN&C team determined ballasting, motor alignment, and launch stand angle requirements. Over the course of the MLAS Project the GN&C team worked closely with the System Engineering and Integration, Aerodynamics, Landing and Recovery System, Propulsion, Avionics, Software, Structures, and Loads and Dynamics teams and also with the MLAS Chief Engineer. The MLAS Project was by far the most extensive activity undertaken by the GN&C TDT over the period of time being covered in this paper.

The MLAS simulated PA flight test was successfully conducted from Wallops Island on 8 July 2009. Figure 2 shows the MLAS FTV shortly after abort motor ignition. Figures 3 and 4 depict the CM altitude versus range and the CM altitude versus time, respectively. Figures 3 and 4 show the position data from the GPS receivers alongside the pre-flight predictions made with the wind, density, static pressure and speed of sound data from the L-3 minute balloon sonde. The as-flown flight trajectory was somewhat steeper than that predicted in the pre-flight simulation; however, the trajectory deviation from the prediction was within 0.75 standard deviations in all directions.



Figure 2. Launch of MLAS FTV from Wallops Flight Facility (8 July 2009).

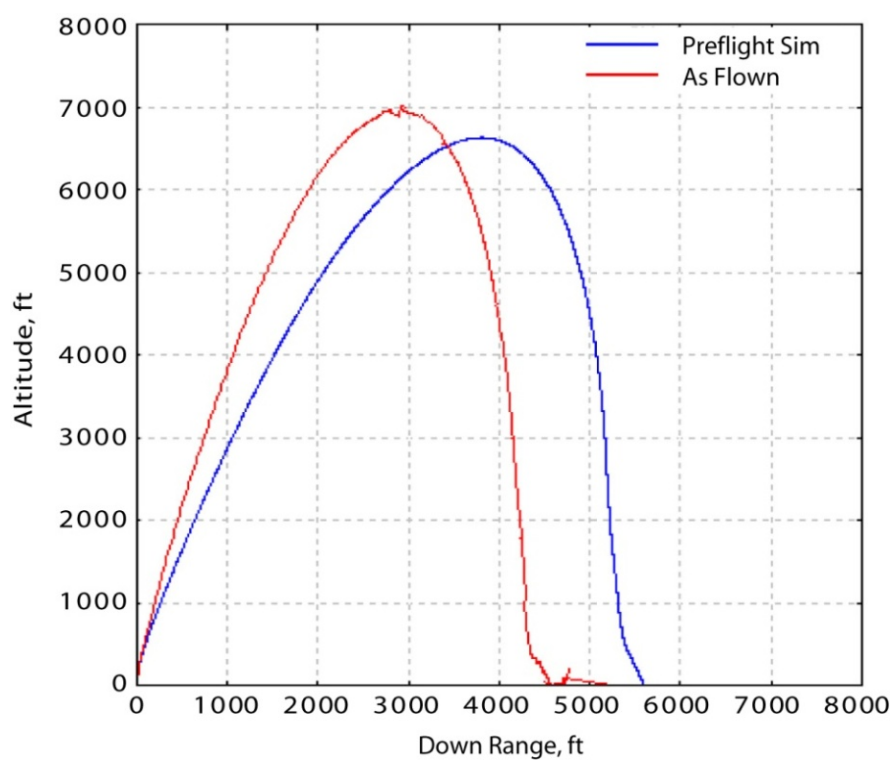


Figure 3. MLAS CM altitude versus range.



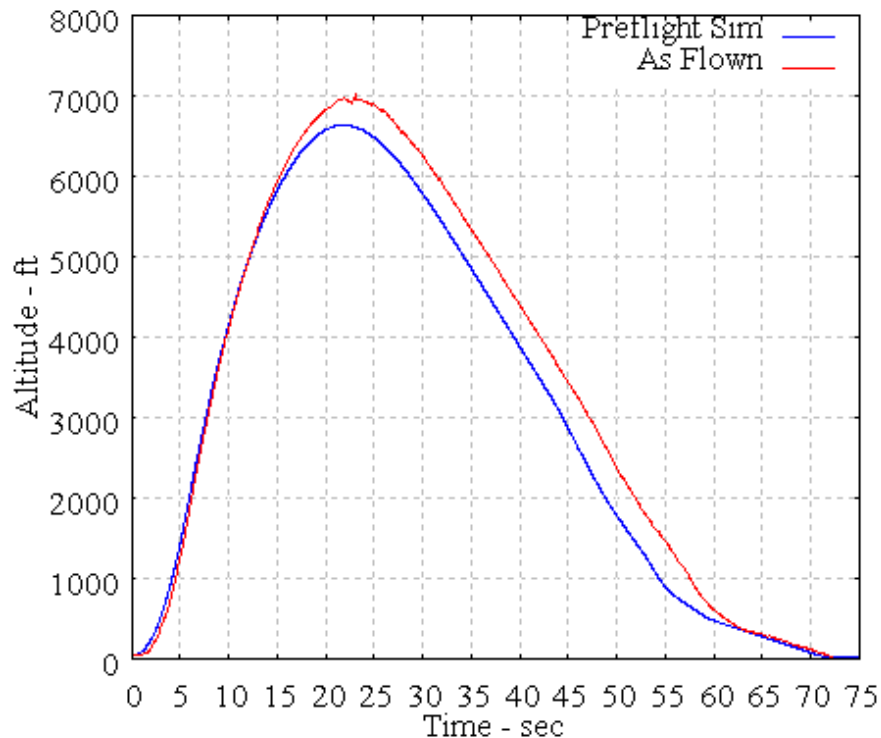


Figure 4. CM altitude versus time.

The GN&C TDT can look back upon the MLAS experience and observe that less than two years after project start the flight test of this alternative launch vehicle abort system was conducted in very close agreement with its operations concept. All the key flight test events occurred in the prescribed sequential order and within acceptable tolerances of the exact pre-planned time and flight dynamic conditions. The entire flight test duration was 88 seconds during which multiple staging events were performed, and nine separate critically timed parachute deployments occurred as scheduled. Overall, the as-flown flight performance was as predicted prior to launch.

The primary lesson learned on MLAS was the extent to which the design and integration of a LAS can impact and influence the overall launch vehicle/spacecraft system design, overall reliability, and performance capabilities. Several other important lessons learned from this MLAS flight test experience are:

- The need for all project team members to look beyond their immediate discipline task to think, speak up, and act like Systems Engineers for the benefit of the project.
- The need for planned periodic crosschecks of critical analytical results by having technical ‘shoot outs’ between different engineering groups using different tools/methods to independently generate analytical products.
- The need for periodic and informal face-to-face peer reviews; the emphasis should be on reviewing the details of modeling assumptions, analytic methods, uncertainty assumptions, simulation results, control law algorithm designs, software code, etc., and not on preparing formal presentations and responding to action items.

- The need for stringent mass properties testing, and vehicle mass properties configuration control measures and routine periodic reports, especially on a passively controlled vehicle.
- The degree of difficulty in safely and reliably performing precision alignment of the solid rocket abort motors was initially underestimated.
- The need to manage and limit insidious unchecked vehicle mass growth which erodes flight performance, degrades system design robustness, increases parachute loads and generally diminishes the probability of overall mission success. Associated with this is the need to incorporate realistic growth margins into the vehicle's design to mass budget. In addition, this can be mitigated in part by defining a robust set of structural loads requirements as early as possible in the project design cycle.
- A rapid prototyping activity like MLAS can be accomplished using virtual meeting technologies supplemented by periodic Co-Locations of the entire team and by leveraging modern online concurrent data sharing and configuration management capabilities.

#### **4.2 Constellation System Preliminary Design Review (PDR) Assessment**

The Constellation Chief Engineer requested the NESC to participate in the CxP Preliminary Design Review (PDR) process as the Independent Review Team (IRT). The NASA Technical Fellow for GN&C, along with members of his GN&C TDT, served on this IRT. The purpose of the IRT was to ensure technical issues were not overlooked due to familiarity with the PDR products. The IRT was asked to identify technical issues in three categories. The first category was an issue or resolution to an issue that was incomplete or not fully addressed. The second category was an issue that was not addressed. The third category was an issue that the IRT disagreed with its resolution or had a contrary opinion.

The CxP PDR process, which culminated in April 2010, had the following several objectives:

- Demonstrate the End-to-End (E2E) understanding of the Initial Operational Capability Mission and where the design is driven by the Lunar Mission
- Demonstrate that the completed analysis and tests provide the results necessary to close the architecture to accomplish the Design Reference Missions
- Demonstrate the architecture performance is capable of accomplishing the E2E mission with acceptable risk
- Identify key architecture risks and associated mitigation status
- Baseline Initial Capability Interface Requirements Documents and draft Spacecraft Interface Control Documents
- Documented Program Test & Verification Strategy and draft System Integration Plans released
- Define the Forward Work plan necessary for a successful CxP Critical Design Review

The IRT members first participated in a series of discipline-specific Face-to-Face Integration Reviews, each led by the respective phase lead engineer. This was an excellent approach to somewhat informally ‘break the ice’ technically in each of the mission phases (e.g., ascent, on-orbit, entry descent and landing, etc.) prior to the actual formal CxP PDR milestone. These mission phase reviews were held near the Johnson Space Center (JSC), Houston, Texas, over the period from November 2009 through December 2009. In addition, the IRT participated in the PDR kickoff meeting held the week of January 12, 2010 and the PDR Pre-Board and PDR Board meetings held the week of March 1, 2010. The IRT provided 41 review item discrepancies (RID) and five comments in the RID system.

Overall, the GN&C Technical Fellow and the participating members of the GN&C TDT believed the CxP PDR process was a good high-level review of the Program maturity and identified the issues, work completed, work to be performed, etc. The face-to-face meetings created an environment of open communication among all participants. The face-to-face teams were very receptive to the IRT’s comments and met separately with the IRT to alleviate concerns and issues. The RID Review Teams (RRT) attempted to understand the issues by speaking directly with the RID initiators rather than just reviewing the RIDs on paper. The RRTs tried to accommodate the initiators’ schedules and coordinated with them to be able to state their case directly. When impasses were reached, the reclama process was recommended to the initiators. The IRT agreed that the RRTs had worked with all the RID initiators to reach mutually agreeable resolutions to the issues that were raised and all RIDs that the IRT submitted were acceptably resolved.

Clearly, the PDR process was a very successful forcing function to bring forth “gaps” and discrepancies. The identification of these occurred because of the open communications with the IRT and between all levels of the program and projects. However, it was apparent that not all the needed integration was occurring during normal program functions prior to the PDR process. It is understandable to have elements that lag behind others when everyone is concentrating on their top issue or latest problem. New issues were raised and clarifications were generated during the PDR process. For example, a RID was written to address the fact that, as presented, the Ares-I Roll Control System (RoCS) propellant margins (at about 8%) were lower than the 20% margin typically desired at the time of the system PDR design milestone.

The issues that were identified by the IRT were grouped into four broad themes and summarized in a NESC White Paper provided to CxP program managers and others. The items discussed in the NESC White Paper fell into all three categories of technical issues that the IRT was charged to identify. The first theme identified issues that were lacking the technical maturity required for a PDR. The areas of launch abort vehicle (LAV) performance in the transonic flight regime, updating of the integrated Probabilistic Risk Analysis (PRA) model, regression test planning, incorporation of human factors to support design trades and studies, and the mismatch of program and project maturity levels fell within this category. The recommendations included pursuing engineering solutions at this early stage of the design process and saving operational changes for later as the program matures and when design changes can be prohibitively expensive to implement.

The second theme addressed uncertainty in models and simulations. The GN&C Technical Fellow and the GN&C TDT members felt the interpretation, quantification, and application of

model and data uncertainty were especially important areas to be addressed by both CxP managers and engineers. It is acceptable to have uncertainty in models and simulations, but quantifying the uncertainty and clearly communicating the model uncertainty to perform trades and to make informed decisions of risk needs to be emphasized.

Mathematical models, and their associated data sets, are used to capture and represent the current state of knowledge of system physical behaviors in every element of the CxP architecture. These models and their supporting data are exercised to analyze and predict system sensitivities, performance against requirements, factor of safety/stability margins, risks and overall mission success.

It is a recognized and accepted reality that these models and their data have limitations. Some models have insufficient experimental data to characterize precisely a probability distribution of critical model parameters and features. In other cases, there is only poor or limited understanding of the underlying physics phenomena or physical coupling between system elements or between sub-elements. Beyond our inability to completely understand the dynamics of a given problem there is also the reality that there will be both variability in the physical features/parameters of the as-built flight systems and additional variability in the operational environments encountered during manufacturing and assembly, ground operations, and mission operations. All of these aspects need to be accommodated and quantified in an uncertainty framework by the engineers using the models/data.

Various methods and approaches have been used across CxP and its elements to characterize the uncertainty in these models and their supporting data. The NASA-STD-7009 for Models and Simulations was developed to help NASA programs/projects consistently address the challenges of documenting, analyzing, and communicating uncertainties, and several other modeling and simulation issues in the Agency. The NASA-STD-7009 also requires clear documentation and communication of model assumptions to decision makers. Reporting uncertainties in model inputs and outputs is required for critical analyses, and data/model uncertainty quantification are factors in the credibility assessment scale (CAS) review. The CAS review provides a common framework to evaluate models and simulations.

However, there is not a consistent interpretation of uncertainty across the CxP architectural elements, and NASA-STD-7009 does not address inconsistency in model uncertainties across a set of analyses within a program. This is a concern since having a proper and consistent application of model/data uncertainties is fundamental to providing CxP decision makers with informed risk analysis information. Consistency is especially important where CxP decision makers are seeking to trade risk across architectural elements, across system elements, and across technical disciplines. Furthermore, flight system designs can be excessively over-conservative if modeled uncertainties are significantly higher than the variations or unknowns of the physical system. Conversely, designs can be at risk of failure if modeled uncertainties are lower than the actual variations of the physical system. Input data uncertainties are included in the integrated loss of crew/loss of mission models, and the PRA results include reporting uncertainty ranges using 5<sup>th</sup> and 95<sup>th</sup> percentiles.

An example of the model uncertainty issue is a recent aerodynamic database model uncertainty distribution change that resulted in a reduction of the LAS attitude control motor (ACM) control authority in the transonic flight regime ( $M = 0.9\text{--}1.3$ , 35–47 sec mission elapsed time). This has driven the need for the CxP to investigate alternative means of improving performance of the LAV (e.g., adding ballast mass). In parallel, special wind tunnel tests are being pursued in an effort to lower the uncertainties in the aerodynamic database.

There is some level of recognition that the application of model/data uncertainties needs to be improved within CxP and certain teams are actively working the issue. It is not clear however that the current practice of inconsistent interpretation and application of uncertainty across CxP has been elevated sufficiently high and captured as an integrated risk for the program. A common uncertainty framework for all CxP elements that is consistent with NASA-STD-7009 would provide needed consistency and rigor in addressing the issues associated with model/data uncertainty. Per NASA-STD-7009, reporting uncertainties in model inputs and outputs is required for critical analyses and data/model uncertainty quantification, documentation, and communication are factors in the CAS review.

With all the great work in models and simulation, a trap can occur where there is an overreliance on models and simulation. This can occur because the people who are doing the day-to-day problem solving are so caught up in working with the models and trying to reduce and define the uncertainty associated in the models that they fail to realize the solution they are obtaining can defy the basic laws of physics and engineering. Using engineering judgment to check the analytical results, engaging the critical end users in the process of quantifying uncertainties, and periodically re-evaluating assumptions and processes should occur to avoid this trap.

The third theme addressed in the NESC White Paper deals with disconnects in the level of maturity between project elements and interfaces. The last theme discussed the process of identifying test needs. The IRT noticed a perception that some testing was not being pursued due to reasons of cost or schedule even though the test might significantly buy-down risk. The IRT recommended the development of a list of minimum required tests (i.e., an ‘incompressible’ test list).

This particular experience reminded all the teams involved that an independent review can provide a fresh perspective not biased by long-term involvement with the project or program. The Face to Face Integration Reviews, led by the respective phase lead engineers, was a tremendously valuable first step in the overall CxP PDR process. For the CxP PDR, the IRT worked with the program and project personnel to identify new issues or issues that the program knew of, but did not have the right management visibility. More importantly, the IRT provided recommendations that should be pursued.

### **4.3 Orion Ascent Abort One (AA-1) Loads Assessment**

In April 2009, the Systems Engineering Integration Team Lead in the Orion Test Flight Office requested that the NESC perform an independent assessment of AA-1 coupled loads analysis performed in support of AA-1 Load Cycle-1(LC-1).

Based on data from AA-1 LC-1, there were concerns regarding the high-load levels predicted during vehicle separation, twang, ascent, and maximum dynamic pressure (Max-Q). The NESC Team was tasked to perform an independent review of data and provide consultation on the analysis approach and associated assumptions, limitations, and uncertainties. The intent of the NESC review was to thoroughly scrub all aspects of LC-1 and then provide findings, observations and recommendations for any changes to be incorporated into the follow-on effort, LC-2. The NESC Team was not expected to provide an independent load analysis unless significant issues were identified.

Figure 5 provides an illustrative comparison between the PA-1 flight test configuration and the AA-1 flight test configuration. The AA-1 LAV system includes the LAS, LAS fairing assembly, and CM. The AA-1 abort flight test will launch from the White Sands Missile Range. During the boost phase, the LAV will be connected to the abort test booster (ATB) through the separation ring (SR). The ATB will boost the LAV to an altitude of nearly 38,000 feet before separation of LAV from ATB/SR. The LAV abort motor (AM) and ACM will ignite and burn for less than five seconds. Then the LAS will separate from the CM, and the CM will descend via parachute to a soil landing.

The critical loads for the LAV occur during the motor burn, parachute deployment, and landing. However, LC-1 covered only the motor burn phase, which included LAV separation from the ATB, ignition of the AM, and flight up to Max-Q.

Several members of the GN&C TDT, together with members of the NESC Flight Mechanics TDT, supported this assessment by investigating and reporting on the technical features of the ATB boost phase flight control system (FCS) and other aspects of the AA-1 GN&C system design that influenced the vehicle loading during flight. In particular, the GN&C and Flight Mechanics TDT members concentrated on how the Monte Carlo analysis of the AA-1 boost phase and resulting separation conditions was performed.

The team determined that LC-1 was adequate as a preliminary set of initial design loads for AA-1 considering the number of uncertain or undefined parameters in structure, aerodynamics, event timing, etc. that existed at the time of the analysis. Given these qualifiers, it is not surprising that numerous areas were noted where improvements could be effected in LC-2.

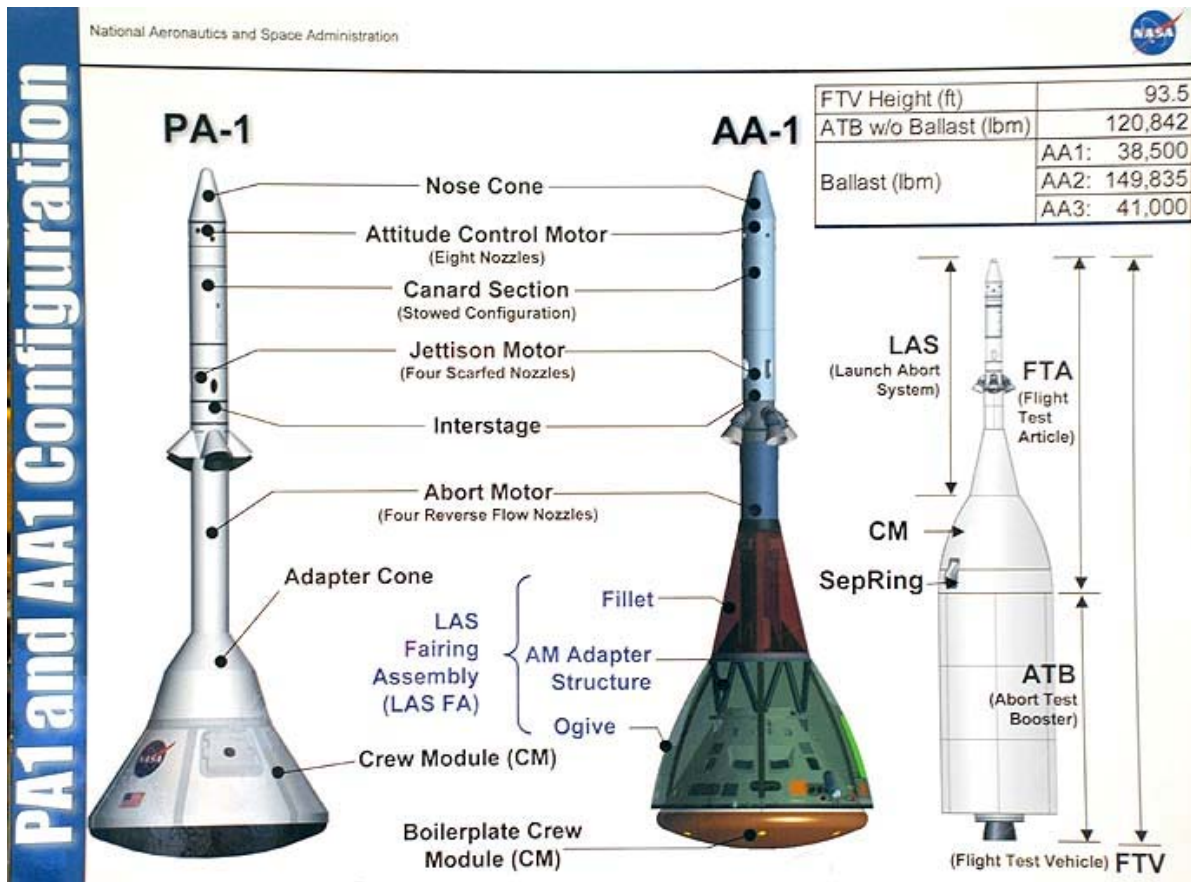


Figure 5. Comparison of PA-1 and AA-1 flight test configurations.

Some of the items the NESC team found necessary to be corrected or implemented for LC-2 to produce a complete set of detailed design loads and thorough structural assessments included:

- Develop a Project Technical Requirements Document that specifically defines AA-1 hardware functional and design requirements, environmental requirements, interfaces with other hardware, etc.
- Document the use of uncertainty factors or dispersions in the various LC-2 inputs to the analysis for concurrence by the responsible technical panels and the Orion Flight Test Office.
- The thrust alignment/offset dispersions of the abort motor should be clearly defined (1 degree was arbitrarily used).
- The AM thrust offset dispersions to be used in the in LC-2 analysis should include such factors as temperature distortions, assembly tolerances, as alignments.
- The boost phase Monte Carlo analysis should be used to define the required range of initial flight conditions at separation for the loads analysis in LC-2.
- The full specified range of allowable center of gravity (CG) locations should be explored in LC-2.

- A sensitivity analysis should be performed to check the effect of extreme “corner of the box” CG mass properties on modal characteristics.
- Propellant mass changes should be included in the LC-2 analysis as those changes affect both structural dynamics and CG shifts.

#### **4.4 Orion CM Boilerplate Water Drop Test Assessment Support**

In October 2009, the NESC initiated an assessment to perform the specific tests and analyses needed to provide the necessary verification to correlate LS-DYNA<sup>®</sup> simulation results with data collected during multiple water drop tests of a full-scale Orion CM boilerplate test article. The LS-DYNA<sup>®</sup> code is an advanced general-purpose multiphysics simulation software package developed by the Livermore Software Technology Corporation and used to design the Orion CM structure. The LS-DYNA<sup>®</sup> software package, which employs finite element analysis methods using explicit time integration, is especially well suited for the simulation of highly nonlinear transient dynamic events such as the impact dynamics of the CM structure when it lands in water. The nonlinear effects typically manifest themselves as changing boundary conditions, relatively large material deformations, and certain materials that do not exhibit ideally elastic behavior. Transient dynamic means analyzing high-speed, short-duration impact events where inertial forces are important.

The fundamental structural design simulation tool for the Orion Project was LS-DYNA<sup>®</sup>, specifically developed to accommodate non-linear load paths as occur during water impacts. The NESC Assessment Team surveyed readily available LS-DYNA<sup>®</sup> literature on the use of the tool to model water impacts, and assessed that some of the techniques used are not deterministic but rely on manipulation by the analyst. Experimental data was required to anchor LS-DYNA<sup>®</sup> analyses of water impacts to mitigate the risk of the sort of impact damage seen during Apollo drop tests. A strong motivation for these NESC-sponsored tests is the very limited number of landing impact tests in the Orion Project plan planned to support the CM primary structure development and qualification. The Orion Project had concerns regarding the possibility that significant uncertainties would remain in the landing load environment, resulting in an unknown structural capability and an inability to achieve structural certification for flight. Since LS-DYNA<sup>®</sup> is being used to establish the structural design of Orion, this program and other NASA programs are critically dependent on the validity of the answers generated by the tool. This independently performed and fast-paced series of drop tests, and the subsequent detailed evaluation of the data collected, are intended to support risk determination for the Orion Project and NASA, potentially influencing future CM testing plans and design options. This particular NESC assessment is contributing to the ultimate NASA goal of developing an integrated landing system design, with a mass-optimized space capsule structure, that will attenuate the impact loads transmitted to the crew to non-injurious levels. The key stakeholders for this assessment are the Orion Project team and the NASA Office of Chief Engineer.

The NESC’s MLAS CM simulator (boilerplate) was identified as a rapidly available test article. This test article was instrumented in two phases, and tested via crane drops into water. Instrumentation included multiple inertial sensors, photogrammetric targets, pressure transducers, and strain gages. The first phase of drop tests were performed at the U.S. Army’s Aberdeen Proving Ground located in Maryland. The test article was hoisted via a crane to a pre-determined level and then released to drop into the water (see Figure 6). In Phase I of this drop



test assessment, a total of eighteen (18) drops were conducted: fourteen (14) were dropped from a height of ten feet and the remaining four (4) were “low-energy” drops released at a height of eight (8) feet.

Members of the NESC GN&C TDT were requested to support both the generation of quick-look, in near realtime, inertial sensor data products as well as to perform the more detailed post-test processing and analysis of the water drop test data generated by multiple inertial sensors. The GN&C TDT members augmented the existing drop test by bringing the necessary skills and expertise to understand, convert, transform, format, process, and analyze data from the multiple gyroscopes and accelerometers mounted on the test article. The inertial sensors included four tri-axial accelerometer packages, two packages mounted very near the CM test article’s CG and the other two mounted near the apex of the test article’s apex. There were also individually mounted analog devices single-axis micro electro-mechanical systems angular rate sensors (gyroscopes) as well as a Humphreys Crossbow<sup>®</sup> IMU. These inertial sensors were mounted on an aluminum structural crossbeam (see Figure 7).



Figure 6. Orion CM boilerplate water drop test at Aberdeen Proving Ground.

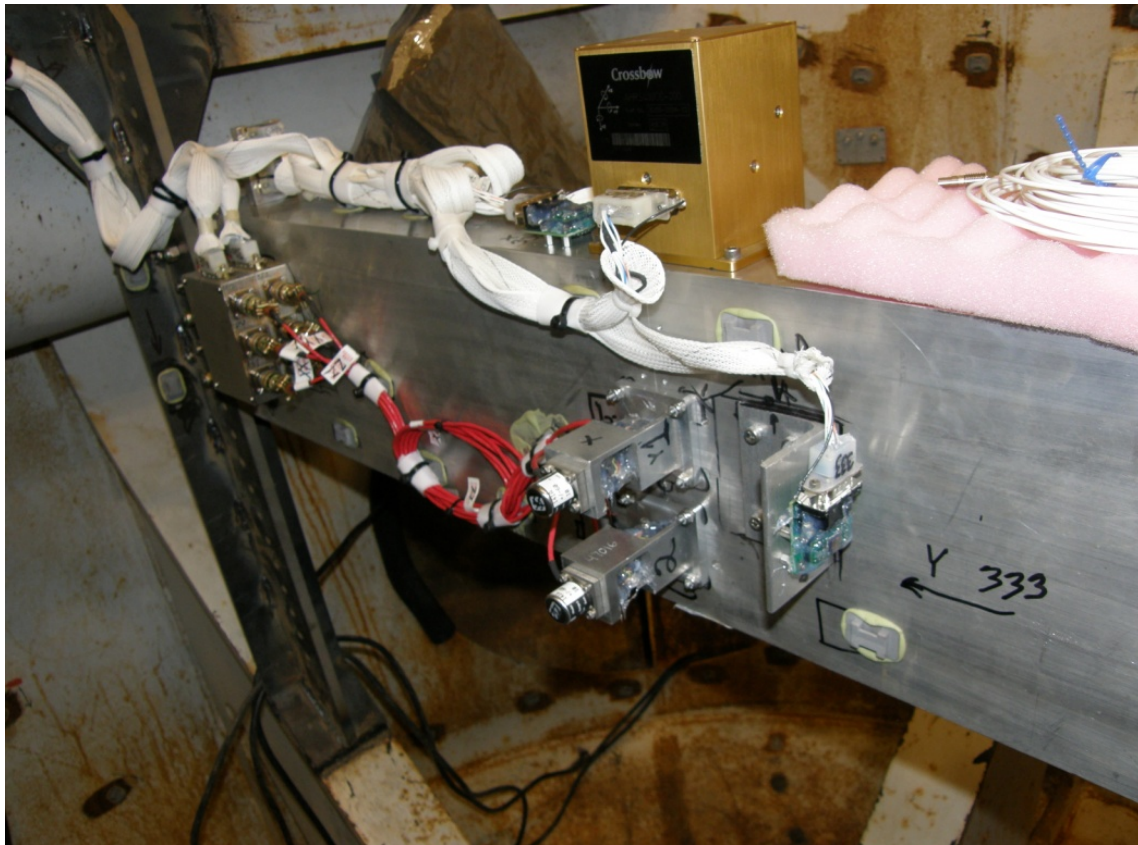


Figure 7. Inertial sensor instrumentation mounted inside CM test article.

Acceleration data was collected using analog sensors with a bandwidth of 1000 Hz, which was then sampled at a rate of 13,888 Hz, embedded in a telemetry stream, and recorded. A representative example of the raw data collected is the longitudinal axis (X-axis) acceleration vs. time data plot is presented in Figure 8. Quick-look analysis of the acceleration data collected revealed a noise floor at approximately  $-15$  dB along with the undesired presence of several unwanted CM structural modes, in particular the structural modes of the aluminum crossbeam on which the sensors were mounted. The flexible body modes can be seen in Figure 8 over the range from 100 Hz – 1000 Hz with the peak flexible mode response occurring at 375 Hz at approximately  $+8$  dB. A proper analysis of the acceleration data therefore required the attenuation of unwanted high-frequency structural “noise” while keeping the low-frequency test article rigid body information and the all-important relatively short duration (150 milli-second) splashdown transient. So, in addition to performing all the necessary data conversions, re-formatting, and coordinate transformations of the various inertial data sets collected, the GN&C TDT contingent spent a great deal of time and effort studying and eventually selecting the type and order of digital filter that would sufficiently attenuate the high-frequency structural ringing effects from the desired rigid body motions.

A third-order low pass filter (LPF) was initially selected to filter the raw accelerometer data collected. This LPF had two second-order poles each at 75 Hz and a single first-order pole at 85 Hz. The second-order poles had a 0.7 damping ratio. The continuous form of the LPF (see

Equation 1 for this representation) was then converted to a digital LPF via the standard bi-linear transformation using a sampling period of 73.5 micro-seconds.

$$F_{lp}(s) = \frac{1}{\left(\frac{s}{\tau_1} + 1\right) \left(\left(\frac{s}{\tau_2}\right)^2 + 2\zeta_2 \frac{s}{\tau_2} + 1\right)} \quad (1)$$

Figure 9 shows the result of digitally low pass filtering the raw X-axis accelerometer data. Clearly, the flexible body effects are significantly reduced leaving a signal more closely representing the CM rigid body response. After much further technical deliberation with the LY-DYNA<sup>®</sup> users a 6<sup>th</sup>-order LPF, applied in one direction only, was selected by the GN&C team to perform the necessary attenuation. Another significant effort concerned determination of the test article's pre-drop initial conditions. Photogrammetric data was utilized to both define the initial conditions and the gyroscope drift and bias estimates. The GN&C TDT members provided sufficient processed inertial sensor test data to permit the comparison and verification of the LY-DYNA<sup>®</sup> simulation results. Phase II water drop test with improved inertial instrumentation are planned for early FY2011.

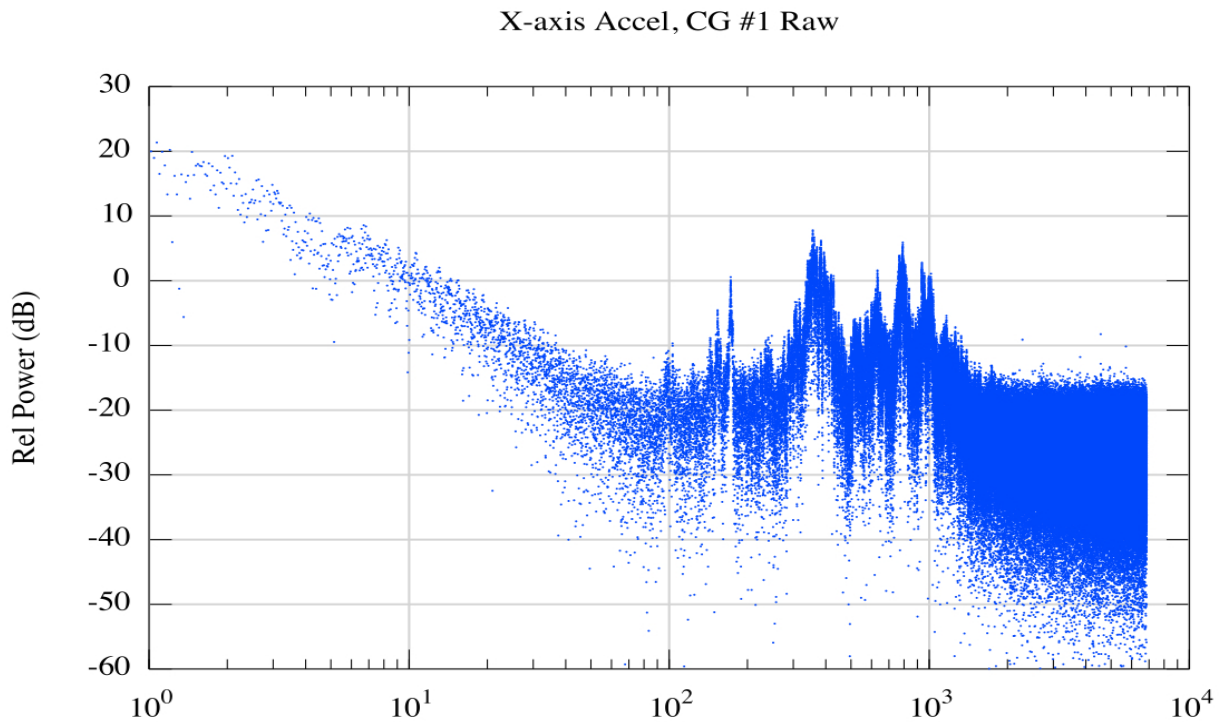


Figure 8. Representative raw X-axis CG#1 accelerometer data from CM water drop test.

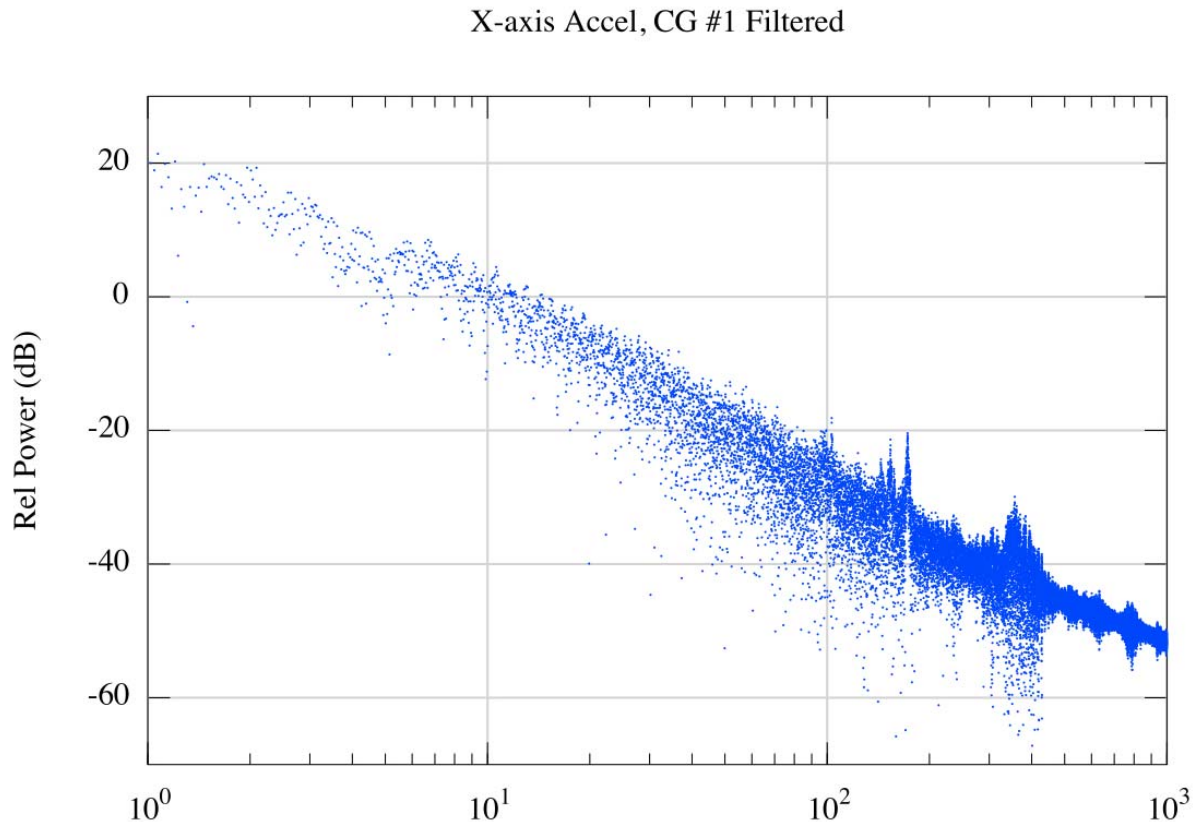


Figure 9. Low pass filtered X-axis CG#1 accelerometer data from CM water drop test.

#### 4.5 Assessment of Orion Slosh Impact on Ares-I FCS Stability

The deleterious effects of propellant sloshing on launch vehicle stability have been long recognized by FCS designers. Slosh dynamics were carefully considered on both the Apollo Saturn-V launch vehicle and the Space Shuttle launch vehicle. The term “sloshing” is used here to describe the phenomenon of the free surface oscillations of the fluid (either fuel or oxidizer) in a partially filled tank.

In December 2009 the NESC GN&C TDT was asked to assess the impacts of the Orion Service Module (SM) slosh dynamics on the Ares-I crew launch vehicle FCS stability and performance. Figure 10 depicts the Ares-I launch vehicle shortly after liftoff from Kennedy Space Center. The NESC assessment team sought resolutions to two fundamental issues: 1) assess conservatism in Marshall Space Flight Center’s (MSFC) Ares-I GN&C impact analysis of Orion SM bare tank slosh dynamics; and 2) Determine if the MSFC GN&C team can design an Ares-I FCS, which accommodates the 0.03% Orion SM bare tank slosh mode damping and satisfies all stability robustness and performance requirements. Given the short time duration of this assessment, the NESC did not perform any independent GN&C modeling, simulation, or analysis. Rather the focus was placed on understanding the details of the Ares-I GN&C modeling, simulation and analyses performed by the MSFC flight control engineers.



Stabilizing the Orion SM slosh mode dynamics on top of the Ares-I flexible-body and LOX/LH<sub>2</sub> slosh dynamics poses a challenging flight-control design problem for MSFC. Extremely low values of Orion slosh damping emerged as early as June 2009 as a key driver in the Ares-I GN&C design. The NESC first became fully aware of the sensitivities of the Ares-I FCS design to the extremely lightly damped Orion slosh dynamics in November 2009. This occurred at the CxP Ascent/Ascent Aborts Integrated Phase Review held at JSC as a precursor to the CxP System-level PDR board. This was true cross-project system engineering and integration issue between Orion and Ares. At that time, as a minimum, it was recommended that a new CxP Program-level risk be created and tracked within the CxP Integrated Risk Management Assessment (IRMA) framework to provide visibility of the Orion/Ares slosh problem. Several elements of risk were to be included in this new IRMA risk item, including:

- Risk to Ares GN&C resources and schedule,
- Lack of flexibility to accommodate future Ares vehicle challenges, changes, and opportunities,
- Loss of Ares capability to accommodate failures,
- Risk for meeting program stability and margin requirements,
- Risk for increased structural loads,
- Loss of significant robustness and hence safety, and
- Risk to Ares' ability to certify GN&C for flight readiness.

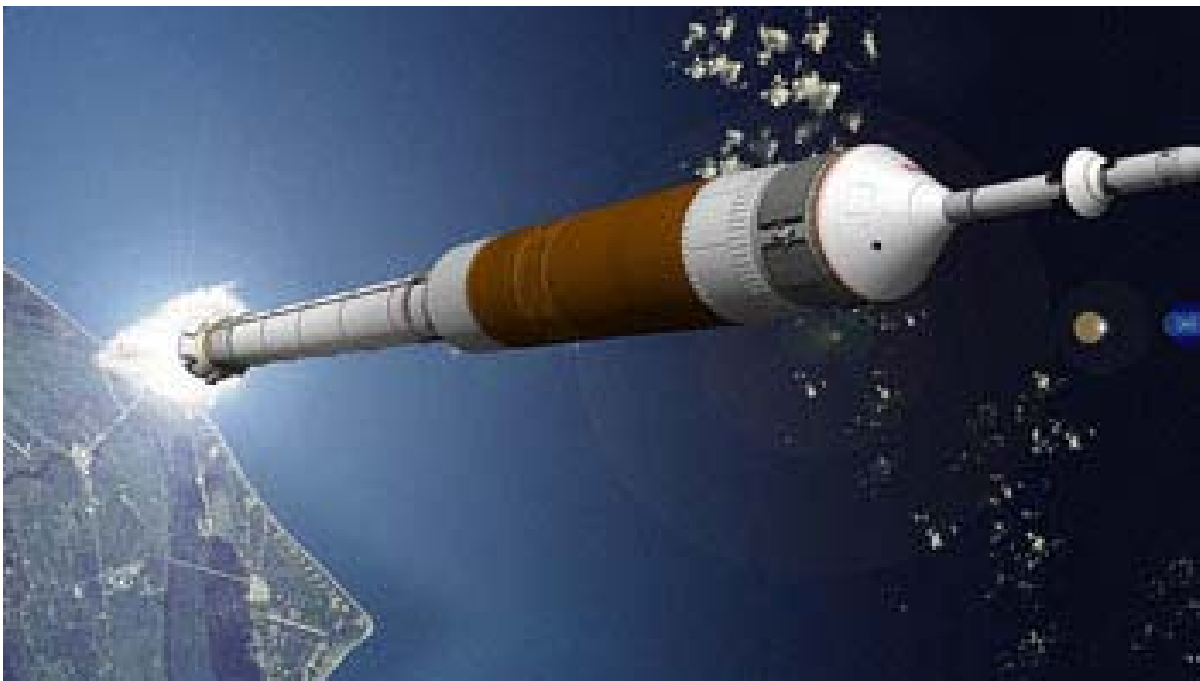


Figure 10. Ares-I launch vehicle shortly after liftoff.

The challenge for the Ares-I FCS designer is to meet simultaneously the stability margin requirements cited above and the linear step response requirements. There are other high-level flight performance requirements that also must be satisfied but these were the one of most interest to the NESC assessment team. Lastly, it should be noted that no minimum fluid slosh damping requirements were ever placed, by the Ares-I Project, on the Orion Project's SM fuel and oxidizers fluid/tank system.

The Ares GN&C 7 design cycle analysis, completed by MSFC flight control engineers in June 2009, had indicated Ares-I FCS sensitivities to Orion SM fuel and oxidizer slosh dynamics. The problem was attributed to two major factors: 1) the Orion's SM fuel and oxidizer tanks are partially filled, resulting in a significant sloshing mass; and 2) the Orion SM tanks have very smooth bare walls. Slosh mode damping values, determined using the industry-standard NASA SP-106 handbook (Reference 2) methodology were computed to be an order of magnitude below NASA heritage. The NESC team performed a comparison of the Orion SM slosh damping values with the Ares-I launch vehicle slosh damping values and legacy slosh damping values from the Space Shuttle Program and the Apollo Saturn launch vehicle. The empirically computed 1-g minimum slosh mode damping value for the Orion nitrogen tetroxide (NTO) oxidizer tank was 0.0003 or 0.03%. Likewise, the empirically computed 1-g minimum slosh mode damping value for the Orion monomethylhydrazine (MMH) fuel tank was 0.0006 or 0.06%. The NESC assessment team verified these empirical 1-g calculations of damping values.

The MSFC Ares-I flight control team was unable to develop a design that would meet stability robustness requirements using the 0.03% (NTO) and 0.06% (MMH) damping values. The Ares-I flight control team was given action to quantify impacts to their FCS design due to the extremely low Orion SM tank damping values. Subsequently multiple Ares-I FCS redesigns were performed to accommodate partially filled, low-damped Orion SM tanks. In order to achieve the required stability margins for both first stage and upper stage flight in the GN&C 7 Ares-I design cycle the Orion SM tank slosh damping values were arbitrarily increased from the empirically calculated smooth wall 0.03 – 0.06% damping values to a damping value of 0.5%. At the time the NESC assessment was initiated these Ares-I analyses were only in a preliminary state and it was recognized that another full Ares-I GN&C design cycle (i.e., the GN&C 8 cycle) would be required to fully quantify the flight control issues and impacts. In particular it was noted that the impacts on the slosh dynamics due to many routine transient events such as liftoff "twang", stage separation, LAS jettison, SM panel deployment, the ullage settling motor firings, and potential interactions with the non-linear reaction control system roll axis controller, had not yet been studied.

As depicted in Figure 11, the FCS architecture for the Ares-I consists of a classical proportional-integral-derivative (PID) controller design with loop shaping compensation (i.e., digital filters) to provide phase and gain stabilization of the flexible body modes and/or fluid slosh modes. The "proportional" term determines the controller response to the currently sensed error, the "integral" term determines the response based on the sum of recent errors, and the "derivative" term determines the reaction based on the rate at which the error has been changing. The weighted sum of these three different control actions is used to generate the thrust vector control (TVC) command for the next control cycle. The PID controller gains and the filter parameters are all gain scheduled which is consistent with industry practice.

The pitch and yaw axes TVC system controllers share this common system architecture. The Ares-I roll axis controller takes a different form and is a non-linear phase-plane RoCS thruster-based controller quite different from the TVC pitch and yaw controllers. The roll controller has been developed from legacy Shuttle and International Space Station ISS phase-plane controller designs.

Table 1 summarizes the Ares-I FCS stability gain and phase margin requirements for the low-frequency rigid body/aero/slosh condition as well as for the cases where the flexible body modes of the launch vehicle are either gain or phase stabilized. Traditionally, the gain and phase margins are used as control system stability robustness metrics and they represent a tolerance to both plant disturbances and environment uncertainties. The requirements shown in Table 1 are consistent with industry practice. Note that under fully dispersed conditions the minimum rigid body/aero/slosh gain and phase margin requirements are suitably lowered to 3 dB and 20 degrees, respectfully, but are not dropped to zero as done on some projects. The establishment of diminished but finite dispersed gain and phase margins in this manner is especially prudent given the developmental nature of the Ares-I launch vehicle. These Ares-I stability margin requirements listed in Table 1 are very similar to, and one can most likely trace their origin to, the stability gain and phase margin requirements levied on the Space Shuttle launch vehicle which are shown in Table 2.

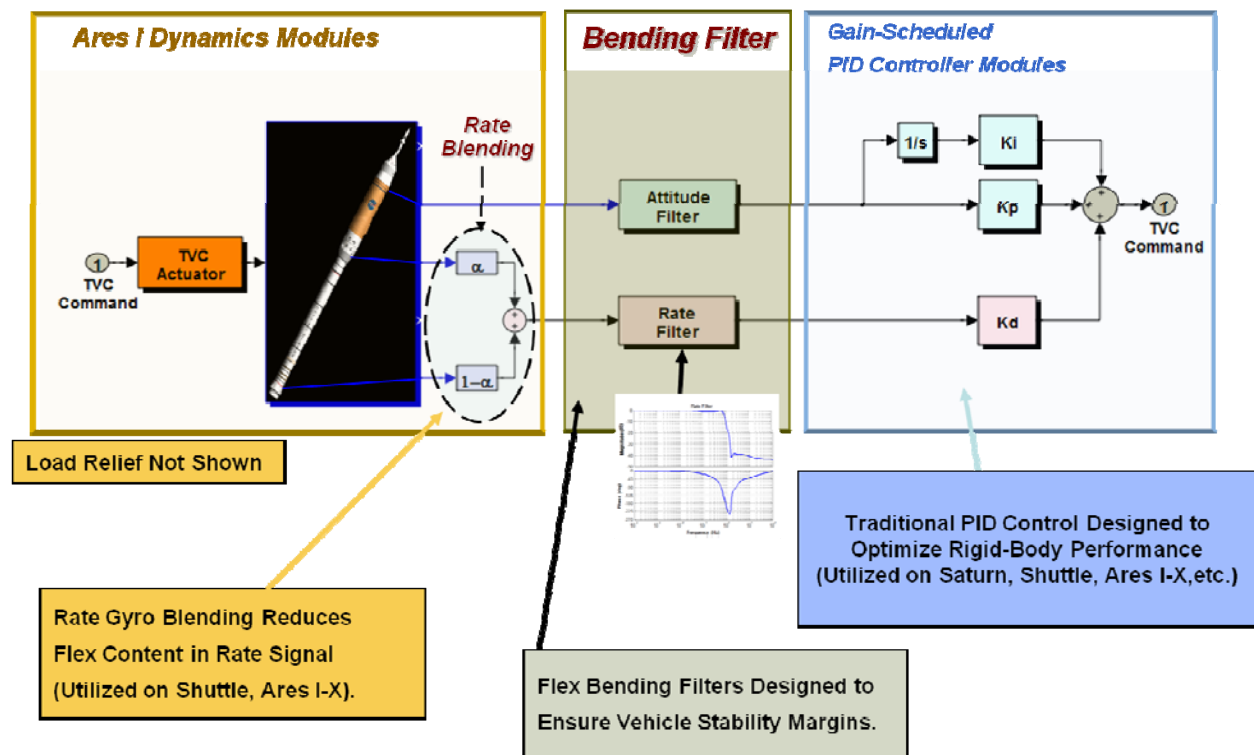


Figure 11. High-level Ares-I FCS architecture.

Table 1. Ares-I FCS stability margin requirements.

	Rigid Body, Aero, Slosh		Flex	
	Gain Margin (dB)	Phase Margin (deg)	Phase Stabilized Flex Modes	Gain Stabilized Flex Modes
			Phase Margin (deg)	Gain margin (dB)
Nominal	>6	>30	>45	>10
Dispersed*	>3	>20	>30	>6
*Assumed 99.73% of cases meet criteria with 10% consumer risk for an allowable failure rate of 0.1% or less in Monte Carlo analysis.				

Table 2. Space Shuttle launch vehicle FCS stability margin requirements.

Parameter	Condition	
	Nominal	Dispersed
Rigid Body GM (dB)	6	3
Rigid Body PM (deg)	30	20
Slosh Mode PM (deg)	25	15
Slosh Mode GM (dB)	6	3
Flexible Body Mode Attenuation (dB)	10	6

The Ares-I gain and phase margin definitions for rigid body, slosh, and flex body dynamics are notionally illustrated in Figure 12 (first-stage example) and Figure 13 (upper-stage example). The red regions reflect  $\pm 6$  dB gain and  $\pm 30$ -degree phase from the critical stability point. Lower frequency gain margins (rigid/aerodynamics and slosh) are defined at the 180-degree phase crossover, while required high-frequency flex gain attenuation is defined as peak gain, measured from the 0 dB axis. For Ares-I phase stabilized flexible modes, both lead and lag phase margins are defined. The general design philosophy for Ares-I first-stage flight is to robustly phase stabilize the first flexible mode, and robustly gain stabilize the second and all higher flexible modes. The design approach for upper-stage flight control is to have all vehicle flexible modes be gain stabilized.



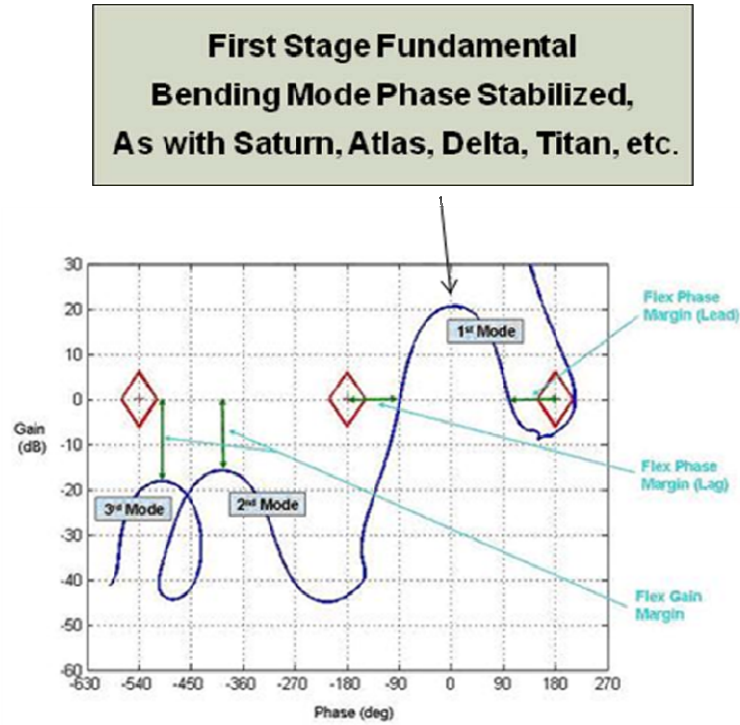


Figure 12. Notional depiction of Ares-I FCS gain and phase margins (first-stage example).

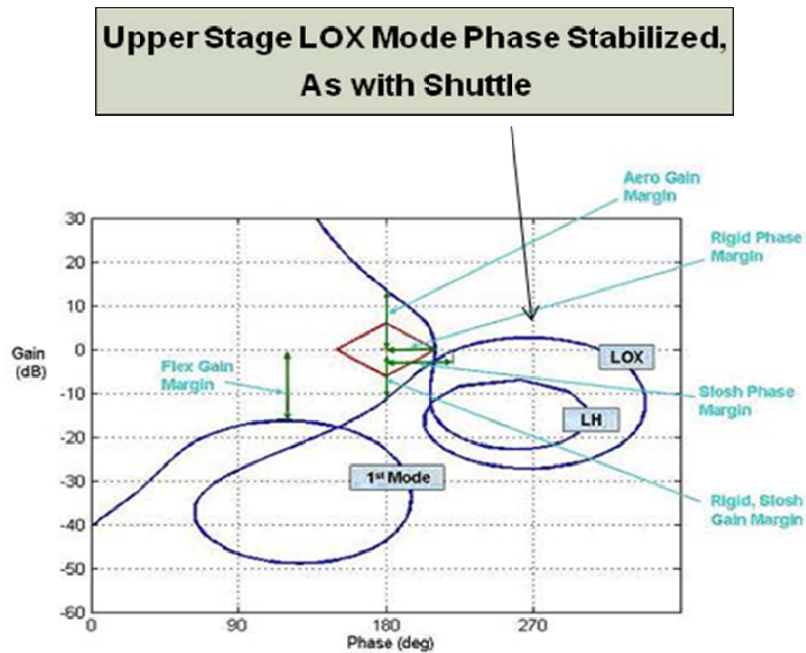


Figure 13. Notional depiction of Ares-I FCS gain and phase margins (upper-stage example).

Figure 14 depicts, for a specific ISS mission case, the control system, flexible body, and slosh mode frequencies as a function of time, with uncertainty included, over the period from launch to 600 seconds after launch. This figure graphically illustrates the challenges of designing a control system for first-stage powered flight. The launch vehicle flexible body dynamics must be stabilized by the FCS throughout flight. A large percentage of the vehicle mass is composed of propellant, which is consumed during the boost phase. This loss of mass significantly changes the structural dynamics as propellant is depleted. For most fill levels, slosh frequency scales proportionally with vehicle acceleration and damping scales inversely. The Ares-I first-stage maximum acceleration is about 3 g's, which results in increased slosh frequencies and decreased damping. Stability issues can occur with this shift in Orion slosh frequency under the influence of the launch vehicle 3-g acceleration.

The potential for destabilizing Ares-I flexible body mode dynamic coupling and interaction with Orion NTO and MMH slosh modes is apparent from an examination of Figure 14. The Ares-I full-stack structure first flexible mode frequency is very near the same frequency as the Orion SM slosh modes, which can cause decreased margins and difficulty in filter design. The MSFC team pointed out that the NASA SP-8031 "Slosh Suppression" guidelines document (Reference 3) recommends separation between the flexible body and fluid slosh mode frequencies to minimize flex body/slosh dynamic interaction.

During this assessment, questions were raised by the GN&C TDT members regarding the implementation details of MSFC's linear spring-mass slosh mechanical model used in their Marshall Aerospace Vehicle Representation In "C" (MAVERIC) 6-degree of freedom (DOF) simulation. There was discussion comparing linear versus non-linear slosh modeling. This topic arose after the NESC team requested to see output data on the slosh amplitudes seen in MSFC simulations. The need for and the potential benefits of a non-linear slosh model were discussed.

Plans for an Ares-I GN&C mini-design cycle where the stability margin and performance sensitivities will be evaluated over a range of Orion damping values from 0.1% to 0.5% were also discussed. The stated objective was to determine if there is a "knee" in the sensitivity trend curve at a damping value less than 0.5%.

Over the period from mid-December 2009 to early February 2010 the NASA Technical Fellow for GN&C, along with several members of his GN&C TDT, met multiple times with the MSFC Ares-I GN&C team. The following items were reviewed by the NESC assessment team:

- Ares-I GN&C architecture,
- Ares-I GN&C stability and flight performance requirements,
- Legacy GN&C references from Saturn,
- Analysis methodology and tools,
- Analytic assumptions,
- Uncertainty assumptions,
- Modeling techniques,

- The technical interaction/model data transfer between the Orion team and Ares-I GN&C team, and
- Analysis results, both frequency domain and time domain.

The MSFC Ares-I GN&C Team has used technically sound and appropriate (traditional industry standard type) analytical methods to assess the impact of the very lightly damped (0.03%) Orion slosh mode. The depth of the MSFC team's technical rigor, physical understanding, and problem insights was clearly apparent.

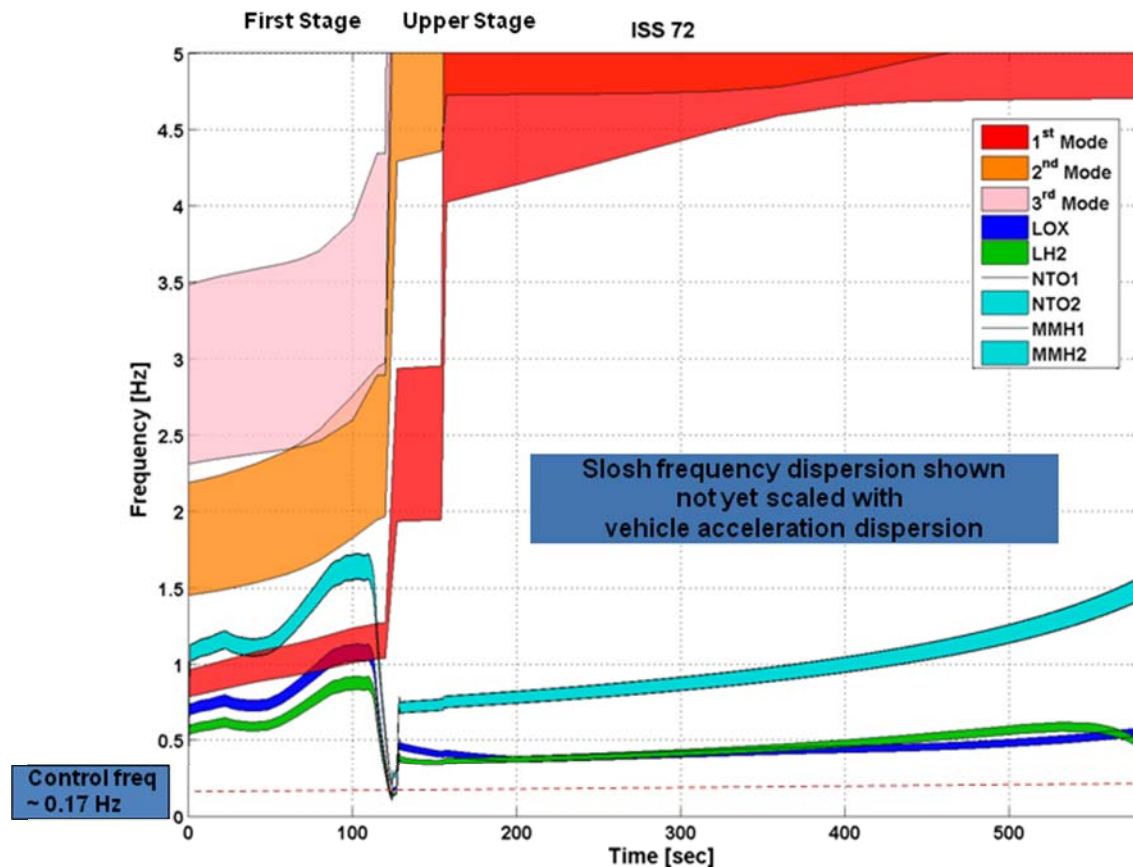


Figure 14. Ares-I control, flexible body, and slosh mode frequencies vs. time.

Specifically regarding the level of conservatism in the MSFC slosh analyses, the NESC assessment team concluded the following:

- The Orion estimates of propellant slosh damping ratios in the Orion SM tanks of 0.03% (NTO) to 0.06% (MMH) are generally consistent with calculations using industry standard and historical techniques, and do not appear to be overly conservative.
- The Orion-provided pendulum mechanical models for Orion SM propellant slosh, provided to the Ares-I personnel, and the integration and use of those models in the Ares-I MAVERIC 6-DOF simulation and linear analysis tools are generally consistent with industry standard and historical techniques, and do not appear to be overly conservative.

However, it was also observed that the MAVERIC 6-DOF simulation tool used by the Ares-I flight control engineers at MSFC does not clearly flag cases in which the displacement of the point mass used in the Orion SM tank slosh spring-mass mechanical model exceeds the maximum displacement consistent with the linear fluid slosh fundamental mode on which they are based. The NESC team felt strongly that this transition point, between the linear slosh regime and the non-linear slosh regime, must be clearly identified.

For linear fluid slosh at the fundamental slosh mode to occur, there is a generally accepted rule of thumb that the maximum height of the fluid wave at the outer wall of the tank should not exceed approximately 10% of the radius of the tank. For greater fluid wave heights, the fundamental anti-symmetric slosh wave tends to break apart into more complex wave shapes because of splashing and breaking of the waves, reducing the amount of mass that continues to slosh at the fundamental mode natural frequency. Using the linear mechanical slosh model beyond this linear range could result in overly pessimistic predictions of the forces imparted on the tank walls by the propellant slosh.

The Southwest Research Institute slosh tool computes an estimate of the ratio of the maximum fluid wave height at the tank outer wall to the maximum amplitude of the pendulum mechanical model. For the Orion propellant tanks at the nominal lunar and ISS mission fill levels, the slosh tool predicts that ratio to be approximately 1.5. That is, the maximum fluid wave height at the tank outer wall is approximately 50% larger than the maximum amplitude of the pendulum mechanical model. Since the Orion propellant tanks are 50 inches in diameter, 10% of their radius is equivalent to a maximum wave height at the tank outer wall of approximately 2.5 inches, which when divided by the ratio of wave height to pendulum displacement, yields a maximum pendulum amplitude (or the equivalent spring-mass displacement) of approximately 1.7 inches.

Until the recent design cycle, the Ares-I MAVERIC 6-DOF simulation did not have the capability to output the time history of the Orion SM tank slosh spring-mass displacement. Only the statistics for maximum amplitude could be examined. However, prior to the analyses of the current design cycle, the simulation was modified to output time history data of the slosh model spring-mass displacement. Initial evaluations of the nominal and typical Monte Carlo time history data does appear to suggest that the Orion SM tank slosh spring-mass displacements may be beyond the maximum allowable range for linear slosh models.

Based on this initial finding, the NESC team recommended that MSFC review all MAVERIC tank slosh displacement data (nominal as well as Monte Carlo dispersed) to confirm operation within the linear range of the spring-mass mechanical models.

As mentioned above, the MAVERIC 6-DOF simulation used for the current Ares-I GN&C design cycle was modified to provide output time history data for the displacement of the spring-mass Orion tank slosh dynamics model. A comprehensive review of the tank slosh spring-mass displacement for nominal missions as well as Monte Carlo simulation ensembles should be performed to confirm whether the slosh model is operating within its linear range. Preliminary data provided for the slosh spring-mass displacement time histories has indicated that for low slosh damping, the Monte Carlo dispersed trajectory data does show significant intervals of operation of the Orion tank slosh dynamic model beyond its linear range.

Figure 15 shows a sample plot of the displacement of the spring-mass corresponding to the Orion NTO tank for a Monte Carlo run of mission TD71, using 0.1% tank slosh damping. In the figure, the red line indicates the nominal mission spring-mass displacement, while the blue lines indicate the 2000 Monte Carlo runs. The black horizontal line shows the approximate limit of 0.14 feet (or 1.7 inches) for operation of the slosh model in its linear range. Clearly, there are significant time intervals where the tank slosh displacement exceeds the maximum limit for linear operation for the dispersed cases, although the nominal simulation run shows operation well within the linear range.

The GN&C TDT members of the assessment team recommended that a comprehensive review of existing MAVERIC simulation data should be reviewed to determine the extent at which the current Orion tank slosh spring-mass mechanical models may be operating outside of their linear range. Following such an analysis, the Ares-I personnel may consider developing and using non-linear tank slosh dynamic models. Recent technical discussions of the NESC assessment team with representatives from United Launch Alliance have suggested that such non-linear tank slosh models have been developed for use with large tank slosh mechanical model displacements and have been used in their tank slosh analyses, which may be of use to the Ares-I analysis of Orion tank slosh.

Therefore, it was also recommended that MSFC consider the development and use of non-linear tank slosh mechanical models for the Orion SM propellant tank slosh. The NESC team observed that the displacement of the Orion tank slosh spring-mass mechanical models may be operating beyond the linear range at which they are considered to be valid mechanical representations of Orion tank slosh dynamics. It was recommended that the Ares-I personnel consider implementing non-linear tank slosh mechanical models in their MAVERIC 6-DOF simulation and linear analysis tools to provide higher confidence in their predictions of the effects of Orion SM tank slosh on the Ares-I vehicle controllability.

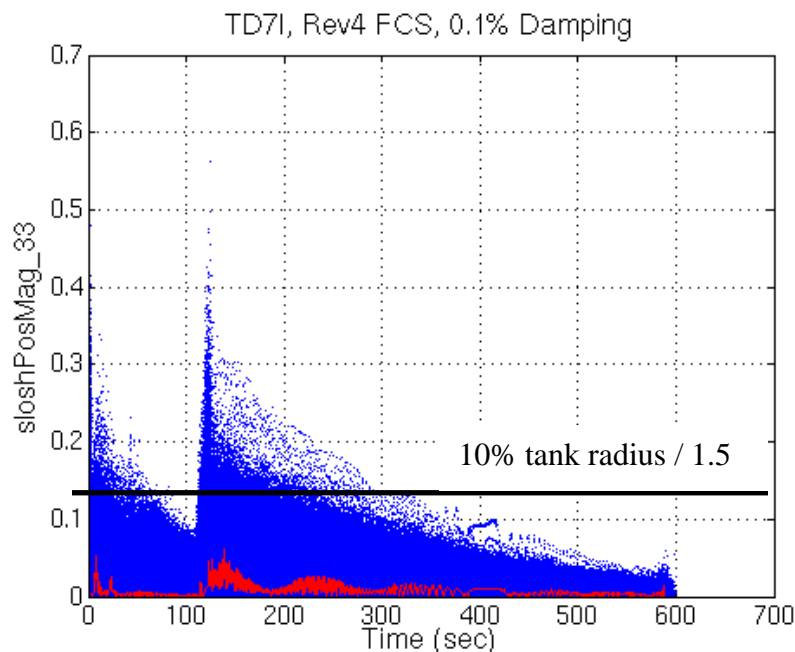


Figure 15. Orion upstream NTO tank slosh displacement (0.1% damping; TD71 mission).

The primary recommendation of the NESC team was for CxP to modify Orion propellant tanks to increase damping.

Any concerns raised about the “degree of confidence” in the Ares-I / Orion SM tank slosh dynamics models used for the analysis of the effects of Orion tank slosh on Ares-I controllability are largely related to uncertainties caused by the very low damping ratios predicted for the Orion SM tank slosh. For example, operating those slosh mechanical models within their linear range and the effects of lateral tank excitation near the fluid slosh fundamental mode natural frequency are largely affected by the low damping, and increasing that damping by an order of magnitude or more, would help improve the confidence in the applicability of those slosh mechanical models.

#### 4.6 Kepler Recurring Anomalies

In January 2010, the NESC was requested to support an investigation into recurring anomalies onboard the Kepler spacecraft. This spacecraft, launched on March 7, 2009, is depicted in Figure 16. The Kepler Mission (NASA *Discovery* mission #10) is specifically designed to survey our region of the Milky Way Galaxy to discover hundreds of Earth-size and smaller planets in or near the habitable zone and determine how many of the billions of stars in our galaxy have such planets. Results from this mission will allow us to place our solar system within the continuum of planetary systems in the Galaxy.

At the time of this request, the spacecraft had been in routine science operations returning high-quality science data for over nine months since operations began on May 12, 2009. The spacecraft had experienced a number of anomalies that have interrupted science data collection, but was operating well within its margins throughout the Science Operations mission phases and was still meeting its science requirements. However, while Kepler had not experienced any spacecraft emergencies it had experienced a number of star-tracker related anomalies.

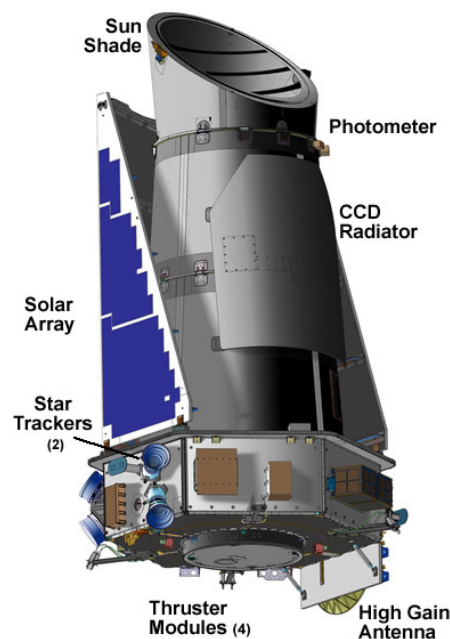


Figure 16. Kepler spacecraft and photometer.

The GN&C Technical Fellow and members of the GN&C TDT supported this NESC assessment of the Kepler anomalies. The NESC team reviewed the spacecraft's general operations philosophy, current analysis of the anomalies, the timelines and fish-bones generated, the mitigations undertaken or under consideration, and the effects of the mitigations. The team also studied the mission's anomaly response and resolution process as well as the available anomaly statistics. The NESC team also investigated the planned paths to get to the root-cause of the anomalies, the remaining work to bring anomalies to closure and any residual risks.

The scientists using the Kepler data prefer long and stable data segments to perform their search for planetary transits. The mission design therefore requires only simple periodic operational interactions with the Kepler spacecraft. There are three key operational activities performed by the Kepler Flight Operations Team (FOT): 1) semi-weekly health and safety contacts; 2) monthly science data downloads via contact with NASA's Deep Space Network (DSN); and 3) quarterly roll maneuvers. The Kepler photometer instrument stares at the same field for the entire mission. The science target location is redefined on the photometer's charge coupled devices after each quarterly roll. There are also small sets of science target changes for Guest Observers and for higher-resolution observations.

Kepler is a data-driven mission, so data completeness is key to mission success. There are two key data completeness requirements to be satisfied. The first is the 92% requirement for Onboard Data Completeness. This requirement essentially has to do with how much of total operational time is the spacecraft actually collecting science data. It is influenced by numerous factors, including the time spent off-pointing to downlink science data, the time needed to perform the quarterly rolls, the time needed to unload excess reaction wheel momentum and the time the vehicle spends in safe mode events or other anomalies. The second major requirement is the Flight-to-Ground Data Completeness metric of 99%, which is directly linked to how much of the science data collected onboard actually reaches the mission's data archive. The quality of the DSN space-to-ground link performance and the ability for data retransmission primarily impacts this requirement.

Since it so fundamentally drives the attainment of the Onboard Data Completeness requirement, the NESC team first considered the Kepler FOT team's anomaly response philosophy. The response to a vehicle anomaly is guided by a realistic and pragmatic three-tiered priority philosophy. The first priority is to ensure vehicle safety by preserving functionality, including on-board fault protection. The second priority is to resume science data collection while the anomaly investigation proceeds in parallel. The third priority is to mitigate against further occurrences of the anomaly in order to reduce the threat of future loss of science or spacecraft functionality. The Kepler engineers budget for the potential loss of up to twelve days of science data collection per year from safing events.

Since operations began on May 12, 2009, as of January 2010, the Kepler spacecraft has entered safe mode three times (June 15<sup>th</sup>, July 2<sup>nd</sup>, and November 18<sup>th</sup> 2009) and the loss of the finepoint attitude control capability needed for science data collection has also occurred three times (August 13<sup>th</sup>, September 14<sup>th</sup>, and October 9<sup>th</sup> 2009). Entry into safe mode is a pre-planned self-protective measure that the spacecraft takes when something unexpected occurs onboard. During safe mode, the spacecraft points the solar panels directly at the sun and begins to slowly rotate about a sun-aligned axis. The spacecraft automatically powers off the

photometer and one redundant subsystem as a safety precaution. Shortly following the November 18<sup>th</sup> safe-mode entry the FOT engineers immediately began telemetry analysis to determine spacecraft subsystem health and root-cause determination of what triggered the safe mode. This was the third safe mode Kepler had experienced since operations began in May 2009 and it was classed as a Criticality 1 anomaly. Criticality 1 anomalies are those that represent an unacceptable risk or have high impact to achieving the Kepler baseline mission objectives. Onboard detection of a Criticality 1 anomaly will automatically force the spacecraft into safe mode.

This particular safe mode occurred when the team was preparing to download another month of scientific data from Kepler. The scientific data was not at risk and was subsequently downloaded successfully via the DSN communications link the day after the safe-mode event. Engineers verified nominal performance of all of Kepler's systems and successfully recovered the vehicle from safe mode. Science data collection was resumed by the evening of November 20. The safe-mode entry was traced to an undesired interaction between the spacecraft's flight software and its star tracker. The root cause is understood. Near-term mitigation of the problem is in place and a long-term mitigation is to be implemented. The anomaly investigation has revealed three star-tracker related issues. The first is that the star trackers unexpectedly drop stars and/or declare stars invalid, leading to a lost-in-space (LIS) condition. The second is that the star tracker remains in LIS mode for unexpectedly long time. The third and last issue is that star tracker directed search commands occasionally fail.

The NESC team is still in the process of reviewing the details of the anomaly investigations and the associated mitigation or resolution plans. The Kepler management team, the NASA engineering team, and the contractor engineering team are using sound risk management principles to guide the process for the resolution of each anomaly and to set appropriate priorities.

## **5.0 Conclusions**

This paper has described how the NESC was formed as an independent organization dedicated to promoting safety through engineering excellence. A resource for the Agency, it is a valuable problem-solving asset for the high-risk programs that NASA has always undertaken. NESC brings together some of NASA's best engineers with experts from industry, academia, and other government agencies to address our highest risk, most complex issues. NESC strives to cultivate a safety-focused culture focused on engineering and technical excellence, while fostering an open environment and attacking the Agency's technical challenges with unequalled tenacity.

The NESC is more than a problem-solving organization however. It is also an organization that works to improve the competence of our entire engineering workforce through the opportunity to work on challenging problems, through exposure to other people, tools, techniques and facilities from across the Agency, through discipline advancing proactive work, and through its promulgation of lessons learned via technical reports and the NESC Academy courses.

The backbone of the NESC is the ready group of engineering experts organized into 15 discipline areas TDTs. In this paper, the purpose of the NESC GN&C TDT has been highlighted and a number of their experiences described. The members of the GN&C TDT have contributed to solving problems in many of NASA's human spaceflight and robotic spaceflight programs and



projects. Their collective efforts have ranged from the assessment of alternative LASs, on-orbit robotic spacecraft anomalies, propellant sloshing impacts on launch vehicle flight stability and control, loads and dynamics support, and specialized ground testing of future flight systems.

The NESC, because of its demonstrated ability to focus the technical talent from across all NASA Centers to bear on diverse high-priority problems, has become a valuable resource to senior Agency decision makers. The NESC has established itself as a reliable, credible and respected organization within the Agency and it is an outstanding example of Engineering Excellence in practice. This is evidenced by the increase in requests, from all levels of the Agency, for NESC support in resolving problems, reviewing activities, and conducting special studies. The NESC, employing the advantages of distributed “virtual organization” architecture, has shown its ability to concentrate appropriate levels of technical expertise efficiently when and where needed to independently address some of NASA’s most challenging and most visible problems. Some consider the NESC to be one of the Agency’s most positive post-*Columbia* success stories.

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14. ABSTRACT The NASA Engineering and Safety Center (NESC) is an independently funded NASA Program whose dedicated team of technical experts provides objective engineering and safety assessments of critical, high risk projects. NESC's strength is rooted in the diverse perspectives and broad knowledge base that add value to its products, affording customers a responsive, alternate path for assessing and preventing technical problems while protecting vital human and national resources. The Guidance Navigation and Control (GN&C) Technical Discipline Team (TDT) is one of fifteen such discipline-focused teams within the NESC organization. The TDT membership is composed of GN&C specialists from across NASA and its partner organizations in other government agencies, industry, national laboratories, and universities. This paper will briefly define the vision, mission, and purpose of the NESC organization. The role of the GN&C TDT will then be described in detail along with an overview of how this team operates and engages in its objective engineering and safety assessments of critical NASA projects.						
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