Ares I-X Range Safety Trajectory Analyses Overview and Independent Validation and Verification

Ashley F. Tarpley
NASA Johnson Space Center
Houston, TX

Brett R. Starr, Paul V. Tartabini
NASA Langley Research Center
Hampton, VA

A. Scott Craig
Jacobs Engineering
Huntsville, AL

Carl M. Merry, Joan D. Brewer, Jerel G. Davis,
Matthew B. Dulski, Adrian Gimenez, M. Kyle Barron
United Space Alliance, LLC
Houston, TX

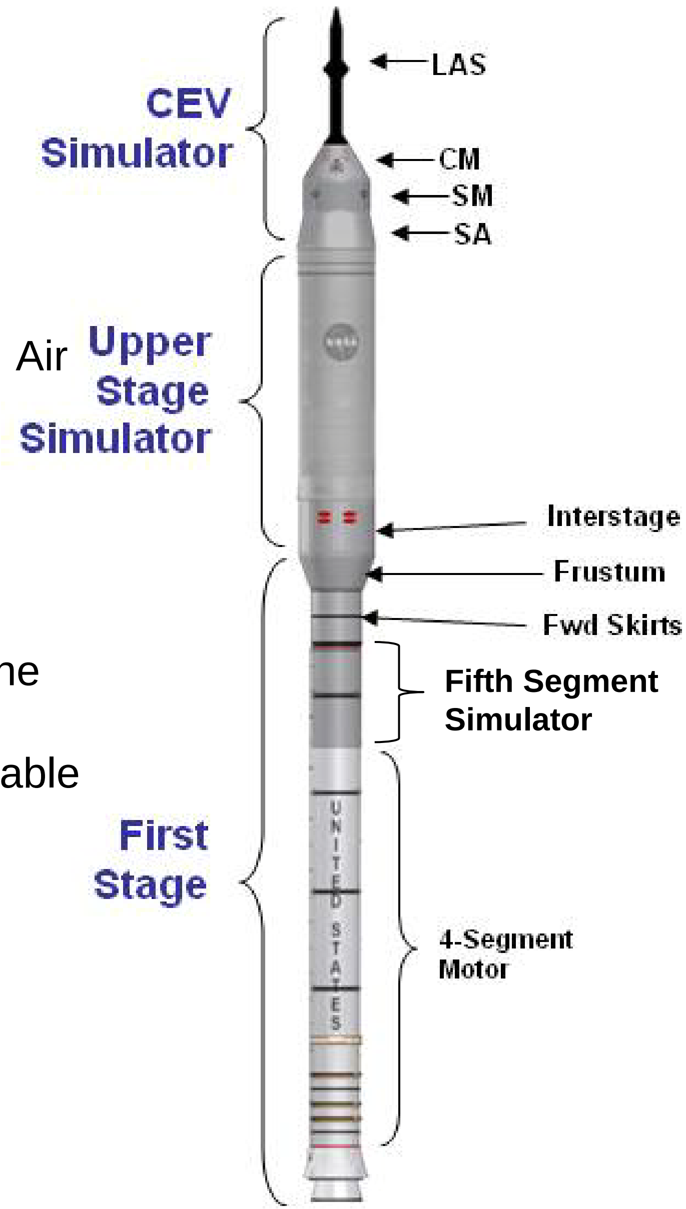
AIAA Atmospheric Flight Mechanics
Portland, OR
August 8-11, 2011

Presentation Objectives

- Provide an overview of the Ares I-X Range Safety flight analysis data products
- Discuss the approach used to develop Ares I-X Range Safety flight analysis data products
- Present validation and verification methods and results for Ares I-X range safety final flight data package products

Ares I-X Test Flight Overview

- **Ares I-X was the first test flight of the Ares I crew launch vehicle (CLV) developed by NASA's Constellation Program (CxP)**
- **Launch:**
  - October 28, 2009
  - Kennedy Space Center Launch Complex 39 Pad B, U.S. Air Force (USAF) Eastern Range
- **Primary Objective:**
  - Demonstrate controllability of the Ares I design
- **Vehicle Description:**
  - Full scale Ares I representation with similar outer mold line (OML)
  - Heritage Space Shuttle Program (SSP) 4 segment Reusable Solid Rocket Motor (RSRM) First Stage (FS)
  - Inert US and CEV simulators (USS and CEVS)
- **Trajectory Description**
  - Due east, suborbital flight
  - Designed to match Ares I dynamic pressure vs. Mach number relationship



Range Safety Final Flight Data Package Requirements Overview

- **The USAF required the Ares Flight Test Program to meet Air Force Space Command Manual (AFSPCMAN) 91-710 requirements to obtain flight plan approval to launch from the Eastern Range**
- **Volume 2 Flight Safety Requirements includes the Final Flight Data Package (FFDP) space vehicle flight analysis requirements:**
  - Nominal trajectory
  - Flight envelopes
  - Impact footprints of all jettisoned bodies and debris
  - Malfunction Turn Analysis
  - Debris Analysis
  - Buoyancy Analysis
  - Acoustic Analysis
  - Sonic Boom Analysis
- **The FFDP is used by USAF 45th Space Wing (45SW) to calculate public safety risk, generate flight rules, launch commit criteria, and range safety displays**
- **AFSPCMAN 91-710 requires a post flight performance analysis**

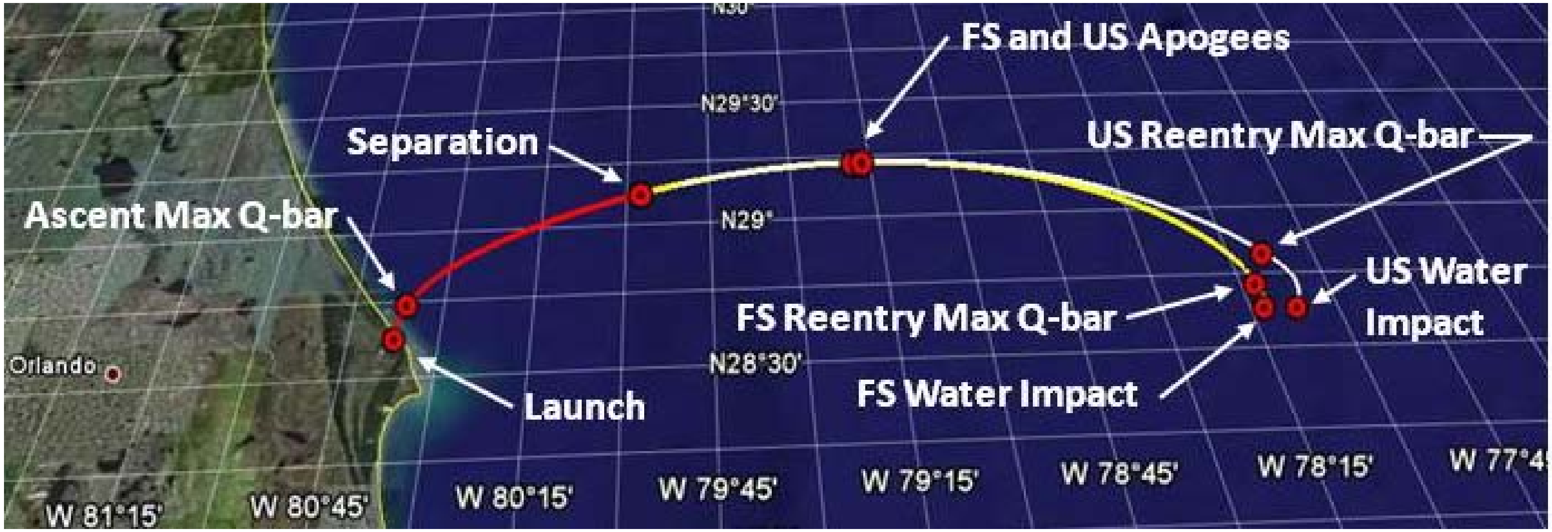
Range Safety Flight Analysis Approach

- All Range Safety flight analyses were approved by the Constellation Program's "Launch Constellation Range Safety Panel" (LCRSP) and Ares I-X SE&I
- The LCRSP Range Safety Trajectory Working Group (RSTWG) provided a forum for the cross-organizational development and review of flight analysis data products
  - Validation that the analysis methodologies and data products met the intent of the requirements was achieved through 45SW participation in the RSTWG
  - Verification of the FFDP data product's accuracy was achieved through agreement with a second set of FFDP data products generated by analysis teams using independent simulation software
    - Non flight simulation data products were verified through organizational reviews

Product	Primary Source	Verification Source
Nominal Ascent Trajectories	LaRC	JSC and MSFC
Nominal Impact Points	LaRC	Aerospace Corp.
Flight Envelopes	LaRC	MSFC
Stage Disposal Footprints	LaRC	Aerospace Corp.
Malfunction Turn Analysis	LaRC	JSC
Debris Analysis	LaRC	NESC review
Acoustic Analysis	LaRC	LaRC review
Sonic Boom Analysis	LaRC	LaRC review
Buoyancy Analysis	JPL	LaRC review

Range Safety FFDP Analyses Overview: Nominal Trajectory

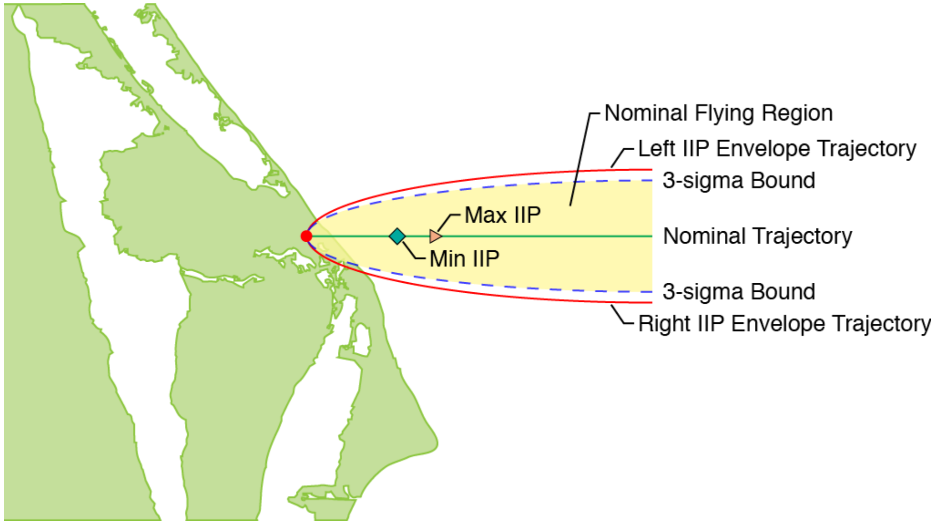
- The most representative reference, or nominal trajectory defines the flight parameter time history and timeline for key events
- Trajectory analyses were performed for a launch season from July 1 through November 30
- Monthly nominal trajectories were developed for mean monthly atmospheric conditions, wind, and propellant mean bulk temperature
- The September nominal trajectory was determined to be representative of the entire launch season
- Nominal product: nominal trajectory time history data



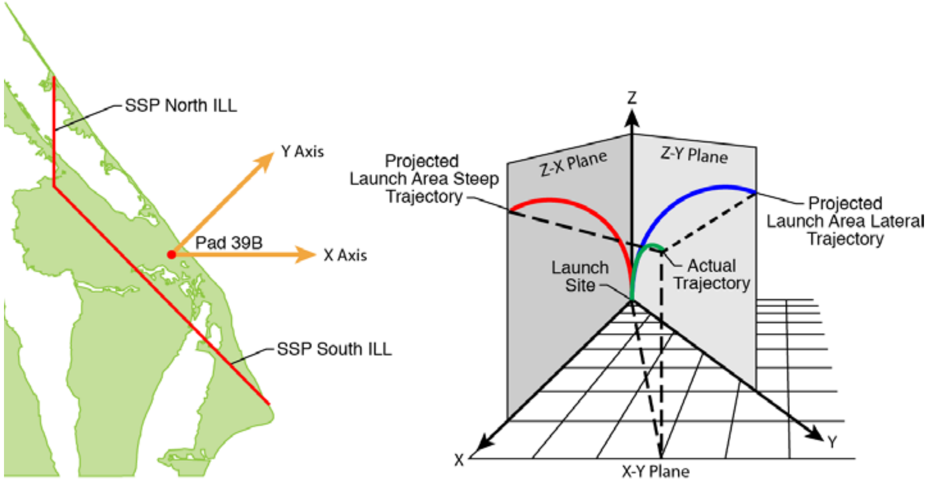
Range Safety FFDP Analyses Overview: Flight Envelopes

- **Flight envelopes defined the limits of flight of the normally operating FTV in the Range Safety horizontal and vertical planes**
- **The vacuum instantaneous impact point (IIP) is tracked in the horizontal plane and provides a measure of the downrange and crossrange travel**
- **The FTV present position is tracked in the vertical planes and provides a measure of the steepness of flight**

Horizontal Plane (Top View)



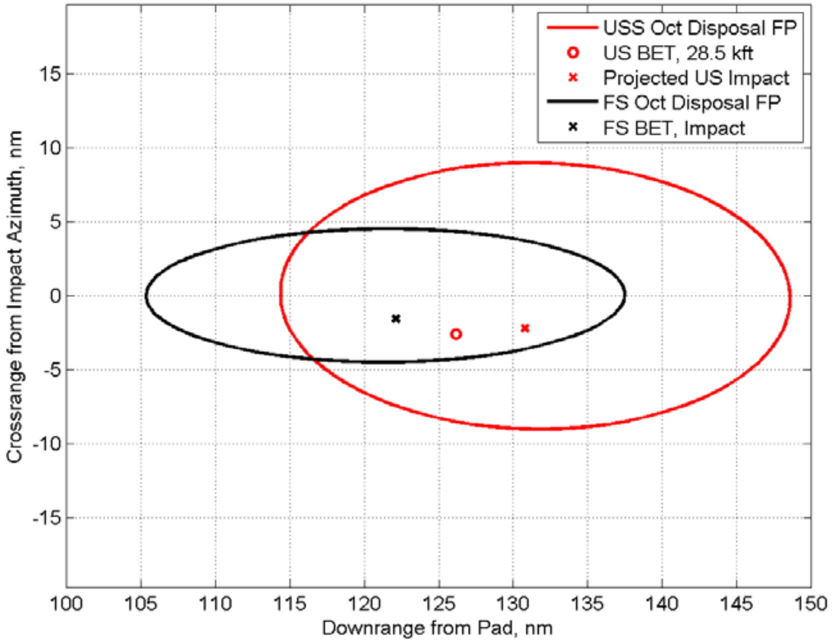
Vertical Plane (Side Views)



- **Envelope product:**
  - 4 horizontal plan envelopes: Maximum IIP, Minimum IIP, Left IIP, Right IIP
  - 2 vertical plane envelopes: Launch Area Lateral (LAL) and Launch Area Steep (LAS)

Range Safety FFDP Analyses Overview: Disposal

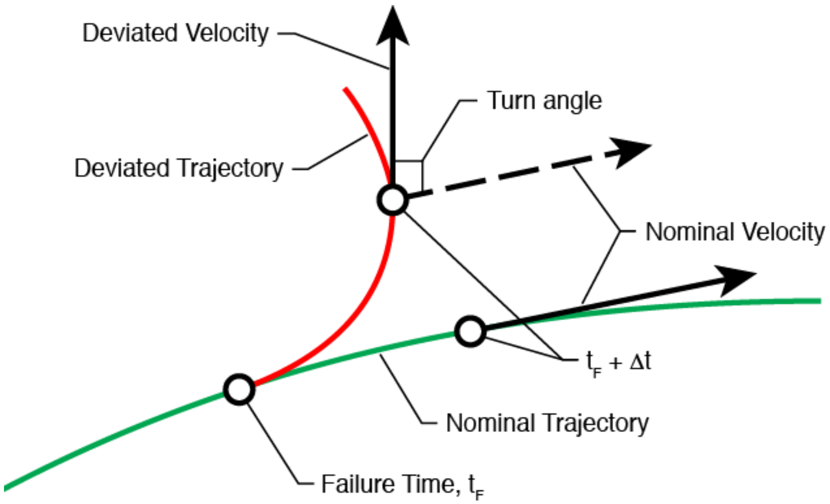
- **Disposal, or impact, footprints defined the area over which all jettisoned bodies impacted the ocean**
- **Ares I-X jettisoned bodies:**
  - USS
  - FS
  - FS nose cap
  - FS forward skirt extension



- **Monthly and seasonal footprints encompassed the 99.73 percentile of FS and USS reentry Monte Carlo analyses impact points.**
- **Disposal product:**
  - Jettisoned bodies reentry data
  - Disposal footprints

Range Safety FFDP Analyses Overview: Malfunction Turn Analysis

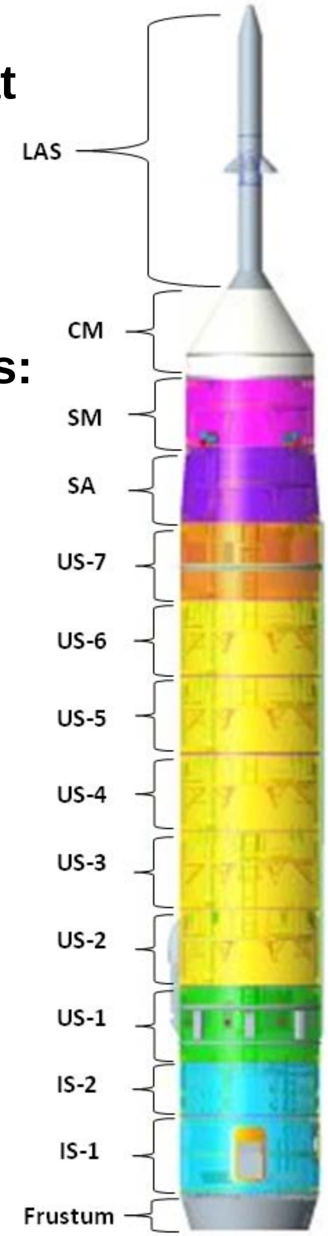
- **The malfunction turn analysis defined the extent to which the FTV could turn from its nominal trajectory due to a failure**



- **Failure modes were defined by a probabilistic risk assessment and failure analysis performed by the RSTWG. Identified failure modes:**
  - Loss of thrust vector control
  - RSRM nozzle burn through
  - RSRM case breach
  - Software failures
- **Malfunction turn product:**
  - 8000+ malfunction turn trajectories
  - Composite table describing the maximum turn angle of the velocity vectors produced from the set of malfunction turn trajectories at time intervals following the malfunction
  - List of all trajectories with the corresponding time of vehicle breakup and the probability of occurrence

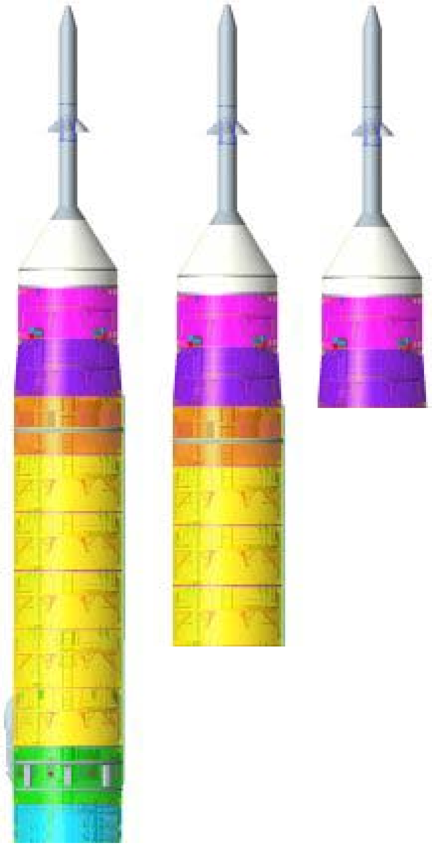
Range Safety FFDP Analyses Overview: Debris Analysis

- **The debris analysis determined the debris configurations that arose from vehicle breakup due to:**
  - Malfunction turn
  - Uncontrolled tumble (USS reentry)
  - Activation of the Flight Termination System
- **The debris analysis characterized each debris configuration's:**
  - Geometry
  - Weight
  - Aerodynamics
    - Stability (trim or tumble)
    - Trim angle
    - Average lift and drag coefficient for aerodynamically unstable configurations.
    - Trim lift and drag coefficient for configurations that trim
  - Ballistic coefficient
- **Breakup was assumed to occur at bolted joints**
- **FS motor segment debris was based on Shuttle data**
- **Debris product:**
  - Catalog of debris configurations and corresponding characteristics



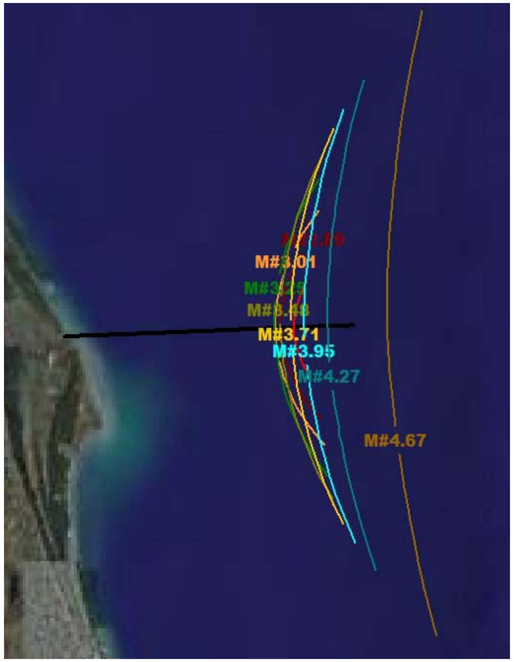
Range Safety FFDP Analyses Overview: Buoyancy Analysis

- **The buoyancy analysis determined the potential for any jettisoned body or debris configuration to float after water impact**
- **Any jettisoned body or piece of debris that has the potential to float must be recovered or sunk**
- **Analysis determined 14 debris configurations could potentially float**
  - Debris configurations with one end closed by the CEV simulator could trap air and float
- **The U.S. Coast Guard was contracted to locate and sink any floating debris**
- **The USS broke up at water impact**
- **No debris floated after water impact**



Range Safety FFDP Analyses Overview: Acoustic Analysis and Sonic Boom Analysis

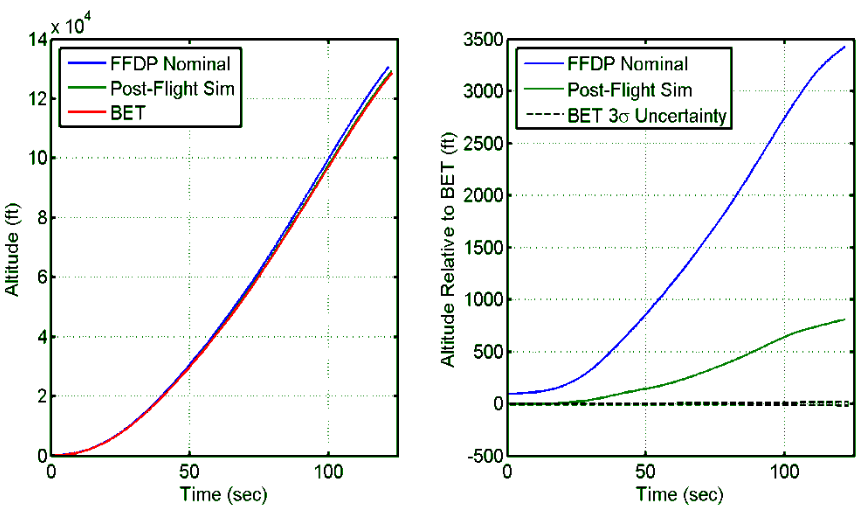
- The acoustic analysis defined the far field pressure level and acoustic spectra around the launch site
- The FTV RSRM generated an acoustic energy of 203 db
- Low frequency sound pressure levels above 85 db extended to Orlando due to lack of atmospheric attenuation



- The sonic boom analysis determined the location and intensity of the sonic boom ground signature
- The sonic boom ground signature was determined from the FTV's near field pressure signature and its pitch attitude along its trajectory
- The ground signature's closest point to the shore was 26.8 nmi

Range Safety FFDP Analyses Overview: Post Flight Analysis

- **The Post Flight Analysis requirements were to document:**
  - FS performance
  - On-board safety instrumentation (FTS) performance
  - Failures that occurred and their affect on the FTV flight
  - Probable cause of failure
  - Comparison of planned and achieved FS cutoff state
  - Estimated impact points of FS and USS
  - Comparison of the best estimated flight trajectory to the FFDP flight envelopes
- **Comparisons between the actual flight, post-flight simulation, and preflight simulation were also included**
- **The preflight simulation was updated with day of launch winds, RSRM PMBT, RSRM measured thrust to create the post-flight simulation**
- **The comparisons verified:**
  1. The flight occurred within the predicted bounds
  2. The simulation accurately predicted the FTV trajectory



Range Safety Trajectory Analyses IV&V: Simulation Verification

- **Each team worked with an Ares I-X version of a 6DOF simulation**

Center / Team	6DOF Simulation	Product
LaRC	POST2	Nominal, Envelopes, MT, Disposal
MSFC	MAVERIC	Nominal, Envelopes
JSC	ANTARES	Nominal, MT
The Aerospace Corp.	PROCONSUL	Disposal

- **Simulation verification was performed prior to product generation to ensure:**
  - Each vehicle and environmental model was implemented properly
  - Methodology and implementation of the system dispersions, environmental dispersions, and failure modes were consistent

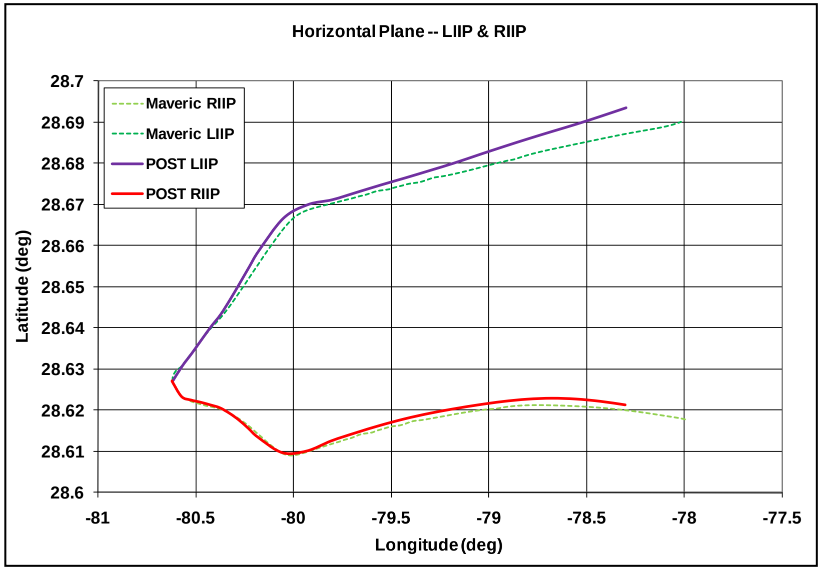
- **Verification process:**
  1. Verify simulation models
     - Simulation configuration management spreadsheet documenting model versions and overall simulation configuration
  2. Execute run matrix
     - Run matrix approved through Ares I-X range safety community, and included:
       - Nominal trajectory
       - Trajectories experiencing Range-defined worst case winds
       - Representative malfunction trajectories
       - Entry cases that stress the models added to the sim for Ares I-X
  3. Establish agreement between simulation results to within tolerances
     - Data comparisons were required to meet quantitative (required) and qualitative (desired) tolerances, including:
       - G&C specific parameters
       - Range-specific parameters were

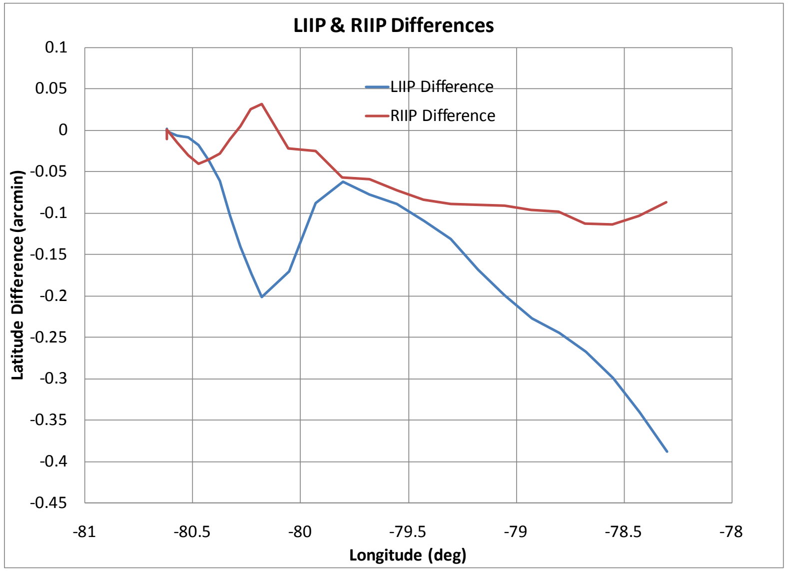
Range Safety Trajectory Analyses IV&V: Simulation Verification Tolerance Development

- **Tolerances were defined as quantitative or qualitative**
  - Quantitative (required) metric violations were investigated to identify and correct the root cause
  - Qualitative (desired) metric violations were evaluated within the allowable timeframe in an effort to resolve the differences
- **Tolerances were derived from the following Shuttle process and range products:**
  - Evolved Shuttle Day-of-Launch I-Load Update (DOLILU) process tolerances
  - Sensitivity tolerances or the effects of differences in certain state parameters on the corresponding differences in downrange and cross range impact positions
  - Range radar tracking accuracy requirement

Range Safety Trajectory Analyses IV&V: Nominal Trajectory and Envelope V&V

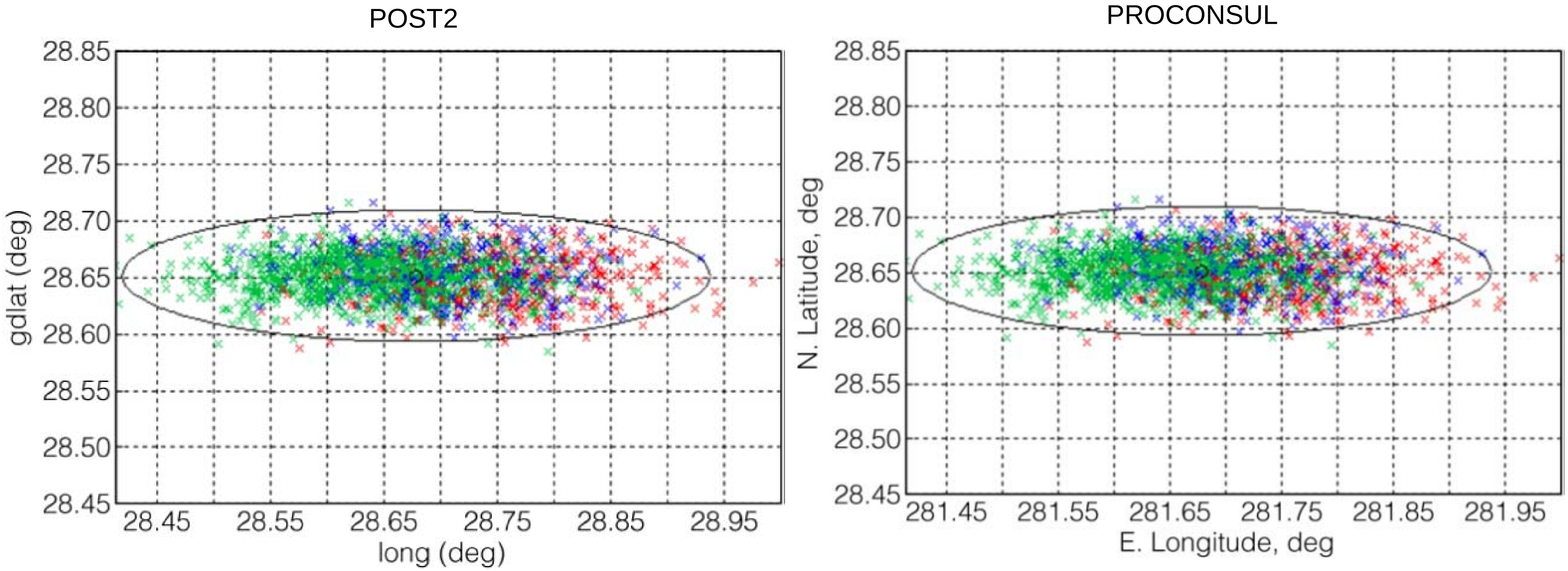
- **Product validation achieved through Ares I-X Range Safety community**
- **Product verification accomplished through qualitative and quantitative assessments of the results, reviewed and approved by the RSTWG**
  - Each team's trajectories were plotted in respective envelope planes and compared qualitatively to ensure that the distribution of trajectories about the nominal were similar
    - Qualitative comparison of envelope trajectories was performed first through visual comparison of Monte Carlo trends
    - Significant errors in the simulations or method of post-processing manifested themselves as diverging dispersed trajectories
    - Qualitative comparisons were adequate to continue on to the quantitative comparisons
  - Differences between the two simulations were quantitatively compared using the simulation match criteria previously established for the simulation verification
- **Quantitative comparison was performed by extracting the calculated boundary from each of the Monte Carlo sets and differencing the plots**





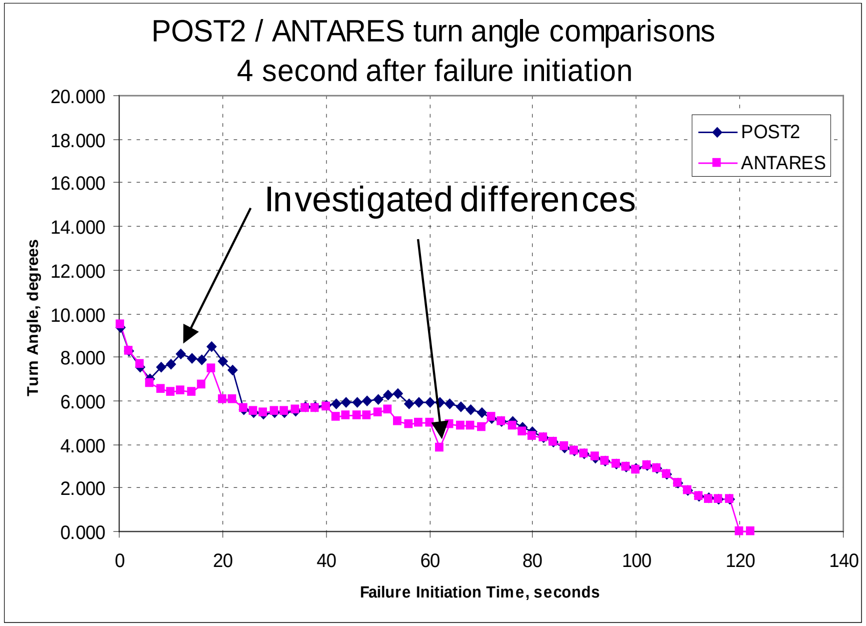
Range Safety Trajectory Analyses IV&V: Disposal V&V

- **Product validation achieved through Ares I-X Range Safety community**
- **Product verification achieved through:**
  - Comparison of disposal footprints of 2000-case Monte Carlo analysis run in both simulations using different random dispersion sets
  - Demonstration that verification cases met required metrics
- **Overall level of agreement in the statistical results for the 2000-case Monte Carlo runs was excellent**
- **Debris ellipses for both simulations were very similar and the coordinates differed by less that 0.005 [deg]**



Range Safety Trajectory Analyses IV&V: Malfunction Turn V&V

- **Product validation achieved through Ares I-X Range Safety community**



- **Product verification:**
  - Time histories for randomly selected were trajectories compared directly to within verification tolerances
  - Composite turn tables compared directly
  - Vehicle breakup times compared directly
- **Product QA:**
  - Confirmation of data frequency and delivery formatting
  - MT trajectories compared to nominal up to malfunction time
  - Numerical comparison of trajectory probability table to PRA documentation

Summary

- All Flight Analysis data products were successfully generated and delivered to the 45SW in time to support the launch
- The IV&V effort allowed data generators to work through issues early
- Data consistency proved through the IV&V process provided confidence that the delivered data was of high quality
- Flight plan approval was granted for the launch
- The test flight was successful and had no safety related issues
- The flight occurred within the predicted flight envelopes
- Post flight reconstruction results verified the simulations accurately predicted the FTV trajectory