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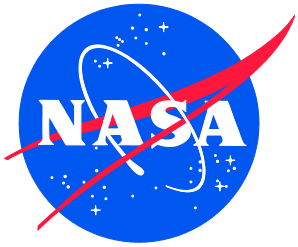



# Check-Cases for Verification of 6-Degree-of-Freedom Flight Vehicle Simulations

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January 2015

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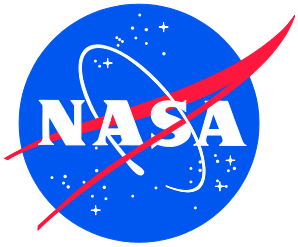


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**Acknowledgments**

The assessment team is grateful to Mr. Edwin Crues for providing permission to reuse this orbital scenario description and would like to express appreciation to Mrs. Pamela Sparks for keeping us organized.



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Page 16, column 6, row 7 check-case scenario 17 change “f(h)” to “Still air” as no winds were implemented in this scenario.

# Check-Cases for Verification of 6-Degree-of-Freedom Flight Vehicle Simulations

**October 30, 2014**

## Report Approval and Revision History

NOTE: This document was approved at the October 30, 2014, NRB. This document was submitted to the NESC Director on December 15, 2014, for configuration control.

| | | |
|---|---|---|
| Approved: | *Original Signature on File* | 12/15/14 |
| | NESC Director | Date |

| Version | Description of Revision | Office of Primary Responsibility | Effective Date |
|---|---|---|---|
| 1.0 | Initial Release | Daniel G. Murri, NASA Technical Fellow for Flight Mechanics, LaRC | 10/30/14 |

# Table of Contents

**Volume I: Technical Assessment Report**

## List of Tables

# Volume I: Technical Assessment Report

## 1.0 Notification and Authorization

This assessment was established to develop a set of time histories for the flight behavior of increasingly complex example aerospacecraft that could be used to partially validate various simulation frameworks. The assessment was conducted by representatives from several NASA Centers and an open-source simulation project.

The primary stakeholders are users of flight simulation tools, including current and future NASA aeronautic and astronautic vehicle projects. Benefactors include NASA, the Department of Defense (DoD) , the aerospace industry, and academia.

## 2.0 Signature Page

Submitted by:

*Team Signature Page on File - 12/18/14*

Mr. Daniel G. Murri Date

Significant Contributors:

E. Bruce Jackson Date

Dr. Robert Shelton Date

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

## 3.0 Team List

| Name | Discipline | Organization |
|---|---|---|
| **Core Team** | | |
| Daniel Murri | NESC Assessment Lead | LaRC |
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| Dr. A. Jackson | Orbital Mechanics Consultant | JSC/Jacobs |
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| Michael Weinstein | Simulation Representative | ARC/SAIC |
| Joseph White | Simulation Representative | LaRC/AMA |
| **Administrative Support** | | |
| Tricia Johnson | MTSO Program Analyst | LaRC |
| Erin Moran | Technical Writer | LaRC/AMA |
| Pamela Sparks | Project Coordinator | LaRC/AMA |

## 3.1 Acknowledgements

The assessment team is grateful to Mr. Edwin Crues for providing permission to reuse this orbital scenario description and would like to express appreciation to Mrs. Pamela Sparks for keeping us organized.

## 4.0 Executive Summary

The rise of innovative unmanned aeronautical systems and the emergence of commercial space activities have resulted in a number of relatively new aerospace organizations that are designing innovative systems and solutions. These organizations use a variety of commercial off-the-shelf and in-house-developed simulation and analysis tools including 6-degree-of-freedom (6-DOF) flight simulation tools. The increased affordability of computing capability has made high-fidelity flight simulation practical for all participants.

Verification of the tools' equations-of-motion and environment models (e.g., atmosphere, gravitation, and geodesy) is desirable to assure accuracy of results. However, aside from simple textbook examples, minimal verification data exists in open literature for 6-DOF flight simulation problems.

This assessment compared multiple solution trajectories to a set of verification check-cases that covered atmospheric and exo-atmospheric (i.e., orbital) flight. Each scenario consisted of pre-defined flight vehicles, initial conditions, and maneuvers. These scenarios were implemented and executed in a variety of analytical and real-time simulation tools. This tool-set included simulation tools in a variety of programming languages based on modified flat-Earth, round-Earth, and rotating oblate spheroidal Earth geodesy and gravitation models, and independently derived equations-of-motion and propagation techniques. The resulting simulated parameter trajectories were compared by over-plotting and difference-plotting to yield a family of solutions. In total, seven simulation tools were exercised.

Participating in the assessment were participants from NASA Ames Research Center (ARC), Armstrong Flight Research Center (AFRC), Johnson Space Center (JSC), Langley Research Center (LaRC), and Marshall Space Flight Center (MSFC), and an open-source simulation tool development project (i.e., JSBSim).

The vehicle models were published in the American Institute of Aeronautics and Astronautics American National Standards Institute (AIAA/ANSI) S-119-2011 Flight Dynamics Model Exchange Standard [ref. 4] markup language, making them realizable in a variety of proprietary and non-proprietary implementations. This set of models and the resulting trajectory plots from a collection of simulation tools may serve as a preliminary verification aide for organizations that are developing their own atmospheric and orbital simulation tools and frameworks.

This document is an overview of the process used and the results of the assessment. Volume II contains details on models, implementation, and results. Simulations from atmospheric check cases found the following:

- Minor differences in results from tabular versus equation-based atmosphere models, and geodetic versus geocentric geometries;
- To a smaller degree, some differences in the implementation of the square-law and harmonic gravitation are also apparent due to differences in gravitation model

implementation or in the conversion of the initial geodetic position into the geocentric position (since position is an input into the gravitation model); and

- Differences in numerical integration methods in the different simulation tools appeared to cause some differences in predicted trajectories.

Comparison of simulations from the orbital check cases showed good agreement; as in the atmospheric check cases, differences in numerical integration methods appeared to cause minor differences in predicted trajectories.

In general, the simulation comparisons showed good agreement. Coding errors, incorrect initial conditions, and invalid assumptions were discovered and corrected as a result of this comparison exercise. Differences between simulation tools in implementation of gravitation, atmospheric, and Earth orientation models remain, which require further effort to resolve.

Not all proposed scenarios were successfully implemented on a sufficient number of independent simulation frameworks (i.e., established minimum number of three) to warrant inclusion in this assessment. However, it is hoped these scenarios can be contributed by other organizations and included in the public repository of results.

The models and data are available from the NASA Engineering and Safety Center's (NESC) Academy website, in the Flight Mechanics area [ref. 7].

This assessment is believed to be the first publically available comparison of a set of 6-DOF flight simulation tools. An earlier NASA study [ref. 1] compared exo-atmospheric scenarios between NASA and international space agency partners, but those results are not publically available.

Lessons learned in this exercise, given in findings, observations, and NESC recommendations, might prove useful in future simulation tool development. Among these is an identified need for a convention regarding initial conditions and an improved method for sharing time-history data.

## 5.0 Assessment Plan

The NASA Technical Fellow for Flight Mechanics assembled an assessment team to develop verification data sets. This team met at LaRC to map out an approach to developing check-cases for comparison and cross-verification purposes.

The assessment team agreed a set of scenarios involving simple models would be developed and simulated by each participant in their preferred simulation tool. The basic parameters were agreed upon and further discussion led to the set of scenarios described in Section 6.2.8. Formats for specifying the models, initial conditions, and resulting time-history data were agreed to and a plan for presenting the data were developed.

Instead of identifying a single "known good" simulation tool, or requiring all trajectories match within a predefined tolerance, the approach taken was to present comparison plots of the results of each simulation tools. If acceptable agreement between the parameter trajectories generated by the tools was found, then those trajectories could serve as a verification guide. If unacceptable difference in results was evident, then an attempt would be made to identify an assumption, design choice, and/or an implementation difference to explain the disparity, and the set of trajectories would serve as a family of possible solutions.

One of the overall objectives was to generate a publically available report containing the salient results for use by current and future organizations.

## 6.0 Problem Description, Proposed Solutions, and Risk Assessment

## 6.1 Problem Description

The independently developed NASA, industry, and commercial flight simulation tools in use for flight dynamics and trajectory predictions have sometimes provided substantially different results. Some of the disagreements have been traced to differences in equations of motion (i.e., kinematics) implementation and the geodetic, gravitational, and atmosphere models. Differences have been caused by the levels of precision used for physical constants, and inconsistent interpretations of how to implement and initialize a given scenario. Other sources of differences have arisen from inconsistent or limited-precision unit conversions.

At the start of this assessment, there were no accepted benchmark check-cases that could be used for verification of a simulation tool. This led to the risk in using unverified tools for flight prediction and design in support of NASA flight projects. Due to the non-linear nature of most simulation scenarios, an analytical (i.e., closed-form) solution of the resulting trajectory is rarely available. The work-around solution has historically been running similar but independently developed simulations of specific flight vehicles and working to resolve differences between the preflight simulations, and later using actual flight data to improve simulation model fidelity.

## 6.2 Proposed Solution

In an attempt to build a "consensus" solution for 6-DOF flight vehicle simulations, a set of relatively simple flight vehicle models was developed, with a set of maneuvers from specified initial conditions, in a variety of atmospheric, gravitational, and geodetic configurations. It was anticipated the resulting trajectories would fall into one or more families of solutions based upon assumptions and simplifications (e.g., flat-Earth conditions).

It was desirable to make the vehicle models and resulting trajectory data available electronically for ease of comparison by developers of other simulation tools.

### 6.2.1 Check-Case Vehicle Models

A set of reference flight vehicles was proposed, based primarily on existing non-proprietary vehicle models, which are described in detail in Appendix B.1.

For the atmospheric scenarios, the "vehicles" included: a spheroid (i.e., cannon ball); a brick to evaluate rotational dynamics; a subsonic fighter with representative nonlinear aerodynamics, propulsion, and control law models; and a two-stage rocket. For the orbital cases, a larger spheroid, a cylindrical rocket body, and a simplified International Space Station were re-used from an earlier comparison study.

### 6.2.2 Check-Case Geodesy Models

One of the challenges in performing 6-DOF flight simulations is the choice in how to model the Earth's shape and motion. Early low-speed atmospheric flight simulations often used a flat-Earth approximation, which was sufficient for recreating landing and takeoff dynamics. Early computational performance limitations made this simplifying approximation attractive for pilot-in-the-loop ("real-time") training or research and development simulations.

As digital computers grew in capability, simulation of flight using more complex spherical and oblate rotating Earth models became practical from a cost/time standpoint. Many atmospheric flight simulation tools incorporate the standard DoD World Geodetic System 1984 (WGS-84) [ref. 2] ellipsoidal Earth model even though an iterative solver, or other multi-step iterative process, is normally required to convert between inertial coordinates and geodetic coordinates (i.e., latitude, longitude, and altitude) with the ellipsoidal geodesy model.

The atmospheric check-case scenarios developed for this study included round non-rotating, round rotating, and oblate spheroidal rotating Earth models. The orbital check-case scenarios used the oblate WGS-84 model exclusively. More information on each geodesy model is described in Appendix B.2.

### 6.2.3 Check-Case Coordinate Systems

A number of coordinate system definitions and transformations were required in this assessment including: J2000 inertial; Earth-centered inertial (ECI); Earth-centered Earth-fixed (ECEF) in either geocentric or geodetic frames; local-vertical, local-horizontal (LVLH); north-east-down

(NED); runway; and body coordinates. These systems and transformations are discussed in Appendix B.3.

### 6.2.4 Check-Case Gravitation Models

In parallel with a choice of Earth geodesy models is a corresponding choice of gravitation models. The simplest model has gravitational attraction varying inversely with the square of the vehicle distance from Earth's center. This simplified model is often used with the approximation of a spherical Earth.

A more sophisticated gravitation model, including gravitational harmonics that vary with latitude and longitude, is normally employed for ellipsoidal Earth models. For atmospheric check-cases with a WGS-84 Earth, the first non-zero term of the harmonic series (i.e., $J_2$ gravitation) is included. Orbital scenarios included the $J_2$ and higher harmonic terms (i.e., to $8 \times 8$). More information on gravitation models is described in Appendix B.4.

### 6.2.5 Check-Case Atmosphere Models

**US 1976.** The US Standard 1976 Atmosphere model [ref. 3] was used for the majority of the atmospheric check-case scenarios. This model can be implemented as linear interpolation of the one-dimensional tables given in the source document with ambient pressure, temperature, and density as a function of geometric altitude ($h$) or geopotential height ($Z$). A more accurate implementation is to realize the non-linear numerical equations from reference 3 used to generate the tables published in the reference.

**Marshall Engineering Thermosphere (MET)**. The MET is appropriate for modeling the thermosphere region of the Earth's atmosphere, located above the stratosphere (i.e., greater than 90 km) and below the exosphere (i.e., less than 500 km). MET is employed for most of the orbital check-cases. This model is not publicly available, but can be requested from the MSFC Natural Environments Branch. Details on MET are in Appendix B.5.

### 6.2.6 Check-Case Data Formats

The use of standard formats should significantly shorten the process of sharing models and comparing results. While some setup was required for each tool to receive models in an unfamiliar format and translate the data in a locally-compatible format, it was hoped the ability to quickly implement model changes and generate new results would be enhanced by this investment.

**Reference models**. Most of the atmospheric check-cases vehicle models were specified using the format in reference 4 (i.e., S-119), which makes use of an extensible markup language (XML) based grammar, DAVE-ML [ref. 5]. This document attempted to define the salient flight characteristics of an aerospace vehicle (i.e., aerodynamics and inertia) in an unambiguous text file that is human- and machine-readable, and with sufficient metadata to be easily converted into code and readily archivable. The most complex model attempted in this study was the single-engine F-16 aircraft defined in DAVE-ML using S-119 variable names that included an

inertial/mass properties model, a non-linear aerodynamic model, and two separate control law subsystem models. These models are available from reference 7 and described in Appendix B.1.

**Time-History Data.** Despite an attempt to identify a more efficient binary data format for the several million data points that were generated in this effort, the assessment team stored data in a comma-separated-values (.CSV) text format. These files used column headers to identify the values represented and rows to group values associated with regular time steps of simulation. The check-case files were large (e.g., 12.MB in one case) as a result of using text instead of binary value representations, but this format was felt to be better suited for archival purposes and to be more readily accessible by other reviewers. The time-history data files are available from

http://nescacademy.nasa.gov/flightsim/index.html

### 6.2.7 Participating Simulation Tools

Developers of several NASA and one open-source simulation tools agreed to participate in this comparison on a voluntary basis. The set of tools involved included simulations suited primarily for atmospheric flight, exo-atmospheric flight, and some were applicable to both flight regimes.

Not all tools attempted to execute every check-case. The assessment team set a ground rule that a minimum of three data sets (i.e., parameter trajectories) were necessary to warrant inclusion in this assessment.

The assembled tool-set included:

- **Core** from ARFC
- **JEOD** from JSC
- **JSBSim** [ref. 6]
- **LaSRS++** from LaRC
- **MAVERIC** from MSFC
- **POST-II** from LaRC
- **VMSRTE** from ARC

Details on each tool are found in Appendix B.6.

### 6.2.8 Check-Case Scenarios

A set of atmospheric and orbital flight scenarios, models, and initial conditions was developed by the assessment team (see Tables 6.3-1 and 6.3-2). Details on each atmospheric and orbital flight scenarios can be found in Appendices C.1 and C.2, respectively.

Seventeen atmospheric check cases were identified and sixteen cases were run with at least three simulation tools (one case, number 14, was also run by three simulation tools, but was not included in the assessment due to lack of agreement on test inputs). Twenty-six orbital check cases were identified and all were run with at least three simulation tools.

## 6.3 Known Risks and Mitigations

For this assessment, the risk of accidental agreement arising from a common error in predicted trajectories obtained from established, independently developed, rigorously tested, simulation tools appears unlikely. However, the consequence of a common error remaining undetected could be consequential. Sharing the results of this assessment with the wider aerospace community is intended to allow others to compare their tools against the ones represented here to minimize this risk.

***Table 6.3-1. Atmospheric Check-Case Scenarios***

| Number | Name | Verifies | Gravitational | Geodesy | Winds |
|---|---|---|---|---|---|
| 1 | Dropped sphere with no drag | Gravitation, translational EOM | $J_2$ | WGS-84 | Still air |
| 2 | Tumbling brick with no damping, no drag | Rotational EOM | $J_2$ | WGS-84 | Still air |
| 3 | Tumbling brick with dynamic damping, no drag | Inertial coupling | $J_2$ | WGS-84 | Still air |
| 4 | Dropped sphere with constant $C_D$, no wind | Gravitation, integration | $1/R^2$ | Round fixed | Still air |
| 5 | Dropped sphere with constant $C_D$, no wind | Earth rotation | $1/R^2$ | Round rotating | Still air |
| 6 | Dropped sphere with constant $C_D$, no wind | Ellipsoidal Earth | $J_2$ | WGS-84 | Still air |
| 7 | Dropped sphere with constant $C_D$ + wind | Wind effects | $J_2$ | WGS-84 | Steady wind |
| 8 | Dropped sphere with constant $C_D$ + wind shear | 2 dimensional wind | $J_2$ | WGS-84 | $f(h)$ |
| 9 | Sphere launched eastward along equator | Translational EOM | $J_2$ | WGS-84 | Still air |
| 10 | Sphere launched northward along prime meridian | Coriolis | $J_2$ | WGS-84 | Still air |

| Number | Name | Verifies | Gravitational | Geodesy | Winds |
|---|---|---|---|---|---|
| 11 | Subsonic F-16 trimmed flight across planet | Atmosphere, air-data calculations | $J_2$ | WGS-84 | Still air |
| 12 | Supersonic F-16 trimmed flight across planet | Supersonic air-data calculations | $J_2$ | WGS-84 | Still air |
| 13 | Subsonic F-16 maneuvering flight | Multidimensional table look-up | $J_2$ | WGS-84 | Still air |
| 14 | Supersonic F-16 maneuvering flight (not completed) | Mach effects in tables | $J_2$ | WGS-84 | Still air |
| 15 | Circular F-16 flight around North pole | Propagation, geodetic transforms | $J_2$ | WGS-84 | Still air |
| 16 | Circular F-16 flight around equator/dateline intersection | Sign changes in latitude and longitude | $J_2$ | WGS-84 | Still air |
| 17 | Two-stage rocket to orbit | Staging, entire atmosphere | $J_2$ | WGS-84 | $f(h)$ |

*Table 6.3-2. Exo-Atmospheric Check-Case Scenarios*

| Number | Name | Verifies | Gravitation | 3rd body pert. | Body |
|---|---|---|---|---|---|
| 1 | Earth Modeling Parameters | Environmental constants | $1/R^2$ | None | ISS |
| 2 | Keplerian Propagation | Integration, rotation-nutation precession, orientation | $1/R^2$ | None | ISS |
| 3A | Gravitation Modeling: 4 × 4 | 4 × 4 harmonic gravitation model | 4 × 4 | None | ISS |
| 3B | Gravitation Modeling: 8 × 8 | 8 × 8 harmonic gravitation model | 8 × 8 | None | ISS |
| 4 | Planetary Ephemeris | Third body gravitational forces | $1/R^2$ | Sun, moon | ISS |
| 5A | Minimum Solar Activity | Free molecular flow | $1/R^2$ | None | ISS |
| 5B | Mean Solar Activity | Free molecular flow | $1/R^2$ | None | ISS |
| 5C | Maximum Solar Activity | Free molecular flow | $1/R^2$ | None | ISS |
| 6A | Constant Density Drag | Response to constant force | $1/R^2$ | None | Sphere |
| 6B | Aero Drag with Dyn. Atmos. | Response to dynamic drag | $1/R^2$ | None | Sphere |
| 6C | Plane Change Maneuver | Response to propulsion firing | $1/R^2$ | None | Cylinder |
| 6D | Earth Departure Maneuver | Response to propulsion firing | $1/R^2$ | None | Cylinder |
| 7A | 4 × 4 gravitation | Translation response | 4 × 4 | Sun, moon | Sphere |
| 7B | 8 × 8 gravitation | Translation response | 8 × 8 | Sun, moon | Sphere |
| 7C | All Models with 4 × 4 gravitation | Translation response | 4 × 4 | Sun, moon | Sphere |
| 7D | All Models with 8 × 8 gravitation | Translation response | 8 × 8 | Sun, moon | Sphere |
| 8A | Zero Initial Attitude Rate | Integration methods for rotation | $1/R^2$ | None | ISS |
| 8B | Non-Zero Initial Attitude Rate | Integration methods for rotation | $1/R^2$ | None | ISS |
| 9A | Zero Initial Rate w/ Torque ($T$) | Rotational response | $1/R^2$ | None | ISS |
| 9B | Non-Zero Initial Rate w/ Torque | Rotational response | $1/R^2$ | None | ISS |
| 9C | Zero Initial Rate w/ $T$ + Force ($F$) | Rotational response | $1/R^2$ | None | ISS |
| 9D | Non-Zero Initial Rate w/ $T + F$ | Rotational response | $1/R^2$ | None | ISS |
| 10A | Zero Initial Attitude Rate | Gravity gradient modeling | $1/R^2$ | None | Cylinder |
| 10B | Non-Zero Initial Rate | Gravity gradient modeling | $1/R^2$ | None | Cylinder |
| 10C | Zero Initial Rate; Elliptical Orbit | Gravity gradient modeling | $1/R^2$ | None | Cylinder |
| 10D | Non-Zero Initial Rate; Ellip. Orbit | Gravity gradient modeling | $1/R^2$ | None | Cylinder |
| FULL | Integrated 6-DOF Orbital Motion | Combined effects response | 8 × 8 | Sun, moon | ISS |

## 7.0 Assessment Results

A case-by-case comparative analysis of each of the check-case trajectories is given in Appendix D. A summary of the results is provided in the following sections separated between atmospheric and orbital regimes.

A ground rule used by the assessment team in providing comparisons was that at least three simulation tools had to submit results for each check-case included in these results. Additional planned cases (e.g., supersonic fighter maneuvering flight and a proposed Apollo-like capsule reentry) were not included due to an insufficient number of implementations achieved. A total of 16 of the 17 atmospheric check cases were completed and all of the 27 orbit check cases were completed.

## 7.1 Atmospheric check-case results

In general, comparisons of the atmospheric check-cases as simulated by several simulation tools indicate minor differences due to two variations in implementation: tabular versus equation-based atmosphere models, and geodetic versus geocentric geometries.

In earlier computationally-constrained simulation implementations, an atmosphere model (e.g., reference 3 employed for these atmospheric flight simulations) was implemented as a table of density, temperature, and pressure values as a function of geometric height above a reference surface. This table was used in a linear interpolation between altitudes since this was typically faster than performing the complex calculations necessary to determine these quantities algebraically.

Improved processors have made the direct calculation approach economically feasible and more precise. However, several of the participating simulation tools continue to use an atmospheric table implementation. Therefore, some of the trajectory differences are due to linear interpolation of atmospheric properties.

The other main difference between results in atmospheric comparisons is an artifact of historical simulation techniques. As mentioned, earlier digital flight simulations of subsonic aircraft often assumed a flat Earth, where latitude and longitude were directly related to a Cartesian grid in the vicinity of a runway or airport. This was an appropriate approximation for low-speed flight in the vicinity of and while maneuvering around the terminal environment. Since the check-cases specified at least a round Earth, some retrofitting was undertaken to adapt the flat-Earth approximations to a round or oblate Earth. However, some artifacts of the simpler geodesy assumption remain, which are noted in Appendix D.

To a smaller degree, some variances in the implementation of the square-law and harmonic gravitation were due to differences in gravitation model implementation, or in the conversion of the initial geodetic position into the geocentric position. Another variance source in the F-16

check-cases was differences in defining the equilibrium (i.e., trim) values for straight and level flight, especially the trimmed rotational rate.

Errors in participating simulation tools that were initially uncovered, but corrected included mistakes in gravitational models, incorrect or imprecise initial condition values and geophysical constants, a one-frame time shift in gravitational value, and a transposition error in atmospheric property tables. For example, one simulation routinely and incorrectly aligned gravitational attraction along the geocentric radius axis, not the geodetic nadir. This led to a very, very small difference in the resulting trajectories that might not have been quickly identified without this assessment.

Finally, differences in numerical integration methods in the simulation tools appeared to cause trajectory differences. These differences are hypothesized, as no specification of (or sufficient data regarding) integration techniques was available.

In all cases, these differences were minor with the comparison plots found in Appendix D. Only when plotting variances between individual simulation results versus consensus or averaged results are the differences apparent.

It should be noted that obtaining correlation between these simulations was an iterative process. Initial results were not as good as those ultimately obtained due to ambiguity in specification or implementation of initial conditions, maneuver inputs, and other simulation implementation differences.

A total of 84 trajectories were generated comprised of nearly four million data points; these data sets are stored in 64 MB of data files available in the repository [ref. 7].

## 7.2 Orbital Check-Case Results

Comparison of orbital check-cases showed good comparisons with few significant differences. As with the atmospheric cases, some iteration was required as significantly different results were initially obtained. These differences included use of different revisions of the MET model, differences in the specification of the Earth's position at the start of various scenarios, differences in integration technique, or to mis-interpreting a sign convention or initial condition specification.

An error was discovered (and corrected) in one of participating simulation tools in which an external force or moment was applied for a length of time other than what was specified in the configuration. This error was introduced in a recent rewrite of that particular module of the simulation tool and had somehow managed to elude detection, despite extensive regression tests that are routinely applied to all revisions. The revised tool had not yet been released, but the error may have affected NASA missions if it had not been detected during this assessment. The tool architect stated that he believed this 'catch' was worth the cost of the assessment.

A total of 103 trajectories were generated comprised of 1.4 million data points. These data sets are stored in 25 MB of data files available in the repository [ref. 7].

## 7.3 Comparison Difficulties

During this assessment, it became apparent that the time required to reach a reasonable level of match had been underestimated. The original schedule developed and agreed to by the team expected to complete this effort in just over 12 months. The effort has, after 30 months, not been completed to the degree expected at the outset, in that one atmospheric check-case (Earth reentry from a lunar return trajectory) has not been attempted, and a second atmospheric case remains incomplete.

Part of the delay was due to the now-apparent need to specify initial conditions and maneuvering inputs exactly. It was believed early in the planning process that it would be sufficient for the scenarios to be described briefly in one axis frame; however, obtaining good matches ultimately required detailed specification of the initial conditions in several axis frames. An example is the initial rotation rate for some of the early atmospheric check-cases: a small numeric difference exists between the inertial and the ECEF angular rate of a body. Ensuring close matches required giving the rotation rate in both frames to ensure all simulation tools started with the same rate, since some simulation tools are initialized in ECEF-relative rates and others in inertial rates. A complete description of the changes and corrections required to improve matching is given in Appendix E, Section E.1.

As knowledge was gained in this process, the initial conditions document had to be revised several times, initially leading to confusion by the team on which version was used in each round of comparison plots, which delayed reaching successful matches.

The process followed by the widely dispersed team also introduced delays. Due to the large amount of data involved, considerable time was spent uploading data sets from each tool to a central server, downloading and plotting the trajectories by one analyst, uploading the results, and downloading and inspecting the large number of resulting plots for differences. Obvious differences were fairly easy to detect, but determining the root cause of the difference often took considerable time and effort.

A formal comparison (comprising Appendix D) by one analyst required a period of several weeks, due to the large number of maneuvers to compare and the in-depth analysis required.

Since most participants were not full-time on this assessment, some of these comparison cycles took longer than others due to Agency priorities. Many more comparison cycles were also required than originally expected (30 sets of comparison plots were generated for the atmospheric cases between May 2013 and August 2014).

## 7.4 Summary of Comparisons

The eventual matches between simulation tools, achieved only after several iterations of comparing results and correcting mistaken assumptions and other errors, was good enough to indicate agreement between a majority of simulation tools for all cases published. Most of the remaining differences are explained and could be reduced with further effort.

Due to differences in trim algorithms, some of the 6-DOF aircraft check-cases (cases 10-16) provide some remaining disagreements on precise numbers, but do indicate a family of solutions that are close enough to serve as a comparison with other simulation tools.

The orbital cases agree quite well. The remaining differences are attributed to either an obvious misconfiguration of the simulation tool or differences in the numerical integration method and step size.

Appendix E gives quantitative measures of matches for each check-case, as well as some ideas for future work. If additional matching were to be funded, the authors welcome participation by other simulation tool developers who might wish to participate.

# 8.0 Findings, Observations, and NESC Recommendations

## 8.1 Findings

The following findings were identified related to the simulation process:

**F-1.** Even modeling simple vehicles posed challenges. Differences in the implementation of simple vehicle models were apparent.

- These arose primarily from differences in interpretation of the scenario and initial conditions.
- Initial attempts to model these scenarios led to some significant miscompares that revealed differences in physical constants and other modeling errors. These differences in constants and modeling errors were corrected in several tools prior to generating this set of comparisons.

**F-2.** It took significant effort to get good agreement on the check-cases. Even simple aerospace vehicle simulation models are non-trivial to implement.

- The comparable results shown in most of these check-cases required extensive iterations and adjustments/corrections to initial conditions and modeling assumptions.

The following findings were identified related to atmospheric simulations:

**F-3.** Tabular versus equation-based atmosphere introduced differences.

**F-4.** Different interpretations of nadir direction can lead to differences due to “non-vertical” gravitational residue.

**F-5.** While the majority of atmospheric simulations appeared to use WGS-84 Earth geodesy, simplifications such as flat- or round-Earth led to differences.

**F-6.** Precise specification of initial conditions would be assisted by a standard for specifying the state vector of a 6-DOF flight simulation.

**F-7.** Every simulation examined eventually matched trajectories with at least two other simulations to a reasonable degree, where the correlation level is a function of the simulation purpose.

The following finding was identified for the orbital simulations:

**F-8.** In general, the orbital cases (implemented in at least three different simulation tools) matched fairly well, but minor differences are apparent.

The following general findings were identified:

**F-9.** In general, the atmospheric cases do not match as well as the orbital cases.

- Atmospheric flight is non-linear, due to forces and moments being related to the square of the air-relative vehicle velocity, and to other non-linear aerodynamic effects.
- The larger number of simulation tools were applied to these initial cases increased the chances of mismatches.

**F-10.** The amount of effort required to develop, specify, and reconcile differences for multiple vehicle models across an array of simulation tools was grossly underestimated.

**F-11.** The comparison check-cases examined form the basis of a comprehensive set of verification data sets for 6-DOF flight simulations. Additional scenarios and results would improve the value of this process.

- Comparison cases are needed for supersonic maneuvering flight and atmospheric re-entry scenarios.

**F-12.** Nearly every simulation framework that participated in this assessment discovered at least one significant implementation difference/error that was modified/corrected to improve correlation with other simulation tools.

## 8.2 Observations

The following observation was identified:

**O-1.** This assessment appears to have been one of the first comparisons of more than two atmospheric 6-DOF simulation tools intended for public release.

## 8.3 NESC Recommendations

The following NESC recommendations were identified and directed towards the NESC and/or flight simulation tool users as noted.

**R-1.** Encourage use of these check-cases to help minimize errors from flight simulation tools. ***(F-11, F-12)*** **– Flight simulation tool users**

**R-2.** Ensure widespread public dissemination and availability of models and results to the aerospace community. ***(F-11, F-12)*** **– NESC**

**R-3.** Flat- or round-Earth simplifications should only be used when appropriate. ***(F-5)*** **– Flight simulation tool users**

**R-4.** Continue development of additional comparisons of missing maneuvers, including supersonic maneuvering flight and atmospheric re-entry scenarios. ***(F-11)*** **– NESC and flight simulation tool users**

**R-5.** Develop a consensus standard for initial state vector description, employing ANSI/AIAA S-119-2011for identifying simulation parameters, for ease of collaboration and dynamic model data exchange. ***(F-1, F-6)*** **– NESC and flight simulation tool users**

**R-6.** Develop a consensus standard for time-history data encoding, employing ANSI/AIAA S-119-2011for identifying simulation parameters, for ease of collaboration and dynamic model data exchange. ***(F-1, F-6)*** **– NESC and flight simulation tool users**

## 9.0 Alternate Viewpoint

There were no alternate viewpoints identified during the course of this assessment by the NESC assessment team or the NRB quorum.

## 10.0 Other Deliverables

No unique hardware, software, or data packages, outside those contained in this report, were disseminated to other parties outside this assessment.

## 11.0 Lessons Learned

No applicable lessons learned were identified for entry into the NASA Lessons Learned Information System (LLIS) as a result of this assessment.

## 12.0 Recommendations for NASA Standards and Specifications

A convention or standard for numerical specification of unambiguous initial conditions for 6-DOF flight simulations should be developed to ensure multiple flight simulation tools start at exactly the same planet-relative position, velocity, attitude and angular rates. A significant portion of this assessment was spent resolving misinterpreted initial conditions despite an attempt to specify this information. Questions regarding whether an angular rate initial condition was with respect to a rotating Earth or to an inertial axis were raised multiple times, as well as ambiguity of initial angular attitude. By way of comparison, the popular two-line element format that specifies orbital parameters provides some of this information for satellites, although attitude is not included.

Also, a structured, binary, compressed format to encode bulky time-history data (which is provided for this assessment as comma-separated-value UNICODE text files at the URL identified by ref. 7), as well as tools to manipulate this data, should be identified and/or developed and adopted by NASA to assist in sharing predicted trajectories from simulation tools. Using a CSV format was expeditious but cumbersome.

## 13.0 Definition of Terms

| | |
| --- | --- |
| Finding | A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation. |
| Lessons Learned | Knowledge, understanding, or conclusive insight gained by experience that may benefit other current or future NASA programs and projects. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. |
| Observation | A noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided. |
| Problem | The subject of the independent technical assessment. |
| Recommendation | A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk. |

## 14.0 Acronyms List

| | |
| --- | --- |
| AIAA | American Institute of Aeronautics and Astronautics |
| ANSI | American National Standards Institute |
| $C_D$ | Aerodynamic coefficient of drag |
| CSV | Comma-separated values |
| DAVE-ML | Dynamic Aerospace Vehicle Exchange Markup Language |
| DoD | Department of Defense |
| DOF | Degree of Freedom |
| ECEF | Earth-centered, Earth-fixed (rotating coordinate frame) |
| ECI | Earth-centered inertial (non-rotating coordinate frame) |
| EOM | Equations of motion |
| $F$ | Force (thrust) |
| $h$ | Geometric altitude |

| | |
| --- | --- |
| $J_2$ | First non-zero gravitational harmonic |
| JSC | Johnson Space Center |
| LaRC | Langley Research Center |
| MSFC | Marshall Space Flight Center |
| MET | Marshall Engineering Thermosphere |
| NED | North-East-Down |
| *R* | Radius |
| S-119 | ANSI/AIAA S-119-2011 Flight Dynamic Model Exchange Standard |
| *T* | Torque |
| WGS-84 | World Geodetic System 1984 |
| XML | Extensible Markup Language |
| *Z* | Geopotential height |

## 15.0 References

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## 16.0 Appendices

Appendix A. Nomenclature
Appendix B. Models
Appendix C. Check-case
Appendix D. Results
Appendix E. Discussion

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**14. ABSTRACT**

This NASA Engineering and Safety Center (NESC) assessment was established to develop a set of time histories for the flight behavior of increasingly complex example aerospacecraft that could be used to partially validate various simulation frameworks. The assessment was conducted by representatives from several NASA Centers and an open-source simulation project. This document is an overview of the process used and the results of the assessment. Volume II contains details on models, implementation, and results.

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