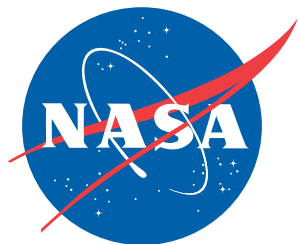


NASA/TM-2011-217085/Volume I  
NESC-RP-09-00598



# Flight Simulation Model Exchange

*Daniel G. Murri/NESC  
Langley Research Center, Hampton, Virginia*

*E. Bruce Jackson  
Langley Research Center, Hampton, Virginia*

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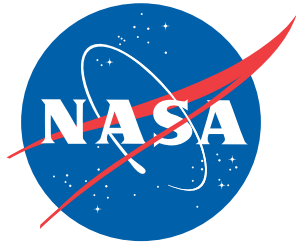
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*Daniel G. Murri/NESC  
Langley Research Center, Hampton, Virginia*

*E. Bruce Jackson  
Langley Research Center, Hampton, Virginia*

National Aeronautics and  
Space Administration


Langley Research Center  
Hampton, Virginia 23681-2199

April 2011

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## **Flight Simulation Model Exchange Volume I**

**NRB Review Date: February 17, 2011**

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## Report Approval and Revision History

### Approval and Document Revision History

NOTE: This document was approved at the February 17, 2011, NRB. This document was submitted to the NESC Director on March 7, 2011, for configuration control.

Approved Version:	Original Signature on File	3/8/11
1.0	NESC Director	Date


Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Version	Mr. Daniel Murri, NASA Technical Fellow for Flight Mechanics	02/17/11

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- Appendix A. NESC Flight Simulation Model Exchange Assessment Report from Johnson Space Center
- Appendix B. American National Standard: Flight Dynamics Model Exchange Standard (draft BSR/AIAA S-119-201x)
- Appendix C. XML Document Type Definition file for S-119 markup: DAVEfunc.dtd
- Appendix D. Dynamic Aerospace Vehicle Exchange Markup Language (DAVE-ML) Reference Manual



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## **Volume I: Technical Assessment Report**

### **1.0 Notification and Authorization**

Mr. Dan Murri, NASA Technical Fellow for Flight Mechanics at Langley Research Center (LaRC), requested the NASA Engineering and Safety Center (NESC) to test the implementation of a draft American Institute of Aeronautics and Astronautics (AIAA) flight-dynamics simulation model exchange Standard by developing and exercising import tools at several NASA Centers with two representative high-fidelity aerospace vehicle aerodynamics models. This implementation will serve as a pathfinder for more rapid vehicle model exchanges in the future, increasing productivity and cross-Agency collaboration.

An NESC out-of-board activity was approved by NESC Director Ralph Roe on November 4, 2009. Mr. Murri was selected to lead this assessment. The assessment plan was approved by the NESC Review Board (NRB) on December 10, 2009.

The key stakeholders for this assessment are the NASA Office of Chief Engineer and the NASA Technical Fellows for Guidance, Navigation, and Control (GN&C); Aerosciences; and Flight Mechanics.

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## 2.0 Signature Page

Submitted by:

*//Team Signature Page on File//*

\_\_\_\_\_  
Mr. Daniel G. Murri    Date

\_\_\_\_\_  
Mr. E. Bruce Jackson    Date

Significant Contributors:

\_\_\_\_\_  
Mr. Edwin Z. Crues    Date

\_\_\_\_\_  
Mr. Robert D. Falck    Date

\_\_\_\_\_  
Mr. David A. Hasan    Date

\_\_\_\_\_  
Ms. Melissa A. Hill    Date

\_\_\_\_\_  
Mr. Matthew V. Jessick    Date

\_\_\_\_\_  
Mr. Thomas G. McCarthy    Date


\_\_\_\_\_  
Mr. William L. Othon    Date

\_\_\_\_\_  
Mr. John M. Penn    Date

\_\_\_\_\_  
Mr. Nghia D. Vuong    Date

\_\_\_\_\_  
Mr. Curtis J. Zimmerman    Date

Signatories declare the findings and observations 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, analysis, and inspections.


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### 3.0 Team List

Name	Discipline	Organization
<b>Core Team</b>		
Dan Murri	NESC Assessment Lead	LaRC
Bruce Jackson	NESC Team Lead	LaRC
Neil Dennehy	Assessment Team Co-Lead	GSFC
Zack Crues	Simulation Representative	JSC
Rob Falck	Simulation Representative	GRC
David Hasan	Simulation Representative	JSC
Missy Hill	Simulation Representative	LaRC
Matt Jessick	Simulation Representative	JSC
Greg McCarthy	Simulation Representative	DFRC
Bill Othon	GN&C Representative	JSC
John Penn	Simulation Representative	JSC
Nghia Vuong	Simulation Representative	ARC
Curt Zimmerman	Simulation Representative	MSFC
Laura Leybold	MTSO Program Analyst	LaRC
<b>Administrative Support</b>		
Diane Sarrazin	Project Coordinator	LaRC/ATK
Linda Burgess	Planning and Control Analyst	LaRC/ATK
Carolyn Snare	Technical Writer	LaRC/ATK

### 3.1 Acknowledgements

The assessment team would like to express appreciation to Mr. Bruce Hildreth of J. F. Taylor, Inc. and Mr. Geoffery Brian of the Australian Department of Defence for their support and initiative in bringing this technology to simulation model exchange. They would also like to thank Mr. Mike Red of the Simulation and Graphics Division at Johnson Space Center (JSC) for supporting the effort and hosting the final meeting; Ms. Linda Burgess, Ms. Laura Leybold, Ms. Diane Sarrazin, and Ms. Carolyn Snare for their unflagging efforts; the NESC for supporting this worthwhile assessment; and Mr. Neil Dennehy and Dr. David Schuster of the NESC for their support.

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## 4.0 Executive Summary


The American Institute of Aeronautics and Astronautics (AIAA) has, through its Modeling and Simulation Technical Committee (MSTC), developed a draft Board of Standards Review (BSR) / American National Standards Institute (ANSI) Standard that establishes a convention for variable names, axis systems, units-of-measure and sign convention abbreviations, and an Extensible Markup Language (XML) grammar. AIAA is using this Standard to encode most of the details for a high-fidelity flight vehicle dynamics model. The draft Standard, *Flight Dynamics Model Exchange Standard*, BSR/ANSI-S-119-201x, hereafter “S-119,” has recently completed a second round of public comments. Several NASA engineers from the flight mechanics; aerosciences; and guidance, navigation, and control (GN&C) disciplines collectively contributed to the development of S-119.

The NASA Engineering and Safety Center (NESC) Review Board (NRB) sponsored an assessment of S-119 that was conducted by simulation and GN&C engineers from several NASA Centers, including Ames Research Center (ARC), Dryden Flight Research Center (DFRC), Glenn Research Center (GRC), Johnson Space Center (JSC), Langley Research Center (LaRC), and Marshall Space Flight Center (MSFC). The assessment team reviewed the conventions and formats spelled out in the draft Standard and the actual implementation of two example aerodynamic models (a subsonic F-16 and the HL-20 lifting body) encoded in the XML grammar. During the implementation, the team kept records of lessons learned and provided feedback to the AIAA MSTC representative.


The team judged the implementation successful if the two example models, which contained internal static check cases, generated outputs to specified inputs that matched the check cases within the specified tolerance. (This self-verification capability is a benefit of S-119.) Each site reported success in verifying the examples in their respective simulation frameworks. A further, optional, exercise was to implement a complete HL-20 simulation with guidance and control law, mass-and-inertia, and landing-gear models to demonstrate the imported model in real-time. This exercise was successful at each Center that attempted to fly a complete HL-20 simulation.

An assessment kick-off was held at LaRC on January 13, 2010, with several introductory presentations and discussions on expectations and existing tools. At the end of a 9-month assessment period, a second face-to-face meeting was held at JSC on October 21, 2010, and included representatives from each Center (one Center’s representative attended via teleconference).

Based on the relative ease of importing the example models by each participating Center, the assessment team recommended the adoption of Flight Dynamic Model Exchange Standard, BSR/AIAA-S-119-201x, with some suggested changes, as a recommended practice for both developing new simulation aerodynamic models and for exchange of such models, when such models involve significant numbers of function tables.

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In addition to providing a practical test of the S-119 format, the assessment resulted in having the ability to share a single flight simulation model format across most NASA Centers, feedback to the AIAA, and identification and correction of several errors in existing S-119 tools.

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## 5.0 Assessment Plan

The AIAA MSTC worked for several years to develop a programming-language-neutral method of encoding a mathematical model, model function data, and verification data using XML, a text-file, data-encoding method adopted as a standard web data-exchange method. Using XML, a specialized grammar was developed to encode aero models in a human- and machine-readable format that captures most of the elements of a high-fidelity engineering math model (including documentation, modification history, data references, uncertainty, and verification check cases). S-119 includes standard variable names, sign conventions, axis systems, and units-of-measure encoding that achieve an unambiguous representation of the data, suitable for automated import to or export from an existing simulation framework.


This assessment focused on the shared implementation of two existing aerospacecraft models, specifically the F-16 subsonic aero and the HL-20 lifting body aero databases. With an accompanying fixed inertia model and Simulink<sup>®</sup> control law, an autoland-capable, flyable HL-20 real-time simulation was realized within the duration of this assessment at three participating Centers.

Most of the effort by each participating Center involved developing import scripts or linking existing application programming interface (API) tools to allow their simulation framework to accept S-119 models. Some additional software development was necessary to implement the existing autocoded HL-20 control laws, landing gear, and inertia models in the simulation, if a complete simulation was desired, as these elements were not available in S-119 format.

This assessment allowed team members from ARC, DFRC, GRC, JSC, and MSFC to implement and evaluate S-119 by adopting existing or developing and exercising new import tools and importing existing aerodynamic models into each Center's real-time simulation or analysis tool framework. One of these import tools was developed and exercised at LaRC prior to this assessment and took approximately 6 staff-months of effort [ref. 1]. LaRC's results and experiences were used as a starting point for the other Centers, and the LaRC team members had the opportunity to update their tool, assist the other Centers with their implementations, and participate in the development of findings, observations, and NESC recommendations.

For all Centers, once an import tool existed, importing new models became much easier. If there were no changes to the model inputs or outputs, an updated aero model of arbitrary size and complexity could be imported in a matter of minutes. A byproduct of adopting S-119 was the automatic verification of the newly realized model via included check case data.

The adoption of a flight simulation model exchange Standard benefits existing cross-Center Programs, such as Exploration and Fundamental Aeronautics, almost immediately. Lessons learned are available for the potential development of a NASA Standard in this area and to help the AIAA MSTC publish the new S-119. (As of February 2011, S-119 had successfully completed two rounds of public comments and was being referred to ANSI for publication.)

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## 6.0 Problem Description, Proposed Solution, and Known Risks

### 6.1 Problem Description

This assessment targeted one of the factors that paces the research and development of new aerospacecraft: the development and distribution of a high-fidelity flight simulation dynamics model. At the time of this report, each NASA Center uses mostly incompatible simulation frameworks for both real-time and analytical simulation studies. The incompatibility arises from the separate growth of simulation capability within each Center, dating back to the 1970s or earlier [ref. 2]. Adopting a common framework at this stage, however, would be counterproductive for several reasons, including significant retooling and retraining costs, loss of unique capabilities that exist at each Center, and potential loss of valuable cross-checking of results. Nevertheless, such incompatibility has served as a pacing item for collaborative research (e.g., the 1990s High Speed Civil Transport (HSCT) [ref. 3]) and accident board/return-to-flight activities (e.g., the X-43A first mission booster failure). Due to the complexity of developing, sharing, and verifying the HSCT Industry Reference H aero database, the Program took approximately 12 months to prepare for a new release of the simulation database. The problem extends beyond NASA as well: a 2002 paper showed that the United States (US) Department of Defense (DoD) loses approximately \$6 million in opportunity cost and negative training per year, due to incompatible simulation formats, for one aircraft type [ref. 4].


### 6.2 Proposed Solution

#### 6.2.1 History

For many years, various organizations have tried to resolve this incompatibility by proposing standards on simulation software and hardware implementations. In 2002, members of the AIAA MSTC, including a co-author of this report, proposed a standards-based approach that focused on standardizing the *exchange* of simulation models, not their actual hosting and execution [ref. 4]. As the idea caught on, tools began to appear that assisted in the implementation and use of standard models. Both Australia's Defence Science Technology Organisation (DSTO) and LaRC's simulation branches developed code libraries or APIs that made using these S-119 models much easier. Other organizations began to develop tools and scripts that would convert S-119 models into analysis source formats (such as Simulink<sup>®</sup>).

#### 6.2.2 Overview of Proposed Solution

The proposed S-119 Standard for dynamic model exchange is composed of three elements: a written document that gives standard identifiers (text-based names or abbreviations) for axis systems, units of measure, sign convention, and variable names; an XML markup specification for encoding vehicle model data, equations, provenance, and check-cases; and a reference manual for the XML markup grammar.

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The written document, known as BSR/ANSI-S-119-201x, *Flight Dynamic Model Exchange Standard*, contains conventions for unique identifiers (text-based names) for axis systems, units of measure, sign convention, and variable name structure and core names. It is found in Appendix B in Volume II of this report. It required use of a NASA-developed XML markup specification.

The XML markup specification (more specifically, a document type definition (DTD)) is known as the Dynamic Aerospace Vehicle Exchange Markup Language (DAVE-ML), and is in Appendix C in Volume II of this report. A reference manual for the DAVE-ML DTD is given in Appendix D. These three documents form the basis for encoding flight dynamic models in XML and are herein referred to as “S-119.”

The identifiers defined in the written Standard are used with the DAVE-ML DTD to create stand-alone XML files that encode a large portion of a flight vehicle’s dynamics. Separate XML files would be required for each subsystem thus encoded (e.g., aerodynamics, inertia, landing gear, propulsion, reaction control, etc.).

Each XML file contains a fixed sequence of elements, beginning with a file header that describes the encoded model and (typically) gives information about the origins of the model (i.e., provenance). Following the header is a definition of all the variables used within the model (including calculations to generate intermediate and output variables) followed by definitions of any non-linear function tables used by the model. The last part of the XML file contains any check cases for verification of proper implementation of the model, with allowable tolerances.

An excerpt of an aerodynamic DAVE-ML model (see Figure 6.2-1 below) shows how variable definitions, breakpoint and function table definitions, and functions combine to map input variables like Mach number and control surface deflections to an aerodynamic coefficient output variable. Not shown are the calculations and check-case sets that such a model would employ for complete definition and verification of the model implementation.





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```
<?xml version="1.0" standalone="no" ?>
<!DOCTYPE DAVEfunc SYSTEM "DAVEfunc.dtd">
<DAVEfunc>
  <fileheader> ... </fileheader>
  <variableDef varID="DBFLL" ...>
    (DBFLL variable description)
  </variableDef>
  <variableDef varID="XMACH" ...>
    ... (Mach variable description) ...
  </variableDef>
  <variableDef varID="CLBFL" ...>
    ... (CLBFL variable description) ...
  </variableDef>
  .
  <breakpointDef bpID="XMACH1_PTS" ... >
    <bpVals>0.3, 0.6, 0.8, ... </bpVals>
  </breakpointDef>
  <breakpointDef bpID="DBFL_PTS_PTS" ... >
    <bpVals>0., 15., 30., ... </bpVals>
  </breakpointDef>
  .
  <griddedTableDef gtID="CLBFL_table">
    <breakpointRefs>
      <bpRef bpID="DBFL_PTS"/>
      <bpRef bpID="XMACH1_PTS"/>
    </breakpointRefs>
    <dataTable>
      -0.864E-02, -0.1026E-01, ...
      -0.863E-02, -0.5367E-02, ...
    </dataTable>
  </griddedTableDef>
  .
  <function ... >
    <independentVarRef varID="DBFLL" .../>
    <independentVarRef varID="XMACH" .../>
    <dependentVarRef varID="CLBFL" .../>
    <functionDefn ... >
      <griddedTableRef gtID="CLBFL_table"/>
    </functionDefn>
  </function>
  .
</DAVEfunc>
```

DBFLL is the lower-left body flap deflection (input to model)

XMACH is flight Mach number (input to model)

CLBFL is the lift coefficient contribution due to lower-left body flap deflection (function output)


Breakpoint set definitions; may be reused by several functions

Multi-dimensional nonlinear function description; may be shared (left- and right-lower body flap lift contribution, for example)

Function element ties together input/output variables, breakpoint sets, and function table points

Check-case (implementation verification) data not shown

**Figure 6.2-1. Excerpt from an Example DAVE-ML Model**

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## 6.3 Known Risks and Mitigations

Potential risks associated with adopting a standard model exchange format, and their mitigations, are briefly discussed below.

### 6.3.1 Loss of Cross-checks from Independently Coded Models

Risk: A benefit of the existing state-of-the-art (where each model has to be rehosted, usually by hand re-coding the subsystem models) is that tracking down the inevitable differences in model behavior generally leads to discovery and resolution of programming errors in the original model. The risk of adopting a common model source format is that this “implicit” validation and verification would be lost.

Mitigation: It is true that independently developed simulations serve as informal cross-checks to the primary simulation. Each program should decide if an independent simulation is warranted. However, often the differences between simulation trajectories arise from different atmospheric models and/or integration of the equations of motion; these are not usually exchanged and thus sharing common vehicle dynamic models would have no effect, good or bad, on these differences.

### 6.3.2 Reliance on a Standard Format Developed and Maintained by a Third Party


Risk: Another risk of adoption of a third-party standard (in this case, the proposed S-119 AIAA Standard, if adopted) would be the loss of control over changes to that Standard.

Mitigation: In mitigation of this risk, the author and current maintainer of the DAVE-ML format (technically an XML DTD) is a NASA employee. The idea of a formal consortium to oversee changes to the DTD should be pursued to provide longevity and consensus to mitigate this risk.

### 6.3.3 Insufficient Flexibility for Modeling Special Use Cases

Risk: Being locked into one model format that may include unforeseen limitations, which could prevent efficient or reasonable representation of the physical behavior of the modeled system.

Mitigation: S-119 is extensible and can be adapted to handle common-use cases; it is anticipated that such changes should be backwards-compatible for the growing library of existing models. It is possible that the format may not lend itself to future special modeling techniques which are not presently foreseen. However, given the diversity of models that have been successfully encoded in S-119 (e.g., F-16 subsonic aero, HL-20 full envelope aero, blended-wing-body multi-control surface aero, Constellation Program models including the Ares I aerodynamics, the Orion Launch Abort Vehicle common aerodynamics, and various aero and inertia models for military aircraft “libraries”), the S-119 format is believed sufficient to handle typical flight dynamics model applications.

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### 6.3.4 Incompatibility with Standards Developed by Other Agency Partners

**Risk:** If NASA were to adopt one standard while another Agency partner adopted a different standard, the competing standards might obviate any benefit of adoption, placing mission success at risk.

**Mitigation:** The S-119 document is proposed to become an ANSI and eventually an International Organization for Standardization (ISO) Standard, which may minimize the potential emergence of another standard. As part of this assessment, several emerging modeling Standards were reviewed. One in particular, Modelica [ref. 5], is an emerging European academic Standard that has some merit. However, at the time of this report, it does not have sufficient treatment of multidimensional interpolated function tables, which are the core of most high-fidelity aerospace vehicle dynamic models, to be useful.

### 6.3.5 Lack of Export Capability for Existing Models

**Risk:** While the assessment focused on importing and reusing existing models written in the standard format, only two Centers have explored exporting existing model data into the format. Such exports will require extensive manual intervention to complete the model.


**Mitigation:** This risk may be mitigated by adoption of the standard format by aerodynamicists who define the original model, if tools can be developed to assist them. The format lends itself to archival status (simple text-based file with sufficient metadata to interpret as a stand-alone document).

## 7.0 Assessment Results

A summary of the efforts of ARC, DFRC, GRC, JSC, and MSFC is given below. A report from the team at JSC on their extensive investigation of S-119 may be found in Appendix A. As mentioned previously, LaRC developed and exercised their import tool prior to this assessment. LaRC's results and experiences were used as a starting point for other Centers, and the LaRC team members had the opportunity to update their tool, assist the other Centers with their implementation, and participate in the development of findings, observations, and NESC recommendations.

### 7.1 Ames Research Center

ARC's Simulation Laboratories (Simlabs) participated in an early (2004) exercise at accepting models encoded in what became the S-119 format [ref. 6]. The extent of participation in this assessment was to revisit the Perl scripts developed for that 2004 effort and to revise them as necessary to accommodate changes that had transpired in the underlying DAVE-ML format since that initial exercise.

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The approach was to convert the S-119 models into the equivalent Formula Translator (FORTRAN) algorithm and the data tables into the equivalent, ARC-unique, function table processor (FTP) input files for subsequent compilation.

This assessment was pursued on a part-time basis as time allowed; as a result, approximately 10 months were required to successfully update the import scripts. However, the test cases for both the HL-20 lifting body aero model and other simple models were matched within the specified tolerance. Importing a new S-119 model at ARC's SimLabs with these scripts should take no more than a few minutes.

## 7.2 Dryden Flight Research Center

At DFRC, an HL-20 simulation was constructed from the example S-119 model using the following components:

- Dryden Core Software v 4.0—March 2010
- Janus API version 1.10, Copyright © 2006, DSTO, Commonwealth of Australia [ref. 7]
- Xerces-c library 3.0.1—sparc-solaris-cc-5.7, Copyright © 1999, IBM Corporation [ref. 8]
- Qhull library 2009.1, Copyright © 1993–2003, Free Software Foundation, Inc. [ref. 9]


The Janus API was chosen to provide access to the DAVE-ML dataset structure. Xerces and Qhull are supporting libraries required by the Janus API.

Examples for loading, testing, and running Janus models were found in sample code provided with its release and proved to be easy to implement. The development platform was a Sun-Sparc V890 computer hosting the Sun OS 5.10 (Solaris 10). The Sun C++ compiler 5.9 was used to generate a simulation executable.

The aero model initialization was accomplished by dynamically loading the `HL20_aero.dml` file using Janus during simulation startup. The test cases were executed and checked to verify the integrity of the aero model. Other HL-20 vehicle models were provided "as is" from LaRC. These models were assumed to be correct.

The simulation was successfully flown in real-time at 200 Hz (5-ms frame time). It was demonstrated to be functional by exercising the control system in each of its major modes (Direct, SAS, and Automatic). Flight path and trajectory plots were compared against data provided in Reference 10 and deemed satisfactory.

As a result of this assessment, re-hosting simulations provided in the S-119 format should be relatively straightforward at DFRC.

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### 7.3 Glenn Research Center

For this assessment, a means to import S-119 models into the Optimal Trajectory by Implicit Simulation, version 4 (OTIS4) non-real-time simulation analysis tool was developed. OTIS4 is a 3 degrees of freedom (DOF)/6DOF trajectory optimization program based on collocation methods originally developed by Mr. Steve Paris and Mr. Charles Hargraves of Boeing. OTIS4 is now maintained by GRC and used by several industry partners, academia, NASA, and the US Air Force.

OTIS4 is primarily used for atmospheric flight optimization, although it is also capable of optimizing in-space trajectories.

GRC chose to develop Perl scripts to convert from the standard model format into OTIS4 input tables. The scripts provided a means to import S-119 tabular data into OTIS4 via the Graphical Otis Dataset Interpolator and Editor (GRODIE) tool. Updates to GRODIE to load S-119 models took only a few days. This capability has been added to the OTIS4 distribution package.

Work is ongoing to provide an export capability (to convert OTIS4 models into S-119 models).

### 7.4 Johnson Space Center

At JSC, a team of analysts undertook several areas of assessment of S-119, including:


1. Integration of two S-119 APIs with the JSC Trick simulation framework, and development of a novel S-119 to C-code generator.
2. Analysis of S-119 interpreter performance.
3. Investigation of some non-aerodynamic S-119 models, including implied dynamic models.
4. Analysis of the S-119 and DAVE-ML XML draft specifications.

Each activity is summarized below; Appendix A contains full details.

#### 7.4.1 Software Integration

The JSC team's effort to integrate S-119 models into JSC simulation software involved two activities: API integration and code generation. The integration activity focused on integrating the two available S-119 interpreter systems (Janus and LaSRS++/DAVE-ML Translator) into Trick. The code generation activity involved the development of an XML-to-C/C++ code generator to create compilable code from an S-119 model.

The code generator addressed, in a novel fashion, the desire of some to convert directly from S-119 model to C source code. It used a new technology, Extensible Style Sheet Language Transformation (XSLT) to convert an XML file into C source code whose input-output mapping matched that described in the S-119 model. Prior to this assessment, such capability was not

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immediately available; instead, autocode had to be generated from an intermediate (and compute-intensive) translation from S-119 into Simulink® models.


For both activities (integration and code generation), the JSC team focused primarily on an HL-20 lifting body simulation, incorporating the HL-20 S-119 aerodynamic model with the Trick simulation framework and a JSC dynamics package (JSC Engineering Orbital Dynamics) to provide a planet model, coordinate systems, vehicle dynamics, and vehicle trajectory. They implemented a single "generic" software model that integrated their Trick-based simulations with either the Janus or the LaSRS++ DAVE-ML interpreters. Details of this generic design are provided in Appendix A. The JSC team also used the XML-to-C/C++ code generator to generate equivalent C-code. The team found this generated code useful as a baseline against which to compare the runtime performance of the interpreted approach. It could also be used to compare against a hand-coded equivalent C-based HL-20 aero model during development.

#### **7.4.2 Execution Time Study of DAVE-ML Interpreters**

The JSC team's performance analysis of S-119 models involved the investigation of a Trick-based HL-20 auto-landing simulation integrated with (1) the Janus DAVE-ML interpreters, (2) the LaSRS++ DAVE-ML interpreter, (3) the C code auto-coded from our XML-to-C/C++ code generator, and (4) some pre-existing hand-written HL-20 source code. In all four cases, the simulations generated the same trajectory. The JSC team found that interpreted DAVE-ML was of comparable speed to auto-generated compiled C-code and hand-tuned code for the limited testing they performed. Detailed results are available in Appendix A, including some of the limitations of the method used for performance analysis.

#### **7.4.3 Non-aerodynamics Models Implemented in DAVE-ML**

In addition to the JSC team's work with the HL-20 aerodynamics model, the JSC team looked at two non-aerodynamic S-119 models: (1) an HL-20 reaction control system (RCS) algorithm and (2) a pneumatic tire force model. The investigation of the RCS algorithm, in particular the successful representation of it in DAVE-ML and subsequent execution of the model using the Janus and LaSRS++ interpreters and their XML-to-C/C++ code generator, offers some evidence that models beyond the aerodynamics niche can indeed be represented through the current DAVE-ML specification. In particular, dynamic models with saved states can be created in DAVE-ML without direct support in the specification, by the caller providing external storage and integration of the state variables. This worked reasonably well when aided by a convenient method of hooking together corresponding simulation and internal DAVE-ML interpreter variables. The JSC team's investigation of a pneumatic tire data compression model showed that the self-documenting properties of DAVE-ML can be used to record provenance, modification, and accuracy data for static data sets; sophisticated models can be created entirely in MathML without recourse to table look-ups; and models can be created in a hierarchy where the outputs from one are then fed into the next in DAVE-ML, even though this feature is not supported directly in the specification. Further details are available in Appendix A.

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#### 7.4.4 DAVE-ML Specification Comments/Suggestions

In the course of their assessment, the JSC team made some observations about the S-119 specification, in particular the DAVE-ML DTD. These observations are primarily the result of (1) the C-code generation work, and (2) a detailed look into the DAVE-ML uncertainty element. Generally it was found that in a few places, the DAVE-ML DTD is insufficiently precise to support automatic code generation (e.g., certain XML element attributes are optional leading to the possibility that an S-119-compliant XML model might not allow code generation without some manual intervention). The JSC team also found that the documentation of the uncertainty element in the reference manual could be improved, and they drafted a proposed replacement for the relevant section of the reference manual to fix some (but not all) of the weaknesses found. These detailed observations are available in Appendix A.


#### 7.4.5 Conclusions and Suggestions for Future Work

The JSC team suggested several clarifications and changes to the DAVE-ML DTD specification that are described in more detail and summarized in Appendix A. They believe these changes will improve the rigor and clarity of the specification, making it easier to develop interpreters and code generators for S-119 and helping to transfer models without ambiguity. The feasibility of an S-119 to C-code generation capability was demonstrated during this assessment. Although incomplete, the system prototyped during this assessment is useful at present and shows considerable potential for future expansion. The utility of the S-119 model format for use by non-aerodynamics models was shown by two test cases. The first case investigated hierarchical models; the second case was a pseudo-dynamic model with saved states implemented via caller-provided memory storage. This second case also demonstrated two ways to use “macros” (essentially) to ease MathML authoring for complex algorithms. The JSC team suggested several areas where future work would be useful. These areas included further exploration of the S-119 and DAVE-ML specifications, continued development of the XSLT code generator toward an operational capability, and testing of the DAVE-ML <uncertainty> element by exercising it to specify dispersion test cases for the Trick Monte-Carlo capability.

### 7.5 Marshall Space Flight Center

The Flight Mechanics and Analysis division (EV40) of MSFC’s Spacecraft and Vehicle Systems Department performs vehicle control system design and analysis as well as guidance, navigation, trajectory design, and mission analysis for launch vehicles and spacecraft. One of the primary tools used by EV40 in these analyses is the Marshall Aerospace Vehicle Representation in C (MAVERIC) simulation. At the time of this report, the efforts of EV40 as a part of this assessment have been focused on incorporating the ability in MAVERIC to read and use S-119 models.

Following a brief evaluation, LaRC’s C++-based DAVE-ML Translator was chosen to be included in MAVERIC. The DAVE-ML Translator software was relatively easy to add to

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MAVERIC but necessitated development of an intermediate “wrapper” function. The wrapper was required to send data from MAVERIC into DAVE-ML translator objects and return data from translator objects into MAVERIC. The development of the DAVE-ML Translator wrapper and use of S-119 in MAVERIC have so far been exclusively for aerodynamics modeling.

Testing of the DAVE-ML Translator software and the S-119/MAVERIC wrapper was performed by re-constituting aerodynamic data and models already used by MAVERIC into the DAVE-ML format and using a DAVE-ML translator object to provide aerodynamic forces and moments. Initially, the aerodynamic buildup equations were encoded in the wrapper function and the DAVE-ML translator was just used for table lookups. Eventually, the entire aerodynamic buildup equations were encoded into the S-119 format and the wrapper was used only as an interface function. Tests were successful and conclusive. The simulation fed by S-119 aerodynamic data exactly matched the simulation using the standard MAVERIC aero model.

Of particular note is that the initial implementation of the HL-20 S-119 aero model into MAVERIC was completed with less than 1 week of effort.

## 7.6 Summary of Results

In general, most Centers found developing the means to import S-119 models into their existing simulation frameworks straightforward, taking as little as less than a week (if an existing API were used) to a few weeks (if a custom import tool was developed). Exporting from an existing simulation framework to the S-119 format was not tested.


Performance of the two existing APIs, which accept S-119 models at run-time, compared favorably with import scripts that convert S-119 models into compilation units and with hand-written C-code equivalent models.

Several limitations to the proposed S-119 format were uncovered and were provided as feedback to the AIAA standards subcommittee. In addition, some errors in one existing API and one existing import script were discovered and fixed during the assessment. Finally, a new import tool was developed that allows direct conversion of S-119 models into C-code.

The assessment was completed on time and well within budget (less than 40 percent of the allocated NESC funds were expended), indicating the burden of adapting an existing flight simulation framework to work with an S-119 model was much less than anticipated.

As a result of the assessment, the real-time flight simulation labs at ARC (SimLabs), DFRC (Dryden Sim), JSC (Trick), and LaRC (LaSRS++) can now accept models written using S-119, as can the analysis simulations at MSFC (MAVERIC) and GRC (OTIS4). Collaboration between these facilities and tools will become much easier if the S-119 model format becomes more common in the US aerospace industry.



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## 8.0 Findings, Observations, and NESC Recommendations

### 8.1 Findings


The following findings were identified:

- F-1.** Current flight simulation frameworks utilized at each Center are mutually incompatible.
- F-2.** A common model format to exchange data would be beneficial to NASA for cross-Agency teams involving flight simulation.
- F-3.** Implementation of necessary import scripts from the S-119 format to individual Center frameworks can be readily achieved (and has been accomplished to a large degree during this assessment).
- F-4.** Several limitations of the format were found that somewhat limit the usefulness of S-119 for NASA.  
 These limitations include: not specifying the valid range attributes for input variables and not requiring identifiers on all table definitions.
- F-5.** Lack of native editing tools for the S-119 model format is a hindrance to the usefulness of S-119.
- F-6.** The author and current maintainer of the custom XML grammar is a NASA employee, giving NASA considerable leverage in maintaining an essential part of the proposed standard.

### 8.2 Observations

The following observations were identified:

- O-1.** The AIAA draft Standard appears better tailored for aerospace applications than other available modeling formats.
- O-2.** Adoption of an existing API can typically be accomplished in less than a week.
- O-3.** Errors in the existing APIs were identified and corrected.
- O-4.** During the assessment, JSC developed a novel C language generation tool to convert from the standard format into C-code that performed almost as well as hand-generated code.

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### 8.3 NESC Recommendations

The following NESC recommendations were identified and directed toward the Office of Chief Engineer and all NASA organizations that conduct flight dynamic analyses and simulations:

- R-1.** Adopt the *Flight Dynamic Model Exchange Standard*, BSR/AIAA-S-119-201x, with suggested changes, as a recommended practice both for developing new simulation aerodynamic models and model exchange, when such models involve significant numbers of function tables. (*F-1, F-2, F-3, F-4, O-1*)


Suggested changes to S-119 for AIAA consideration include: add optional valid range attributes for input variables; require identifiers on all table definitions; and consider adopting National Institutes of Standards and Technology's UnitsML encoding for units of measure.

The first and second items have been adopted by AIAA MSTC with the third item undergoing evaluation.

- R-2.** In concert with other users of the AIAA S-119 Standard, support development and refinement of the necessary tools to make the format more useful and mutually beneficial. (*F-5*)
- R-3.** NASA should, through continued representation on the AIAA Modeling Standards subcommittee, remain cognizant of changes to the S-119 Standard and the associated DAVE-ML DTD to mitigate the risk of unilateral changes to S-119. (*F-6*)

### 9.0 Definition of Terms


Finding	A conclusion based on facts established by the investigating authority.
Janus	A specialized computer library (API) that understands and manipulates DAVE-ML model files.
Observation	A factor, event, or circumstance identified during the assessment that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur. Alternatively, an observation could be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Parsing	The act of reading and interpreting an encoded data file.
Perl	An interpreted script programming language.

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Qhull	A programming library (API) that deals with ungridded tabular data interpolation.
Recommendation	An action identified by the NESC to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible Center/Program/Project/Organization in the preparation of a corrective action plan.
RT3D	A graphics package for simulation visualization, used at DFRC.
S-119	AIAA draft standard for Flight Dynamic Model Exchange.
Simlabs	ARC Simulation Laboratories.
Simulink <sup>®</sup>	A dynamic system analysis and programming tool. It is a commercial product of The Mathworks, Inc. of Natick, MA.
UnitsML	A markup language for units-of-measure encoding.
Xerces	A programming library (API) that understands and manipulates data files encoded in XML.

## 10.0 Acronyms List


AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
API	Application Programming Interface
ARC	Ames Research Center
ATK	Alliant Techsystems, Inc.
BSR	ANSI Board of Standards Review
DAVE-ML	Dynamic Aerospace Vehicle Exchange Markup Language
DFRC	Dryden Flight Research Center
DMLT	DAVE-ML Translator
DoD	Department of Defense
DOF	Degree of Freedom
DSTO	Australian DoD Defence Science Technology Organisation
DTD	Document Type Definition
FORTTRAN	Formula Translation programming language
FTP	Function Table Processor
GN&C	Guidance, Navigation, and Control
GRC	Glenn Research Center

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GRODIE	GRaphical Otis Dataset Interpolator and Editor
GSFC	Goddard Space Flight Center
HDD	Heads Down Display
HSCT	High Speed Civil Transport
ISO	International Organization for Standardization
JSC	Johnson Space Center
LaRC	Langley Research Center
MAVERIC	Marshall Aerospace Vehicle Representation in C
MSFC	Marshall Space Flight Center
MSTC	AIAA Modeling and Simulation Technical Committee
MTSO	Management and Technical Support Office
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
OTIS4	Optimal Trajectory by Implicit Simulation, version 4
RCS	Reaction Control System
SAS	Stability Augmentation System
Simlabs	Simulation Laboratories
US	United States
XML	Extensible Markup Language
XSLT	Extensible Style Sheet Language Transformation


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- Appendix A. NESC Flight Simulation Model Exchange Assessment Report from Johnson Space Center
- Appendix B. American National Standard: Flight Dynamics Model Exchange Standard (draft BSR/AIAA S-119-201x)
- Appendix C. XML Document Type Definition file for S-119 markup: `DAVEfunc.dtd`
- Appendix D. Dynamic Aerospace Vehicle Exchange Markup Language (DAVE-ML) Reference Manual

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