Development of NASA’s Models and Simulations Standard
NASA-STD-7009

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Topics

- Introduction
- Organization
- Schedule
- Example NASA Simulations
- Complexity of the Task
- Overview of the Models and Simulation Standard
  - Core Requirements
  - Credibility Scale
- Pending Release of the Standard
- Lessons Learned
Introduction
Response to Columbia Accident

Columbia Accident Investigation Board (CAIB)

Return to Flight Task Group (Stafford-Covey Report)

A Renewed Commitment to Excellence (Diaz Report)
Organization

- NASA Langley commissioned by NASA Office of Chief Engineer to respond to Diaz Action #4
- NASA Langley Development Team provided early drafts of the standard
- Topic Working Group
  - NASA Langley provides Working Group Chair as non-voting member
  - Each NASA Center provides a representative to the Topic Working Group serving as a voting member
  - NESC participates in the TWG as a non-voting member
- Technical Standards Working Group responsible for release of standards
- Engineering Management Board provides formal NASA Center response as to concurrence or non-concurrence with the standard
Schedule

- 2 ½ Year Development Effort
- NASA Headquarters wanted a practitioner emphasis for this standard and provided appropriate resources to ensure this occurred
  - Included support for performing pilot studies addressing the potential impact of the new standard and responding to questionnaires addressing the scale and decision maker input
  - Included 5 workshops primarily focused on developing the credibility scale
Example NASA Simulations

- Crew training (ascent and entry simulations, payload simulation, landing simulation)
- Aerodynamics & aerothermodynamics [e.g. external fuel tank on Columbia, shuttle re-entry]
- Atmospheric models
- Guidance, Navigation, and Control models
- Propulsion models
- Structural/Thermal Finite Element Models
- Orbital Debris Models
- Shuttle and ISS operations models

Integration of multiple models as noted in a typical Mars Entry, Descent, and Landing Simulation
Complexity of the Task

- There are conflicting opinions about the contents of the Standard across NASA because the standard is trying to cover many areas
  - Human flight with large hierarchical organizations where decision makers are not involved with the technical details of the simulation
  - Robotic flight with flat organizations where the decision makers have intimate familiarity with the simulation
  - Simulations with a long life that are reused
  - Short term simulations developed for a single project
  - Some simulations have a development team that deliver to an operations group where training is key – other simulations, the developers are the operators
  - Different types of simulations such as partial differential equation based versus discrete event simulations versus cost models
Overview of the Standard (2 Parts to the Standard)

**PART 1**
Core requirements to be met regardless of Credibility Level Required

- Programmatic
- Model Documentation
- Simulation Documentation
- Verification, Validation & Uncertainty Quantification

**PART 2**
Credibility Scale with 8 factors having graduated levels (Level 0 to 4)

- Recommended Practices
- Training
- Credibility Scale
- Reporting to Decision Makers

8 Requirement Sections in M&S Standard

Credibility Scale

- M&S Results Credibility
  - Verification
  - Validation
  - Input Pedigree
  - Results Uncertainty
  - Results Robustness
  - Use History
  - M&S Management
  - People Qualifications
  - Supporting Evidence
Part 1 - Core Requirements

- Requirements Defined Over M&S Life Cycle Emphasizing Improved Communication to Decision Makers
  - Programmatic
    - Develop M&S Plan addressing acquisition, development, credibility criteria, operation, and maintenance
  - Development
    - Document assumptions, inputs, mathematics, input data, limitations in domain applicability, and M&S usage
  - Verification and Validation
    - Define V&V techniques and uncertainty quantification
  - Training
    - Provide training in M&S operation
  - Reporting Results to Decision Makers
    - Estimate of uncertainties and processes used to obtain estimates
    - Identify unfavorable outcomes, violation of assumptions or limits of operation
    - Credibility Assessment
  - Unique Approach to Documentation Requirements
    - The required documentation for an activity that was not conducted, may be satisfied by recording that the activity was not conducted
Part 2 - Credibility Scale

Credibility Scale Process

- Project identifies desired credibility level (black bars)
- Assessment performed to determine achieved credibility level (color bars)
- Perform roll-up of credibility score

Example Credibility Scale Assessment

Project Desired Credibility Levels = (3, 4, 3, 1, 2, 0, 3, 3)
## Credibility Scale Summary Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Verification</th>
<th>Validation</th>
<th>Input Pedigree</th>
<th>Results Uncertainty</th>
<th>Results Robustness</th>
<th>Use History</th>
<th>M&amp;S Management</th>
<th>People Qualifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Numerical errors small for all important features</td>
<td>Results agree with real-world data</td>
<td>Input data agree with real-world data</td>
<td>Non-deterministic &amp; numerical analysis</td>
<td>Sensitivity known for most parameters; key sensitivities identified</td>
<td>De facto standard</td>
<td>Continual process improvement</td>
<td>Extensive experience in and use of recommended practices for this particular M&amp;S</td>
</tr>
<tr>
<td>3</td>
<td>Formal numerical error estimation</td>
<td>Results agree with experimental data for problems of interest</td>
<td>Input data agree with experimental data for problems of interest</td>
<td>Non-deterministic analysis</td>
<td>Sensitivity known for many parameters</td>
<td>Previous predictions were later validated by mission data</td>
<td>Predictable process</td>
<td>Advanced degree or extensive M&amp;S experience, and recommended practice knowledge</td>
</tr>
<tr>
<td>2</td>
<td>Unit and regression testing of key features</td>
<td>Results agree with experimental data or other M&amp;S on unit problems.</td>
<td>Input data traceable to formal documentation</td>
<td>Deterministic analysis or expert opinion</td>
<td>Sensitivity known for a few parameters</td>
<td>Used before for critical decisions</td>
<td>Established process</td>
<td>Formal M&amp;S training &amp; experience, and recommended practice training</td>
</tr>
<tr>
<td>1</td>
<td>Conceptual &amp; mathematical models verified</td>
<td>Conceptual and mathematical models agree with simple referents</td>
<td>Input data traceable to informal documentation</td>
<td>Qualitative estimates</td>
<td>Qualitative estimates</td>
<td>Passes simple tests</td>
<td>Managed process</td>
<td>Engineering or science degree</td>
</tr>
<tr>
<td>0</td>
<td>Insufficient evidence</td>
<td>Insufficient evidence</td>
<td>Insufficient evidence</td>
<td>Insufficient evidence</td>
<td>Insufficient evidence</td>
<td>Insufficient evidence</td>
<td>Insufficient evidence</td>
<td>Insufficient evidence</td>
</tr>
</tbody>
</table>

**Level Definition for the Verification Factor is provided in the backup charts.**

Detailed wording for each factor level definition is contained in Appendix A of the Standard.
Pending Release of the Standard

- The proposed permanent standard is under final Agency review
- NASA Headquarters is working to resolve objections from some of the NASA Centers

Prospective Follow-on Activities

- Deployment
  - Monitor Usage
  - Collect Data from the variety of M&S types
  - Suggest improvements
- Development of Recommended Practices
  - For each M&S Type & Implementation Domain
Lessons Learned

• A high-level champion, in this case, the OCE, was indispensable to overcoming barriers
• Developing an M&S standard that covers all types of models and simulations and all phases of the modeling and simulation process is extremely challenging.
• Dedicated funding (as opposed to a volunteer activity) and involvement of a variety of M&S practitioners was extremely beneficial to ensure the Standard is feasible to the broad M&S community
• Pilot studies are very important in bringing practical experience to bear on the development of a new standard
• Trained facilitation was extremely useful in containing the passionate “discussions” about the scale
• Once a decision is made, the temptation to revisit that decision is only contained by a firm rule requiring a formal motion accompanied by a second to even begin the discussion
Lessons Learned

• The supermajority rule for final decisions was critical to ensuring that the final product had consensus support from the TWG

• Unique approach to handling compliance with documentation requirements
  – Addressing documentation for an activity that was not conducted

• Interaction with other NASA Standards Working Groups was key to ensuring a complementary relationship between the standards without duplication
  – The NASA Software Engineering Requirements Standard (NPR 7150.2) has one high level requirement to test, validate, and certify software models and simulations
  – In discussions between the working groups, it was decided that the new M&S standard contains implementation details for the above requirement in addition to requirements that are unique to M&S
  – So, the M&S Standard added the wording

  This standard does not apply to M&S that are embedded in control software, emulation software, and stimulation environments. However, Center implementation plans for NPR 7150.2, NASA Software Engineering Requirements, should specifically cover embedded M&S, and address such M&S-specific issues as numerical accuracy, uncertainty analysis, sensitivity analysis, M&S verification, and M&S validation
Backup
Diaz Report & CAIB Recommendations

• Diaz Action #4 (primary driver)

  Develop a standard for development, documentation, and operation of models & simulations (M&S).

  – a. Identify best practices to ensure that knowledge of operations is captured in the user interfaces (e.g. users are not able to enter parameters that are out of bounds).
  – b. Develop process for tool verification and validation, certification, re-verification, re-validation, and re-certification based on operational data and trending.
  – c. Develop standard for documentation, configuration management, and quality assurance.
  – d. Identify any training or certification requirements to ensure proper operational capabilities.
  – e. Provide a plan for tool management, maintenance, and obsolescence consistent with modeling/simulation environments and the aging or changing of the modeled platform or system.
  – f. Develop a process for user feedback when results appear unrealistic or defy explanation.

• Columbia Accident Investigation Findings are directly evident in the M&S Standard
  – F6.3-10

  • The Team’s assessment of possible tile damage was performed using an impact simulation that was well outside Crater’s test database. The Boeing analyst was inexperienced in the use of Crater and the interpretation of its results. Engineers with extensive Thermal Protection System expertise at Huntington Beach were not actively involved in determining if the Crater results were properly interpreted.

http://www.nasa.gov/pdf/55691main_Diaz_020204.pdf
Part 1 – Core Requirements

• Documentation Guidance
  – The required documentation for an activity that was not conducted, may be satisfied by recording that the activity was not conducted.

• Documentation Requirements
  – Develop and M&S Plan
    • Objectives, Requirements, V&V
  – Assumptions and abstractions
  – Basic structure and mathematics of the model
  – Data sets, facilities, and any supporting software
  – Limits of operation
  – Uncertainty quantification
  – Proper use of the model
  – Parameter calibrations
  – Updates of the model (change log)
  – Data used as input to the simulation, including its pedigree and its uncertainty
  – Unique computational requirements
  – Processes for conducting analysis, simulation, and uncertainty quantification
  – Verification techniques and status
  – Numerical error techniques
  – Validation techniques and studies
  – Quantified Uncertainties and processes
  – Identify and document Recommended Practices
  – Results from credibility scale assessment
  – Presentation to Decision Makers
Credibility Scale Example Level Definitions

- **Verification Primary Subfactor**
  - Definition
    - Verification is the process of determining that a computational model accurately represents the underlying mathematical model and its solution from the perspective of the intended uses of the M&S. At its most elementary levels this involves assurance that the conceptual and mathematical models are correct.
    - Beyond that, there are two different aspects of the verification of the computational model: (a) is it coded correctly (code verification) and (b) are the numerical errors small (calculation verification), i.e., what is the numerical accuracy? In the case of mathematical models based upon differential equations (ordinary or partial), a detailed discussion of the distinction between these two aspects is provided in *ASME V&V 10* and Oberkampf and others, 2007.
  - **Level 0**
    - Insufficient evidence.
  - **Level 1**
    - Favorable evidence of verification for conceptual and mathematical models.
  - **Level 2**
    - Favorable results from unit and regression testing of key features of the computational model.
  - **Level 3**
    - Some formal method is used to assess numerical errors associated with unit testing with significant coverage of the code.
  - **Level 4**
    - Reliable error estimation methods are used to quantitatively assess numerical errors. These estimates show that the errors are small from test suites which exercise all important algorithms, all important features and capabilities, and all important couplings (physics, modules, etc.) of the full computational model.
Credibility Scale Example Level Definitions

- **Verification Technical Review Subfactor**
  - Level 0
    - Insufficient evidence.
  - Level 1
    - Favorable informal internal peer review
  - Level 2
    - Favorable formal internal peer review
  - Level 3
    - Favorable external peer review
  - Level 4
    - Favorable external peer review accompanied by independent factor evaluation.