Verification, Validation and Uncertainty Quantification Theory Meets Aerospace Practice: NASA Experience with Formal Requirements for VV&UQ

Thomas A. Zang, Langley Research Center
Timothy S. Barth, NASA Engineering & Safety Center
William J. Bertch, Jet Propulsion Laboratory
Wei A. Lin, Ames Research Center
Gary E. Mosier, Goddard Space Flight Center
Martin J. Steele, Kennedy Space Center

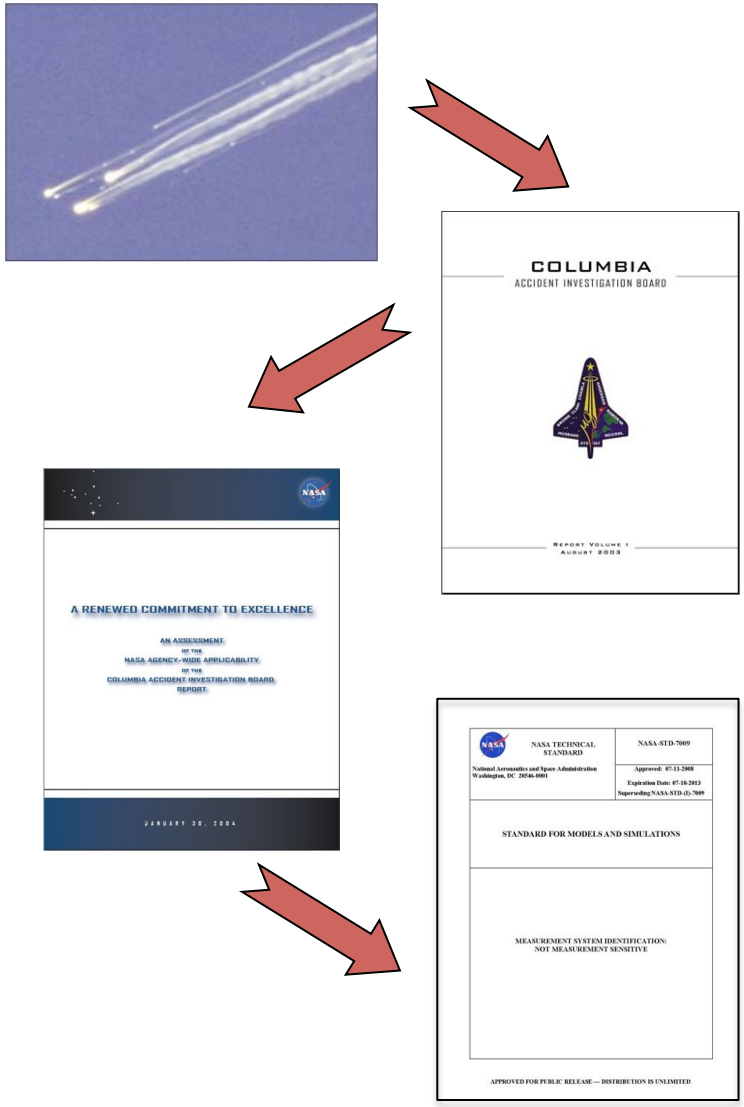
Outline

- NASA M&S Standard
- Examples
- Observations

Background

NASA M&S Standard Development

- **NASA M&S Standard development started in May 2005 as a result of the Columbia Accident and general NASA concerns about the use of M&S for critical decisions**
- **NASA Interim M&S Standard was issued on Dec 2006 as NASA-STD-(I)-7009**
- **The permanent NASA M&S Standard was issued by the NASA Chief Engineer on July 11, 2008 as NASA-STD-7009**
- **The M&S Standard ("7009") has had the strong top-level support of**
  - NASA Administrator
  - NASA Chief Engineer
  - NASA Chief of Safety & Mission Assurance
  - NASA Aerospace Safety Advisory Panel
- **7009 was developed by a team with members from 9 of the 10 NASA centers**



Summary of the M&S Standard

- **Primary Goal**
  - "Ensure that the credibility of the results from M&S is properly conveyed to those making critical decisions"
- **Applicability**
  - Applies to any type of M&S that is in scope (next bullet)
- **M&S Risk Assessment**
  - Those M&S that are in scope for a project are determined by assessing the risk posed by the anticipated use of the M&S results in technical decisions
- **Requirements**
  - 49 requirements in all
  - 12 requirements deal directly with verification, validation or uncertainty quantification
- **Credibility Assessment Scale**
  - "Assesses the M&S results, and the rigor of the processes used to produce them, against key factors that affect the credibility judgment"

Some Requirements from 7009

- **[The responsible party] shall document any verification techniques used and any domain of verification … [4.4.1]**
- **[The responsible party] shall document any validation metrics, referents, and data sets used for model validation. [4.4.5]**
- **[The responsible party] shall document any uncertainty quantification processes used for … [4.4.7]**
- **Reports to decision makers of M&S results shall include an estimate of their uncertainty and a description of any processes used to obtain this estimate … [4.8.2]**
- **Reports to decision makers shall include the level of credibility for the M&S results … [4.8.3]**

- ***Note: Some requirements … are to be interpreted as meaning that the activity in question is not required per se, but that whatever was done is to be documented, and if nothing was done a clear statement to that effect is to be documented***

Requirements in System Engineering

- **Requirements are necessary (but not sufficient) for the successful design, development, and operation of any system**
- **Requirements are not**
  - Recommendations
  - Suggestions
  - Guidance
  - “Desirements”
- **Requirements are verified at major review stages of the design, development, and operations of NASA systems**
- **Approval to proceed in the presence of an unsatisfied requirement is only given if a formal waiver is granted**

Credibility Assessment Scale

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

*This factor has a Technical Review subfactor

Information Reported to Decision-maker

- **The best estimate of the results**
- **A statement on the uncertainty in the results [4.8.2]**
- **Any explicit caveats that accompany the results [4.8.1]**
- **The evaluation of the rigor of the M&S processes on the Credibility Assessment Scale (CAS) [4.8.3]**

- **"Reported uncertainty estimates shall include one of the following:**

  (1) A quantitative estimate of the uncertainty in the M&S results, or

  (2) A qualitative estimate of the uncertainty in the M&S results, or

  (3) A clear statement that no quantitative or qualitative estimate of uncertainty is available" [4.8.2]

When Must the Standard be Used? (for Human Exploration Systems)

- **Emphasis on in-house development of new Exploration Systems (2005–2009)**
  - A select subset of NASA standards were mandatory
  - Programs had to argue out of using them
  - The M&S Standard was on track to be mandatory
- **Emphasis on reliance on commercial cargo and crew development of new Exploration Systems (2010+)**
  - A select subset of standards (NASA and consensus) are endorsed
    - 7009 is an endorsed standard
  - In-house programs are encouraged to use them
  - Commercial developments will be subject to a very small set of NASA requirements
- **The guidance for commercial development is almost, but not quite, final**
  - The M&S Standard will not be in the small set of applicable documents
  - But it is a reference document, and the primary intent is captured in the requirements

Examples

Ares I-X Usage

- **The Ares I-X was the first (& only) flight test for the (now cancelled) Ares I launch vehicle**
- **The SE&I Chief Engineer did the Risk Assessment and the Credibility Assessment to respond to a formal request from the Critical Design Review**
  - It took about a day to read the standard, do the assessment, and put together a 20-slide briefing
  - Ares I-X did not adopt 7009 as a project requirement (7009 was issued in the middle of the project)
- **The Lead Systems Engineer found the documentation requirements useful guidance when Ares I-X produced its final documentation**

October 28, 2009 Launch

Ares I-X M&S Risk Assessment

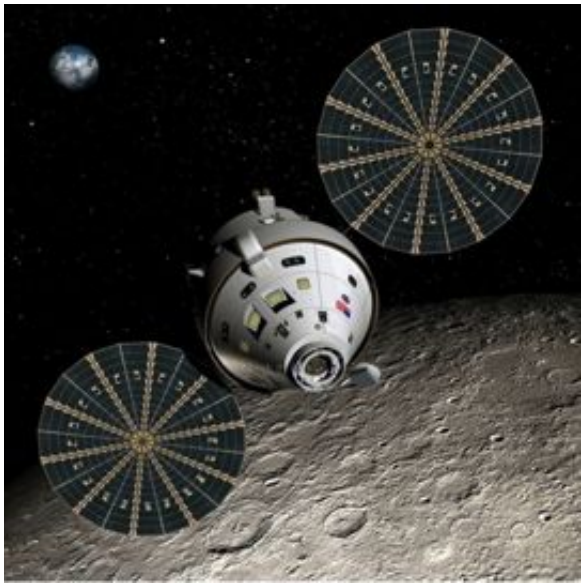
- **Scope Categories**
  - "Red" category are within scope
  - "Yellow" category are at the project discretion
  - "Green" category are not within scope

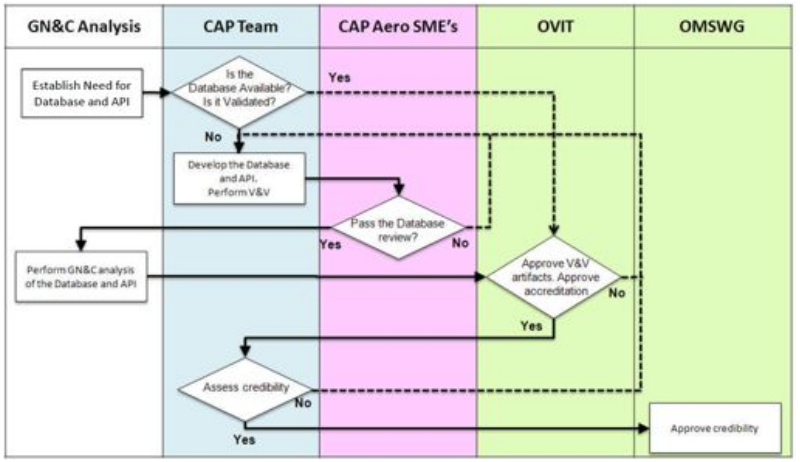
5: Controlling			**H**	**A, B**
4: Significant			**E, F**	
3: Moderate		**D**	**C, G**	
2: Minor		**I**		
1: Negligible				
	IV Negligible	**III Marginal**	**II Critical**	**I Catastrophic**

A - GN&C
B - Structures
C - Thermal
D - Trajectory
E - Aerodynamics
F - OML
G - Mass Properties
H - Vibro-Acoustics
I - System ProE

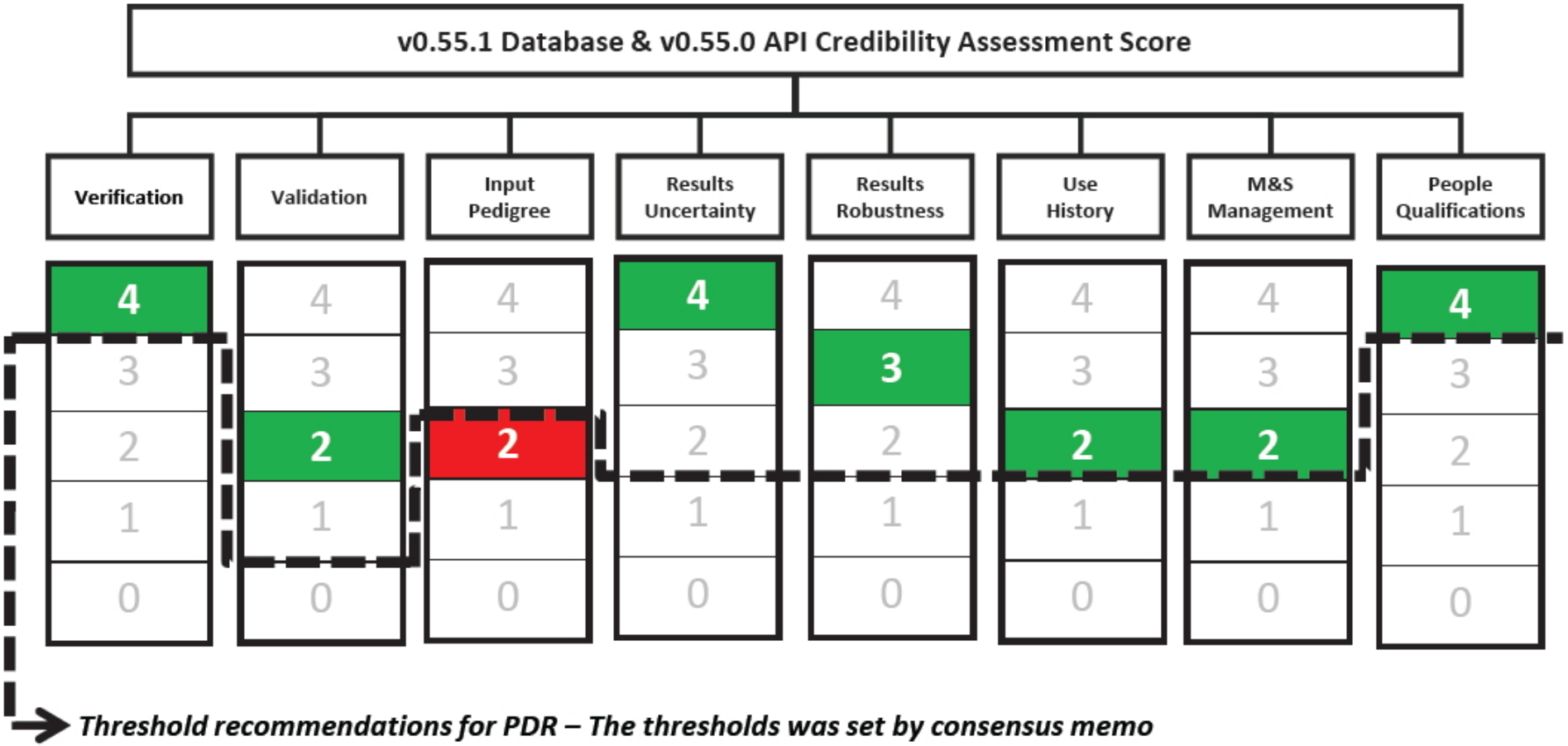
Orion Project Usage

- **The Orion Project was an early adopter of 7009**
  - Levied on the Lockheed-Martin contract
  - Incorporated in Orion VV&A processes
- **Lockheed-Martin cost assessment**
  - LM determined that use of 7009 would add a few percent to their M&S cost
    - LM was already CMMI Level 3 certified
    - Only uncertainty quantification and credibility assessment were not covered by existing LM processes
- **Credibility assessment was performed for in-house work on the Aero database**
  - Considerable learning was required for the first assessment
  - Subsequent assessments took much less time than the first one
- **VV&A Office was been discontinued under the revised Exploration Systems program**





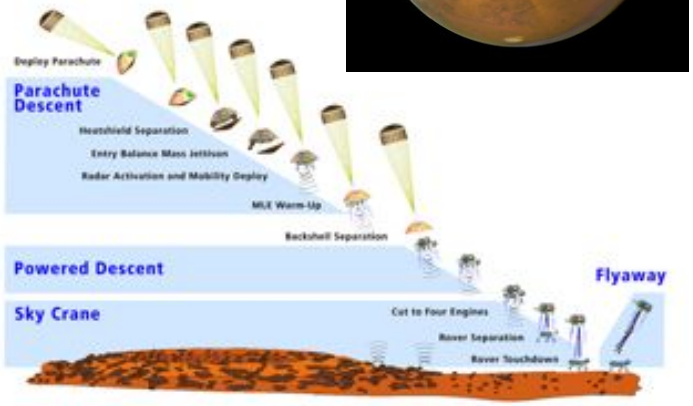
CAS Applied to Orion Aero Database



JPL 7009 Review Comments

- **At the senior NASA management review of 7009, JPL**
  - Supported the requirements
  - Requested clarification of scope
  - Objected to the inclusion of the Credibility Assessment Scale
- **The V&V and UQ requirements were well received**
- **The M&S Risk Assessment was added for clarification of scope**
- **JPL project managers want to see the raw data not a CAS assessment**
- **JPL prefers an optional, tailorable checklist (next slide) in lieu of the CAS**
  - Some, but not all, Mars Science Laboratory reviews used the checklist

Mars Science Laboratory
Launch Date: Nov. 25, 2011



Model Review Certification Record
(Use of a tailored version is optional at JPL)

Model Review Certification Record (MRCR)

Project:	Delivery ID:	Model Configuration ID:	MRCR Number:

Assembly / Subsystem / System Scenario	☐ Preliminary Design ☐ Final Design (CDR) ☐ System Verification (II&T)	Model Cognizant Engineer	HW CogE or System Engineer	Date

CHECK APPLICABLE ANSWER. IF "N" OR "N/A" PROVIDE EXPLANATION	YES	NO	N/A
Requirements			
1. Are model requirements complete and sufficient for this point in the life cycle?			
Stakeholders & Inputs			
2. Are user stakeholders, their roles and responsibilities documented? Have they met responsibilities given for this stage in the lifecycle?			
3. Have all known necessary inputs been identified. Have all planned inputs been received and placed under configuration management?			
4. Final Maturity & later: Are relevant design documents identified (i.e. MICD, IICD, Phasing ...), complete, approved, released and under change control?			
5. For all inputs, but particularly preliminary documentation, are caveats and qualifications documented?			
Design			
6. Have all effects been identified and analyzed for relevance to this model? Is this list, the related analyses and decisions documented?			
7. Has the model been reviewed by the function provider and all identified user stakeholders to assure it meets its objectives, is complete, is using all inputs correctly and has correctly modeled all relevant attributes?			
8. All Maturity Levels: Are all known design shortcomings identified and adequately documented?			
Validation			
9. Preliminary Maturity: Has final validation approach been outlined? Do test plans adequately support model validation?			
10. Maturity Levels prior to System Verification: Are model validation records complete?			
11. Sys. Verif. Maturity: Is model validation complete and documented? Are validation test procedures, results and analyses recorded?			
12. All Maturity Levels: Are all model known validation shortcomings identified and adequately documented?			
Delivery & Closeout			
13. Is planned model delivery documentation complete? Are test cases for each user stakeholder application and platform documented?			
14. Are there any model caveats or qualifications that are not addressed in earlier questions? If so document and attach.			
15. Has there been a previous MRCR for this model? If yes, provide a description of any differences.			
16. Is this model ready for its intended use?			

DATA ATTACHMENTS Reference verified repository location.	YES	NO	N/A
Model Planning Documentation (requirements, stakeholders, validation plans) (items 1, 2, 9)			
All Model input documentation - List controlled documents, attach all others. (items 3, 4)			
Design & review records (items 6,7)			
Model validation test results or other validation records (items 10, 11)			
Device as-built records (i.e. calibration) - trace to EIDP			
Documentation of known model deficiencies, caveats and qualifications. (items 5, 8, 12, 14)			

REMARKS

APPROVALS (Bold are required; Model Lead may tailor others.)

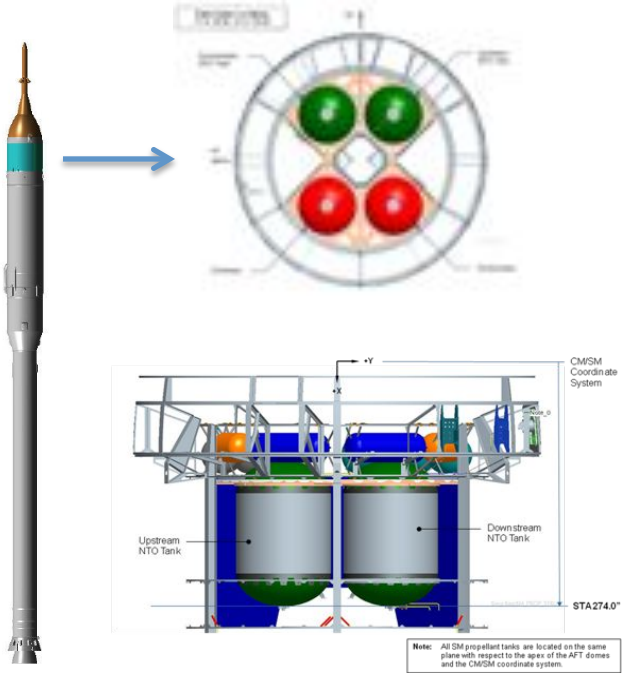
Model Lead	Date	**Model Co-Lead**	Date
Systems Engineering	Date	**Function Provider**	Date
User Stakeholder	Date	User Stakeholder	Date
User Stakeholder	Date	User Stakeholder	Date

James Webb Space Telescope

- **Essential features of the James Webb Space Telescope cannot be tested in ground facilities**
- **The NASA lead for JWST M&S applied the CAS to the jitter performance prediction models to produce an example for training purposes**
- **The contractors were reluctant to have the CAS results shared**
- **The JWST notional applications highlighted**
  - Acknowledged weakness in the CAS for assessing coupled M&S
  - Difficulty in assessing COTS M&S tools, esp. Verification, due to unavailability of documentation

NESC Pathfinder Studies

- **The NASA Engineering and Safety Center (NESC) has sponsored the development of a Handbook for 7009**
- **Several NESC assessments were examined in light of 7009**
  - Orion water landing structural dynamics
  - Ares GN&C modeling of Orion Crew Module Propellant Tank slosh dynamics
  - Ares thrust oscillation
- **The objective was to provide the NESC with guidance on employing 7009 in their assessments of NASA technical issues**
- **A general conclusion was that the NESC assessments of M&S frequently focus on validation through independent M&S and additional testing**
- **NESC leadership has advocated for use of 7009 in NESC assessments and commercial crew programs**



Observations

General Observations

- Even with top NASA management and advisory panel support, there is resistance to using 7009
- The documentation burden and the credibility assessment are the two potential obstacles to wider adoption of 7009
- The standard is perceived as imposing considerable cost (money and time) to a project
- A smaller number of requirements would ease acceptance
- The M&S Risk Assessment process helps to determine which M&S are in scope

VV & UQ Observations

- **The standard does not prescribe any particular verification, validation or uncertainty quantification approaches, but concerns abound on the burden of having to document what was done**
- **NASA's traditional assessments of M&S pay the most attention to Validation**
- **The uncertainty reporting requirement is controversial**
  - Project managers prefer the present requirement that permits a statement of ignorance about the uncertainty
  - Many researchers would prefer eliminating the option to plead ignorance
  - Many engineers are concerned that they lack the knowledge and tools to make a probabilistic uncertainty estimate

Credibility Assessment Observations

- **Assessing Input Pedigree for codes with hundreds of input variables is not well addressed**
- **Assessing coupled M&S is not well addressed**
- **Some engineers feel that the CAS challenges their own technical credibility**
- **The strongest M&S practitioner resistance occurs for the People Qualifications factor,**
  - but this factor has a strong influence on decision-makers
- **A checklist may fit better with NASA culture than a "scale"**

References

- **CAIB Report**
  - http://caib.nasa.gov/
- **Diaz Report**
  - http://www.nasa.gov/pdf/55691main_Diaz_020204.pdf
- **NASA-STD-7009**
  - https://standards.nasa.gov/documents/viewdoc/3315599/3315599
- **NESC Report**
  - Zang, T. A., et al., "NASA Standard for Models and Simulations (M&S): Development Process and Rationale," NASA Engineering and Safety Center Technical Report RP-08-118, Nov. 20, 2008 (http://hdl.handle.net/2060/20090028626)
- **AIAA Papers**
  - Blattnig, S.R., Green, L.L., Luckring, J.M., Morrison, J.H., Tripathi, R.K., and Zang, T.A., "NASA Standard for Models and Simulations: Philosophy and Requirements Overview," AIAA -2009-1010, Jan. 2009
  - Babula, M., Bertch, W. J., Green, L. L., Hale, J. P., Mosier, G. E., Steele, M. J., and Woods, J., "NASA Standard for Models and Simulations: Credibility Assessment Scale," AIAA-2009-1011, Jan. 2009
- **NASA-STD-7009 Handbook**
  - Currently under review
  - Expected to be published in 2012

Supplementary Information

NASA Standard Teams

- **Development Team (2005–2006)**
  - Steve Blattnig, Larry Green, Mike Hemsch, Jim Luckring, Joe Morrison, Ram Tripathi, Tom Zang [all from LaRC]
- **Topic Working Group (2006–2007)**
  - ARC: Unmeel Mehta: Fluid Dynamics
  - *DFRC: none*
  - GRC: Maria Babula (Jeff Rusick): Mission Analysis (S&MA)
  - JSC: Andre Sylvester (Galen Overstreet): Simulation (Structures)
  - GSFC Gary Mosier: Controls
  - JPL: Bill Bertch: Space Science Missions
  - KSC: Martin Steele: Discrete Event Simulation
  - LaRC: Larry Green (Dick Davis): Systems Analysis (Instruments)
  - MSFC: Joe Hale: Constellation IM&S
  - SSC: Jody Woods: Systems Analysis–Fluids, Structures, Thermal
  - Chair: Tom Zang: Systems Analysis

A DoE Analogy to the NASA Team

• Los Alamos NL	physics package design
• Lawrence Livermore NL	weapons effects
• Oak Ridge NL	nuclear physics R&D
• Sandia NL, NM	weapons storage
• Sandia NL, CA	delivery system
• AF Missile Command	weapons operation
• Argonne NL	nuclear energy research
• Idaho NL	nuclear plant design
• Savannah River Site	nuclear materials processing
• Hanford Site	nuclear waste storage
• Nuclear Regulatory Com.	nuclear plant operation

Requirements

Requirement Categories

4.1 Programmatic Requirements
4.2 Models
4.3 Simulations and Analyses
4.4 Verification, Validation and Uncertainty Quantification
4.5 Development and Use of Recommended Practices
4.6 Training
4.7 Assessing the Credibility of Models and Simulations
4.8 Reporting Results to Decision Makers

Project and TA Responsibilities

Responsibility
Jointly identify the responsible parties for the requirements
Jointly identify the level of documentation required
Jointly identify the critical decisions to be made with M&S
Jointly determine which M&S are in scope based on a risk assessment
TA ensures objectives & requirements for the M&S are appropriately defined

4.1 Programmatic Requirements

	Requirement
4.1.1	**Document the Scope risk assessment**
4.1.2	**Identify & document which M&S are in scope**
4.1.3	**Define objectives and requirements for M&S products**
4.1.4	**Develop plan for acquisition, development, operation, and maintenance of M&S used for critical decisions**
4.1.5	*Document technical reviews*
4.1.6	**Document M&S waiver process**
4.1.7	**Document M&S Management evidence**

Requirements in bold in 4.1–4.8 are to be interpreted as meaning that the activity in question is not required per se, but that whatever was done is to be documented, and if nothing was done a clear statement to that effect is to be documented.

4.2 Models

	Requirement
4.2.1	**Document assumptions and abstractions of the conceptual model**
4.2.2	**Document basic structure and mathematics of model**
4.2.3	**Document data sets and supporting software for model development & input**
4.2.4	**Document units and reference frames**
4.2.5	**Document limits of operation of models**
4.2.6	*Document uncertainty in model-development data*
4.2.7	**Document guidance on proper use of model**
4.2.8	*Document parameter calibrations*
4.2.9	**Document updates of the model**
4.2.10	**Document obsolescence criteria**
4.2.11	**Provide a feedback for unusual results**
4.2.12	**Maintain models & documentation in configuration management system**
4.2.13	**Maintain data sets and supporting software configuration management system**

4.3 Simulations and Analyses

	Requirement
4.3.1	**Ensure simulations are not used outside limits or provide warning**
4.3.2	**Document and explain observed execution warning and error messages**
4.3.3	**Document which models were used**
4.3.4	**Document versions of M&S**
4.3.5	**Document data used as input and it's pedigree**
4.3.6	*Document any unique computational requirements*
4.3.7	**Document processes for conducting analysis, simulation, and uncertainty quantification**
4.3.8	**Document the use history of M&S**
4.3.9	**Document the use assessment**
4.3.10	**Document rationale for setup and execution**

4.4 Verification, Validation, and Uncertainty Quantification

	Requirement
4.4.1	*Document verification techniques & domain of verification*
4.4.2	*Document numerical error estimates*
4.4.3	**Document verification status**
4.4.4	*Document validation techniques & domain of validation*
4.4.5	*Document validation metrics, referents and data sets*
4.4.6	*Document validation studies and results*
4.4.7	*Document uncertainty quantification processes*
4.4.8	*Document quantified uncertainties*
4.4.9	*Document sensitivity analyses*

4.5 Development and Use of Recommended Practices

	Requirement
4.5.1	**Identify existing Recommended Practices that apply**

4.6 Training

	Requirement
4.6.1	**Determine depth of required training**
4.6.2	**Document training topics, training process & training verification**
4.6.3	**Determine qualifications of developers, operators & analysts**

4.7 Assessing Credibility

	Requirement
4.7.1	**Assess credibility of results using the 8 factors in the Scale**
4.7.2	**Justify and document the credibility assessment**
4.7.3	**Perform roll-up to an overall score on the Scale**

4.8 Reporting Results to Decision Makers

	Requirement
4.8.1	**Report explicit caveats for any of 6 critical areas**
4.8.2	**Report uncertainty estimate (and basis for this estimate)**
4.8.3	**Report evaluation of the results on the Scale**

M&S Risk Assessment

Risk-informed Scope Guidance

- *Program and project management in collaboration with the Technical Authority have the responsibility to … identify and document the critical decisions to be addressed with M&S and to determine which M&S are in scope. The latter determination should be based upon the risk posed by the anticipated use of the M&S.*

M&S Risk Assessment Matrix

M&S Results Influence	5: Controlling	(G)	(Y)	(R)	(R)
	4: Significant	(G)	(Y)	(R)	(R)
	3: Moderate	(G)	(Y)	(Y)	(R)
	2: Minor	(G)	(G)	(Y)	(Y)
	1: Negligible	(G)	(G)	(G)	(G)
		IV: Negligible	III: Marginal	II: Critical	I: Catastrophic
		Decision Consequence			

Decision Consequence

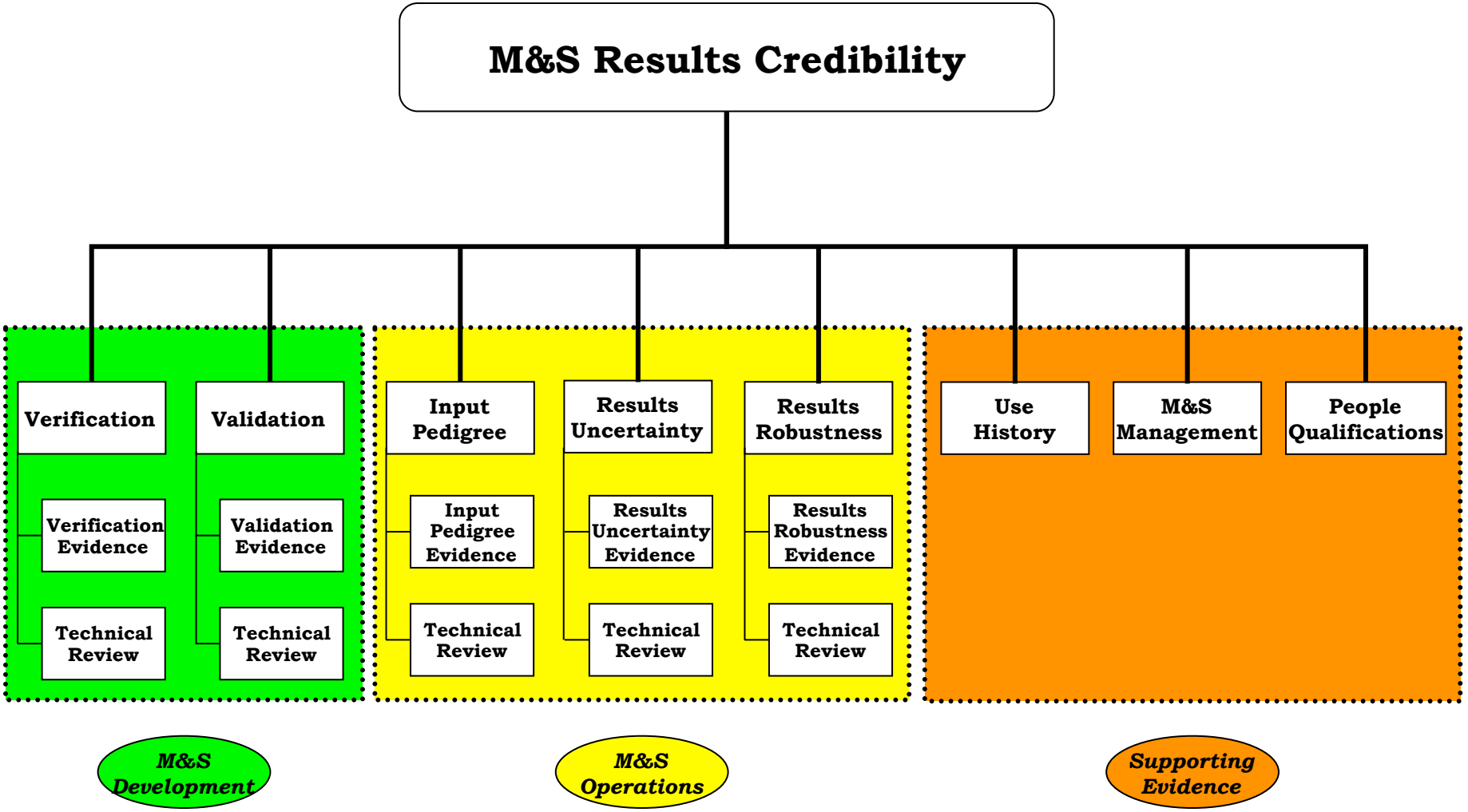
- **Catastrophic**. A poor decision may result in death or permanently disabling injury, facility destruction on the ground, or loss of crew, major systems, or vehicle during the mission; schedule slippage causing launch window to be missed; cost overrun greater than 50 percent of planned cost; most (more than 75 percent) mission success criteria not met due to severe performance degradations.
- **Critical**. A poor decision may result in severe injury or occupational illness, or major property damage to facilities, systems, equipment, or flight hardware; schedule slippage causing launch date to be missed; cost overrun between 15 percent and not exceeding 50 percent of planned; many (between 25 percent and 75 percent) mission success criteria not met due to substantial performance degradations.
- **Moderate**. A poor decision may result in minor injury or occupational illness, or minor property damage to facilities, systems, equipment, or flight hardware; internal schedule slip that does not impact launch date; cost overrun between 2 percent and not exceeding 15 percent of planned cost; a few (up to 25 percent) mission success criteria not met due to performance degradations.
- **Negligible**. A poor decision may result in the need for minor first aid treatment but would not adversely affect personal safety or health; damage to facilities, equipment, or flight hardware more than normal wear and tear level; internal schedule slip that does not impact internal development milestones; cost overrun less than 2 percent of planned cost; all mission success criteria met, with at worst minor performance degradations.

M&S Results Influence

- **Negligible**. Results from the M&S are a negligible factor in engineering decisions. This includes research on M&S methods, and M&S used in research projects that have no direct bearing on program/project decisions (for NASA missions).
- **Minor**. M&S results are only a minor factor in any program/project decisions. Ample flight or test data for the real system in the real environment are available, and M&S results are used just as supplementary information.
- **Moderate**. M&S results are at most a moderate factor in any program/project decisions. Limited flight or test data for the real system in the real environment are available, but ample flight or test data for similar systems in similar environments are available.
- **Significant**. M&S results are a significant factor in some program/project decisions, but not the sole factor for any program/project decisions. Ample flight or test data for similar systems in similar environments are available.
- **Controlling**. M&S results are the controlling factor in some program/project decisions. Neither flight nor test data are available for essential aspects of the system and/or the environment.

Credibility Assessment Scale

Credibility Assessment Scale Structure



M&S Development Level Defns

Level	Verification Evidence	Validation Evidence
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.	M&S results compare favorably for the real-world system at validation points by comparison of M&S results to an acceptable referent, which is measurements on the real-world system.
3	Some formal method is used to assess numerical errors associated with unit testing with significant coverage of the code.	M&S results compare favorably for problems of interest at validation points by comparison of M&S results to an acceptable referent, which is experimental measurements on problems of interest.
2	Favorable results from unit and regression testing of key features of the computational model.	M&S results compare favorably for unit problems at validation points by comparison of M&S results to an acceptable referent, which is either experimental measurements or higher-fidelity M&S results.
1	Favorable evidence of verification for conceptual and mathematical models.	M&S conceptual and mathematical models compare favorably with "general problem" and "textbook" referents.
0	Insufficient evidence.	Insufficient evidence.

- **The project decides *a priori* what constitutes "favorable" agreement**

M&S Operations Level Defns

Level	Input Pedigree Evidence	Results Uncertainty Evidence	Results Robustness Evidence
4	The input data compare favorably with measured data from the real-world system, or the input data came from M&S with a summary credibility rating above 3.5. Uncertainty associated with the input data is known.	Uncertainty estimates are quantitative and based upon nondeterministic and numerical analysis.	Sensitivity of the M&S results for the real-world system is quantitatively known for most of the variables and parameters, including all of the most sensitive variables and parameters.
3	The input data compare favorably with acceptable measured referent data from problems of interest, or the input data came from M&S with a summary credibility rating above 3.0. Uncertainty associated with the input data is known.	Uncertainty estimates are quantitative and based upon nondeterministic analysis.	Sensitivity of the M&S results for the real-world system is quantitatively known for many variables and parameters.
2	The input data is traceable to formal documentation, or the input data came from M&S with a summary credibility rating above 2.0.	Uncertainty estimates are quantitative and based upon deterministic analysis or expert opinion.	Sensitivity of the M&S results for the real-world system is quantitatively known for a few variables and parameters.
1	The input data is traceable to informal documentation, or the input data came from M&S with a summary credibility rating above 1.0.	Uncertainty estimates are qualitative.	Sensitivity of M&S results for the real-world system is estimated by analogy with the quantified sensitivity of similar problems of interest.
0	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.

- **The project decides *a priori* what constitutes "favorable" agreement**

Technical Review Level Defns

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

- **Technical Review is an important part of NASA process**
- **Technical Review can adjust the score by at most one level**

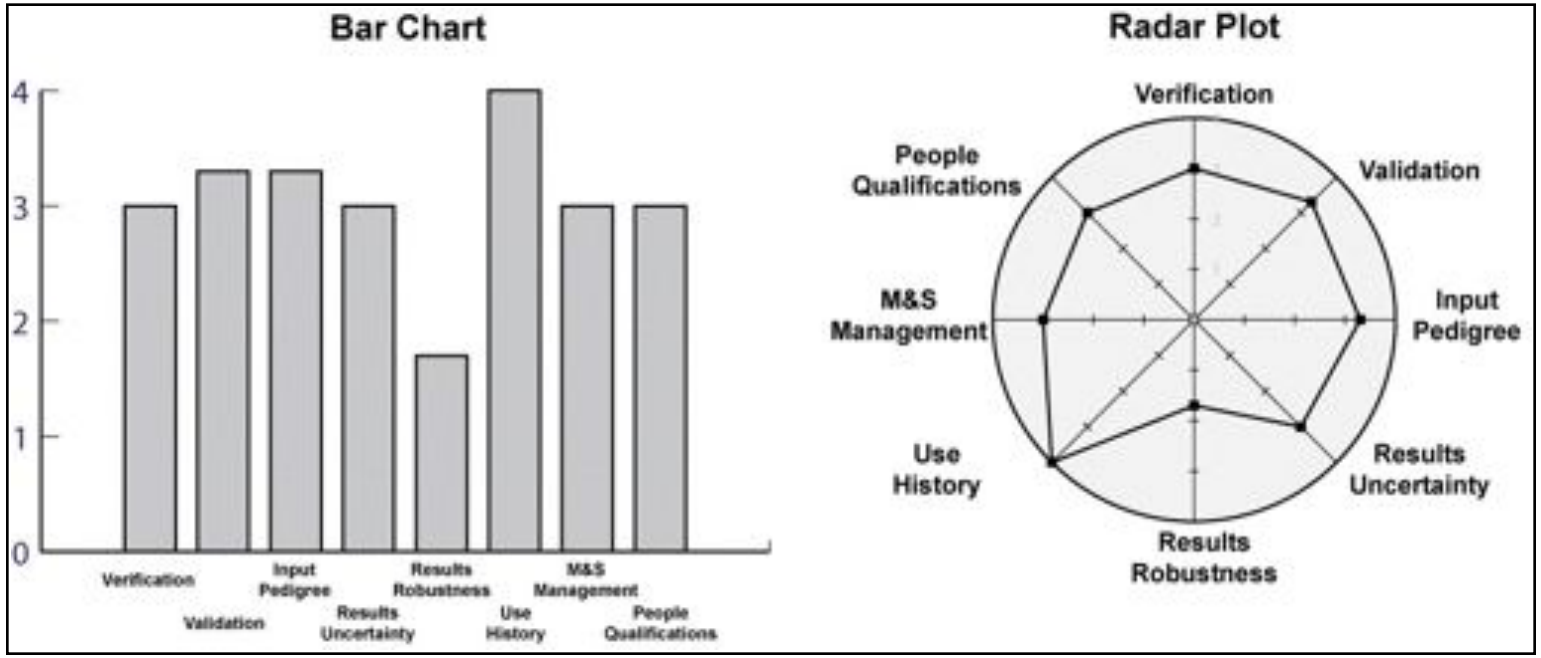
Supporting Evidence Level Defns

Level	Use History	M&S Management	People Qualifications
4	De facto standard.	Continuing Process Improvement: The M&S effort is using measurements on M&S processes to improve the repeatability of the M&S results.	Possesses an advanced engineering or science degree or extensive work experience in M&S, has extensive experience with the development and use of the M&S being reviewed, and has employed specific recommended practices relevant to current application.
3	Post-decision real-world events have been accurately represented in results (e.g., validated by mission data).	Predictable Process: The M&S effort is measuring repeatability of the M&S results generated by the M&S processes.	Possesses an advanced engineering or science degree or extensive work experience, has general M&S training, has specific experience with the M&S being reviewed, and has been trained on specific recommended practices relevant to the current application.
2	Used previously to perform analysis upon which critical decisions have been made.	Established Process: The M&S effort has established a documented process for M&S development and operations.	Possesses an engineering or science degree, has received formal training in formulation of M&S and generic training in recommended practices for M&S, and has developed M&S products.
1	Specific scenarios have been created to test application, or results compare favorably with outputs from other similar tools.	Managed Process: The M&S roles and responsibilities have been defined.	Possesses an engineering or science degree, has been introduced to the topic of M&S, and has been exposed to generic recommended practices in M&S.
0	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.

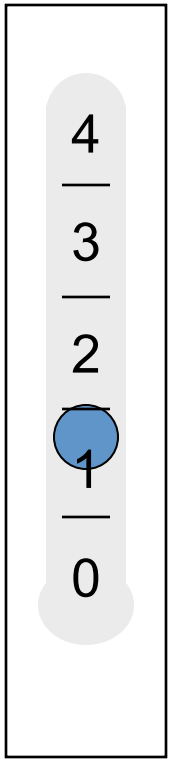
- **M&S Mgmt & People Qualification are driven by CAIB/Diaz**
- **Use History ("heritage") is important to NASA decision makers**

Sample Report Formats

Individual Factor Scores

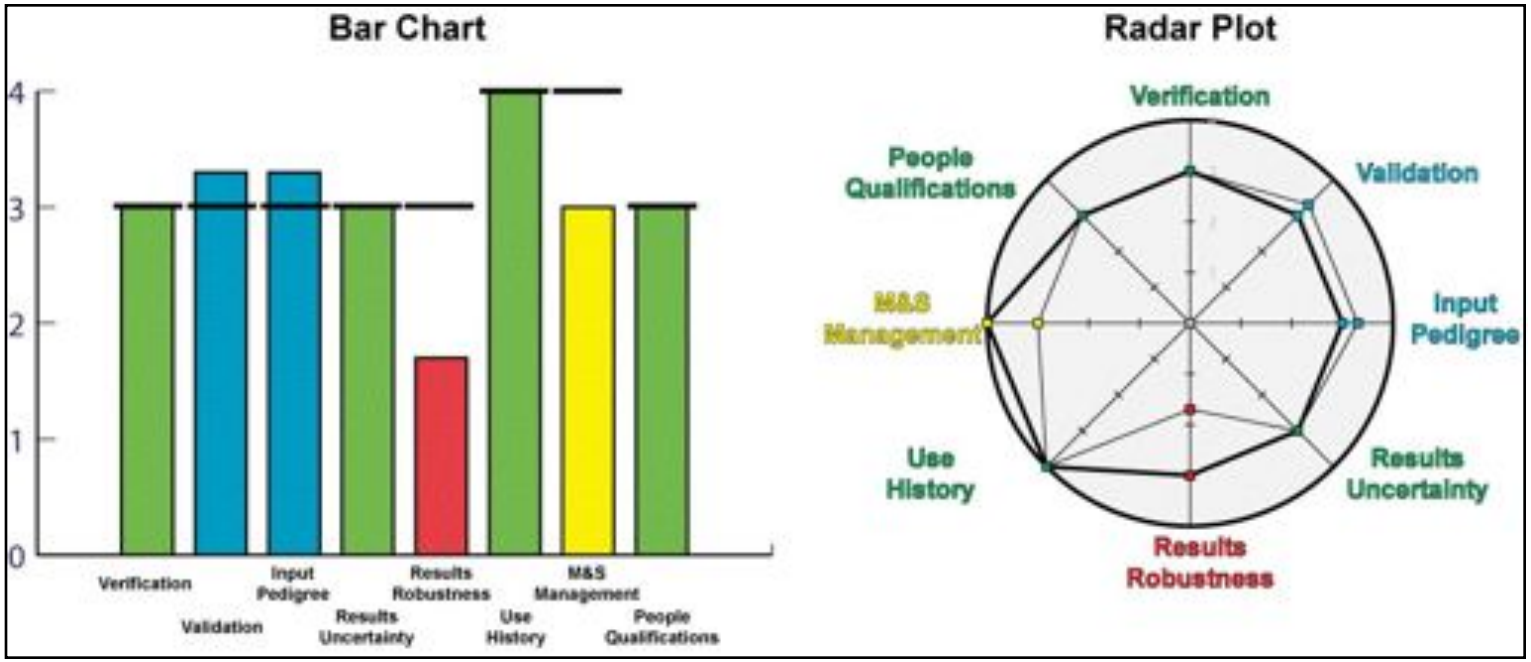


Overall Score



Comparison with Thresholds

Individual Factor Scores



Overall Score