

# Semantic Fidelity Reckoning: Toward Normalized Simulation Interoperability in Digital Engineering

**Ric Roca**  
The Aerospace Corporation  
Chantilly, VA  
ric.roca@aero.org

**Daniel B. Winton**  
The Aerospace Corporation  
El Segundo, CA  
daniel.b.winton@aero.org

## ABSTRACT

Semantic Fidelity Reckoning (SFR) aims to extend, generalize, and repurpose the Dead Reckoning mechanism from the Distributed Interactive Simulation standard to convey, detect, and reconcile fidelity specification disparities among distributed analytic simulators. SFR thus leverages a familiar mechanism to implement an emergent Semantic Fidelity (SF) paradigm originally intended to normalize fidelity specifications for computable models underlying analytic simulators. SF/SFR are being examined toward semantic interoperability and semantic validation & verification within and across modeling domains in the Digital Engineering (DE) continuum —such as the handshake between analytic models (e.g., orbital-mechanics and projectile-motion simulators) and between analytic models and descriptive models (e.g., orbit/trajectory simulators and satellite/missile Model-Based Systems Engineering (MBSE) system models). DE is a continuum of models from multiple domains, implying a dependency on semantic interoperability (i.e., information transmission; unambiguous contextual meaning in data exchange) which remains elusive in all forms of distributed simulation. Semantic interoperability has been riddled by arbitrary generic taxonomies, domain-specific ontologies, and data models focused on local needs —all leading to information silos requiring complex, costly, and often untenable cross-domain ontology-matching algorithms to reconcile semantic gaps, conflicts, and contradictions. SF is grounded on a novel taxonomy/classification framework that borrows from phylogenetic systematics and other formal methods to promote a consistent and repeatable ontological/specification approach within and across domains toward mitigating ambiguity and the need for costly ontology matching. A novel albeit rudimentary distributed-simulation environment of analytic models involving anti-satellite missile intercepting low Earth orbit satellite was stood up to demonstrate and provide a glimpse of error propagation for satellite orbit due to disparate model fidelities, as well as for error mitigation with SF/SFR. Results suggest SF specifications facilitate the handshake between analytic models and constraint block parameters of descriptive models which propagate to MBSE operational-environment system requirements, design, and risk among other model elements.

## ABOUT THE AUTHORS

**Dr. Ric Roca** is a systems engineer specialized in modeling & simulation (M&S) projects and technologies with over 36 years of professional experience, primarily as an independent consultant ([ricroca@simulatedinstruments.com](mailto:ricroca@simulatedinstruments.com)) in federally funded DoD research & development (R&D). He is currently a Senior Engineering Specialist in M&S R&D at The Aerospace Corporation, Chantilly, VA. Ric earned a B.S.E. in Electrical Engineering from Tulane University, an M.S. in Systems Engineering from George Mason University, and a Ph.D. in Modeling & Simulation Engineering from Old Dominion University. His research interests include M&S engineering life-cycle process improvement with emphasis on conceptual modeling, fidelity specification, validation & verification, reverse engineering, restructuring, and re-engineering (RE3) of legacy computable models and simulation systems, and generation and validation of affordance referents for simulation-based training/learning in academia, sports, military, and industry.

**Daniel B. Winton** is a Senior Project Engineer at The Aerospace Corporation with 32 years of industry experience. He holds M.S. degrees in Systems Management and in Systems Architecting and Engineering from the University of Southern California. As a Digital Engineering practitioner, he applies expertise in Model Based Systems Engineering, simulation, systems engineering, and systems architecting as well as in acquisition, risk, requirements, cost, scheduling, software, systems integration, and databases to solving difficult and often ill-defined problems.

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## **INTRODUCTION**

The Digital Engineering (DE) movement in Department of Defense (DoD) modeling & simulation (M&S) communities of interest (COIs) manifests persistent semantic interoperability shortcomings in various forms of distributed simulation. An on-going feasibility study, extending research of an emergent Semantic Fidelity (SF) paradigm (Roca, 2021; Roca & Coatanea, 2018; Roca, 2013; Roca, 2010), is addressing this shortcoming and premises that a working-standard/best-practice for semantic interoperability across domains in DE is needed and depends on a working-standard/best-practice for computable-model fidelity specification —neither of which currently exists. A novel albeit rudimentary distributed simulation environment was used to demonstrate the feasibility of emergent SF specification and Semantic Fidelity Reckoning (SFR) specification-reconciliation paradigms. SFR implements SF toward generalizing the Dead Reckoning (DR) mechanism from the Distributed Interactive Simulation (DIS) standard (IEEE, 2012) to enable normalized computable model fidelity specifications and to promote semantic interoperability among distributed analytic simulators. In this manner, SF/SFR provides an objective baseline, pertinent to DE.

Although syntactic interoperability (i.e., data transmission using common format structure) in distributed simulation has been well served by various interoperability protocol standards, such as DIS and High Level Architecture (HLA) (IEEE, 2001), semantic interoperability (i.e., information transmission; unambiguous contextual meaning in data exchange) (Dobrev, Kalaydjiev, & Angelova, 2007) remains elusive among M&S COIs and the DE enterprise. Reconciling computable model lexica and fidelity specifications even within domains has proven elusive, making the prospect of DE semantic interoperability across various domains seemingly unrealistic given current trends and realities that reveal arbitrary practices and the need for semantic interoperability cross-domain ontology standards.

SF is grounded on a “phylogenetic taxonomy,” similarly to taxonomies for classifying plants and animals, and thus conducive to “numerical DNA” specification/ontology building blocks amenable to classification of “computable model species” in a consistent and repeatable way that potentially mitigates the ambiguity inherent to generic/subjective ontologies and taxonomies —a key concern to practical semantic interoperability.

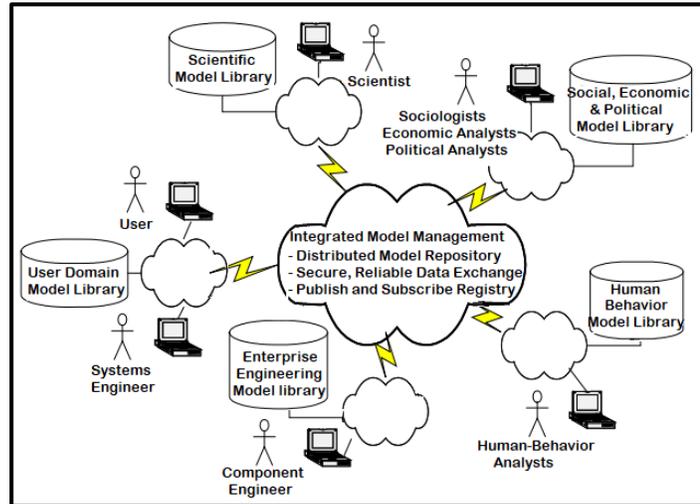
SFR, like DR, avails centralized/agreed-upon algorithm resources —another key concern to practical semantic interoperability. But whereas DR synchronizes a handful of agreed-upon flight dynamics algorithms (limited in accuracy and largely intended to reduce bandwidth traffic to mitigate jitter associated with data transmission discontinuities), SFR aims to synchronize computable-model fidelity specifications by communicating SF nomenclature bitmasks corresponding to the numerical-DNA constituent building blocks of computable-model algorithms. SF bitmask nomenclature approach potentially provides for a very large number of computable-model species specifications to accommodate practically most domains. The extensibility of the DIS interoperability standard, coupled with DIS-DR familiarity in M&S COIs, makes SF/SFR implementation a not-so-intrusive, practical, and viable solution to semantic interoperability in distributed simulation —including DE semantic interoperability.

SF’s potential toward semantic interoperability in the DE continuum would facilitate, for example, objective specification of operational environment boundary conditions, critical values, constituting relations, and other parameters in model-based systems engineering (MBSE) descriptive models —needed in parametric diagrams (e.g., constraint blocks) to bound conceptual models. Further, SF’s underlying phylogenetic taxonomy approach conduces to physical-phenomena analogies to non-physical phenomena, opening the possibility to extend SF specifications to other DE domains, such as program management, acquisition, manufacturing, supply chain, training, and other sciences lacking in standardized lexica and/or in formal semantic interoperability protocols.

## SEMANTIC INTEROPERABILITY IN DIGITAL ENGINEERING

DE (Figure 1) refers to “... an integrated digital ... continuum across disciplines to support acquisition lifecycle activities from concept through disposal ... [with an enabling ecosystem consisting of] interconnected infrastructure, environment, and methodology for the exchange of digital artifacts from an authoritative source of truth” (Department of Defense, 2018; DAU, 2017; INCOSE, 2014) —implying a dependency on DE semantic interoperability standardization.

Toward this implication, consider and focus on the prevalence of analytic simulators and MBSE descriptive models in the DE continuum. Analytic simulators involve computable models of various phenomena from the physical, life, social, econometric, and other sciences whereas MBSE involves descriptive models constructed from standardized visual languages (e.g., structure, behavior, parameter diagrams) directed by methods and employing tools. Because of their prevalence, resolving or even making improvements toward semantic interoperability within each of these domains—and certainly between them—would go a long way toward establishing a repeatable and/or transferable baseline toward DE semantic interoperability.



**Figure 1. Cross Domain Model Integration (INCOSE, 2007)**

MBSE descriptive models involve those aspects of model-based engineering (MBE; an approach to engineering using models as an integral part of the technical baseline) specifically associated with systems engineering —such as system requirements, design, analysis, and verification and validation activities. These activities are informed by available axiomatic domain referents (i.e., the body of knowledge about specific domains) such as established axioms/principles, subject matter expertise, manuals, handbooks, formalisms, empirical data, and other sources. But they also rely-on or benefit-from analytic simulators that avail not only codified axiomatic referents but also codified experimental/hypothetical referents into computable models aimed to extend, complement, validate, retrofit, and/or fill knowledge gaps in axiomatic domain referents. These referents can/are commonly captured in parameter diagrams/constraint-blocks, which serve as proxies for analytic simulators and thus provide a natural handshake between analytic simulators and MBSE descriptive models —to facilitate at least one interface in the DE continuum.

The sheer volume, complexity, selection, specialization, and computational demand for axiomatic and theoretical referents encoded into computable-models within analytical simulators means that they must be readily available and capable to be harnessed and interoperate in distributed-computing simulation environments (distributed simulation) to aggregate and avail information to MBSE parameter diagrams/constraint blocks that is meaningful to users.

But semantic interoperability in distributed simulation involving natural or man-made physical/physics-based phenomena (arguably the most objective and quantifiable themes for computable models) is at best inconsistent within and across M&S COIs —and is even less coherent among analytic simulators involving more-subjective non-physics-based phenomena (e.g., life, social, econometric, political, cultural sciences). Further, subjectivity-induced semantic gaps become even more widespread among models from other domains (e.g., systems engineering, acquisition and logistic protocols, cost analysis, complexity and risk management, resource/supply-chain estimation, etc.) (Figure 1).

These semantic gaps occur because humans have different experiential and domain perspectives (i.e., multi-perspectivity (Feistner & Holl, 2006)) which lead them to model problems and to express models differently (Arp, Smith, & Spear, 2015) —a condition that can be exacerbated by arbitrary MBSE practices. Arguably and ironically, semantic interoperability standardization efforts have fallen short in part because of domain multi-perspectivity and bias, suggesting semantic interoperability standardization efforts should consider the more insidious root-cause — which is the arbitrary fidelity specification practices for computable models.

**SEMANTIC FIDELITY**

SF is an emergent paradigm addressing the lack of M&S fidelity specification standardization (Roca, 2021). Its research effort recognizes that fidelity consistency is foundational to M&S life-cycle engineering, affecting not only conceptual model engineering, validation & verification, and other subprocesses (Department of the Army, 1999; Gross, Pace, Harmon, & Tucker, 1999; Gross D. , 1999) but also semantic interoperability in distributed simulation.

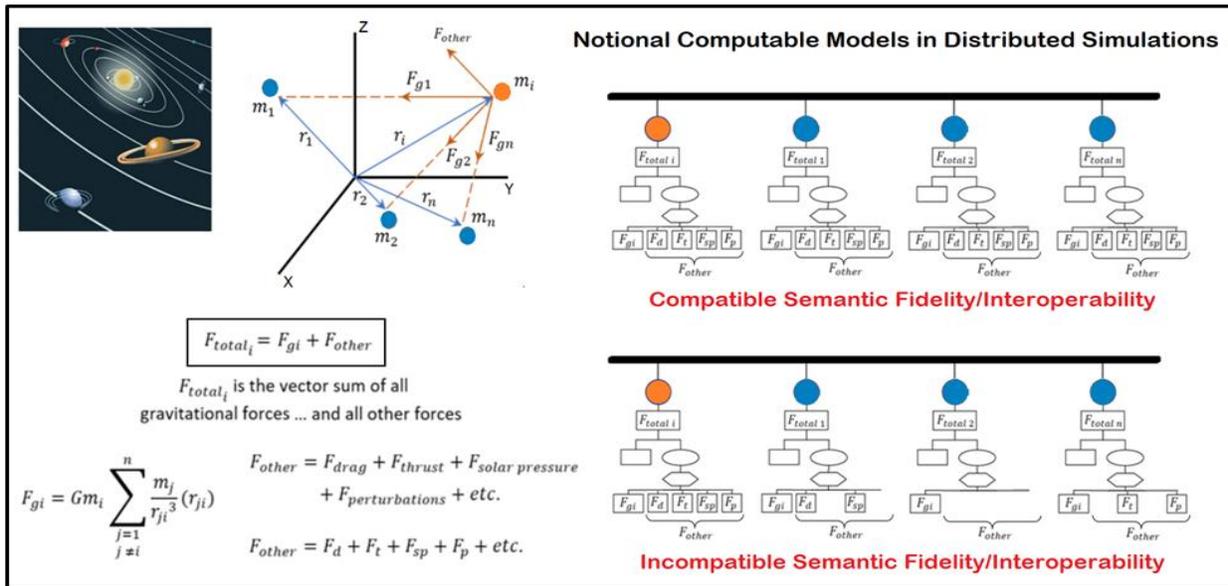
SF is premised on the notions that 1). Fidelity is context-specific rather than a designated quantity with corresponding units-of-measure (Harmon & Youngblood, 2005; Missile Defense Agency, 2010), such that 2). Fidelity specification of computable models is akin to design of experiments (DOE) (Albrecht, Nachtsheim, Albrecht, & Cook, 2013) in that it prescribes stakeholder information needs (i.e., specific intended uses) that simulation systems must attend-to and synthesize to support decisions, answer questions, and/or enable development of cognitive/motor skills.

SF is grounded on dimensional analysis and other formal methods to provide a transdisciplinary phylogenetic taxonomy that enables unique classification of computable-model species based on unique numerical DNA configurations.

Unique numerical DNA configurations can be encoded into unique bitmask codes toward objective fidelity specification nomenclature. This objective nomenclature offers an alternative not only to uninformative “low-med-high fidelity” monikers but also to communicate, detect, and reconcile fidelity compatibility among analytic computable models participating in distributed simulation —transferable to DE.

**Missing Fidelity Specification Standards in M&S**

Currently no fidelity specification standard exists to guide M&S life-cycle engineering as it pertains to simulation-system computable models. Fidelity has multiple connotations among M&S practitioners and has been designated “the most commonly and least-consistently used term” in the M&S community (Gross, Pace, Harmon, & Tucker, 1999), casually interchanged with such related terms as “accuracy, precision, and resolution” leading to ambiguity and confusion (Gross D. , 1999). Leading M&S researchers assert that “fidelity represents the most important requirements set for simulation, and without a clear understanding of fidelity, these requirements are the most difficult to specify” (Gross, Pace, Harmon, & Tucker, 1999).



**Figure 2. Notional Compatible and Incompatible Semantic Fidelity Specifications in Distributed**

In common informal practice, arbitrary selections of simuland referents (i.e., the body of knowledge of entities being simulated) are encoded into computable models —routinely leading to monolithic/stove-piped simulators that are difficult to interoperate-with in distributed simulation and/or become sources of unpredictable errors due to

propagation of computations resulting from inconsistent or incompatible fidelity specifications. Figure 2 depicts notional distributed simulation environments involving interoperating models of celestial bodies subject to various forces; one shows compatible semantic fidelity in which all models include the same scope of referents whereas the other shows incompatible semantic fidelity in which each of the participating models selects referents arbitrarily, making it susceptible to produce erratic results such as inconsistent celestial body positions.

### M&S Fidelity is Context-Specific

Arguably, M&S fidelity specification is context-specific rather than designated quantity and units-of-measure. This has led to the inference that fidelity must be decomposed into applicable measures of quality, such as accuracy, precision, resolution, sensitivity, granularity, fitness, tolerance, abstraction, detail, and error (Harmon & Youngblood, 2005; Missile Defense Agency, 2010; Gross D. , 1999) among others.

This inference is instructive because simulation environments involve all kinds of entities characterized by any number of physical or non-physical attributes to which measures of quality (i.e., metrology) can be assigned. Further, the mathematical approach (i.e., numeracy) that describes an entity in terms of its physical attributes is also relevant, as are the variables, parameters, and constants (i.e., variableness) used. This suggests a more nuanced approach to fidelity specification—and the need for a fidelity classification framework.

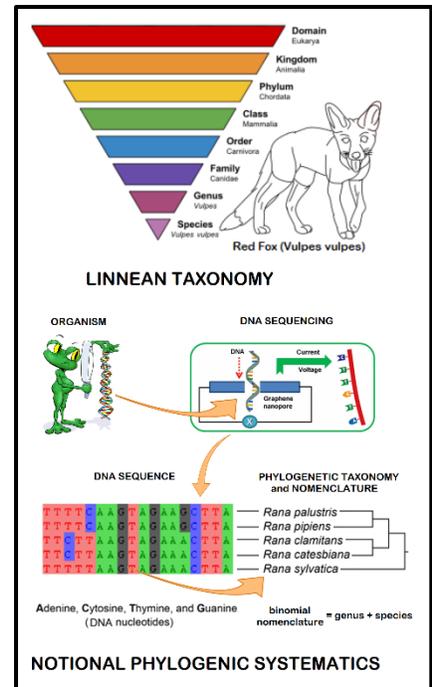
Classification involves differentiating between specified things, processes, individuals, groups, etc. For example, Linnean taxonomy and phylogenic systematics (Amphibiaweb, 2021) have been used for classification of plants and animals (Figure 3). In zoology, “differentia” refers to defining characteristics that make a species more specific than its subsuming genus, serving to set it apart from other species of the same genus. The combination of genus and differentia establish the classification and nomenclature of a type of animal.

Toward a similar end, the SF paradigm goes beyond arbitrary measures of quality and includes numerical ranks of dimensionality, variableness, metrology, and numeracy types (Figure 4) amenable to a “numerical phylogenic taxonomy” for classifying computable models according to their numerical constituents. That is, a numerical phylogenic taxonomy would help enumerate the relevant simuland referents to be included in computable models by construing their numerical ranks into various “numerical DNA” configurations that would serve as “numerical differentia” for establishing the classification and nomenclature of unique “computable model species.”

### M&S Fidelity Specification is Akin to Design of Experiments

Computable models and simulation systems are built for specific purposes that are commonly expressed as Specific Intended Uses (SIUs). M&S researchers indicate that “in every application, simulations provide knowledge to support various decisions” (Harmon & Youngblood, 2005) and further explain that “A simulation model is developed for a set of intended uses (IUs) and its acceptability is judged and is certified with respect to those IUs ... IUs define the point of reference by which a simulation model is developed and used” (Balci & Ormsby, 2007). The U.S. Navy established that SIUs “describe the decision a model supports and the information the model provides to the decision process” (Naval Sea Systems Command, 2010).

From that perspective, SF specification is arguably akin to design-of-experiments (DOE) in that fidelity specification, as in experimental design, aims to predict dependent-variable outcomes from preconditions captured in independent and control variables. This is significant not only because of the all-too-common tendency of M&S practitioners to be liberal and arbitrary in the inclusion of referents but also because an SF specification approach potentially mitigates this arbitrary practice by providing an objective conceptual-model-engineering mechanism that facilitates ascertaining the scope of referents to be included in a simulation environment and corresponding to its problem space context.



**Figure 3 – Linnean Taxonomy and Phylogenic Systematics (notional)**

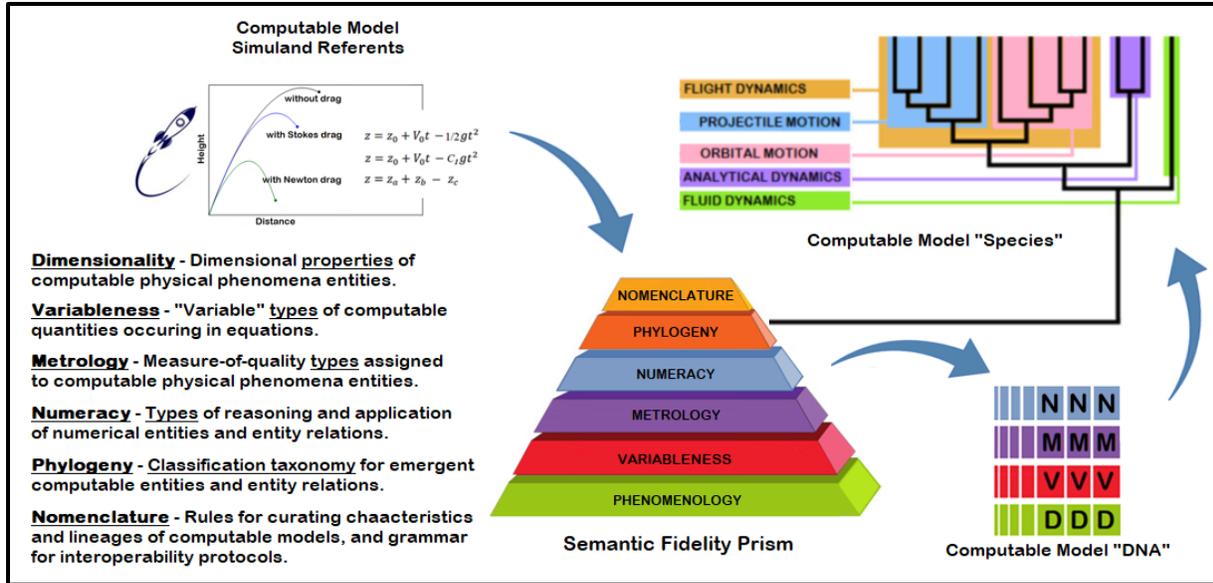


Figure 4 – Semantic Fidelity Prism Ranks

**Dimensionality**

SF is grounded on dimensional analysis (DA) to establish the dimensional content (i.e., dimensionality) of the relevant physical phenomena to be included in a simulated problem-space/operational environment.

DA is a branch of algebraic theory with a broad range of applications in the physical, life, and social sciences (Santiago, 2019; Szirtes, 2007) and is arguably one of the most foundational scientific modeling methods. It has been considered in an ontology for mathematical engineering (Gruber & Olsen, 1994), though not in the context of simulation fidelity specification and nomenclature.

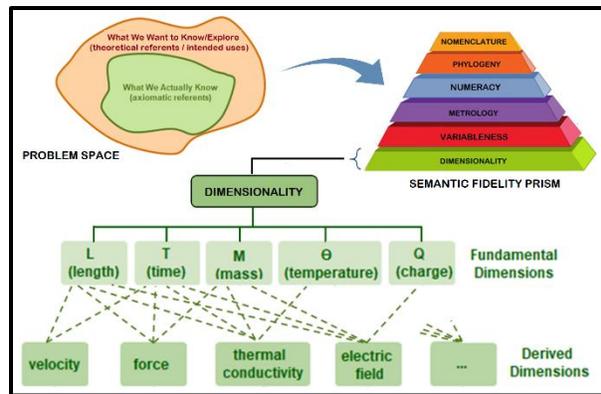


Figure 5 - Dimensionality Rank of Semantic Fidelity

Dimensionality is relevant and a key to a viable cross-domain taxonomy for normalizing computable models because the physical world (natural and man-made) consists-of and is describable-by the fundamental dimensions of time [T], length [L], temperature [Θ], mass [M], and charge [Q] which are combined into products and/or quotients to derive composite dimensions, such as velocity [LT<sup>-1</sup>], acceleration [LT<sup>-2</sup>], force [MLT<sup>-2</sup>], density [ML<sup>-3</sup>], others (Figure 5). Man-made systems (e.g., missiles) interact with phenomena of natural systems (e.g., atmospheric density) but can also generate their own “man-made phenomena” (e.g., heat, projectile motion, electromagnetic radiation). Axioms, postulates, and formalisms of physical science and engineering domains involve understanding and manipulation of physical phenomena dimensions and their interactions —and have well-established concepts and lexica, amenable-to/basis-of interdisciplinary collaboration. Dimensionality and DA affords a natural and well-established order of entities and entity relations for cross-domain taxonomy and ontology constructs not available by domain-specific or generic taxonomies/ontologies.

**Variableness**

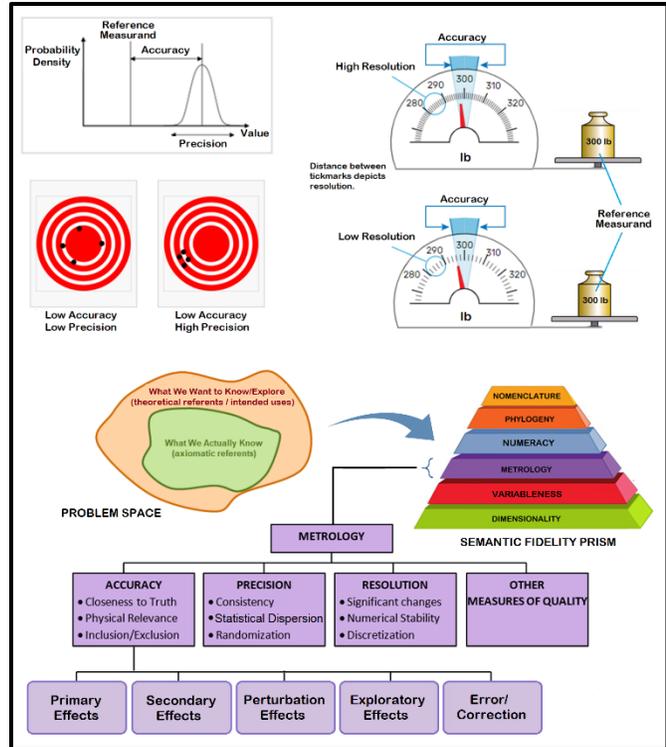
SF adopts DA depictions of a constant as a physical quantity that never changes; a parameter as a physical quantity that is constant in the context in which it is implemented and thus can change in different contexts; and a variable as a physical quantity that can change directly or indirectly (i.e., dependent, independent variables) (Szirtes, 2007). For example, the speed of light in vacuum and the universal gravitational constant (a.k.a., “Big G”) are generally believed

to be both universal in nature with constant values in time. The gravitational acceleration (a.k.a., “small g”) is not constant even in the same location on earth, varies slightly with changes in latitude and altitude, and varies significantly on different planets and celestial bodies (Szirtes, 2007).

Constants and parameters help to establish boundary conditions, ranges of operation, assumptions, and other relevant restrictions which facilitate and improve validation by containing scope and level of effort. Naive reassignment of established constants and parameters is not uncommon and is a significant venue for the introduction of computational errors. Variableness provides an opportunity to make computable models more specialized and thus mitigate ambiguity as well as improve their validation and verification.

**Metrology**

Metrology refers to the scientific study and practice of measurement that establishes a common understanding of units and measures crucial to industrial, societal, and legal processes (JCGM, 2008). Three of the most commonly used/misused measures of quality merit clarification: accuracy refers to closeness to truth, precision to the variance with respect to a mean, and resolution to the smallest detectable change (Figure 6).



**Figure 6 - Metrology Rank of Semantic Fidelity**

Accuracy is particularly significant as it enables a more meaningful account for closeness to truth by enumerating axiomatic dimensional content, such as simple projectile motion, Stokes and Newtonian drag, and Coriolis force to account for primary, secondary, and perturbation effects, respectively. Precision serves to quantify variation and uncertainty present in inaccurate or unpredictable experimental conditions whereas resolution accounts for discretization and numerical stability of the architectural design and computational environment. The significance of specifying resolution to fundamental dimensions in contrast to composite dimensions is illustrated by the rudimentary velocity computation in equations (1-2) where the exact same resolution result of velocity (v) can be achieved from different resolution specifications of distance (x) and time (t).

$$x = 20.25 \text{ ft}, t = 2.0 \text{ s} \quad v = \frac{x}{t} = 20.25/2.0 = 10.125 \text{ ft/s} \quad (1)$$

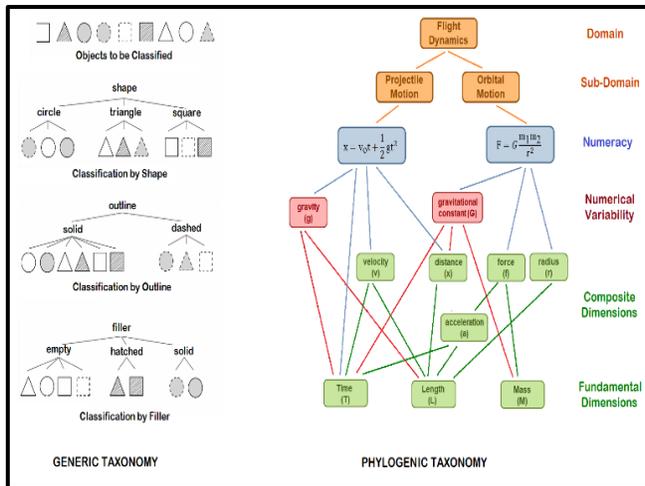
$$x = 22.78125 \text{ ft}, t = 2.25 \text{ s} \quad v = \frac{x}{t} = 20.78125/2.25 = 10.125 \text{ ft/s} \quad (2)$$

**Numeracy**

Numeracy specification concerns the reasoning and application of the type of mathematical expressions employed to represent numerical entities and entity relations, such as closed form (e.g., well-known functions, formulas), analytic form (e.g., special functions, infinite series), numerical approximation (e.g., integration, differentiation, interpolation, root-finding algorithms), and a host of other categories (e.g., approximation and perturbation theory, combinatorics, stochastic processes, graph and set theory, geometry, etc.). The numeracy rank may be the one aspect of fidelity specification where domain expertise, creativity, originality—and controversy—are fully manifested.

**Phylogeny**

Phylogeny refers to the evolutionary history or course of development of an organism, system, concept, thing, or idea (Amphibiaweb, 2021). A phylogenetic taxonomy for classifying computable models and their fidelity specifications



**Figure 7. Generic vs. Phylogenetic Taxonomies (notional)**

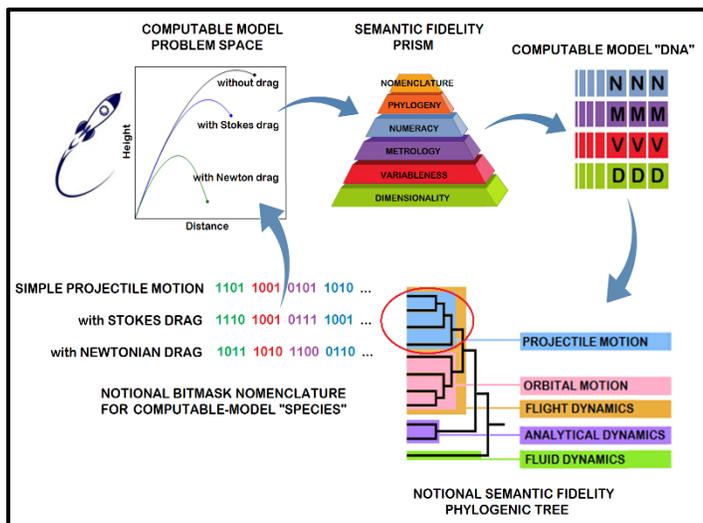
velocity, acceleration, force) and of individual constituent fundamental dimensions (i.e., time, length, mass). This approach mitigates the subjectivity inherent to generic taxonomies since the phylogeny of computable models is not arbitrary or interchangeable as is the case with generic taxonomies (Figure 7).

**Nomenclature**

The phylogenetic taxonomy inherent to SF conduces to objective and unique “numerical DNA” configurations that enumerate the essential differentia of computable models which amounts to their fidelity specifications. In contrast to arbitrary and subjective fidelity specification, the SF specification approach conduces to objective and quantifiable combinations which may be encoded into bitmasks and used as standardized predicates for clear and efficient execution control of instructions in software programs. Standardized fidelity specification bitmasks would not only offer a practical way to ascertain, catalogue, discover, validate, and otherwise manage fidelity content in simulation systems but also provide a mechanism for communicating, detecting, and reconciling fidelity disparities among participating computable models in distributed simulation (Figure 8) —with potential transfer to DE.

bodes well for simulation-system engineers given the tendency of computable-model requirements to evolve as stakeholder intended-uses change, team multi-perspectivity clarifies direction, and serendipitous discoveries realign scientific knowledge, beliefs, cultural differences, and other priorities that are difficult to accommodate with generic taxonomies (Hoetzlein, 2007).

SF computable-model phylogeny depicts the unique emergence and relationships of its constituent numerical entities, giving way to classification of holistic properties that are different and more complex than the sum properties of individual entities. For example, the composite properties of simple projectile motion and orbital motion are not only different from each other but also different from the properties of individual constituent composite dimensions (i.e.,



**Figure 8 - Fidelity Bitmask Nomenclature (notional)**

**SEMANTIC FIDELITY RECKONING AND SEMANTIC INTEROPERABILITY**

Semantic Fidelity Reckoning (SFR) aims to extend, generalize, and repurpose DIS Dead Reckoning (IEEE, 2012) to convey, detect, and reconcile fidelity specification disparities among distributed analytic simulators. It leverages the established and standardized DIS best-practice to provide a foothold for Semantic Fidelity specification toward normalized conceptual modeling, requirements specification, validation/verification —and semantic interoperability.

DIS Dead Reckoning facilitates and reduces communication processing using agreed-upon flight dynamics algorithms (Figure 9) to keep simulated entities synchronized among distributed simulators, reduce bandwidth traffic, and mitigate jitter (i.e., “jerky” behavior) due data discontinuities associated with data transmission latency. It is a method of position and orientation extrapolation to estimate entity states and thus limit transmission of entity state updates,

such that updates are only required when a state change exceeds a specified threshold value (IEEE, 2012; McCall & Murray, 2010). There are nine dead-reckoning algorithms defined in the DIS standard to facilitate these estimates which accommodate limited combinations of model attributes (e.g., rotating- or fixed body, position or velocity changes, world- or body coordinate system) (McCall & Murray, 2010). The current nine algorithms do not include perturbations, such as atmospheric drag, solar pressure, or other forces that would affect flight dynamics projections. Notwithstanding, DIS Dead Reckoning does, in fact, constitute a limited form of semantic interoperability in that it communicates flight dynamics information/context that supplements non-contextual entity-state data (i.e., state data that doesn't include metadata as to its axiomatic essence).

DIS is an Institute of Electrical and Electronics Engineers (IEEE) standard (IEEE 1278.1-2012, Version 7) (IEEE, 2012) for conducting distributed simulation, especially wargaming by military organizations, but also for mission analysis by agencies involved in space exploration and for other domain contexts. State information of simulated entities is encoded in formatted standard protocol data units (PDUs) and exchanged among hosts in distributed simulation using User Datagram Protocol (UDP) and other existing standard transport layer protocols.

SFR aims to extend, generalize, and repurpose DIS Dead Reckoning by substituting the field of agreed-upon flight-dynamics algorithms with SF specifications for any type of phenomena. DIS applications communicate which Dead Reckoning algorithm to use through Entity State PDU enumeration fields. SF bitmask nomenclature emulates this semantic interoperability mechanism but conveys the complete context of phenomena specification in models.

**APPROACH**

Rudimentary distributed-simulation environment implemented SF/SFR for specifying, communicating, detecting, and reconciling compatible/incompatible fidelity specifications. Simulation context was anti-satellite (ASAT) missile intercepting low Earth orbit (LEO) satellite (Figure 10). ASAT missile simulator (ASAT-SIM) implemented simple projectile motion; LEO satellite simulator (LEO-SIM) implemented simple Keplerian orbit without and with perturbing atmospheric drag. LEO-SIM included user interface to transmit simple SF bitmasks for notifying AST-SIM of current context of computations —i.e., perturbed or unperturbed orbit. Both simulators were built in C/X-Windows/OpenGL, single Linux dense core server, Linux/CentOS. X-Server inter-client communication atom/property constructs provided interoperability to minimize transmission delays (Figure 11). ASAT-SIM used simple projectile motion only; focus was on fidelity disparities for which orbit changes sufficed.

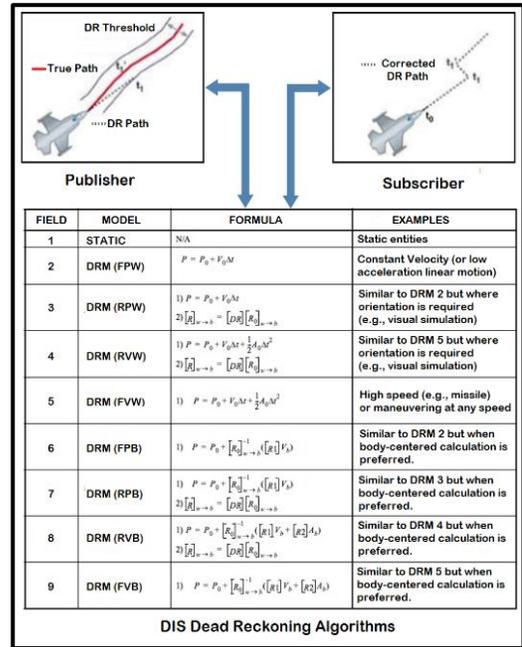


Figure 9. Dead Reckoning Algorithms

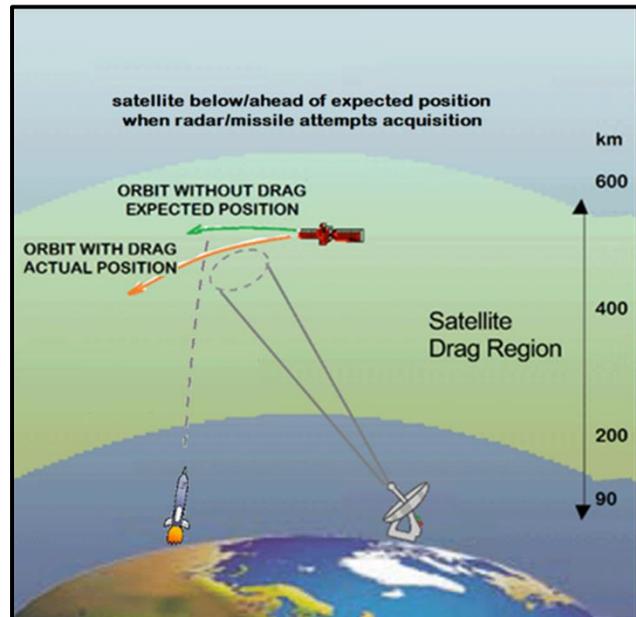


Figure 10 – Simulation Context – Drag Effect on Orbit

## RESULTS

### Simple Semantic Interoperability with SFR

Unperturbed/circular LEO satellite ephemerides (positions) were represented-by/computed-with trigonometric functions as well as ellipse standard form and demonstrated slight numeracy and resolution discrepancies. These computed ephemerides were then transmitted to ASAT-SIM (i.e., observed data) and fitted to a predictive ellipse intended as the target function for computing ASAT-missile/LEO-satellite interception trajectory. In addition to observed data, ASAT-SIM computed LEO satellite ephemerides using agreed-upon algorithms (i.e., unperturbed/perturbed orbits) as prescribed by SF bitmasks received from LEO-SIM; unperturbed orbit was represented by ellipse standard form and perturbed orbit by Archimedean spiral to analogize rudimentary satellite orbit decay (Australian Space Weather Agency, 1999) albeit without atmospheric, aerodynamics, and/or other parameters.

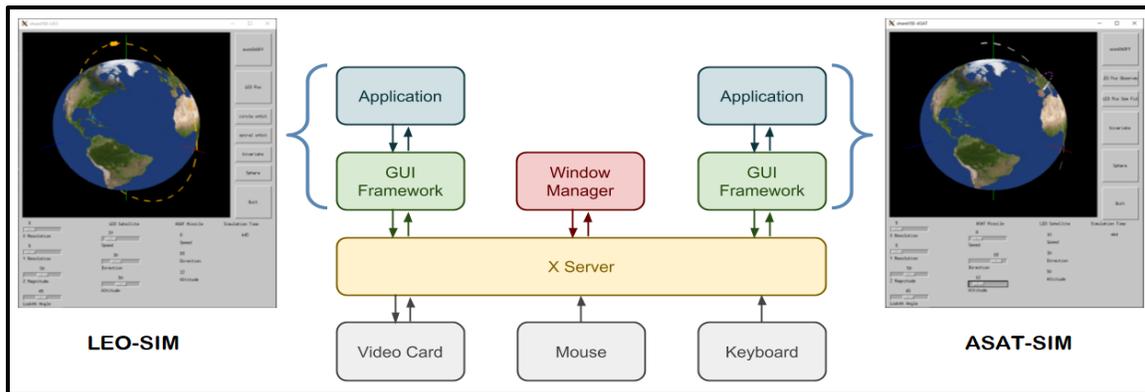


Figure 11 - Rudimentary Distributed Simulation Experimental Environment

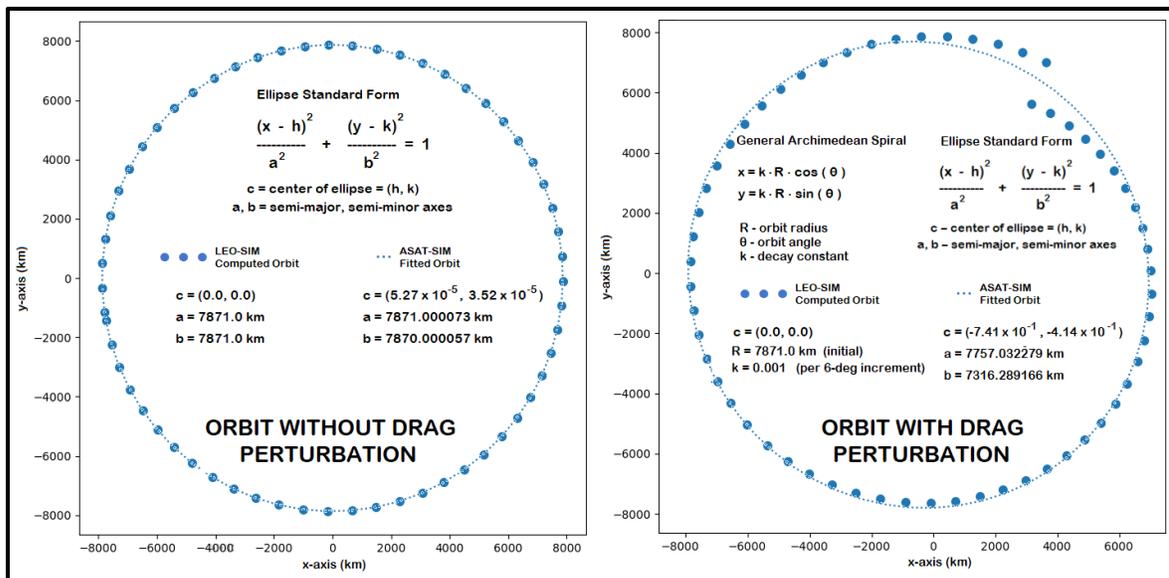


Figure 12 - Elliptical Fittings to Satellite Orbits Unperturbed and Perturbed by Drag (notional)

Ellipse fitting was used for both perturbed and unperturbed orbits to illustrate common overfitting/underfitting approach resulting from perturbation unawareness/disregard such as drag as well as propagated error (Figure 12). Simple SFR bitmask mechanism worked as intended in that unperturbed and perturbed orbits were computed by ASAT-SIM thus generating the appropriate target function for determining an effective missile trajectory as well as eliminating necessity to fit observed data to arbitrary functions (fitting was done here for comparison).

## Intersection Between M&S Engineering and MBSE/DE

M&S is most commonly employed to answer stakeholder, architect, or designer questions that are associated with a system and that cannot easily be derived by simpler means. The results inform decisions associated with a system's requirements, structure or behavior. However, how a system is built intersects with not only the hardware and software but also with risk, cost, and schedule. Capturing the interrelationships between all aspects of a system's acquisition, manufacturing and maintenance is the core of digital engineering. One approach to successfully representing all aspects of the system in a single model uses a Common Information Infrastructure (CII) (Winton, 2022). Similar to Semantic Fidelity, CII uses common syntax and semantics in defining its element types and relations. This approach is used by the MBSE/DE tool, GENESYS. Figure 13 shows a subset of the element types from the GENESYS CII.

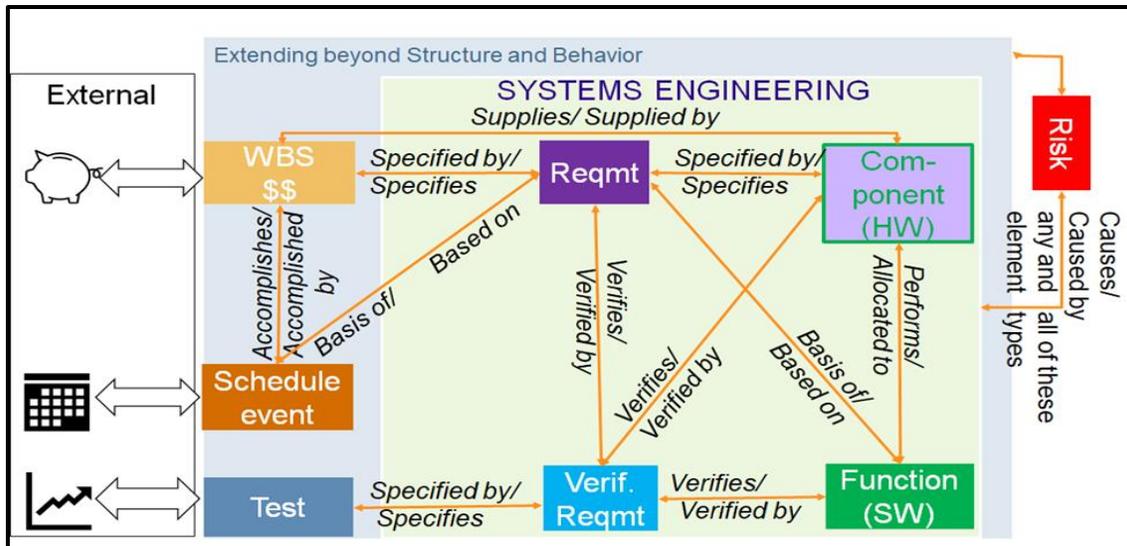


Figure 13 – Subset of Elements & Complementary Relationships in GENESYS

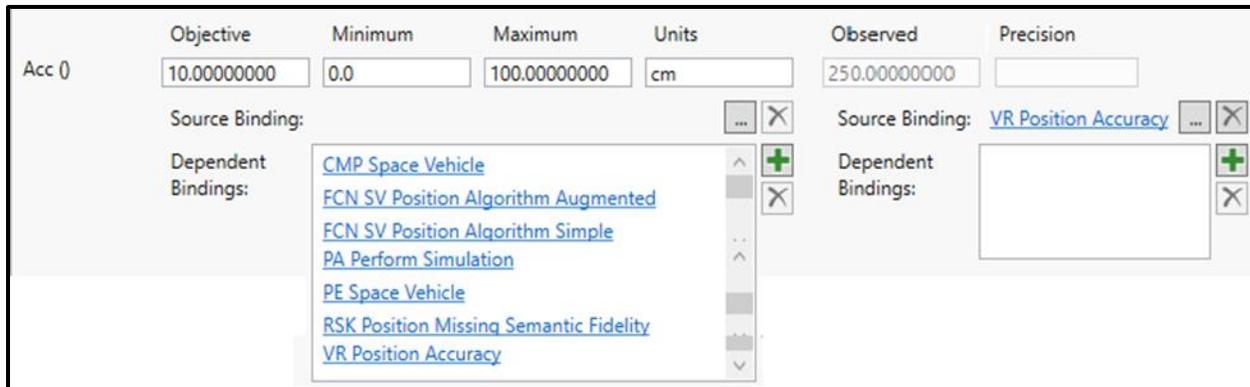
The Requirement Element (Figure 14) is the parametric source for desired values for a verification requirement, risk, design components, behavior. Changing a value in the requirement updates them in all of those areas including work breakdown structure (WBS) and schedule. The Test Activity has parameters that are updated based on the results of the external M&S. The relationship follows through so that source and dependent bindings to similar parametrics are updated simultaneously in the requirements.

Parameter in the Requirement Element:

- Values for Objective, Minimum, Maximum and Units are sourced at the Requirement element's Position Accuracy Parameter (Acc)
  - Dependent bindings to elements using the same parameters include
    - CMP: Components (Structure)
    - FCN: Function (Behavior)
    - PA: Program Activity (Schedule)
    - PE: Program Element (Work Breakdown Structure)
    - RSK: Risk
    - VR: Verification Requirement
- Observed parameter value comes from Test Activity Element that is informed by semantic fidelity

### Using M&S with Semantic Fidelity in MBSE/DE

Results from the SF/SFR-based simulations demonstrate differences between simple Keplerian orbital mechanics that neglect perturbations and more accurate ones that do incorporate perturbations, such as atmospheric drag. These are the insights, albeit more complex, that concern and impact architecting and designing a spacecraft. SF/SFR was instrumental for communicating algorithm used by one simulator so the other can predict states (e.g., orbital position).



**Figure 14 - Accuracy Parameter in the Requirement**

The credibility of a simulator depends on meaningful validation which requires a fidelity specification baseline that can be confirmed by empirical data and/or subject matter expertise—and relative to prescribed specific intended uses. The utility of the SF/SFR intervention, for example, is to increase the confidence of the information provided by a simulation environment to a development team wanting to determine if an interceptor launched from the ground is a credible threat/risk to an asset such as a LEO satellite. Knowing that interoperating simulators are operating on the same agreed-upon phenomena representations provide the confidence that any discrepancies are due to something other than propagated errors from incompatible models. This confidence impacts cost, schedule, and other system development life-cycle parameters since re-work and retrofitting costs are mitigated.

This excursion into the CII demonstrates how SF can be a stabilizing agent to a DE ecosystem as it can impact not only requirement and design trades but also cost and schedule information.

## DISCUSSION AND FUTURE WORK TOWARD SEMANTIC FIDELITY OPERATIONALIZATION

Rudimentary LEO-SIM/ASAT-SIM demonstration premised that attempts to classify and interoperate computable models peripherally (e.g., wrappers, containers; i.e., without close accounting of computable entities and entity relations making up inner-workings of simulation-systems) are unreliable and insufficient, and that DE semantic interoperability depends on transdisciplinary taxonomy for meaningful model fidelity specification and algorithm classification. Dead Reckoning-inspired SFR demonstrated a possible non-intrusive SF implementation approach.

As of this writing, efforts to operationalize SF/SFR are on-going, to include an initiative that aims to express a phylogenetic taxonomy for selected flight dynamics phenomenology in MBSE tools (e.g., Cameo/SysML, GENESYS). This MBSE-based phylogenetic taxonomy is intended to be an open source, centralized, simuland-referent repository that includes systems-engineer-friendly selectable SF-based reusable modeling primitives (RMPs). Selectable RMPs conduce to combinatorics of entity and entity-relation regimes toward a variety of flight-dynamic species ontologies (e.g., projectile motion, orbital mechanics) that characterize/bound operational system (e.g., satellite, missile) flight requirement specifications. The aim is to include regimes that capture man-made and natural system perturbations, such as interferences, air/atmospheric drag, and other perturbations. In this manner, a common taxonomy informs complementary distributed simulators—such as an operational system simulator (e.g., missile) interacting with an operational environment simulator (e.g., atmosphere)—and promotes semantic interoperability. A symbiosis between MBSE descriptive models and M&S analytic models is thus grounded on SF/RMP specifications conducive to analytic computable models and simulations systems responsive to SIUs prescribed by MBSE descriptive-model Constraint Block parametric information needs. The MBSE-based phylogenetic taxonomy and initial set of RMPs may be analyzed, scrutinized, validated, refined, and extended by subject matter experts—and availed to the user community.

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