CHOOSING A COORDINATE FRAMEWORK FOR SIMULATIONS

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ABSTRACT: *For good reasons many different coordinate systems and associated earth reference models are in use in C^4ISR systems. The same is true for M&S applications in the DoD community. However, it is not clear that the choice of a coordinate system for near-Earth simulation applications has always been either well informed, or especially rational. In this paper, we review the generic spectrum of available coordinate systems and earth-reference models from the perspective of the simulation model developer, whose intuitive knowledge of the world sometimes assumes a "flat Earth" with the gravity vector pointed downwards. Given that perspective (and its interesting range of appropriateness), for many simulation applications (and models) a rigorous geodetic coordinate space—with its accompanying requirement for relatively expensive coordinate-space calculations on the surface—looks unnecessarily complex and computationally expensive. We examine the primary assumptions that environment and military modelers make about their coordinate-space, under what conditions those assumptions lead to errors, and how those errors can best be ameliorated. We highlight the impact of coordinate system selection on both kinetic and kinematic dynamics formulations.*

1. Introduction

Legacy models used for simulating combat operations are often simplified in their representation of the battlefield environment (i.e., the natural geophysical factors that influence battlefield operations). These encompass the shape of the earth, the earth density distribution, the oceans and other bodies of water, the terrain, the atmosphere, the radiation environment caused by the sun, and a host of other physical phenomena. In the simulation domain, this collection of geophysical data is often called the environmental database. In legacy simulations, numerous simplifications have been made in depicting the battlefield environment to reduce both military and environmental model complexity, particularly computational complexity. Conse-quently, these simulations only apply to very limited domains and do not include the majority of environmental elements.

New DoD Modeling and Simulation (M&S) requirements have made such simplifications less acceptable, if not untenable. Now and in the future, we must be able to simulate joint combat operations that involve increasingly precise weapon delivery over extended ranges. Even land combat applications involving armor-anti-armor configurations must now contend with an extended battle space in which organic anti-armor weapons will operate at ever increasing ranges. As a result, many of the assumptions made to restrict the application domains in legacy models are no longer appropriate. In addition, some of the simplifications make it virtually impossible to federate across dissimilar domains and still maintain a "level playing field." In the context of environmental interactions, this means that one simulation element does not gain an unrealistic advantage over an opposing simulation element due to having a different perception of the environment.

Meaningful interoperability of combat-related simulations over a joint confederation is a challenging problem with a number of different aspects to it. Hierarchies of models have been proposed and employed for both analysis and training support applications for a number of years, sometimes with limited success. These usually involve what is popularly called "swivel chair interfaces." That is, during the execution of the simulation, humans interpret the output of one class of simulations to develop inputs to another level (higher or lower class of simulations) in the hierarchy. Such configurations tend to be very expensive in terms of personnel requirements and risky in terms of consistent interpretations. Recent developments in automation have addressed some aspects of these problems by use of either the Aggregate Layer Simulation Protocol (ALSP) [1] or Distributed Interactive Simulation (DIS) Protocol.

Simultaneous networking between simulations at differing levels of representation has been demonstrated using ALSP and DIS. However, many open questions remain concerning the validity and efficacy of this approach for general applications. Such endeavors have been only partially successful, in part because the legacy simulations involved were not designed to interface with each other, either at the same or different levels of aggregation. Some demonstrations have been likened to a person who speaks only English having a telephone conversation with a person who speaks only German—they may have demonstrated the ability to network and interchange data, but it is questionable whether they had meaningful interoperability.

Fortunately the interoperability situation is improving. Introduction of the High Level Architecture (HLA) with its concept of a Federation Object Model (FOM) forces those who are attempting to interoperate to define common interfaces and semantics [2]. The parallel development of the Runtime Infrastructure (RTI) encourages standard use of networking services. If the federation is operating at the same aggregation level with the same or very similar representations of the real world, then the problem is simplified and reasonably consistent interoperablility is achievable. Consistency in this context does not necessarily imply validity, particularly if the portrayal of critical models like the environment is oversimplified or missing. In essence, the HLA concept addresses critical federation issues in a top-down fashion. However, if the component simulations in the federation are at differing levels of representational accuracy, other critical and very difficult modeling considerations are left to the federation developers to address. In this paper, we address one of those issues: the influence of spatial reference models on adequate portrayal of both the geophysical environment and military systems.

2. Spatial Reference

Several diverse papers on the subject of spatial referencing and environmental modeling issues have been presented at the Simulation Interoperability Standards Organization (SISO) Simulation Interoperability Workshops (SIWs) and at the predecessor DIS workshops. Even as early as the second DIS workshop, these papers were the subject of much discussion. Some of the seminal observations made at the second DIS workshop are in references [3,4,5,6,7]. As the field of distributed interactive simulation has matured—and with the increasing requirement for joint, allied, and coalition applications—a more standardized approach has evolved.

Of particular importance to the portrayal of the geophysical environment of the earth is a standardized Spatial Reference Model (SRM) and associated coordinate reference frameworks [8,9]. The SRM includes earth reference models (ERMs) that represent the geometrical shape of the earth and the gravitational potential associated with the earth. These ERMs are coupled with appropriate coordinate systems to enable proper determination of the location, both statically and temporally, of environmental elements and battlefield elements.

One of the larger impediments to a common understanding of spatial reference is semantics. The SRM defines standard terms so that there is a common understanding of the elements of the SRM. Some examples where misunderstandings have occurred include confusing the earth with a particular ERM. These are clearly not the same. Another example that leads to representational problems is confusing geodetic height with mean sea level height or with orthometric height. These are all different measures of the vertical. The uninformed use of terminology can only be mitigated through standards and education.

A common view of location, both static and temporal, is essential for simulating a battlefield. In stand-alone simulations, the environment must be portrayed in a manner that properly simulates the interactions of modern weapons and combat systems with the environmental elements. A standard portrayal of the environment is needed to provide valid comparisons, both between different simulations and with expected real-world behavior. This conclusion is equally applicable to simulation nodes in federations. In addition, in distributed applications a standardized portrayal of the environment is essential to providing a valid, level playing field.

Initial efforts in networking distributed simulations have uncovered a number of impediments to interoperability that are related solely to spatial referencing. The distortions resulting from the use of non-real-world ERMs, such as flat earth or spherical earth models, can make preparation of environmental databases a very labor-intensive and expensive operation. For example, a major cost of operating distributed simulations for land-based operations is due to the preparation of the terrain databases. Authoritative terrain source data are collected and archived in a real-world coordinate framework with respect to a standard ERM (e.g., theWGS84 ellipsoid and geoid).

Since legacy models for land combat simulations are essentially all portrayed in a non-real-world spatial framework, intensive manipulation of the databases is required to turn the data into application-specific databases. This has resulted in approved terrain databases that are portrayed in non-real-world frameworks. When these databases, in turn, are needed for applications based on real-world frameworks, additional expensive manipulation is required. As the modeling community makes increasing use of other environmental databases, the difficulty of the problem is greatly increased and the cost will become increasingly prohibitive, unless standardized automated process are developed [10]. As a result of this, the Synthetic Environment Data Representation & Interchange Specification (SEDRIS) project was conceived to address many of the issues involved in environmental database generation [11].

3. SEDRIS

A common representation of the physical environment is a critical element in modeling and simulation (M&S) and is a necessary precondition for the interoperability of heterogeneous simulations. The level of interoperability achieved depends heavily upon the degree of consistency, completeness, and unambiguous definition of environmental data. Prior to SEDRIS, no uniform and effective standard mechanism existed for describing, reusing, and interchanging environmental data among M&S applications. In addition, data sharing rarely occurs between the operational and simulation communities, even though each community uses representations of the same physical aspects of the real world.

Without an effective interchange mechanism, most simulated environment database interchange continues to be accomplished by point-to-point unique conversions between two applications. Conversion of one system's data to another format is based upon rigidly defined database format specifications for both the source and target system. Because of the differing proprietary database formats, each conversion requires development of a customized data converter software application. These point-to-point solutions are expensive, time-consuming, and often unreliable. To meet the specific implementation needs of the target system, the converted database usually undergoes several additional conversions before a useable run-time format is obtained. Each conversion adds to the risk of data loss or corruption. In addition, the number of unique conversions increases geometrically with the number of sources involved. Development and maintenance of these software conversion modules is cost-prohibitive. Based on these factors, a new solution to support the efficient interchange of simulated environment databases was required. The SEDRIS project was initiated to address these issues.

The SEDRIS project was conceived and implemented to capture and provide a complete (terrain, ocean, atmosphere, and space) data model of the physical environment, access methods to that data model, and an associated interchange format. These mechanisms developed for SEDRIS facilitate interoperability among heterogeneous simulations by providing complete and unambiguous interchange of environmental data. The range of M&S applications addressed in the SEDRIS development includes training, analysis, and system acquisition, and supports (for example) visual, computer-generated forces, and sensor perspectives. SEDRIS also provides a standard interface for geographic information systems, which are key components in generating complex integrated databases for simulation applications. The data interchange specification supports the pre-runtime distribution of source data, three-dimensional models, and integrated databases that describe the physical environment for both simulation and operational use.

One of the technologies developed under the SEDRIS project is the Spatial Reference Model (SRM) mentioned in Section 2, which includes not only the best treatment on the most commonly used spatial reference systems, but also contains a coordinate conversion library that is both accurate and fast. The SRM deals with spatial reference systems for real-world coordinate frameworks map projections and non-real-world coordinate frames formed by augmenting map projections with a vertical axis.

4. Earth Reference Models

The SEDRIS Spatial Reference Model includes definitions of 21 standard ellipsoidal ERMs, vertical datums including the WGS84 geoid, and numerous local datum shifts. In the most recent delivery of the SEDRIS coordinate transformation software, new capabilities were provided for a set of standard spherical ERMs and include map projections for spheres.

The coordinate frameworks and associated transformations used for SEDRIS support are included in References 4 and 8. The most recent SEDRIS delivery also added a capability to support the Transverse Mercator map projection with an arbitrary origin. This was done to accommodate the United Kingdom Close Combat Tactical Trainer (CCTT) program, which uses the British National Grid system. This is an Augmented Transverse Mercator system with its origin located near the center of the British Isles, but directly south of the land areas.

5. Fundamental Simulation Functions

Combat simulations are designed to represent the real world of combat operations. There are many components to a theory of combat [12]. However, certain fundamental functions occur in the real situation that must be emulated in the design and development of almost all simulations of combat. Principal functions, including unit movement, geometric intervisibility, weapon flyout, and communications modeling. The physical environment can potentially degrade all these fundamental functions. As a result, it is important to ensure that the environment and battlefield elements are properly represented, both spatially and temporally.

To portray movement, a notion of dynamics must be considered. Both kinetic and kinematic motion models are used. Kinetic models are based on modeling the forces acting on a moving object, while kinematic models portray motion without the direct consideration of forces. As more of the environment is modeled and greater fidelity in military models is required, it is expected that the use of kinetics models will increase.

The target acquisition process starts with a purely deterministic geometric assessment of intervisibility. The principal impediment to geometric intervisibility is blockage by the terrain and opaque features on the terrain surface. Once it is determined that geometric intervisibility is possible, a potential target is tested to see if it is even in the field of view of the observer/sensor combination. This is followed by the assessment of degradation due to the rest of the environment, which usually involves probabilistic considerations. The final determination of target detection and identification may also involve a layered human factors model.

The ability to communicate can also depend on achieving geometric intervisibility. Disturbances caused by solar radiation can have significant effects on communication and, in turn, on command and control functions. Such space weather is usually modeled in an inertial (non-earth-fixed) or quasi-inertial spatial frame, as are any space-based assets. Correctly “tying” these to earth-fixed spatial frames is non-trivial.

Weapon flyout may involve considerations of air density, wind forces, the acceleration of gravity, Coriolis and centrifugal effects, and most certainly geometric properties of the ERM.

It is clear that all of these fundamental functions depend on location, both static and dynamic, of the elements of the environment. To promote realistic behaviors and to have any chance of portraying a level playing field, it is imperative that all of these effects be referenced to a real-world spatial framework.

In addition, DoD M&S directives include a requirement to perform verification, validation. and accreditation (VV&A) of simulations. This implies that a reasonably detailed ground-truth model will be required to support the VV&A process. This ground-truth model must be complete and detailed enough to perform assessments that would be useful to support validation and verification of simulations. This requirement is an analogue to field-testing of weapons systems. but may be much harder to accomplish.

As an example, in the real world, when an air defense system acquires tracks and shoots at a target drone. it uses an embedded fire control system. The fire control mechanization may make many simplifying assumptions about the local physical environment when it performs its calculations and use a simplified dynamics models. When this process is simulated, the same mechanization would be used in the simulation for computing pointing angles and time to fire. However, it is relatively easy to determine when a hit occurs in the real situation.

The challenge comes in determining that a hit occurred on a target moving in the simulated environment. It would not be correct to make the same simplifying assumptions in the validation model. The weapon flyout and the target must be modeled in a fairly detailed manner—after all, the real weapon system operates against a target in a real environment. One cannot get by in this case with flat earth models and gravity fields that are not correctly modeled. Fortunately, this kind of validation does not have to be done in real time. Thus, a complete, fully functional environment and detailed dynamics models can be used.

6. Non-real-world Spatial Reference Frameworks

Simplifications made in legacy models have led to the ubiquitous use of non-real-world spatial reference frames. ERMs in many legacy simulations are also often overly simplified. For land combat simulations, this has unfortunately led to the associated use of non-real-world coordinate systems based on map projections.

A map projection, such as Universal Transverse Mercator (UTM), can be viewed as generating a two-dimensional coordinate system by mathematically mapping points on the three-dimensional surface of an ERM onto a two-dimensional plane. Map projections are very useful, if not essential, for the visual portrayal of the surface of the earth, but they are not adequate as a basis for deriving simulation models for future applications.

Generally the projection is made from the surface (zero altitude) of an ellipsoidal ERM representing the shape of the earth onto a two-dimensional plane. By augmenting the resulting projected system with a vertical axis, a three-dimensional rectangular system can be defined. There is a lack of consistency in defining the vertical axis, which could represent pressure altitude, geodetic altitude, orthometric altitude, or even other vertical measures. Part of this inconsistency is due to the semantics problem previously mentioned. (For the definitions of the different measures of the vertical, see Reference 9.) When a UTM projection is used, the resulting coordinate system is sometimes loosely and incorrectly called the UTM coordinate system, which is by definition only two-dimensional. The augmented projection is an artificial system that distorts the majority of the geometric properties of the real world; that is why we categorize it as a non-real-world coordinate system. In the SEDRIS SRM, care is taken to denote such systems as augmented, projection-based systems [9]. As a result, for example, two-dimensional UTM coordinates augmented with a vertical axis are referred to as AUTM (Augmented UTM) coordinates.

In such augmented systems, distances are not preserved. If the projection is conformal, angles are only preserved for points in the plane of the projection (elevation angles are not preserved) and essentially all geometric relations including vector operations are distorted. The concept of distance can have several meanings. Euclidean distance is well defined in a rectangular system, but it is not the same as distance traveled when an object is restricted to an ERM surface. Neither of these is coincident with distance traveled when the terrain is added on top of the ERM surface. To further complicate this issue, motion may be constrained. For example, when vehicles move on roads, often there are impediments to movement (e.g., soft ground, water, a canyon), all of which change the meaning of distance. Euclidean distance in a real-world system is not preserved in an augmented, projection-based system. This is another example where semantics and lack of standards can and has caused much confusion.

The distortions introduced by augmented map projections also affect the modeling of fundamental combat simulation functions such as movement, intervisibility, weapon flyout prediction and communications modeling. Dynamic models (involving forces, velocity and acceleration) in an augmented projection-based system are also distorted and are only approximately correct over small distances or short time spans.

The effects of such simplifying assumptions are almost always assumed to be small, usually with no supporting analysis to justify the assumptions. The resulting anomalous effects are often difficult to quantify unless the model is also simulated in a higher-resolution, real-world framework and simulated battle outcomes are compared. Even small anomalies can propagate and cause significant cumulative effects. However, the effects of non-real-world reference frames are often immediately apparent when simulations based on them are linked to a simulation that uses a real-world framework. For simulations that have a graphical interface, including virtual simulations, all credibility of the simulation may be lost when anomalous effects are displayed.

Several applications exist in which the elevation distortion is likely to have a substantive impact. The requirement to simulate joint combat, long-range precision weapons, long-range observation systems, and communications assets all combine to enlarge the battle space and increase the range at which intervisibility calculations are needed. Even in modeling direct-fire systems, an error of half a meter in elevation may cause a tank round to miss the aim-point (turret ring). Because of this, embedded tank fire control systems routinely compensate for this effect.

Figure 1 illustrates one distortion effect caused by using AUTM.

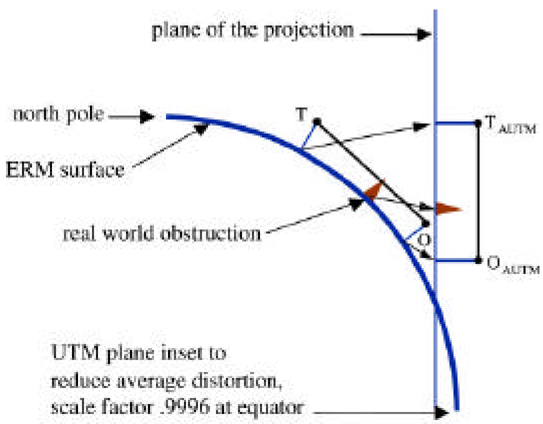

FIGURE 1 USE OF AUTM INCREASES INTERVISIBILITY

A real-world observer located at O does not have geometric intervisibility to a target located at T due to blockage by an intervening feature (side view shown). Both the target and observer are at the same geodetic height (perpendicular to the ellipsoidal ERM). Map projections only transform points on the surface of the ellipsoid onto a plane (in this case, the UTM plane). Points above the surface, like O and T, are not transformed. As is shown in Figure 1, the points on the surface that correspond to O and T are mapped onto the plane of the map projection (shown stylistically in Figure 1). To form a three-dimensional coordinate system, the geodetic height is associated with the appropriate UTM points to define the observer and target locations in the (now augmented) AUTM framework. These points are labeled O_{UTM} and T_{UTM}. Of course, when the obstruction is represented in AUTM. its height is unaltered. A straight-line ray propagation model is usually used for intervisibility calculations in AUTM. As shown in Figure 1, after the transformation, the observer now has intervisibility to the target. In general, intervisibility is almost always increased after the transformation to AUTM. It should be noted that there are also other distortions inherent in this process. For example, the distance from O to T is generally not the same as the distance from O_{UTM} to T_{UTM}.

It is often claimed that the effect of the vertical distortion is small for the simulation of ground combat because it is essentially (but not precisely) the effect of ignoring the curvature of the ellipsoid and these are assumed to be small at direct-fire ranges. To substantiate such a view, one would need to simulate combat in a real-world system and then simulate it in AUTM for comparison of battle outcomes (with, of course, all the sub-models being the same except for terrain effects). As far as we know, this has not been done.

Also, in the case of simulating direct-fire armor-anti-armor engagements, it is questionable whether the elevation distortion can be ignored. Many potential battlefields are nominally planar with numerous small occlusion factors (undulations, wadis, rocks, vegetation, and structures). There are apt to be many observer-target pairs for which intervisibility is only blocked by small deviations in intervening elevations (including just centimeter differences). Suppose that there are a large number of such cases in a real-world battlefield. After transformation to AUTM, a large number of these pairs would become intervisible. If the entire simulation is implemented in AUTM, the increased visibility may cause battles to prosecute too fast, principally due to increased attrition rates. This phenomenon may be at its worst in urban environments where very small intervisibility changes may have a major effect.

For distributed simulation, the elevation distortion could be critical. If some nodes are in real-world systems and some are in AUTM, a decided advantage is given to combat elements in the AUTM-based simulation. Elements in the AUTM system can detect and shoot at elements in the real-world system, which cannot even see the firer in the common (dead reckoning) environment.

We have been emphasizing just the effects of elevation distortions. Several other position and motion distortions will occur when using augmented, projection-based systems. Some of these distortions may be significant factors in adjudicating simulated battle outcomes. The use of augmented, projection-based systems should be avoided when developing fundamental models of combat operations, particularly when those models may be joined into federations.

7. Computational Complexity

Computational resources, principally computational speed, limit the number of combatants and the level of detail that can be simulated. To meet the performance requirements of real-time simulations involving live participants (e.g., virtual simulation), it is critical that simulation nodes have sufficient computational resources to maintain or exceed real-time modeling performance. If they slow down, even temporarily, fair-fight conditions are violated, causality may be lost, counter-productive training may ensue, and the results of the exercise may become invalid.

For stand-alone stochastic simulations used for analysis, computational performance not only limits the level of detail but also the number of replications that can be supported. In essence, almost all combat simulations are limited by computational performance. As a consequence, the design of most combat simulations is driven by performance considerations. This continues to happen in spite of the astonishing growth in computational capabilities over the last decade. It is our perception that simulation designers continue to sacrifice dynamic and geometry relationships in favor of performance. At the same time, users and DoD M&S directives demand greater scope and more functionality. Perhaps it is time to revisit the basic assumptions of model design, including the choice of spatial reference framework.

Computational complexity is a principal factor in choosing a spatial framework for simulating motion dynamics and geometric relations. Computational complexity simply means that some formulations will be slower to compute than others. The more complex the formulation, the slower it executes. Computational complexity in dynamics models is almost totally dependent on the number of trigonometric functions involved in the formulation.

In many real-world coordinate systems, the principal component of the acceleration of gravity does not line up with a coordinate axis. This means that computation of force component requires trigonometric evaluations. In addition, transformations between rectangular coordinates and curvilinear coordinates, like spherical or geodetic, lead to the introduction of trigonometric terms in the transformed acceleration and velocity components, principally sines and cosines. Evaluation of even the simpler trigonometric functions usually takes more than an order of magnitude greater in run time than a single floating point operation [13]. In dynamics formulations, the time required to evaluate trigonometric functions may exceed all the time needed to do the rest of the computations involved in the dynamics model. For this reason, model designers prefer to use rectangular coordinates in which the gravity vector is nearly aligned with the vertical axis (and is usually simply defined as exactly aligned with the vertical axis). This is one of the reasons that legacy modelers have used systems such as AUTM as a coordinate system. This strategy sidesteps the need to evaluate trigonometric functions, but at the same time compromises the representational fidelity of the model.

It is important to note that augmented, projection-based spaces themselves introduce distortions prior to any additional assumptions about how forces are modeled. In other rectangular formulations, such as local tangent plane systems, the coordinate system is not distorted. In such a system, gravity is almost aligned with the vertical axis and designers may make approximations to reduce the computational complexity if they choose to do so. Approximations that result from this process are not due to the coordinate system, as they are in augmented, projection-based systems, but to the simplifying modeling assumptions made by the developer. For example, the global coordinate system (GCS) is a collection of local tangent plane systems wherein each system is not distorted, but additional approxima-tions may be made to increase performance.

For geometric intervisibility determination, it is preferable to use a rectangular system (real world, of course). The undisturbed optical path is then a straight line, which can be represented by parametric equations of a line, which are linear functions of the independent variables and therefore simple to compute.

Of course, determination of line of sight and finally acquisition will require information about the environment, which is probably best represented in geodetic coordinates. It is possible that future simulations will use several real-world coordinate frames simultaneously, as will the Joint Simulation System (JSIMS) at Initial Operational Capability (IOC).

Another important complexity issue involves the coordinate system used to communicate position information between nodes in a distributed simulation application. The DIS protocol standard used geocentric coordinates for this purpose. Since most of the simulations involved did not use geocentric coordinates, there was a continuous need to convert coordinates both when sending and receiving. It has been estimated that 20% of the processing time per simulation node in the Close Combat Tactical Trainer (CCTT) program was devoted to just the coordinate transformation processing associated with protocol services. While new algorithms are reducing this load, it is still an important consideration in distributed simulation design [13,14,15,16].

8. Environmental Data Modeling

Another common practice associated with dynamics models has an impact on the SEDRIS program and ultimately on the environmental data representations used in M&S. Those who develop meteorological and oceanographic data use dynamics models to populate authoritative databases both in time and space. In particular, the models are non-linear partial differential equations in both space and time. These equations have to be solved numerically by discrete methods, usually on a uniform grid. A relatively small set of real-world measurement data is used to define initial and boundary conditions for the differential equations. The goal of this process is to produce (at regular time intervals) three-dimensional gridded data representing the environment. Needless to say, this is a very computationally intensive process. Many of the fundamental dynamics formulations for this application domain were developed even before the digital computer revolution. As a consequence, simplifications were made to reduce computational complexity.

It is common in the meteorological field to use augmented map projections as a basis for proceeding. In doing so, some terms in the differential equation can be deemed small and set to zero. In addition, the equations can be formulated in the resulting rectangular coordinate system, which makes it easier to use uniform grids to support numerical integration. Of course, the resulting coordinate system is distorted in the same fashion as discussed in Section 6. Further simplifications (reduction in computational complexity) are attained by using spherical ERMs in formulating the map projections instead of ellipsoids [18,19]. This adds an additional layer of distortion to the coordinate system and resulting dynamics model.

Advanced research facilities now commonly solve diffusion problems employing unstructured adaptive meshes using supercomputers. Eventually these techniques will be used for environmental predictions. In the interim, we have legacy models and large databases generated from these. This leaves SEDRIS with the problem of translating such gridded data sets into real-world coordinates for use in simulation. Of course, it is not mathematically possible to exactly repair the accumulated affects of the sequence of distortions. However, the SEDRIS coordinate transformation library performs the necessary coordinate transformations to obtain locations in the real world. Simulation users want this data to be represented on a regular grid in the real-world system. This can, of course, be accomplished by interpolation.

9. Summary

We have observed that:

- Better representations of the geophysical battlefield are needed to support the user, the requirement for joint simulation, and DoD M&S directives.
- The environment, geometric, and dynamic models are strongly coupled to the spatial reference model that is employed.
- Many archived environmental databases were developed in augmented, map projection-based systems with respect to spherical earth models.
- The use of augmented, map projection-based coordinate frameworks distorts reality and may lead to an unlevel playing field.
- Computational performance drives the selection of spatial reference models and coordinate systems at the expense of validity.
- Standards and automation are needed to decrease the cost of populating simulations with environmental data.
- More complete and detailed models using real-world coordinate frameworks may be required to support VV&A.

We recommend that only real-world coordinate systems and standardized earth reference models be used for future simulation developments. When computational complexity needs to be reduced to meet performance goals, approximations in dynamic and geometric computations should be made in the context of non-distorted, real-world coordinate systems. Finally, a more-detailed model should be developed and maintained for calibrating approximations and to support VV&A.

Acknowledgments

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