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Authors:

Dr. Michael R. Hieb
Center of Excellence in C4I
George Mason University
4400 University Drive
Fairfax, VA 22030
USA
001-703-993-3990
mhieb@gmu.edu

Michael W. Powers
US Army Engineer Research and Development Center
Topographic Engineering Center
7701 Telegraph Road
Alexandria, VA 22315
USA
001-703-428-7804
Michael.W.Powers@erdc.usace.army.mil

Sean Mackay
Atmospheric and Environmental Research, Inc.
131 Hartwell Avenue
Lexington, MA 02421
USA
001-781-761-2315
smackay@aer.com

Martin Kleiner.
Center of Excellence in C4I
George Mason University
4400 University Drive
Fairfax, VA 22030
USA
001-609-723-2150
mkleiner@gmu.edu

J. Mark Pullen, D.Sc.
Center of Excellence in C4I
George Mason University
4400 University Drive
Fairfax, VA 22030
USA
001-703-993-1538
mpullen@gmu.edu

Abstract

As Command and Control practices are transformed by Network Centric Operations, the effect of the environment needs to be incorporated. The constraints of terrain and weather are two key limitations that apply to all operations. Sensor models will quantify these effects. Technologies developed by the commercial world to deal with these constraints, such as Geospatial Information Systems (GISs), have direct relevance to coalition forces. Conversely, advanced environmental reasoning services developed for coalition forces can also, in selective areas such as mobility analysis, have applicability to civil, humanitarian operations. Thus, technologies developed in these selective areas have the ability to leverage commercial technologies while transforming C2 processes.

In this paper we present a conceptual framework for relating environmental effects, including Sensors, to Network Centric Command and Control, and investigate the utility of applying this framework through an advanced technology program. Battlefield Management Language (BML) is being developed as a common representation of military mission suitable for automated processing. Geospatial BML (geoBML) is used to relate terrain features to operations resulting in a methodology that identifies the key environmental aspects needed for specific missions. geoBML enhances a Command and Control process, whether military or civilian, by making terrain information explicit and computational.

1 Introduction

Current and future Network Centric concepts for Command and Control (C2) are predicated upon the effective, agile use of battlefield information. Information dominance in turn, is achieved through the employment of all relevant information to the planning and execution of missions and tasks. Technological and analytic advances now permit the effects of the physical environment, both terrain and weather to be used as actionable information for inclusion among more traditional battlefield information contributing to superior Situational Awareness (SA).

Central to the incorporation of actionable geo-environmental information supporting C2 services and processes is the requirement to achieve a high degree of interoperability and value to the C2 process. Optimized interoperability should possess two necessary characteristics. First, there must be a well-specified syntax for the information as a fundamental basis for establishing interoperability. Second and more importantly, information should have a semantic precision to ensure that the employment of shared information is consistent within C2 processes and across C2 services. As Alberts and Hayes [2003, chapter 7] described, the most direct way to ensure a desired degree of interoperability is to exchange information by communicating in a common language. The potential value of network-supplied information increases when the information is immediately available for application or use within the C2 process [Alberts, et al., 1999, Appendix A]. This last point argues that a structuring and mapping of actionable information to missions, tasks and C2 processes should increase its utility and value.

The incorporation of actionable geo-environmental information into networked C2 processes and systems requires: 1) a conceptual framework that encompasses this information from mission receipt and planning through execution, situation development and analysis; 2) a language capable of defining the exchange and use of this information; and 3) a commonly shared data model relating geo-environmental information products to missions, tasks and C2 processes. These requirements are addressed through the evolution of a tiered framework for geo-environmental information, the development of a geospatial Battle Management Language (geoBML) to enhance interoperability [Hieb et al., 2006], and the use of this language to effectively relate actionable geo-information to mission information using C2 semantics as specified in the Joint Consultation, Command and Control Information Exchange Data Model (JC3IEDM).

1.1 Why the Environment Matters

Military history is replete with battles lost by a force failing to accurately consider the impacts of terrain and weather. Those liabilities have not diminished with force modernization. The environment's effects can be either an enabler or a constraint when applied to tactics, units, platforms, systems and the soldier. Understanding these effects can provide for enhanced planning and execution at all levels.

Moreover, an integrated application of environment effects can yield exponential efficiencies in situation development and assessment as well as force management. Military actions (tactics and behaviours) are not random. Terrain and weather either constrain or enable tactics as well as platform and system effectiveness. In combination, these two forcing functions make powerful contributions to the science and art of C2, if one considers the environmental effects comprehensively. Considering environmental effects allows the construction of a relational organization of the battlespace with respect to tactics and operational effectiveness of units and systems. Understanding these relationships clearly allows for better force employment. Assuming that the opposing force also seeks optimal terrain and understands the effects of the weather, these relationships form a basis for improving information dominance by applying surveillance and reconnaissance assets effectively (spatially and temporally) to maximize the quality of information acquisition. These relationships also provide a context for relating battlefield information, de-cluttering the battlescape's complexity and aiding in the development of the enemy's situation, as well as assessing the enemy's effectiveness as a function of environmental influences. These advantages apply to both humans and automated systems when precision in meaning and representation is unified with a common language.

1.2 Relating Environmental Effects to Command and Control Processes

Currently there are well-defined processes for the C2 of military operations, such as Observe, Orient, Decide and Act (OODA) or the Military Decision Making Process (MDMP). There also is doctrine on how the environment affects both coalition and enemy operations. The end result is the identification of how the battlespace environment influences courses of action of the threat and friendly forces. Whether one considers the cyclical nature of OODA or the cascading nature of MDMP, there is an underlying concept of a course to fine need for, and use of, information. This course to fine concept is also valid when applied to geo-environmental information.

The US Army uses OAKOC - Observation and fields of fire, Avenue of approach, Key terrain, Obstacles, Concealment and cover to address initial geo-environmental information needs associated with Course of Action (COA) development and assessment as well as Intelligence Preparation of the Battlespace (IPB). Additionally, today's class of analytic tools allow for the incorporation of weather interaction with terrain to create OAKOC products of greater accuracy and prognostic quality.

Moving forward, C2 information needs extended to incorporate geo-environmental information within the framework of the mission: adding additional environmental context to the organization of the battlespace; supporting wargaming; refining task organization; and identifying Command Critical Information Requirements (CCIRs). Organizing the battlespace and identifying terrain suitable for tasks and units can define sets of geo-environmental information with relationships between a unit type and the task it is to perform. C2 processes can then bring geo-environmental information into alignment with the Who, What and Where components of an evolving Operations Order. The When component of the original mission statement provides an index in time to which weather effects can be added.

Continuing C2 processes address incoming SA information that further refines the set of possible COAs and specific force positioning. Refinements can continually be assessed against terrain suitability, and the impacts of weather on maneuver, information operations, and unit/system effectiveness. These last steps create the final Operations Order and describe the activities during the execution phase of the mission.

A fundamental tenet of Network Centric C2 concepts is founded in the promise of information superiority. This end-state has its beginnings with the CCIR developed within the context of the mission. The success of the information-gathering chain is dependent on an initial observation of sufficient certainty to add to the development and assessment of the situation. It would, therefore, seem that effective observation is the first and most critical step leading to information superiority. Environmental effects have a powerful role in optimizing the value of an observation. The first step is to look in the appropriate location. Terrain analysis, coupled to perceived threat tasks, actions and COAs can provide information on where to look and what might be expected to be observed. Applying terrain and weather effects within mobility and maneuver analysis can be used for accurate space-time predictions further refining a location and time for observation. This space and time refinement allows for detailed environmental effects assessment on sensor spectrum effects on expected targets and the natural background. This analysis provides information of the ability of a given sensor to detect the required information. Therefore, terrain and weather effects can provide essential Collection Management (CM) information regarding, where, when and how to observe for the best probability of gathering initial battlefield information.

The capability to create and incorporate actionable geo-environmental information within C2 services is evolving technically. Future C2 services must not only be interoperable from a geo-information perspective but must also incorporate that information within automated decision aids for course of action development and analysis tools, mission rehearsal simulations and the management and synchronization of force assets. Current C2 systems use a variety of digital map data for display, but this map information is not well integrated with either C2 services or processes.

To achieve consistent geo-environmental analysis between systems, the critical effects of terrain and weather must be organized, articulated and represented in such a way that they can be exchanged and contribute to a common, shared awareness and coordination of operations. There are many interoperability issues associated with the lack of clear semantics for military missions. One approach to improving interoperability is to have all systems use the same representation for their data and information. However, this has not worked in practice. Rather, interface services and layers have been devised to share data and information that needs to be exchanged. Consistent geo-environmental information use between systems must be based upon a representational framework supporting the course-to-fine aspects of C2 decision-making. Additionally, geo-environmental information must be supported by a precision of semantics and use, originating from a common language founded in orders, units, tasks and systems.

1.3 Need for a Framework to integrate Network Centric Operations, Environmental Effects and Sensor Models

The currently well-defined planning processes for military operations, such as OODA and the MDMP provide structure from which an organizing framework for geo-information classes and their application within C2 processes. A framework for Environmental Effects must represent the earlier facts and assumptions. First, the C2 decision process is fundamentally coarse-to-fine as it progresses from receipt of command intent, through activities to develop and refine the situation, to development of an operations order, and finally execution of the mission. Second, it must be noted that the as these decision processes advance, the decision environment becomes increasingly time-dominated. Consequently, the framework should parallel this need with efficiency in geo-information creation and use, and adopt a more precise coupling with respect to the tactical situation. It has been proposed that terrain and weather effects are ubiquitous, constraining or enabling mission and unit tactics as well as platform, system and soldier effectiveness.

In [Hieb et al., 2006], an initial geo-environmental information framework was presented. That framework address terrain effects information as it relates to OAKOC, the development of plans and COAs as they related to unit level tactics. The framework also addressed the course-to-fine mature of the OODA and MDMP process. This framework defined a series of tiers in response to these requirements (Figure 1).

Tier 1 information products reflect characteristics of 1st principle geo-environmental effects or qualities or military value (e.g. Observation and fields of fire, Avenue of approach, Key terrain, Obstacles, Concealment and cover (OAKOC). These products are not coupled tightly to the mission, tactics or situation. A quality of this class is its high level of generalization; the products are highly reusable across different domains (such as intelligence or logistics) and different C2 Services developed for these domains. Re-use is a critical quality. Through high rates of reuse, this information becomes a consistent foundation upon which parallel C2 functions and decision can be made. It is proposed that parallel use of information: (1) accelerates the traditionally cascading plan development associated with the MDMP, (2) increases the coherence within the distributed C2 structure of Network Centric operations and (3) supports a premise of Metcalf's Law stating that N-way interactions will be the most significant in value creation [Alberts et al., 1999].

Tier 2 information products are extended and refined in content through the integration and tailoring of actionable geo-information to specific unit/force type/force aggregation or multiple force types in the performance of well-defined military tasks or actions consistent with a mission or objective. However, the integration with tactics begins to limit re-use, as these products are mission and task specific. For a set of users with common or dependent tasks, this tier of products will allow greater precision and consistency in the planning process, especially with collaborative planning. Tier 2 products support planning activities. In addition, they provide the detail required to bridge from COAs to wargaming.

Tier 3 information products are further refined in content through the integration and tailoring of actionable geo-information to specific unit/force type/force aggregation or multiple force types associated with the current situation. Tier 3 products support planning activities. However, their precision to the current situation supports the challenges of situation development and assessment as well as asset and force management during mission execution.

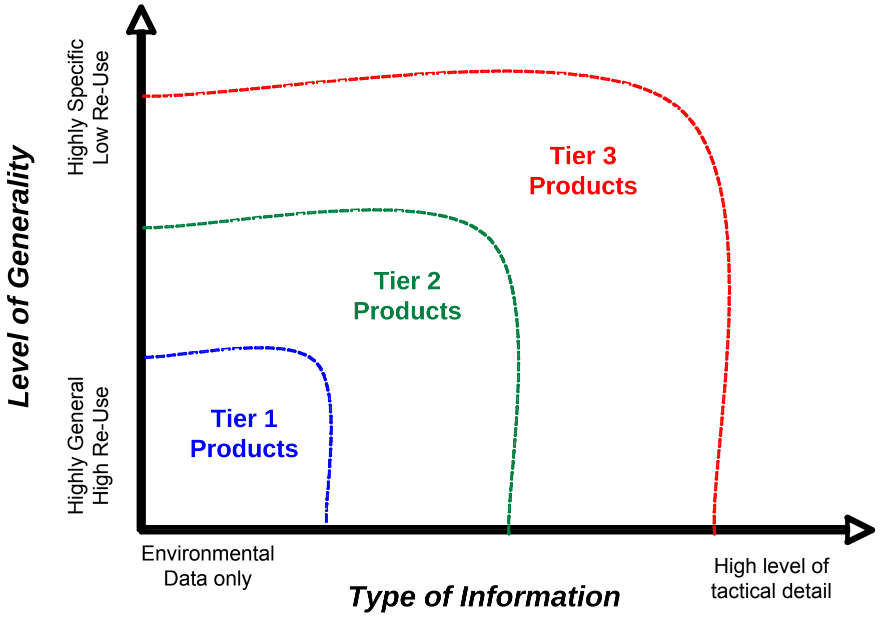

Figure 1: Geo-environmental Information Framework

The incorporation of weather into this framework is at one level straight-forward and consistent. Weather effects can be used to describe generalized impacts in mobility and tactical advantages represented in OAKOC under Tier 1. Weather effects can become more specific to the mission by addressing impacts on unit and platforms and system effectiveness within through more precise analysis of the force and equipment supporting the aspects of the order from a Who, What, When and Where perspective (Tier 2). It is proposed that as precision for information is extended to the situation, that weather effects can be further refined to address C2 processes in information operation and asset management, particularly sensors. Weather does present one significant hurdle with respect to the current framework. The effects of weather are dynamic. This quality, within the context of course-to-fine decision processes and re-use require that the framework be extended to capture issues of persistence verse dynamics in information content and representation.

1.4 Organization of the Paper

Section 1 provides an introduction to actionable geo-information for military operations. The need for a framework that relates terrain & weather effects, sensor models and mission information are introduced. Section 2 presents previous work in this area, known as Geospatial Battle Management Language (geoBML). In Section 3, environmental effects in a Network Centric Environment are described for terrain, weather and sensors. Section 4 presents an integrating framework for the impact of the environment upon Network Centric Operations. Section 5 presents conclusions.

2 Battle Management Language and Geospatial Battle Management Language

BML is an emerging concept that is the formalization of warfighting doctrine into an unambiguous C2 Language. In Network Centric Operations the intent of a commander is still the start of planning and executing a mission. It is more important than before that this intent be well structured and unambiguous. A persistent issue with the original BMLs has been the lack of formal syntax and semantics – in other words, the lack of a grammar. In the following section, we will describe the previous work done with BML and current research in developing a formal grammar for military orders.

In order to introduce BML, we first describe a standard for C2 Semantics that BML uses.

2.1 JC3IEDM

Development of an unambiguous C2 Language requires a vocabulary by which the terms are fixed in their meaning. The Multinational Interoperability Programme has already produced a semantic definition for C2 terms suitable for coalition operations. This is documented in the Joint Command, Control and Consultation Data Exchange Model (JC3IEDM).

The JC3IEDM consists of both a Data Model and an Exchange Mechanism. The Data Model is intended to represent the core data types identified for exchange across multiple functional areas. The approach is generic and not limited to a special level of command, force category, etc. The JC3IEDM describes all objects of interest on the battlefield, e.g., organizations, persons, equipment, facilities, geographic features, weather phenomena, and military control measures such as boundaries using a common and extensible data modeling approach.

The Data Model of the JC3IEDM defines the semantics of coalition C2 terms, for a well-established and standardized vocabulary of a C2 Language. In addition to the Data Model, there is an Exchange Mechanism that uses a replication protocol that allows the exchange of data between two systems that have a JC3IEDM Data Model.

The JC3IEDM provides an excellent framework for evolving the necessary elements of interoperable geo-environmental information and knowledge. Consequently, any geoBML should be organized as the necessary extensions to that framework meeting the conditions laid out in earlier sections of this paper. The wide range of geo-information application in C2 decision making also presents a sufficiently broad use case for advancing and validating the necessary element of: 1) a unifying language, 2) a vocabulary based in doctrine which defines the appropriate contexts for use and 3) a grammar defining the syntactical structure of that information. Finally, a geoBML should comprise the necessary representations to support both human and machine reasoning and provide a semantic consistency that seamlessly compliments automated system output with human cognition and use. A geoBML developed around these principles advances the unity of Coalition C2 and the challenges that arise through net centricity, distributed decision making and the continued proliferation of automated and intelligent systems and tools.

2.2 BML and JBML

Taking the widest possible interpretation, BML has been defined [Carey et al., 2002] as:

> ***The unambiguous language used to command and control forces and equipment conducting military operations and to provide for situational awareness and a shared, common operational picture.***

The objective of the BML work is to define an unambiguous language to describe the commander's intent in a way that soldiers and systems can understand and make use of it. The resulting language should be applicable to operational C2 systems, simulation systems and robotics.

BML has been supported by the US Army and the Defense Modeling and Simulation Office (DMSO). BML was demonstrated as the focus for use of Web-based technologies: service-oriented architecture/Web services incorporating the JC3IEDM data model. Currently, a project is underway to show the effectiveness of Joint BML (JBML) spanning ground/air/maritime/littoral domains.

2.3 International BML Activities

Within SISO, the Coalition BML (C-BML) Study Group was formed in September 2004 to investigate the concept of BML. The Study Group consisted of participants from 11 different countries. After the Study Group published it's final report in September 2005 [Blais et al., 2005], a Product Development Group (PDG) was formed to standardize BML.

In parallel to the C-BML Study Group activities, the NATO Modeling and Simulation Group (NMSG) established a 12 month Exploratory Team (ET-016) on C-BML [Tolk et al., 2004]. The team, led by France, endorsed the requirement for a C-BML and proposed that a 3-year Technical Activity Program should be established. Their recommendation was submitted to a meeting of the NMSG in October 2005 with the result that a NATO Technical Activity (MSG-048) has been approved for 2006-2009.

2.4 A BML Grammar

The format of orders is defined by the NATO standard STANAG 2014 "Format for Orders and Designation of Timings, Locations and Boundaries." An Operational Order is divided into five paragraphs: 1) Situation, 2) Mission, 3) Execution, 4) Administration and Logistics, 5) Command and Signal, and the respective annexes. For conveying the essence of an order to a simulation system, Paragraph 3 is currently the most applicable given the behaviors available. Paragraph 3 will "summarize the overall course of action," "assign specific tasks to each element of the task organization," and "give details of coordination." In the following, we briefly summarize the types of production rules needed to generate and to parse a formal BML grammar. More detail is given in [Schade & Hieb, 2006a, 2006b].

The basic rule for the BML Grammar is:

OB → Verb Tasker Taskee (Affected|Action) Where
Start-When (End-When) Why Label (Mod)*

The abstract rule for spatial coordination is:

C_Sp → Control_Feature Tasker (Taskee) Start-When (End-When) Label

The spatial coordination rules correspond to the basic rules in their form. The key words denote control features, e.g., lines or areas. These are taken from JC3IEDM's table "control-feature-type-category-code." For example, an area of responsibility is assigned by a commander to be used by a subordinate and is considered an area well defined by natural features or control measures for the exclusive operation of the subordinate unit's forces.

The abstract rule for temporal coordination is:

C_T → Temporal-Term Qualifier Action Action

In temporal coordination, the non-terminals Action have to be expanded by different unique identifiers that serve as labels for basic expressions. Temporal-Term is either **start** or **end** signifying whether the start or the end of the first Action is determined by the expression. Qualifier is expanded by a relational expression that determines how the start (or the end) of the first Action is related to the temporal interval the second Action defines. Qualifier2 is taken from JC3IEDM's table "action-temporal-association-category-code."

Examples of BML rules used for formalizing orders are given in [Schade & Hieb, 2006a], Appendix A. In addition to Orders, a grammar for BML Reports is described in [Schade & Hieb 2006b, 2007]

2.5 geoBML

Since BML is built upon shared C2 semantics, there must also be a representation of environmental effects and concepts in the C2 lexicon for geoBML. The lexicon for implementing BML is the JC3IEDM. Typical environmental data is stored in a Geographic Information System (GIS) that has a quite different data structure than the JC3IEDM. Thus the implementation of geoBML will be the extension of existing concepts (such as the Control Measures Entity in the JC3IEDM) and the creation of new concepts to support the planning process with terrain products.

All militaries incorporate a deliberate planning process beginning with an initial order, its iterative refinement at each aggregation or element of the force to be employed, Course of Action development and analysis, validation of the plan and then its implementation in execution. The C2 process continues with dynamic Intelligence Preparation of the Battlespace along with level two and three fusion in an effort to maintain accurate predictive battlespace awareness. Comprehensively, these C2 operations occur simultaneously and at varying levels of fidelity. There are tremendous challenges in defining spatial objects capable of providing this flexibility. First, the objects should possess general through specific information to support the appropriate stage in the planning or execution process. Second, the articulation of an object must possess sufficient parameters and content for use of the product at multiple echelons. Third, both dimensions of the first and second qualities of a spatial object should be internally consistent to facilitate coherence between simultaneous and echeloned activities with regard to the effects provided by terrain and weather. A fourth essential aspect is that the objects be of a size capable of exchange on tactical communication networks. The final challenge is to construct objects which maximize the persistence of their utility. This last challenge has two aspects in turn. The first requires that dynamic weather impacts be represented appropriately at the object level for the task/unit/system dependent on this information. The second seeks to define object methods that respond to other tactical information (e.g. observations, reports).

The successful definition of Tactical Spatial Objects (TSOs) that satisfy these challenges must be addressed in a systemic approach. Fundamental in the evolution of the objects is the use of experience operators who can relate: (1) doctrine and terms (language and vocabulary), (2) the operational context of an object or product's use as it relates to an aggregation of force type, mission or task (content), (3) the sufficiency of a product's use as a function of the underlying quality of geo-environmental facts (general to specific).

The systemic implementation of a robust set of objects becomes a hierarchy with an is-a and part-of dimensionality with explicit inheritance. Building from the level of facts, the first tier of spatial objects (as described in Section 1.3) represent general aspects of the military value of the terrain and weather (e.g. OAKOC). Upon this, other products such as the Combined Obstacle Overlay (COO), mobility corridors and mobility potential (platform specific) can be abstracted and spatially represented. The most specific object definition at Tier 1 analysis defines areas supportive of generalized deployment value (e.g. engagement areas, choke points or defensive positions) with an articulation of general optimal orientation. These objects might contain information regarding the type and aggregation of force that they should be employed. However, they would not possess extensions that are highly mission or situation dependent. Finally, Tier 1 objects would hold parameters or methods characterizing the sensitivity of the object to predicted weather effects. As a general statement, Tier 1 products can be pre-computed and are to a degree, mission independent.

Tier 2 objects reflect objects from employing greater mission and task information. As the Commander's intent becomes more understood and the force package better defined, generalized deployment information can be made more specific defining positions of advantage for specific force type, aggregation and task. Mobility corridors get defined as Avenues of Approach (AA) and may be further compartmented or organized as a function of its battlefield geometry and operational value (e.g. optimal for defense). Lastly, Tier 3 processing provide information objects that have greater situational qualities addressing the current state of battlefield participants, their location and orientation of action.

The complete set of information objects, evolved from accepted doctrine: (1) provide a meaningful structure for relationship to the JC3IEDM, (2) provide a complex set of interrelated use cases for evolving a language addressing both planning and execution and (3) provide a unified representational foundation capable of supporting cognitive and automated processes.

A geoBML builds upon the BML work presented in previously in this Section. A key goal of geoBML is to make available actionable geo-information products from a computational level to the C2 processes in the same conceptual framework (Hieb et al., 2006). The Battlefield Terrain Reasoning and Awareness (BTRA) Program, a U.S. Army Science and Technology Objective (STO) and Defense Technology Objective (DTO), is developing BML for its geospatial products. Currently, geospatial products are created using varying techniques and procedures resulting in fundamentally different representations and processes than are used in the C2 planning process for forces and equipment. These inconsistencies result in a non-uniform context regarding geospatial impacts on C2 processes.

3 Environmental Effects

Incorporating environmental effects on the battlespace into a concise flexible framework for actionable information requires a structured conceptualization of the applicable parameters including the identification of the elements of the mission planning and execution process that are impacted by environmental variables. In this section we describe the background and significance of the various aspects of environmental impacts in the broad areas of Terrain and Weather. In addition, Environmental impacts on sensors are discussed in detail in order to provide context and demonstrate a primary area for actionable information derivation through the development of an integrated framework.

At the highest level, environmental effects can be separated into (1) the impacts of terrain (topology and elevation only), (2) direct impacts of weather on the performance of military objects (such as impacts on aerial platforms), (3) indirect impacts of weather on military objects and battlespace physics (such as target signature physics and signal transmission though the atmosphere) and (4) impacts that occur as a result of complex interactions at the terrain-weather interface. Impacts at the terrain-weather interface can be describes as the effects of weather on terrain physical properties (such a soil moisture, soil strength, soil and vegetation temperatures, etc) as well as coupled terrain-atmosphere physics effects (such as acoustic ad RF signal ducting). Each of these areas, in addition to Sensor impacts are addressed below.

3.1 Transforming Geo-environmental Data into Information

Across the network, C2 operations are constantly at work transferring data into actionable information. With respect to geo-environmental data, the transformation to information comes through the application of context provided by an actor and associated doctrine. An actor can be of many forms and abstractions (e.g. unit, platform of system). But each actor possesses a set known geospatial or environmental characteristics that affect the optimal state for that actor in a positive or negative manner. The characterization of these affects, as they relate to the battlefield actors is the actionable information to which this paper refers. Each specialty area has its own terms, references and processes codified in doctrine. At the data level, various unifying standards in syntax and format exist for terrain (e.g. Theater Geospatial Database (TGD) [Theater Geospatial Database, 2007] and Environmental Data Coding Specification (EDCS)) and the atmosphere and weather (e.g. Joint METOC Brokering Language (JMBL). In many contexts, the data previously described could be actionable within its specialty area. However, if information from any specialty area is to become actionable within an overarching concept of integrated, networked C2, that information needs to be unified within the tenets of doctrine, actors, missions and tasks. Through this unification, a common basis for a language emerges. For the purposes of this discussion, the language is the geoBML. From the process framework, through the semantic explicitness offered in the geoBML, the JC3IEDM can be empowered to house or point to the actionable geo-environmental information available on the network to support C2 operations.

3.1.1 Terrain Effects

The role of terrain effects and their incorporation within a C2 decision framework is discussed in Section 1.2. Of importance is that the terrain information concepts of that discussion provide the initial battlespace landscape organization, objectification and geoBML relationship between terrain effects and unit and platform entities.

3.1.2 Weather Effects and Terrain / Weather Interface Effects

The atmosphere is a highly complex system that exhibits a broad range of dynamic behavior and effects in both the spatial and temporal dimensions. In order to effectively utilize the diversity of environmental impact on battlespace actors within a uniform C2 information structure, certain bounding constraints, structural paradigms, and abstractions to the standard implementation of weather effects must be established. Through the tiered framework and structured objects, there becomes a meaningful basis for organizing and assigning significant effects caused by the atmosphere and weather. In extension, the unit type provides the basis for applying environmental effects to the equipment and/or systems associated with that unit.

An approach is necessary to bound the problem when parsing through this large data and parameter space in a way that ultimately provides actionable information to the warfighter via a structured process framework and derived C2 grammar. These organizing principles provide a linkage between the sets or classes of information from applicable Weather data representations and types to the *impact* that they will eventually have on the applicable battlespace elements, C2 services and decision-making processes. The practical realities of the battlespace network-centric environment will inherently limit the available Weather data feed to a reduced set of available products. The challenge, therefore, is to validate the existing framework to ensure it is flexible enough to accommodate the broad applicability of weather impacts while working within the realistic constraints of the practical availability of weather data.

It is well established that atmospheric conditions impact battlespace dynamics through a number of interrelated mechanisms. The impact classes can be broadly delineated into (1) direct impacts on the performance of units or platforms (2) impacts on the movement associated with ground units as well as ground and air platforms and (3) impacts on the performance of specialized equipment associated with a unit or platform. Of particular interest within this paper are the impacts of weather on sensors and in extension, the impact on the information chain associated with SA. Within each of these impact classes, the dynamics of the impact mechanism can be classified into (1) immediate ($t = 0$) direct impacts (i.e. very cold temperature will increase the risk of icing for certain Unmanned Aerial Vehicles (UAVs)), (2) cumulative direct impacts (i.e. prolonged exposure to very cold temperatures will adversely effect the performance of certain vehicles) and (3) immediate and cumulative indirect impact, typically effecting the performance of a system as it interacts with the terrain (i.e. after a period of rain for a given soil type, the expected thermal cross-over period will differ from the dry ground case).

As a first order analysis, the effects of weather and terrain can be analyzed as separate environmental drivers impacting different aspects of the battlespace information value chain. However, for several elements of the battlespace, this simplification breaks down significantly when all but the simplest environmental conditions are considered.

With this rough overview of the classification of impacts established, an approach can be formulated that traverses from weather data to actionable weather *impact* information. As a framework is developed for incorporating the dynamic effects of weather in the battlespace into a comprehensive flexible network-centric BML model, the problem parameter space can be significantly bounded by focusing on matching the weather source, level of data persistence, and fidelity demands to an understanding of the ultimate impact that the target weather will have on a relevant battlespace element. This mapping can be further refined by identifying the appropriate aggregation of relevance for each category of weather impact.

3.2 Environmental Impacts on Sensors and Sensor-related Battlefield Elements

Most battlefield elements that are susceptible to environmental effects can be categorized according to their relative susceptibility to terrain conditions verses instantaneous and cumulative weather conditions. Much of the traditional geospatial IPB elements are based primarily on elevation and terrain type considerations that, at a basic level, can be divorced from all but the most dramatic weather impacts. Several battlefield elements relevant to the C2 problem-space are less directly dependent on terrain and are almost completely dependent on weather alone (i.e. high winds impacting UAS effectiveness).

However, a large portion of battlespace elements are impacted, to some degree by both weather and terrain or a complex composite effect of the terrain/weather interface.
The primary focus of the remainder of this discussion will focus on military sensors and general sensor platform types. Although multiple battle-space elements are impacted by weather and terrain in some way, focusing on sensors will provide a center to the analysis and allow for the illustration of specific examples.

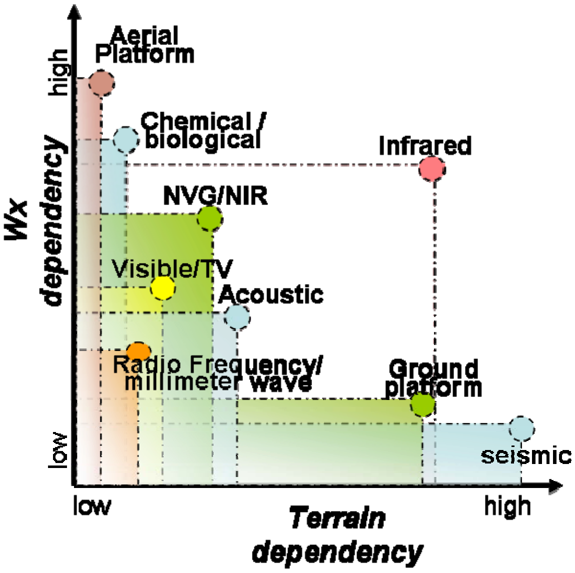

Figure 2: Sensor modalities plotted against performance dependency on Terrain and Weather

Active and passive sensor technologies are continuingly evolving in their ability to supply ISR (Intelligence, Surveillance and Reconnaissance) and targeting capability. Although sensor technologies and our ability to model their behavior are rapidly developing, the fundamental physics drivers influencing their behavior remain, fixed for each sensor modality. A correlation exists between a sensor modality's "natural" level of impact from each of these dimensions and the level of data/information required in that dimension in order to effectively model the sensor behavior. Figure 2 depicts various sensor modalities and sensor platform types with their performance capabilities mapped against the respective influence of terrain and weather (Wx). In Figure 2, NVG denotes Night Vision Goggle and NIR, Near IR.

4 An Integrated Framework for Terrain, Weather and Sensor Performance related to Military Missions

Attempts have been made to incorporate dynamic environmental data into a generalized coherent environmental information framework and technical architecture. Many efforts have encountered limitations to data storage, computing capacity, semantic incompatibilities, insufficient input data, etc. and have, at best, resulted in a suite of separate Tactical Decision Aid (TDA) paradigms and stove-piped components that address a limited subset of the core problem space. If a coherent general structure is to be generated, it must overcome the substantial challenges presented by this task through a focus on generating a structured mapping between the level/type of environmental input and the associated *impact* on target military element.

This section illustrates a tiered geo-environmental information framework with specific sensor performance examples. In addition, the robust incorporation of dynamic elements into this framework is discussed and examples of actionable geo-environmental information are given.

4.1 Sensor Performance Products

Various sensor-related TDAs and metrics are designed to convey mission applicable information about sensor and platform performance under environmental conditions. Output products created from these applications and algorithms span a broad spectrum of utility, incorporate different levels of specificity in both space and time, are applicable to various actions from planning–to-execution, and are aimed at different aggregations of forces for final consumption. BTRA, and similar systems, aim to enrich the information content and applicability of sensor TDAs by directly incorporating integrated terrain, weather, force, and mission information at the sensor product selection, generation, and dissemination phases. The common element among each of these approaches is that they are bound by limitations on data specificity and fidelity imposed by sensor modality, analysis intent, and raw data availability.

Capturing these various information products, associating them with the correct level of confidence, referencing them to the correct level of aggregated forces and C2 Services, and communicating their meaning in a uniform fashion becomes a significant challenge in an integrated framework.

A general classification of Sensor Information Classes and Products is presented in Table 1 below. However, note that the categories are not mutually exclusive and significant overlaps and variations exist at the Tier 2/3 level of the framework. This is due to the need to address both spatial and temporal uncertainties during refinement in the coarse-to-fine decision process and the times where SA is uncertain.

The tiered structure of actionable geo-environmental information aligns the coarse-to-fine information extraction and utilization concept implicit in a planning process and general doctrine practices with a categorization of spatial information products. The extension of the framework to explicitly include weather impacts on C2 services, and high level planning activities has required the delineation of product attributes including temporal dynamics, persistence, generality, and relation to data availability. Specifically, sensor performance information and its impact on ISR levels can become stand-alone information objects or can contribute to the derivation of composite information that incorporate additional non-sensor specific terrain information.

4.2 Aligning Information Products to a Framework

Table 1 combines aspects of terrain and weather effects into an effective integrated framework to enable the conceptualization and communication of actionable geospatial information that is ideally targeted to the relevant information needs with a C2 decision process. This framework captures and communicates information content in an expandable, yet uniform manner that incorporates weather, atmospheric and terrain elements at all levels of the planning and within the execution action chain. In Section 1.3, it is stated that the real challenge of the frameworks sufficiency in incorporating this information would lie in its ability to handle the dynamic aspects of the weather domain. In this section, we expand on concepts introduced in Sections 1.3 and conclude with a general conceptual framework that incorporates environmental impacts while enabling actionable information communication, the maximization of persistence and utility, and maintaining network-centric applicability

As has been described above, creating actionable environmental information requires the use of varying levels of raw environmental data dependent on the type and required fidelity of the impact being analyzed. Furthermore, the implementation activity on the doctrinal analysis chain will directly influence the types of environmental information required. Creating a mapping between the implementation of environmental effects information and the process of creating that information will lead to the development of logical anchor points within the planning and execution process at which to establish links into a geoBML–focused framework.

Tier	Category	Sensor Information Classes	Sensor Products	Examples
1	Foundational information	Information derived from raw base terrain and weather data to enable sensor reasoning	Dynamic Terrain Temperature and Moisture Map	**(Ex)** Determine a re-usable information construct that provides dynamic physics-realistic information about the state of the terrain.
1	General in Time and Space	Information is required to address general situations where the exact time and location are unknown	Tactically Significant Sensor Behavior Regions	**(Ex)** For long term planning purposes, determine the optimal placement of an Observation Point such that maximum performance can be expected of an IR sensor suite located at that Observation Point over the course of several weeks.
2	General in Time, Specific in Space	Information is required for an exact location over a long / or unknown time period	Aggregate-Time Sensor Employment Optimization map	**(Ex)** Determine the optimal sensor array location and type allocation for a given number of acoustic sensors to cover a specific identified movement corridor.
2	Specific in Time, General in Space	Information is applicable to an exact time, but the location of the target/ concealment area, etc. is not precise	Region Specific Probability of Detection Optimal Sensor Employment Parameters	**(Ex)** for a given exact mission time, determine the probability that a target can be located within a given general area.
3	Specific in Time and Space	Information is applicable to a specific known location at an exact time.	Spatio-Temporal Sensor Performance Map Acquisition Geometries	**(Ex)** determine the optimal Infrared (IR) sensor equipped UAV ingress angle that will result in the earliest detection time of a target at a known location.

Table 1: Sensor Performance Products in the Tiered Framework

The operational implementation of sensor-related and dynamic information products through the MDMP process (planning through to execution) will track a parameter space bounded by time and space specificity level (from general to specific). This parameter space is mirrored in the terrain vs. weather parameter space introduced in Figure 2, Section 3.2.1 for the categorization of sensor and dynamic environmental impact products. Figure 3 graphically represents the tight coupling between environmental data requirements, doctrinal analysis stage, and echelon relevance.

Consider the following hypothetical situations represented in Figure 3:

1. *Figure 3 location "A"; early planning stages*. The exact enemy location is unknown and the time of engagement is unknown (but estimated to be within the near future), an information product may be produced to give general sensor performance over a wide area modeled under a set of climatology / historical weather or through standard diurnal estimation models. This corresponds to Tier 1 information in Table 1.
2. *Figure 3 location "B"; early planning stages.* Various long-term (period of weeks/months) Areas of Interest (AOIs) are identified. Optimal re-supply routes are being located. A product may be produced that computes general IR concealment behavior for the particular season of interest, interpolated against expected diurnal effects. This corresponds to Tier 1 information in Table 1.

3. *Figure 3 location "C";* Mid planning stages; reconnaissance plans are being formulated in response to the CCIR. This planning requires information addressing both atmospheric information on aerial platforms as well as sensor performance. A family of candidate sensing locations, air platform flight times and paths are produces. However, the exact location of the target is unknown and the search will take place over a wide area. A product that could predict the general performance over the entire region for a given time for an IR sensor or perhaps the best time throughout the region to fly for maximum AC concealment from a human listener on the ground, etc. would add to the probability of

information acquisition with the forces available sensor payloads. This corresponds to Tier 2 information in Table 1.

4. *Figure 3 location "D"; Late planning stages and into execution.* An exact target location and engagement time are identified. A product may be produced that could predict the best sensor emplacement location(s) for Acoustic or Infrared sensors in order to support the kill. This corresponds to Tier 3 information in Table 1.

Figure 3 illustrates the complex, yet tractable, relationship between environmental information products and the implementation of that information within the C2 action chain. Creating a structure for its implementation, communication, and standardization requires a framework that explicitly incorporates this complex relationship.

4.3 Example Sensor Information Products as Actionable Information

Through exploiting a tight coupling between enriched terrain information and task-specific weather information, sensor performance data can be contextualized, localized in space and time, and targeted to the correct force level to become actionable sensor performance information.

Figure 4 shows an example of an IR Spatio-Temporal Sensor Performance Map that communicates the effectiveness of an IR sensor in performing a detection task at each spatial location within a defined Region of Interest under an exact forecast weather condition. This particular example represents information in multiple dimensions including time, target class (wheeled vehicle) and orientation, and nominal view geometry. The variation represented within the example results from complex interactions between the weather, the exact terrain type, slope aspect orientation, and target thermal behavior specifics. The high level of predicted spatial variation shown in this sensor product is primarily due to the

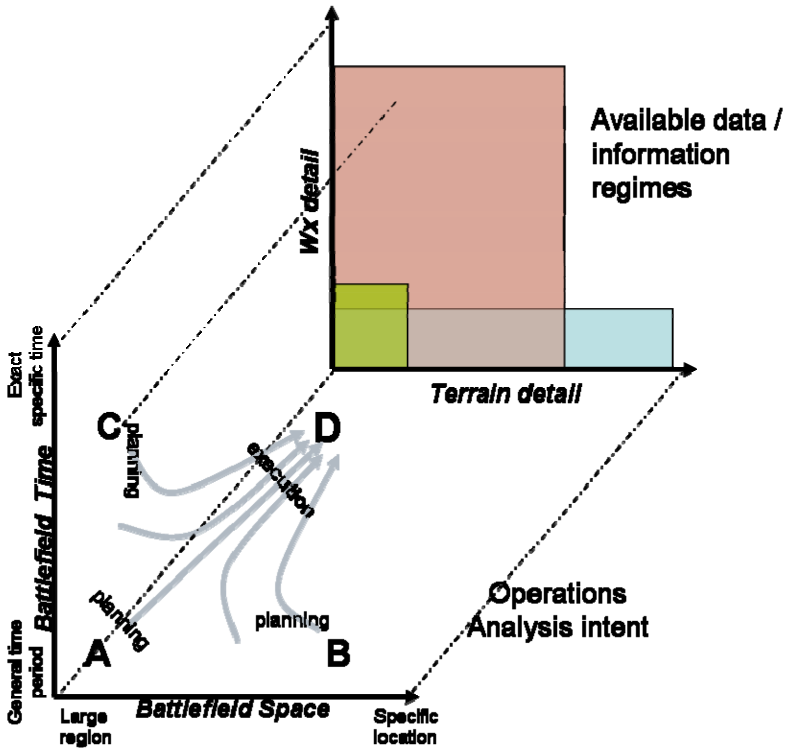

Figure 3: Integration of Terrain, Wx and Sensor Effects on Missions

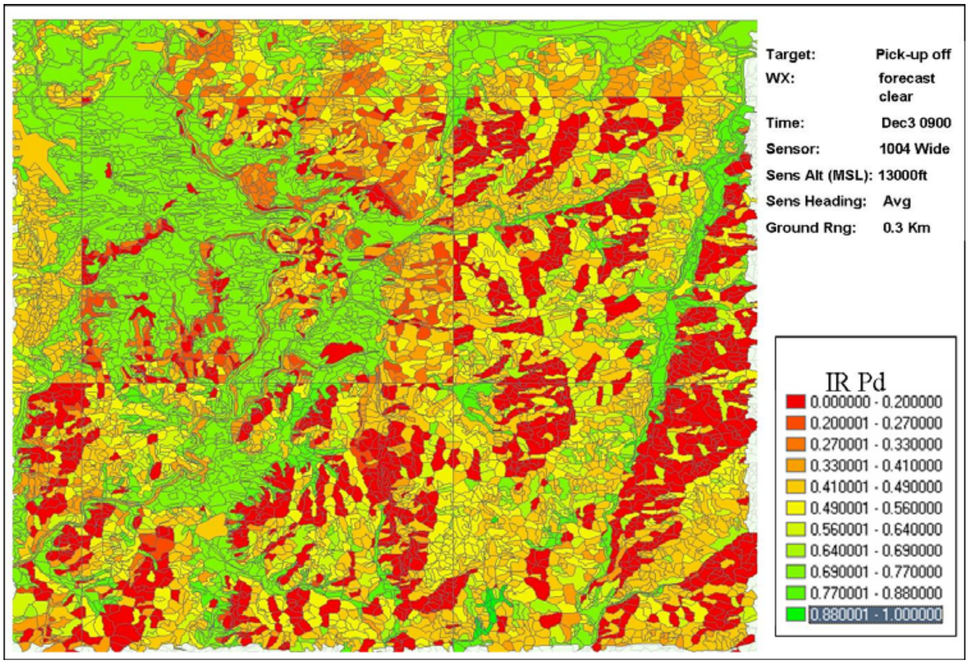

Figure 4. Spatio-temporal specific sensor performance map

interaction of weather, terrain, and target driving thermal crossover events at separate times and severity levels for different locations within the map region.

Although this example information product is highly specific, similar information layers can be created that aggregate one or more of the problem dimensions (view geometry, sensor ID, target ID, etc.), thereby yielding a higher level of generality and re-usability at the expense of a reduction in tactical specificity. In all cases, this and similar sensor performance information products gain actionable utility through an explicit linkage back to the terrain location and time specifics. This utility can be increased even more by using a geoBML to relate the product to explicit mission impacts.

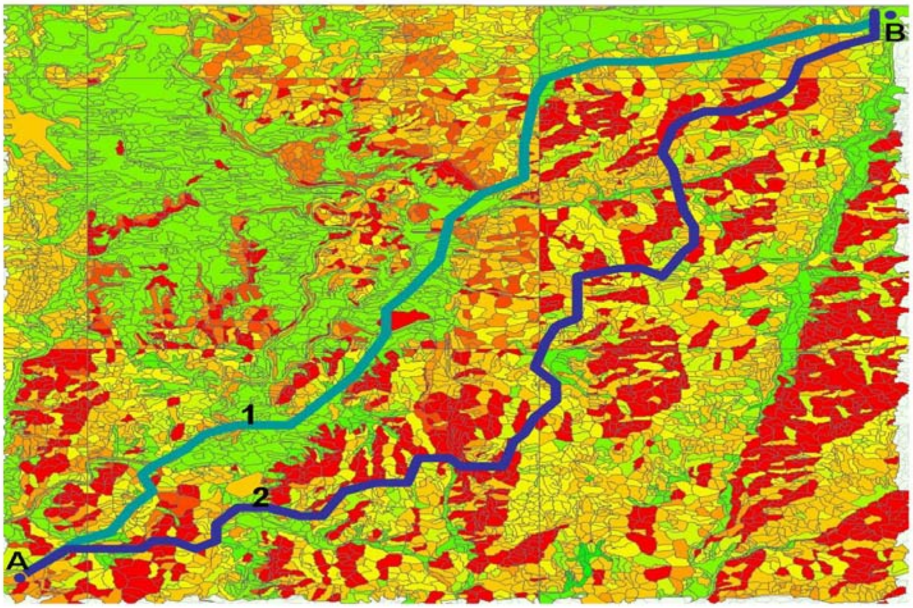

Figure 5. Route 2 selected to minimize vulnerability to IR detection (i.e. the path crosses the most red area).

The actionable information quality of this and similar products can be accessed through two general usage paradigms. The first employment strategy is as a force level-specific visual aid for asset employment (i.e. to determine UAV flight times and routes that meet mission goals of detection and acquisition with explicit links back to the state of the terrain). The second approach leverages the rich information content available in the suite of sensor performance information layers to enhance and expand the information content of other related TSOs and information products.

It is the second employment methodology that has the potential to fully exploit and actualize the information content of the sensor product suite. As a dynamic input providing additional downstream spatial decision knowledge, this content can influence the dynamic reasoning of related products and applications to produce an aggregate output that is rich in both spatial and temporal information content while incorporating task-specific sensor performance knowledge.

An example would be to utilize the time and space dependent IR performance values as weighting functions to influence the choice of optimal route generation in order to minimize vehicle vulnerability to IR detection. As an input to the BTRA, sensor information layers can provide time-indexed vulnerability values that can be linked to exact locations and projected time of asset passing for every point along a series of candidate routes (Figure 5). Moreover, the parameters of the sensor performance information layer input can be varied and aggregated over multiple dimensions (target vehicle class, target vehicle formation size, platform altitude (for aerial sensors), sensor type, etc.) to derive routes that optimize over complex weighting functions of various different sensor-related parameters. For example, an information layer may be created to provide a route and travel start time that minimizes time taken in transit, while incorporating a minimum tolerance threshold of IR vulnerability within the entire region and applying a separate weighting function to minimize acoustic sensor vulnerability only within in a specific region previously identified as likely to contain enemy sensors.

In each of these nominal examples, derived knowledge of coupled terrain and weather effects have been exploited to enable the creation of directly actionable information. As a general information layer, specific-to-general dynamic sensor performance information can be combined with, and referenced by, other BTRA products in addition to the example given above. Engagement Areas, Positions of Advantage, Avenues of Approach, and other TSO constructs could conceivably ingest sensor information products.

4.4 Incorporating Environmental Dynamics into a Framework

Developing an integrated framework to incorporate dynamic weather effects and terrain constraints within a comprehensive C2 communication and information conceptualization framework requires the mapping across various problem parameters introduced by the highly dynamic nature of the environment. The basic tiered geo-environmental information structure [Hieb et al., 2006] was introduced in Section 1.3 as it applies primarily to terrain-focused environmental impact information objects. Extending this structure to accommodate the robust incorporation of dynamic elements requires additional breadth in the way the objects are conceptualized, stored, referenced, and utilized. This process builds upon the tiered paradigm to incorporate weather impact-specific structure to establish a paradigm that incorporates terrain and weather in an integrated fashion.

A comprehensive environmental structure should allow for the definition and categorization of actionable spatial information objects to be directly influenced by the level of dynamic dependence implied by each information object. The level of dynamic influence for a given aspect of information will have a substantial, yet complex impact on the level of reusability (persistence) inherent within it. In practice, almost all standard spatial information objects incorporate a dynamic element at some level. Spatial information objects that incorporate sensor performance information typically contain a higher degree of dynamic specificity, and, therefore a higher dependence on dynamic constraints.

The final dynamic level assignment of a given spatial information objects is not always directly related to the level of environmental dynamics that drive the physics behind the creation of the objects. Certain spatial information objects can remain valid over a long period of time, yet may be based on environmental properties that change rapidly. The definition of the object will determine this relationship. For example, consider the spatial definition associated with an Engagement Area. Through the use of BTRA [Hieb et al., 2007] and other advanced terrain analysis and modeling tools, this Engagement Area can be further refined through selecting an optimal region from candidate engagement areas that exhibits physics behavior favorable for maximum IR sensor performance over a multi-week long period (soil backgrounds resulting high Probability of Detection (Pd) through the typical diurnal cycle, low IR clutter, favorable slope/aspect for solar radiation to cause target-background differentiation). Creation of this modified Engagement Area object incorporates statistical metrics that are valid over a specific multi-week period (driven by historical or climatological weather). Therefore, although IR performance is impacted by environmental drivers that change on a timescale of minutes to hours, the final Engagement Area object, created for a specific time period, contains a relatively low dynamic dependence because of the long time period explicitly utilized in its creation.

Spatial-temporal information objects will, by definition, implicitly incorporate a time definition element that is one of the following:

1. *No Time Element.* The information object is based entirely on static terrain considerations (i.e. elevation only.
2. *Exact Time Only.* The information object is valid for a given exact time, or a very limited time period.
3. *Single Time period.* The information object is valid for the entire length of a specified time period. This time period usually correlates to the time period over which dynamic elements impacting the information object were calculated
4. *Cyclical Time Period.* The information object incorporates elements that can be reasonably estimated to re-occur based on some given time cycle. This is typically most applicable to TSOs for which the standard diurnal progression is the prime driving force.
5. *Exact Time Output for a Given Time Period.* The information object output is valid for an exact time only. However, the information object creation process considered the battle environment at different times over a specific time period before locating the "optimal" time as specified in the output information object.

4.5 Framework Summery

The tiered structure of actionable geo-environmental information aligns the course to fine information extraction and utilization concept implicit in a planning process and general doctrine practices with a categorization of spatial information products. The extension of the framework to explicitly include weather impacts on C2 services, and high level planning activities has required the rough delineation of product attributes including temporal dynamics, persistence, generality, and relation to data availability. Specifically, sensor performance information and its impact on ISR levels can become stand-alone information objects or can contribute to the derivation of composite information that incorporate additional non-sensor specific terrain information. As a means to explicitly delineating geo-environmental information needs as they are encountered in OAKOC, the framework addresses a structured approach to temporal variation inclusion.

As Figure 6 depicts, both the effects on unit, platforms and systems as well as the dynamics associated with the data domain can be effectively mapped to the geo-environmental framework laid out in [Hieb et al., 2006] and reintroduced in this paper. The ability to extend the framework is based in the framework's basic coupling to doctrine, mission, tasks and orders. Through this coupling, a language and geoBML addressing the impacts of weather and atmospherics can be conceived and advanced.

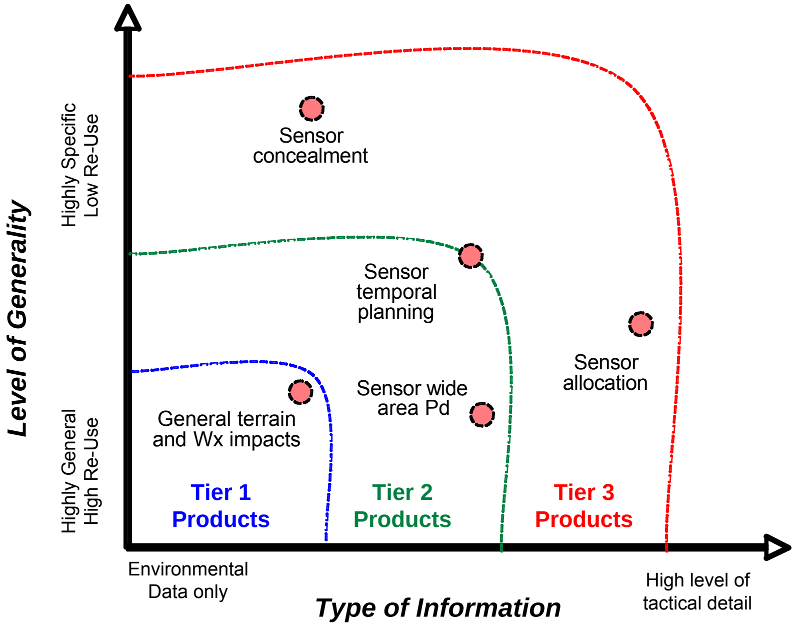

Figure 6: Sensor Products within the Framework

5 Conclusions

In this paper we have described a new approach to the representation of environmental information and knowledge in a multi-level computational model that organizes computable objects for aspects of Intelligence Preparation of the Battlespace, Level Two and Three Fusion and Situational Awareness that have not previously been represented. Through this approach, environmental battlespace effects can be incorporated in automated C2 tools and services that perform geospatial and temporal reasoning across nodes of the networked force. This will facilitate a balance to traditional geospatial constructs centered on visualization and manual methods, as well as enabling and transforming C2 Services in the future.

Our work in coalition BML indicates that the general principles of BML, facilitating communication generally and also the simulation of plans to validate their effectiveness [Hieb et al., 2004], also applies to coalition C2 services. Expanding geoBML to incorporate weather and sensor effects only increases the validity of this principle in that the C2 planning process and its evaluation via simulation become much more effective where the effects of the environment can be incorporated with high accuracy.

While the theoretical basis for this work is from US Army doctrine using the MDMP, the framework developed is general and applicable to more collaborative Network Centric Operations. Indeed, if current military forces become less hierarchical, Commander's will still require the same environmental information for missions – maps, terrain analysis, weather forecasts and sensor products. A framework that relates environmental products to missions will facilitate collaborative planning and distributed decision-making and provide essential guidance as C2 services are developed for the 21st century.

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