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THESIS

CREATING DIGITAL ENVIRONMENTS FOR MULTI-AGENT SIMULATION

by

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There are few tools available for military and civilian simulation developers to quickly and efficiently develop high-fidelity digital environments capable of supporting high-resolution, agent-based simulation. In this work, the author has tried to lay a solid foundation for further understanding the digital terrain support available to simulation developers.

This thesis explores numerous digital terrain data representations and tools available to create digital environments. The work explores the specific problem of terrain database generation for agent-based ground combat simulation. To accomplish this, the author explores the more general problem of where to find the data, what tools are available, and how to put the pieces together to create a registered digital environment on a state-of-the-art computer. The author envisions this methodology to be the first step in the design of an automated planning tool capable of importing real world digital terrain data and quickly generating agent-based military combat scenarios for any location on earth.

This work provides a logical construct and design methodology for an analyst to create high fidelity terrain data sets. It functions as a "how to" manual to help analysts understand which information and tools are available to use for different types of simulation projects.

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CREATING DIGITAL ENVIRONMENTS FOR MULTI-AGENT SIMULATION

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF ACRONYMS

ACT	-	Advanced Concepts and Technology
ACTD	-	Advanced Concept Technology Demonstration
ADRG	-	ARC Digitized Raster Graphics
ADS	-	Advanced Distributed Simulation
ALSP	-	Aggregate Level Simulation Protocol
AMSEC	-	Army Model and Simulation Executive Council
AMSO	-	Army Modeling and Simulation Office
ANSI	-	American National Standards Institute
API	-	Application Programmer Interface
ASCII	-	American Standard Code for Information Interchange
ASNE	-	Air and Space Natural Environment
AWACS	-	Airborne Warning and Control System
BIIF	-	Binary Imagery Interchange Format
BV	-	Battlefield Visualization
C3I	-	Command, Control, Communications, and Intelligence
C4I	-	Command, Control, Communications, Computers, and Intelligence
C4ISR	-	C4I Surveillance and Reconnaissance
CADRG	-	Compressed ARC Digitized Raster Graphics
CAS	-	Complex Adaptive System
CBS	-	Corps Battle Simulation
CIB	-	Controlled Image Base
CIG	-	Computer Image Generator

CGF	-	Computer Generated Forces
CMMS	-	Conceptual Model of the Mission Space
COTS	-	Commercial Off-The-Shelf
CT	-	Coordinate Transformation
CTDB	-	Compact Terrain Data Base
DARPA	-	Defense Advanced Research Projects Agency
DBGS	-	Data Base Generation System
DCHUM	-	Digital Chart Update Manual
DCW	-	Digital Chart of the World
DEM	-	Digital Elevation Model
DFAD	-	Digital Feature Analysis Data
DFDD	-	Data Format Design Document
DIF	-	Data Interchange Format
DIGEST	-	DIgital Geographic information Exchange STandard
DII/COE	-	Defense Information Infrastructure/Common Operating Env.
DIS	-	Distributed Interactive Simulation
DMA	-	Defense Mapping Agency (see NIMA)
DMAFF	-	DMA Feature File
DMSO	-	Defense Modeling and Simulation Office
DoD	-	Department of Defense
DOI	-	Digital Orthorectified Imagery
DRM	-	Data Representation Model
DTAD	-	Digital Terrain Analysis Data

DTED	-	Digital Terrain Elevation Data
DTM	-	Digital Terrain Model
EDBIPT	-	Environmental Database Integrated Product Team
EDCS	-	Environmental Data Coding Specification
EXCIMS	-	EXecutive Council In Modeling and Simulation
FACC	-	Feature Attribute Coding Catalogue
FACS	-	Feature Attribute Coding Standard
FAQ	-	Frequently Asked Questions
FGDC	-	Federal Geographic Data Committee
FID	-	Feature IDentifier
FMI	-	Feature Model Instance
FTP	-	File Transfer Protocol
FOV	-	Field of View or Vision
GCC	-	GeoCentric Coordinate System
GCI	-	Geocentric Celestial Inertial coordinate system
GCS	-	Global Coordinate System
GDC	-	GeoDetic Coordinate system
GEI	-	Geocentric Equatorial Inertial coordinate system
GIS	-	Geographic Information System
GLIS	-	Global Land Information System
GM	-	GeoMagnetic coordinate system
GMI	-	Geometry Model Instance
GPS	-	Global Positioning System

GRIB	-	GRIdded Binary format
GTDB	-	Generic Transformed Data Base
HLA	-	High Level Architecture
IG	-	Image Generator
I/ITSEC	-	Interservice/Industry Training, Simulation, and Education Conf.
IMS	-	EOSDIS Information Management System
ISAAC	-	Irreducible Semi-Autonomous Adaptive Combat
ISAACA	-	ISAAC Agents
ISO	-	International Standards Organization
JSIMS	-	Joint SIMulation System
JTA	-	Joint Technical Architecture
JTASC	-	Joint Training, Analysis, and Simulation Center
JWARS	-	Joint WARfare System
LandSat MSI	-	Land Resources Satellite Multispectral Imaging
LOD	-	Level of Detail
M&S	-	Modeling and Simulation
MARVEDS	-	MARitime Virtual Environment Data Specification
MAS	-	Multi-Agent Systems
MCCDC	-	Marine Corps Combat Development Command
MCG&I	-	Mapping, Charting, Geodesy, and Imagery
MEL	-	Master Environmental Library
METOC	-	METeorology and Oceanography
MIL-STD	-	U.S. Military Standard

ModSAF	-	Modular Semi-Automated Forces
MOVES	-	Modeling, Virtual Environments, and Simulation
MRTDB	-	Model Reference Terrain Data Base
MSRR	-	Modeling and Simulation Resource Repository
NASM	-	National Air and Space (warfare) Model
NBC	-	Nuclear, Biological, and Chemical
NIMA	-	National Imagery and Mapping Agency
NITF	-	National Imagery Transmission Format
PC	-	Personal Computer
ONC	-	Operational Navigation Chart
PCS	-	Projected Coordinate System
RPF	-	Raster Product Format
SAF	-	Semi-Automated Forces
SDTS	-	Spatial Data Transfer Standard
SEDRIS	-	Synthetic Environment Data Representation and Interchange Spec.
SIMNET	-	SIMulation NETwork
SLF	-	Standard Linear Format
SM	-	Solar Magnetic coordinate system
SNE	-	Synthetic Natural Environment
SRM	-	Spatial Reference Model
STF	-	SEDRIS Transmittal Format
STOW	-	Synthetic Theater Of War
STRICOM	-	Simulation, TRaining, and Instrumentation COMmand

SWM	-	Solar Wind Magnetospheric coordinate system
TDB	-	Terrain Data Base
TEC	-	Topographic Engineering Center
TIFF	-	Tagged-Image File Format
TIN	-	Triangulated Irregular Network
TM	-	Transverse Mercator PCS
TROPO	-	TROPOsphere scatter
UCDM	-	USIGS Conceptual Data Model
UFAC	-	User-defined Feature Attribute Codes
USGS	-	U.S. Geological Survey
USIGS	-	United States Imagery and Geospatial System
UTM	-	Universal Transverse Mercator
VCS	-	Vertical Coordinate System
VMAP	-	Vector Map
VPF	-	Vector Product Format
VRF	-	Vector Relational Format (DIGEST VPF)
VRML	-	Virtual Reality Modeling Language
V&V	-	Verification and Validation
WARSIM	-	WARfighters SIMulation
WGS-84	-	World Geodetic System - 1984
WMO	-	World Meteorological Organization

DEFINITION OF KEY TERMS

Aggregation

A relationship between objects in the data representation model where one object contains other objects.

Aggregator

An object that is comprised of other objects (components). A 'has-a' relationship exists between the aggregator object and its component (see component) objects. For example, a polygon is an aggregator for its vertex objects (components). Synonym: container.

Application Programmer's Interface (API)

An encapsulation of functionalities common to many applications into reusable modules. This encapsulation provides consistency among applications, as well as a reduction in complexity for access of data.

Areal Feature

A geographic entity that encloses a region. For example, a lake, administrative area, or state.

Association

A relationship between two or more objects in a data representation model. This is the weakest relationship, and can include multiplicity of objects at either end of the relationship.

Atmospheric Representation

The depiction of the atmosphere environment which includes data on the location and characteristics of the zone from the earth's surface to the upper boundary of the troposphere, and includes: (a) particulate and aerosol data on haze, dust, and smoke (to include nuclear, biological, and chemical effects), and (b) data on fog, clouds, precipitation, wind, condensation (humidity), obscurants, contaminants, radiated energy, temperature, and illumination.

Attribute

A quantifiable property of an object. For example, the color of a building or the width of a road.

Base

1: the 'world' encompassed by an environment. Boundaries are specified to define the extent of the Base. 2: the root of an environment object hierarchy of objects with fixed positions in the world.

Component

An object that is a part of an aggregator object. For example, vertex objects are components of their aggregator polygon. See aggregator.

Computer Generated Forces (CGF)

A generic term used to refer to computer representations of forces in simulations that attempt to model human behavior sufficiently, so that the forces will take some actions automatically (without requiring man-in-the-loop interaction). Also referred to as semi-automated forces (SAF).

Constructive Simulation

Models and simulations that involve simulated people operating simulated systems. Real people stimulate (make inputs to) such simulations, but are not involved in determining the outcomes.

Coordinate System

An organized system for describing 2- or 3-dimensional locations.

Correlated Initial Environment

The convergent representation of the same physical environment in two or more separate environments prior to their use in a combined exercise.

Correlated Levels of Detail (LOD)

The equal representation of environmental objects at comparable levels of presentation (i.e., the same object seen or detected at a distance of 10 meters).

Correlation

A convergent relationship between parallel representations of the same data.

Datum

A mathematical approximation to all or part of the earth's surface. Defining a datum requires the definition of an ellipsoid, its location and orientation, as well as the area for which the datum is valid.

Data Derivation

The calculation or interpolation of information not present in the original data.

Data Dictionary

A table or set of records whose values define the allowable content and meaning of attributes.

Data Loss

The loss of original information through multiple conversions or transformations of data.

Data Representation Model

1: a description of the organization of data in a manner that reflects the information structure of an enterprise. 2: a description of the logical relationships between data elements. Each major data element with important or explicit relationships is captured to show its logical relationship to other data elements.

Data Pre-distribution Interchange

The complete exchange of environmental data prior to the start of an exercise.

Data Representation

A variety of forms used to describe the terrain surface itself, the features placed on the terrain, the dynamic objects with special 3-D model attributes and characteristics, the atmospheric and oceanographic features, and many other forms of data.

Edge

A one dimensional primitive used to represent the location of a linear feature and/or the border of faces.

Elevation

The vertical component in a 3-dimensional measurement system. Elevation is measured in reference to a fixed datum.

Environmental Database

An integrated set of data elements, each describing some aspect of the same geographical region and the elements or events expected there.

Environmental Domain

The physical or abstract space in which the entities and processes operate. The domain can be land, sea, air, space, undersea, a combination of any of the above (including permanent or semi-permanent man-made features), or an abstract domain, such as an n-dimensional mathematics space, or economic or psychological domains.

Environmental Representation

An authoritative representation of all or part of the natural environment, including permanent or semi-permanent man-made features.

Face

A region enclosed by an edge or set of edges. Faces are topologically linked to their surrounding edges, as well as to the other faces that surround them. Faces are always non-overlapping, exhausting the area of a plane.

Fair Fight

A simulation or exercise conducted such that differences in the simulator or training system technology do not unduly result in one force or entity having an advantage over another.

Feature

1: a model of a real world entity. 2: a static element of the environment which exists but does not actively participate in environmental interactions.

Fidelity

1: the accuracy of the representation when compared to the real world. 2: (a) the similarity, both physical and functional, between the simulation and that which it simulates, (b) a measure of the realism of a simulation, or (c) the degree to which the representation within a simulation is similar to a real world object, feature, or condition in a measurable or perceivable manner.

Geocoding

An image is geocoded if a precise algorithm for determining the earth-location of each point in the image is defined.

GeoDetic Coordinate System (GDC)

A measurement system that relates earth-centered angular latitude and longitude (and optionally height) to an actual point near or on the earth's surface.

GeoKey

In GeoTIFF, a GeoKey is equivalent in function to a TIFF tag, but uses a different storage mechanism.

Geographic Coordinate System

A Geographic CS consists of a well-defined ellipsoidal datum, a Prime Meridian, and an angular unit, allowing the assignment of a Latitude-Longitude (and optionally, geodetic height) vector to a location on earth.

GCS Cell

Each cell covers one degree of latitude by one degree of longitude.

Geometry

A very abstract class, encapsulating both the concepts of traditional geometry as well as other classes containing measured data, and organizational methods used to organize these traditional geometry and other 'real' data classes within an environment.

Georeferencing

An image is georeferenced if the location of its pixels in some model space is defined, but the transformation tying model space to the earth is not known.

GeoTIFF

A standard for storing georeference and geocoding information in a TIFF 6.0 compliant raster file.

Grid

A coordinate mesh upon which pixels are placed.

Ground Truth

The actual facts of a situation, without errors introduced by sensors or human perception and judgment. For example, the actual location, orientation, and engine and gun state of an M1 tank in a live simulation at a certain point in time is the ground truth that could be used to check the same quantities in a corresponding virtual simulation. Or the actual direct and diffuse solar irradiance at a terrain point is the ground truth that could be used to check the same quantity in a corresponding virtual simulation.

Inheritance

An object-oriented programming concept where a child class also has the features (attributes and methods) of its parent class. One of the types of relationships between objects in the data representation model.

Interoperability

1: enables distributed heterogeneous simulation systems to be interactive so that a meaningful exercise may be conducted. 2: the ability of a model or simulation to provide services to and accept services from other models and simulations, and to use the services so exchanged to enable them to operate effectively together. 3: two training systems interoperating to present a single training exercise in the same simulated space to a geographically dispersed audience.

Library

A complete list of unique item(s) of a certain type (whatever type the library contains) which can be referenced within the environment.

Linear Network

A geographic entity that defines a linear (one-dimensional) structure. For example, a river, a road, or a state boundary.

Littoral Region

1: defined as (a) seaward - the area from the open oceans to the shore that must be controlled to support operations ashore, and (b) landward - the area inland from the shore that can be supported and defended directly from the sea. 2: the area from the ten-fathom curve shoreward to the most inland point of the shoreline.

Live Simulation

A simulation involving real personnel operating real systems.

Location 3-D Vertex

A coordinate in 3-dimensional space.

Meridian

Arc of constant longitude, passing through the poles.

Model

A physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process.

Model Space

A flat geometrical space used to model a portion of the earth.

Natural Environment

An earth-based environment modeled by an environment.

Node

A zero-dimensional primitive used to store a significant location.

Oceanographic Representation

The depiction of the ocean environment which includes data on the location and characteristics of the ocean bottom (e.g., depth curves, bottom contours, sediment types), as well as the representation of processes required to describe the natural and man-made static and dynamic surface and sub-surface ocean conditions (e.g., temperature, salinity gradients, acoustic phenomena).

Original Data

The source data utilized by a resource provider to construct their initial environmental representation.

Parallel

Lines of constant latitude, parallel to the equator.

Pixel

A dimensionless point-measurement, stored in a raster file.

Point Feature

A geographic entity that defines a zero-dimensional location. For example, a well or a building.

Polygon

Thematically homogenous areas composed of one or more faces.

Positional Accuracy

Positional accuracy refers to the root mean square error (RMSE) of the coordinates relative to the position of the real world entity being modeled. Positional accuracy shall be specified without relation to scale and shall contain all errors introduced by source documents, data capture, and data processing.

Projected Coordinate System (PCS)

An instantiation of a coordinate transformation. A planar, right-handed cartesian coordinate set which, for a specific map projection, has a single and unambiguous transformation to a geodetic coordinate system.

Property

A characteristic of an object.

Projected Coordinate System

The result of the application of a projection transformation of a Geographic coordinate system

Raster Space

A continuous planar space in which pixel values are visually realized.

Rational

In TIFF format, a Rational value is a fractional value represented by the ratio of two unsigned 4-byte integers.

Representational Polymorphism

Multiple representations of the same data to serve the needs of different users.

Resolution

The degree of detail and precision used in the representation of real-world aspects in a model or simulation. Granularity.

SDTS

The USGS Spatial Data Transmission Standard.

Scalability

The ability of a distributed simulation to maintain time and spatial consistency, as the number of entities and accompanying interactions increase.

SEDRIS

An infrastructure technology that enables information technology applications to express, understand, share, and reuse environmental data.

SEDRIS Transmittal Format (STF)

Provides users of SEDRIS, both data consumers and data providers, with a means of cross-platform interchange by supplying a universally specified external storage format.

Semantics

The implied meaning of data. Used to define what entities mean with respect to their roles in a system.

Sensor Model

A model of a sensing system (sensor) other than a direct human eye visual model. It may and usually does include a sensor signature model, a sensor atmospheric model, and a sensor effects model. Examples of sensor models include radar system models, sonar system models, and FLIR (forward looking infrared) imager models.

Space Representation (including ionosphere)

The depiction of the space environment which includes data on the location and characteristics of regions beyond the upper boundary of the troposphere, and including neutral and charged atomic and molecular particles and their optical properties.

Terrain Representation

The depiction of the terrain environment, which includes data on the location and characteristics of the configuration and composition of the surface of the earth, including its relief, natural features, permanent or semi-permanent man-made features, and related processes. It includes seasonal and diurnal variation, such as grasses and snow, foliage coverage, tree type, and shadow.

Tag

In TIFF format, a tag is packet of numerical or ASCII values, which have a numerical "Tag" ID indicating the information content.

Textures

Application of surface detail to a polygon by mapping an image to the polygon (i.e., to show foliage on a polygon to represent a tree).

Tile

A spatial partition of a coverage that shares the same set of feature classes with the same definitions as the coverage.

Topology

Any relationship between connected geometric primitives that is not altered by continuous transformation.

Tagged Image File Format (TIFF)

A platform-independent, extensive specification for storing raster data and ancillary information in a single file.

Universal Transverse Mercator (UTM)

An ellipsoidal transverse mercator projection to which specific parameters, such as central meridians, have been applied. The earth, between latitudes 84.0 degrees North and 80.0 degrees South, is divided into 60 zones, each generally 6 degrees wide in longitude.

Vertical Positional Accuracy

Vertical positional accuracy is based upon the use of USGS source quadrangles which are compiled to meet National Map Accuracy Standards (NMAS). NMAS vertical accuracy requires that at least 90 percent of well defined points tested be within one half contour interval of the correct value. Comparison to the graphic source is used as control to assess digital positional accuracy.

Vertices

Vertices are the intersecting points of lines. These points define either unique locations which represent end points of a line feature, or corners of a polygon or area feature.

Virtual Simulation

A simulation involving real personnel operating simulated systems.

World Geodetic System 1972 (WGS 72)

The definition of DMA DEMs, as presently stored in the USGS database, references the WGS 72 datum. WGS 72 is an Earth-centered datum. The WGS 72 datum was the result of an extensive three-year effort to collect selected satellite, surface gravity, and astrogeodetic data available throughout 1972. These data were combined using a unified WGS solution (a large-scale least squares adjustment).

World Geodetic System 1984 (WGS 84)

Defines the current U.S. DoD standard horizontal and vertical reference datums for a geodetic coordinate system, collected and standardized in 1984. The WGS 84 datum was developed as a replacement for WGS 72 by the military mapping community as a result of new and more accurate instrumentation and a more comprehensive control network of ground stations. The newly developed satellite radar altimeter was used to deduce geoid heights from oceanic regions between 70 degrees north and south latitude.

Worldwide Reference System (WRS)

The WRS is a global indexing scheme designed for the Landsat program based on nominal scene centers defined by path and row coordinates.

Zenith

The point on the celestial sphere vertically above a given position or observer.

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I. INTRODUCTION

A. THESIS STATEMENT

My thesis requirement is to conduct a survey of the digital terrain data representations and tools available to create a digital environment capable of supporting multi-agent simulation using a state-of-the-art desktop personal computer.

B. MOTIVATION

There are few tools available to quickly and efficiently develop a digital environment capable of supporting a high-resolution, agent-based simulation. An accurate model of any location on earth can take up to six months to develop. The author believes it is possible to create an accurate terrain representation on a state-of-the-art personal computer (PC) or laptop in half a day. The author's far-reaching goal is to build a tool to quickly and efficiently create a situated military simulation allowing planners to emplace any collection of weapons systems onto any terrain on earth. To do this a user must be able to create an accurate terrain representation derived from numerous terrain data sources. The sources may include but are not limited to Digital Terrain Elevation Data (DTED), Digital Feature Analysis Data (DFAD), digitized raster graphics and imagery.

C. GOALS

The author will explore the specific problem of terrain database generation for a Java-written, agent-based ground combat simulation similar to Ilachinski's Irreducible Semi-Autonomous Adaptive Combat (ISAAC) model (See Chapter 2). To accomplish this, the author will review the more general problem of where to find the data, what tools are available, and how to put the pieces together to create a registered digital environment on a state-of-the-art computer. The author envisions this methodology to be the first step in the design of an automated planning tool capable of importing real world digital terrain data and quickly generating agent-based military combat scenarios for any place on earth. The author will execute this research by analyzing alternatives of the most commonly used digital terrain manipulation and visualization packages.

The author will leverage current commercial off-the-shelf (COTS) techniques in this effort. The author's long-term vision is to be able to create a complete high-fidelity simulation in less than four hours. The digital environment is the most difficult and complex aspect of this effort. An automated planning tool could be developed to leverage existing technologies and research and integrate these tools into a unique model capable of running on a desktop PC.

The process would include dynamically integrating gridded data and raster graphics to create both a graphically and physically correct model of elevation, vegetation, trafficability, and man-made features. This will create a baseline from which we can develop a finished product. From this point, the analyst takes real-time imagery and manually updates the model. Two tools are implied: the first is a tool to automatically read gridded data and lay raster graphics over the top. The second is an authoring tool allowing us to quickly update an area based on digital imagery. The good news is that both tools exist today. The bad news is that they are not powerful or fast enough to provide the fidelity needed to make military decisions that may risk U.S. soldiers' lives.

In summary, this work will provide both a tool and design methodology for an analyst to create high fidelity terrain data sets. It will function as a "how to" manual to help analysts understand which information and tools are available to use for different types of projects. This work will directly contribute to the further development of high-resolution terrain generation for simulation analysis and the integration of real terrain into on-going agent-based MOVES simulation research.

D. ORGANIZATION

This thesis is organized into the following chapters:

- Chapter I: Introduction. Identifies the purpose and motivation for conducting this research. Establishes the goals and objectives for this thesis.

- Chapter II: Background and Related Work. Discusses basic digital topology concepts, describes the parts of basic ground combat simulation and describes previous research in the field of adaptive multi-agent systems and agent-based modeling.

- Chapter III: Data Representations. Describes the mainstream data representations and formats available to the military and civilian developer. Discusses ease of use and availability of each data representation. Describes the organizations involved in developing common terrain data formats. Recommends the best data representations for developing agent-based simulation tools.

- Chapter IV: Terrain Manipulation Tools. Discusses and analyzes the different terrain manipulation tools available to the developer. This includes cost, system requirements, data inputs and outputs, and potential uses of the product. Recommends the tools best suited to for creating digital terrain representations for agent-based ground combat simulation tools.

- Chapter V. Applied Summary. Summarizes the work completed in Chapters I-IV and offers a step-by-step approach to assist in defining and refining terrain space for use in multi-agent system simulation tools.

- Chapter VI: Future Work. Discusses follow on work and more advanced topics in the field of multi-agent system simulation applications.

- Chapter VII: Conclusion.

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II. BACKGROUND AND RELATED WORK

A. PARTS OF A GROUND COMBAT SIMULATION

Simulation modeling techniques have come a long way in the last three decades, however, the ability to quickly create accurate, high fidelity digital environments to support simulation and Command, Control, Communications, Computers and Intelligence (C4I) activities is still a very difficult problem. High fidelity synthetic natural environment data is often hard to come by and difficult to use once the data is correctly formatted. Environmental data sets are extremely large and complex processes are often necessary to change and manipulate the data. Computing power was once a major problem in managing and storing environmental data sets. In the past decade, CPU speeds, hard drive space and RAM have reached a point where the creation of large environmental data sets are no longer a problem for a normal desktop PC or laptop. Unfortunately, the environment is only the first step in the creation of a high fidelity combat simulation.

Three critical components of accurate military simulations include the environment, interactions, and physics. The environment may be the most challenging of the three conjoined parts. The digital environment is the area in which all agent interactions and physics take place. Numerous theories and methods exist to define and register a digital environment. If the terrain and physical objects are not accurately registered within the environment, the physical interactions between agents (and their environment) will be inaccurate. Critical aspects of combat simulation such as line of sight and ballistics will return erroneous results if the environment is not properly constructed.

It is key to understand that a computer tracks the digital environment in three separate coordinate systems. These coordinate systems are the world (user) coordinate system, the database coordinate system, and the pixel coordinate system. The world coordinate system is the area in which the user and human interface will interact. This could include tracking entities via Universal Transverse Mercator (UTM) and latitude-longitude coordinate systems. A database coordinate system uses a local x-y-z (0,0,0) scale to track local situated objects. The computer uses the image coordinate system to make physics calculations for physical interactions within the simulation. The computer uses the pixel coordinate system to actually draw the entities and synthetic environment on the screen for the human eye to process.

When developing Synthetic Natural Environments (SNE), it is important to integrate different data representations to create graphically and physically correct models of elevation, vegetation, trafficability, and man-made features. Real-time imagery could be used to further update the model. Two tools are implied. The first is a tool to automatically read terrain representations into our tool. The second is an authoring tool allowing us to quickly fill in or change features based on updated digital imagery. The author proposes Commercial Off the Shelf (COTS) techniques be modified and/or leveraged wherever possible.

The author envisions this work created in three steps. First, identify and explore the availability, ease of use, and flexibility of various data representations. Second, conduct an analysis of alternatives of the COTS tools available to create a situated registered environment. Finally, conduct a proof of concept for this methodology by creating a situated digital environment capable of being registered into multi-agent applications. This thesis will specifically focus on the first two steps (See Figure 2-1).

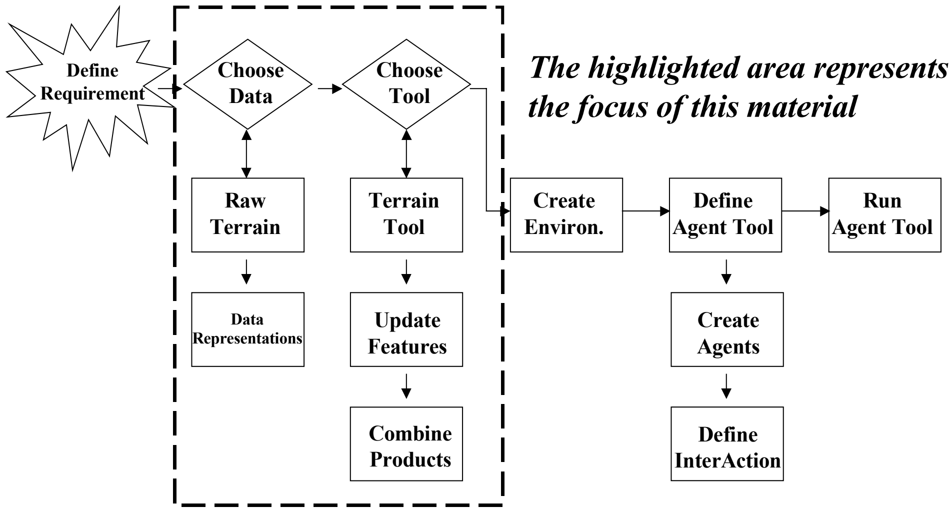

Figure 2-1. Thesis Focus

B. DATA INTEROPERABILITY

To obtain a basic understanding of this subject, one must understand the uses of digital terrain, the available types of terrain data, and where to find this data. Digital terrain models (DTM) are used in many applications including earth sciences, environmental studies, engineering and modeling & simulation. The U.S. military is the leading consumer of digital terrain models, and was once the leading producer of digital terrain products. Military operation planning greatly depends on having a reliable and accurate understanding of the terrain. This includes detailed modeling of elevation, slope, and aspect, as well as the minute features contained therein. The military uses DTMs for visualization, inter-visibility analysis, virtual displays and line of site analysis.

A major challenge in the civilian and Department of Defense (DoD) simulation community's is the definition of a common environmental format. This includes activities like interoperability, data interchange, common formats and common data representations. There are numerous activities and organizations in DoD addressing these problems. Interoperability and interchange are often assumed to be synonymous concepts. People often inaccurately equate the ability to share data between two systems to interoperability between those systems. This is analogous to expecting French and Russian speakers to understand each other based solely on the premise that they possess the capability for speech. Robust interchange mechanisms are critical to system interoperability. Good interchange means using a mechanism that minimizes noise in the medium, employs clear, unambiguous syntax and semantics, and does not resort to cumbersome or unwieldy formats.

Clear and robust interchange does not guarantee interoperability. If two people speak the same language, are not impeded by noisy mediums, and use understandable words and phrases to form clear sentences, they still may not understand each other. One may be speaking about a subject that requires considerable background and context to be understood by the other. We recognize that with poor interchange mechanisms such exchanges would be even more difficult to comprehend. Good interchange is about clearly understanding data. Interoperability is about understanding the information that such data carries, and being able to act on it. Therefore, a good interchange mechanism becomes a pre-condition and a critical step to interoperability. We will discuss common data representations and data formats in Chapter III.

C. ADAPTIVE AND AUTONOMOUS MULTI-AGENT SYSTEMS

> If patterns of ones and zeroes were 'like' patterns of human lives and deaths, if everything about an individual could be represented in a computer record by a long string of ones and zeroes, then what kind of creature could be represented by a long string of lives and deaths?
>
> Thomas Pynchon, Vineland

Previous work in the extension of Irreducible Semi-Autonomous Adaptive Combat (ISAAC) was one of the driving factors in leading the author to choose this thesis topic. Multi-Agent Systems (MAS) distinguish themselves from traditional modeling techniques by emphasizing communications, interactions and adaptability between system elements [Ferber, 1999]. Agents are the primary elements used to represent a digital MAS world. Ferber provides the following set of descriptive characteristics that make up interactive agents [Ferber, 1999]: agents act within an environment given a set of resources; agent actions are driven by a function of their propensities; agents sense their environment within a prescribed set of limitations; agents behave in a way that best satisfies their objectives while self-monitoring resources and adjusting their goals and intentions based on how they perceive their environment. The author considers the last characteristic to be autonomous behavior. Agent parameters and characteristics drive the agent to conduct autonomous behaviors.

Ferber describes two methodologies for assigning agent intelligence: cognitive and reactive [Ferber, 1999]. Cognitive agents possess pre-coded goals and intentions that drive them to act in concert with their objectives. They possess the necessary rules to deal with any situation they may confront within their environment. Reactive agents display behavior by assimilating sensed environmental information. They do not react based upon pre-conceptions or a set of personal objectives. A well-designed MAS integrates both reactive and cognitive characteristics.

According to Ferber, agents are but one of the six elements that make up a MAS. Other MAS elements include: the environment, objects, relations, operations, and laws [Ferber, 1999]. The author will focus most of his effort on the concept of environment.

Environmental objects are situated and passive. The inability to dynamically interact separates the environment from agents. Agents are always *objects*, but objects are not always agents. *Relations* serve to describe the synergistic group effects and describe group interactions. *Operations* are rules that define agents' ability to manipulate objects and other agents. *Laws* are what Ferber defines as the portrayal of the MAS world reactions to attempted modifications of the overall system. Ferber's explicit and concise definitions of these elements clarify the process by which a MAS and adaptive, agent-based simulation could be used as a baseline to create a flexible, situated ground combat simulation.

D. IRREDUCIBLE SEMI-AUTONOMOUS ADAPTIVE COMBAT (ISAAC)

ISAAC is an agent-driven model developed to explore individual ground combat as a Complex Adaptive System (CAS). Dr. Andrew Ilachinski developed ISAAC for the Marine Corps Combat Development Command (MCCDC) in 1997. This research was commissioned by the U.S. Marine Corps to attempt to capture new concepts of land warfare [Ilachinski, 1997].

Most U.S. ground combat models are derived from Lanchester Equations [Lanchester, 1914]. These equations are based on relative combat power and mathematically derive the winner and loser of combat outcomes based on relative deterministic combat scores. Ilachinski hypothesized ground combat as a Complex Adaptive System. He viewed ground combat as a dynamic, non-linear system made up of many semi-autonomous entities interacting in an ever-changing situated environment. Lanchester attrition algorithms are still applied to modern warfare models even though minimal correlation exists between Lanchester algorithms and historical combat data. Ilachinski felt that aggregate Lanchester Equations poorly represented the autonomous and adaptive tactical operations of intelligent, ever-thinking soldiers on the battlefield. Ilachinski developed ISAAC for the U.S. Marine Corps to assist their analysts in the study of small-unit combat by illuminating specific aspects of emergent ground combat phenomena resulting from the collective, nonlinear actions of ground combat agents [Ilachinski, 1997]. Ilichinski uses a bottom-up approach to the modeling of ground combat, vice the more traditional top-down, aggregate approach. His work was an initial step toward developing a complex adaptive system capable of identifying, exploring, and exploiting emergent collective ground combat behaviors.

Ilachinski uses ISAAC Agents (ISAACAs) to represent combatant entities in his simulation. These agents adapt to their environment and react to the local information presented to them. Agent decision-making is decentralized and driven by the individual propensities for each ISAACA. ISAACA movement is nonlinear, adaptive and based solely on an agent’s attempt to satisfy its own goals and intentions (See Figure 2-3 for additional movement information). Figure 2-2 is a screen-capture of the ISAAC simulation interface.

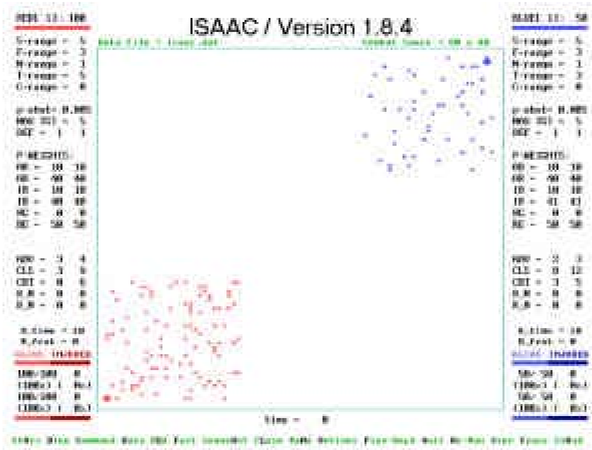

Figure 2-2. Screen-capture of the ISAAC Simulation (From: www.cna.org/isaac/sampscrn.htm)

The ISAAC situated environment is a flat, two-dimensional battlespace. Red and blue ISAACA's are placed at random around their friendly flag. Only one ISAACA may occupy any grid position at any one time. The goal of the simulation is to explore how the red and blue units interact while trying to capture the enemy's flag. A winner is determined when one side captures the enemy's flag or destroys all enemy ISAACAs. ISAACAs can be injured or killed by enemy fire. Diminished health levels (injured ISAACAs) affect agents' ability to sense, shoot, move, and communicate. Diminished ranges can have significant effects on what and how information is sensed and perceived by the ISAACAs. [Ilachinski, 1997].

ISAAC implements dynamic personality vectors to drive individual ISAACA behaviors. These personality propensities drive the movement and actions of each ISAACA. The vectors consist of six character traits: *alive friendly, alive enemy, injured friendly, injured enemy, red flag, or blue flag*. Movement is driven by their overriding personality trait. *Alive friendly* means the ISAACA will move toward a friendly agent. *Red flag* means the ISAACA will move toward the red flag. The user can adjust these personality attributes to explore different simulation adaptation patterns [Ilachinski, 1997].

ISAACA movement is initiated via the agent personality vector and calculated by a movement algorithm called the penalty function. The penalty function is a mathematical algorithm that calculates the next movement step based on the ISAACA's overriding personality trait. At each ISAACA turn, the simulation calculates the penalty function for each possible movement location (See Figure 2-3). The ISAACA moves to the grid location with the smallest penalty function value not already occupied by another ISAACA. This location best satisfies the ISAACA's goals and personality vector.

Figure 2-3 is an example of a single ISAACA movement step. The 7 x 7 grid is the ISAACA sensing area. The ISAACA has nine movement choices (shaded area of Figure 2-3). It can move into one of eight grid squares or remain in its current location. The penalty function takes into consideration the agent's overriding personality vector and the data sensed about nearby agents, agent statuses, and distances to both flags. The penalty function calculates a value for each of the nine movement choices. The grid square with the lowest penalty function value is selected for the next move.

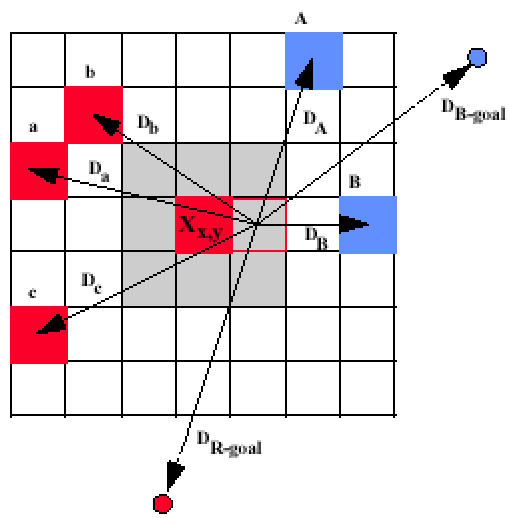

Figure 2-3. Sample Penalty Calculation (From: Ilachinski, 1997)

In 1999, the author extended the ISAAC work with three other NPS graduate students. The group created a similar simulation with two simple rules: move towards the enemy flag; if there is an enemy within sensing range, attack the enemy. The group discovered organized military movement patterns evolved out of these simple behaviors [Tanner, 1999]. These movement patterns were not explicitly coded into the simulation (See Figure 2-4, Multi-Agent System Testbed).

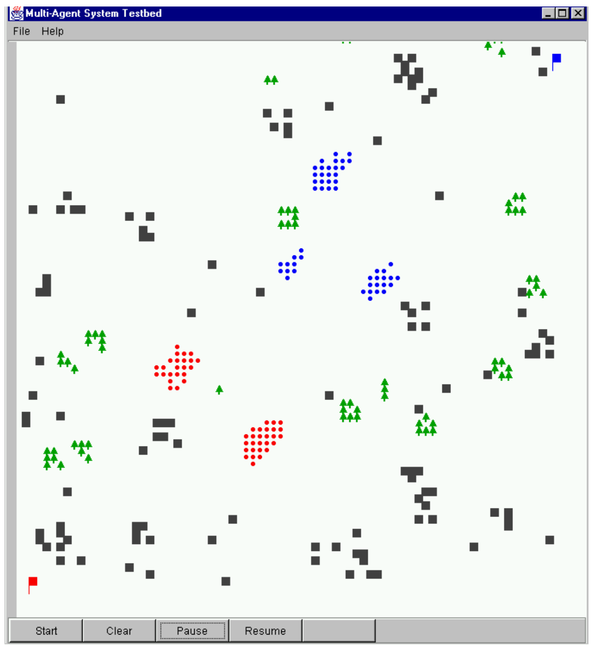

Figure 2-4. Multi-Agent System Testbed (From: Tanner, 1999)

Over the past 4 years, numerous students at the Naval Postgraduate School have extended Dr. Ilachinski's modeling methods. NPS research in agent decision-making has been tremendous. Student research in MAS's has contributed to the development of automated route planning algorithms, leadership algorithms, reconnaissance algorithms, helicopter planning research, and ground combat tactics research. Most of the prior NPS research projects have used student-built (made-up) gridded terrain models to conduct their analysis. Without using real terrain models, analysis is difficult to apply to real world application. The significance of engaging the MAS Testbed on real, digital terrain is critical, as it quickly transitions theoretical agent work into real world application.

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III. DATA REPRESENTATIONS

A. INTRODUCTION

This chapter describes the mainstream data representations and formats available to the military and civilian developer. A tremendous number of terrain data representations exist for a myriad of uses. This chapter discusses common data representations, the availability and ease of use of each data representation type, and the organizations involved in developing the mainstream common terrain data formats. The most common terrain data representations are: gridded, raster (dumb data), vector (smart data) and imagery. This chapter will discuss each type and provide recommendations on specific data representations.

B. TERRAIN REPRESENTATIONS

Digital terrain data representations are produced by a variety of government and private institutions. National Imagery and Mapping Agency (NIMA) and U.S. Geological Survey (USGS) are two of the most prominent suppliers of terrain data for the government developer. It is often a very difficult task to identify and obtain the most appropriate representation for the terrain information desired. Very often, the success of a simulation tool depends on the accuracy and fidelity of the data used. Terrain data is available in many common representations with each having its own pros, cons and uses. Data representations include: gridded, raster, vector, or imagery (this list is not inclusive). These representations are discussed in this chapter.

1. Gridded Representations

Gridded representations are a rectangular grid of evenly spaced elevation values and are probably the most commonly used digital terrain modeling structures. This is a popular representation because data is structured similarly to the manner in which data is stored on the hard drive of a computer. Elevations are normally stored as a two-dimensional array, and every elevation point is assigned a row and column location. Due to the similarity of data structures, each data point is recorded implicitly with no special encoding of data. This makes data retrieval very simple. The most common types of gridded representations are Digital Terrain Elevation Data (DTED) and Digital Elevation Models (DEM).

a. Digital Terrain Elevation Data (DTED)

Digital Terrain Elevation Data is a gridded representation produced by NIMA. DTED data graphically defines terrain elevation, slope, or surface information. DTED is proposed in 5 levels (See Figure 3-1). Only DTED0 and DTED1 are available for all areas of the world. DTED2 is available for limited areas and is no longer being produced. SRT-2 (Shuttle data) is 30-meter resolution data now being developed in lieu of DTED2. DTED data is photo derived, SRT-2 data is radar derived. The SRT-2 data will eventually become the 30-meter benchmark data standard for M&S and other uses. Certain areas (e.g. canopy forests) may not be accurately captured using the SRT-2 data and accuracy modifications may need to be made. SRT-2 data is still being evaluated as to its accuracy and ease of use for application development. North and South America are being produced first (available summer 03) followed by the other continents.

DTED Level	Post Spacing/ Ground Distance	Data Points (for one degree by one degree cell)	Storage Space
DTED Level 0	30 arc seconds (~1 kilometer)	150 Thousand data points	500 KB
DTED Level 1	3.0 arc seconds (~100 meters)	1.5 Million data points	5 MB
DTED Level 2	1.0 arc seconds (~30 meters)	13 Million data points	54 MB
DTED Level 3	0.3333 arc seconds (~10 meters)	144 Million data points	583 MB
DTED Level 4	0.1111 arc seconds (~3 meters)	1.3 Billion data points	6,297 MB
DTED Level 5	0.0370 arc seconds (~1 meter)	11.6 Billion data points	68,000 MB

Figure 3-1. DTED Level 0-5 Post Spacing

Figure 3-1 estimates the data points and hard drive space necessary to store a one-degree cell (60 square nautical miles at the equator) of DTED data.

DTED1 is a medium resolution elevation source for all systems that require landform, slope, location and terrain roughness. DTED1 is made up of terrain elevation values with a post spacing of 3 arc seconds (approximately 100 meters). The graphic resolution is approximately equal to the contour information represented on a 1 to 250,000-scale paper map.

DTED2 is a high-resolution elevation source for military activities and systems. DTED2 has a post spacing of 1 arc second (approximately 30 meters). The graphic resolution is approximately equal to the contour information represented on a 1 to 50,000-scale paper map.

DTED levels 3-5 are proposed by NIMA, but are not currently being produced. All DTED is Limited Distribution for government and contractors.

NIMA has ever-increasing demands for higher terrain data resolutions. Faster processors and increased storage capacity is prompting users to demand higher fidelity digital terrain data. DTED1 and DTED2 data is available on CD and can be ordered by government users directly from NIMA. Expect a two-three week turn-around time when ordering terrain CD's from NIMA. NIMA will also entertain requests for higher-level resolution data if the user is willing to pay NIMA to produce the data.

b. Digital Elevation Model (DEM)

DEMs are a gridded representation produced by the U.S. Geological Survey (USGS) as part of the National Mapping Program. DEMs are sold in 7.5-minute (30 x 30 m data spacing), 1-degree units (3 x 3-arc-second data spacing), and 30-minute DEMs (also known as 2-arc-second data spacing). The 7.5 minute DEMs are included in the large-scale category, the 2-arc-second DEMs fall within the intermediate scale category and 1-degree DEMs fall within the small-scale category. The DEMs come in sample spacing of three arc seconds (70-90 meters).

DEM's are available from USGS on 9-track, 8mm, and 3480 cartridge tape. 1-degree DEM's can be downloaded for free via FTP (File Transfer Protocol). The 7.5-minute and 2-arc-second DEM's are available over the Internet via FTP. For more information about current pricing and distribution contact any **Earth Science Information Center** or call **1-888-ASK-USGS**. You may aso purchase a two CD-ROM set of 1- by 1-degree DEM's of the United States for $45.00 from http://www.geodatas.com/.

The USGS plans to convert all DEM products to the Spatial Data Transfer Standard (SDTS) format and offer data free over the Internet. SDTS is the transfer mechanism for all Federal agencies and provides automatic transfer of data between dissimilar computer systems. More information about the SDTS and the Federal Processing Standard 173 can be found on the **SDTS Home Page**.

2. Raster Representations

Raster data consists of spatially coherent, digital numeric data, derived from numerous sources including sensors, scanners, and other mediums. Spatial features can be modeled with grids or pixels. Raster files store only one attribute, which is in the form of a "z" value or color value. ARC Digitized Raster Graphics (ADRG) is a digital image created by scanning a flat lithographic paper map or chart. NIMA produces ADRG datasets by scanning maps and geometrically re-sampling them into an equirectangular projection, so that they may be indexed with WGS84 geographic coordinates. The scale for one map is 0.2 degrees per pixel horizontally, 0.1 degrees per pixel vertically. The data is normally stored and described in the standard Tagged-Image File Format (TIFF) specification. The Geographic-TIFF (GeoTIFF) representation was an effort by over 160 different cartographic and surveying organizations to establish a TIFF based interchange representation for geo-referenced raster imagery. Raster data values are organized into two-dimensional arrays; the indices of the arrays are used as coordinates. There may be additional indices for multi-spectral data.

a. ARC Digitized Raster Graphics (ADRG)

A common NIMA raster representation is ADRG. It can support Mission Planning Systems, Moving Map Displays, Command and Control Information Systems and Situational Background displays.

The original source graphics for ADRG data were scanned at a 100 micron (μ) pixel resolution (254 pixels per inch) in both East-West and North-South directions, and then warped from the datum of the original paper map or chart to the ARC projection using the WGS-84 ellipsoid. To digitally replicate the hard copy source graphic three raster images are created of red, green, and blue pixels that when combined produce a multicolored graphic of up to 16 million different color combinations.

Currently, all ADRGs are created at NIMA St Louis with the current production being about 6,700 ADRG CD ROMs. Figure 3-2 lists the number of map sheets that fit on a CD-ROM along with approximate coverage of a particular series.

ADRG Chart Type	Scale	Media	Coverage
Global Navigation Chart (GNC)	1:5,000,000	1 per CD ROM	World Coverage
Jet Navigation Chart (JNC)	1:2,000,000	1 per CD ROM	World Coverage
Operational Navigational Chart (ONC)	1:1,000,000	1 per CD ROM	80% Landmass
Tactical Pilotage Chart (TPC)	1:500,000	1 per CD ROM	80% Landmass
Joint Operations Graphic (JOG)	1:250,000	4 per CD ROM	20% Landmass*
Topographic Line Map (TLM)	1:50,000	1-6 per CD ROM	5% Landmass
Topographic Line Map (TLM)	1:100,000	1-9 per CD ROM	5% Landmass
City Graphic (CG)	varies	1 per CD ROM	1% Landmass
Hydrographic (ACO)	varies	varies per CD ROM	1% Ocean

Figure 3-2. ADRG Chart Coverage

*The paper coverage of the JOG series is much more extensive than the ADRG coverage. Consult the Digital Data Products Quarterly Bulletin for the latest listings (NSN# 7643-01-429-6984) – (From: www.nima.mil/publications/vepgdb/vep1.html)

Today, the main purpose for ADRG is to support Compressed ADRG (CADRG) production. There is a more detailed description of CADRG in the next paragraph. ADRG data can be used to support both operational and logistical military problem sets. Previous uses of the product include: Air Force Mission Planning using the FalconView application, a Moving Map Display in the E3 Airborne Warning and Control System (AWACS) and Land Resources Satellite Multispectral Imaging (LandSat MSI) registration by Army Terrain Teams.

ADRG is often a difficult data representation to work with. It is very high quality and very dense. Quality might be mitigated due to the difficulty to use. ADRG data sets are designed to be seamless; unfortunately, gaps often exist because of datum differences between source graphics and missing source material. There may also be overlaps in border areas as a result of multiple datums in use in the same area. ADRG features often look distorted. This occurs in the conversion process from the source map projection to the rectangular Arc-Second Raster Chart (ARC) projection. In each non-polar zone (-80 degrees South to +80 degrees North) distortion occurs when moving in an East-West direction as you move away from the center parallel that is used for the baseline projection. As much as 18.03% stretching can occur as you move poleward; conversely, 18.03% shrinkage can occur as you move equatorward.

The ADRG catalog is organized by scale and purpose. The best way to find and order ADRG data is using the NIMA ADRG specifications and catalog at www.nima.mil/ocrn/nima/pub.html.

b. Compressed ARC Digitized Raster Graphics (CADRG)

CADRG is another NIMA raster representation. It is derived by down sampling, filtering, compressing, and reformatting ADRG to the Raster Product Format (RPF) Standard. It is designed to be a seamless library. The edges of contiguous source maps are normally indistinguishable, except by color variations in the original source graphics. Some gaps in coverage still exist, primarily where source coverage does not exist over oceans, nonexistent charts and datum errors. CADRG is National Imagery Transmission Format (NITF) compliant.

CADRG is a 55:1 reduction in size compared to source ADRG. When complete, the CADRG dataset will consists of approximately 250 CDs. A good portion of the CADRG data was designed to support the Air Force and Navy NAVPLAN (approximately 50 CDs). The data contains a configuration control mechanism that supports updating with Digital Chart Update Manual (DCHUM) data. CADRG offers distinct operational, logistical, and supportability benefits to many users of digitized map/chart and imagery data.

3. Vector Representations

Vector data represents points (no dimensions); lines or arcs (1 dimension); and areas or polygons (2 or 3 dimensions). Points are used to describe lines and lines are used to describe polygons. Each point, line and polygon is an individual feature with its own attributes.

Vector Map (VMap) data comes in levels 0 through 2. VMAP0 is a 1:1,000,000 scale vector base-map of the world. VMAP0, previously named Digital Chart of the World (DCW®), provides worldwide coverage of vector-based geo-spatial data. The primary source for the database is the 1:1,000,000 scale Operational Navigation Chart (ONC) series co-produced by the military mapping authorities of Australia, Canada, United Kingdom, and the United States. The database is organized into 10 thematic layers. These layers include major road and rail networks, hydrologic drainage systems, utility networks (cross-country pipelines and communication lines), major airports, elevation contours, coastlines, international boundaries and populated places. VMap is used in many geographic information system (GIS) applications.

VMAP1 is a very popular product. VMAP1 graphic resolution is approximately equal to the contour information represented on a 1 to 250,000-scale paper map. VMAP2 provides very limited coverage. VMAP2 graphic resolution is approximately equal to the contour information represented on a 1 to 50,000-scale paper map. VMap Level 0's world coverage is divided into four libraries based on geographic areas. The geographic areas and library names, by disk, are: Disc 1 - North America (NOAMER); Disc 2 - Europe and North Asia (EURNASIA); Disc 3 - South America, Africa, and Antarctica (SOAMAFR); and Disc 4 - South Asia and Australia (SASAUS). The data structure is Vector Product Format (VPF) to US Military Standard (MIL-STD-2407), which is compliant with the international standard, Digital Geographic Information Exchange Standard (DIGEST) Annex C. The VMap Level 0 feature and attribute content is defined in the US Military Specification for VMap Level 0 (MIL-V-89039). Application software (VPFVIEW V2.1) to view VMAP data can be downloaded from the NIMA website (http://www.nima.mil). There are many other vector products out available for use. Only the widely used formats have been mentioned here.

4. Imagery Representations

Imagery representations are normally created using aerial photographs that have been rectified to have the scale and geometry of a map. Seamless orthophoto datasets can be made from rectified grayscale aerial images. These datasets can support various weapon systems, Command, Control, Communications and Intelligence (C3I) Systems, mission planning systems, digital moving map displays, terrain analysis, simulation, and intelligence systems.

Digital Orthorectified Imagery 10-meter (DOI 10) data are derived from digital images that are compressed and reformatted to conform to the Raster Product Format (RPF) Standard. This data consists of unclassified seamless orthophotos, made from rectified grayscale aerial images. DOI 10 files are physically formatted per the National Imagery Transmission Format (NITF). The DOI 10 may be derived from a grayscale image, from one band of a multispectral product, or from an arithmetic combination of several multispectral bands.

Controlled Image Base (CIB) is an orthorectified, panchromatic (single color) imagery format published by NIMA to allow the distribution of large areas of tiled imagery. CIB data is structured using the NIMA RPF. CIB comes in a number of resolutions including CIB-5 and CIB-10, which are standard 5-meter and 10-meter resolution. Higher resolutions can be developed based on customer demand. CIB is NIMA's primary mechanism for distributing satellite imagery.

CIB images are gray-scale (monochromatic), although the input for CIB can be multispectral. The CIB may be derived from a gray-scale image, from one band of a multispectral product, or from an arithmetic combination of several multispectral bands. Processing involves projecting the image data into the Equal Arc-second Raster Chart/map (ARC) system, grouping pixels into frames and sub-frames of constant size and vector quantization image compression.

CIB has been used for C4I systems and image exploitation, rapid analysis of areas of operation, as a map substitute for emergencies and crises, as a metric foundation for anchoring other data, for texturing images in terrain visualization, and as an image background for mission planning and rehearsal. It is capable of supporting C3I systems, mission planning, terrain analysis, simulation, and intelligence analysis.

5. Other Popular Representations

a. Global 30-Arc-Second Elevation Data Set (GTOPO30)

Global 30-Arc-Second Elevation Data Set (GTOPO30) was completed in 1997 after 3 years of work at the U.S. Geological Survey's EROS Data Center in Sioux Falls, South Dakota. GTOPO30 DEM was derived from eight data sources. The primary data source is DTED level 1, but gaps in the DTED data are filled with data from other sources. Often Digital Chart of the World (DCW) contour data is used to fill in these gaps. GTOPO30 is 1000 meter post spacing, thus has limited utility to high fidelity combat modeling.

The GTOPO30 global data set covers latitude from 90 degrees South to 90 degrees North and longitude from 180 degrees West to 180 degrees East. The horizontal grid spacing is 30-arc seconds (0.008333 degrees), resulting in a DEM dimension of 21,600 rows by 43,200 columns. The horizontal coordinate system is decimal degrees of latitude and longitude referenced to WGS84. The vertical units represent elevation in meters above mean sea level. The elevation values range from -407 to 8,752 meters. In the DEM, ocean areas have been described as *no data* areas and are thus assigned a value of -9999. This is to ensure that low-lying coastal areas with an elevation of at least 1 meter will be maintained. For simplicity and to better support the raster structure, small islands in the oceans less than 1 square kilometer are not represented.

GTOPO30 is been divided into 33 segments called tiles. The area from 60 degrees South latitude to 90 degrees North latitude and from 180 degrees West longitude to 180 degrees East longitude is made up of 27 tiles. Each tile covers 50 degrees of latitude and 40 degrees of longitude. There is no tile overlap thus; by abutting adjacent tiles a complete global data set may be assembled.

The GTOPO30 data has been used for many applications, including climate modeling, continental-scale land cover mapping, extraction of drainage features for hydrologic modeling, and geometric and atmospheric correction of medium and coarse-resolution satellite image data. GTOPO30 uses the Global Land Information System (GLIS) and the EOSDIS Information Management System (IMS) for interactive query and visualization. Data can be ordered on 8MM tape, CD, DVD or via FTP from the USGS website at http://edcdaac.usgs.gov/gtopo30/form.html. Data sizes come in one Global granule per 8MM tape, pre-defined tiles on CD, all global granules on one DVD and pre-defined tiles via FTP. Costs are $15 per 8MM tape, $10 per CD, $25 per DVD and no charge for FTP. To search for a specific CD number for the tile you are interested in, use the GTOPO30 Index Map located at http://edcdaac.usgs.gov/gtopo30/gifs/cds.gif.

b. Triangular Irregular Network (TIN) Data

TINs are one of the more common data representations used for Modeling & Simulation (M&S) analysis because the CPU cycle savings in graphic depiction helps create better throughput for simulation runs. The triangular irregular network model consists of a network of interconnected triangles with irregular spaced nodes or observation points. The model stores coordinate information using x, y, and z locations. The desirable feature of this data structure is its ability to store more information in areas of complex relief. It tends to reduce the amount of redundant data for areas of simple relief. The downside is that algorithm development is very complex because of the random positioning of each of the data points creating complex interpolation.

Computer cartography has a problem of how to store and quickly retrieve terrain elevation postings. An obvious method is to create an array of heights for each grid location. This often takes a tremendous amount of space. One optimization technique involves approximating the surface structures with a TIN. 1) Initially, one approximates the map using a square with 2 triangles, 4 points, and 5 edges. 2) We then find the most deviant point in either triangle and split that triangle into 3 triangles by inserting a new point and 3 edges. 3) One then checks all quadrilaterals composed by the new triangle and the old triangle to see if the diagonal should be swapped. 4) Finally, we find the new most deviant point. 5) Repeat.

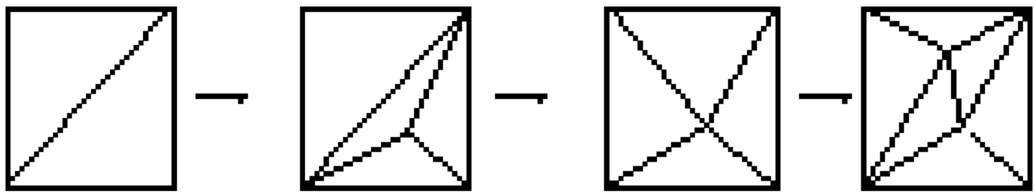

Figure 3-3. Inserting Points Into a Triangulated Irregular Network

Although a popular and easy to use M&S technique, there are accuracy concerns using tinning techniques. Different tinning algorithms may give different representations of the same landscape. Developers must be careful in how these algorithms are used and what applications they are used for. The Army M&S community should look carefully at this problem.

6. Data Representation Analysis

Figure 3-4 provides an analysis of the pros and cons of using gridded, raster and vector data representations. Not all representation types are the same. This quick reference guide is simply to provide the developer a general set of guidelines in choosing the correct data representation to match the problem set.

	PROs	CONs
GRIDDED	• Stored like computer • Simple data structure • Easy to acquire • Fairly easy to put into an M&S tool • Close to global coverage	• Data/CPU intensive • Missing or sparse data difficult to fill-in • Standard visualization algorithms often fail when there are missing data points
RASTER	• Very high quality data (dense) • Can be very good for visualization • Good for complex analysis • Common data structure for imagery • Good for overlay use	• Large datasets • Difficult to make line of sight and physics calculations in M&S • Can become distorted when moving away from equator (18% stretching) • Can be difficult to work with • Gaps and overlaps exist in coverage
VECTOR	• Smart data • Good for spatial analysis and land representation • Thematic layers include road and rail, hydrologic, utility networks, international boundaries and built-up areas • Compact data storage	• Complex structure • Lacking coverage • Can be difficult to use in M&S • Polygon errors may give false impression of accuracy • Overlay building difficult

Figure 3-4. Data Representation Quick Reference Guide

The author's recommendation for a baseline data representation used for developing an agent-based M&S environment is gridded data. Gridded data is an excellent baseline data for developing a ground-combat M&S environment. The data is stored in an array or a matrix, very similar to the way the computer stores data. The simple storage structure makes the gridded data much easier to use than raster or vector data. There is nearly global coverage for 30-meter terrain. This makes it a good choice for developing M&S analysis tools for nearly any place on earth.

7. Ordering Common Terrain Products

The Department of the Interior, U.S. Geological Survey (USGS) is the distributor of public sale NIMA topographic maps, publications and digital products. To order, contact:

USGS Branch of Information Services
Map and Book Sales
Federal Center, Building 810

P.O. Box 25826
Denver, CO 80225
Phone: (888) ASK-USGS or (303) 202-4700
Internet: www.usgs.gov

C. DATA FORMATS

1. Vector Product Format (VPF)

The Vector Product Format (VPF) allows software applications to read data directly without prior conversion to an intermediate form. VPF uses tables and indices to allow direct access to spatial location and thematic content. VPF defines data object format and the georelational data model defines the data organization how the application can interact with VPF data objects. A Product Specification defines the contents of the feature tables and their relationships in the database. VPF data is compatible with a wide range of applications and products.

The Vector Product Format, MIL-STD-2407 specifies how the structure for directories, tables, table columns, table join relationships, and media exchange conventions is defined for all VPF data. VPF is made up of three data structures: Directories, Tables, and Indices. These are organized into several hierarchical directories. The directories consist of ASCII or binary tables. Feature, attribution, location, geometry, and topology information are stored in specific VPF tables. Indices are special kinds of tables consisting of pointers to other tables and records.

VPF data is made up of location, geometry, and topology of an area, line, point, and text features that describe an area. Data are stored in the lowest level VPF structure, to facilitate faster access to primitive data. Most VPF products are tiled, meaning the library is divided into equal sized areas. The VPF structure is a relational structure. Relationships and pointers are defined in various tables where attributions of geospatial features of the topology are located. Without relational structures, the data would contain only a simple geometry of the features, not the topology. The topology feature makes VPF products attractive to developers and users of Geographic Information Systems (GIS) where spatial analysis is important.

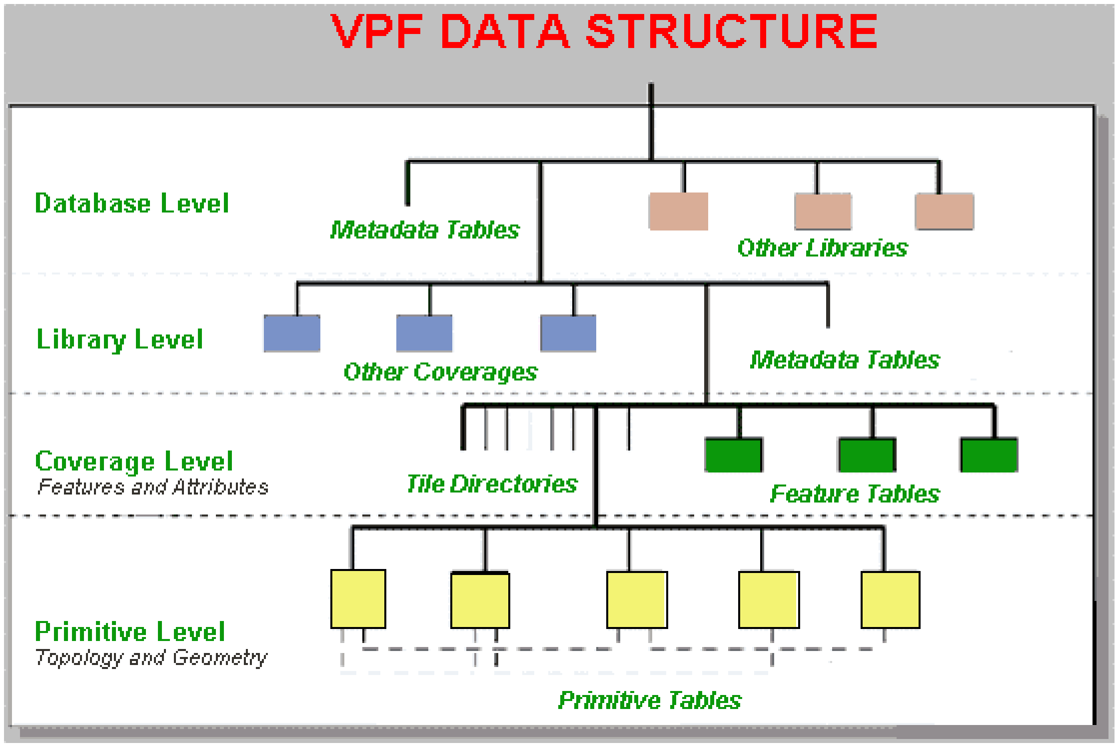

Figure 3-4. VPF Data Structure

There are several types of VPF products of different levels of fidelity. Military Standard, Vector Product Format, MIL-STD-2407 describes the structure and format conventions which must be met for a dataset to be considered VPF data. The "Product Specification defines the specific contents which make up a particular VPF product. This includes which features, attributes, and attribute values will be included, as well as how the features will be grouped into coverages and what tiling scheme will be used.

Several VPF products are being produced by NIMA, commercial VPF providers, and mapping agencies in several countries throughout the World. For more information about the current suite of VPF products, the Geospatial Standards and Specifications web page contains a list of many NIMA product specifications, with downloadable specifications.

2. Raster Product Format (RPF)

RPF is the standard exchange format for CADRG and ADRG representations.

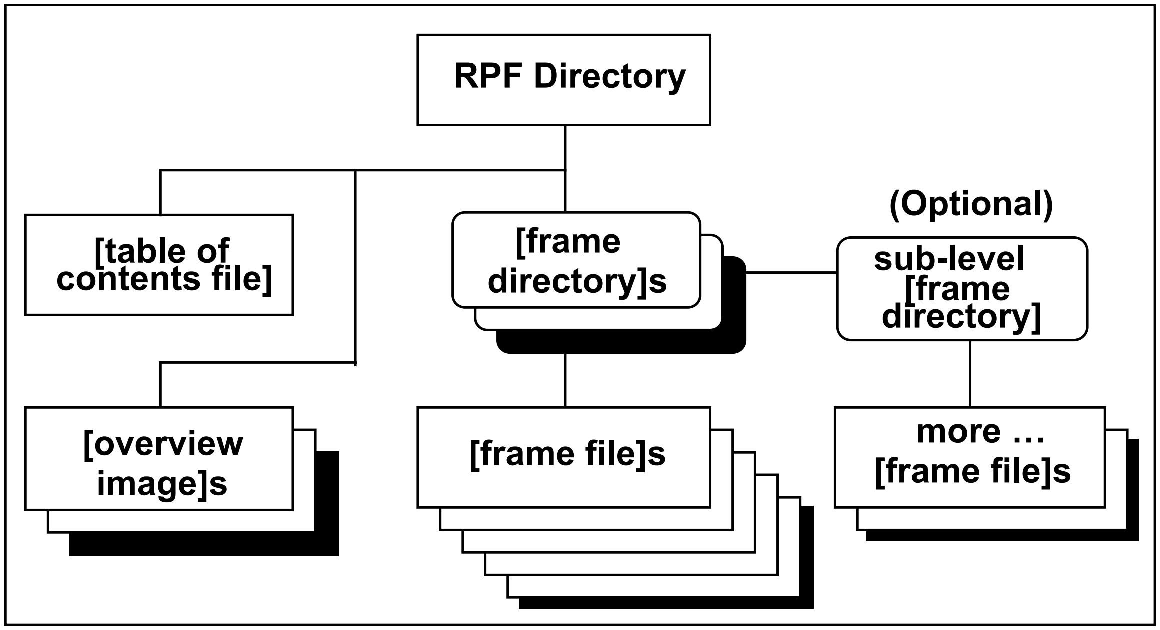

Figure 3-5. Representation of RPF Directory and File Structure

3. National Imagery Transmission Format Standard (NITFS)

The National Imagery Transmission Format Standard (NITFS) is the standard format for the exchange of digital imagery and imagery related products for the DoD Intelligence Community. DoD uses this interoperability standard for formatting, transmitting, receiving, exchanging and processing imagery–related information. The NITSF has evolved over time to meet the needs of user systems.

D. DEVELOPMENT OF COMMON DATA MODELS

Much work is done every year to create high fidelity environmental models. Unfortunately, most of this work is proprietary and unusable for other modeling and simulation activities. A tremendous amount of work is undertaken every year to create unique conversions between specific simulation systems to share environmental data. The simulation community is still a long ways from creating common standards planners and programmers can use to describe physical environments across different programming and design platforms. This section discusses two groups addressing interoperability problems between and C4I and M&S communities.

1. Environmental Database Integrated Product Team (EDBIPT)

EDBIPT is an Army Modeling and Simulation Office (AMSO) sponsored organization chartered to identify terrain and environment standards the Army must develop to generate, maintain, use and re-use accurate and realistic Synthetic Natural Environments. These solutions must be cost effective and support a wide variety of warfighter applications. This includes synthetic environmental support to M&S and C4I Systems.

Focus areas of the EDBIPT include:

- Interoperability of environmental databases (EDB) and associated algorithms (e.g., effects of weather and soil content on trafficability).
- Interoperability between M&S systems and C4I systems.
- Rapid and inexpensive processes for data and model development and reuse.
- Development of an EDB repository and efficient check-in/out procedures.
- Development of dynamic, multi-resolution, and interoperable pre-simulation and runtime editors to allow on-demand updates of the battlespace environment.
- Identification of Research and Development (R&D) investment areas to solve key technical challenges.
- Integrated activities with NIMA, TEC, AMSO, DMSO, industry, and other key stakeholders.

The EDPIPT goals and objectives include (but are not limited to):

- Promote dynamic, multi-resolution, and interoperable digital environments for Army M&S and C4I systems.
- Develop a common set of Joint environmental requirements based on common authoritative data (i.e., NIMA, NMOC, AFCCC, TEC. Etc.).
- Establish a standardized set of data processing procedures and tools.

- Coordinate with the providers of authoritative data to develop and promote rapid and inexpensive procedures to generate EDBs to support M&S and C4I systems.

- Establish production, co-production and re-use standards for EDBs and models.

- Develop a repository to capture and catalog newly developed environmental data, algorithms, and models including the documentation and associated metadata.

- Promote the development of common dynamic environmental representations and low-cost HLA compliant mechanisms to support M&S and C4I systems.

- Coordinate with the Simulation to C4I Interface (SIMCI) IPT to assure both groups are pursuing synergistic efforts to best serve the Army's M&S and C4I communities.

- Pursue cost effective Commercial Off the Shelf (COTS) applications to promote evolving.

The EDBIPT is responsible for Department of the Army (DA) level recommendations to the Army Model and Simulation Executive Council (AMSEC) for all terrain and environment standardization initiatives. These initiatives drive the policies and action plans needed to meet the Chief of Staff of the Army (CSA) guidance on developing accurate, cost-effective environment data in support of training and operational requirements.

2. SEDRIS

The Synthetic Environment Data Representation and Interchange Specification (SEDRIS) project was developed to create an all-encompassing data model that articulates terrain, ocean, and atmospheric data in a common interchange format. SEDRIS is an infrastructure designed to enable applications to express, understand, share, and reuse environmental data. SEDRIS was spawned by the need of the modeling and simulation community to find a common set of data standards to meet the interoperability needs of both the M&S and C4I communities. SEDRIS specifications are applicable across the analysis, training, and acquisition communities.

In the 1980's, Project 2851 and the Defense Advanced Research Projects Agency (DARPA) Simulation Network (SIMNET) program highlighted the need for a solution to the long-standing and complex environmental representation problem. Project 2851, a joint service program lead by the Air Force, was primarily concerned with virtual database development. The SIMNET program had an additional requirement of integrating networked simulation with both visual and non-visual environmental applications.

SEDRIS was sanctioned in 1994 by the Simulation, Training, and Instrumentation Command (STRICOM) and DARPA to tackle the complex problem of environmental representation and data interchange. Initially, the SEDRIS group focuses their efforts on the following specific requirements: an environmental framework, an open exchange mechanism to support distributed simulation processes, a means of integrating the different views of air, land, sea, space, and coordinate systems. The natural evolution of these requirements was the need for a common data representation model for everyone. This could only be accomplished through collaborative efforts between academia, government, and industry. The Defense Modeling and Simulation Office (DMSO) became the sponsoring organization.

The greatest challenge for SEDRIS is how to represent and share environmental data that is both efficient in practical use and also specific enough to address the needs of a myriad of applications. One of its biggest challenges is to find common definitions and semantics between the services, the metrological and oceanographic communities, the simulation communities (both military and commercial), the GIS (or more broadly the environmental information systems) community, and the C4I community and others who needed to communicate environmental data.

A question implicit to this process was how SEDRIS can break down barriers between the stovepipe views of the environment, and provide a mechanism allowing for integrated environmental data to be represented.

A one-week SEDRIS conference each year brings together all of the government and civilian institutions to evaluate where they are at and discuss the road ahead for the upcoming year. This is a great data interchange between many organizations that have digital terrain and environmental requirements.

The following two figures (Figure 3-6 and 3-7) offers two quick reference guides. Figure 3-6 is a data representation key. This chart shows the more common data representation types and their abbreviations. Figure 3-7 is a quick reference guide showing the more common data representations scale and fidelity.

Raster Representations		
	Compressed ARC Digitized Raster Graphics	CADRG
	10 Meter Controlled Image Base	CIB10
	5 Meter Controlled Image Base	CIB5
	1 Meter Controlled Image Base	CIB1
	National Imagery Transmission Format	NITF 2.0
	ARC Digitized Raster Graphics	ADRG
	Geo-Tiff	TIF
Vector Representations		
	Digital Chart of the World	DCW
	World Vector Shoreline Plus	WVSPLUS
	Vector Smart Map Level 0	Vmap0
	Vector Smart Map Level 1	Vmap1
	Vector Smart Map Level 2	Vmap2
	Urban Vector Smart Map	UVMap
	Digital Nautical Chart	DNC
	Littoral Warfare Data	LWD
	Tactical Ocean Data	TOD
	Vector Interim Terrain Data	VITD
	Feature Foundation Data	FFD
	ESRI Shape Files	Shp
Elevation Models		
	Digital Terrain Elevation Data	DTED
	Digital Bathymetric Database – Variable	DBDBV
Text		
	Digital Aeronautical Flight Information File	DAFIF
	Airfield Data	AAFIF
	Geographic Names database	GeoNames

Figure 3-6. Data Representation Types

DATA TYPE	DATA REPRESENTATION	DATA RESOLUTION	MAP SCALE (Approx.)
GRIDDED	**DTED**		
	DTED0	1000 meters	1:1,000,000
	DTED1	100 meters	1:250,000
	DTED2	30 meters	1:50,000
	DEM		
	30 minute	90 meters	1:250,000
	7.5 minute	30 meters	1:100,000
RASTER	**ADRG**		
	JNC	2500 meters	1:2,000,000
	ONC	1000 meters	1:1,000,000
	JOG	100 meters	1:250,000
	TLM	30 meters	1:50,000
VECTOR	**VMAP**		
	VMAP0	1000 meters	1:1,000,000
	VMAP1	100 meters	1:250,000
	VMAP2	30 meters	1:50,000
IMAGERY	**CIB**		
	CIB 10	10 meters	1:25,000
	CIB 5	5 meters	1:10,000
	DOI 10	10 meters	1:25,000

Figure 3-7. Data Representation Scale and Resolution

IV. TERRAIN MANIPULATION TOOLS

A. INTRODUCTION

The intent of this chapter is to investigate the utility and potential of various terrain manipulation tools currently available to military modeling and simulation developers and analysts.

The tools explored were:

SOCETSet
SOCETSim
Falcon View
EdgeViewer
TerraTools
Sitebuilder 3D
PVNT
ARCGIS
Other Tools: Joint Mapping Toolkit, ArcExplorer, OpenMap, MapInfo ProViewer, ERDAS ViewFinder, Geomedia Viewer, MicroDEM / TerraBase II

B. ANALYTICAL METHOD

The following criteria were used to evaluate each tool:

1. Cost

Estimated cost to purchase the product for a government or educational institution.

2. Manufacturer

Company responsible for the development, upgrade, maintenance and sale of the product.

3. System Requirements

Specifications of the computing requirements necessary to adequately run the product. This includes processor speed, operating system options, hard drive space, RAM requirements, and any other software needed to run in support of the application. The author is including recommended system specification and the minimum system specification necessary to successfully support the product.

4. Data In

Data formats the product/application can import and understand.

5. Data Out

Data formats the product/application can export to other products.

6. System Description

Detailed description of what the application is designed to do. This includes what the system manufacturers claim it does better than its competition or what it can do that other applications cannot.

7. Integration with Other Tools

Lists what other tools the application can easily interact with, share data back and forth with or work with in an integrated fashion.

8. What Does it do Better Than Other Tools

Describes the most desirable product/application attributes and what the application does better than other similar tools.

9. Time to Learn

The author's opinion on the necessary learning curve to become adequately capable of leveraging product attributes.

10. Potential Uses

Describes how the product/application may be leveraged to support military, government, and civilian applications.

11. Where to Get a Demo Version

Lists points of contact to send for a demo or evaluation version of the product/application; also lists sources for additional information about the product/application.

C. PRODUCT ANALYSIS

1. SOCETSet – Digital Photogrammetric Software

a. ***Cost:*** $20,000 – 30,000.

b. ***Manufacturer*****:** BAE Systems.

c. ***System requirements*****:** PC: Dual Pentium (or single 2 Ghz), 512 MB RAM, 20GB HD

d. ***Data in*****:** All standard classified and unclassified Imagery sources (TIFF, SUNRASTER, NITF, Plain Raster, Targa, VITEC, TIFF-JPEG, BIL) including SPOT, LandSAT, JERS and IRS. Spectral sources include: IR, EO, RADAR, HSI and MSI. Other sources include: DTED, USGS (DEM and DOQ), ASCII DTM, GeoTIFF, DXF AutoCAD Vector, and ArcInfo GIS.

e. ***Data out*****:** OpenFlight, OpenInventor, ArcInfo ESRI, DTED, USGS DEM, Feature ASCII, AutoCAD DXF Vector, Microstation DGN Export, ArcGrid, ArcCoverage, Terrain Contours, SDE, and Triangulation Data; Image exports: Image map, USGS DOQ, GeoTiff, NITF, Anaglyph Stereo, Multi-Spectral Sharpening, Layer Mosaicking, Image Balancing, MPEG Videos, Photo-realistic video.

f. ***System description*:** Photogrammetric image exploitation software. Imagery can be input from reconnaissance or cartographic cameras, SPOT, IKONOS, other satellites, and softcopy sources. SOCETSet can be used with monoscopic or stereo hardware configurations. Platforms include Windows, NT, SGI-NT, SGI-IRIX and Sun.

g. ***Integration with other tools*:** SOCETSim

h. ***What does it do better than other tools*:** Simultaneously registers images from multiple data sources. Provides automatic texture capability for 3D models.

i. ***Time to learn*:** A two-week training course will provide users sufficient knowledge to execute the basic functionality of the software.

j. ***Potential uses:*** 3D Visualization, map-making, photo-interpretation.

k. ***Where to get a demo version:*** Mark Oldknow, (703) 668-4179.

2. SOCETSim

a. ***Cost*:** $8,000 - 10,000.

b. ***Manufacturer*:** BAE Systems.

c. ***System requirements:*** Dual Pentium (or single 2 Ghz), 512 MB RAM, 20GB HD.

d. ***Data in*:** USGS, DEM, DTED, ASCII DTM, Shape files, pre-triangulated stereo imagery (classified and unclassified), LiDAR.

e. ***Data out*:** OpenFlight and ASCII DTM files.

f. ***System description*:** A photogrammetric product used for visualization and simulation. Users can quickly create three-dimensional databases of buildings and terrain from stereo imagery. SOCETSim uses the shape and position of terrain feature data in three dimensions using latitude, longitude and elevation. This gives the user control over X, Y and Z dimensions. SOCETSim has an automatic texturing function that allows a user to place photo-realistic texture on features. The database can be easily imported into commercial visualization and simulation applications using an OpenFlight export function.

g. Integration with other tools: SOCETSet, and many other mainstream 3D visualization tools.

h. What does it do better than other tools: Automatic texture capability for 3D models. Ability to generate textured 3D models from 2D shape files and LiDAR.

i. Time to learn: A three-day training course will provide users the basic functionality and sufficient knowledge of the software.

j. Potential uses: Mout mission planning, route planning and training.

k. Where to get a demo version: Mark Oldknow, (703) 668-4179.

3. Falcon View

a. Cost: Free to DoD Employees

b. Manufacturer: Georgia Tech Research Institute (Funded by U.S. Air Force, USSOCOM, U.S. Navy, U.S. Army).

c. System requirements: Windows NT, 2000, or XP; Pentium 200 or higher, 800x600 16bit graphics card, 1GB hard drive space (for map data).

d. Data in:

(1) Maps and imagery. NIMA raster map data (CADRG), NIMA imagery data (CIB 1,5, 10), NIMA elevation data (DTED 1, 2), NIMA Vector maps (VMAP 0,1 and DNC), GeoTIFF (includes USGS, DRG and 1-meter Digital Orthophoto Quadrangle (DOQ) imagery as well as most commercial imagery).

(2) Overlay data. Aeronautical planning information (NIMA DAFIF), Vector Vertical Obstruction Display (VVOD), and ESRI "shape" files.

(3) Intelligence data. Near real time broadcast data: USMTF Messages (TACELINT, SENSOREP), TDIMF, TAB37, MIL-STD overlays: import from TAIS messages, ASAS messages, MCS (JCDB) and MCS-Light (XML) (new in version 3.4).

e. Data out: Graphic depiction of terrain including a variety of hardcopy output formats.

f. ***System description*:** FalconView is a Windows based mapping system that displays various types of maps and geographically referenced overlays. It supports many types of maps including aeronautical charts, satellite images and elevation maps. FalconView supports a large number of overlay types that can be displayed over any mapping background. The overlay set is targeted toward military mission planners, aviators and aviation support personnel. FalconView is an integral part of the Personal Flight Planning Software (PFPS). This software suite includes FalconView, Combat Flight Planning Software (CFPS), Combat Weapon Delivery Software (CWDS), Combat Air Drop Planning Software (CAPS) and several other software packages built by various software contractors.

FalconView is used by U.S. Air Force mission planners and the U.S. Special Operations Command. The initial version was used almost exclusively by U.S. Air Force F-16 pilots. Later versions were quickly adopted by other fighters as well as the airlift, bomber, and tanker communities. FalconView is currently in use by all branches of the military: Air Force, Navy/Marine (air), Army Aviation, and US Special Operations Forces. There are several European nations also using a special version of FalconView that has been approved for export.

g. ***Integration with other tools*:** None.

h. ***What does it do better than other tools*:** FalconView's windows interface has some powerful data management features that allow users to manage map and other data without the need to understand NIMA file types. FalconView is very lightweight. It was originally designed to run on a 100MHz Pentium, and is extremely fast for displaying maps and overlays.

i. ***Time to learn*:** Most users find that they can be productive with FalconView with less than a day of training. The system support Facility at Hill AFB gives 1-week courses that cover FalconView as well as the rest of the PFPS suite of Mission Planning tools.

j. ***Potential uses*:** Display map data, mission planning, onboard map display, intelligence fusion.

k. ***Where to get a demo version*:** Write or email:

Mission Planning System Support Facility

OO-ALC/LIRMHill AFB
UTDSN 777-6538
Commercial 1-800-SSF-SSFX (1-800-773-7739)
e-mail: mpssfa@gateway.hill.af.mil

4. EdgeViewer

a. Cost: Anyone with a '.gov' or '.mil' email address is approved to have EDGEViewer free of charge via an enterprise purchase through NIMA.

b. Manufacturer: Boeing-Autometric.

c. System requirements: 750MHZ, 256 MB RAM, 64MB on Graphics Card, 500MB hard drive space. Supports Win 2000/NT, Unix Solaris 2.6 and 2.7, Sun Irix 6.5.5 (www.nima.mil/edgeviewer/EDGEViewerSystemRequirement.htm).

d. Data in: CADRG, CIB, DTED Level 1 and DTED Level 2, VPF data and ESRI Shape files, ArcView Shape files, DXF, SVF and VRML, DBDBV, GeoTIFF and NITF2.0.

e. Data out: ARCVIEW RASTER, ATIF, BMP, ERDAS LAN, GEOTIFF, JPG, MAPINFO, NITF2.0 and TIFF.

f. System description: EdgeViewer is a map and imagery data-viewing package developed by Boeing, Autometric of Springfield, Virginia. EdgeViewer® is a flexible 2D and 3D data visualization tool. EdgeViewer® 1.4 was fielded as a replacement for NIMA's legacy NIMAMUSE software. A built in Simulation Clock controls the execution of simulation events within EdgeViewer such as solar position. EdgeViewer includes capability for multiple time steps and simulation speeds, as well as real time mode control. NIMA entered into a contract with Boeing Autometric to provide NIMA customers with free licenses throughout FY 02.

g. Integration with other tools: None.

h. What does it do better than other tools: Free viewer of NIMA products.

i. Time to learn: A day or two of self-paced training. EdgeViewer software includes a computer based training application covering each module

j. Potential uses: 2D and 3D terrain visualization.

k. ***Where to get a demo version:*** As mentioned above in item a, anyone with a '.gov' or '.mil' email address is covered under the NIMA EDGEViewer Enterprise Purchase. You may also contact Rob Frucella, 703-923-4408 (rfrucella@autometric.com).

5. TerraTools

a. Cost**:** $2300 (single, stand-alone copy) to $23,000 (with GIS and SOCETSet Plug-ins); product training is $1500-$3000.

b. Manufacturer**:** TerraSim.

c. System requirements**:** Pentium III (500 MHZ or higher), 512 MB RAM (256 minimum), OPEN GL supported graphics card with 64MB RAM (128 MB recommended), 384 MB hard drive space. Operating System: Windows NT 4.0, SP4+, Windows 2000 Professional, and Windows XP Professional. Can also be used with IRIX 6.5.x.

d. Data in: USGS DEM, DLG, SDTS, NIMA DNC®, DTED®, DFAD, ITD/TTD, VPF, DTOP, CIB®, CADRG, VMAP, MSDS, CDBW, CHRTR (DBDB-V), TDF2.0 (TOWAN), & YXZ Bathymetry, ArcView® Shape, Shape 3D, AutoCAD® DXF, Bentley MicroStatation® DGN, GRIDASCII, MOSS, GeoTIFF, XML, AutoCAD® (.dxf), 3D Studio Max® (.3ds), MultiGen OpenFlight® (.flt), and Designers Workbench® (.dwb).

e. Data out: MultiGen® OpenFlight® 14.2, 15.4, ArcView® Shape, Shape 3D, VRML, TIFF, SEDRIS 3.0.x, TSG (Tiled Scene Graph) format, S1000, ADDWAMS, GRIDASCII, and MOSS.

f. System description: TerraTools is a high fidelity, rapid generation 3D simulation database builder. TerraTools provides a comprehensive set of integrated terrain generation tools, including heterogeneous data import, rapid and incremental database construction, realistic and accurate geometry construction, detailed feature attribution, paging support, high levels of automation, and detailed diagnostics in a flexible stand-alone package. It automatically transforms raw digital cartographic, imagery and GIS source data into complex 3D visualizations suitable for real-time flyovers, walk or drive through. TerraTools has an easy-to-use interface and enables users to rapidly construct complex geospecific virtual worlds with little or no manual modeling.

TerraTools supports the ingestion of national source data such as imagery, terrain digital elevation models - DEMs, terrain cultural features, high resolution out sources from GIS, land use, photogrammetry and remote sensing tools. It supports the import of CAD models, design and architectural models, producing highly accurate 3D environments for urban, suburban, and natural environments. It is capable of displaying underground building structures, utility services and bridge abutments. Terratools has excellent support for bathymetric source data, and builds databases that allow seamlessly control across the shoreline through the littoral zone. It is a popular tool in the Joint Community.

g. Integration with other tools: Can be used as a plug in for SocetSet.

h. What does it do better than other tools: Building cost effective urban environments leveraging existing GIS source data. Their unique flow graph interface allows users to encapsulate their process and make changes to source GIS rather than editing database geometry.

i. Time to learn: One to three months of schooling and experience.

j. Potential uses: Current client applications include aerospace, defense and intelligence, homeland security, safety planning and evacuation rehearsal, law enforcement, training, transportation, AEC-Architecture Engineering Construction, facilities management, urban planning and education.

k. Where to get a demo version: Request a Demo CD from www.TerraSim.com (Craig Ramsdell, 781-461-0478).

6. Sitebuilder 3D

a. Cost: $1995.

b. Manufacturer: MultiGen Paradigm, a Computer Associates Company.

c. ***System requirements*****:** Pentium III (500 MHZ or higher), 512 MB RAM (256 minimum), OPEN GL supported graphics card with 64MB RAM (32 minimum), OS: Windows NT 4.0, SP4+, Windows 2000 Professional, Windows XP Professional, ARCView GIS 3.x or higher (Spatial Analyst v2.x and 3D Analyst v1.x are recommended).

d. ***Data in*****:** DTED, DFAD, CAD**,** ARCView shape files, ESRI TIN, ESRI GRID, GeoTIFF, OpenFlight, most popular image texture formats or any ArcView 2D product.

e. ***Data out:*** Export any real-time 3D scene created in SiteBuilder 3D to MultiGen Creator, Vega or other programs that support MultiGen-Paradigm's real-time 3D OpenFlight file format.

f. ***System description*****:** SiteBuilder 3D can automatically generate a 3D scene from an ArcView GIS 2D product. Quickly generates correlated 3D scenes directly from an ArcView GIS product. 3D Viewer allows users to navigate freely (fly-throughs) through the resultant 3D scene, change environmental effects, measure distances and export still images, movie files and OpenFlight files. SiteBuilder 3D is an ArcView® GIS software extension. The 3D scene generation is done from inside ArcView GIS and is transparent to the user.

g. ***Integration with other tools*****:** Any tools that can accept OpenFlight format including ArcView, ModelBuilder 3D, MultiGen Creator, Vega and Vega Prime.

h. ***What does it do better than other tools*****:** Quickly creates a fully interactive OpenFlight 3D environment of your 2D ArcView products and allows for real time rapid visualization.

i. ***Time to learn*****:** 1-2 weeks.

j. ***Potential uses*****:** Mission planning, facilities planning, and mission rehearsals.

k. ***Where to get a demo version*****:** Demo version can be downloaded from: **www.multigen-paradigm.com**. Additional information on SiteBuilder 3D and ModelBuilder 3D can be accessed from same.

7. PVNT

a. ***Cost***: Free.

b. ***Manufacturer***: Naval Postgraduate School (currently maintained by Nascent Systems Inc).

c. ***System requirements***: Quad Pentium IV (700 MHZ or higher), 512 MB RAM (256 minimum), OPEN GL supported graphics card with 64MB RAM (32 minimum), OS: Windows NT 4.0, Windows 2000 Professional.

d. ***Data in***: DTED, ortho-photo data.

e. ***Data out:*** Gridded representations.

f. ***System description***: PVNT addresses data generation and data utilization issues involved in creating high-fidelity real time databases. It provides support for producing metrically accurate representations of the battle space. It is designed to operate in an environment where the live and virtual reality worlds come together. This system provides the capability to generate 1-meter fidelity terrain databases and 1-cm target view databases for use in weapon substitution, command and control applications, and after action test review in force-on-force operational field tests.

g. ***Integration with other tools***: None.

h. ***What does it do better than other tools***: Has the ability to quickly create higher fidelity databases than any other tool looked at in this author's analysis. The problem is finding the high fidelity data sets to support the users work.

i. ***Time to learn***: 1 week.

j. ***Potential uses***: Weapon substitution analysis, command and control applications, and after action test review in force-on-force operational field tests.

k. ***Where to get a demo version***: A demo version and sample 1-meter terrain data are available on CDROM from Dr. Wolfgang Baer at NPS. Please go to http://www.cs.nps.navy.mil/people/faculty/baer/pegasus.html for more information on PVNT.

8. ArcGIS

a. ***Cost***: $1500.

b. ***Manufacturer***: ESRI.

c. ***System requirements***: Pentium 3 or higher; Minimum: 450 Mhz with 128 MB RAM; Recommended 650 Mhz or higher with 256 MB RAM or better; Windows NT, Windows 2000 or XP.

d. ***Data in***: TIFF, BIL, SunRaster, USGS DEM, SDTS, and DTED.

e. ***Data out:*** Export any TIFF, BIL, SunRaster, USGS DEM, SDTS, and DTED format.

f. ***System description***: ArcView is an integrated system for geographic geospatial data creation, management, integration, and analysis. Known as ArcGIS. The ArcGIS family consists of ArcView, ArcEditor, ArcInfo, and the ArcGIS servers ArcSDE and ArcIMS. ArcGIS is a modular system where each member can be used independently or simultaneously. This allows for scalability found in few geospatial terrain products. ArcView is a family of products used for terrain visualization and analysis. The core products of the ArcView family are ArcMap, ArcCatalog, and ArcToolbox. ArcMap's primary function is to be the workhorse for mapping, editing, and analysis. ArcCatalog's primary function is to create, organize, manage, and browse geographic and tabular data. ArcToolbox's primary function is data conversion and data management. ArcToolbox for ArcView and ArcEditor contains the ArcView most commonly used tools and extensions. ArcEditor is a new function to version 8.1 and allows a user to create and edit features in a multi-user environment. ArcInfo's function is to provide advanced geoprocessing capabilities. ArcSDE is the database service provider of the ArcGIS family. ArcIMS enables Internet services.

g. ***Integration with other tools***: Arc GIS Family of products.

h. ***What does it do better than other tools***: Quickly creates a fully interactive OpenFlight 3D environment of your 2D ArcView products, allowing for real time rapid visualization via an integrated family of terrain tools and services.

i. ***Time to learn***: 1-4 weeks.

j. ***Potential uses***: Terrain visualization and analysis.

k. Where to get a demo version**:** You can request a free 60-day trial version from http://www.esri.com/.

9. Additional Products

NIMA discontinued its support for NIMAMUSE 2.1 and VPFView 2.1. on 1 January 2002. Here are some additional products that are capable of providing similar functionality as NIMAMUSE 2.1 and VPFView 2.1. These products can be used to import, view and manipulate NIMA data.

a. Joint Mapping Toolkit (JMTK)

Collection of Application Programmer Interfaces (APIs) designed to support the military Mapping, Charting, Geodesy, and Imagery (MCG&I) requirements. Specifically, these APIs enable mission applications to interface with the COE MCG&I component. Capabilities within JMTK are organized into five major domains: The **Spatial Data Base Module (SDBM)** provides capabilities to import, manage, query, retrieve, and export standard NIMA data products and user or mission application created data sets: The **Analysis Module** is a collection of terrain analysis algorithms applied to geospatial information retrieved from the SDBM: The **Visualization Module** is designed to render NIMA standard products and results obtained from the Analysis Module on standard workstation platforms: The **Imagery Toolkit (IMTK)** is a set of software tools designed to provide standard image exploitation: The **Utilities Module** is a library of platform independent capabilities to perform fundamental geodetic computations such as unit of measure conversions, datum transformation and coordinate conversions.

b. ArcExplorer

ArcExplorer (**http://www.esri.com/software/arcexplorer/index.html**) is a lightweight GIS data viewer developed by ESRI (See ARCGIS above). This software performs basic GIS functions. ArcExplorer supports a wide variety of standard data sources and can be used for various display, query, and data manipulation applications. It can be used with local data sets, or as a client to Internet data and map servers.

c. OpenMap

Open source Java Beans toolbox used for building applications and applets for manipulating geospatial data. OpenMap is a set of Swing components that understand geographic coordinates. These components help you show map data, and help you handle user input events to manipulate that data. A demo version may be downloaded at www.openmap.com.

d. MapInfo ProViewer

Provides a map-sharing capability and information created by MapInfo Professional (http://dynamo.mapinfo.com/products/web/Overview.cfm?productid=62).

e. ERDAS ViewFinder

Free terrain data-viewing tool that provides basic image viewing and geospatial manipulation (http://www.erdas.com/erdasCentral/freeDownloadsPVT.asp).

f. Geomedia Viewer

Used to create Thematic Maps. Users can view and analyze the data in either Microsoft Access or ArcView Shape formats. Provides the capability to load and manipulate raster images (http://www.intergraph.com/gis/demos/viewer).

g. DLGV32

Windows 95/NT compatible application for viewing USGS digital cartographic data (http://mcmcweb.er.usgs.gov/viewers/dlg_view.html).

h. MicroDEM / TerraBase II

Free mapping program written by Professor Peter Guth of the Oceanography Department, U.S. Naval Academy. **MICRODEM** displays and merges digital elevation models, satellite imagery, scanned maps, vector map data and GIS databases. Terra Base II and MICRODEM is the same program. The US Army Engineering School has supported the development of Terra Base II for training soldiers about digital data and terrain analysis. This software can be requested from the US Army Engineering School, Fort Leonardwood, MO (www.wood.army.mil/TVC/)

D. FINAL ANALYSIS

After investigating numerous terrain data tools, the author has come to the conclusion that there is not one single tool that can solve all data problems (See Figure 4-1). The choice of the tool depends on its intended use and the users end-state. The author has identified six tools under $2500 and three that are free of charge to DoD employees. The most robust capability is achieved through using multiple tools in a synergistic manner. If resources and time to learn are unconstrained, the best suite of tools analyzed in this effort are the SOCETSet, SOCETSim and Terratools (plug-in) family of terrain applications.

Data is also a key element in using any of these applications. If a user does not have the right data representation in the correct format, the chosen tool may not ever get the user to their desired end-state.

E. CONCLUSION

In this chapter, the author has explored a variety of mainstream terrain data manipulation tools available to the government modeling and simulation developer. Each tool is aimed at filling a particular need in the M&S community. Developers need different tools to tackle different types of jobs. Different requirements are often driven by the type of data needed to answer specific questions and are often constrained by the type of accurate terrain data the developer has available (See Figure 4-1). The list of applications assessed here is by no means an all-inclusive list of the tools available to government and civilian developers.

	COST	TRAINING	KEY FUNTIONALITY	DATA SOURCES
SOCETSet	$20-30 K	2 Week Course	Photogrammetric image exploitation can be output to OpenFlight and other 3D formats.	Most imagery sources, DTED, USGS DEM, GeoTIFF, ASCII DTM, ARCView shape files
SOCETSim	$8-10 K	3 Day Course	3D database generation from 2D terrain and stereo imagery.	DTED, USGS DEM, ASCII DTM, many stereo imagery sources
Falcon View	Free to DOD Members	One Week Course	Easy viewing and integration of NIMA products.	DTED, CADRG, VMAP, GeoTIFF, DOQ, many commercial imagery sources
EdgeViewer	Free to DOD Members	2 Days CBT	2D and 3D visualization tool. Primarily to view NIMA products.	DTED, CADRG, VPF, ERSI shape files, ARCView shape files, GeoTIFF, VRML
TerraTools	$2300 (Single) to $23K (w/GIS & SOCETSet Plug-ins)	3 Week Course	3D simulation database generation.	DTED, DFAD, CADRG, VMAP, USGS DEM, VPF, ARCView shape files, AutoCAD, GeoTIFF, XML
Sitebuilder 3D	$1,995	1-2 Weeks Formal & CBT	Builds interactive 3D OpenFlight environment from 2D ARCView products.	DTED, DFAD, ESRI TIN, ESRI GRID, CAD, GeoTIFF
PVNT	Free to DOD Members	One Week Formal Training	Builds very high fidelity and accurate terrain databases for use in analysis.	DTED, many orthophoto and stereo imagery sources
ARCGIS	$1,500	2-4 Weeks of Formal Training	Builds interactive 3D OpenFlight environment for terrain visualization and analysis.	DTED, USGS DEM, GeoTIFF, SDTS, SunRaster

Figure 4-1. Tools Analysis

V. APPLIED SUMMARY

Based upon the above exploration of available data formats and representations, the author has compiled the following guidelines to apply the previous information and build a basic simulation tool. This step-by-step approach is offered to provide assistance to those defining and refining terrain space for use in multi-agent system simulation tools.

Initially, developers must define the overall problem set to be solved via the simulation (See Figure 5-1). The user must then define the terrain space/environment associated with the problem. This is arguably the hardest step in the development process. Developers must identify the terrain data representations they wish to use and the terrain data tools available to manipulate and work with the particular representations. Unfortunately, the cart often ends up in front of the horse, meaning a developer starts with a particular terrain data tool, then tries to find an environmental data set that meets his needs. This is a common approach, but this author does not recommend it. Ideally, the terrain representation is chosen based on the output desired, then the terrain tool (ARCVIEW, EdgeViewer etc…) is applied to add-in or pare down the features needed for the problem set.

The problem in utilizing "the right technique" is that many of the mainstream terrain manipulation tools are very expensive and time consuming to learn. This is why the simulation community often takes the "hammer looking for a nail" approach. Developers often try to force the wrong data and tools into incongruent problem sets.

During problem definition, the developer should begin to consider available terrain representation data sources. For ground combat agent-based simulation development, the author recommends DTED as a solid starting point, and notes that it is the easiest available terrain representation to work with for most developers. Once a DTED baseline is established, a developer can then use more complex or specialized data formats such as VPF for refinement.

Based upon the final data-types needed and available, the developer then must consider available data manipulation tools. It may be necessary to combine multiple types of data, reduce the data scope, or combine data sets to achieve the desired result.

As documented above, data manipulation tools each have positive and negative aspects, and there is no one "perfect" catchall tool. Due to this fact, the most important factor becomes the terrain representation and the data formats against which each tool can most appropriately be applied. In most cases, this problem is addressed by what a developer knows, not what is the best tool for the job. Learning curves are very steep with many commercially available tools. The author will now provide a theoretical example applying this process (See Figure 5-1). This example is completely fictional. Any similarities to any other systems analysis are completely coincidental.

Step One is to *Define the Requirement*. In this example the author is building an Intelligence, Surveillance and Reconnaissance (ISR) analysis tool. The author is primarily concerned about elevation values (aspect and slope) and vegetation. The author also needs to build an environment that will provide 2D and 3D visualization inside the simulation tool. The goal for the project is to understand (analyze) where the dead space and blind spots are for Airborne and Space surveillance and reconnaissance systems. The author needs terrain data for Fort Hunter Liggett, California, where much of the actual system testing will occur. The double boxes in figure 5-1 represent the final products that will be taken forward into the next step.

Step Two is to *Choose the Data Representation* that will best suit this requirement. The author believes that a gridded representation is the best data to use as a baseline for this project, and has chosen DTED2 as the gridded baseline data representation. The fidelity of DTED2 is 30-meter terrain postings. The author would like to use higher fidelity data, but this testing and analysis must be unclassified. If we use higher fidelity gridded data, the testing environment will likely need to be classified. The author will first apply the DTED2 data to create a baseline representation. The author will use raster and stereo imagery data to further refine the terrain set.

Step Three is to *Choose the Data Manipulation Tool(s)* that can work with the chosen data representations. For this project we need a tool to work with DTED, raster and stereo imagery. The author chose the SOCETSet/SOCETSim family of tools for this effort. The SOCET family of tools is an excellent toolkit to create OpenFlight environments and generate 3D visualization databases from 2D terrain and stereo imagery. The author will first apply the DTED2 and raster data using SOCETSet. The author will then apply stereo imagery using SOCETSim. The raster data is very useful for visualization and complex analysis. The stereo imagery will provide increased fidelity for a 3D OpenFlight environment. Finally, the author will use SOCETSim to create a 3D *OpenFlight* image.

Step Four is to *Create the Environment*. The author created an OpenFlight 3D environment of Fort Hunter Liggett in Step Three using the SOCET family. The author must now define how the autonomous software agents will interact with the environment. For this application the author will create a two-dimensional array to store the DTED Z values (terrain postings). DTED data can quickly be converted into a 2D array using a XML script [Neushul, 2002]. This 2D array will be used to execute agent line of site calculations for the ISR analysis.

In Step Five, the author will apply this environment and 3D terrain database to the *Multi-Agent System Testbed* [Tanner, 1999]. To do this, the author must set up / create the software agents and place them on the terrain set, either dynamically or deliberately, give them goals or objectives, and define their interactions with other agents. The author will set up a placement box where the computer dynamically places the agents in random starting positions within the defined area. Prior to placing the agents on the terrain, the developer must create the agents and define their interaction with the terrain and most importantly with each other. For this ISR analysis requirement, the author will create 50-100 ground agents in random places in the "play-box". Their goals are to seek the best cover and concealment while maintaining maximum visual coverage of the terrain around them (fields of fire). The author will also create 2 or 3 ISR collection system agents that will fly the terrain and assess how many ground agents are visible at any given time. The ISR agents will fly pre-defined search patterns based on specific specifications about how far and wide an area their sensors can cover. This is a very simple problem set.

Step Six is to *Execute the Simulation Runs.* Once the simulation database is created, the developer will execute their simulation runs. The developer will execute as many simulation runs as necessary to meet the analysis requirement. The author would expect to collect and analyze the data on 50-100 runs to have a good statistical baseline for this example.

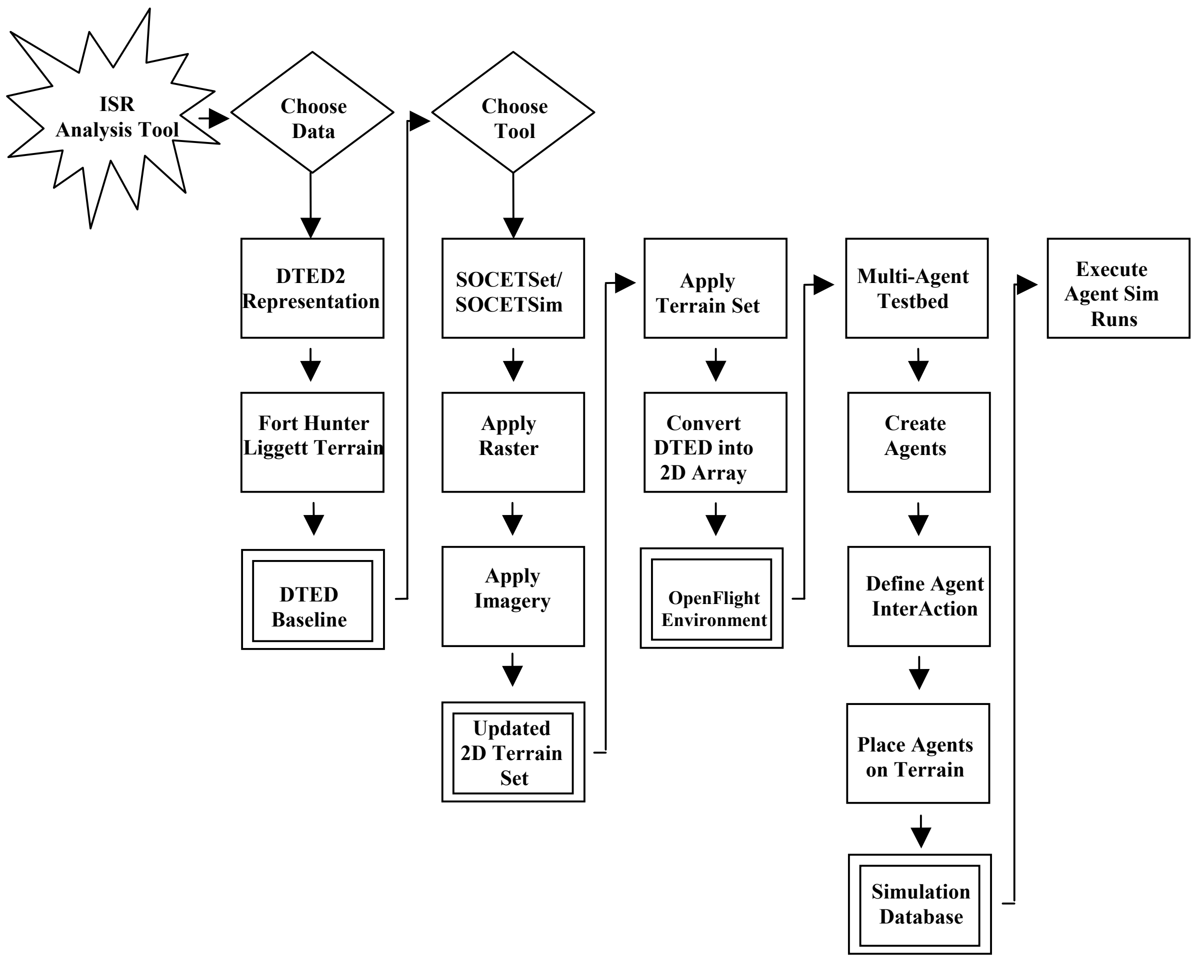

Figure 5-1. Data Flow Diagram Example

Once a robust environment has been defined and created, developing a great simulation is often the easy part. Simulation developers across the globe are very good at creating complex, dynamic simulation tools. Far too often, developers are weighed down by the community's inability to quickly create the right terrain sets in the right format and the right fidelity. Too often, simulation tools are run on available terrain sets, not on terrain where the developer envisioned the tool being used. NIMA and other resources are out there working similar tough terrain problems everyday. Unfortunately, they are not resourced to do much more than meet real-world requirements.

The US Pacific Command is currently developing a notional continent in the middle of the Pacific Ocean to support multinational simulation exercises in the Pacific Theater of Operations. The primarily reason for creating this notional continent is to alleviate the concerns voiced by US allies' neighbors during multinational training exercises conducted via simulation. The Exercise Simulation Center – Pacific is in charge of this effort with strong support from NIMA and the Joint Warfighting Center.

Every agent-based ground combat simulation is a complex, symbiotic system that should be uniquely based upon the specifications of the developer. The author's goal has been to give the reader a grasp of the multitude of issues to be considered while developing useful combat simulation. Simulation tools have evolved dramatically in the past decade. The author believes that new simulation techniques, like multi-agent simulation systems, will grow dramatically in the decades to come. Only high fidelity, easy-to-create environments will facilitate the evolution of newer techniques to the forefront of the modeling and simulation of complex joint combat.

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VI. FUTURE WORK

The author pointed out early in this work that the terrain/environment is only the first part of creating accurate agent-based ground combat simulation. As the military moves toward studying how to fight and win battles in urban environments, there will be an ever-increasing need for higher and higher fidelity simulations. The author envisions agent-based planning tools will be leveraged to tackle these complex problem sets.

An accurate, physics-based, agent-based simulation could allow trained analysts to explore the non-tangible types of combat effects. Military modeling and simulations solutions of the past have accurately modeled the physics, ballistics and line-of-sight of modern battlefields and weapons systems. There are not, however, standards in place to model the intangible combat effects of battle, or *combat multipliers*. How does one model leadership? How does one model fear? How does one model the psychological aspects of the battlefield? How do simulation developers address issues such as unit sustainability, mental health or sleep deprivation? Statistics can help us in this regard by studying the psychological effects of past battles. Unfortunately, data in these areas is very scarce or hard to substantiate.

The author believes that the key to incorporating various human factors into combat simulations, yielding more realistic training and analysis, lies in the opportunities presented by agent-based systems. Computer scientists in the 1970's hypothesized that rule-based artificial intelligence (AI) would be the antecedent to our complex human behavior representation issues. They were wrong. Scholars and researchers have proven beyond a reasonable doubt that the complexity of these rule-based models grows too fast to be useful in our training and analytical simulation tools. They remain, however, very useful resolving problems of limited scope. Unfortunately these techniques do not scale.

Multi-agent systems are not the solution to all of our military modeling and simulation problems. These concepts allow a simulation developer to create very complex systems and systems of systems that are much easier for a simulation developer to get their head around. These techniques have shown great promise in modeling the complex behavior systems of the contemporary battlefield using relatively simple rule sets.

VII. CONCLUSION

Work in this area will never be complete. The more fidelity given to the simulation audience, the more fidelity the audience will ask for. Modeling the environment is a key first step in the development of a mature set of military en route planning tools.

In this work, the author has tried to lay a solid foundation for further understanding the digital terrain support available to simulation developers. In chapter 2, the author presented some background work to provide the reader the requisite knowledge to understand combat simulation and agent based modeling techniques. The author proposed a generic formula to create a digital environment to support multi-agent system simulations. The author discussed previous work on multi-agent systems conducted by Dr. Andy Ilachinski and related work conducted at the Naval Postgraduate School.

Chapter III explored the mainstream data representations available to the military and civilian simulation developer. The author provided a description and conducted an analysis of many common data representations used in the simulation community. Additionally, the author discussed some of the organizations involved in the development of common data formats and standards.

Chapter IV addressed many of the mainstream terrain data manipulation tools available and provided a brief analysis of each. Many terrain data development applications are addressed in this work. Each tool has its desirable attributes and specific utility. Unfortunately, there is not one all-inclusive terrain application to address every simulation problem set. A good developer must understand the tools available and take the time to learn the strengths and shortcomings of each application. Data is also a key ingredient in this process. If a developer does not have the right data set in the right representation or format, s/he will find great difficulty creating accurate, high fidelity data sets for agent-based simulations. A quick reference matrix is provided in the final pages of Chapter IV.

Chapter V is an applied summary of Chapters II-IV. The author walks the reader through the development of a terrain set and multi-agent system tool to analyze Airborne and Space ISR collection platforms. The author discussed this example from requirement to data collection and analysis. The author makes some assumptions about this fictional scenario to walk the reader through some of the choices a developer has to make as they journey from requirements development to applied autonomous multi-agent simulation runs.

Chapter VI briefly discusses some advanced concepts and areas of future work. The Army's modeling and simulation community has struggled with the development of reusable terrain data. The Army's Training, Analytical, and Acquisition simulation communities have a requirement to develop low, medium and high fidelity terrain sets to create accurate simulation environments. It is very rare that these terrain sets are shared between communities. The author will not discuss the details of this disjoint in this work. He is simply making the point that a tremendous amount of work on terrain sets every year is completed, but much of this work is never captured or shared with others who might leverage it.

The author's intent is not to throw stones from inside one's own glass house, but to raise awareness about a simulation issue that currently lacks an adequate solution. Many such issues must be addressed, and good solutions approached, before our current simulation models mature, evolve, and improve to the point that we can claim to have accurately modeled the contemporary environment and battlefields of the future.

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