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High Resolution Terrain Study

by J. G. Green, E. A. Baylot, C. D. Bullock, J. H. Robinson, WES
N. A. Renfroe, MEVATEC Corporation

Prepared for TRADOC Analysis Center

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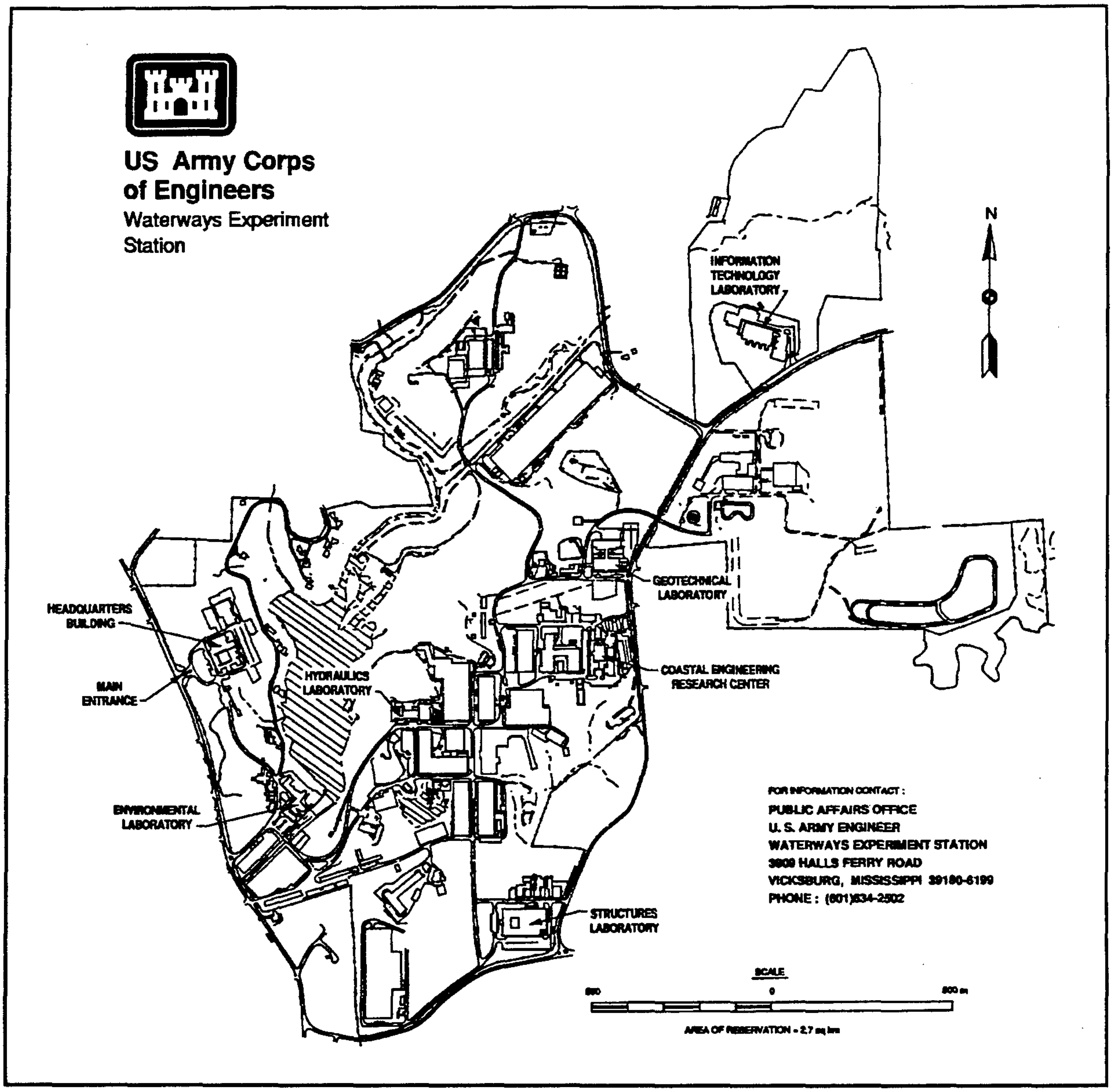

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Preface

The study reported herein was conducted from January 1995 to May 1995 by the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, for the Training and Doctrine Command (TRADOC) Analysis Center (TRAC), Fort Leavenworth, Kansas, under the Army Model Improvement Program, Project Number A-04-01, entitled "Very High Resolution Terrain." TRAC's Technical Monitor was Mr. Rudy Pabon.

The study was conducted under the general supervision of Dr. W. F. Marcuson III, Director, Geotechnical Laboratory (GL); Mr. N. R. Murphy, Jr., Chief, Mobility Systems Division (MSD), GL; and under the direct supervision of Mr. R. P. Smith, Chief, Modeling and Simulation Branch, MSD, GL. Personnel in the MSD supporting this study were Messrs. E. A. Baylot, W. C. Dickson, Jr., J. G. Green, J. H. Robinson, and Ms. C. D. Bullock. Contract personnel assisting were Mses. S. G. Sippel and N. A. Renfroe, MEVATEC Corporation, Vicksburg, MS.

The report was prepared by Messrs. Baylot, Green, Robinson, and Mses. Bullock and Renfroe.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
nautical miles (nm)	1.8520	kilometers (km)
feet (ft)	0.3048	meters (m)
square miles	2.5900	square kilometers
degrees (angle)	0.01745329	radians

1 Introduction

Background

A high level of terrain correlation is required for simulations participating in a Distributed Interactive Simulation (DIS) environment to achieve consistent outcomes among the simulations, convey realism, and impart credibility to the results. With respect to virtual simulations, each computer image generator (CIG) is constrained by the computational power available to depict images. That is, each CIG possesses hardware and software architecture limitations that require CIG tradeoff decisions be made that in-turn affect the number of polygons and pixels that can be processed to portray a realistic image on a "real time" basis. On the other hand, constructive models typically use raster format for elevations and features; although, models in the Janus lineage are using polygons to represent features. Line-of-sight (LOS) calculations are demanding consumers of processing capabilities in constructive simulations. As terrain resolution increases, LOS calculations, generally, increase as well. With these varying terrain representations and hardware restrictions, the question remains regarding the level of terrain resolution required for agreement in a DIS environment between live and the modeling and simulation (M&S) domain. From an interoperability viewpoint each "participant" must "see" and "interact" within the same terrain environment to ensure a "level playing field."

If technology and cost were not limiting factors, one might say that ground truth is the requirement for M&S. However, resources are indeed limited; consequently, prior to answering the terrain data resolution and correlation issues, the impacts, constraints, trade-offs, and associated costs of using varying terrain resolution in simulations, stand-alone and the DIS environment, must be thoroughly examined and analyzed.

Purpose and Scope

The purpose of this study was to perform a quantitative and qualitative analysis of existing information relating to the impact of terrain resolution on M&S outcomes with respect to line-of-sight, battle outcomes, processing and preprocessing time.

The scope of this study was to formulate a basis to describe or propose:

a. cost-benefit relationships of developing, storing, processing, and transmitting terrain data of varying resolutions.

b. the relationship between terrain resolution and M&S outcomes.

c. cost effective solutions to "fix" terrain related inconsistencies between M&S and live exercise when applied to constructive/virtual simulations and simulators. M&S were limited to Janus(A), CASTFOREM, ModSAF, BDS-D, and CCTT.

Definitions

a. *Aerotriangulation.* The process for the extension of horizontal and/or vertical control whereby the measurements of angles and/or distances on overlapping photographs are related into spatial resolution using the perspective principles of the photographs.

b. *Battlefield Distributed Simulation - Developmental (BDS-D).* An ongoing Army program to network distributed simulators, constructive simulations, and (if feasible) live simulations (that are instrumented) to support all phases of doctrine and tactics development, training, materiel development, and testing and evaluation. Initial effort focused on networking between existing SIMNET-D sites and linkage to the constructive analytical model, Eagle.

c. *CASTFOREM.* A force-on-force model which is used to simulate combined arms conflicts for brigade and below. CASTFOREM generally models ground conflicts with representation of support helicopters, fixed-wing aircraft, dismounted infantry fire teams, and air defense assets. It employs an imbedded expert system implemented by way of decision tables. Terrain is represented by a grid cell system which contains data for elevation, trafficability, and surface feature.

d. *Close Combat Tactical Trainer (CCTT).* The Close Combat Tactical Trainer (CCTT) is the first system in the Combined Arms Tactical Trainer family of training systems. CCTT will utilize the DIS network protocol to provide a virtual environment for training of armor and mechanized infantry personnel. CCTT is composed of a variety of manned modules, an Operations Center, Semi-Automated Forces, and several support workstations. There are three correlated databases used throughout the CCTT system: the visual database is used for all out-the-window visual displays; the PVD ("plain-view" database) provides a two dimensional plan view for display on user interfaces; and the "Model Reference" terrain database (or MRTDB) is used for all other terrain operations. MRTDB is designed first and foremost to support terrain reasoning operations on the CGF systems; however, the CCTT manned modules will also utilize this database for terrain functions such as collision detection, munition impact detection, and height of terrain.

e. *DFAD-1.* Digital Feature Analysis Data - level 1 is produced by the Defense Mapping Agency (DMA). The database consists of selected natural and manmade planimetric features, classified as point, line, or area features as a function of their size and composition. Each feature is assigned an identification code and further described in terms of composition, height, length and orientation. The data are stored in vector format and segregated into 1 deg by 1 deg geographic cells. DFAD-1 is collected from photogrammetric source material. Feature density is roughly equivalent to that of a 1:250,000 scale map.

f. *DFAD-2.* Digital Feature Analysis Data - level 2 is produced by DMA. The database consists of selected natural and manmade planimetric features, classified as point, line, or area features as a function of their size and composition. Each feature is assigned an identification code and further described in terms of composition, height, length and orientation. DFAD-2 is more detailed that DFAD-1. It is typically stored in variable patch sizes ranging from 2 nautical miles by 2 nautical miles up to 3.75 nautical miles by 3.75 nautical miles. DFAD-2 is collected from photogrammetric source material, and feature density is roughly equivalent to that of a 1:50,000 scale map.

g. *DTED-1.* Digital Terrain Elevation Data - level 1, produced by DMA, is a uniform matrix of terrain elevation values. DTED1 provides basic quantitative data for all military systems that require terrain elevation, slope, and/or surface roughness information. Level 1 post spacing is 3 arc seconds (approximately 100 m). The information content is approximately equivalent to a 1:250,000 scale resolution.

h. *DTED-2.* Digital Terrain Elevation Data - level 2, produced by DMA, is a uniform matrix of terrain elevation values. DTED2 provides basic quantitative data for all military systems that require terrain elevation, slope, and/or surface roughness information. Level 2 post spacing is 1 arc second (approximately 30 meters). The information content is approximately equivalent to a 1:50,000 scale resolution.

i. *DTED++.* Digital Terrain Elevation Data ++, produced by DMA, is a uniform matrix of terrain elevation values with post spacing less than 1 arc second (generally 3 m).

j. *DTED-2D.* DTED-2 that has been downsampled to match the same post spacing as DTED-1.

k. *Interim Terrain Data (ITD).* ITD portrays those natural and manmade features which are of tactical military significance. ITD consists of contiguous digital data sets covering specified geographic areas. These data sets are composed of attributed and unsymbolized feature information and are used in conjunction with DTED-1. The six standard data sets include: surface configuration (slope), vegetation, surface materials, surface drainage, transportation and obstacles.

l. *Janus.* Janus is an interactive, two-sided, closed, stochastic, ground combat simulation featuring precise color graphics. Interactive refers to the interplay between the military analysts who decide what to do in crucial situations during simulated combat and the systems that model that combat. Two-sided refers to the two opposing forces, Blue and Red, directed simultaneously by two sets of players. Closed means that the disposition of opposing forces is largely unknown to the players in control of the other force. Stochastic refers to the way the system determines the results of actions like direct fire engagements according to the laws of probability. Ground combat means that the principal focus is on ground maneuver and artillery units.

m. *Joint Operations Graphic (JOG).* The Standard 1:250,000 scale Department of Defense cartographic product which may be produced in any of the following three versions to meet the validated Unified and Specified Commands and Military Department area requirements: the JOG/G (Series 1501) is designed to meet ground use requirements; JOG/A (Series 1501 Air) is designed to meet air use requirements, and JOG/R (Series 1501 Radar) is the Air Target Material version in support of radar/intelligence planning and operations requirements.

n. *Line-of-Sight (LOS).* A geometrically straight line that represents an observer's unobstructed view of an observed point or an object of interest.

o. *ModSAF.* A Distributed Interactive Simulation (DIS) system for simulating and controlling entities on a virtual battlefield. ModSAF is a fully distributed system which allows application programs to be linked over a network. The programs communicate physical battlefield state and events between themselves via DIS protocol packets, and information about missions and mission state.

p. *Perspective View Generator and Analysis System for Unmanned Sensors (PEGASUS).* PEGASUS consists of two parts:

(1) The Perspective View Generator (PVG) uses target and terrain databases and target position measurements from the range and flight console input commands to calculate the real-time fire seen from the eye of the FOG-M missile. This view is relayed back to the field over microwave links, closing the data flow loop.

(2) The PEGASUS-I Database Creation System is a complex system of computers and algorithms designed to input, measure, and parametrize a set of visual images and generate a compact, object-oriented data base.

q. *Protocol Data Unit, DIS (PDU).* A standard that specifies the format and structure in which data will be organized. The purpose is to facilitate the electronic transfer of data between M&S with different data structures.

r. *Resolution.* The distance across a grid square used to define an area basis for elevation and features on the earth's surface. Resolution or grid size may vary from 1 m to 30 m for high resolution terrain.

s. *Tactical Terrain Analysis Data Base (TTADB).* The TTADB is a set of transparent overlays, keyed to 1:50,000 scale topographic maps, portraying natural and man-made features of military significance. The database consists of six overlays: surface configuration (slope), vegetation, surface materials, surface drainage, transportation, and obstacles.

t. *Terrain Visualization.* A component of battlefield visualization, it portrays and allows a detailed understanding of the background upon which enemy and friendly forces and actions are displayed. Topography provides the "picture" whereby the user can visualize the terrain.

2 Cost to Develop Digital Terrain Data

DMA Production Times and Costs for Various Products

One of the major factors in the development of digital terrain data for use in M&S is cost. Table 1 shows the principal source and the cost, both in time and money, to produce several Defense Mapping Agency (DMA) products for a 50-km by 50-km area. These data were calculated from per square kilometer costs provided by DMA. The costs for a given level of data resolution vary as complexity, accuracy and completeness are considered. The average time along with the range required to produce data is provided for products for which DMA has experience. Costs for 3-m and 10-m elevation data do not have the robust set of samples that exist for the other data sets and are DMA's best approximations (Lenczowski 1995). There is a factor of 2.2 increase in man-hours and costs required to go from DTED 1 at approximately 100-m resolution to DTED 2 at approximately 30-m resolution, a factor of 15.9 increase from DTED 1 to DTED++ at 10-m resolution and a factor of 107.8 increase from DTED 1 to DTED++ at 3-m resolution . There is a factor of 20.3 increase in man-hours and costs requirements to go from DFAD-1, in which the feature content is approximately equal to the radar-significant features found on a 1:250,000 scale map, to DFAD-2, in which the feature density is roughly equivalent to that of a 1:50,000 scale map. The table also shows the principal source and average production times and costs for Interim Terrain Data (ITD), Topographic Line Map (TLM) at 50-m resolution, and Joint Operation Graphic (JOG). On occasion, where features are being attributed, additional hardcopy products are used to supplement imagery sources.

Photo- or imagery-source data are typically produced on a digital photogrammetric workstation. Digital photogrammetric workstations allow analysts to use digital imagery to easily extract feature information to produce a variety of map themes such as elevation models, orthophotos, overlay graphics, terrain contours, and user defined feature data. Each of these layers of information can be exported from the workstation in a variety of formats for further use and manipulation with a geographic information system or a specific user application. The key advantage gained in using such a system is the specific user application. The key advantage gained in using such a system is the speed and accuracy at which data can be collected with the workstation after the imagery has been regist ed to points. With the mapping analyst acting as a "man in the loop" for rocessing control, feature data can be collected rapidly through automated techniques. Software that drives the system is written to support a variety of off-the-shelf hardware platforms, operating systems, and supporting peripheral devices, allowing the user to choose and configure a platform which best suits his total processing needs.

Digital data produced from cartographic source are typically based on scaled hard-copy maps. The process includes hand-digitizing or scanning the map features of interest (i.e., contours, roads, landuse type, drainage, etc.) to create a digital replication. Then, specialized software is used to assign feature attributes. The combination of features and attributes referenced to a geographic location on the earth's surface can then be imported to a geographic information system (i.e., ARC/INFO, Intergraph, etc.) to undergo further data processing techniques. For instance, a digital replication of contours could be imported to ARC/INFO where it would be converted to a triangular irregular network (TIN) and finally to a grid of elevation values.

Table 1
Production Times and Costs for Various DMA Products[1]
(Based on 50-km x 50-km area)

Product	Avg Hours	Avg Cost	Range of Hours
DTED 1[2]	250	$12,500	150 - 800
DTED 2[2]	550	$27,500	375 - 2500
DTED + + (10 m)[2]	3,975	$197,500	2,000 - 17,000
DTED + + (3 m)[2]	26,950	$1,350,000	12,500 - 40,000
ITD[3]	6,750	$337,500	4,750 - 11,250
DFAD level 1[2] (Digital Feature Anal. Data)	400	$20,000	Unknown
DFAD level 2[2]	8,100	$405,000	Unknown
TLM (50 m)[3] (Topographic Line Map)	5,400	$270,000	Unknown
JOG[3] (Joint Operations Graphic)	325	$16,250	Unknown

[1]These data calculated from per sq km costs provided by DMA
[2]Source: imagery
[3]Source: combination (imagery and cartographic)

Adequacy of Various DTED Levels

The U. S. Army Topographic Engineering Center (TEC) conducted a study on the influence of DTED 1, DTED 2, and DTED 2D (DTED 2 downsampled to 100 m) on Army terrain elevation applications in four different areas each with a distinct terrain type (Fatale 1993). The four different areas included Qasr Od Dasht, Iran, (very rough terrain), Redding, California, (rough terrain), Millinocket, Maine, (moderate terrain), and El Dorado, Arkansas, (smooth terrain). The study found that in terrain visualization, DTED 2 performs better than DTED 1 in most terrain types. However, DTED 1 adequately depicts very rough terrain. DTED 2 is absolutely necessary for adequate depiction of smooth terrain. When the source data is solely photographic, DTED 1 compares favorably to DTED 2D. Table 2 gives a comparison of DTED Levels 1, 2, and 2D for the four terrain roughness classifications.

The landform map in Figure 1 indicates areas of the world where DTED 1 might be adequate, and where DTED 2 or better would be essential. Approximately 29 percent of the world is mountainous (rough - very rough), 43 percent hills (moderate), 28 percent plains (smooth).

Table 2
Comparison of DTED Levels 1, 2, and 2D for Terrain Visualization

Region	Terrain Roughness Classification	Sigma-t (feet) (Standard Deviation of Terrain Height)	Comparison
Qsar Od Dasht, Iran	Very Rough	>800	1. Level 2 superior in rolling terrain. 2. Level 1 adequately depicts very rough terrain. 3. No difference between level 1 and level 2D.
Redding, California	Rough	200-800	1. Level 2 highly superior to level 1 at 4 of 6 sites. 2. Level 2 only slightly better than level 1 at other 2 sites. 3. No difference between level 1 and level 2D.
Millinocket, Maine	Moderate	60-200	1. Level 2 highly superior to level 1 at 3 of 6 sites. 2. Level 2 slightly better than level 1 at other 3 sites. 3. No difference between level 1 and level 2D.
El Dorado, Arkansas	Smooth	<60	1. Level 2 highly superior at level 1 at all sites. 2. No difference between level 1 and level 2D.

Figure 1. Worldwide map of landform types

DMA produces an array of data products. The production times for several different DMA products for a 28-km by 28-km area are given in Figure 2. These products include:

a. DTOP - Digital Topographic Data

b. TLM - Topographic Line Map

c. DTED 2 - Digital Terrain Elevation Data Level 2 (resolution of 1 arc second or roughly 30 m)

d. VMAP2 - Vector Map Version 2

e. ITD - Interim Terrain Data

DTOP is the next-generation high resolution digital product after ITD. Currently DMA is negotiating with the user community for a minimum essential data set (MEDS) of DTOP in order to decrease production time and cost.

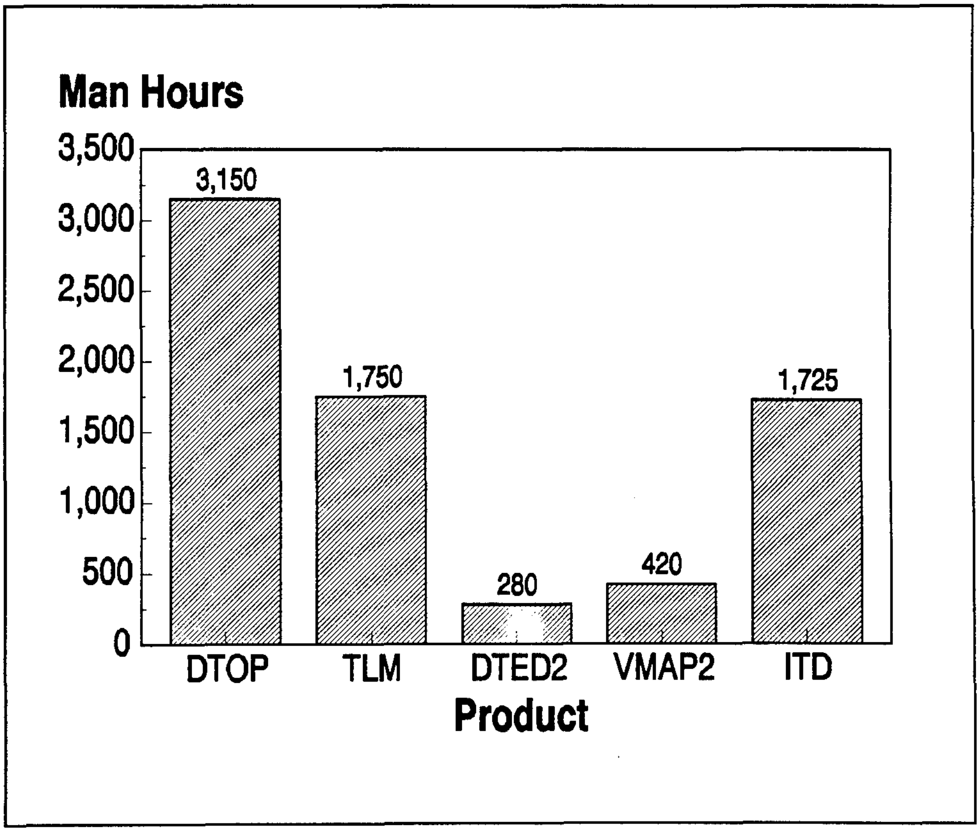

Figure 2. Average production times for tactical terrain data and related products on digital production system

Average Production Times for ITD and DTED 1

The source used to produce terrain data affects cost as well as quality. Figure 3 shows average production times required to produce imagery-based and cartographic-based (TTADB) ITD accompanied by DTED 1 for a 28 km by 28 km area (which is the standard 15 min by 15 min mapsheet) (Morgan 1995). It is important to note that the time required to produce DTED1 is almost insignificant compared to the time required to produce ITD. It should also be noted that the production times represent times for a person or persons skilled in photogrammetry and computer applications.

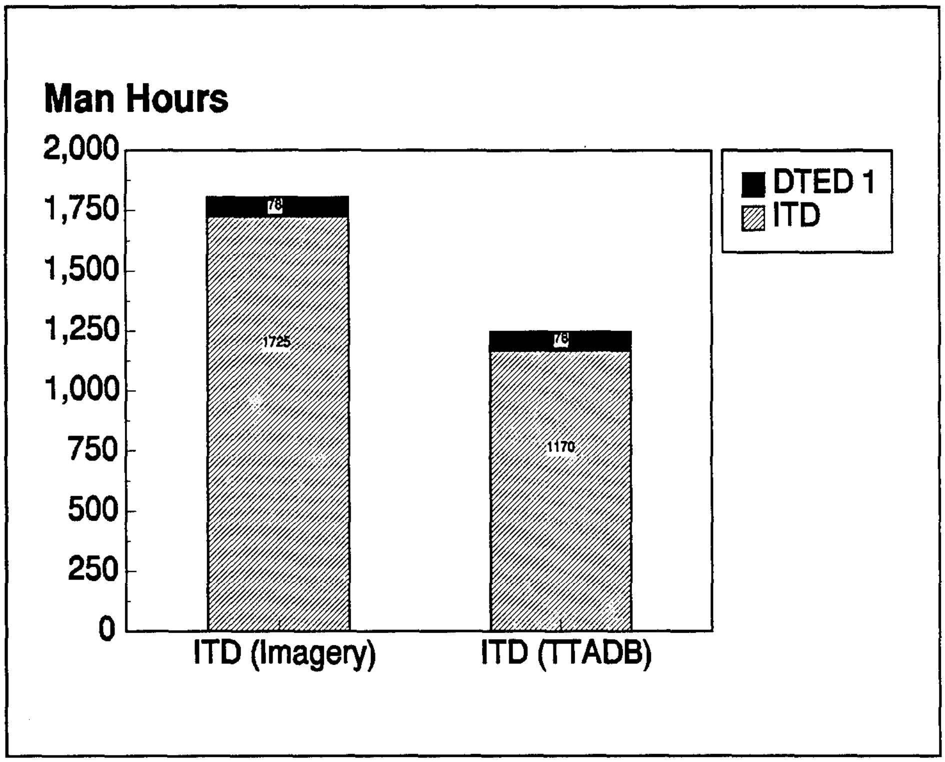

Figure 3. Average production times for ITD and DTED 1

The time required for DMA to produce data can vary as production conditions vary from routine to committed to crisis. Table 3 provides the estimated time to produce a typical 1° by 1° cell of DTED 1 and DTED 2 and a 15 min x 15 min cell of ITD under various production conditions (Daniel 1995). Routine production of a single cell of ITD using imagery sources requires about 321 days with one 5 hour-a-day shift committed to data production. For committed production with two 6 hour-a-day shifts, the number of days required is reduced to 144. The production time is reduced even more to 75 days under crisis production using three 8 hour-a-day shifts.

Table 3
Time Required to Produce DMA Products Under Various Levels of Constraint

	Routine Production (1 shift per day 5 days/week)	Committed Production (2 shifts per day 5 days/week)	Crisis Production (3 shifts per day 7 days/week)
ITD (15 min x 15 min) (28 km x 28 km)			
Image Source	1,725 hrs 321 days	1,725 hrs 144 days	1,725 hrs 75 days
TTADB Source	1,170 hrs 290 days	1,170 hrs 100 days	1,170 hrs 56 days
DTED 1 (1° x 1°) (111 km x 69 km)	925 hrs 283 days	925 hrs 77 days	925 hrs 39 days
DTED 2 (1° x 1°) (111 km x 69 km)	1,625 hrs 371 days	1,625 hrs 82 days	1,625 hrs 51 days

At the Waterways Experiment Station (WES) time and cost to produce digital terrain elevation data are dependent on landforms of plains, hills and mountains. Figure 4 depicts the time and cost to produce digital terrain elevation data for a 15 min by 15-min area (28 km x 28 km) based on landforms. The data source is a 1:50,000 mapsheet (roughly 30-m resolution). The more complicated the landform, the higher the cost to produce at any resolution (WES 1995).

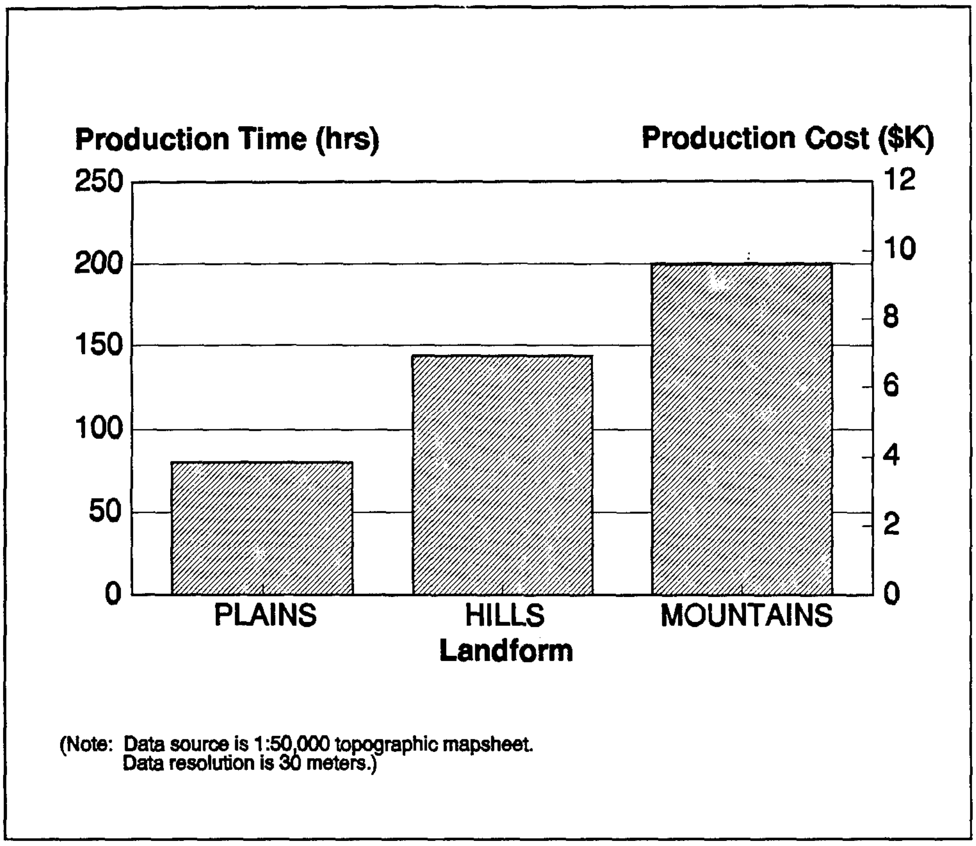

Figure 4. WES DTED production times based on landforms

TEC has produced some very high resolution databases. Table 4 states some basic information about four of these databases. Table 5 gives a cost breakdown for the production of each database (Morgan 1995). It is important to note that these databases cover very small areas. The 29 Palms database covers 7.26 sq km at a cost of $51,541. A brigade size area (50 km by 50 km) is roughly 345 times as large as the area covered by the 29 Palms database.

Table 4
Time Required for TEC to Produce High Resolution DEMs

DEM	Size (km x km))	UTM Coordinates (m E) (m N)	Horizontal Resolution (m)	Horizontal Accuracy (m)	Vertical Resolution (m)	Vertical Accuracy (m)	Production Time (hours)
29 Palms	2.2 X 3.3	SW 592750 3795671 NE 594950 3798945	1.0	0.00	0.1	0.15	320
NTC West	7 X 7	SW 540000 3920000 NE 547000 3927000	5.0	0.00	0.1	0.30	80
NTC East	6.4 x 7.9	SW 555105 3911220 NE 551505 3919120	5.0	1.00	1.0	1.00	80
Yakima	15 x 9	SW 696963 5171083 NE 711963 5180083	5.0	1.00	1.0	1.00	360

Table 5
Cost for TEC Produced High Resolution DEMs

	29 Palms	NTC West	NTC East	Yakima
Field Survey	$9,966.00 TEC	$9,966.00 TEC	$9,966.00 TEC	$9,966.00 TEC
Aerial Photography	$20,422.00 PSI	$20,422.00 PSI	$20,422.00 PSI	$25,504.00 PSI
Aerotriangulation	$8,075.00 PSI	$1,635.00 TEC	$1,767.00 PSI	$10,856.00 PSI
DEM Generation	$13,078.00 TEC	$3,270.00 TEC	$3,270.00 TEC	$6,539.00 TEC
Total	$51,541.00	$35,293.00	$35,425.00	$52,865.00

The Perspective View Generator and Analysis System for Unmanned Sensors (PEGASUS) is a computer based system for very high resolution terrain database development and real-time perspective view generation. The U.S. Army Test and Experimentation Command (TEXCOM) initiated the development of PEGASUS for Fiber Optic Guided Missile (FOG-M) evaluation. Since that time, TRAC-Monterey has been working closely with the original developer of PEGASUS to further the development of such technologies.

The cost curves shown in Figure 5 provide estimated trends to produce very high resolution terrain data by the PEGASUS system. These curves are based on limited data and are only to provide general trends as to the cost of terrain data generation at varying resolutions for a job size of approximately 400 sq km. More than 70 percent of the total effort and cost for database generation is attributed to stereo compilation and aerotriangulation. The PEGASUS system can also accommodate DTED from DMA when desirable (Ackeret 1990). The PEGASUS II system, not referenced in Figure 5, and ultimately the PEGASUS III system will be more automated and thus reduce database generation cost. At the 5 m posting, it is expected that the PEGASUS III system will allow a cost reduction of 60 percent when compared with PEGASUS I.

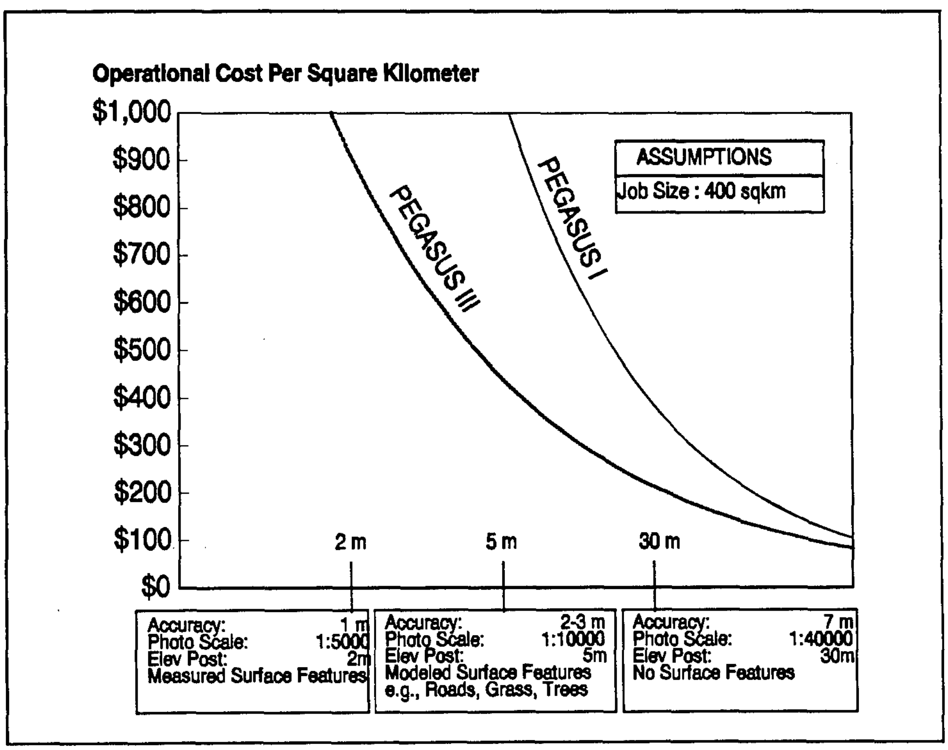

Figure 5. PEGASUS terrain database creation cost

For the constructive models Janus and CASTFOREM, processing of existing digital terrain and feature data into model-ready data only requires about 2-3 weeks (Pabon 1995). For the virtual simulation Close Combat Tactical Trainer (CCTT) the time required to process existing digital data such as ITD, DTED, DFAD, etc., into a format required by the Evans & Sutherland database generation system is approximately 9 months. At least one additional week is required to compile these data into a CCTT runtime database for the appropriate Image Generator System (IGS) (Woodward 1995).

Conclusions

In summary, the findings concerning cost to develop digital terrain data, yielded the following conclusions and statements:

a. Cost to develop digital terrain data increases exponentially with resolution. Time required to produce very high resolution (i.e. higher than 10 m) is prohibitive for large areas and source information is limited.

b. Very high resolution feature information requires large scale imagery (1:5000) and the associated very time intensive analysis to produce data with high fidelity.

c. DTED2 or better, is required for realistic terrain visualization in most terrain types and is absolutely critical for portrayal of smooth terrain. DTED1 may be adequate in very rough terrain.

d. DTED from solely photographic sources provides data which exhibit substantially more fidelity than from non-photographic sources.

e. Currently DMA is negotiating with the user community for a minimum essential data set (MEDS) of DTOP in order to decrease production time and cost.

f. For constructive simulations, processing time is insignificant when compared to the time required to generate the basic digital data. For CCTT, the time required to process existing digital terrain data is very significant, being approximately 9 months.

One shortfall noted is that information about feature data at various resolutions is limited. Thus comparisons of cost at different resolutions are difficult at this time.

3 Cost to Store Digital Terrain Data of Various Areas of Coverage at Various Resolutions

Database Storage Requirements

Another factor to be considered in M&S is the cost to store digital terrain data of various areas of coverage at various resolutions. In Figure 6 the storage requirements in megabytes for selected databases of various sizes and resolutions are shown.

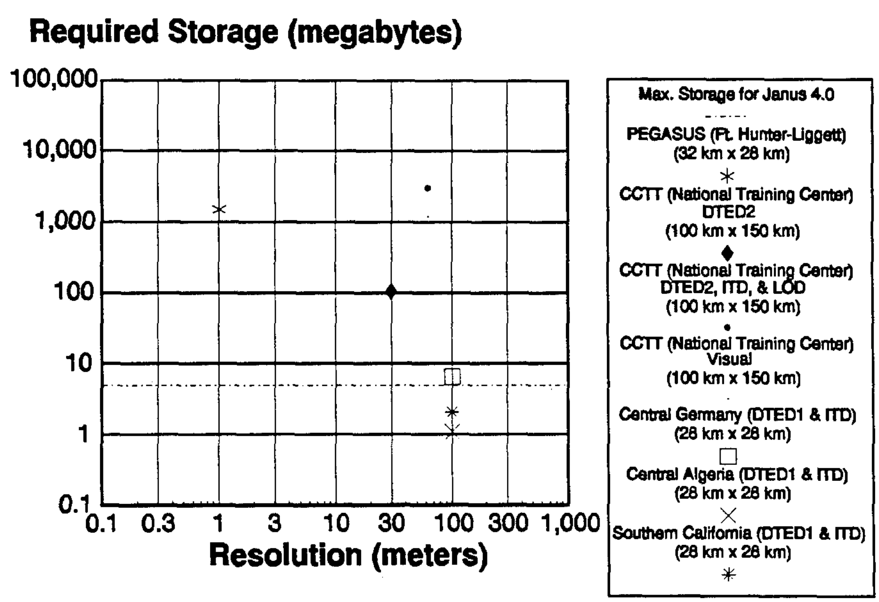

Figure 6. Terrain storage requirements

The maximum size for a Janus(A) 4.0 terrain file is approximately 5 megabytes. The horizontal line represents this storage limitation. It should be noted the line does not represent the actual storage requirements for any specific Janus(A) 4.0 terrain data. It is shown merely as the limitation that exists. Typical Janus(A) 4.0 terrain resolutions are 50 and 100 m. One other point that should be made about Janus(A) 4.0 terrain data is that Janus(A) 4.0 allows a maximum area of 1000 X 1000 grid cells. Therefore, as resolution varies, the total area of the grid varies (TRAC 1994).

The PEGASUS/Ft. Hunter Liggett database occupies about 1.5 gigabytes of storage. More than 50 percent of this area of coverage is at 1-m resolution (Baer 1995).

For the 100 km by 150 km CCTT gaming area, the raw DTED2 (which is 30-m resolution) source data used approximately 90-120 megabytes of disk storage depending upon the latitude of the location. The completed CCTT Primary 1 database (Central U.S.) with all of the supporting level of detail (LOD) files and ITD feature data and models added is approximately 3 gigabytes in size. After compiling the Primary 1 database into a run time ESIG-2000 image generator database, the size is reduced to a 1.2 gigabyte file. This reduction in size is caused by the elimination of all extraneous information which is not vital to image generation (Daniel 1995). The databases for Central Germany, Central Algeria, and Southern California represent the average of the database sizes of all available cells of data in each area. These databases are for a 1:50,000 mapsheet representative area (WES 1995).

Cost of Storage

Disk storage is relatively cheap. Figure 7 depicts initial hardware costs versus storage capacity in megabytes and indicates that cost versus storage capacity is a fairly linear relationship for the range of values up to ten gigabytes. Ten gigabytes is sufficient to store any terrain data discussed so far. Thus disk storage is not really an issue (Insight Direct, Inc. 1994).

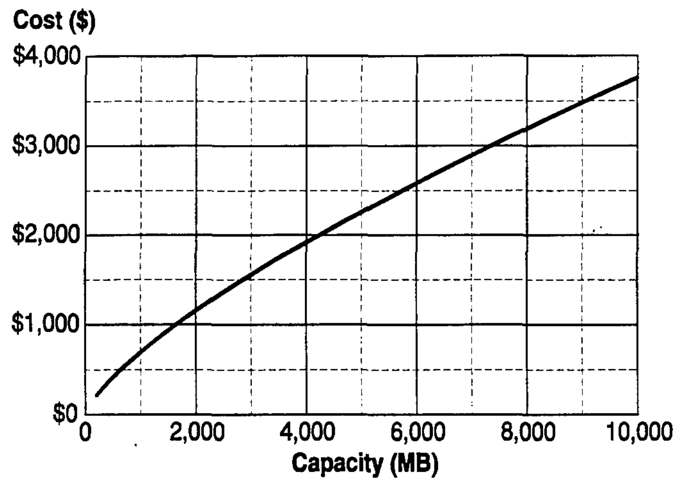

Figure 7. SCSI cost versus storage capacity

Memory limitations for computer systems are more of an issue. When large quantities of data are required to be loaded from the terrain database into computer memory to do virtual fly-throughs, you can be restricted to a load of 100-200 megabytes worth of data in computer memory at one time. This problem is managed with a model workaround called terrain paging. Terrain paging is a methodology where terrain, well in advance of the simulator vehicle (e.g., 8 km) is paged into memory while terrain in the opposite direction is removed from memory (Mackey 1991). This methodology allows a large area of terrain to be used by the simulator, plus it aids in allowing vehicle movement to appear at a realistic frame rate.

Conclusions

In summary, the costs to store high resolution digital terrain data for use in M&S are insignificant when compared to production costs. Size of model ready data files is significant only when the data file is too large for active memory during model run. Terrain paging and variable levels of resolution help alleviate this problem.

4 Cost to Transmit Large Volumes of Data

Transmission Times

The nomograph in Figure 8 shows transfer time of DTED over various bandwidths at 50 percent efficiency for a fixed area with dimensions of 50 km by 50 km at various resolutions. For example, using a T-1 circuit (which has a 1.5 Mbits/sec transfer rate) at 10-m resolution takes about 9 minutes, whereas transfer time at one meter resolution takes approximately 15 hours. Storage requirements for each grid cell is assumed to be 2 Bytes.

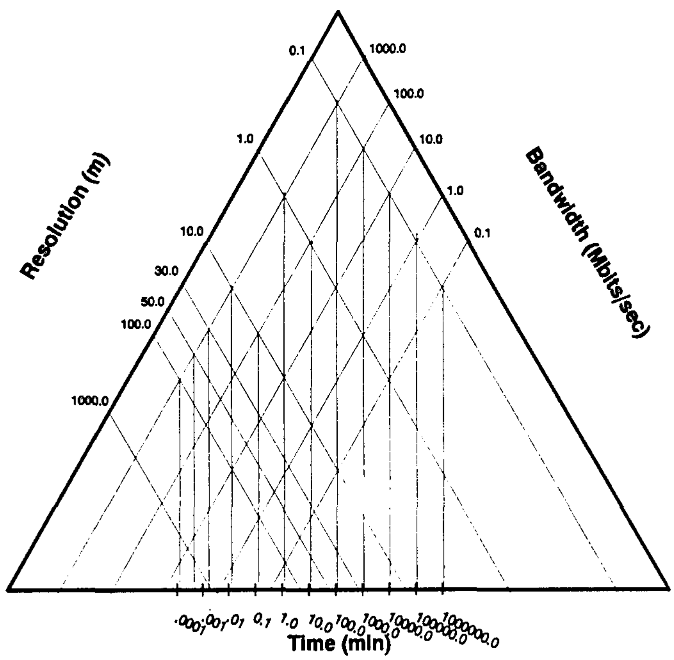

Figure 8. Nomograph for computing transfer time for 2,500-km^2 area

A second nomograph, Figure 9, shows transfer time of DTED over various bandwidths at 50 percent efficiency for areas up to 10,000 km^2 of coverage at different resolutions. For example, transfer time using a T-1 circuit for a 10-km by 10-km area at 1-m resolution takes about 36 minutes. Storage requirements for each grid cell is assumed to be 2 Bytes.

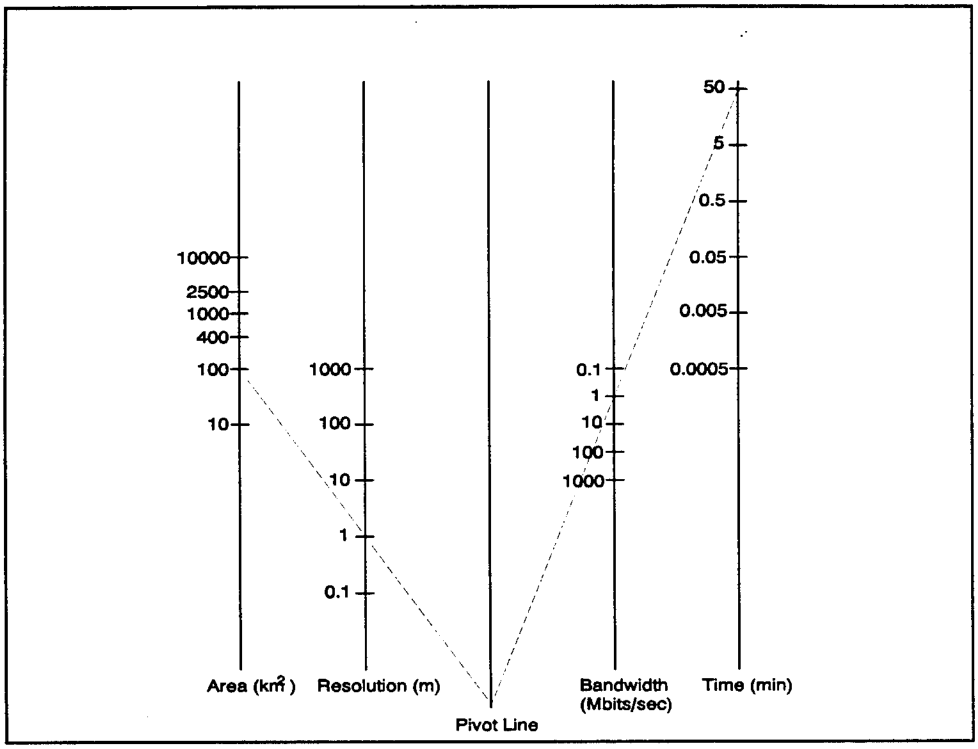

Figure 9. Nomograph computing transfer time for various areas of coverage

Transmission Rates

The current and predicted transmission rates for local area networks (LAN) and wide area networks (WAN) are shown in Figure 10. As can be seen from the two curves, in any given year LAN shows a much higher transmission rate than WAN. The same technology is available for both networks. But due to cost constraints, overall performance potential for WAN will lag a forecasted 5 to 6 years behind LAN.

Currently, transfer rates of 2.5 gigabytes per second are technologically possible, but all the hardware and cabling requirements are not in place to achieve this over WAN. This technology will be in place in the near future at many high performance computer centers on a LAN basis. What this means for the DIS community is that the use of higher resolution terrain requires larger databases and larger databases require faster transmission rates in order to maintain real time update capabilities over the network. Even as we move into the year 2000 and beyond, the bandwidths will lag behind the demand of increasing transmission requirements (Department of the Army 1994), (WES 1995).

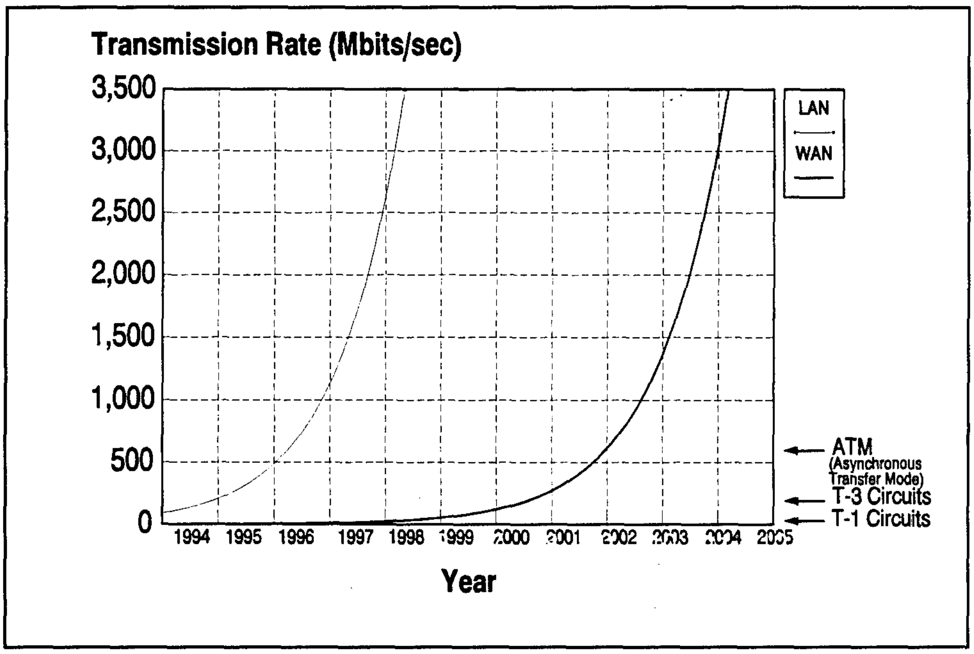

Figure 10. DSI transmission capability

Defense System Internet

In Figure 11, the top map shows current Defense System Internet (DSI) bus topology and the bottom shows possible future star topology. Currently these sites are connected by a T-1 line which will provide transmissions rates of 1.5 Mbits per second between DSI nodes. In the LAN arena, the bus topology is rapidly disappearing in favor of the star because the star offers significant advantages in the areas of management and performance. If one arm of the star goes down, others are not affected. A star can be configured to be several different networks, so different exercises could occur and be physically separated. To make a star topology work for the DSI requires some modification to the concept. Instead of the hub of the star being a single hardware system, it would need to be a high speed backbone of Fiber Distributed Data Interface (FDDI) or Fast Ethernet at one central site with multiple connections into it - one from each of the outlying sites. In this layout, sites that need higher bandwidth to the hub can obtain it (Juliano 1995). It is envisioned that a site running an infantry M&S exercise would require more data transmissions than a site running a tank model.

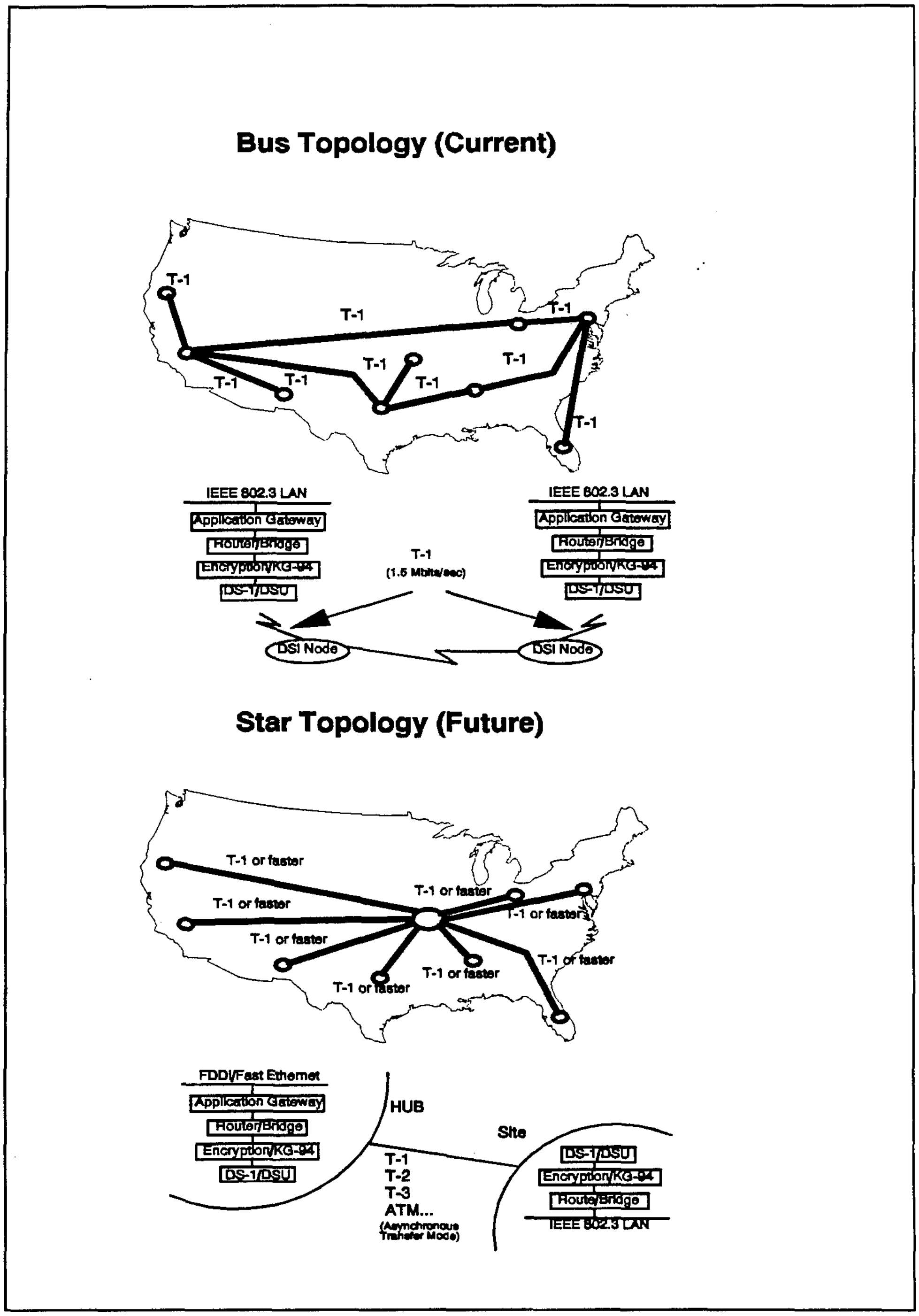

Figure 11. DSI network topology

Conclusions

Findings as to the cost to transmit large volumes of data across LAN and WAN in the DIS environment follow:

a. A 1.5 Mbits/sec transfer of DTED for a 10-m resolution 50 km by 50 km area at 50 percent efficiency takes approximately 9 minutes, while a 1-m resolution 50 km by 50 km area takes 15 hours.

b. Current available bandwidths on DSI are 1.5 Mbits/sec. By the year 2000 this should increase to 45 Mbits/sec and to 600 Mbits/sec by 2003. Note: LAN will have 600 Mbits/sec capability by 1998.

c. DIS is more dependent on existing WAN than on the technologies existing at DSI nodes and WANs are expected to continue to serve as the bottleneck.

5 The Relationship Among Terrain Resolution, Processing Capacity, and Modeling and Simulation Runtime

Virtual Simulation

A major concern in M&S is the relationship among terrain resolution, processing capacity and M&S runtime. Processing capacity in terms of MIPS (million instructions per second) should not be used as the basis for comparison of different computer systems' CPU's because of the difference in architecture between systems. A better comparison can be achieved by running the algorithm SPECint 92 on each system which will provide a more accurate comparison between systems. Even with this comparison, system efficiency is dependent upon hardware and software interaction. The best measure is the speed of the system to accomplish the desired task, i.e. frames/sec. Figure 12 expresses performance based on frames/sec as a function of terrain resolution for several virtual simulations. The horizontal dash line in Figure 12 represents the 15 frames/sec required to generate a real time visual image. An input rate of 15 frames/sec into a graphic processor will usually output 30 frames/sec. The graphic processor does this by interpolating between two frames to give an effective doubling of the frame rate.

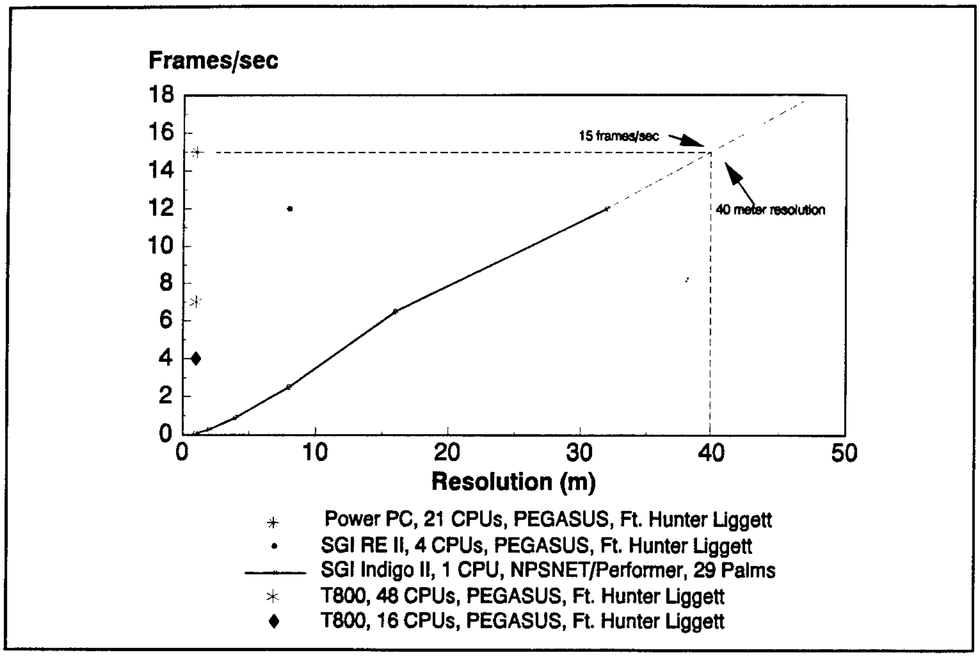

Figure 12. Terrain resolution versus virtual processing capabilities

The Naval Postgraduate School (NPS) examined the performance of the Silicone Graphics software, Performer, running on a SGI Indigo II, to determine the frame speed that can be achieved by resampling the 1-m 29 Palm's database to lower resolutions (Pratt 1995). Performer is a graphic processor used by NPSNET, a virtual modeling environment. The data from these comparisons display a somewhat linear relationship. The actual data only go to 32-m resolution. If, however, this linear relationship is consistent, the extrapolated portion indicates that an approximate 40-m resolution would allow Performer to achieve the required 15 frames/sec for this computer system.

Other points on the graph represent frame rate capability of various systems using PEGASUS software and the Ft. Hunter Liggett l-meter database. (Note: SGI Reality Engine II used an 8-m sampling.) Both T800 systems using 16 CPU's and 48 CPU's fall considerably short of the real time 15 frames/sec. The SGI Reality Engine II consisting of 4 CPU's achieves 11 frames/sec at 8-m resolution. It would appear that only minor adjustments in computer power and/or resolution could increase this system's performance to the desired 15 frames/sec. Real time can, however, be achieved at 1-m resolution given enough computing power as demonstrated by the Power PC prototype system which consists of 21 CPU's and operates at TRAC Monterey and a few other select sites. It is important to note that the PEGASUS systems were using model workarounds which allowed terrain at far range to be displayed at a low resolution while near range was displayed at a high resolution. The Performer software had this feature turned off. Use of this scheme in Performer could possibly double the frame rate thereby allowing the use of 20-m resolution terrain data to achieve real time. This workaround will be discussed later (Baer 1995).

Constructive Models

Figure 13 presents the ratios of real time or clock time to simulation time for three different computers each with a separate scenario over various terrain resolutions. Conclusions should not be drawn as to the performance capability of one computer over another. Figure 13 illustrates the relative performance of a particular computer and scenario with respect to terrain resolution. All three scenarios were run using some release of Janus(A) 4.0. At 50-m resolution the real time to simulation time ratio for the Desert Hammer scenario was approximately 6 to 1 which is an unacceptable ratio for Janus gaming. Working under the assumption that, for this particular scenario, fidelity would not be lost by decreasing terrain resolution, the developers decreased the resolution to 100 m to obtain an approximate 2 to 1 ratio (Watson 1995). This 2 to 1 ratio is an acceptable/desirable ratio for gaming and simulation because the gamer has sufficient time to interact with the computer to conduct the simulation.

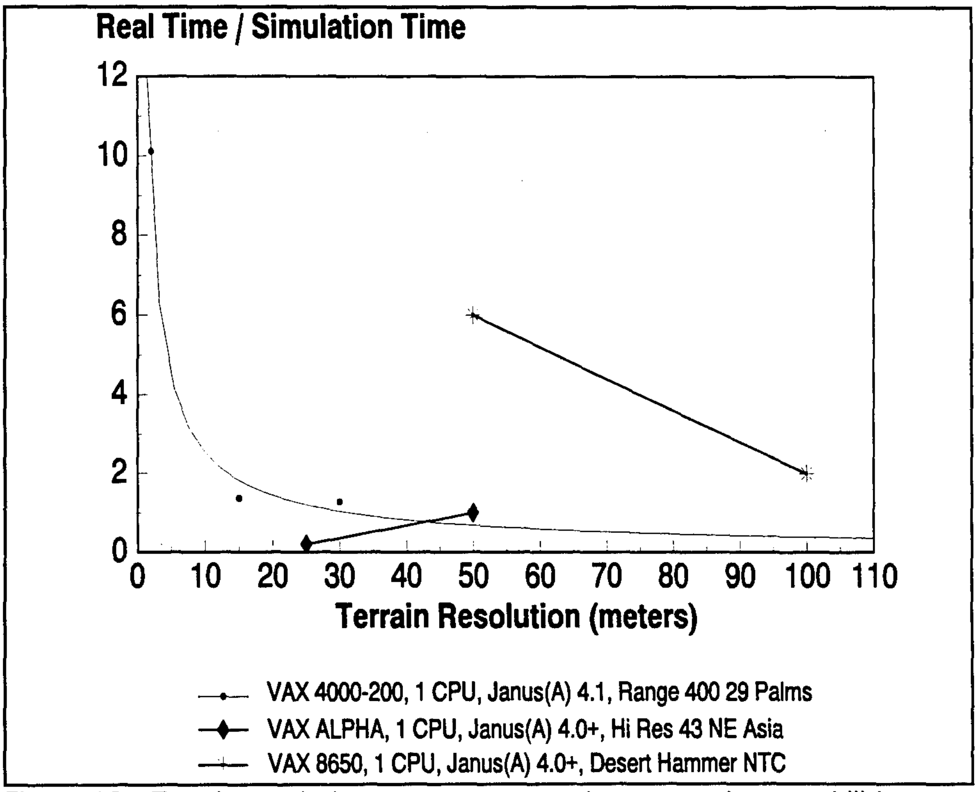

Figure 13. Terrain resolution versus constructive processing capabilities

The next scenario at Range 400 29 Palms was performed on a VAX 4000-200 (D'Errico 1994). The data were used to produce a curve demonstrating the exponential relationship of the ratio of real time to simulation time and terrain resolution. For this particular machine there is a sharp decrease from the 2 m to 15-m resolution and it remains fairly stable thereafter. The two scenarios discussed thus far exhibited expected results in that as resolution decreased, the real time to simulation time ratio decreased because fewer terrain grids were processed.

The third scenario, Hi Res 43 NE Asia, was conducted on a VAX Alpha with 1 CPU. The two ratios shown for the two resolutions are counter-intuitive. However, NE Asia is a feature rich terrain. In this scenario, the feature data at 25-m resolution caused a decrease in the Line-of-Sight (LOS) to targets that were visible in the 50-m resolution data. The 25-m data required less processing time because LOS from a weapon system to a target was blocked more frequently. Thus, the 25-m data required less LOS calculations than the 50-m data . Because the real time to simulation time ratio was less than 2 to 1, the scenario developers chose to add additional complexities into the scenario that were not terrain related. This added fidelity to the scenario while still achieving the approximate 2 to 1 ratio (Watson 1995).

Line of Sight Algorithms

Figure 14 relates LOS algorithm computational time to terrain resolution. The data have been normalized with the 50-m resolution having a value of 1 and the other resolutions having their respective computational time indexed to this 50-m resolution. As expected, the curve is exponential. The values represented in Figure 14 are an aggregation of 4 different areas including Yakima, Ft. Irwin (east), Ft. Irwin (west), and Range 400 29 Palms (none of these is feature rich). This figure illustrates that a factor of 40 increase in LOS computational time can be expected when using 1-m terrain resolution instead of 50-m resolution in a feature-sparse terrain. This figure does not represent any one LOS algorithm, as these values represent a compilation of five algorithms studied (Bresenham, ALBE, DYNTACS, ModSAF, Janus). (Champion 1995).

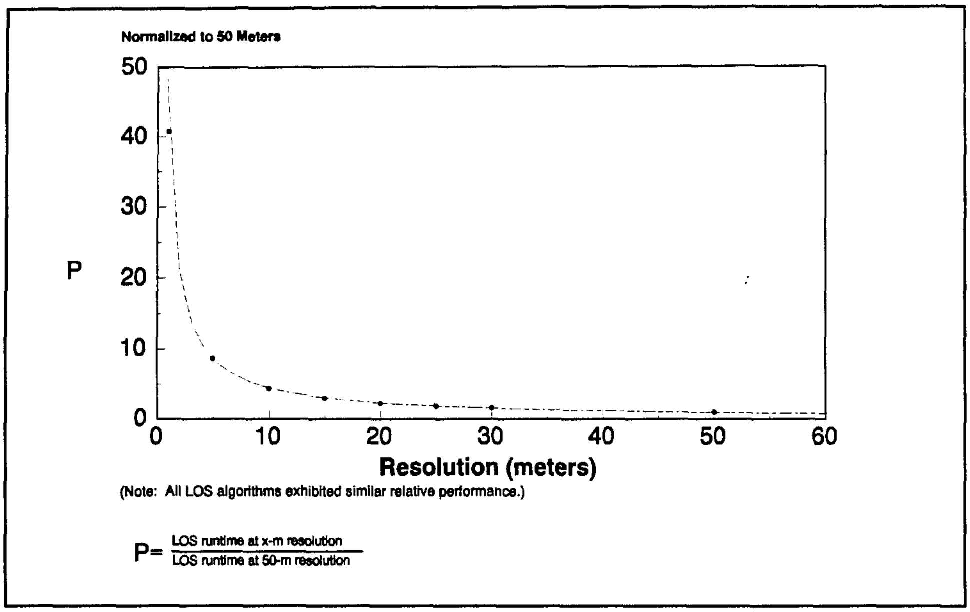

Figure 14. LOS runtime at varying terrain resolution

The relative computation time of the LOS algorithms for four different models is displayed in Figure 15. Each model has a different LOS algorithm: CASTFOREM uses the Bresenham algorithm, UCCATS uses the DYNTACS and ModSAF and Janus each have their own algorithms. All computational times for these algorithms have been normalized to the CASTFOREM's Bresenham algorithm. The ModSAF algorithm is the most computationally intensive and therefore requires the most time. One can estimate that putting the ModSAF algorithm in the CASTFOREM model would result in an approximate factor of 5 increase in the relative computational time in the LOS calculations (Champion 1995).

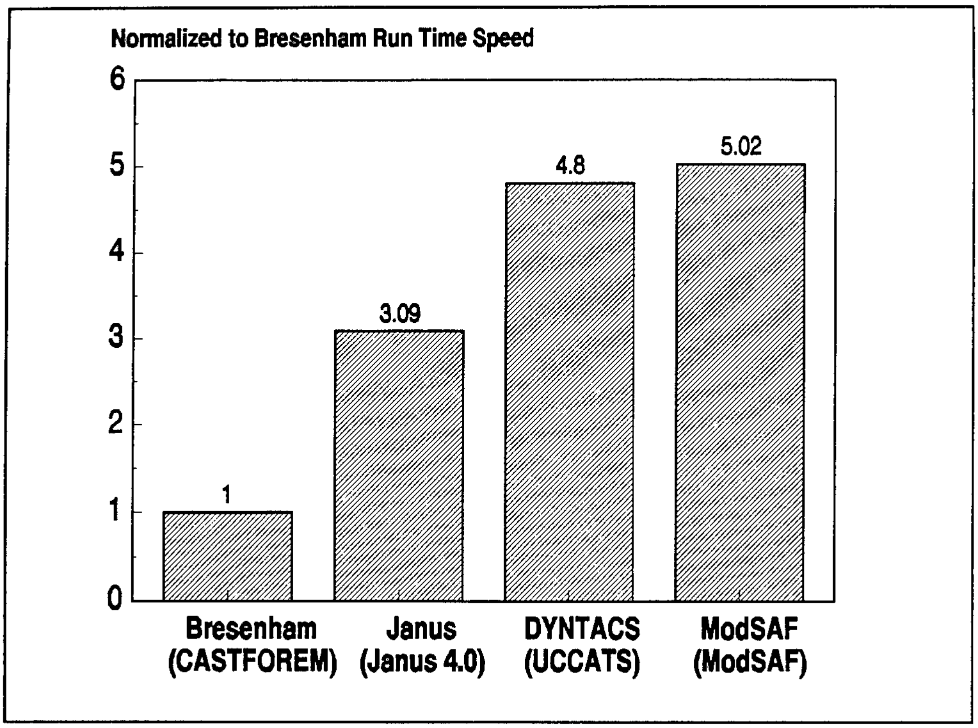

Figure 15. Relative runtimes of LOS algorithms

Conclusions

In examining the relationship among terrain resolution, processing capacity and model and simulation runtime, a shortfall of information was found. Most analysts do not perform comparative studies on the effect of terrain resolution on processing capacity. Rather, in cases where the fidelity of the scenario is not resolution dependent, if the scenario runs too slow at the best terrain resolution available, they will lower the resolution of the terrain in order to achieve the desired runtime when it is believed that scenario fidelity will not be compromised.

It can be concluded that only with special purpose high-power hardware such as the Power PC with 21 CPU's can real time visualization or fly-throughs of terrain be obtained using very high resolution data.

In feature sparse areas, LOS calculations increase dramatically at very high resolutions. In feature dense locations, high resolution data could actually reduce simulation runtime.

Variability in LOS calculation time exists between currently used algorithms. This variability can be as high as a factor of five.

6 Agreement Among Constructive Models, Virtual Simulations, and Live Exercises

Line of Sight Algorithms

For effective M&S there must exist agreement among constructive models, virtual simulations and live tests or training exercises with respect to combat measures of effectiveness. At varying levels of terrain resolution, what level of agreement exists is another important M&S concern. Figures 16 and 17 present data from a study comparing LOS algorithms over various terrains with field test measurements at varying terrain resolutions (Champion 1995). These same algorithms were discussed in the previous chapter where relative computation time was being compared. Here the correlation these algorithms provide with field test data will be presented. The Pearson Product Moment Correlation (PHI) was used to measure this correlation. The calculation of PHI was accomplished as follows:

		LOS Algorithm: LOS	LOS Algorithm: No LOS
Field Test Data	LOS	A	B
	No LOS	C	D

where A= the number of observations where both the LOS algorithm and the field test data indicated there would be line-of-sight.

B= the number of observations where the field test data indicated line-of-sight, but the LOS algorithm indicated no line-of-sight.

C= the number of observations where the LOS algorithm indicated line-of-sight, but the field test data indicated no line-of-sight.

D= the number of observations where both the LOS algorithm and the field test data indicated no line-of-sight.

$$PHI = \frac{AD-BC}{\sqrt{(A+B)\ (C+D)\ (A+C)\ (B+D)}}$$

The possible values of PHI range from -1 to +1. A value of -1 indicates total disagreement of the algorithm with field test data. A value of 0 indicates that the model has a 50/50 chance of agreeing with field tests. A value of +1 indicates perfect agreement between the model and the field test data. The value of PHI which indicates significant correlation varies with the number of samples in the data set. Typically, desirable reliability coefficients fall in the 0.80's and 0.90's (Anastasi 1976). For the aforementioned LOS study, it was determined that a value of 0.85 should be used as the lowest significant value of PHI (Champion 1995). The comparisons were conducted at Yakima, Ft. Irwin West, Ft. Irwin East and Range 400 29 Palms. Figure 16 shows correlation of LOS algorithms at Ft. Irwin East. CASTFOREM's Bresenham LOS algorithm diverges at lower terrain resolutions beginning at 20 m. Figure 17 shows similar findings at Range 400 29 Palms. Again, CASTFOREM's Bresenham LOS algorithm diverges as resolution lowers and the divergence increases significantly at 20 m. Also note that the Janus LOS algorithm experiences some problems at very high resolution (1 to 5 m) and again at 20 to 30 m. Overall, the ModSAF and DYNTACS LOS algorithms correlate well with field data at most resolutions.

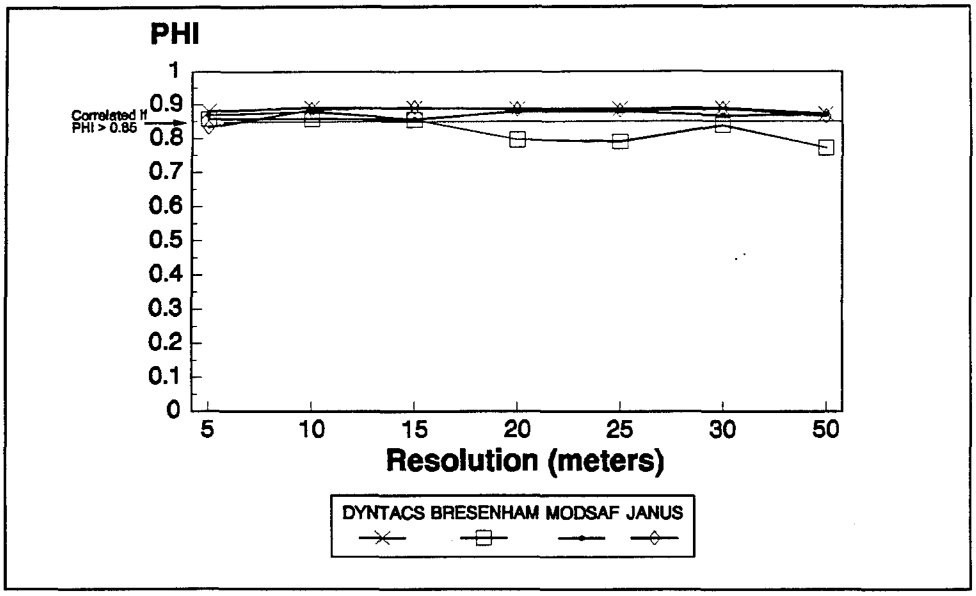

Figure 16. Correlations of LOS algorithms to field LOS at Fort Irwin (East)

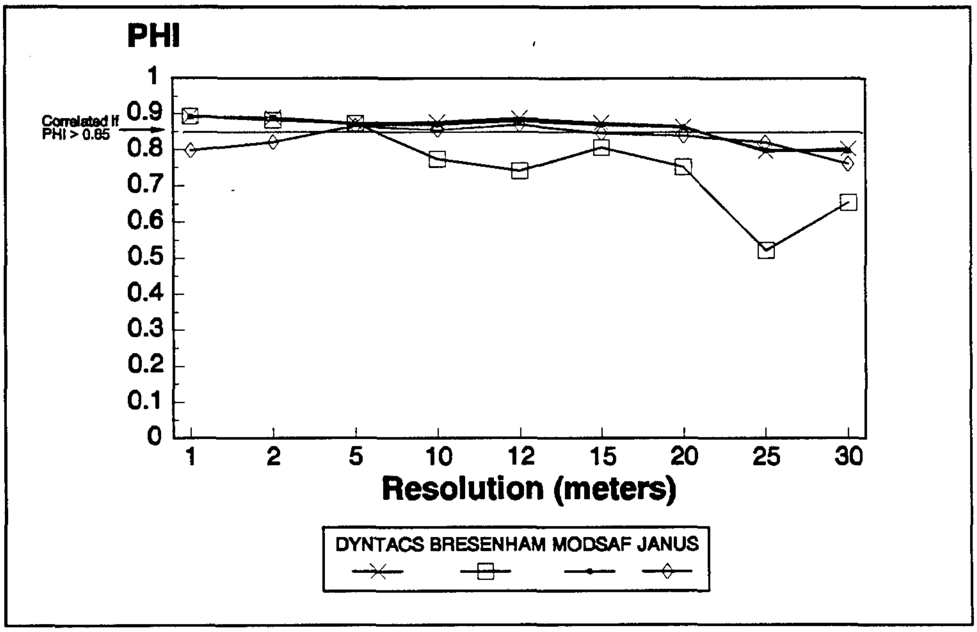

Figure 17. Correlations of LOS algorithms to field LOS at 29 Palms

A study entitled "Digital Terrain Elevation Study, Final Report" was published in May 1992 by D.A. Marline with Hughes Aircraft Company. Unfortunately this report contained very little pertinent information. There was no explanation as to quality, source or content of terrain that was used. Also, the LOS algorithms included were not representative of the LOS algorithms commonly in use today.

Combat Measures of Effectiveness

Figure 18 shows the relationship between one measure of effectiveness, number of detections, and terrain resolution. This relationship was taken from a U.S. Infantry School study on Terrain Resolution Evaluation at 29 Palms (D'Errico 1994). The number of detections of red by blue were highly variable from 2-m resolution through 30-m resolution. The graph shows similar variability for weapons with sensors and for eyes only detections. A regression line shows a slow overall rise in the number of detections at lower resolution. The assumption is that high resolution allows for finer terrain detail which provides more areas of concealment.

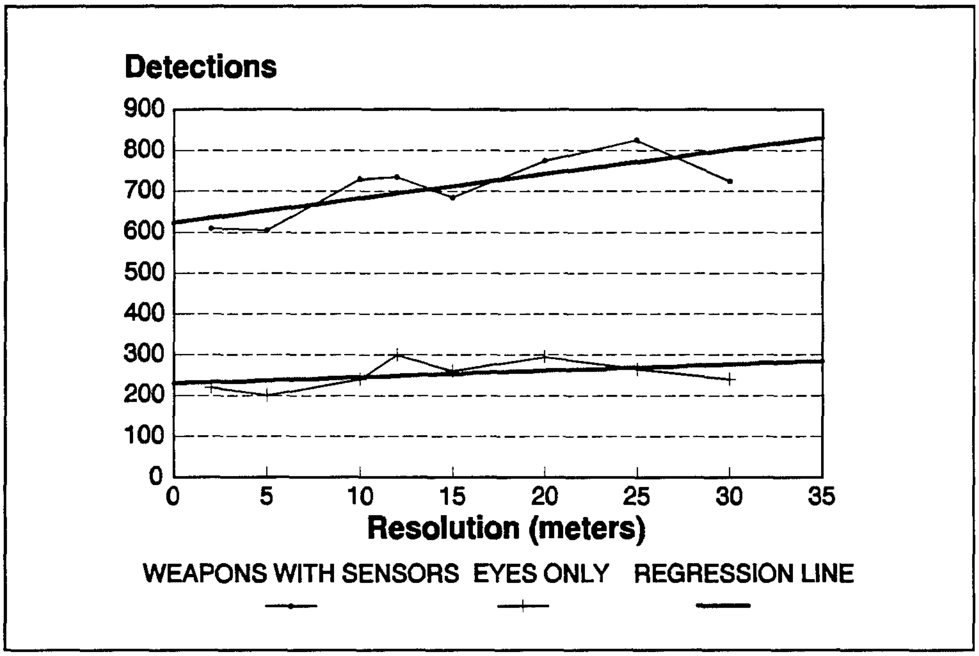

Figure 18. Blue detections of Red in Janus 4.1

Figure 17 showed that correlation of Janus LOS with field data at 29 Palms decreases beginning at 20-m resolution. This poor correlation beyond 20-m resolution may contribute to the increase in force exchange ratio and loss exchange ratio seen in Figure 19 (D'Errico 1994). Other models using these algorithms would probably experience similar results. More analysis is needed to help explain why these models behave as they do.

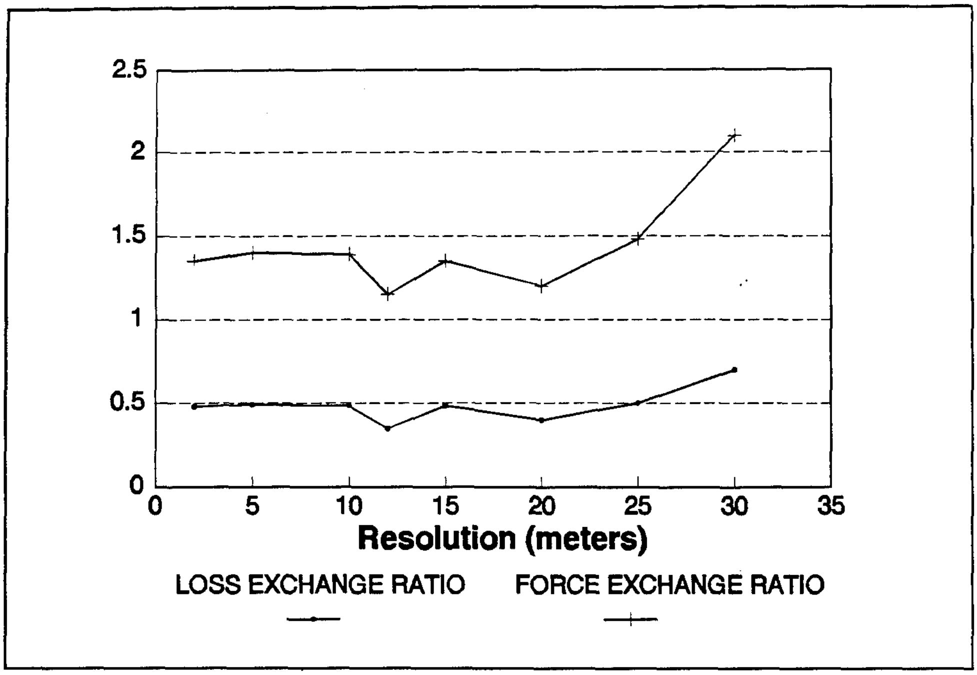

Figure 19. Force effectiveness ratio in Janus 4.1

In the fall of 1991, TEXCOM Experimental Center at Fort Hunter Liggett, California, conducted an operational test of the M1A2 tank for comparison with the M1A1 tank. A series of trials explored the tank's operational performance, using a variety of scenarios, to include deliberate defense, hasty defense, movement to contact, and hasty attack for both M1A2 and M1A1.

In July 1992, TRAC-Monterey obtained data from this experiment and conducted a post-test comparison of Janus (50-m elevation data) versus field test data, as part of the Model-Test-Model paradigm. Post-test analysis encompassed three Janus runs of each of the tank trials, to include hasty defense, deliberate defense, movement to contact, and hasty attack. The measure of effectiveness (MOE) is first engagement range, meaning that the analysis considered only the first shot taken by a combat system at any particular enemy system. The results of this comparison indicate that Janus represents the M1A2/M1A1 field test adequately for almost every scenario. Results from the basic two-sample t-test comparisons showed no statistical difference between Janus and the corresponding field test occurred except for the deliberate defense trials of both tanks. Attempts were made to improve the deliberate defense results using an integrated Janus/PEGASUS system (1-m elevation data) with a physical LOS algorithm (Paulo 1994). These attempts, however, were inconclusive.

The Anti-Armor Advanced Technology Demonstration (A^2ATD) is a joint Department of the Army/Department of Defense program. The first A^2ATD experiment (completed 14 Sep 94 at Ft. Hood, Texas) replicated two M1A2 Initial Operational Test (IOT) vignettes to validate virtual simulation (BDS-D) with live simulation (IOT) and to validate constructive simulation (ModSAF and CASTFOREM) with live and virtual simulation. Two M1A2 IOT vignettes were replicated: Hasty Attack and Hasty Defense. In the Hasty Attack a company of M1A2 Tanks attacked a platoon of T80 tanks and 3 BMP's. In the Hasty Defense, a company of M1A2 tanks defended against an attrited T80 Tank Battalion. One platoon and a BMP held an overwatch position while the rest of the battalion attacked. Forty-eight trials were run over a 12 day period. Twenty-four trials were run for each vignette (12 trials with manned simulators and 12 trials with ModSAF only). Four M1A2 simulators were used in the manned simulator trials. To minimize crew learning effects, the scenario and platoon location were randomized (Brooks 1994).

In this study the MOE was number of shots and losses. This MOE was chosen over number of detections because the analysts involved in the experiment believed that first detections were difficult to determine in virtual simulation/simulators. Some results for Hasty Attack shots and losses found in this ongoing study are shown in Figure 20. Field data are indicated with the cross symbol and the remaining data indicate the range of values for CASTFOREM, BDS-D (with ModSAF LOS), and ModSAF. As one can see, in most cases the field data fall into a range of values for these three models. This gives an idea of how these three models match with field data for particular terrain resolutions -- CASTFOREM uses 25-m data (source: WES), BDS-D simulators use DTED1 resampled to 125-m resolution and ModSAF uses DMA DTED1 data resampled to 30-m. Perhaps further study would show that with use of the same terrain source these models would have a smaller range of values and more closely match field test data.

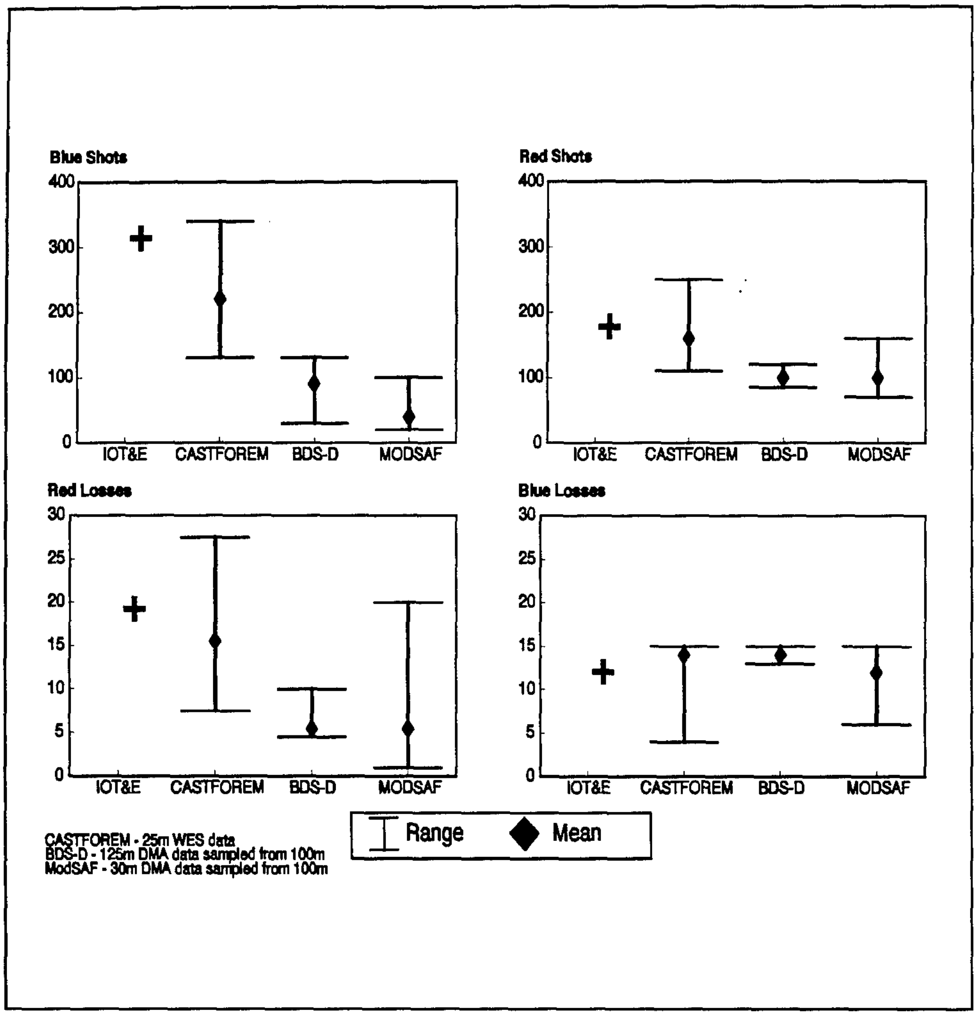

Figure 20. Comparison of live, virtual, and constructive simulation in A²ATD hasty attack

Similar to Figure 20, Figure 21 displays the relationship of hasty defense shots (Brooks 1994). There is more variability from model to model for blue shots and red losses than in the hasty attack. In both hasty attack and hasty defense the CASTFOREM/Bresenham LOS model compared more favorably to live than either ModSAF or BDS-D (which uses the ModSAF LOS) in spite of the poor performance of the Bresenham LOS algorithm in earlier studies. This may be attributed to the difference in both terrain resolution, source, and quality of data. An analyst evaluation for the Ft. Hood DTED1 indicated that the data were of poor quality.

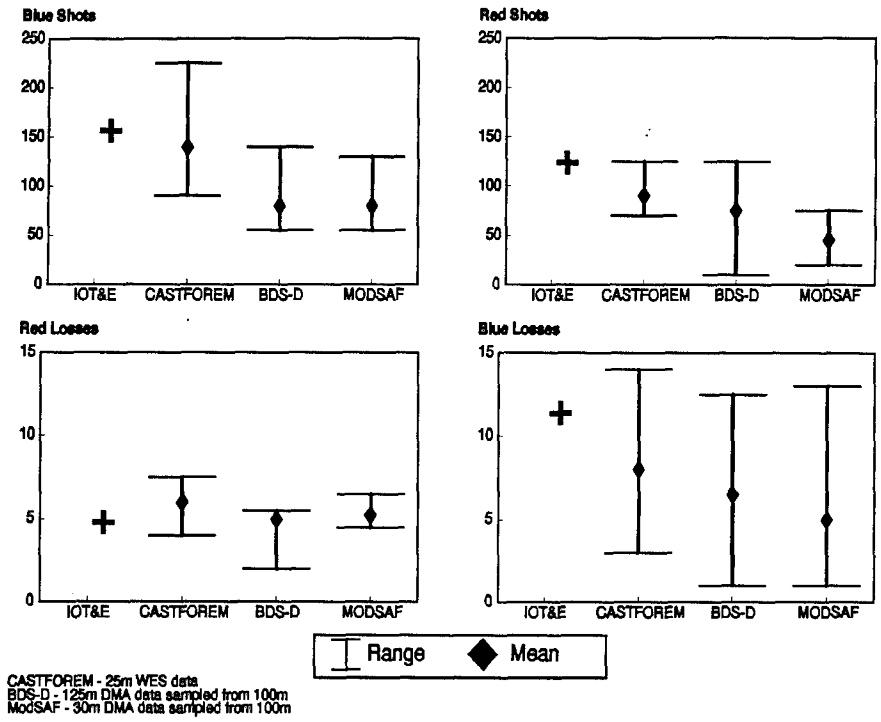

Figure 21. Comparison of live, virtual, and constructive simulation in A^2ATD hasty defense

In an attempt to address the questions that arose during the A^2ATD analysis, the CASTFOREM hasty defense exercise was rerun using ModSAF terrain in place of CASTFOREM terrain (Burrough 1995). Results, shown in Figure 22, indicate very little change. Next, the same exercise was run again replacing the CASTFOREM LOS algorithm with the ModSAF algorithm. Again, there was very little change. Finally, both ModSAF terrain and ModSAF LOS algorithm in combination were run in CASTFOREM and the results show a higher correlation to live in 3 of the 4 major end game measures. It may be informative to take the CASTFOREM data and resample it for ModSAF to see if higher resolution data would improve ModSAF performance.

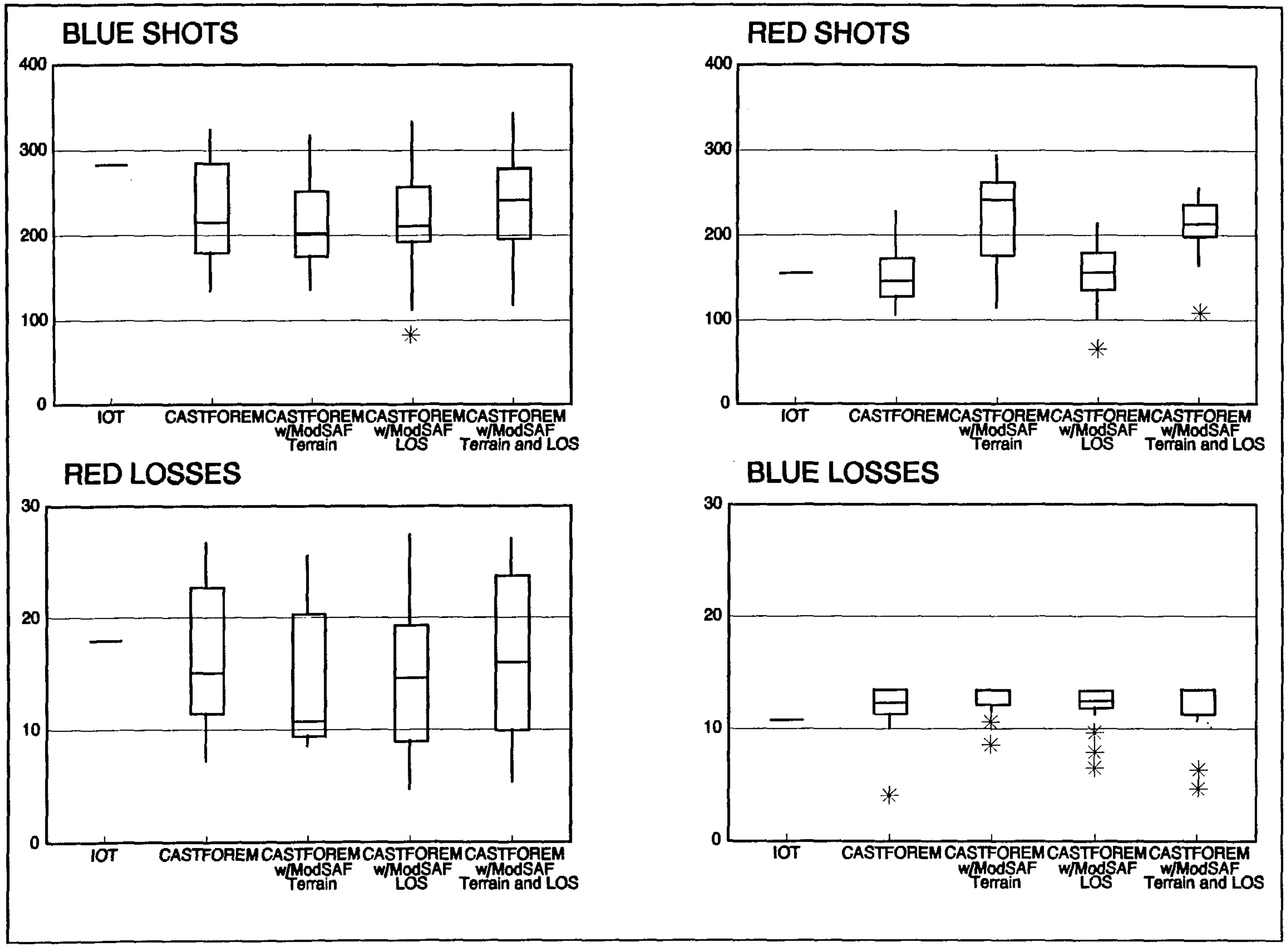

Figure 22. Hasty defense CASTFOREM excursions

The information displayed in Figure 23 is taken from the M1A1 Early User Test Experimentation report (McCool 1993). The study was performed at a single terrain resolution of 100 m using the Ft. Hunter Liggett database and compares the total number of M1A1 engagements from the field test with results from CASTFOREM. Separate bar graphs for CASTFOREM with surface features, CASTFOREM with no surface features, and CASTFOREM with tabletop data (no elevations) are shown. The no surface feature scenario was run in order to test the hypothesis that feature data represented in the 100-m resolution Ft. Hunter Liggett data did not allow the correct LOS for the weapon systems in the model. The plan was to remove the feature data and thus improve the LOS of the weapon system in the model and that is indeed what happened. However, the removal of surface features only slightly increased the number of engagements. The removal of elevation data entirely caused the greatest increase in the number of engagements. We conclude that 100-m data severely limits the correlation to field tests. Similar studies need to be conducted at higher resolutions to support this conclusion.

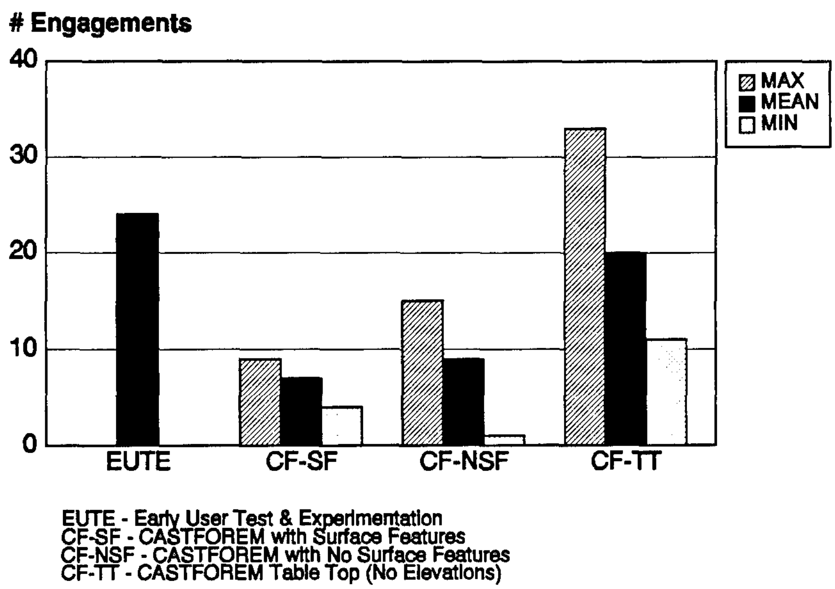

Figure 23. M1A1 early user test experimentation deliberate defense

Conclusions

Conclusions as to what is the level of agreement among constructive models, virtual simulations and live tests or training exercises with respect to combat measures of effectiveness are:

a. The ModSAF and DYNTACS line of sight algorithms show high correlation to field tests at all resolutions from 1 to 30 m at all sites. The Janus algorithm shows good correlation to field tests at all resolutions, from 1 to 30 m, at Ft. Irwin(east) and Yakima. The CASTFOREM/Bresenham algorithm shows low correlation to field tests at resolution of 10 m and lower.

b. A limited study by the Infantry School revealed that terrain resolution had a statistically insignificant effect on detections in the 2- to 15-m range when using the Janus 4.1 model to model an infantry scenario at 29 Palms.

c. Emerging results from the A^2 ATD hasty defense and hasty attack show that terrain resolution can have a significant impact on battle outcome especially when terrain resolution is lower than 30 m (i.e. 100 m, 125 m, etc.).

d. More analysis needs to be done at resolutions lower than 30 m.

e. With currently available data, it is difficult to pinpoint a particular terrain resolution at which constructive and/or virtual simulations depart from live. Adding to the problem is the fact that departure from live tests is algorithm dependent as well as resolution dependent. Other factors which can complicate the issue are quality of data and sources used to produce the data. Having identified these complications, in general, departure from live appears to occur at resolutions lower than 30 m (i.e. 50 m, 100 m, etc.) for most M&S.

Some shortfalls and limitations identified are:

a. Much of the analysis on model agreement with live tests or training exercises was conducted at only one particular resolution or mismatched resolutions.

b. Only the comparison of LOS algorithms and their agreement with field LOS data has been studied extensively at varying resolutions.

7 Modeling Workarounds

To overcome some inconsistences and/or shortfalls in the DIS environment, model workarounds can be used. Some terrain representation workarounds include:

a. To decrease runtime of a model, data can be resampled to a lower resolution. While this should have a positive effect on runtime, it may have a negative effect on other modeling aspects. An example of this workaround is the resampling of the DTED1 at 100-m resolution to create the 125-m resolution database for SIMNET and BDS-D (Zobrist 1994), (TEC 1995).

b. PDU's can be used to resolve differences between models. In a technical paper presented at the 12th DIS workshop, a PDU solution to the inter-visibility problem in DIS due to mis-correlated terrain was presented (Purdy 1995). The author suggests that PDU's can be used to create a compromise terrain to serve as an equal playing field. However, this workaround was received with skepticism.

c. Cross indexing routines can also be used to resolve differences between models. In a report by TRAC-Monterey, this workaround was used to resolve differences in location references between NPSNET and the Janus terrain database (generator) which NPSNET uses to construct 3D terrain. Janus references the Cartesian coordinates using its Universal Transverse Mercator (UTM) coordinate. These UTM coordinates must be translated to a local coordinate system where the lower-left hand corner of the map has the coordinate (0,0). NPSNET uses a local coordinate system where the upper-left hand corner of the map is labeled (0,0). To accurately reference the Janus terrain database, each set of Janus coordinates are again translated to reflect the NPSNET system. The X coordinate in Janus is the same in NPSNET. However, the Y coordinate must be translated (Pate 1994).

d. Algorithms may be used to populate terrain data with trees and buildings. An example of this workaround is explained in the TRAC-Monterey report mentioned in the previous workaround (Pate 1994). NPSNET has its own set of models to draw cultural objects such as houses and trees. Janus uses a density factor for each grid square to describe these features. Using NPSNET to draw objects based on Janus requires determination of the appropriate number of single trees and buildings to render in any given grid cell. Degradation of the graphics frame rate occurs if the terrain is even moderately wooded. The project overcame frame rate degradation by using three-dimensional canopies to draw heavily wooded and large urban areas. The height of a canopy is taken from the urban and vegetation height factors extracted from Janus. Using canopies over roads was not realistic. To prevent this from happening researchers developed an algorithm that randomly placed trees and buildings within a grid cell. Another algorithm was developed to prevent a tree or building from being placed on a road or river.

e. In lieu of very high resolution terrain elevation data, one could develop distributions of surface roughness values based on terrain types used in conjunction with DTED to produce higher resolution elevation postings for use in M&S. (Purdy, 1995), (WES 1995).

f. Terrain walk-throughs can be used for verification of terrain features. In a report from NPS, terrain walk-throughs were conducted to verify the existence of uniform tree heights for a particular scenario location (McFadden 1993).

g. Database levels of detail (LOD) help increase runtime efficiency. In a report from NPS, multiple resolutions of data were used to display terrain and objects at varying ranges from the viewer. This workaround allowed terrain in four resolutions to be displayed out to 6000 m at approximately the same frames/second as terrain in single resolution could be rendered out to 2500 m (Mackey 1991).

h. Computationally-intensive operations such as LOS algorithms can be off-loaded onto a separate parallel processor system to reduce M&S runtime (Dunbar 1994). The feasibility of this workaround has been demonstrated through research at NPS and TRAC-Monterey. Using a 15 processor computer with each CPU rated at 10 Mips each, the time to compute LOS was reduced by a factor of 2.6. More powerful parallel processing computers are available which would reduce the computation time even further (Dunbar 1994).

i. A draft report by RAND explained the application of adjustment parameters on LOS calculations during the Janus/BDS-D link project (JLINK). The goal was for the models to be stochastically equal, which means the respective sums of the probability of LOS (or equivalently, the average probability of LOS) are equal. In this case, only one simple adjustment was required to bring the Janus and BDS-D (ModSAF) LOS algorithms into very good agreement. The cost of this approach is lower than the cost of reprogramming one or both models to bring them into acceptable agreement (Zobrist 1994).

j. Terrain paging is a methodology useful when a computer running a simulation does not have enough main memory to load all the data files including the terrain files. Terrain paging refers to the process of 'paging' sections of terrain into and out of main memory when needed. Using this methodology, a simulator can have all the terrain for a study area available even when it will not fit into active memory. Terrain paging is described in more detail in a report by the NPS (Mackey 1991).

8 Conclusions

In conclusion, Figure 24 shows the relationship between terrain resolution, LOS performance and production cost of terrain data. The DYNTACS algorithm is included as it had the best overall correlation to field data at all resolutions for the four sites evaluated. This is an aggregation of the performance of the DYNTACS algorithm at four sites. The ModSAF algorithm yielded high correlation as well. Perhaps with a different set of samples or larger sample size, it may have been the better. All four algorithms (Janus, Bresenham, DYNTACS and ModSAF) have been aggregated at the four sites to form the mean combined curve. The LOS lower bound and the LOS upper bound represent regression lines that were calculated using the lowest and highest PHI values of the four algorithms, respectively. It can be seen that as resolution increases LOS algorithms tend to converge with the live or test data.

The exponential curve is a depiction of production cost as resolution increases, normalized to 100-m data. These data show that with proper choice of a LOS algorithm, acceptable correlation of M&S LOS to live LOS can be achieved when using 30-m data at a reasonable cost. However, consideration should also be given to model runtime when selecting a LOS algorithm.

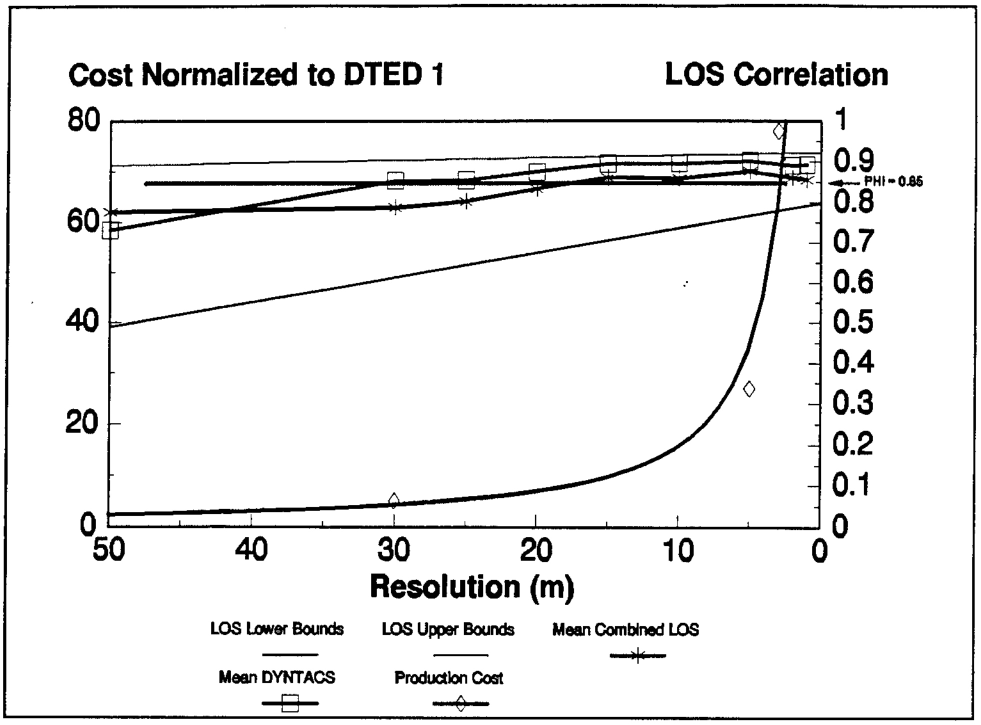

Figure 24. Cost - benefit relationship

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Appendix A
Statement of Work

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STATEMENT OF WORK

1. Project Title: Very High Resolution Terrain

2. Purpose: To provide the Operational and Model & Simulation (M&S) community an analytical resource for use in considering terrain data resolution issues, i.e. what is required and what is affordable in terms of terrain data resolution. Also, to offer possible solutions that compensate for the lack of complete terrain correlation among constructive, virtual, and live exercises.

3. Background.

   a. *Simulation issues*. A high level of terrain correlation is required for simulations participating in a DIS environment to achieve consistent outcomes among the simulations, convey realism and impart credibility to the results. With respect to virtual simulations, each computer image generator (CIG) is constrained by the computational power available to depict images. That is, each CIG possesses hardware and software architecture limitations that require CIG tradeoff decisions be made that in-turn affect the number of polygons and pixels that can be processed to portray a realistic image on a "real time" basis. On the other hand, constructive models typically use raster format for elevations and features; although, models in the Janus lineage are using polygons to represent features. Line-of-sight (LOS) calculationsare consumers of processing capabilities in constructive simulations. As terrain resolution increases, LOS calculations increase as well. With these varying terrain representations and hardware restrictions, the question remains regarding the level of terrain resolution required for M&S to achieve outcomes in stand alone simulations and sufficiently correlated outcomes among live and virtual/constructive simulations linked together in a DIS environment. From an interoperability viewpoint each "participant" must "see" and "interact" within the same terrain environment to ensure a "level playing field".

b. *Resource issues*. If technology and cost were not limiting factors, one might say that ground truth is the requirement for M&S. However, resources are indeed limited; consequently, prior to answering the terrain data resolution and correlation issues, the impacts, constraints, trade-offs, and associated costs of using varying terrain resolutions in simulations, stand alone and linked in a DIS environment, must be thoroughly examined and analyzed.

c. *Current research*. TRAC is involved in two areas of related research. TRAC-WSMR and TEC are currently working on a study titled "The Effects of Different Line-of-Sight Algorithms and Terrain Elevation Representations on Combat Simulations". This project is examining how different levels of resolutions (elevation only) and line-of-sight (LOS) algorithms compare to field surveyed LOS as well as how they effect model outcomes. Also, TRAC-MTRY is supporting research at the Naval Postgraduate School to develop line-of-sight and acquisition algorithms using very high resolution terrain data bases. This research is being performed in conjunction with recent tests during Model-Test-Model research which attached a very high resolution terrain data base to a Janus simulation model. Emerging results from that study demonstrate that terrain resolution makes a statistically significant difference in modeling results of weapon system tests. The results from these ongoing initiatives and other indings should provide relevant input to this project for synthesis with the final product bringing the practical aspects of the terrain resolution issues more clearly into focus.

4. Description. This research project entails a comprehensive and thorough information collection and analysis effort. This project will capture and leverage research initiatives ongoing in the academic, industry, and government M&S and DIS communities. The major thrust of this project is directed at acquiring and analyzing all relevant information related to the essential elements of analysis (EEA) articulated in paragraph 7. The research will address the impact of terrain resolution on model outcomes, a cost-benefit analysis of developing and managing varying terrain data resolutions, and propose alternative solutions to resolving terrain-related inconsistencies, e.g. line-of-sight, between M&S and live exercises. The LOS algorithms and target engagement logic of each of the M&S analyzed must be addressed in the M&S analysis phase of this SOW. The final product must articulate the relationships among the EEA variables and display these relationships in the context of trade-off considerations and future trends.

5. Scope. A quantitative and qualitative analysis of the information is required to formulate a basis to: a) describe the relationship between terrain resolution and M&S model outcomes; b) describe the cost-benefit relationships of developing, storing, processing, transmitting terrain data of varying resolution; and, c) propose cost-effective solutions to "fix" terrain-related inconsistencies between M&S and live exercises. A comparative analysis of the resolution issues is to be conducted on the model architectures such as Janus, CASTFOREM, BBS, CCTT, and BDS-D. The focus is to be on these M&S but not necessarily limited to these models.

6. Deliverables. WES will be required to brief TRAC management officials NLT 27 Jan 95 on the analysis methodology to be employed to execute this SOW . By 1 May 1995, a final report and scripted briefing which answers the specific research questions and a scripted brief summarizing the findings, insights, and trend projections are required. Charts or other forms of graphical displays will be used in a scripted brief to simplify the interpretation of results.

7. Research EEA:

   a. What is the relationship among terrain resolution, processing capacity, and M&S run time?

      (1) Example: 2-dimensional graph.

      (2) x-axis is terrain resolution.

      (3) y-axis is run time.

      (4) Dependent variable is ratio of M&S run time-to-real time.

      (5) Another possible dependent variable is descrete levels of processing speeds (e.g. MIPs).

   b. At varying levels of terrain resolution what is the level of agreement among constructive models, virtual simulations, and live test or training exercise with respect to combat measures of effectiveness?

      (1) Example: 3 or more 2-dimensional graphs.

      (2) x-axis is resolution.

      (3) y-axis is number of detections and engagements.

      (4) Dependent variable of interest is total number of Blue and Red detections and engagements.

and

(5) x-axis is kilometers.

(6) y-axis is resolution.

(7) Dependent variable is first opening range.

and

(8) x-axis is ratio scale.

(9) y-axis is resolution.

(10) Dependent variable of interest is loss exchange ratio and fractional exchange ratio.

c. What is the M&S terrain resolution threshold that results in outcomes that depart from live test or training results?

(1) Example: 2 2-dimensional graphs.

(2) x-axis is combat time.

(3) y-axis is cumulative scale.

(4) Dependent variable of interest is total number of detections and engagements.

and

(5) x-axis is combat time.

(6) y-axis is scale between +1 to -1

(7) Dependent variable of interest is Surviving Maneuver Force Ratio Differential.

d. What is the cost to develop digital terrain data (DTD) at varying levels of resolution, e.g. 1 m, 1 to 5 m, 5 to 10 m, and 10 to 20 mr terrain resolution data for a 50x50 km Brigade size area? (Describe the processes to develop varying levels of resolution and identify the expected sources that can develop these data).

(1) Example: 2-dimensional graph.

(2) x-axis is resolution.

(3) y-axis is $.

(4) Dependent variable is cost.

e. What is the cost to store DTD of varying resolutions, e.g. for a Brigade size area?

(1) Example: 2-dimensional graph.

(2) x-axis is resolution.

(3) y-axis is cost.

(4) Dependent variable is "cost" in terms of required storage capacity and $ to acquire storage media (GSA prices).

f. What is the cost to process digital terrain data, i.e. transforming source data into specific constructive model-ready data and virtual simulation-ready data base, of varying resolutions?

(1) Example: 2-dimensional graph.

(2) x-axis is resolution.

(3) y-axis is cost.

(4) Dependent variable is "cost" in terms of hardware, software, people (e.g. qualifications and skills).

g. What is the cost to transmit large volumes of data across LAN and WAN DIS environment?

(1) Example: 2-dimensional graph.

(2) x-axis is resolution

(3) Dependent variable is "cost" in terms of communication equipment, hardware, and bandwidth.

h. What are "modeling workarounds" or techniques that could be used to overcome terrain resolution inconsistencies or shortfalls in a DIS environment? For example, in a live environment that is linked to virtual and constructive environments, LOS between opposing players may exist in the live scenario but may not in the simulated environment. A modeling workaround could be that the live LOS occurrences overrule and dictate occurrences in the simulated environments when these contradictions arise. Another, example is in the simulated environments. If a dismounted infantryman in the constructive environment goes into a wadi for concealment, the virtual environment can portray this incident by depicting the upper half of the infantryman's torso.

8. As a result of research findings and insights, follow-on experimental and study efforts may be required to further investigate and analyze specific issues.

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13. ABSTRACT *(Maximum 200 words)*

A high level of terrain correlation is required for models and simluations participating in a distributed interactive simulation environment to achieve consistent outcomes among the simulations, convey realism, and import credibility to the results. From an interoperability viewport, each "participant" must "see" and "interact" within the same terrain environment to ensure a "level playing field." This report presents a quantitative and qualitative analysis of existing information relating to the impact of terrain resolution on modeling and simulation outcomes with respect to line of sight, battle outcomes, and preprocessing time.

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