21 Military applications of digital terrain models

M.W. GRIFFIN

21.1 Introduction

Over the last decade the increase in the power, capability and availability of computer hardware and software has coincided with the willingness of the analyst and military end-user to exploit computer technologies. At EASAMS Limited, work began in the 1970s on relatively straightforward applications of digital terrain models (DTMs) for use in intervisibility studies for the Army. Initially, these activities merely automated processes previously carried out by means of cartographic exercises and field trials. In replacing the laborious elements of such essentially manual methods, it was realised that DTMs became not just part of the operational analysts' toolkit, but were established as important military system elements in their own right. Subsequent development led to the inclusion of DTMs in Command, Control, Communications and Information (C3I) Systems, Geographical Information Systems (GIS), automated cartography, advanced display systems, simulations, navigation systems and robotics.

The following sections describe three 'case-study' military systems and discuss some of the problems encountered. An attempt is made to demonstrate the ways in which the functionality and power of such systems have been expanded since the 1970s and have reflected the changing pace of technology.

21.2 Military applications

21.2.1 Intervisibility studies (Case Study 1)

(i) Background. During the late 1970s, DTMs and related software were produced to assess the effects of observer-to-target intervisibility on the development of anti-tank guided weapons (ATGWs). The data sets used were limited to a 12 km × 12 km area of gridded datum points at a 50 m resolution, containing spot heights and cultural information. The latter was restricted to buildings, trees and a vector-based representation of road, tracks and powerlines.

(ii) Intervisibility analysis. A set of software routines, written in FORTRAN and APL, was produced in order to manipulate and process the clients' 'raw' data. Running in batch mode on ICL 1900 series and CDC Cyber mainframes, the software permitted the rapid production of intervisibility plots on a map overlay. The area plots or 'sweeps' radiated up to 360° from the observer positions and allowed for user-specified observer-to-target ranges. These sweeps plotted the 'dead' ground for one or

a combination of topography, culture (trees and/or buildings and/or pylons) and atmospheric obscuration. Such results were most usefully presented as radial 'spokes'—lines originating at an observer position—or area infill superimposed on the map background. Multiple, overlapping sweeps helped identify optimum engagement zones or were used to plot dead-ground approaches for route planning and weapon siting. Figure 21.1 shows the relationships, using the DTM, between an observer position and a column of 14 vehicles moving over the terrain. Four exposure windows are plotted against the map background, with target intervisibility indicated for each of three one-second 'snapshots'.

Sectional views of the intervisibility from point *A* to point *B* were also produced. Such sections, utilizing vertical scale exaggeration for clarity, were plotted against a map background. Subsequent development addressed the problems of modelling the movement of changing target arrays over the terrain and their intervisibility or detectability in relation to various types of culture. Detection, both visual and by missile seekers in conjunction with various search patterns, was studied and a six-degrees-of-freedom missile model used to represent the flight of various missile types (command to line-of-sight and lock-after-launch) over the terrain. Work was also performed on the modelling of engagement scenarios where missile and target travel over, and interact with, the terrain.

(iii) Perspective viewing. Eventually, perspective plotting routines were developed from first principles. Such techniques are now widely used throughout the military and civil world. Most viewing techniques are concerned with the form of the ground; more sophisticated techniques add cultural, atmospheric and tabular information to the topographic view. Normally, each DTM point (in X, Y, Z space) is transformed with respect to an observer point, with a resultant azimuth and elevation (angular value) mapped to a pixel address on the display device. Enhancements include hidden line/area removal, field-of-view (FOV) restrictions, illumination effects (texture, shadows, haze) and automatic scaling. Unfortunately, processing penalties are incurred by high-resolution perspective viewing algorithms, and even now few systems produce detailed views in real time (e.g., frame rates > 20 Hz). Currently, the need for geographic data standardization is being recognized at EASAMS with the creation of perspective viewing software to handle any common data format.

The solftware also allowed a user-defined choice of algorithms for both fully detailed perspective views and less detailed views for rapid appraisal situations by using lower resolutions, 'mathematical' instead of 'true' perspective algorithms and FOV restrictions. Such perspective views were produced initially in order to synthesize a 'rasterized' view of the target from a simulated missile position. The perspective views were subsequently used for general perusal of the digital landscape (Fig. 21.2). The techniques were also used for non-military work (Griffin, 1981). An important shift in emphasis here was from batch processing to interactive processing, with the adoption of faster, multiuser mainframes in the late 1970s. Perspective views were supported by field surveys, aerial photographs and cartography, mainly as a means of validating the results being produced. For example, photographs of the area of interest were compared with perspective plots using the same grid references, fields of view and viewing direction.

Other interesting results were obtained. Earth curvature, for instance, was calculated and allowed for, but was found to be insignificant for the small engagement ranges (up to 5 km) involved. Darkness and atmospheric obscuration (e.g., smoke, haze, precipitation), on the other hand, were not modelled but were found to affect target intervisibility dramatically during field work.

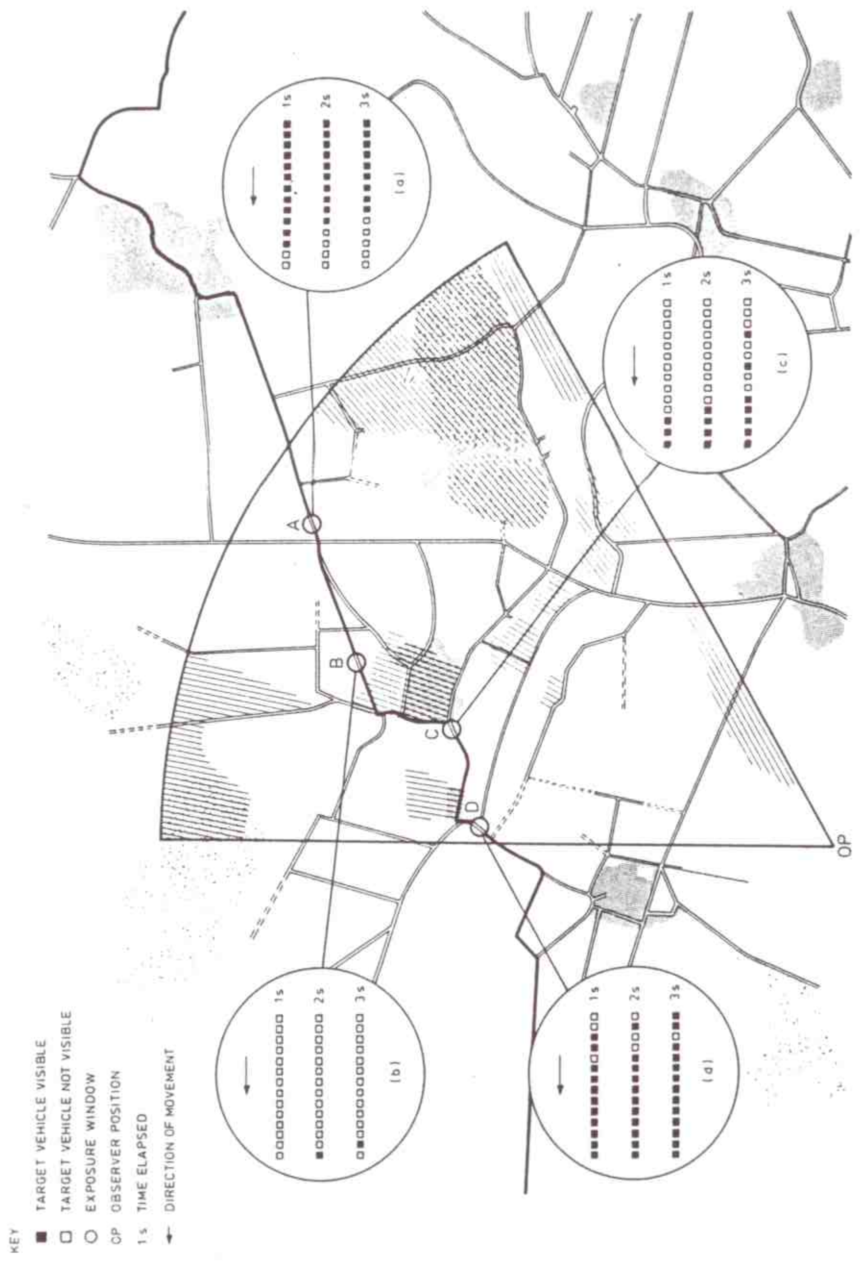
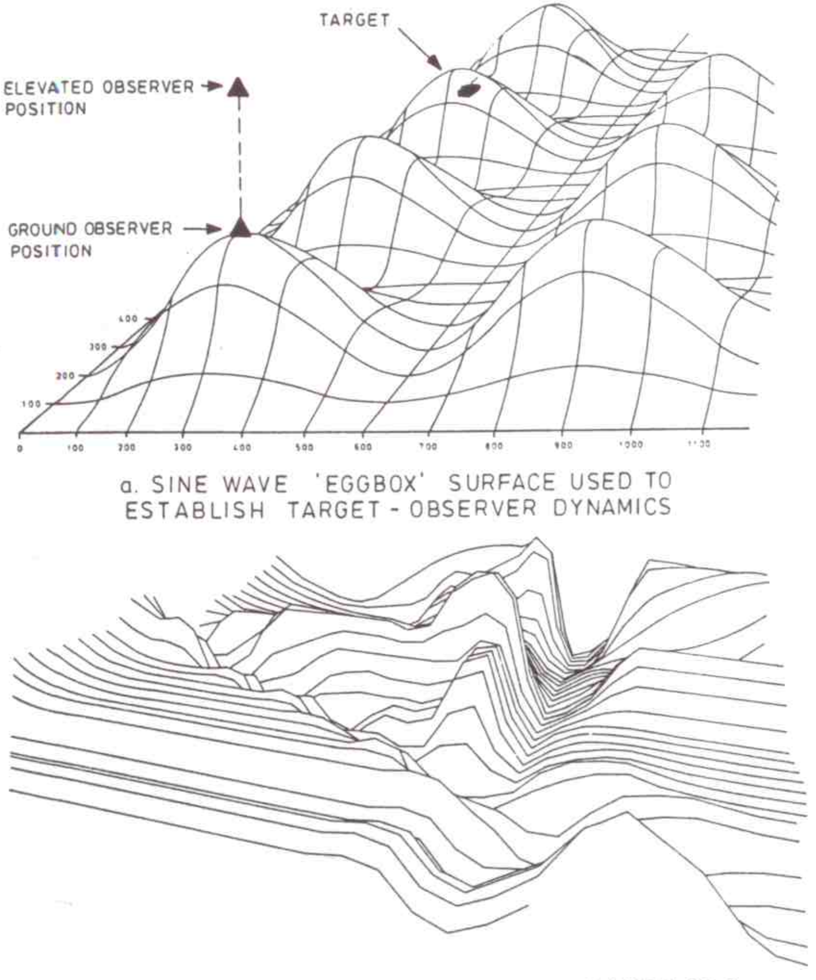


Figure 21.1 Multiple-target intervisibility sampling.

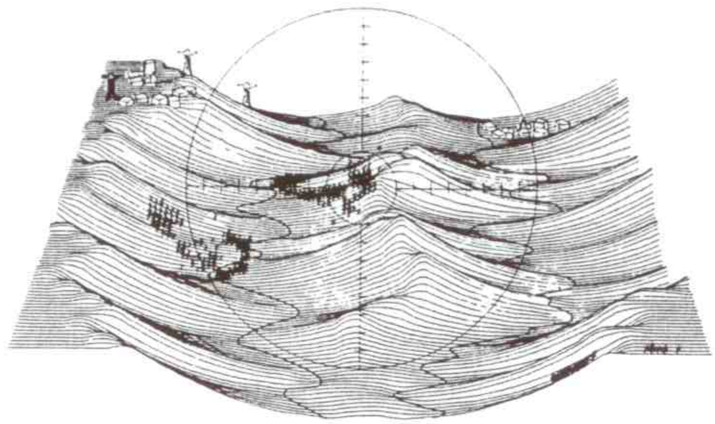
21.2.2 Unmanned vehicles (Case Study 2)

(i) Background. In the early 1980s, EASAMS became involved with the MAID (Mobile Autonomous Intelligent Device) research program, which was initiated by MOD to assess the feasibility of using unmanned vehicles (UMVs) for the Army (Smith, 1986). UMVs generally have potential for a variety of military roles, including surveillance, sentry duty, mine laying or clearing, rescue operations, tactical and terrain surveys or offensive action (Ogorkiewicz, 1986). The UMVs are envisaged as operating in three modes: remotely controlled, semi-autonomous and fully autonomous (robotic). Clearly such UMVs must interact with, and navigate over, the terrain.



a. SINE WAVE 'EGGBOX' SURFACE USED TO ESTABLISH TARGET - OBSERVER DYNAMICS

..ATION OF 5



c. SYNTHESIS BY MEANS OF LANDSCAPE EVOLUTION MODEL

Figure 21.2 Synthesized digital landscapes.

What was identified, therefore, was a large investment in software in order to simulate and assess terrain-related UMV subsystems prior to actual construction and testing of the various UMVs.

(ii) Software environment. The first part of this work was devoted to developing new DTMs and refining existing software. Software design was carried out and new 'structured' languages, such as Pascal, adopted. Host computers included DEC PDP 11/44s with Floating Point Systems (FPS) 120 Array Processors, Digital Equipment Corporation (DEC) VAX and MicroVAX minicomputers, and a Control Data Corporation (CDC) Cyber mainframe.

(iii) Data sources. Unlike most C3I or aerospace DTM applications, the UMV study required terrain data at a very high resolution in order to simulate detailed aspects of vehicle motion, since ground features such as ditches and embankments would need to be taken into account. In addition, the vehicle needs to use its sensors (scanning laser range finder, TV cameras, Doppler radar and so on) to process information about the terrain to avoid obstacles such as individual trees, ditches and fences. Less detailed DTMs were also required, as the UMV needs to carry an on-board digital terrain system for position-fixing and dead reckoning. It was the proposed navigation of such an autonomous vehicle over unprepared terrain that produced some of the most profound problems of the research work.

Four data collection methods were investigated and assessed in order to supply high-resolution altitude and culture data.

(a) *Data collection by survey.* Accurate three-dimensional coordinates may be collected by field survey methods, existing map sources and photogrammetry (Petrie and Kennie, 1987 and part A, this volume) depending on the scale and the extent of the area involved. Such survey techniques are now well documented, and were examined by the project team only for their cost-effectiveness and relevance to the particular requirements.

(b) *Existing data.* The requirements of UMV navigation and tactical planning could have made use of existing data, such as the Digital Landmass System (DLMS) levels 1 and 2, and various related data sets. Digital data sets associated with remote sensing applications were also considered (House of Lords Select Committee, 1983). Other digital data sets at a 1:10 000 scale were available under licence from the UK Ordnance Survey (OS). Ordnance Survey digital data sets were selected as the most convenient cost-effective source for the UMV project. Such data sets are provided as vectors or strings, since this is the most convenient way of automating the map facsimiles that show linear features such as road or streams. However, such data sets sometimes require conversion to a grid-based system for more efficient and cost-effective processing as arrays or matrices.

Conversion programs were written in Pascal to provide an 'assembly line' approach to reformatting Ordnance Survey digital data to gridded data sets. This first involved a process of interpolation (using second- or third-order polynomials) to obtain the elevation data from the sparsely-distributed spot heights. The accuracy of fit was verified by field work and aerial photographs, and the level of error was felt to be acceptable for the requirements of the UMV simulation. Culture features were then encoded to the nearest grid point (using a 1-m resolution data set). Interestingly, the same software allowed users to add 'bogus' features to the DTM, thus catering for updates and for experimentation.

Such activities allowed any OS digital data to be encoded to a high-resolution gridded set. Moreover, aerial surveys of selected areas of interest could be commissioned by the client and produced to the OS specification. The processed data represented 1 km^2 and was stored as a set of rapid-access data files in a hierarchical database. Finally, other specialized, high-resolution data sets were encoded by digitizing large-scale maps. This was done for example, for soil survey maps in order to provide the artificial intelligence (AI) software component of the UMV with a 'going' or mobility database.

(c) *Data synthesis by mathematical functions.* The third method of data collection involved the synthesis of topographic and other information by means of computer simulation. This was to provide vehicle simulation and display software with a 'meaningful' data input while other data sources were still in preparation. Initially, a set of mathematical functions was derived and encoded, and, by experimentation, several synthesized terrain 'surfaces' were produced. All functions were based on the 'right-handed' Cartesian axis system where the x-axis points north, the y-axis points east, and the z-axis points down. There is a minor disadvantage here in that all heights above the origin are negative. However, this convention accorded with existing matrix manipulation software and allowed the use of familiar and well-documented mathematical notation (Blakelock, 1965; Britting, 1974).

The mathematical surfaces varied in complexity. A simple sine-wave 'eggbox topography' (Fig. 21.2a) was employed with successful results, using an equation of the form:

$$z = -a(\sin^2 bx)(\sin^2 by)$$

where a is the relief amplitude (e.g., 200 m) and b is a scaling factor (e.g., 0.3).

More complicated (but no less valid) pseudo-terrain surfaces were constructed using a combination of mathematical and statistical functions. This approach involved combining two 2D curves to produce a 3D surface, which was then combined with other curves in an additive process. An example composed of five surfaces is shown in Figure 21.2b. Although some interesting results were obtained, the methods provided only limited inputs to the vehicle simulation.

(d) *Data synthesis by geomorphological simulation.* A technique was devised whereby users could obtain 'geomorphologically-sensible' 3D digital terrain data both cheaply and rapidly. This involved a specially-constructed computer model of

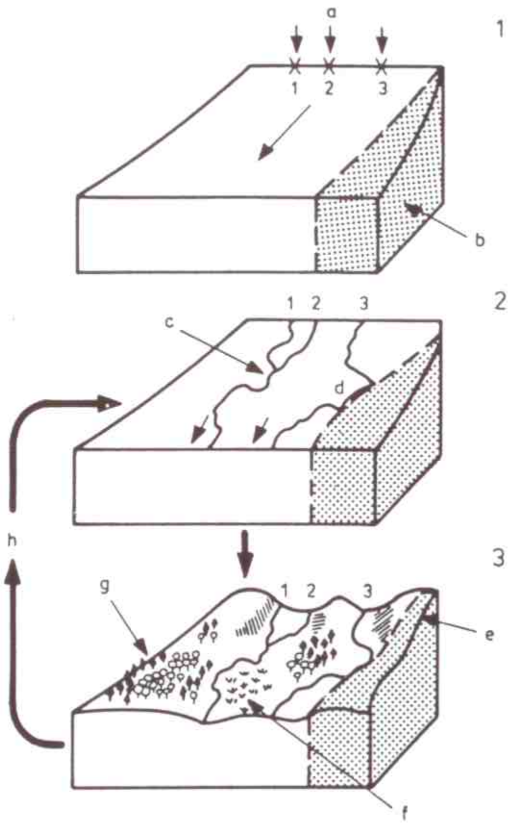


Figure 21.3 Theoretical sequence of synthesized terrain evolution.

Key:
Phase 1: Primary surface and other parameters initialized
  a—Stream entry positions established on highest surface edge.
  b—Band of resistant rock defined.
Phase 2: Stream patterns established by random-walk process.
  c—Stream 1 becomes tributary of Stream 2.
  d—Stream 3 avoids resistant lithology.
Phase 3: Slope profiles established.
  e—Additional slope retreat on steep ground to simulate instability.
  f—Evaluation of terrain features and attributes.
  g—Wooded areas established on 'game-of-life' basis.
  h—Feedback loop to Phase 2.

landscape evolution (Griffin, 1987). The approach adopted a computer program that simulated the establishment of a stream network on a tilted surface, with accompanying fluvial downcutting and slope adjustment. This was achieved by an interactive mechanism that combined deterministic and stochastic processes with geomorphological theory. The effects of differentially resistant lithology and wooded areas were also simulated (Fig. 21.2c). Although more detailed process-response models have been implemented (Anhert, 1977, 1987; Armstrong, 1976, 1980; Craig, 1980), the rapid method (called GEOMIX) allowed data sets to be tailored to specific UMV tasks by altering initial parameters prior to program execution. Moreover, the results—a matrix of high-resolution altitude and mobility data—could be produced in a matter of seconds, and plotted either as a relief (contour) map or as a 3D view (Fig. 21.2c).

The GEOMIX algorithm was evolved in preference to alternative computer-generated artificial landscapes, such as the 'fractal' computations of Mandelbrot (1982) and others (Fournier and Fussell, 1982), since these were founded on purely stochastic principles regardless of the visually impressive and sometimes unrealistically spectacular results obtained.

(iv) Software. By 1987, a suite of software routines designed to manipulate the DTM had been designed, implemented, tested, installed and accepted at the users' site. These routines allowed the user to create, update and maintain the digital terrain models required for the UMV project, and included the software packages shown in Fig. 21.4, together with extensive documentation. Some functions, such as the contour plotting software, were originated in the early 1970s before any reliable commercially-available equivalent was felt to be widely available.

(v) Artificial intelligence. The DTM was intended for use with on-board vehicle artificial intelligence (AI) software. Such AI software, written in the languages PROLOG and LISP, could utilize the DTM for route planning and as part of the intended integrated navigation system. The route planning software was based on various heuristic algorithms which could find routes by means of roads and over 'unprepared' terrain.

21.2.3 EAMACS (Case Study 3)

In parallel with other terrain work, EASAMS produced the EAMACS (EASAMS Architecture for Management and Control Systems) graphics system in the early 1980s. This was a response to the relative lack of processing power and colour displays associated with early DTMs and Geographic Information Systems. The EAMACS System utilized a dedicated PDP 11/73 computer with customized graphics processing boards. The display device employed a touch screen MMI (man-machine interface) for a single display or combination of rasterized, vector or video pictures. The EAMACS system incorporated many of the algorithms for digital map display and terrain analysis described above. The main application and market area of this system was in the C3I field, where the potential for rapid processing and display of tactical information on a map background has long been realized (Neel *et al.*, 1982; Ogier-Collin, 1988). Advanced functionality such as 'panning' and 'zooming', and digital removal or enhancement of cartographic features, were found to be useful in operational environments.

Current developments are making use of relational database management systems, and proposed industry standards such as the *X*-windows system and secure-UNIX operating environments.

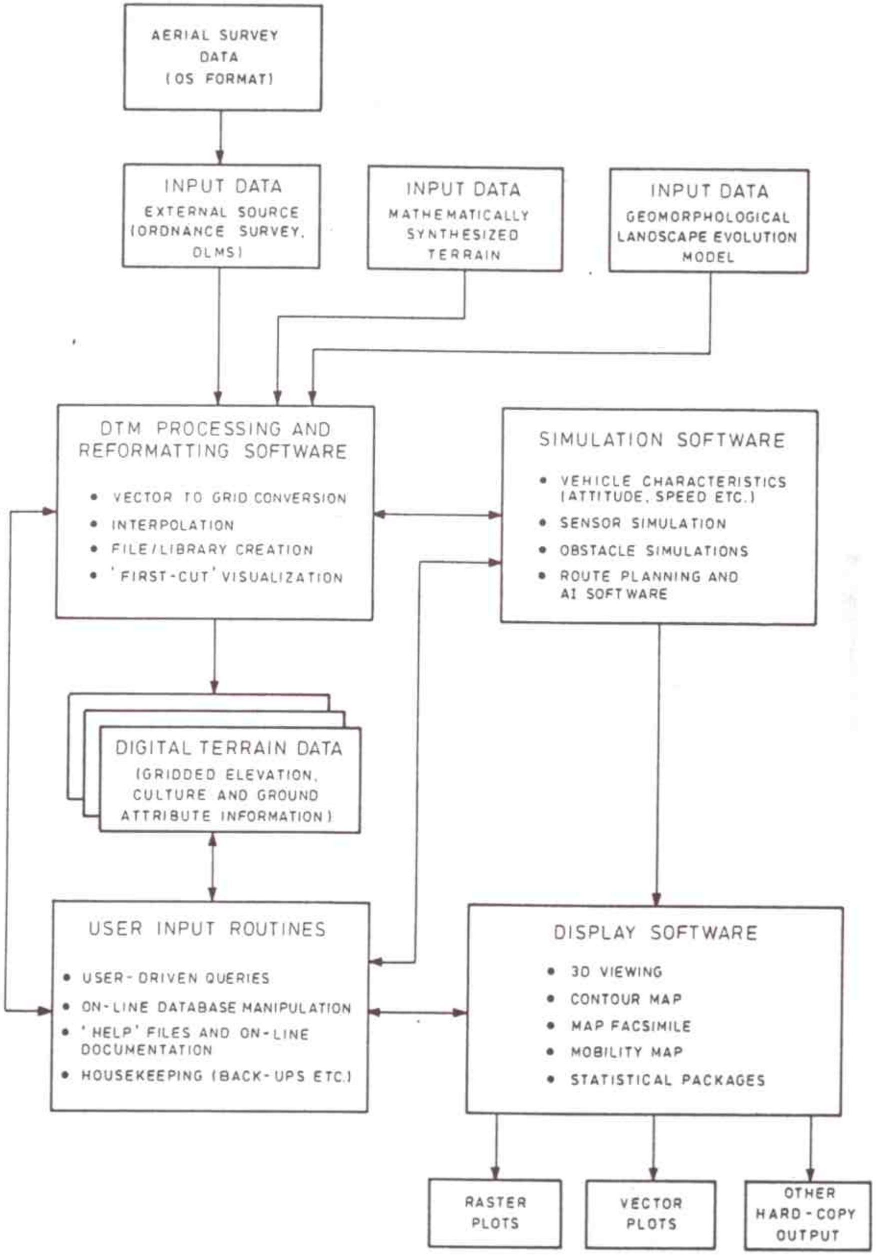


Figure 21.4 Structure of DTM and utility software for the UMV project (simplified).

21.3 Discussion

21.3.1 Overview

This section discusses some of the problems and constraints encountered by terrain analysts at EASAMS with reference to the application 'case study' examples described above. Although many aspects will be recognized by workers in the civil field, there are felt to be some special problems encountered in the military sphere. Systems incorporating digital terrain models and other terrain-related software may be used as tools in operational analysis, or they may be implemented as in-service systems. In the case of the latter, implementations vary between robust, high-performance systems for use in aircraft (e.g., for terrain-referenced navigation) and battlefield C3I systems (Kennie and McLaren, 1988). There may be constraints imposed by the processing power, size or weight of the hardware, which itself may be 'ruggedized' or may conform to the appropriate military specifications for shock, temperature, humidity, electromagnetic (EM) environment and so on.

Military software requirements for security (encryption, access control and operating system limitations), interoperability, robustness and portability, add to the complexity and cost of such systems. Similarly, system designs which cater for high-integrity error-checking and other defensive software, so-called user-friendliness and redundancy will also incur high development and maintenance costs.

21.3.2 Performance aspects

(i) Volume of data. The storage, processing and display of large volumes of terrain data poses one of the most severe and common problems to the software engineer. Consider, for example, the fairly modest requirement of 25-m gridded points over an area 200 km × 200 km. This gives 6.041×10^6 datum points, which (at 2 bytes per point) yields a storage overhead of about 13 megabytes, with associated data transmission and processing penalties. Current trends point to the use of optical storage devices for large volumes of data. Since, at present, optical disks (for example) tend to be read-only devices (Bouwhuis, 1985), such technology is being employed initially for the static components of military terrain information systems, such as elevation data, while more dynamic data components, such as threat or tactical information, may reside on more conventional magnetic media.

(ii) Processor speed. Another limiting factor is the power, performance and configuration of the Central Processing Unit (CPU) and display devices being used. Machines capable of running at more than 50 MIPS (million instructions per second) are now widely available, but they may be prohibitively expensive. Moreover, benchmarks of processing speeds may provide misleading results which are sometimes inappropriate for particular DTM applications.

For flight simulation applications involving terrain models, the processing requirements may be formidable where realistic colour video images are concerned (Yan, 1985).

(iii) Parallel processing. Concurrent or parallel processing concepts are generally implemented as important and useful methods for solving time-critical and large-volume data processing problems. Essentially, concurrency is achieved, both in software and hardware terms, by avoiding serial dependency and instead 'pipelining' or partitioning tasks whenever possible (Spriet and Vansteenkiste, 1982).

Work on the UMV project reflected the general requirement for more processing power, where at first FPS AP-100 series array processors were utilized to carry out limited arithmetic operation in parallel. This gave way to Meiko computing surfaces ('transputers') and an exposure to concurrent programming languages, such as Occam (May and Taylor, 1984; Fisher, 1986). It is worth noting that the large-array or matrix operations that tend to be carried out during DTM processing were found to be conveniently incorporated in concurrent designs. Other languages, such as Ada, offer concurrency (or 'tasking') as a built-in feature (Barnes, 1984), although operating systems, design tools (Brubaker and Case, 1986) and debugging tools must improve before significant gains can be made.

(iv) Display devices. Processing problems are encountered in the area of display devices, where the compromise between colour/resolution and processing speed is well known. The combination of vector images with a raster-scan map background display is a useful technique for presenting high-resolution linear detail (e.g., roads, contours, symbols and feature outlines) while optimizing processing and storage resources. Raster-vector integration and other display processes (such as windows) may be executed by dedicated processors on board the display device. Typically, high-performance graphics workstations are in general use for military terrain modelling and map display applications.

(v) Real-time processing. Real-time processing is characterized by the presence of deadlines, where failure to meet a deadline is considered a system fault. In effect, the use of such a term is an admission that digital computers are sometimes unable to cope with the demands of a 'real' world. Such a time-critical interaction with real events is demonstrated, for example, by a real-time digital terrain navigation and display system on board high-performance military aircraft. Some of the UMV software was targeted at a real-time environment. In these cases, great care was taken at the design and implementation stage to ensure that no overall system degradation would take place. Hopefully, real-time DTM processing problems will be eased by the adoption of more powerful hardware, more efficient software and the use, where appropriate, of concurrent methods.

21.3.3 Standardization

Standardization is clearly of importance to any system distributed between collaborating users, whether they are divisions in an Army Corps or the countries in the NATO alliance. For military terrain-related systems, particularly those intended for future field service, efforts are currently being made to adopt certain hardware and software standards. Some of these measures are well known. For example, the language Ada is currently being used in the UK defence scene. Ada has been adopted by the US Department of Defense and is a standard for both NATO (North Atlantic Treaty Organisation) and the UK MOD. The language was designed in order to provide cost-effective reliability, maintainability and portability for 'embedded' systems. Other standards and recommendations are emerging for 'Open' systems where hardware and software from different vendors can be designed to function together in an integrated environment. At EASAMS, individual projects are sometimes required to conform to design methods such as SSADM (Structured System Analysis and Design Method) and software components such as Ada, SQL (Structured Query Language) and GKS (Graphical Kernel System).

Currently, efforts by the UK Military Survey and NATO partners are being directed towards producing a range of standard digital geographic data products (Military Survey 1988). However, true interoperability lies in the future, in spite of commercial and military pressures to achieve such standardization.

21.4 Conclusion

This chapter describes some military applications of digital terrain models. Some of the problems associated with the applications are identified along with proposed solutions against a background of advancing technology and changing requirements. The three case studies outlined are felt to mirror these advancing technologies and the shifting problems of definition and analysis over the last two decades. Work at EASAMS has reflected the problems and benefits of the terrain modelling environment during this time.

Acknowledgements

This unclassified work is published by kind permission of EASAMS Limited. The opinions expressed are those of the author alone. The author would like to express his thanks to Miss J.A. Hopkinson, Brigadier A.W. McKinnon, Mrs C.A. Hose and Mr P.O. Blanchard of EASAMS Limited.

References

Ahnert, F. (1977) Some comments on the quantitative formulation of geomorphological processes in a theoretical model. *Earth Surface Processes* **2**, 191–201.
Ahnert, F. (1987) Approaches to dynamic equilibrium in theoretical simulations of slope development. *Earth Surface Processes* **12**, 3–16.
Armstrong, A. (1976) A three-dimensional simulation of slope forms. *Zeitschrift für Geomorphologie, N.F. Supplementband* **25**, 20–28.
Armstrong, A. (1980) Soils and slopes in a humid temperate environment: a simulation study. *Catena* 7(4), 327–338.
Barnes, J.G.P. (1984) *Programming in Ada.* International Computer Science Series, London.
Blakelock, J.H. (1965) *Automatic Control of Aircraft and Missiles.* John Wiley, New York.
Bowhuis, G. (1985) *Principles of Optical Disc Systems.* Adam Hilger, Bristol.
Britting, K.R. (1974) *Inertial Navigation Systems Analysis.* John Wiley, New York.
Brubaker, D. and Case, D. (1986) Task partitioning eases concurrent programming. *Computer Design*, 83–87.
Craig, R.G. (1980) A computer program for the simulation of landform erosion. *Computer and Geosciences* **6**, 111–142.
Fisher, A.J. (1986) A multi-processor implementation of Occam. *Software Practice and Experience* **16**(10) 875–892.
Fournier, A. and Fussell, D. (1982) Computer rendering of stochastic models. *Comm. ACM* **25**(6), 371–384.
Griffin, M.W. (1987) A rapid method for simulating three-dimensional fluvial terrain. *Earth Surface Processes* **12**, 31–38.
Griffin, M.W. and Gilmour, J.N. (1981) Morphological imaging techniques and the presentation of large-scale erosional features of the Land's End Peninsula. *Proc. Ussher Soc.*, **5**(2), 222–226.
House of Lords Select Committee on Science and Technology (1983) *Remote Sensing and Digital Mapping*, (Vol. 1). HMSO, London.
Kennie, T.J.M. and McLaren, R.A. (1988) Modelling for digital terrain and landscape visualisation. *Photogrammetric Record* **12**(72), 711–745 (October).
Kennie, T.J.M. and Petrie, G. (1987) Terrain modelling in surveying and civil engineering. *Computer-Aided Design* **19**(4) 171–187.
Mandelbrot, B.B. (1982) *The Fractal Geometry of Nature.* W.H. Freeman, San Francisco.
Military Survey (1988) Military Survey Digital Product Information Sheets. Military Survey, Ref: STU/40/25/7/2, September 1988.
May, D. and Taylor, R. (1984) Occam—an overview. *Microprocessors and Microsystems* **8**(2) 73–79.
Neel, E.E., Stuttz, S.J. and Tysszka, R.J. (1982) Digital terrain analysis data—a critical element in future tactical C3I. *Signal*, March 1982, 51–54.
Ogier-Collin, J. (1988) The application of digitalized geographical information to C3I systems. *Proc. AFCEA Europe Paris Symposium 1988*, 61–63.

Ogorkiewicz, R.M. (1986) Automated unmanned and robotic tanks. *International Defence Review*, 1283–1290.
Smith, G. (1986) War without people. *Soldier Magazine*, 14–16.
Spriet, J.A. and Vansteenkiste, G.C. (1982) *Computer-Aided Modelling and Simulation.* Academic Press, New York.
Yan, J.K. (1985) Advances in computer-generated imagery for flight simulation. *IEEE Computer Graphics and Applications* **8**(6), 37–51.

22 Graphical display and manipulation in two and three dimensions of digital cartographic data

L.W. THORPE

Introduction

Digital cartographic data capture, display and manipulation is expanding within both civil and military mapping organizations, such that the creation of digital geographic databases is becoming a prerequisite for the new generation of civil and military communications, command control and information (C3I) systems. SD-Scicon's work has been committed to the establishment of suitable databases of this material for efficient retrieval, manipulation and display in both two- and three-dimensional form in conjunction with user information of asset deployment. To this end, SD-Scicon have produced the product VIEWFINDER, which this chapter describes.

The generation of the three-dimensional information and derived mappings of slope, aspect and intervisibility become available by the combination of contour or randomly sampled height data of the region, with the associated topographic or cultural features which make up a conventional map. The following sections highlight the processing of digital map data pertinent to terrain shapes from various capture modes, with the databanking of the cultural features for use in a mission planning, communications planning, navigation and asset deployment environment.

22.1 Digital terrain data capture sources

Three sources of digital material are described which form the basic inputs to digital terrain modelling systems.

22.1.1 Discrete samples

This source of digital terrain data is the most important and the remaining sources reduce to this variety during processing. This type of data is represented by a single triplet of numbers which define the location in three- dimensional space of a point on the surface under consideration.

This surface may be any single-valued function which represents a land surface, a sea surface or perhaps an underground surface formed as the interface between two types of rock. To adequately represent this function in three-dimensional space, the

location and height/depth of a suitably large number of points on the surface must be measured, or sampled. It is important to define the surface with the correct number of sample points, such that:

(a) the surface is correctly sampled with respect to the sampling theorem;
(b) the minimum number of samples are obtained that are necessary from an economic standpoint;
(c) the total area of the surface under consideration is sampled at a density (sample/unit area) commensurate with both sampling theorem and economic considerations.

The sampling theorem states that the highest frequency, or shortest wavelength components involved in the Fourier transform of the surface must be sampled at least twice per cycle. This theorem can be interpreted as saying that if the surface is made up of long wavelengths, e.g., rolling hillsides, then the samples can be taken, on average, at a separation less than half the distance between the tops of the hills. If, however, the surface is undulating and irregular, with very steep-sided valleys, then the surface must be sampled at a rate at least twice per cycle of the shortest-wavelength undulations and irregularities that are required in the model of the surface. Under the constraints of the sampling theorem and with a knowledge of the detail that is required on the surface, the number of sample points required to define the surface can be estimated.

Similarly, the cost per sample, in terms of survey equipment, mapping or photogrammetric resources, man effort, etc., involved in the data collection, can be divided into the available budget, to indicate the number of samples that are possible. If the budget for data collection does not allow sufficient samples as dictated by the sampling theorem, then the specification of the detail over the whole surface area may have to be relaxed, or the area of coverage reduced. It is clear that these two factors are in conflict, and their implications must be carefully considered prior to undertaking detailed sampling of the surface. The best-known examples of discrete sample points on surfaces are:

(a) Soundings on hydrographic charts, where the depths of the ocean have been measured at a sequence of sample points taken along the path of the survey vessel as it moved over the ocean surface. This path may have been organized on a criss-cross basis to provide the sampling rate determined by the considerations given above. This would be typical of a detailed hydrographic survey of an area, or it may be a routine measurement of the depth of the ocean taken along the course of a vessel for safety and monitoring purposes.
(b) Borehole data obtained by mineral prospecting companies in their investigation of substrata for oil- and mineral-bearing rocks.

In each case, the information representing the surface is formed from random sampling of the surface in the three axes of the coordinate system, and this is recorded as discrete point information represented as (X, Y, Z) triplets.

22.1.2 Photogrammetric sampling

This source of digital terrain data is obtained via the analysis of overlapping photographic images of the surface obtained from aircraft or satellites. The area being investigated is overflown by a survey aircraft, which takes a series of overlapping photographs of the region. The resulting photographs are subsequently analysed in stereo-viewing systems connected via shaft encoders to digital recording equipment. The human operator focuses the stereo viewing system on to the three-dimensional image created by two of the overlapping photographs. By this procedure, a particular level or height value is selected. Then by skilful manipulation of the 3D image under his view, a series of points of the same height value are identified as a continuous curve defining a contour line. This procedure is continued until the required series of lines are identified covering the area of interest to the required detail. This material is captured, in a digital format, as a string, or series of strings of (X, Y) coordinates, all associated with a particular Z value, representing the contour height. On older photogrammetric equipment, without digital interfaces, map output will then require digitization.

22.1.3 Existing contour maps

This source of terrain data perhaps represents the largest source, as a very large number of maps already exist in printed form. The contours on these printed maps have often been created by photogrammetric methods, (without the digital interface). Existing maps are converted into a digital format by digitization. This is achieved using a variety of techniques, each of which has associated advantages and disadvantages.

(a) Hand digitizing, whereby a person follows the contour lines by hand on a flat digitizing table, coding each line in turn with its height.
(b) Mechanical line following, whereby a laser-controlled automatic machine follows the shape of the line and associates the code either automatically or by human voice or finger keying.
(c) Scanning, whereby the paper map is scanned in a raster fashion with a flying spot to identify each 'pixel' on the map containing contours. These pixels are subsequently converted to vectors and the corresponding height codes associated with them are defined.

When the contours are in digital format they are again defined as a string or series of strings of (X, Y) coordinates all associated with a particular Z value representing the contour level.

22.1.4 Conversion of contours to discrete samples

Photogrammetric and digital map data generally occur as line strings of (X, Y) coordinates with an associated Z value for the contour level. It is necessary to convert these line strings into discrete samples by associating the particular Z value for the line string with each component point of the line to form (X, Y, Z) triplets. It can be seen that this form of discrete data point input is formed from random (X, Y) data but quantized Z, to produce the triplets required for further analysis.

22.2 Digital terrain model creation

VIEWFINDER provides a comprehensive data reduction facility for the class of problems relating to surfaces in a three-dimensional space. To use these facilities, it is necessary to convert the array of input (X, Y, Z) data points into a more suitable representation of the surface which can be efficiently and effectively processed by computers. The most convenient representation of a surface for such processing is in the form of a set of height values on a uniform square grid distribution. The numerical approximation, from the irregularly distributed points to height values on a regular grid, provides an efficient and accurate transformation which generates a representation of the surface that best fits each of the input data points. This is achieved using a plane-fitting technique utilizing least-squares methods. This is based on the selection of the nearest set of at least eight sample points distributed in the eight quadrants around the matrix node under consideration. Using these points, the best-fit plane is calculated to pass through the input points from which the value of the node is then interpolated. This process is continued for the whole area to produce the digital terrain matrix.

Once the matrix has been calculated, it can be used for a large variety of purposes. The following paragraphs give a number of examples, which are not exhaustive.

(*i*) *Calculation of contours.* From the matrix, the shape of the contour figure field can be produced. This can be done by using linear interpolation through the grid cells, or by an alternative method producing an approximation to a smooth surface based on derivative estimates at grid intersections. The latter produces a more desirable result, and the validity of the matrix can be checked by this algorithm whereby the contours interpolated from the matrix can be compared with the input data (see Figs. 22.1,

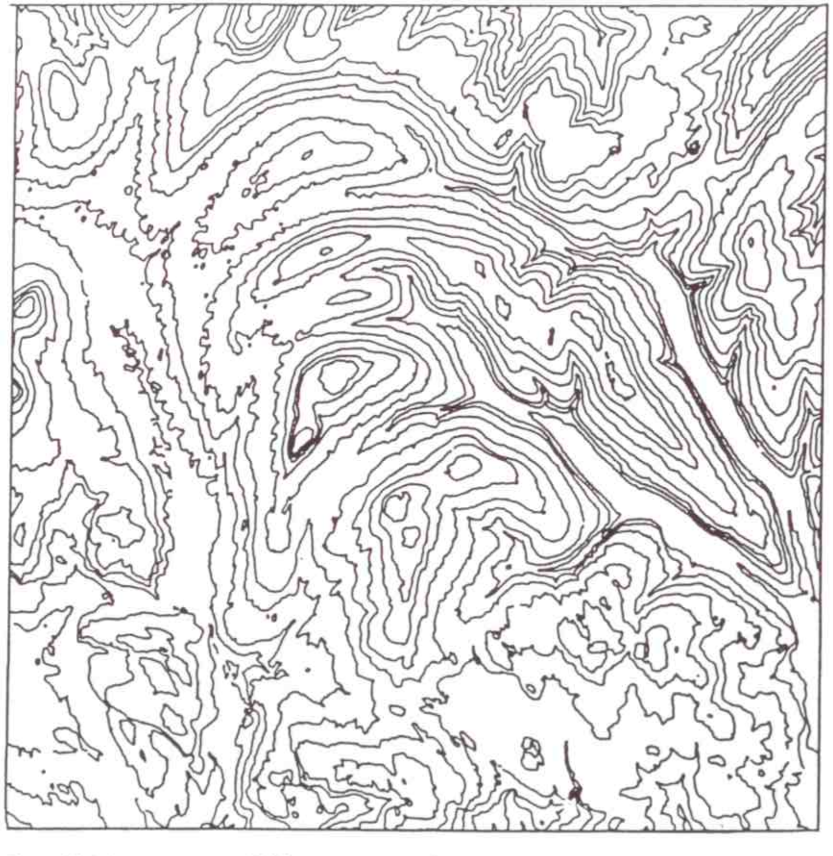


Figure 22.1 Input contours of 20 km square area of Yorkshire.