Progress in Physical Geography 22,1 (1998) pp. 33–60

Combined analysis of digital terrain models and remotely sensed data in landscape investigations

Igor V. Florinsky
Institute of Mathematical Problems of Biology, Russian Academy of Sciences, Pushchino, Moscow Region, 142292, Russia

Abstract: This article presents a review of the combined analysis of digital terrain models (DTMs) and remotely sensed data in landscape investigations. The utilization of remotely sensed data with DTMs has become an important trend in geomatics in the past two decades. Models of more than ten quantitative topographic variables are employed as ancillary data in the treatment of images. The article reviews the methods for DTM derivation and the basic problems of DTM operation that are important for handling DTMs with imagery, namely: 1) the choice of a DTM network type; 2) DTM resolution; 3) DTM accuracy; and 4) the precise superimposition of DTMs and images. The processing of remotely sensed data and DTMs in combination is used in the following procedures: 1) the image correction of the topographic effect; 2) the correction of geometric image distortion; 3) image classification; 4) statistical and comparative analyses of landscape data; and 5) three-dimensional landscape modelling. These procedures are applied to solve a wide range of problems in geobotany, geochemistry, soil science, geology, glaciology and other sciences. The joint use of imagery and DTMs can increase the total amount of information extracted from both types of data. The trend has been towards the incorporation of the combined analysis of remotely sensed data and DTMs into mixed environmental models. The following potential applications of the treatment of imagery in association with DTMs are identified: 1) the prediction of the migration and accumulation zones of water, mineral and organic substances moved by gravity along the land surface and in the soil; 2) the investigation of the relationships between topographically expressed geological structures and landscape properties; 3) the improvement of geological engineering in industrial planning (e.g., the construction of nuclear power stations, oil and gas pipelines and canals); and 4) the monitoring of existing industries. Digital models of plan, profile, mean and total accumulation curvatures, and nonlocal and combined topographic attributes should be included in data processing both to solve the problems indicated and to improve the outcome of some regular tasks (for example, the prediction of soil moisture distribution and fault recognition).

Key words: digital terrain model, remote sensing, topographic effect, image classification, landscape study.

 0309–1333(98)PP173RA

I Introduction

Relief is a base of landscape and is one of the main factors in its development. Topography influences the migration and accumulation of substances moved by gravity along the land surface and in the soil (Young, 1972; Gerrard, 1981), some climatic and meteorological characteristics (Geiger, 1966; Raupach and Finnigan, 1997), soil formation (Huggett, 1975; Gerrard, 1981) and vegetation cover properties (Yaroshenko, 1961; Kirkby, 1995). In addition, topography is an indicator of geological structures (Meshcheryakov, 1965; Ollier, 1981), particularly faults which can control mineral deposits, seismic foci and may affect soil and plant characteristics.

In this connection, digital terrain models (DTMs) are used in a wide range of landscape investigations (Moore *et al.*, 1991; Shary *et al.*, 1991; Franklin, 1995). Furthermore, the combined use of remotely sensed data and DTMs has become an important trend in geomatics in the past two decades. The following are the basic reasons why researchers use images with DTMs (Richards *et al.*, 1982; Walsh, 1987; Franklin, 1990).

- Topography influences the formation of remotely sensed data.
- The geometrical characteristics of the land surface determine a complicated distribution of the brightness and spectral properties of landscapes. This can result in additional mistakes in image understanding and interpretation.
- In some cases a correct interpretation of remotely sensed data is impossible without ancillary data.
- Scene interpretation can be improved by taking into account prior known relationships between topography and other landscape components.
- The joint employment of images and DTMs can increase the total information extracted from both types of data.
- Remotely sensed data are an increasingly important source of DTMs.

Several theoretical and applied aspects of the joint processing of images and DTMs have been discussed but, up to now, there has been no systematic analytical review of these studies. This article reviews the use of remotely sensed data with DTMs in landscape investigations.

II DTMs

This section reviews the types of DTMs, the methods for DTM derivation and the basic problems of DTM operation that are important for the correct treatment of DTMs with images – i.e., the choice of DTM network type and resolution, DTM accuracy, and the precise superimposition of DTMs and remotely sensed data.

1 Types of DTMs

DTMs can be defined as digital representations of variables relating to a topographic surface, such as digital elevation models (DEMs) and digital models of gradient, aspect, horizontal curvature and other topographic attributes (Miller and Leflamme, 1958;

Doyle, 1978; Burrough, 1986; Felicisimo, 1994a). Researchers use the following types of DTMs (Table 1) in landscape investigations:

- DEMs.
- Models of local topographic characteristics, i.e., gradient, aspect, profile/vertical, plan/horizontal (Evans, 1980), mean and total accumulation land-surface curvatures (Shary, 1995) and a topoclimatic index (Frank, 1988).
- Models of nonlocal topographic variables, for example, a specific catchment area (Speight, 1968), slope length (Wischmeier and Smith, 1978), 'relief' (Frank, 1988) and a sediment delivery ratio (Hession and Shanholtz, 1988).
- Models of combined topographic characteristics, such as topographic factor (Wischmeier and Smith, 1978) and topographic (Beven and Kirkby, 1979) and stream power indices (Moore *et al.*, 1991).

In the earth sciences, topographic variables are employed because they 1) are connected with several processes affecting landscape development; and 2) can be used to recognize geological structures (Table 2). Topographic attributes can be applied to landscape studies not only in their ordinary forms but also within the framework of some mixed models of natural processes. For instance, a topographic index is employed in TOPMODEL, a distributed hydrological model (Beven and Kirkby, 1979; Quinn *et al.*, 1991). A topographic factor is invoked to calculate the universal soil loss equation (Wischmeier and Smith, 1978). In addition, DEMs are utilized to extract drainage networks (Peucker and Douglas, 1975; O'Callaghan and Mark, 1984; Skidmore, 1990; Smith *et al.*, 1990; Band, 1993), to visualize catchments (Jenson and Domingue, 1988; Band, 1993), and to map land-surface insolation (Haverlik and Krcho, 1973; Miklos *et al.*, 1991) and reflectance (Horn, 1981). Detailed reviews of DTM implementation in ground soil, hydrological, geomorphologic, plant and geological studies are given by Moore *et al.* (1991), Shary *et al.* (1991) and Franklin (1995).

In beginning work it is extremely important to choose the topographic variables affecting the object under study correctly. However, this is not a simple task because the influence of topography on landscape properties varies in different climatic, geomorphic and geological conditions. Therefore, it is desirable to use a wide range of DTMs in each study to determine the most useful ones.

2 Derivation of DTMs

DEMs are the initial data needed to produce all other types of DTMs. DEMs can be compiled by the following basic approaches:

1) Conventional ground topographic surveys, such as levelling, tacheometrical, plane-table (Modrinsky, 1972) and phototheodolitic (Bobir *et al.*, 1974) surveys. Results of these surveys can be used as source material for large-scale DEMs of modest-sized areas.
2) Photogrammetric procedures involving the use of two overlapping aerial or satellite orthoimages. Analytical photogrammetric processes involve the treatment of aerial hardcopy photos using steroplotters or automated image correlators (Bobir *et al.*, 1974; Kumler, 1994). Digital photogrammetric processes (softcopy photogrammetry) involve the handling of digital images with computers (Saleh, 1996). To obtain

Table 1 Definitions and formulae of some topographic variables

Topographic variable (unit)	Definition and formula
Elevation (m)	Elevation above sea level at a given point on the land surface
Gradient (degree)	An angle between a tangent and a horizontal plane at a given point on the land surface: $$G = \arctan\sqrt{p^2 + q^2}$$ (Shary, 1991)*
Aspect (degree)	An angle clockwise from north to a projection of an external normal vector to a horizontal plane at a given point on the land surface: $$A = \arctan\left(\frac{q}{p}\right)$$ (Shary, 1991)*
Profile curvature (m^{-1})	A curvature of a normal section of the land surface by a plane, including a gravity acceleration vector at a given point: $$k_v = -\frac{p^2 r + 2pqs + q^2 t}{(p^2 + q^2)\sqrt{(1 + p^2 + q^2)^3}}$$ (Shary, 1991)*
Plan curvature (m^{-1})	A curvature of a normal section of the land surface. This section is orthogonal to the section of profile curvature at a given point on the land surface: $$k_h = -\frac{q^2 r - 2pqs + p^2 t}{(p^2 + q^2)\sqrt{1 + p^2 + q^2}}$$ (Shary, 1991)*
Mean curvature (m^{-1})	$H = (k_h + k_v)/2$, where k_h and k_v are plan and profile curvatures, respectively (Shary, 1991)
Total accumulation curvature (m^{-2})	$K_a = k_h \cdot k_v$, where k_h and k_v are plan and profile curvatures, respectively (Shary, 1995)
Topoclimatic index	$SAI = A \sin\sqrt{p^2 + q^2}$, where A is aspect (Frank, 1988)*
Specific catchment area ($m^2\ m^{-1}$)	A ratio of an area of an exclusive figure, which is formed on the one hand by a contour intercept with a given point on the land surface and, on the other by flow lines coming from higher zones of slope to the ends of this contour intercept and to length of this intercept (Speight, 1968)
Slope length (m)	The distance from a point of flow origin to a point where either gradient decreases enough that deposition begins or a flow enters a channel (Wischmeier and Smith, 1978)

Table 1 Continued

Topographic variable (unit)	Definition and formula
'Relief' (m)	$RF_i = h_{max} - h_i$, where h_{max} is the highest elevation in a study site and, h_i is the elevation value at a given point on the land surface (Frank, 1988)
Sediment delivery ratio	$DR = 10RF/L$, where RF and L are 'relief' and slope length, respectively. Their values are calculated for an agricultural cell and a water cell, with which the first is associated (Hession and Shanholtz, 1988)
Topographic factor	A ratio of soil loss per unit area from a slope to that from a 22.15 m length of uniform 9% slope under otherwise equal conditions: $$LS = (L/22.15)^m(65.41 \sin^2 S + 4.56 \sin S + 0.065)$$ where L is slope length, S is a gradient (%) and $m = 0.2$–0.5 depending on gradient (Wischmeier and Smith, 1978)
Topographic index	$TI = \ln(CA/G)$, where CA and G are the specific catchment area and gradient, respectively (Beven and Kirkby, 1979)
Stream power index	$SI = CA \cdot G$, where CA and G are the specific catchment area and gradient, respectively (Moore *et al.*, 1991)
Reflectance (the Lambertian model)	$$R = \frac{1 - p\cos\theta/\tan\psi - q\sin\theta/\tan\psi}{\sqrt{1+p^2+q^2}\sqrt{1+(\cos\theta/\tan\psi)^2+(\sin\theta/\tan\psi)^2}}$$ where θ and ψ are the solar azimuth and zenith angles, respectively (Horn, 1981)*

*r, t, s, p and q are partial derivatives of the function

$$h = f(x, y):\ r = \frac{\delta^2 h}{\delta x^2}, \quad t = \frac{\delta^2 h}{\delta y^2}, \quad s = \frac{\delta^2 h}{\delta x \delta y}, \quad p = \frac{\delta h}{\delta x} \quad \text{and} \quad q = \frac{\delta h}{\delta y}$$

Moving the 3 × 3 elevation submatrix along a regular DEM, we can calculate values for r, t, s, p and q for all points of the DEM, except boundary points (Evans, 1980; Zevenbergen and Thorne, 1987; Moore *et al.*, 1993; Shary, 1995).

DEMs, digital photogrammetric systems can treat both scanned photos and images collected digitally, such as SPOT satellite imagery (e.g., Gugan and Dowman, 1988; Sasowsky *et al.*, 1992; Sharif and Salim, 1996), Landsat MSS and NOAA AVHRR multisensor steropairs (Akeno, 1996), video scenes (Spreeuwers and Houkes, 1996) and data from other sensors. Interferometric techniques are used to derive DEMs from synthetic aperture radar (SAR) data (e.g., Zebker *et al.*, 1994). Photogrammetric procedures can be used to produce DEMs in a wide range of scales.

3) Scanning and manual digitizing contours and spot elevations of published topographic maps of different scales (Carter, 1988; Khalugin *et al.*, 1992; Felicisimo, 1994a; Kumler, 1994).

Felicisimo (1994a) suggested that, in some cases, altimetrical and global positioning system techniques may be applied to compile DEMs. The choice of DEM compilation

Table 2 Relationships between topographic variables and landscape characteristics

Topographic variables	Landscape characteristics
Elevation	The vertical zonality of vegetation and soils in mountainous regions. An indicator of the rock's stability to weathering
Gradient	Flow velocity, runoff and soil loss (Wischmeier and Smith, 1978), thickness of soil horizons, some plant characteristics (Zakharov, 1940)
Aspect	Flow direction, thickness of soil horizons, some plant properties (Zakharov, 1940)
Gradient and aspect	Insolation, intensity of rain evaporation, snow detention and melting (e.g., Zakharov, 1940; Moore *et al*., 1993)
Gradient, aspect and elevation	Microclimate (Geiger, 1966)
Profile curvature	Relative deceleration of flows (Speight, 1974), soil moisture, pH, thickness of soil horizons, organic matter (Moore *et al*., 1991; Shary *et al*., 1991), plant cover distribution (Florinsky and Kuryakova, 1996). An indicator of lineaments, ring structures (Florinsky, 1992) and fault morphology (Florinsky, 1996)
Plan curvature	Flow convergence (Kirkby and Chorley, 1967), soil moisture, pH, thickness of soil horizons, organic matter (Moore *et al*., 1991; Shary *et al*., 1991), plant cover distribution (Florinsky and Kuryakova, 1996). An indicator of lineaments, ring structures (Florinsky, 1992) and fault morphology (Florinsky, 1996)
Plan and profile curvatures	Landslide distribution (Lanyon and Hall, 1983)
Mean curvature	Flow convergence and relative deceleration with equal weights (Shary, 1995), soil moisture (Sinai *et al*., 1981; Kuryakova *et al*., 1992), plant cover distribution (Sinai *et al*., 1981; Florinsky and Kuryakova, 1996)
Total accumulation and mean curvatures	Distribution and intensity of flow dissipation, transit and accumulation (Shary, 1995). An indicator of fault intersections (Florinsky, 1993)
Topoclimatic index	Wind effects on soil and plant distribution (Frank, 1988)
Specific catchment area	Soil moisture (Burt and Butcher, 1985), concentration of natural radionuclides in soil (Martz and De Jong, 1990), plant cover distribution (Florinsky and Kuryakova, 1996)
Slope length	A soil loss (Wischmeier and Smith, 1978)
'Relief'	Landscape drainage characteristic (Frank, 1988)
Sediment delivery ratio	Value of sediments reaching streams (Hession and Shanholtz, 1988)
Topographic factor	A soil loss (Wischmeier and Smith, 1978)

Table 2 Continued

Topographic variables	Landscape characteristics
Topographic index	Flow accumulation, soil moisture, distribution of saturation zones, depth of water table, evapotranspiration (Beven and Kirkby, 1979; Quinn and Beven, 1993), thickness of soil horizons, organic matter, pH, silt and sand content (Moore *et al*., 1993), plant cover distribution (Florinsky and Kuryakova, 1996)
Stream power index	Potential erosive power of overland flows (Moore *et al*., 1991), thickness of soil horizons, organic matter, pH, silt and sand content (Moore *et al*., 1993), plant cover distribution (Florinsky and Kuryakova, 1996)

method depends on such factors as area sizes, data cost, and the resolution and the accuracy required in the investigation.

DEM databases are available from a number of national mapping agencies, for example, from the US Geological Survey (USGS) (Carter, 1988; Kumler, 1994). DEM databases are collected by 1) scanning and digitizing contours (e.g., USGS Digital Line Graph hypsography files derived from 1:24 000 scale maps); 2) the photogrammetric processing of aerial orthophotos (i.e., USGS DEMs with resolutions of 30 m, 2 arc-seconds and 3 arc-seconds) (Kumler, 1994); and 3) a combination of data from different sources (e.g., 5-minute global DEM, ETOPO5 – NOAA, 1988).

Local topographic variables can be derived from an elevation analysis undertaken in a small neighbourhood of each DEM point. The methods of Evans (1980), Zevenbergen and Thorne (1987), Moore *et al*. (1993) and Shary (1995) can be used to calculate gradient, aspect, profile, plan, mean and total accumulation curvatures, the topoclimatic index, reflectance (Table 1) and insolation. These methods are based on the approximation of differential operators by finite differences (Ames, 1977). The Evans method is the most precise algorithm for this purpose (Florinsky, 1998). An analysis of larger land-surface areas is required to derive nonlocal and combined topographic attributes. The methods of Jenson and Domingue (1988), Martz and De Jong (1988), Freeman (1991) and Quinn *et al*. (1991) can be applied to generate digital models of a specific catchment area, and topographic and stream power indices. Regular DEMs are used to derive all these DTMs.

3 Co-ordinate systems and networks of DTMs

It is convenient to use different projection and co-ordinate systems as well as elevation descriptions in the different steps of DTM derivation, storage and application (Tjuflin, 1996). Converting a DTM from one description system to another is a regular photogrammetric task (Tjuflin, 1996). However, to process DTMs correctly with remotely sensed data, they have to be registered in a common co-ordinate system (Franklin, 1989).

The following basic elevation descriptions can be used in DEMs: 1) relative elevations; 2) normal elevations in the Baltic System; 3) geodetic elevations of different terrestrial ellipsoids; 4) elevations in different reference co-ordinate systems; 5) elevations in the unified geocentric co-ordinate systems; and 6) lengths of geocentric radius vectors of terrain points (Tjuflin, 1996). The horizontal position of DTM points can be defined in the following main co-ordinate systems: 1) relative Cartesian co-ordinates; 2) Gauss–Kruger horizontal rectangular co-ordinates; 3) different geodetic ellipsoidal co-ordinates;

4) spherical co-ordinates in different reference co-ordinate systems or the unified geocentric system, etc. (Tjuflin, 1996).

DTMs can be compiled using the following basic networks: 1) random irregular networks; 2) irregular networks with allowances for specific surface features (e.g., ridges and thalvegs); 3) random regular (i.e., square, rectangular) grids; 4) regular grids of geographical/geodetic co-ordinates; 5) triangulated irregular networks (TINs) with nodes at critical surface points; 6) parallel strips of points captured at critical surface points; and 7) the description of contours by points collected at contour bends and flexures (Carter, 1988; Florinsky, 1996). In varying degrees, these networks meet the requirements of the combined processing of DTMs with remotely sensed data. It has been argued that regular networks have marked disadvantages when compared with irregular networks involving critical surface points (Mark, 1979; Pozdnyakov and Chervanyev, 1990; Rieger, 1996). Thus, Mark (1979) argued that a structural phenomenon is a controlling factor for DEM compilation, rather than for computational reasoning. However, the different typical sizes of landforms correspond to different point densities in irregular DTMs. This can result in the simultaneous mapping of topographic characteristics that belong to different scales on a map of a given scale. Neighbouring areas on this map can be marked by different resolutions (Florinsky, 1996). It is also desirable to use rectangular nets because these DTMs can be marked by different resolutions along the x and y axes of the Cartesian co-ordinate system. Kumler (1994) found that the highest accuracy is specific to square-gridded DEMs. Also, it is profitable to employ regular DTMs as 1) regular DEMs are used to calculate all other types of DTMs (Table 1); and 2) both square-gridded DTMs and remotely sensed data are represented in a raster form.

Users often employ irregular DEMs as initial data. Various interpolation algorithms can be applied to derive regular DEMs from irregular ones (Schut, 1976). However, all these methods are marked by drawbacks (Schut, 1976; Lobanov and Zhurkin, 1980), and artifacts could arise due to the Gibbs phenomenon (Gibbs, 1898). Therefore the use of interpolation techniques influences the accuracy of a DEM.

4 Resolution of DTMs

A central problem of DTM implementation is choosing the grid size (resolution) (Balce, 1987; Ivanov and Kruzhkov, 1992). A grid size has to provide a specified accuracy of surface presentation using a minimum number of points. The closely related resolution of DTMs and remotely sensed images is the most important condition for the correct treatment of these data in combination.

Different methods of DEM compilation provide different DTM resolutions, and it goes without saying DTM resolution cannot be higher than the resolution of the source materials. The Peuker criterion states that a DEM grid size has to be fully 4.3 times larger than the contour interval of a digitized map (Sasowsky *et al.*, 1992). Ivanov and Kruzhkov (1992) gave a table for choosing a DEM grid size in different geomorphic conditions as a function of the root mean square error (RMSE) of a DEM.

A *formal* DTM resolution may clearly be increased by interpolation (Schut, 1976), but this procedure does not increase an *actual* DTM resolution. Moreover, the author's experience suggests that the calculation of local topographic variables using DEMs marked by 'increased' resolution leads to artifacts. If a DEM of this kind is interpolated by triangulation algorithms (Schut, 1976), triangular patterns will be revealed.

If 'increased' DEM resolution is achieved by weighted average interpolation methods (Schut, 1976), contour 'signs' will be recognized. These artifacts may introduce significant errors into the results of a combined analysis of DTMs and images. There is also an intimate connection between DEM grid size and discretization errors.

In landscape studies, choosing the DTM grid size generally depends on the investigation tasks. When DTMs are used to recognize topographically expressed faults, a DTM grid size should be a function of a typical size of these structures (Florinsky, 1996). In plant investigations, DTM resolution can be defined as a function of a typical size of vegetation patterns or landforms influencing plant distribution (Florinsky and Kuryakova, 1996). In soil and geochemical studies, a DTM grid size depends on a typical size of the processes of interest. Obviously, this task is rather complicated and, as a rule, may be solved by expert opinion (Moore *et al*., 1993). Besides, the scale of the maps to be obtained can influence which DTM grid size to choose.

5 Accuracy of DTMs

DTM errors can obviously adversely affect the accuracy and impartiality of the investigation and modelling of natural processes. The closely related locational accuracy of DTMs and remotely sensed images is therefore a necessary condition for the combined treatment of these data (Hutchinson, 1982).

a Accuracy of DEMs: causes of errors Generally, DEM accuracy depends on geomorphic conditions, the DEM compilation method (Isaacson and Ripple, 1990; Li, 1994; Hunter and Goodchild, 1995), network type and resolution. The accuracy of DEMs compiled by conventional topographic surveys depends essentially on systematic instrumental errors and random surveyor errors (Modrinsky, 1972).

The accuracy of DEMs produced by photogrammetric techniques is affected by 1) random and systematic human errors of DEM compilation, for example, the 'firth effect' (Hunter and Goodchild, 1995); 2) systematic and random instrumental errors of DEM compilation; 3) the spatial resolution of aerial/satellite images depending mainly on the characteristics of the camera/sensors; 4) the vertical resolution of images dictated essentially by the base : height ratio; 5) snow, vegetation and cloud covers; and 6) imagery accuracy depending on camera distortion/sensor stability, the earth's curvature, atmospheric refraction, aeroplane/satellite stability, image processing, errors of image transformation for removing geometric distortion and some other factors (Bobir *et al*., 1974; Akovetsky, 1994). In digital photogrammetry errors of elevation measurements can comprise from 5 to 20% of the total number of measurements according to image accuracy (Akovetsky, 1994). Aerial photos can be used to derive DEMs of a wide range of scales. SPOT data may be applied to produce relatively high-accuracy DEMs at large scales (e.g., 1 : 50 000) for canopy-free gently sloping areas (Sasowsky *et al*., 1992; Bolstad and Stowe, 1994; Sharif and Salim, 1996). However, SPOT-derived DEMs are not suited to the calculation of local topographic variables (Bolstad and Stowe, 1994). The utilization of multisensor stereopairs, NOAA AVHRR and Landsat MSS, provides a vertical accuracy fitting only the Digital Chart of the World (Akeno, 1996).

The accuracy of DEMs derived from topographic maps depends on 1) the accuracy of topographic maps dictated by the precision of photogrammetric processes (see above); 2) random human errors in digitizing maps; and 3) systematic instrumental errors in digitizing maps (Carter, 1988; Khalugin *et al*., 1992; Kumler, 1994). Li (1994) produced an equation for a DEM variance that is a function of a map variance and a contour interval. Generally, the RMSE of DEMs derived from contours is about 1/3 to 1/5 of the contour interval. This RMSE may be reduced by 40–60% if additional feature-specific data (e.g., thalvegs and ridges) are incorporated into DEMs. Humans are responsible for more than 90% of errors in digitizing maps (Khalugin *et al.*, 1992). These DEMs, therefore, are characterized by the least accuracy as compared with DEMs created by topographic surveys and photogrammetric processing. Stow and Estes (1981) show that the accuracy of a DEM compiled by digitizing contours is not sufficient for large-scale land-use studies with remotely sensed data. Gaps between images and other DTMs can be even greater. This is because, in most cases, DTM generation is realized by calculating partial derivatives of elevation (Table 1). These calculations increase DEM errors (Brown and Bara, 1994; Giles and Franklin, 1996).

The type of DEM network influences DEM accuracy. Kumler (1994) performed a detailed comparison of accuracy of 1) two square-gridded DEMs produced by linear and inverse-distance interpolations of elevations from digitized contours; 2) two TINs created from the gridded DEMs by VIP and LATTICETIN point selections; and 3) four TINs derived from digitized contours by ArcTIN distance weeding, the Douglas sampling of digitized contours, a combination of the Douglas simplification and proximal thinning, and the Douglas simplification with a TIN containing considerably more points than the standard TINs. The study was carried out for 25 terrain types. Kumler (1994) found that the highest accuracy is specific to regular DEMs produced by linear interpolation of elevation values from digitized contours. The accuracy of DEMs of this sort can be linear or parabolic with a DEM grid size (Li, 1994).

A DEM compilation is a discretization of the elevation continuous function using some grid size. This process is responsible for DEM discretization errors (Ivanov and Kruzhkov, 1992; Florinsky, 1996). Indeed, from the Kotelnikov theorem, a two-variable continuous function with a finite spectrum can be determined by its values with a grid size equalled to a half period of a space harmonic corresponding to the smallest surface details (Korn and Korn, 1968; Pratt, 1978). In practice, we have to insert a reserve multiplicative coefficient of 2–5 into values of limiting frequencies, F_x and F_y (Fivensky, pers. comm.). Assume the size of the smallest surface detail to be S. The space frequencies of this detail are $F_x = F_y = 1/S$. Consequently, $w = S/n$, where w is a grid size and $n = 2$–5. However, the land-surface frequency spectrum is not finite. So the Kotelnikov theorem condition is not met. This gives rise to discretization errors in DEMs. As users are interested in land-surface elements with S not smaller than a threshold, we can consider that all the spatial harmonics with frequencies more than $1/S$ are noise.

Rieger (1996) proposed the following classification of DEM errors:

- Low-frequency errors resulting, for example, from the photogrammetric orientation process. These are systematic errors. Generally, these errors can influence the superimposition of DTMs and imagery.
- Medium-frequency errors concerned, for instance, with photogrammetric measurements and DEM interpolation. These errors are both systematic and random. They are the most important for DTM implementation.
- High-frequency errors associated with, as a rule, image defects and sensor instability. These errors are random.

Methods for analysis and operation of DEM errors DEM accuracy can be determined, for instance, in terms of the RMSE of the elevation computed by comparing the DEM points and reference points (e.g., Ivanov and Kruzhkov, 1992; Bolstad and Stowe, 1994). However, a number of reference points are limited. This can lead to an improper estimation of the RMSE. This approach was elaborated by Rieger (1996) within a method based on the comparison of test and reference DEMs. However, it is unreasonable to suggest that a 'reference' DEM is the correct one.

Li (1994) suggested that elevation RMSE can be linear with a contour interval for DEMs produced by digitizing contours. However, DEM accuracy is a function of planimetric co-ordinates (e.g., Hunter and Goodchild, 1995). Generally, only a systematic component of DEM errors (Rieger, 1996) may be estimated by the Li criterion.

Macarovic (1972) proposed estimating DEM accuracy by a mean deviation of sinusoidal amplitudes obtained after interpolation from sinusoidal amplitudes existing before interpolation. Tempfli (1980) evaluated DEM accuracy by spectral analysis. Frederiksen (1981) developed a method for prediction of DEM accuracy based on summing the Fourier spectrum for high-frequency components of topographic profiles. Polidori *et al*. (1991) attempted to estimate DEM interpolation errors by the calculation of the DEM fractal dimension (Mandelbrot, 1967) at different scales and in different directions. However, these approaches are marked by rather tedious mathematical procedures and cannot represent a reliable estimate of DEM accuracy (Li, 1994).

Ackermann (1978) and Li (1994) proposed formulae for the estimation of elevation RMSE as a function of gradient. However, it is not profitable to use these formulae because the accuracy of the gradient calculation also depends on elevation RMSE (Felicisimo, 1995; Florinsky, 1998). Hannah (1981) developed a technique for the detection of DEM random errors. This method is based on a point comparison with adjacent points, using gradient and change-gradient values with specified thresholds. However, Hannah (1981) did not propose the criteria to be used to define threshold values. Felicisimo (1994b) developed an elegant method using the differences between two elevation values for each DEM point: the first is recorded in the DEM, and the second is interpolated from four neighbouring points. An arithmetic mean, a standard deviation and the Student test are then calculated. Relatively high test values are indicators of possible errors.

Discretization errors can be reduced by the well-known methods of surface low-pass filtering or smoothing (e.g., Bassett, 1972; Pratt, 1978). Hannah (1981) used a smoothing-like algorithm to correct the random errors detected in DEMs. Felicisimo (1994b) applied kriging (e.g., Royle *et al*., 1981) to correct these errors.

Kraus (1994) and Hunter and Goodchild (1995) described two approaches for the mapping of the horizontal accuracy of elevation data. In the first approach the 'epsilon band' is drawn around the position of a contour which defines the elevation of h_i. The borders of the epsilon band are two contours defining elevations of $(h_i - \Delta h)$ and $(h_i + \Delta h)$, where Δh is a half-contour interval. The epsilon band approach means that the true position of the h_i contour is somewhere between the band borders. In the second approach the researcher should calculate and map the likelihood of the true value of elevation being exceeding by a threshold.

b Accuracy of other types of DTMs: The accuracy of other types of DTMs has not been adequately explored. The accuracy of data on gradient, aspect and profile curvature was studied by a comparison of calculated and 'reference' values of these variables. For reference data researchers used hand measurements of gradient and aspect from topographic maps (Evans, 1980; Skidmore, 1989a), field measurements of gradient, aspect and profile curvature (Bolstad and Stowe, 1994; Giles and Franklin, 1996), gradient and aspect derived from reference DEMs of actual surfaces (Chang and Tsai, 1991) and imaginary ones (Carter, 1992; Felicisimo, 1995; Hodgson, 1995). However, these reference data, measurements and computations cannot be considered to be the correct ones, so this strategy can lead to some artifacts and subjective and conflicting conclusions. For instance, it was found that aspect errors are typical for flat areas (Chang and Tsai, 1991; Carter, 1992), while gradient errors are predominantly positioned on steep slopes (Chang and Tsai, 1991; Sasowsky *et al.*, 1992; Bolstad and Stowe, 1994). However, Carter (1992) found that both gradient and aspect errors grow to high values within flat areas. At the same time, Davis and Dozier (1990) found that gradient and aspect errors concentrate within zones of rapid change in slope and exposure. The map accuracy of gradient, aspect, plan and profile curvatures depends on DEM grid size (Evans, 1980; Isaacson and Ripple, 1990). For example, small steep zones can transform to broad areas marked by medium gradient values with increasing DEM grid size (Chang and Tsai, 1991). At the same time, Carter (1992) found that as a DEM grid size is increased, computed values of gradient and aspect more closely correspond to their reference values.

It is clear that the accuracy of data on topographic variables principally depends on 1) the accuracy of the initial data, that is, DEMs; and 2) the precision of a derivation technique. Attention has therefore to be focused on these two main factors. Hence Felicisimo (1995) found that gradient errors increase with increasing elevation RMSE. Skidmore (1989a) and Hodgson (1995) compared the accuracy of different methods for gradient and aspect derivation. Skidmore (1989a) found that algorithms using data on six points of the 3×3 elevation submatrix (Table 1) are more accurate than an algorithm using data on four points of this submatrix. Hodgson (1995), on the other hand, obtained opposite results. These studies were also carried out with a comparison of calculated and 'reference' values of topographic variables.

The accuracy of revealing a drainage network was studied by Skidmore (1990) and Lee *et al.* (1992). Rieger (1996) developed formulae for gradient and aspect accuracy. The formulae were based on the variance estimation. However, he also used the unnecessary concept of correlation between two neighbouring DEM points, which resulted in insufficiently workable expressions for gradient and aspect variances. At the same time, Kuryakova (1996) proposed that the RMSE of a measured variable's function would be appropriate when evaluating the accuracy of local topographic characteristics – an approach best suited to the problem at hand. Florinsky (1998) produced RMSE formulae for gradient, aspect, plan and profile curvatures. He demonstrated that mapping is the most convenient and pictorial way for the practical implementation of these formulae. High data errors on local topographic variables are typical for flat areas (Florinsky, 1998).

The regularities of the spatial distribution of DTM errors should be taken into account when combining the analysis of remotely sensed data and DTMs. The RMSE of DTMs can be used 1) to account for their spatial distribution in the analysis of images with DTMs (Carter, 1992); 2) to refine a DEM within areas marked by high RMSE values, and then to recalculate DTMs within these areas (Hunter and Goodchild, 1995); and 3) to correct DTM errors by methods that may process the RMSE of DTMs together with DTMs (Heuvelink *et al.*, 1989). Kraus (1994) proposed the use of the epsilon band and probability mapping for the visualization of the horizontal accuracy of DTMs.

6 Superimposition of DTMs and remotely sensed data

The precise superimposition of DTMs and remotely sensed scenes is a necessary condition for the combined processing of these data. This can be achieved using reference points. Assume that four or more reference points are specified at both an image and a DTM. The image can then be transformed in relation to the DTM reference points by well-known photogrammetric methods (e.g., Bobir *et al.*, 1974).

Seidel *et al.* (1983) developed a further automated method to register a DEM and an image. This method involves 1) the extraction of ridges from a scene and a reflectance map derived from the DEM (Table 1); 2) the crosscorrelation of the ridge image's pair; and 3) the derivation of an affine transformation of the scene and the DEM. However, there are different algorithms to reveal valley/ridge networks (Peucker and Douglas, 1975; O'Callaghan and Mark, 1984; Skidmore, 1990; Smith *et al.*, 1990; Band, 1993). These have drawbacks that can result in errors of DTM and image registration.

Tjuflin (1996) proposed a method for the registration of a satellite image defined by spherical co-ordinates and a DEM described by normal elevations in geodetic co-ordinates. The method includes 1) the iterative computation of new geodetic co-ordinates of the DEM using image spherical co-ordinates; 2) the interpolation of normal elevations related to the new geodetic co-ordinates; and 3) the iterative conversion from new normal elevations to lengths of geocentric radius vectors of terrain points. These lengths correlate with image pixels. Elevation interpolation, however, can also introduce additional errors into the DEM.

There is clearly no need to register DTMs and images if the DTMs are derived from these images by photogrammetric processing.

III Procedures, including the combined treatment of remotely sensed data and DTMs

Remotely sensed data and DTMs are treated together in the following procedures:

- The correction of the topographic effect.
- The correction of geometric image distortion.
- Image classification.
- Statistical and comparative analyses of landscape data.
- Three-dimensional (3D) landscape modelling.

1 Correction of the topographic effect

The topographic effect is the variation in radiance from an inclined surface compared to the radiance from a horizontal surface as a function of the surface orientation relative to the light source and sensor position (Justice *et al.*, 1981). The greatest topographic effect is produced in images of territories that have geomorphic contrasts (Woodham and Gray, 1987) and a low solar zenith angle (Justice *et al.*, 1981). Correcting the topographic effect can decrease classification mistakes as this reduces the brightness variation in a scene.

To estimate the topographic effect, researchers use a statistical analysis of scenes and digital models of reflectance. Reflectance can be calculated using several models of light reflectance from a surface (Horn, 1981). The main problem is the choice of an adequate reflectance model. The most well known is the Lambertian model (Table 1). However, analyses of Landsat and SPOT images have shown that the applicability of this model is rather limited (Smith *et al.*, 1980; Justice *et al.*, 1981; Cavayas, 1987; Jones *et al.*, 1988). Colby (1991), therefore, proposed the use of the Minnaert model (Horn, 1981). However, it should be stressed that using arbitrarily chosen reflectance models can complicate the interpretation of remotely sensed data (Jones *et al.*, 1988).

The model of choice, in the main, depends on the solar zenith angle in the scene formation and on certain other landscape properties (Jones *et al.*, 1988), such as the density and height of vegetation cover (Karaska *et al.*, 1986; Cavayas, 1987). Leprieur *et al.* (1988) presented diagrams of relationships between landscape reflectance, gradient, forest species and age for six Landsat TM bands. They found that reflectance depends on tree age. However, Walsh (1980; 1987) and Woodham and Gray (1987) demonstrated that landscape brightness variations are mainly controlled by gradient and aspect rather than by vegetation cover density, species differences, tree age and size. Therefore, the combined processing of imagery and reflectance models can be adapted 1) to estimate diffuse sky illumination and atmospheric transparency (Woodham, 1980); and 2) to map the reflectance factor with a simplified scene radiance equation (Yang and Vidal, 1990). The formation of SAR scenes is also controlled, on the whole, by gradient and aspect (Wu, 1987; Domik *et al.*, 1988). This allows one to use reflectance for the simulation of radar images (e.g., Domik *et al.*, 1988).

Landscape temperature depends on elevation both in mountainous (Hummer-Miller, 1981) and in flat terrains (Florinsky *et al.*, 1994), gradient, aspect (Gillespie and Kahle, 1977) and mean and profile curvatures (Florinsky *et al.*, 1994). These topographic variables should be taken into account when reducing the topographic effect on thermal scenes. The mean and profile curvatures may also control the topographic effect on reflectance images. For instance, such effects as the light spots of a curvilinear reflector can, on occasion, be recorded on glacier scenes (Malinnikov, pers. comm.). These effects can possibly be recognized and reduced using data on land-surface curvatures.

Reducing the topographic effect can be achieved by 1) dividing the brightness values in a scene by the corresponding values of a reflectance model (Justice *et al.*, 1981); and 2) subtracting the reflectance values from the corresponding grey values in an image (Domik *et al.*, 1988). However, in some cases these approaches are unsuitable for the correction of the topographic effect. Therefore, Civco (1989) proposed calculating the values of the corrected brightness (B_i^N) using the following equation:

$$B_i^N = B_i + K \cdot B_i \frac{\bar{R} - R_i}{\bar{R}} \tag{1}$$

where B_i is the initial brightness value, R is the reflectance values, $\bar{R}$ is the average reflectance value and K is an empirically derived calibration coefficient.

2 Correction of geometric image distortion

The correction of geometric image distortion (that is, the production of orthographic scenes) is a preliminary stage in handling remotely sensed data. Automated geometric image correction involves 1) determining the displacement at each pixel due to its elevation; and 2) shifting every pixel to its proper position (e.g., Imaizumi *et al.*, 1987). DEMs are used to correct both multispectral sensor data (Imaizumi *et al.*, 1987; Leprieur *et al.*, 1988; Farrag, 1996) and radar data (Naraghi *et al.*, 1983; Domik *et al.*, 1988). Farrag (1996) found that the accuracy of orthoimages generated from SPOT scenes decreases with increasing DEM grid size. Orthimages of flat terrain are less affected by increasing DEM grid size than the imagery of moderate and rough terrains.

The geometric correction of remotely sensed data is important from an application point of view. For example, this procedure may enhance the accuracy of plant (Imaizumi *et al.*, 1987) and rock type classification (Naraghi *et al.*, 1983).

3 Image classification

The classification of cover types in remotely sensed data can be improved significantly by applying some deterministic and probabilistic approaches that involve the processing of images with DTMs (Hutchinson, 1982; Richards *et al.*, 1982; Franklin, 1990). Neural network methods may also be useful when classifying aerial/satellite scenes with DTMs.

a Deterministic approaches: Deterministic approaches include 1) a preclassification scene stratification used before the classification commences; and 2) a postclassification class sorting applied to existing classifications.

Stratification involves breaking a scene up into zones that relate to several value intervals of topographic variables influencing the object under study. Postclassification class sorting includes the breaking up of a classification obtained by image processing into class groups. These groups also relate to several of the value intervals of topographic attributes. These approaches are realized using strata masks created with DTMs. Both stratification and class sorting permit the determination of differences of image patterns that have equal spectral characteristics (Hutchinson, 1982).

Deterministic approaches allow users to improve the data dissimilarity level and hence the accuracy classification. However, a researcher has first to determine the data transformation rules, particularly, 1) the topographic characteristics influencing the object of interest; and 2) an adequate quantification step for these characteristics that allows the fine differences in object classes to be recognized (Hutchinson, 1982; Franklin, 1989).

b Probabilistic approaches: The simplest probabilistic approach is a 'logical channel' method: *n* spectral data channels are used with *m* topographic variable channels in image classification (e.g., Tom and Miller, 1980). However, in some cases a simple increase in a channel number will not enhance the interpretation of remotely sensed data. On the contrary, this increase can introduce new classification problems into scene analysis (Hutchinson, 1982; Franklin, 1989).

Another method includes the modification of the maximum likelihood rule. Different probabilities that are already known have to be attributed to the different classes of the object under study before the classification can begin (Hutchinson, 1982). However, this method also demands knowledge of the relationships between the topographic variables and the objects of interest. Furthermore, the maximum likelihood rule presumes that the Gaussian distribution is justified for the data under analysis. This hypothesis, however, is not suitable for topographic variables (Evans, 1980). To solve this, Richards *et al.* (1982) developed a method based on probabilistic label relaxation procedures and the processing of DTMs as a set of probabilities. This method is applied to existing classifications and does not involve the Gaussian distribution hypothesis for topographic attribute values.

Tom and Miller (1980) demonstrated clearly the efficiency of probabilistic approaches to image classification, including DTM treatment. They used a stepwise linear discriminant classification of Landsat and ancillary data to test this information for significance in the mapping of a forest site index. The following data combinations were employed: 1) 4 MSS bands; 2) 4 MSS bands plus 6 MSS band ratios; 3) 4 DTMs (i.e., DEM, and digital models of gradient, aspect and insolation) plus vegetation-type data interpreted from an aircraft image; 4) 4 MSS/insolation ratios plus 4 DTMs and vegetation-type data; and 5) all the 19 variables indicated. The classifications achieved had an accuracy of 43, 59, 68, 95 and 97%, respectively. Richards *et al.* (1982) and Franklin (1989; 1990) obtained similar results in improving the accuracy of vegetation and geomorphic classifications.

c Neural network approaches: Neural networks (e.g., Haken, 1988) may offer an alternative to deterministic and probabilistic methods for the classification of imagery with DTMs. The term 'neural networks' is used for any net consisting of discrete elements – neurones. Each neurone has some inputs and a single output. Output neurone signals arrive at neurone inputs. There signals are combined using specified weights and control output signals. The operational properties of neural networks depend on 1) the interior properties of neurones; and 2) the weight values generated in the education or self-education of neural networks.

Neural network principles are the closest to biological systems of information processing. Neural networks are best applied to the solution of difficult-to-formalize problems (e.g., pattern recognition). Neural networks are non-parametric systems – that is, input network signals can be of any type. DTMs and images can therefore be entered directly to neural networks. Fair results were achieved at the first attempt to use neural networks in the interpretation of scenes with a DEM and gradient data (Gong *et al.*, 1996).

4 Statistical and comparative analyses of landscape data

The main purpose of these procedures is to determine regularities in the structure and development of a landscape – particularly relationships between topography and other landscape components (Table 2). The influence of topography on landscape properties obviously varies in different climatic, geomorphic and geological conditions and hence the results of these investigations, as a rule, reflect regional characteristics.

Correlation and regression analyses of DTMs and remotely sensed data are mostly used (e.g., Campbell, 1983; Wu, 1987), together with a simple visual comparative analysis of scenes and topographic variable maps (e.g., Gurov and Kertsman, 1991). These procedures basically provide a better understanding of natural processes and the results can be used to determine the data-transformation rules in image classification.

5 Three-dimensional landscape modelling

Three-dimensional landscape models (or 3D terrain videophotomodels) are geometrically rigorous terrain images derived from DTMs and digital photometric data of one or several aerial/satellite scenes using specified extents (Tjuflin, 1995). Three-dimensional landscape modelling is a useful data-processing step concerning the human perception of spatially distributed phenomena and information.

The 3D modelling of landscape characteristics includes: 1) 3D modelling of the land surface by DEM processing (i.e., the generation of a block diagram – e.g., Jenks and Brown, 1966); 2) the draping of a scene, or a thematic map derived from a scene, over a block diagram; and 3) the perspective viewing of a 3D model from different points in space (e.g., Frank, 1988; Jones *et al*., 1988; Butler *et al*., 1991; Band *et al*., 1993). Three-dimensional landscape modelling can enhance the visual interpretation of images and an understanding of the relationships between landscape elements. There procedures can also be used in remote-sensing design, satellite orientation control, and aircraft and spacecraft training.

IV Applications

In this section, a number of typical plant, geochemical, soil, geological, climatological, glaciological and natural hazard investigations carried out using remotely sensed data integrally with DTMs are reviewed. Most, if not all, of these works can be considered to be not site-specific. These strategies can also be used in other regions with some small modifications that take into consideration the natural conditions specific to that region.

1 Plant studies

Strahler (1981) and Franklin *et al*. (1986) used a strategy of scene stratification 1) to improve the classification of forest vegetation at a regional level; and 2) to improve a timber inventory. They employed elevation, gradient and aspect masks. Shasby and Carneggie (1986) applied a class-sorting method to the classification of land-cover types obtained by Landsat MSS data processing. They used strata masks of elevation, gradient and aspect (Table 1) to determine mountain and valley shrub patterns that had equal spectral characteristics. Frank (1988) employed a discriminant analysis of five Landsat TM band ratios and transformations, a DEM, and data on gradient, aspect, topoclimatic index and 'relief' (Table 1) to distinguish patterns in alpine and subalpine vegetation that cannot be separated by the usual treatment of imagery.

Skidmore (1989b) developed a rule-based expert system for the classification of eucalyptus forest types. This system was based on a nonparametric classifier of Landsat TM images and data on gradient, aspect and topographic position (i.e., valleys and ridges). Prior knowledge on the relief location in which particular forest types occur was included as rules in the classification. Band *et al*. (1993) modelled forest canopy net photosynthesis and total evapotranspiration with the combined use of TOPMODEL (a distributed hydrological model – Beven and Kirkby, 1979; Quinn *et al*., 1991) and FOREST-BGC (a model of the forest carbon, water and nitrogen budget – Band *et al*., 1993). DEM was used to calculate the topographic index (Tables 1 and 2) in TOPMODEL and to extract the drainage networks. Drainage network information was used to break the study site up into hillslopes – that is, model units. Sets of hillslope maps were then employed as masks to parameterize separately each model unit with soil and canopy data. Soil information (depth, texture and transmissivity) was calculated using soil maps. Canopy variables, such as leaf area index and biome type, were estimated with Landsat TM images.

In my opinion, the main problem with these studies is that they ignore land-surface curvatures (Table 1). This is possibly connected with an underestimation of the role of topographic variables indicated in the formation and development of plant cover. Indeed, Peddle and Franklin (1991) noted a minor improvement in spectral and radar data classification after digital models of plan and profile curvatures were incorporated into data processing when studying the vegetation of Newfoundland. They acknowledged the important role of land-surface curvatures in soil formation (Table 2) and explained the results obtained by the local influence of plan and profile curvatures on landscape properties. Peddle and Franklin (1991) considered that the registration of vegetation dependencies on plan and profile curvatures is impossible using DTMs with a resolution of 20 m. However, Florinsky *et al*. (1994) were not able to demonstrate sufficient correlations between plan, profile and mean curvatures and the landscape radiational plant-controlled temperature using a thermoimage and DTMs with a resolution of 3.5 m in central Russia. They concluded that this indicates the lessened sensitivity of *boreal* and *sub-boreal* vegetation to variations in land-surface curvatures as compared with soils. (In *arid* regions a strong correlation between plant cover and mean curvature was found by Sinai *et al*., 1981.)

Nevertheless, Florinsky and Kuryakova (1996) showed that vegetation properties correlate strongly with plan, profile and mean curvatures as well as with elevation, gradient, aspect, specific catchment area, topographic and stream power indices (Tables 1 and 2) in a mountainous *boreal* region. In this study, vegetation data were derived from large-scale aerial photos. A DTM grid size of 400 m was used. The conclusions they reached on the minor effects of land-surface curvatures on vegetation (Peddle and Franklin, 1991; Florinsky *et al*., 1994) may either be correct for some ranges of DTM grid sizes or were arrived at following inadequate descriptions of plant characteristics. It is this author's opinion that digital models of land-surface curvatures should be included in data processing to obtain correct results in vegetation studies carried out with remotely sensed images.

2 Landscape geochemistry and environmental pollution

Campbell (1983) attempted to estimate the uranium deposit distribution in the landscape. She used a statistical analysis of gamma-spectrometric and magnetometric aerial data, Landsat scenes, DEMs and ground geochemical data. The correlation between elevation and uranium concentration at stream sediments and surface waters was determined to be $+0.49$ and -0.52, respectively. However, the use of data on a single topographic variable can be considered inadequate because the specific catchment area and plan and profile curvatures (Table 1) also influence the concentration of radionuclides in the soil cover (Martz and De Jong, 1990). Also, a visual comparison of gamma-spectrometric aerial data with plan and profile curvature maps demonstrated that areas heavily polluted with ^{137}Cs correlate with flow accumulation zones even in extremely flat terrains (Gurov and Kertsman, 1991). These zones are defined by the negative values of both plan and profile curvatures (Shary *et al*., 1991) or by the positive values of total accumulation curvature with the negative values of mean curvature (Table 1) (Shary, 1995).

The studies cited above show promise for the analysis of remotely sensed data with DTMs in the prediction of the migration and accumulation of mineral and organic substances moved in a landscape by gravity. DTM processing allows the determination of the topographic prerequisites of substance movement, and image analysis permits the correction and enrichment of this forecasting. Such a combined analysis would be useful to predict the migration and accumulation of 1) nitrates, pesticides and natural and artificial radionuclides in ecological monitoring; 2) hydrocarbons in oil and gas pipeline monitoring; and 3) leakage waters in reclamation monitoring.

3 Soil science

Lee *et al*. (1988) argued that methods of preclassification image stratification using DTMs are not appropriate to the study of soil properties in hilly terrains. They believed that such stratification can be useful for terrains with several water/temperature soil regimes. Lee *et al*. (1988) applied the logical channel method to improve a soil-cover classification using Landsat TM data. The DEM and data on gradient were used as ancillary channels. There was a 72% agreement between an existing soil map and the classification obtained.

In investigating water erosion, Anys *et al*. (1994) compiled maps of soil loss, potential erosion and sediment delivery rate using a DEM, digital models of gradient, a topographic factor and a sediment delivery ratio (Tables 1 and 2), a soil map, Landsat-5 TM, aerial scenes and ground meteorological data. Images were applied to map land use by calculating a vegetation index (Bannari *et al*., 1995). The land-use map and the DTMs were used as initial data in calculating a universal soil loss equation (Wischmeier and Smith, 1978). Anys *et al*. (1994) demonstrated that the highest soil loss rate correlates not only with the absence of vegetation cover but also with combinations of topographic factors and soil fragility.

To estimate a balance of evapotranspiration, infiltration and rainfall, and to develop a catchment groundwater model, Drayton and Said (1989) used statistical processing of a DEM, digital models of gradient and aspect, ground meteorological data and the results of a supervised maximum likelihood classification of Landsat MSS and soil data. To classify soil cover by moisture content, Feranec *et al*. (1991) analysed Landsat TM images and data on elevation, aspect, gradient and plan and profile curvatures. They found that plan and profile curvatures are the most useful topographic information for this classification. Digital models of total accumulation and mean curvatures, a specific catchment area and a topographic index (Table 1) can also be used to improve studies of this kind because these variables influence the spatial distribution of soil moisture and saturated zones as well as the depth of the water table (Table 2).

4 Geology

McMahon and North (1993) used 3D modelling of the land surface, basement surface, gravity and magnetic fields, the draping of Landsat TM scenes over block diagrams and perspective viewing of the 3D models obtained. This approach allowed them to enhance the lithological interpretation of the imagery, the recognition of lineaments and the determination of fault strikes and dips.

To improve lineament visibility and rock-type discrimination, reflectance models (Table 1) were employed to correct 1) the topographic effect on Landsat scenes (e.g., Rochon, 1981); and 2) the distortion of radar images (Naraghi *et al*., 1983). A comparative analysis of reflectance maps, side-look aperture radar and Landsat scenes demonstrated that reflectance maps are best for revealing lineaments (Schowengerdt and Glass, 1983).

Revealing topographically expressed geological structures can perhaps best be realized by a more rigorous technique based on the mapping of plan and profile curvatures (Florinsky, 1992). This method also allows the recognition of fault morphology (Florinsky, 1996). Using total accumulation curvature together with mean curvature is also useful in revealing fault intersections (Florinsky, 1993). Seismic foci and landslides, as well as abnormally high concentrations of water, salts and microelements, may be located in these sites. Therefore an analysis of imagery together with digital models of plan, profile, total accumulation and mean curvatures (Tables 1 and 2) can be of help, for instance, in 1) studying relationships between faults and soil/vegetation properties; 2) improving geological engineering in industrial planning (e.g., the construction of nuclear power stations, oil and gas pipelines, and canals); and 3) optimizing the monitoring of existing industries.

5 Climatology

Menz (1988) developed a method of mapping heat stress by the multiple linear regression analysis of day infrared HCMM scenes, ground meteorological data, DEMs and land-use maps derived from Landsat MSS data. This method can provide a high level of accuracy in calculating the heat stress values in areas between weather stations. However, as landscape temperature depends not only on elevation but also on gradient , aspect (Gillespie and Kahle, 1977) and mean and profile curvatures (Florinsky *et al*., 1994), these data should also be used to compile human-bioclimatological and other climatological maps.

6 Glaciology

Seidel *et al*. (1983) developed a method to determine snow-cover distribution by the combined classification of Landsat MSS scenes, a DEM, digital models of gradient, aspect and reflectance (Table 1), land-use maps and ground meteorological data. The method permits the forecasting of snow distribution without ground control and can be useful in hydrological modelling. Seidel *et al*. (1983) argued that this method may be used to predict snow distribution within zones obscured by clouds.

Gratton *et al*. (1993) used Landsat-5 TM, a DEM and data on gradient, aspect and reflectance to estimate and model a glacier radiation balance. DTMs were applied to correct for the topographic influence of irradiance which was calculated with Landsat TM images, some meteorological data and LOWTRAN-6 (a spectrally based radiative transfer model). The irradiance values obtained were used to map albedo and brightness temperature. The daily net shortwave radiation field of snow and ice cover was then mapped using 1) the topographic correction of the shortwave irradiance components calculated with LOWTRAN-6; and 2) albedo values.

Unfortunately, Seidel *et al*. (1983) and Gratton *et al*. (1993) did not attempt to introduce data on plan, profile and mean curvatures (Table 1) into their models. Such fine information on surface geometry could be useful in glaciological studies if these topographic variables influenced the topographic effect on glacier scenes. In addition, landscape radiational temperature depends on profile and mean curvatures (Florinsky *et al*., 1994). Plan and profile curvatures also control, in many respects, the lateral movement of substance flows (Table 2). Therefore, it is this author's opinion that these topographic attributes can be used to improve the DTM-based estimation and modelling of ice and snow distribution, melting and redistribution by gravity (Seutova and Chistov, 1993).

7 Natural hazard studies

Barberi *et al*. (1991) and Butler *et al*. (1991) have shown that 1) an analysis of Landsat TM data together with a DEM and data on gradient; and 2) a visual analysis of 3D landscape models permit one to determine the sites of natural hazards (i.e., the location of lava outflows, landslides and avalanches). Shikada *et al*. (1996) analysed landslide distribution with the use of landslides and geological maps, Landsat TM data and DEMs. DEMs were utilized to derive gradients, drainage networks and catchments.

The combined use of plan and profile curvatures (Table 1) allowed Lanyon and Hall (1983) to forecast landslide spatial distribution. Landslides strongly correlate with areas characterized by negative values of both these curvatures (Lanyon and Hall, 1983) – that is, flow accumulation zones (Shary, 1995). These zones are also determined by the positive values of total accumulation curvature with the negative values of mean curvature (Table 1) (Shary, 1995). Image processing may be applied to improve the prediction of landslide distribution. Studies of this kind can be useful for geological engineering in industrial planning and in the monitoring of existing industries.

V Conclusions

A review of the combined analysis of remotely sensed data and DTMs allows us to formulate the following statements:

1) During the past two decades, the use of aerial and satellite images with DTMs has become an important trend in geomatics. These methods are applied to solving problems in geobotany, forestry, geochemistry, soil science, geology, glaciology and other sciences. The trend has been towards the incorporation of the joint analysis of remotely sensed data and DTMs into mixed environmental models.
2) More than ten types of DTMs are integrally employed with imagery in the following procedures: 1) image correction of the topographic effect; 2) correction of geometric image distortion; 3) image classification; 4) statistical and comparative analyses of landscape data; and 4) 3D landscape modelling.
3) The following basic problems of DTM operation are important in the processing of DTMs with remotely sensed data: 1) a proper choice of DTM network type and resolution; 2) the provision of the greatest possible accuracy in DTMs; and 3) the precise superimposition of DTMs and images.
4) The joint treatment of remotely sensed scenes and DTMs can increase the total information extracted from the two types of data.
5) The following are potential applications of imagery in association with DTMs:
   - The prediction of the migration and accumulation zones of mineral and organic substances moved by gravity along the land surface and in the soil.
   - Investigations of relationships between topographically expressed geological structures and landscape properties.
   - The upgrading of geological engineering in industrial planning (i.e., the construction of nuclear power stations, oil and gas pipelines and canals).
   - The monitoring of existing industries.

6) Digital models of plan, profile, mean and total accumulation curvatures, and nonlocal and combined topographic attributes can be included in data processing both to solve the problems indicated above and to improve the outcome of some regular tasks (e.g., the prediction of soil moisture distribution and fault recognition).

Acknowledgements

This work was carried out with partial support from NATO grant ENVIR.CRG 950218 as well as with the technical assistance of Drs G.L. Andrienko, N.V. Andrienko, A.R. Skovoroda and S.R. Aglyamov (Institute of Mathematical Problems of Biology, Russian Academy of Sciences, Pushchino, Russia).

References

Ackermann, F. 1978: Experimental investigation into the accuracy of contouring from DTM. *Photogrammetric Engineering and Remote Sensing* 44, 1537–48.

Akeno, K. 1996: DEM generation from multisensor stereopairs – AVHRR and MSS. In Kraus, K. and Waldhäeusl, P., editors, *International archives of photogrammetry and remote sensing* (Vol. 31, Part B4, Commission IV), Vienna: Austrian Society of Surveying and Geoinformation, 36–40.

Akovetsky, V.G. 1994: Improvement of stereoscopic measurement efficiency. *Geodesiya i Carographiya* 1, 29–33 (in Russian).

Ames, W.F. 1977: *Numerical methods for partial differential equations*. New York: Academic Press.

Anys, H., Bonn, F. and **Merzouk, A.** 1994: Remote sensing and GIS based mapping and modeling of water erosion and sediment yield in a semi-arid catchment of Morocco. *Geocarto International* 9, 31–40.

Balce, A.E. 1987: Determination of optimum sampling interval in grid digital elevation models (DEM) data acquisition. *Photogrammetric Engineering and Remote Sensing* 53, 323–30.

Band, L.E. 1993: Extraction of channel networks and topographic parameters from digital elevation data. In Beven, K. and Kirkby, M.J., editors, *Channel network hydrology*, Chichester: Wiley, 13–42.

Band, L.E., Patterson, P., Nemani, R. and **Running, S.W.** 1993: Forest ecosystem processes at the watershed scale: incorporating hillslope hydrology. *Agricultural and Forest Meteorology* 63, 93–126.

Bannari, A., Morin, D., Bonn, F. and **Huete, A.R.** 1995: A review of vegetation indices. *Remote Sensing Reviews* 13, 95–120.

Barberi, F., Bernstein, R., Pareschi, M.T. and **Santacroce, R.** 1991: Displaying morphological and lithological maps: a numerically intensive computing and visualization application. *IBM Journal of Research and Development* 35, 78–87.

Bassett, K. 1972: Numerical methods for map analysis. *Progress in Geography* 4, 217–54.

Beven, K.J. and **Kirkby, M.J.** 1979: A physically-based variable contributing area model of basin hydrology. *Hydrological Science Bulletin* 24, 43–69.

Bobir, N.Ya., Lobanov, A.N. and **Fedoruk, G.D.** 1974: *Photogrammetry*. Moscow: Nedra (in Russian).

Bolstad, P.V. and **Stowe, T.** 1994: An evaluation of DEM accuracy: elevation, slope and aspect. *Photogrammetric Engineering and Remote Sensing* 60, 1327–32.

Brown, D.G. and **Bara, T.J.** 1994: Recognition and reduction of systematic error in elevation and derivative surfaces from 7.5-minute DEMs. *Photogrammetric Engineering and Remote Sensing* 60, 189–94.

Burrough, P.A. 1986: *Principles of geographical information systems for land resources assessment*. Oxford: Clarendon Press.

Burt, T.P. and **Butcher, D.P.** 1985: Topographic controls of soil moisture distribution. *Journal of Soil Science* 36, 469–86.

Butler, D.R., Walsh, S.J. and **Brown, D.G.** 1991: Three-dimensional displays for natural hazards analysis, using classified Landsat Thematic Mapper digital data and large-scale digital elevation models. *Geocarto International* 6, 65–69.

Campbell, K. 1983: Statistical techniques using NURE airborne geophysical data and NURE geochemical data. *Computers and Geosciences* 9, 17–21.

Carter, J.R. 1988: Digital representations of topographic surfaces. *Photogrammetric Engineering and Remote Sensing* 54, 1577–80.
—— 1992: The effect of data precision on the calculation of slope and aspect using gridded DEMs. *Cartographica* 29, 22–34.
Cavayas, F. 1987: Modelling and correction of topographic effect using multi-temporal satellite images. *Canadian Journal of Remote Sensing* 13, 49–67.
Chang, K.-T. and **Tsai, B.-W.** 1991: The effect of DEM resolution on slope and aspect mapping. *Cartography and Geographical Information Systems* 18, 69–77.
Civco, D.L. 1989: Topographic normalization of Landsat Thematic Mapper digital imagery. Photogrammetric Engineering and Remote Sensing 55, 1303–309.
Colby, J.D. 1991: Topographic normalization in rugged terrain. *Photogrammetric Engineering and Remote Sensing* 57, 531–37.

Davis, F.W. and **Dozier, J.** 1990: Information analysis of a spatial database for ecological land classification. *Photogrammetric Engineering and Remote Sensing* 56, 605–13.
Domik, G., Leberl, F. and **Cimono, J.** 1988: Dependence of image grey values on topography in SIR-B images. *International Journal of Remote Sensing* 9, 1013–22.
Doyle, F.J. 1978: Digital terrain models: an overview. *Photogrammetric Engineering and Remote Sensing* 44, 1481–85.
Drayton, R.S. and **Said, M.A.** 1989: Improvements to the estimation of groundwater recharge using satellite and digital elevation data. In *Remote sensing for operational applications: technical contents of the 15th annual conference of the Remote Sensing Society, Bristol, 13–15 Sept., 1989*, Bristol: RSS, 107–12.

Evans, I.S. 1980: An integrated system of terrain analysis and slope mapping. *Zeitschrift für Geomorphologie* Suppl Bd 36, 274–95,

Farrag, A.F. 1996: The influence of terrain type and density of digital elevation model on the geometric quality of satellite orthoimages. In Kraus, K. and Waldhäeusl, P., editors, *International archives of photogrammetry and remote sensing* (Vol. 31, Part B4, Commission IV), Vienna: Austrian Society of Surveying and Geoinformation, 246–51.
Felicisimo, A.M. 1994a: *Modelos Digitales del Terreno. Introduccion y Aplicaciones en las Ciencias Ambientales*. Oviedo: Pentalfa Ediciones.
—— 1994b: Parametric statistical method for error detection in digital elevation models. *ISPRS Journal of Photogrammetry and Remote Sensing* 49, 29–33.
—— 1995: Error propagation analysis in slope estimation by means of digital elevation models. In *Cartography crossing borders: proceedings 1 of the 17th international cartographic conference and 10th general assembly of the International Cartographic Association, Barcelona, 3–9 Sept., 1995*, Barcelona: Institut Cartografic de Catalunya, 94–98.
Feranec, J., Kolar, J. and **Krcho, J.** 1991: Mapping of the surface water logging intensity of the soils by applying Landsat TM data and complex digital terrain model. *Bulletin du Comité Français de Cartographie* 127–28, 154–57.
Florinsky, I.V. 1992: *Recognition of lineaments and ring structures: quantitative topographic techniques*. Pushchino: Pushchino Research Centre Press (in Russian, with English abstract).
—— 1993: Digital elevation model analysis for linear land-surface structure recognition. PhD thesis summary. Moscow State University of Geodesy and Cartography (in Russian).
—— 1996: Quantitative topographic method of fault morphology recognition. *Geomorphology* 16, 103–19.
—— 1998: Accuracy of local topographic variables derived from digital elevation models. *International Journal of Geographical Information Science* 12, 47–61.
Florinsky, I.V., Kulagina, T.B. and **Meshalkina, J.L.** 1994: Influence of topography on landscape radiation temperature distribution. *International Journal of Remote Sensing* 15, 3147–53.
Florinsky, I.V. and **Kuryakova, G.A.** 1996: Influence of topography on some vegetation cover properties. *Catena* 27, 123–41.
Frank, T.D. 1988: Mapping dominant vegetation communities in the Colorado Rocky Mountain Front Range with Landsat Thematic Mapper and digital terrain data. *Photogrammetric Engineering and Remote Sensing* 54, 1727–34.
Franklin, J. 1995: Predictive vegetation mapping: geographic modelling of biospatial patterns in relation to environmental gradients. *Progress in Physical Geography* 19, 474–99.
Franklin, J., Logan, T.L., Woodcock, C.E. and **Strahler, A.H.** 1986: Coniferous forest classification and inventory using Landsat and digital terrain data. *IEEE Transactions on Geoscience and Remote Sensing* GE-24, 139–49.
Franklin, S.E. 1989: Ancillary data input to satellite remote sensing of complex terrain phenomena. *Computers and Geosciences* 15, 799–808.
—— 1990: Topographic context of satellite spectral response. *Computers and Geosciences* 16, 1003–10.

Frederiksen, P. 1981: Terrain analysis and accuracy prediction by means of the Fourier transformation. *Photogrammetria* 36, 145–57.

Freeman, T.G. 1991: Calculating catchment area with divergent flow based on a regular grid. *Computers and Geosciences* 17, 413–22.

Geiger, R. 1966: *The climate near the ground* (translated by Scripta Technica from the 4th German edn). Cambridge, MA: Harvard University Press.

Gerrard, A.J. 1981: *Soils and landforms. An integration of geomorphology and pedology*. London: Allen & Unwin.

Gibbs, J.W. 1898: Letters to the editor: Fourier's series. *Nature* 59, 200.

Giles, P.T. and **Franklin, S.E.** 1996: Comparison of derivative topographic surfaces of a DEM generated from stereoscopic SPOT images with field measurements. *Photogrammetric Engineering and Remote Sensing* 62, 1165–71.

Gillespie, A.R. and **Kahle, A.B.** 1977: Construction and interpretation of a digital thermal inertia image. *Photogrammetric Engineering and Remote Sensing* 43, 983–1000.

Gong, P., Pu, R. and **Chen, J.** 1996: Mapping ecological land systems and classification uncertainties from digital elevation and forest-cover data using neural networks. *Photogrammetric Engineering and Remote Sensing* 62, 1249–60.

Gratton, D.J., Howarth, P.J. and **Marceau, D.J.** 1993: Using Landsat-5 Thematic Mapper and digital elevation data to determine the net radiation field of a mountain glacier. *Remote Sensing of Environment* 43, 315–31.

Gugan, D.J. and **Dowman, I.J.** 1988: Topographic mapping from SPOT imagery. *Photogrammetric Engineering and Remote Sensing* 54, 1409–14.

Gurov, V.N. and **Kertsman, V.M.** 1991: Topography as a factor for feasible movement of radionuclides. In *Geochemical migration ways of artificial radionuclides in the biosphere: proceedings of the 5th conference, Pushchino, Dec. 1991*, Moscow: Vernadsky Institute of Geochemistry and Analytical Chemistry, 17 (in Russian).

Haken, H., editor, 1988: *Neural and synergetic computers*. Berlin: Springer-Verlag.

Hannah, M.J. 1981: Error detection and correction in digital terrain models. *Photogrammetric Engineering and Remote Sensing* 47, 63–69.

Haverlik, I. and **Krcho, J.** 1973: Mathematical generalization of forming isoline thematic maps by computer exemplified by morphometric analysis of relief and dynamics of relief insolation. *Acta Geographica Universitatis Comenianae, Geographico-Physica* 1, 235–424.

Hession, W.C. and **Shanholtz, V.O.** 1988: A geographic information system for targeting nonpoint-source agricultural pollution. *Journal of Soil and Water Conservation* 43, 264–66.

Heuvelink, G.B.M., Burrough, P.A. and **Stein, A.** 1989: Propagation of errors in spatial modelling with GIS. *International Journal of Geographical Information Systems* 3, 303–22.

Hodgson, M.E. 1995: What cell size does the computed slope/aspect angle represent? *Photogrammetric Engineering and Remote Sensing* 61, 513–17.

Horn, B.K.P. 1981: Hill shading and the reflectance map. *Proceedings of IEEE* 69, 14–47.

Huggett, R.J. 1975: Soil landscape system: a model of soil genesis. *Geoderma* 13, 1–22.

Hummer-Miller, S. 1981: Estimation of surface temperature variations due to changes in sky and solar flux with elevation. *Geophysical Research Letters* 8, 595–98.

Hunter, G.J. and **Goodchild, M.F.** 1995: Dealing with error in spatial databases: a simple case study. *Photogrammetric Engineering and Remote Sensing* 61, 529–37.

Hutchinson, C.F. 1982: Techniques for combining Landsat and ancillary data for digital classification improvement. *Photogrammetric Engineering and Remote Sensing* 48, 123–30.

Imaizumi, S., Ishihara, O. and **Saitou, I.** 1987: Research on forest type classification based on TM data with geometrical correction for elevation. In *IGARSS'87. Remote sensing: understanding the earth as a system: proceedings of the IEEE international geoscience and remote sensing symposium, Ann Arbor, 18–21 May, 1987. Vol. 2*, New York: IEEE, 927–32.

Isaacson, D.L. and Ripple, W.J. 1990: Comparison of 7.5-minute and 1-degree digital elevation models. *Photogrammetric Engineering and Remote Sensing* 56, 1523–27.

Ivanov, V.I. and **Kruzhkov, V.A.** 1992: Evaluation of the optimal discretization step for a digital elevation model. *Geodesiya i Cartographiya* 5, 47–50 (in Russian).

Jenks, G.F. and **Brown, D.A.** 1966: Three-dimensional map construction. *Science* 154, 857–64.

Jenson, S.K. and **Domingue, J.Q.** 1988: Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogrammetric Engineering and Remote Sensing* 54, 1593–600.

Jones, A.R., Settle, J.J. and **Wyatt, B.K.** 1988: Use of digital terrain data in the interpretation of SPOT-1 HVR multispectral imagery. *International Journal of Remote Sensing* 9, 669–82.

Justice, C.O., **Wharton, S.W.** and **Holben, B.N.** 1981: Application of digital terrain data to quantify and reduce the topographic effect on Landsat data. *International Journal of Remote Sensing* 2, 213–30.

Karaska, M.A., **Walsh, S.J.** and **Butler, D.R.** 1986: Impact of environmental variables on spectral signatures acquired by the LANDSAT thematic mapper. *International Journal of Remote Sensing* 7, 1653–67.

Khalugin, Ye.I., **Zhalkovsky, Ye.A.** and **Zhdanov, N.D.** 1992: *Digital maps*. Moscow: Nedra (in Russian).

Kirkby, M. 1995: Modelling the links between vegetation and landforms. *Geomorphology* 13, 319–35.

Kirkby, M.S. and **Chorley, R.J.** 1967: Throughflow, overland flow and erosion. *Bulletin of the International Association of Scientific Hydrology* 12, 5–21.

Korn, G.A. and **Korn, T.M.** 1968: *Mathematical handbook for scientists and engineers. Definitions, theorems, and formulas for reference and review* (2nd edn). New York: McGraw-Hill.

Kraus, K. 1994: Visualization of the quality of surfaces and their derivatives. *Photogrammetric Engineering and Remote Sensing* 60, 457–62.

Kumler, M.P. 1994: An intensive comparison of triangulated irregular networks (TINs) and digital elevation models (DEMs). *Cartographica* 31, 1–99.

Kuryakova, G.A. 1996: Strategy for the investigation and preparation of initial data for biogeocoenosis mapping with digital terrain models. Abstract of PhD thesis. Moscow State University of Geodesy and Cartography (in Russian).

Kuryakova, G.A., **Florinsky, I.V.** and **Shary, P.A.** 1992: On the correlation between soil moisture and certain topographic variables. In *The modern problems of soil geography and mapping: proceedings of the all-union conference, Moscow, 24–26 Sept., 1991*, Moscow: Dokuchaev Soil Institute, 70–71 (in Russian).

Lanyon, L.E. and **Hall, G.F.** 1983: Land surface morphology. 2. Predicting potential landscape instability in eastern Ohio. *Soil Science* 136, 382–86.

Lee, J., **Snyder, P.K.** and **Fisher, P.F.** 1992: Modeling the effect of data errors on feature extraction from digital elevation models. *Photogrammetric Engineering and Remote Sensing* 58, 1461–67.

Lee, K.-S., **Lee, G.B.** and **Tyler, E.J.** 1988: Thematic Mapper and digital elevation modelling of soil characteristics in hilly terrain. *Soil Science Society of America Journal* 52, 1104–107.

Leprieur, C.E., **Durand, J.M.** and **Peyron, J.L.** 1988: Influence of topography on forest reflectance using Landsat Thematic Mapper and digital terrain data. *Photogrammetric Engineering and Remote Sensing* 54, 491–96.

Li, Z. 1994: A comparative study of the accuracy of digital terrain models (DTMs) based on various data models. *ISPRS Journal of Photogrammetry and Remote Sensing* 49, 2–11.

Lobanov, A.N. and **Zhurkin, I.G.** 1980: *Automation of Photogrammetric Processes*. Moscow: Nedra (in Russian).

Macarovic, B. 1972: Information transfer in reconstruction of data from sampled points. *Photogrammetria* 28, 111–30.

Mandelbrot, B. 1967: How long is the coast of Britain? Statistical self-similarity and fractional dimension. *Science* 156, 636–38.

Mark, D.M. 1979: Phenomenon-based data-structuring and digital terrain modelling. *Geoprocessing* 1, 27–36.

Martz, L.W. and **De Jong, E.** 1988: CATCH: a Fortran program for measuring catchment area from digital elevation models. *Computers and Geosciences* 14, 627–40.

—— 1990: Natural radionuclides in the soils in a small agricultural basin in the Canadian Prairies and their associations with topography, properties and erosion. *Catena* 17, 85–96.

McMahon, M.J. and **North, C.P.** 1993: Three-dimensional integration of remotely sensed geological data: a methodology for petroleum exploration. *Photogrammetric Engineering and Remote Sensing* 59, 1251–56.

Menz, G. 1988: Deduction of human-bioclimatological maps by means of remote sensing data and a digital terrain model using a correlation approach. *Geologiches Jahrbuch* A 104, 383–91.

Meshcheryakov, Yu.A. 1965: *Structural geomorphology of plain lands*. Moscow: Nauka (in Russian).

Miklos, L., **Matecny, I.** and **Kozova, M.** 1991: Interpretation of the morphometric relief indices for spatial differentiation of microclimatic conditions. *Ekologia* 10, 223–46.

Miller, C.L. and **Leflamme, R.A.** 1958: The digital terrain model – theory and application. *Photogrammetric Engineering* 24, 433–42.

Modrinsky, N.I. 1972: *Geodesy* (3rd edn). Leningrad: Gidrometeoizdat (in Russian).

Moore, I.D., **Gessler, P.E.**, **Nielsen, G.A.** and **Peterson, G.A.** 1993: Soil attribute prediction using terrain analysis. *Soil Science Society of America Journal* 57, 443–52.

Moore, I.D., **Grayson, R.B.** and **Ladson, A.R.** 1991: Digital terrain modelling: a review of hydrological, geomorphological and biological applications. *Hydrological Processes* 5, 3–30.

Naraghi, M., Stromberg, W. and **Daily, M.** 1983: Geometric registration of radar imagery using digital elevation models. *Photogrammetric Engineering and Remote Sensing* 49, 195–99.

NOAA 1988: *Data announcement 88-MGG-02. Digital relief of the surface of the earth*. Boulder, CO: NOAA, National Geophysical Data Center.

O'Callaghan, J.F. and **Mark, D.M.** 1984: The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics, and Image Processing* 28, 323–44.

Ollier, C. 1981: *Tectonics and landforms*. London: Longman.

Peddle, D.R. and **Franklin, S.E.** 1991: Image texture processing and data integration for surface pattern discrimination. *Photogrammetric Engineering and Remote Sensing* 57, 413–20.

Peucker, T.K. and **Douglas, D.H.** 1975: Detection of surface-specific points by local parallel processing of discrete terrain elevation data. *Computer Graphics and Image Processing* 4, 357–87.

Polidori, L., Chorowicz, J. and **Guillande, R.** 1991: Description of terrain as a fractal surface, and application to digital elevation model quality assessment. *Photogrammetric Engineering and Remote Sensing* 57, 1329–32.

Pozdnyakov, A.V. and **Chervanyev, I.G.** 1990: *Self-organization in landform development*. Moscow: Nauka (in Russian).

Pratt, W.K. 1978: *Digital image processing*. New York: Wiley.

Quinn, P.F. and **Beven, K.J.** 1993: Spatial and temporal prediction of soil moisture dynamics, runoff, variable source areas and evapotranspiration for Plynlimon, mid-Wales. *Hydrological Processes* 7, 425–48.

Quinn, P.F., Beven, K.J., Chevallier, P. and **Planchon, O.** 1991: The prediction of hillslope flowpaths for distributed modelling using digital terrain models. *Hydrological Processes* 5, 59–80.

Raupach, M.R. and **Finnigan, J.J.** 1997: The influence of topography on meteorological variables and surface–atmosphere interactions. *Journal of Hydrology* 190, 182–213.

Richards, J.A., Landgrebe, D.A. and **Swain, P.H.** 1982: A mean for utilizing ancillary information in multispectral classification. *Remote Sensing of Environment* 12, 463–77.

Rieger, W. 1996: Accuracy of slope information derived from DEM-data. In Kraus, K. and Waldhäeusl, P., editors, *International archives of photogrammetry and remote sensing* (Vol. 31, Part B4, Commission IV), Vienna: Austrian Society of Surveying and Geoinformation, 690–95.

Rochon, G. 1981: Geologic application of Landsat imagery enhanced by topographic data. In *Machine processing of remotely sensed data with special emphasis on range, forest, and wetlands assessment: proceedings of the 7th international symposium, June 23–26, 1981*, West Lafayette, IN: Purdue University, 124–31.

Royle, A.G., Clausen, F.L. and **Frederiksen, P.** 1981: Practical universal kriging and automated contouring. *Geoprocessing* 1, 377–94.

Saleh, R.A., editor, 1996: Special issue on softcopy photogrammetry. *Photogrammetric Engineering and Remote Sensing* 62, 675–736.

Sasowsky, K.C., Petersen, G.W. and **Evans, B.M.** 1992: Accuracy of SPOT digital elevation model and derivatives: utility for Alaska's North Slope. *Photogrammetric Engineering and Remote Sensing* 58, 815–24.

Schowengerdt, R.A. and **Glass, C.E.** 1983: Digitally processed topographic data for regional tectonic evaluations. *Geological Society of America Bulletin* 94, 549–56.

Schut, G.H. 1976: Review of interpolation methods for digital terrain models. *The Canadian Surveyor* 30, 389–412.

Seidel, K., Ade, F. and **Lichtenegger, J.** 1983: Augmenting Landsat MSS data with topographic information for enhanced registration and classification. *IEEE Transactions on Geoscience and Remote Sensing* GE-21, 252–58.

Sharif, M. and **Salim, M.J.** 1996: DEM optimization using satellite images. In Kraus, K. and Waldhäeusl, P., editors, *International archives of photogrammetry and remote sensing* (Vol. 31, Part B4, Commission IV), Vienna: Austrian Society of Surveying and Geoinformation, 774–79.

Shary, P.A. 1991: The second derivative topographic method. In Stepanov, I.N., editor, *The geometry of earth surface structures*, Pushchino: Pushchino Research Centre Press, 30–60 (in Russian).

—— 1995: Land surface in gravity points classification by complete system of curvatures. *Mathematical Geology* 27, 373–90.

Shary, P.A., Kuryakova, G.A. and **Florinsky, I.V.** 1991: On the international experience of topographic methods employment in landscape investigations (the concise review). In Stepanov, I.N., editor, *The geometry of earth surface structures*, Pushchino: Pushchino Research Centre Press, 15–29 (in Russian).

Shasby, M. and **Carneggie, D.** 1986: Vegetation and terrain mapping in Alaska using Landsat MSS and digital terrain data. *Photogrammetric Engineering and Remote Sensing* 52, 779–86.

Shikada, M., Muramatu, N., Kusaka, T. and **Goto, S.** 1996: Application of GIS and remote sensing to extraction of landslide areas. In Kraus, K. and Waldhäeusl, P., editors, *International archives of photogrammetry and remote sensing* (Vol. 31, Part B4, Commission IV), Vienna: Austrian Society of Surveying and Geoinformation, 786–91.

Sinai, G., Zaslavsky, D. and **Golany, P.** 1981: The effect of soil surface curvature on moisture and yield – Beer Sheba observations. *Soil Science* 132, 367–75.

Skidmore, A.K. 1989a: A comparison of techniques for calculation of gradient and aspect from a gridded digital elevation model. *International Journal of Geographical Information Systems* 3, 323–34.

—— 1989b: An expert system classifies eucalypt forest types using Thematic Mapper data and a digital terrain model. *Photogrammetric Engineering and Remote Sensing* 55, 1449–64.

—— 1990: Terrain position as mapped from a gridded digital elevation model. *International Journal of Geographical Information Systems* 4, 33–49.

Smith, J.A., Lin, T.L. and **Ranson, K.J.** 1980: The Lambertian assumption and Landsat data. *Photogrammetric Engineering and Remote Sensing* 46, 1183–89.

Smith, T.R., Zhan, C. and **Gao, P.** 1990: A knowledge-based, two-step procedure for extracting channel networks from noisy DEM data. *Computers and Geosciences* 16, 777–86.

Speight, J.G. 1968: Parametric description of landform. In Stewart, G.A., editor, *Land evaluation*, Melbourne: Macmillan, 239–50.

—— 1974: A parametric approach to landform regions. *Special Publication of the Institute of British Geographers* 7, 213–30.

Spreeuwers, L and **Houkes, Z.** 1996: The construction of DEMs using aerial video image sequences. In Kraus, K. and Waldhäeusl, P., editors, *International archives of photogrammetry and remote sensing* (Vol. 31, Part B4, Commission IV), Vienna: Austrian Society of Surveying and Geoinformation, 819–22.

Stow, D.A. and **Estes, J.E.** 1981: Landsat and digital terrain data for county-level resource management. *Photogrammetric Engineering and Remote Sensing* 47, 215–22.

Strahler, A.H. 1981: Stratification of natural vegetation for forest and rangeland inventory using Landsat digital imagery and collateral data. *International Journal of Remote Sensing* 2, 15–41.

Suetova, I.A. and **Chistov, S.V.** 1993: Study of ice dynamics in the Antarctic by computer modelling. *Geodesiya i Cartographiya* 3, 45–50 (in Russian).

Tempfli, K. 1980: Spectral analysis of terrain relief for the accuracy estimation of digital terrain models. *ITC Journal* 3, 478–510.

Tjuflin, Yu.S. 1995: Terrain videophotomodel construction using digital photometric information from space photos. *Geodesiya i Cartographiya* 4, 32–38 (in Russian).

—— 1996: Co-ordinate conversions in photogrammetric works with digital elevation models. *Geodesiya i Cartographiya* 2, 21–25 (in Russian).

Tom, C.H. and **Miller, L.D.** 1980: Forest site index mapping and modeling. *Photogrammetric Engineering and Remote Sensing* 46, 1585–96.

Walsh, S.J. 1980: Coniferous tree species mapping using Landsat data. *Remote Sensing of Environment* 9, 11–26.

—— 1987: Variability of Landsat MSS spectral responses of forest in relation to stand and site characteristics. *International Journal of Remote Sensing* 8, 1289–99.

Wischmeier, W.H. and **Smith, D.D.** 1978: *Predicting rainfall erosion losses – a guide to conservation planning. Agriculture Handbook 537.* Washington, DC: US Department of Agriculture.

Woodham, R.J. 1980: Using digital terrain data to model image formation in remote sensing. *Proceedings of the Society of Photo-Optical Instrumentation Engineers* 238, 361–69.

Woodham, R.J. and **Gray, M.H.** 1987: An analytic method for radiometric correction of satellite multispectral scanner data. *IEEE Transactions on Geoscience and Remote Sensing* GE-25, 258–71.

Wu, S.-T. 1987: Integration of topographic data with synthetic aperture radar data for determining forest properties in mountainous terrain. In *IGARSS'87. Remote sensing: understanding the earth as a system: proceedings of the IEEE international geoscience and remote sensing symposium, Ann Arbor, 18–21 May, 1987. Vol. 2*, New York: IEEE, 1499–503.

Yang, C. and **Vidal, A.** 1990: Combination of digital elevation models with SPOT-1 HRV multispectral imagery for reflectance factor mapping. *Remote Sensing of Environment* 32, 35–45.

Yaroshenko, P.D. 1961: *Geobotany. The main concepts and methods*. Moscow: Soviet Academic Press (in Russian).

Young, A. 1972: *Slopes*. Edinburgh: Oliver & Boyd.

Zakharov, S.A. 1940: Importance of slope aspect and gradient for soil and vegetation distribution in the Great Caucasus. *Journal Botanique de l'URSS* 4/5, 378–405 (in Russian).

Zebker, H., Werner, C., Rosen, P. and **Hensley, S.** 1994: Accuracy of topographic maps derived from ERS-1 interferometric radar. *IEEE Transactions on Geoscience and Remote Sensing* 32, 823–36.

Zevenbergen, L.W. and **Thorne, C.R.** 1987: Quantitative analysis of land surface topography. *Earth Surface Processes and Landforms* 12, 47–56.