3 Keynote Paper

Representing Surfaces in the Natural Environment: Implications for Research and Geographical Education

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CONTENTS

OVERVIEW

Representing surfaces is fundamental to research concerning the natural environment. The state of the art as addressed in current textbook literature is discussed. This is followed by an historical account that describes the development of the three primary ways of representing surfaces, namely, as triangulated irregular networks, as digital elevation models, and as interpolated, contoured surfaces. New representations of surfaces as global spheres are described along with their role in the teaching of grade-school geography. Current research from the neurosciences on the ways in which individuals encode spatial data are recounted for the first time in the geographical literature and the implications of this research for learning to think spatially are discussed. The chapter concludes with an exploration of the future of surface representations.

3.1 INTRODUCTION

The natural environment may be characterized in various ways. Researchers need to represent the surface of the earth, the environment that exists above it, and the vegetation and wildlife that populate the environment. This chapter addresses how researchers represent the surface of the earth and why this is important for studying and learning geography.

Surface representation, in its most basic form the elevation of the land, an ice surface or indeed some abstracted climate variable, is fundamental to much subsequent research. For example, by knowing the height of points on the earth's surface the researcher can determine critical points; assess the complexity of the landscape; build surface representations; infer aspect, slope, vegetation, microclimate; and, if they are a habitat modeler, they can determine prey and predator distributions and build their habitat models to gain an understanding of landscape processes [1] (see Chapter 7, this volume). It is a chain of logic that has a certain elegance.

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The second half of the chapter will consider how surface representations can enhance the learning of geography. A short section on how human and physical geographic approaches to surface representation have cross-fertilized will precede the final section, which anticipates the future. Throughout the chapter it will be important to realize how closely representation is linked to visualization and how both representation and visualization inform those approaches used in modeling the natural environment. Occasionally, discussions in the literature have made these links explicit (see the remarks by Mitas and Mitasova [2] on the role of interpolation in modeling). Even the words digital elevation model (DEM) and digital terrain model (DTM) conflate a surface representation procedure with a model, and by implication with a method for visualization. Weibul and Heller [3] argue that the modeling process includes surface representation (generation and manipulation), visualization, and application (analysis). Yuan et al. [4] suggest that representation may occur at three levels—data models, formalization and, visualization—and so again the concepts of representation, modeling, and visualization within a GIS are hopelessly entangled between common English usage and language that has been adopted by computer and mathematical scientists.

3.2 REPRESENTING THE SURFACE OF THE EARTH

3.2.1 The Existing Literature: A Brief and Critical Review

Characterization of the earth's surface has been researched extensively. Pity the poor student of digital terrain models, for the literature has exploded in recent years. Five volumes are of note [5–9]. Li et al. [7] opine that, finally, the more than decade-long absence of a textbook on terrain modeling following the publication of Petrie and Kennie's text [10] has been comprehensively resolved. Unfortunately, their observation on the lack of literature in the years following 1996 ignores the publication of the first edition of David Maune's *DEM Users Manual* [11], a benchmark reference work that is widely used in the industry, and Wilson and Gallant's [12] volume on *Terrain Analysis*.

The relative contemporaneity of the more recent texts has meant that they do not reference one another and so our putative student of terrain modeling, on reading one of these tomes, may remain unaware of the others. El-Sheimy et al. [6] aggravate this problem of inadequate referencing by citing texts that have been superseded by new editions published fifteen or more years later. Relying on references to Davis' first edition [13] for models that summarize the features of a surface or, similarly, Clark [14] for kriging explanations to characterize and represent the covariance structure of a DEM is unfortunate. Davis has provided a greatly expanded third edition of his classic text [15] and Clark similarly has published a comprehensively lengthened version of her seminal work along with extensive online resources, software, and data sets [16,17].

Maune [9] offers the most exhaustive review of the literature on representing the surface of the earth through the use of DEMs. The second edition of his widely cited resource opens with an introduction to 3-D surface representations. Confusion over terminology among DEMs, DTMs, and DSMs (digital surface models) is resolved, although it is noted that in many countries these terms are used interchangeably and this is largely the approach that Maune himself adopts and is essentially the attitude employed by Weibul and Heller [3] in their review. This acronym soup is further complicated by the use of the acronym DTED (digital terrain elevation data) by the U.S. National Geospatial-Intelligence Agency (NGA). The NGA uses the DTED acronym for the data collected in 2000 by the Shuttle Radar Topography Mission (SRTM), which obtained the most complete, relatively high resolution (90 m) and near global coverage of the earth's elevation data to date [18].

3.2.2 REPRESENTING SURFACES: THE THREE PRIMARY OPTIONS

Three surface representation methods will be considered in detail here: the triangulated irregular network, the DEM, and isolines. However, it must be noted that there are other possibilities, including the use of voxels for fully three-dimensional graphics, and also representations by LiDAR (light detection and ranging) point clouds. Voxel-based approaches are of particular interest to geologists, atmospheric scientists, and oceanographers, but the awareness of voxels extends beyond research on the physical environment. Medical scientists, among others, use these representations extensively. Software packages that are designed to represent volumetric data, such as ScienceGL, are often marketed primarily for medical applications, though GIS applications are also prominent [19]. The management of extremely large LiDAR point clouds for surface representation is discussed by Cothren [20] and software for handling this type of surface representation is available (e.g., Ref. 21).

3.2.2.1 The Triangulated Irregular Network

Surface elevation may be represented in various ways but most commonly either as a grid, a triangulated irregular network (TIN), or as contours. The TIN method is credited to Peucker (now Poiker; see Peucker [22] and the discussion in Mark [23]). Mark [23] attributes the original idea for representing the surface as a set of triangles to Bengtsson and Nordbeck [24]. According to Mark, it was Peucker's contribution to develop this as a topologically integrated data structure. However, Bengtsson and Nordbeck did consider topology because, using hardware with the limited capacities of the time, they faced storage problems and had to "connect-up" isarithms stored separately [24: 103]. Thus the concepts of topology and connectivity were explicitly integrated into their software system. Surprisingly, Mark, in his historical review of the development of the TIN approach to surface representation, fails to mention Warntz's [25] conceptual breakthrough in deriving the critical points of a surface that came a few years earlier than Peucker's primary contributions. Even more interesting is the fact that Warntz extended this conceptualization to a "surface" that lacked any physical representation but had applications in economic geography and physical geography (specifically climatology) [26].

The merits of the TIN versus the grid-based approaches have been examined by Mark [27] and by Kumler [28]. Wang and Lo [29] have reviewed the earlier work and have conducted their own experiments. They concluded, in conflict with Kumler, that TINs are superior in terms of the accuracy of their surface representation but these differentials decreased as the number of sample points increased. Wang and Lo's results were further qualified by their understandable admission that the results apply only to the software employed (Arc/Info 6.0) and might vary depending on which software and algorithms were used. For their experiments the algorithms involved were proprietary to ESRI [30] and therefore could not be described in detail.

More recently, Smith and Mark [31] have addressed the question of whether mountains exist at all, arguing that geographers, geographic information scientists, and the public at large use both object and field oriented views of the world in determining what is and what is not a mountain. The critical points approach would appear to favour an object oriented view of the world but as Warntz and Waters [26] demonstrated a surface could be represented either as a set of peaks (mountains) or pits (depressions) but the latter would scarcely capture the imagination. They are not the "quintessential geographic things" to which Smith and Mark [31: 423] so eloquently refer. Smith and Mark argue for a field-based ontology (see Chapter 4, this volume, for a discussion of ontologies from the perspective of the domain expert) and yet it is ironic that a true systems approach to geomorphology would indeed adopt an object-based approach, a "stocks and flows" representation as implemented in system dynamics models. The inability to accommodate these two approaches to representing the natural environment is perhaps why the system dynamics view of the world has never been fully and successfully spatialized (for a somewhat incomplete attempt, see "Appendix I—Spatial Dynamics" in Ford [32]). Development of a comprehensive ontology for geoscientific data is provided by Brodaric and Gahegan [33].

3.2.2.2 Digital Elevation Models

DEMs are gridded surfaces that reflect the limitations of the interpolation methods used to create them and the spatial distribution of sampling points. Such interpolation methods include inverse distance weighted (IDW) algorithms [15], natural neighbor interpolation (NNI) [34], kriging [16], and splines, among others.

Mitas and Mitasova [2], in an authoritative review of interpolation methods, categorize the various surface representation techniques as follows: the local neighborhood approach, where existing points influence the surface up to a given distance (e.g., IDW, NNI, and TIN-based algorithms to produce smooth surfaces for the flat faces of the triangles); the geostatistical approach (e.g., kriging in its various forms); and the variational approach that requires that the surface honor the data points and should, in addition, be as smooth as possible (splines epitomize this method).

Each technique may have certain features that make it particularly attractive. Thus, natural neighbors take advantage of any increased sampling in areas of high variability. Geostatistical approaches utilize the covariance structures of the data and allow for the examination of the strength and range of these properties, together with variations in sampling that are captured by the nugget effect, directional biases, and covariation with associated attributes (namely, cokriging). Algorithms available in commercial GIS software, such as the Geostatistical Analyst in ArcGIS, and in the Idrisi and Surfer software packages for variogram modeling tend to be complementary. As such, procedures and variogram estimation strategies available in one package may not be included in the others and vice versa. That kriging is being subjected to innovative new approaches for surface interpolation is amply demonstrated by Goovaerts [35] for area-to-point estimates.

Geostatistical approaches are also being used to represent uncertainty in the data. Gotts [36] provides a contemporary review of sequential Gaussian simulation, a technique that permits an assessment of how the uncertainty in the data varies spatially. A tutorial on this intriguing method of spatial exploratory data analysis is available from the γ Statios Web site [37], and downloadable public domain software at the γ gslib Web site [38]. Figure 3.1 from Gotts displays porosity values for one possible realization of the top surface of a single facies, mature, petroleum reservoir.

The United States Geological Survey's (USGS) recently established Center of Excellence in Geographic Information Science (CEGIS) has launched various research projects including one focused on the use of fractal and variogram analysis to determine the effects of scale and resolution on data integration for the National Map and National Spatial Data Infrastructure [39].

Mitas and Mitasova [2] note that many interpolation methods are application specific and that for any given application the interpolation process may be specially modified. Of particular interest are interpolation methods for data on the sphere where the interpolation functions are dependent on angle rather than distance. Representation of surfaces on the sphere is considered in Section 3.3.

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3.2.2.3 Interpolation to a Contour or Isoline

The automatic generation of isarithms or isolines was of concern to Bengtsson and Nordbeck [24] (see above), and remains a method of characterizing the surface that

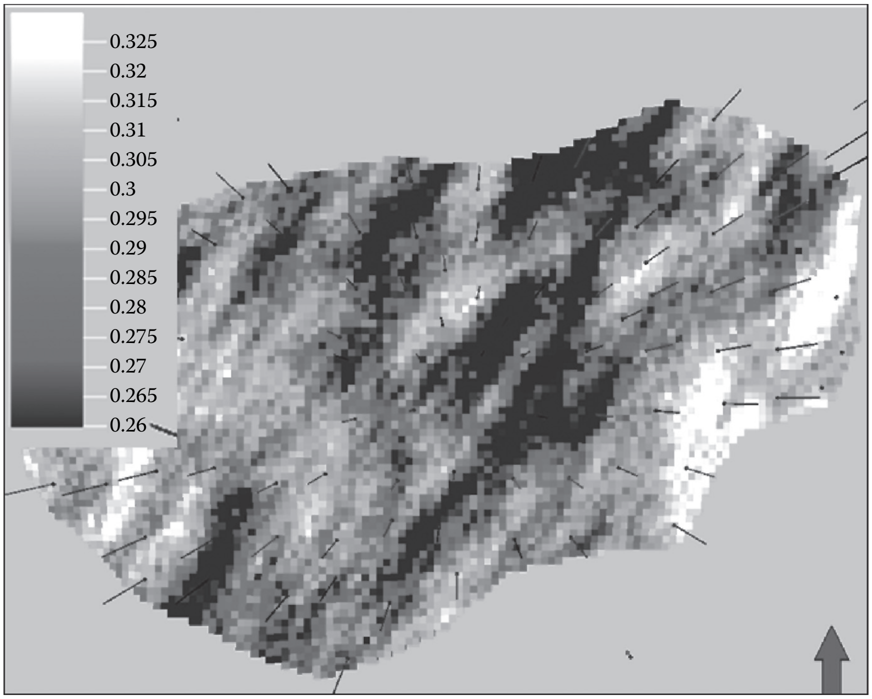

FIGURE 3.1 Percentage porosity values for a sequential Gaussian simulation in a single facies, Mature, Petroleum Reservoir (Source: Gotts [36]; used with permission.)

is dominated by local interpolation approaches [40]. The converse problem of producing a digital representation from a set of contours is of equal interest and has produced various solutions that again favor local interpolation [41].

Dahlberg [42] has compared computer-based contouring algorithms and hand-drawn solutions for the hydrocarbon exploration industry and has shown that the computer algorithms behave analogously to a conservative geologist, resisting the urge to play a hunch. Wren [43], by contrast, makes a plea for the objectivity of the computer algorithm. Mulugeta [44], apparently unaware of Wren's study, agrees with Dahlberg citing the improved appearance of hand-drawn maps that emphasize regional patterns while admitting that the computer-generated surfaces had an accuracy that "equals or surpasses that of manually drawn maps" [44: 339]. He concludes by advocating some combination of the manual editing process that is combined with an automated contouring algorithm. The potential for approaching the contouring problem through the use of expert systems has been addressed by Maslyn [45], Waters [46], and Dutton-Marion [47]. It is to be hoped that there will remain a role for expert interpretation of model-based output. Controversial new estimates of Antarctic ice mass loss [48], while touted as improvements that exploit new sensor technology for ice surface estimation not available when estimates were made in the past [49,50], might well benefit from expert intervention into the modeling process.

Carrara et al. [51] review the literature evaluating procedures for generating digital elevation data (DED) from contour lines and then conduct their own experiments on four data sets using five evaluation criteria: DED for spots close to the original contour lines should vary by less than 5%; DED falling between two contour lines should have values falling within this range; DED values should vary linearly between contour lines; DED in areas of low relief should reflect this morphology; and DED defining unrealistic morphological features (artifacts) should represent less than 0.2% of the data. In the future the authors suggest that new procedures for generating extremely high resolution DEMs will include the use of softcopy photogrammetric methods and this is indeed the approach used by Delparte [52] to produce a high resolution, 5 m DEM to represent the terrain in Rogers Pass, Glacier National Park, British Columbia, for the modeling of avalanche runout paths. Interestingly, this was produced using expert, manual identification of the critical points to improve the accuracy of the final result (see Mulugeta's conclusions [44], Molander [53], and more recently McGlone [54] for a discussion of the strengths and weaknesses of such automated methods). Nevertheless, and as Delparte notes, the future belongs to LiDAR but at present these data are not widely available and their acquisition for specific applications on an ad hoc basis is expensive [55]. Flood [56] argues for an integration of photogrammetry, including existing hardware and personnel skill sets and expertise, with LiDAR imaging in his article on lidargrammetry.

3.3 REPRESENTING SURFACES ON A SPHERE

3.3.1 Tobler's Call to Arms

Tobler [57] has commented with dismay on how most of the early GIS packages were designed merely to represent small parts of the earth's surface without representing the earth's curvature. Considering that a version of his paper was originally presented in 1992, his comments on representing GIS data on a sphere were prescient. Even more discerning was Lukatela's earlier development of the Hipparchus GIS [58] that remains the only GIS conceptualized from the outset so as to represent the surface of the earth as a sphere. Tobler boldly asserts that not only should the representation of the earth change but that we should develop a truly geographic analysis system that abandons the notion that the earth is flat. That researchers in other disciplines, such as operations research, have long had solutions for location problems on a sphere [59]—indeed their own geographic analysis systems—is somewhat embarrassing.

In an era of globalization, it is ironic that Friedman's [60] book, *The World Is Flat*, has become a best seller. Despite its popularity, the book has been widely criticized [61] and runs counter to current concerns over globalization and planetary processes such as global warming. These concerns, editorials such as Tobler's, and the development of new software and hardware technologies have produced innovative representations of the surface of the globe. The most obvious examples are Google Earth and Microsoft's Virtual Earth programs. New interest in these technologies and the world as a single entity has led to the development of the *Digital Earth* journal, published for the first time in January 2008 by Taylor & Francis and the International Society for Digital Earth [62]. Grossner et al. [63] have argued that a useful representation of a digital earth is one of the grand challenges for the GIS community to address in the immediate future.

3.3.2 Virtual Globe Representations in Scientific Research

Virtual globe sessions have been organized at leading scientific conferences such as the American Geophysical Union for some time [64] and a list of those conferences that occurred in 2006, 2007, and early 2008 is available [65]. Representing the surface of the spherical earth has proved extremely useful for climatologic studies and the American Meteorological Society organized a special session at its annual meeting in New Orleans in January 2008 [66]. One paper presented at this special session showed how radar beam propagation could be affected by terrain (beam occultation) and other variables (e.g., wind power generators) leading to flawed predictions of precipitation events [67]. Images representing these problems may be downloaded from the Wx Analyst Web site [68] (also see Figure 3.2).

The implementation of hardware solutions has resulted in the National Oceanic and Atmospheric Administration's (NOAA's) Science-on-a-Sphere educational program [69]. This sphere is essentially a room-sized globe that uses computers and video projectors to display planetary data to enhance the understanding of terrestrial processes. It remains to be seen whether representing the physical environment in this fashion has any additional pedagogic value. This topic is discussed next. Intuitively this would seem to be the case but studies similar to those conducted for various approaches to the teaching of GIS [70] should be implemented as soon as

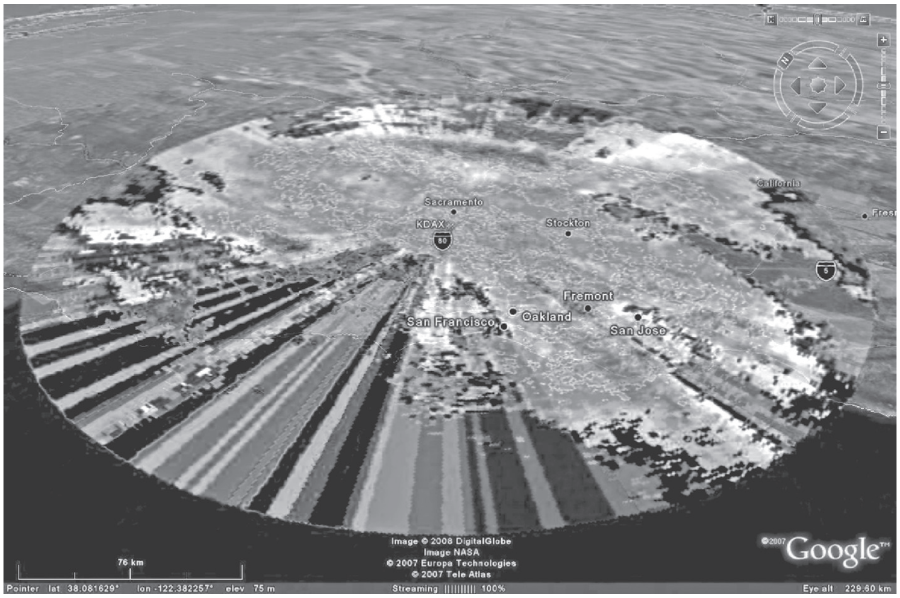

FIGURE 3.2 Three-dimensional occultation pattern overlaid with radar reflectivity on 4 January 2008. (Source: Shipley et al. [64]; used with permission.)

possible to determine if the investment in these kinds of technologies has an acceptable cost–benefit ratio.

3.3.3 DIGITAL EARTH IN THE SCHOOLS

Spatial representations such as Google Earth have been advocated for teaching geography in schools. Specifically, Patterson [71] has used Google Earth in seventh-grade classroom exercises. He suggests that the work of Solem and Gershmel [72] provides evidence that online resources increase students' comprehension of skills and concepts while also increasing their knowledge of geographic issues. Among Google Earth's advantages, Patterson cites first its entertainment value, a quality advocated by Greenspan [73]. Second he notes the ability to use this freeware at any location, including the child's home, as long as there is a computer with an Internet connection. Patterson lists the third advantage as the support of an online community that may be accessed at the Google Earth Community Web site [74] (see also the Google Earth Projects Web site [75]), a resource that includes KMZ files for illustrating aspects of the geography of the environment. Such assets allow the worldwide community of teachers to build resources in a collaborative manner. They can volunteer information at their community level that can then be shared globally. Volunteered geographic information is a new way to represent local knowledge [76]. There are numerous Web sites that provide online support for the neophyte using Google Earth. One of the more popular may be found at the Google Maps Mania Web site [77], a site that provides links to online tutorials to assist students in creating their own Google Earth content and representations. Finally, the ability to represent features, such as the Grand Canyon, from a variety of geographical perspectives can aid students' comprehension of the physical characteristics and processes that created these landforms.

According to Patterson [71], the main disadvantage of Google Earth and, presumably closely related technologies such as Microsoft's Virtual Earth and ESRI's ArcExplorer [78], is their inability to carry out basic GIS operations that permit spatial analysis. Perhaps they might be conceived as some form of "minimal GIS" that Marsh et al. [79] have recently advocated, although one suspects that those authors are unlikely to be satisfied by this technology regardless of its attraction for students. Patterson concludes his discussion of the usefulness of Google Earth to represent the world and to teach students about geography with a demand for scientifically designed studies to determine its effectiveness in the educational process. If the arguments of Lynch et al. [80] are to be believed, the development of an effective practice that integrates representations of the earth into a true e-learning environment is likely to be a complex process.

Traditional teaching of geography has relied on two-dimensional representations of the earth's surface. GeoWall attempts to move beyond this method of representing geographical features and surfaces by using stereo images that allow for the projection of three-dimensional representations [81]. Other new ways to represent the natural environment include computer-assisted virtual environments (CAVE). Although much of this research has been associated with the reconstruction of buildings, archaeological features, and urban areas, new work is extending these approaches into reconstructions of the physical environment [82].

3.4 LEARNING TO UNDERSTAND SPATIAL REPRESENTATIONS

3.4.1 PRINCIPLES OF SURFACE REPRESENTATION

Morse [83] provided two guiding principles for the comprehension and subsequent analysis of computer-generated data: proportional effect and least effort. Proportional effect, the first principle, requires that the size and identity, namely, the relevant attributes of the data, have to be encoded. Common approaches are to do this using position (e.g., location on a map; a pseudo representation of a third dimension such as height), length, size, angle, color, brightness, texture, time (in animation), or symbols. The various ways of portraying surfaces and spatial data are commonly covered in cartography texts [84], by graphic design specialists such as Tufte [85–87], or on Web sites such as that maintained by Cindy Brewer, a cartographic professor at Penn State University [88].

The second of Morse's [83] principles, that of least effort, requiring ease of perception and interpretation, includes optimal scaling (i.e., allowing meaningful distinctions without allowing unnecessary detail), display integration, and minimization of stimulus load (although too little stimulus may be as undesirable as too much). Finally, conceptual and task compatibility must also conform to the viewer's expectations and this may vary with the experience of the viewer.

The National Research Council's report "Learning to Think Spatially" states that "spatial representations are powerful tools that can enhance learning and thinking" [89: 281]. The report argues that this is achieved, first, because spatial representations are a powerful way to encode new information. Second, the report states that generating images of existing information allows for a greater degree of recall. Third, spatial representations are claimed to enhance problem solving in some but not all instances. Each of these claims will be considered in turn.

3.4.2 LEARNING AND ENCODING NEW DATA FROM SPATIAL REPRESENTATIONS

There is evidence to suggest that representing new data, both spatial and nonspatial, as a map is an effective way to encode the data [90,91] and GIS researchers have long asserted that spatial is special [92,93]. Current research into the brain suggests that it is even more special than the authors of the National Research Council report might have suspected. Research at the Medical Research Council (MRC) Centre for Synaptic Plasticity at the University of Bristol has focused on "how, where and why the brain modifies synaptic strength during normal function" [94]. This work includes research into place cells, neurons in the hippocampus that fire when the subject is in a particular location [95]. The neuroscience research completed to date is even more intriguing and, so far, largely ignored by geographers.

Muller [96] states that, in a seminal paper, O'Keefe and Dostrovsky [97] discovered place cells. The latter two researchers showed the importance of place cells by demonstrating that they will fire whenever a rat returns to a familiar location known as a place field. The fact that place cell activity appears goal oriented may have important implications for habitat modeling. Directional bias also occurs in linearly constrained environments. Existing research has largely been conducted in lab environments (involving animals such as rats and cats) and in virtual environments for humans [98]. It remains to be seen whether this research translates to natural environments, how it varies for wildlife (for example, do wildlife corridors generate the same directional biases and how does the acquisition of spatial information in the dark occur and differ among species), and how persistent are the spatial representations. For the habitat modeler, it is intriguing to note that there are several representations of the animal's environment: (a) the real world, (b) the representation in the internal hippocampus and other parts of the brain, and (c) the researcher's attempt to replicate what is important in the habitat and in such devices as resource selection functions. The extent to which these are one and the same is important but moot.

Besides place cells, neuroscientists have identified head direction cells [96] that fire when an animal (usually a rat) looks in a certain direction, spatial view cells for primates (monkeys) observing objects in an environment [99], and grid cells where the neuron firing patterns have a distinct topographical structure with strong spatial autocorrelation properties [100]. Again this research raises questions for spatial representations of the natural environment. First, to what extent does it translate to human observations of the environment? Second, what spatial representations are most suited to learning about the environment? Perhaps more specifically, is the best representation for learning a large wall that can be viewed in three dimensions (such as the GeoWall discussed earlier) a physical sphere or a three-dimensional virtual environment? It might be a good idea to perform the research before schools, universities, and museums invest large sums of money on one or another of these strategies.

Burgess et al. [98] reviewed neuroscience research into spatial memory, compared studies across species and within species, and introduced new research involving virtual reality representations of a town. They described and contrasted the egocentric and allocentric spatial frameworks. In the former, the framework moves with the observer and locations of objects are not fixed, but in the latter the locations of objects do not change as the observer moves through the environment. Memory tests associated with two-dimensional landscape scenes, for example, do not discriminate between the two frameworks, but a virtual reality environment allows for an allometric spatial framework to be examined. Indeed Arthur et al. [101: XX] concluded, following a set of experiments where subjects were asked to reproduce the spatial layout of a virtual environment, that "interaction with a virtual environment was indistinguishable from interaction with real objects at least within the constraints of the present procedure." Burgess et al. and Arthur et al. reported gender differences. Both reported superior performances from males in terms of the accuracy of spatial reconstructions, and Burgess et al. also discuss strategy differences between males and females, with males making use of geometric and landmark information to aid learning and recall, whereas females relied more exclusively on landmarks. Inexplicably these results are contradicted in the work of some geographers [102].

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3.4.3 Improving Recall through Spatial Representations

Returning to the discussion in the National Research Council Report "Learning to Think Spatially" [89], the authors of that report argue for the use of spatial representations as an aid to memory. The argument is that by teaching children to learn to think spatially, they will then be able to use spatial representations as an aid to memory. Others have argued in a similar vein [103], but it is likely that a spatial representation only aids the memory when it is a highly familiar environment and it is possibly little better than a mnemonic. Indeed it may work the other way around; a mnemonic may aid recall and retention of a spatial arrangement.

3.4.4 Spatial Representations and Problem Solving

When problem solving it is often, though not always, better to represent the problem spatially or so argues the report "Learning to Think Spatially" [89]. A virtual representation of a dangerous environment such as avalanche terrain (see Delparte [52], and Figure 3.3) can provide recreational, backcountry skiers with an understanding of the terrain that they are proposing to enter. This is even more effective if it is merged or mashed up in a Google Earth setting and combined with an effective warning system that is based on current weather conditions [52].

3.4.5 Cross-Fertilization between the Geography of the Human and Natural Environments

Human geographers and geoinformation scientists at large have considered many of the problems that have been addressed here. Thus the problem of occultation noted by Shipley et al. [67] with respect to wave beam propagation, has been analyzed by ReMartinez [104] when considering the reach of radio stations in the mountainous terrain of Peru (Figure 3.4). Such models were required to determine the influence of radio stations on the indigenous electorate and involved the integration of wave propagation models, DEMs, and socioeconomic data showing population distributions and languages spoken [105].

The rich literature in human geography on how place matters and such classic texts that describe the geography of the city in terms of landmarks and visual cues [106],

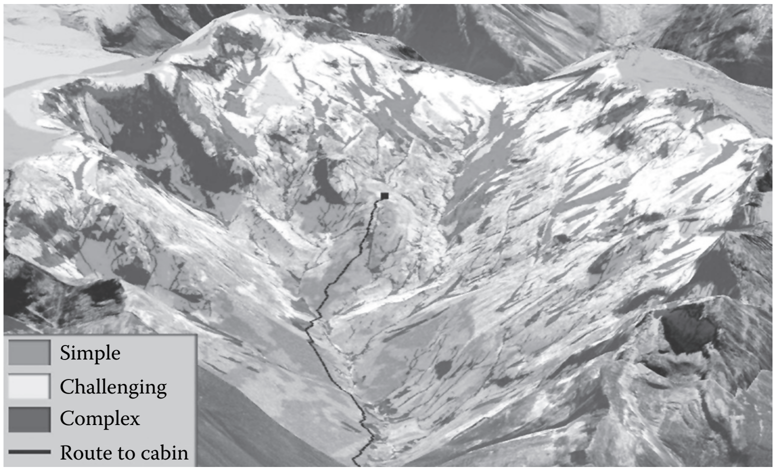

FIGURE 3.3 Avalanche exposure map. (Source: Delparte [52]; used with permission.)

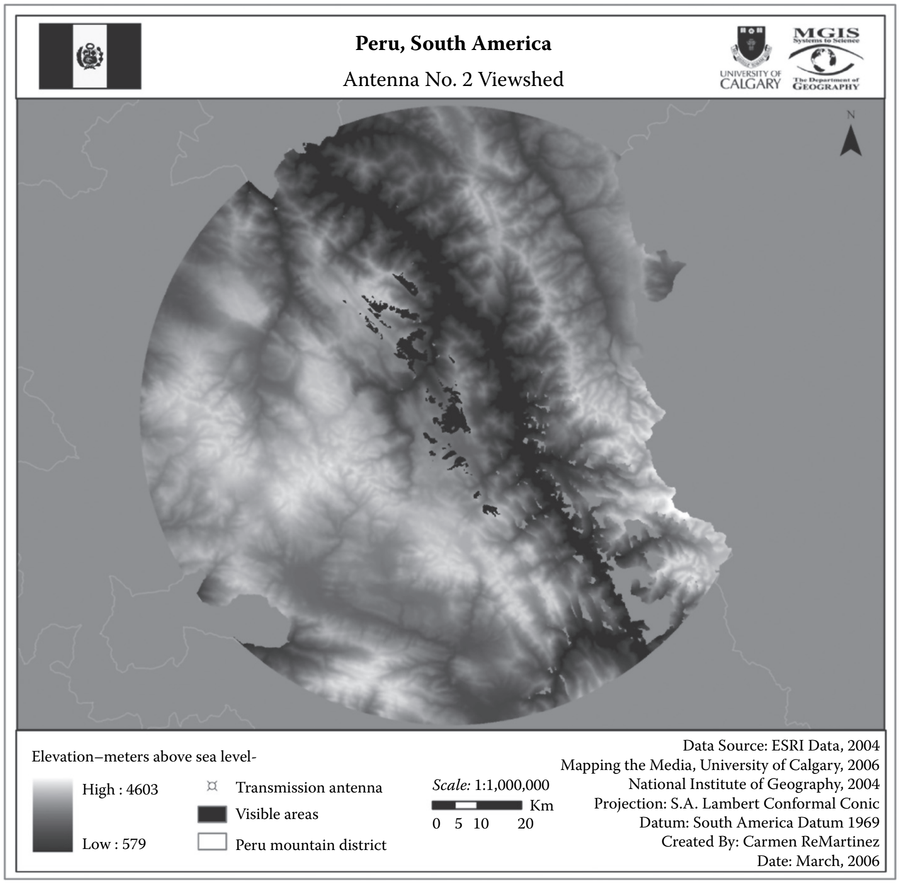

FIGURE 3.4 Represention of a Radio Antenna Viewshed in the Peruvian Andes. (Source: ReMartinez [104], used with permission).

validated by work in neuroscience (see Section 3.4.2), also authenticates and extends research that seeks to produce an understanding of the natural environment. Virtual environments do generate synaptic responses that assist in an understanding of the real world, endorsing the research of all those who seek to provide more interesting and accurate representations of natural environments.

GIS specialists have long been interested in human cognition of the spatial environment. Early summaries of this literature have been provided in both versions of the core curriculum for GIS developed at the National Center for Geographic Information and Analysis (in the original version by Suchi Gopal, “Spatial Cognition,” and in the revised version by Daniel Montello, “Human Cognition of the Spatial World” [107]). This is a large and growing literature in GIS but it has yet to be linked effectively with that in neuroscience discussed earlier. Perhaps the best hope for such an integration lies in the work of Barkowsky [108] and his MIRAGE model that seeks to reconstruct mental images of space based on topological properties, orientations, and shapes.

3.5 THE FUTURE OF SURFACE REPRESENTATIONS

Goodchild [93: 22] notes that in existing DEMs "time is ignored because elevation is assumed to be a static property." Many applications require that temporal changes in the natural environment be easily represented to aid visualization, analysis, and understanding. The theoretical basis of including time in GIS is now beginning to be understood [109] and temporal animations are now facilitated in new versions of commercial GIS software such as ArcGIS 9.3 [110]. ArcGIS 9.3 will include an image server making it still easier to incorporate new data and surface representations, but understanding how the data were produced and the implications of the error incorporated into every surface portrayal will remain paramount, and caveat emptor will still be critical for the user whether a teacher or researcher.

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The research agenda for the portrayal of geographic data in the future may be discerned in the updates to McMaster and Usery [111] (see, for example, Buckley et al. [112]); in the newly published *Handbook of Geographic Information Science* [113]; in state-of-the-art developments in cognate disciplines; in specialized software that can be integrated with GIS packages; and in the priorities set by such agencies as the National Geospatial-Intelligence Agency [114]. It is hoped that this chapter has covered the primary issues that have been and will be of concern in surface representation during the coming years.

ACKNOWLEDGMENTS

I would like to acknowledge Jeff Gotts, Scott Shipley, Donna Delparte, and Carmen ReMartinez for permission to reproduce figures from their unpublished work.

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