Integration of Remote Sensing with Geographic Information Systems: A Necessary Evolution

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ABSTRACT: Geographic information systems (GIS) have developed from the need to combine attribute information about land with its cartographic representation in order to perform spatial analyses. Remote sensing and image analysis technology have been used in parallel to obtain information about the Earth at resolutions as small as a few tens of centimetres to planetary scales. The integration of such capable data acquisition and analysis technologies is becoming increasingly important for resource management. Some of the many preliminary efforts to this end which have been made over the past few years, both in the commercial world and in research circles, are discussed. Several key impediments to this integration are identified. It is noted that, when presented in an evolutionary perspective, the solutions to these problems are more clearly defined. This leads to the formulation of a three-stage process of integration which combines the strengths of both technologies. These three stages are defined as "separate but equal," "seamless integration," and "total integration." The paper concludes with a discussion of areas where collaboration between remote sensing specialists and GIS specialists would be useful.

INTRODUCTION

REMOTE SENSING and its associated image analysis technology provides access to spatial information on a planetary scale. New detectors and imaging technologies are increasing the capability of remote sensing to acquire digital spatial information at very fine resolutions (on the order of a few metres from satellite platforms and a few tens of centimetres from airborne platforms) very efficiently. The management of such information is going to be one of the major challenges of the coming decades. Merely the storing of data from existing space platforms such as Landsat or SPOT already taxes the management capabilities of organizations which need these data (Table 1).

With the advent of space programs such as the Earth Observing System (EOS), this problem is going to become even greater. A variety of imaging (and non-imaging) sensors will be employed to cover the full range of the electromagnetic spectrum available for remote sensing of the Earth (Butler *et al.*, 1986). For example, a 30-m resolution imaging spectrometer will provide image data with a spectral coverage of 0.4 to 2.5 μm and a spectral resolution of 9.4 to 11.7 nm (Goetz *et al.*, 1987). This amounts to 196 simultaneously recorded spectral bands. In addition, other sensors will provide information in spectral bands such as the thermal infrared and microwave and/or at different spatial resolutions, yielding data volumes and spectral band combinations for which efficient storage and processing methods are yet to be developed (Ehlers, 1988).

TABLE 1. CURRENT HIGH RESOLUTION SATELLITE REMOTE SENSING MISSIONS SUITABLE FOR GIS APPLICATIONS

Platform/ Year	Sensor	#Spectral Bands	Spectral Range[1]	Ground Resolution	Pixelsize	Data Volume[2]	Country
Shuttle	SIR-B	1	Radar	17 – 58 m	12.5 m	64 Mb	U.S.
1983-	MOMS	2	VIS/NIR	20 m	20 m	50 Mb	W.-GERM.
Landsat-4/-5	MSS	4	VIS/NIR	80 m	56 m	13 Mb	
1982/84 -	TM	7	VIS/NIR/ MIR/TIR	30 m (TIR: 120m)	28.5 m	86 Mb	U.S.
SPOT	HRV-P	1	Pan(VIS)	10 m	10 m	100 Mb	FRANCE
1986-	HRV-XS	3	VIS/NIR	20 m	20 m	75 Mb	
MOS 1987-	MESSR	4	VIS/NIR	50 m	50 m	16 Mb	JAPAN
IRS-1A 1988-	LISS	4	VIS/NIR	36.5 m	36.5 m	30 Mb	INDIA

[1] VIS = Visible
NIR = Near Infrared
MIR = Middle Infrared
TIR = Thermal Infrared
Pan = Panchromatic

[2] Standardized to 8 bits/pixel and a ground coverage of 100 × 100 km

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The means for overcoming these problems exist in the form of geographic information system (GIS) technology (e.g., Estes, 1985; Ehlers, 1989). However, the technology must be adapted, modified, and extended if it is to serve the needs of managing this kind of information. In this paper, the questions involved in integrating existing geographic information systems with remotely sensed data and with image analysis are addressed. Such integration is viewed as an evolutionary extension of the capabilities of existing geographic information systems technologies. A few comments concerning the development of existing systems are first presented. This is followed by a discussion of the current status quo with respect to incorporating image analysis in GIS. Two aspects of the status quo are examined in some detail: commercial GIS on the one hand and the experimental R&D efforts in collaborative projects between universities, government, and private industry on the other. This is followed by a presentation of our view of the needs for better long-term integration and suggestions about how such integration might be achieved.

THE STATUS QUO

BACKGROUND

Geographic information systems arose out of efforts by land managers to formalize the ways in which data about properties (e.g., ownership, zoning, natural resources) were combined with spatial information (e.g., location, property size, polygon geometry). Initially, such integration was handled solely by manual methods within an organization framework, and indeed many Land Information Systems (LIS) in operation today are still organized along such lines. Efforts to automate and computerize the collating of such information, however, led to the rise of new technologies for handling and manipulating spatial information. In particular, commercial and/or in-house databases were coupled with vector-based cartographic processing, and spatial analysis capabilities were added. The combined product was called a geographic information system (GIS). For a more detailed discussion of the history and background of GIS technology see, for example, Berry (1987) or Tomlinson (1987).

This technology evolved from separate software packages (database management systems, or DBMS, and digital cartographic processing tools), sometimes running on different machines (Figure 1a), through separate software modules sharing the same user interface (Figure 1b), to a single software unit in which cartographic (vector) processing is linked directly with DBMS (Figure 1c) (Bédard, 1986). In recent years, awareness of the need to exploit remotely sensed data, and the potential that GIS offer for managing and analyzing such data, has been growing. As a result, many commercial GIS products have been adapted to offer image display capabilities and the rudiments of more extensive image analysis. This is in keeping with the evolutionary approach to developing new technology which is a characteristic of the business world. Research in academia and government agencies, on the other hand, has been oriented towards tackling problems of a highly specific nature.

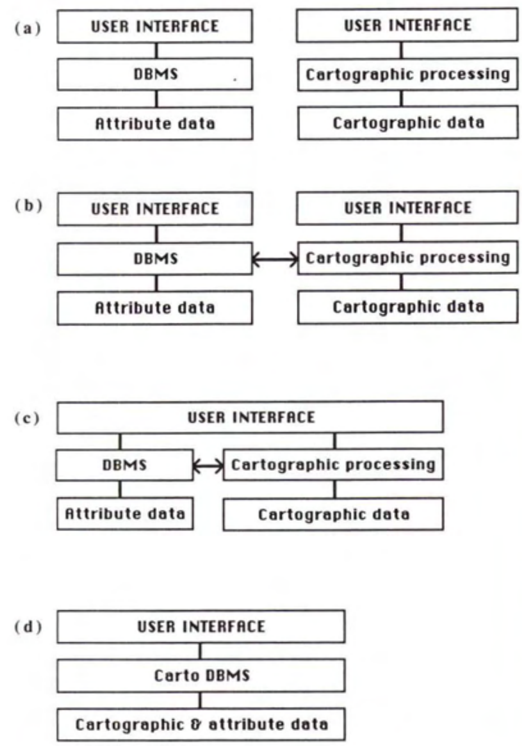

FIG. 1. (a) Stage one in the evolution of GIS: Two separate software packages running in tandem (1970s). (b) Stage two in the evolution of GIS: Two software packages running in tandem, linked interactively (more advanced) or by import/export modules (less advanced) (1980s). (c) Stage three in the evolution of GIS: Two software modules with a common user interface. The status quo in many of today's spatial information systems. (d) Stage four in the evolution of GIS: One software unit with combined processing. The state of the art in today's geographic information systems. Some systems may also have a link with an external DBMS.

COMMERCIAL SYSTEMS

Commercial GIS technology has been extended to allow, for example, simultaneous display of raster images and vectorial cartographic elements (points, lines, polygons) and to provide data exchange formats with image processing systems. The commercial availability of such basic functionality at acceptable cost has led to a great deal of experimental integration on the part of diverse groups, albeit at a relatively basic level (e.g., the exchange of thematic maps between image analysis systems and GISs). This has been beneficial, because many tasks which are quite difficult to do in an image processing system are relatively easy in a GIS and vice versa. For example, geometric or overlay operations are easier to perform in the raster domain whereas network analysis or topologic operations are more suited to the vector domain. Consequently, advantages for both data structures have been discovered and explored, leading inevitably to increased functionality for the user (Welch and Ehlers, 1988a).

Commercial systems which have incorporated some additional evolutive features (e.g., raster-to-vector and vector-to-raster conversions) and limited image processing (e.g., acquiring image statistics within vector polygons) are bringing new capabilities to production units. However, commercial systems which are designed around limited forms of such basic functionality may tend to become hampered by a lack of flexibility when dealing with higher levels of integration. For example, research in image analysis and remote sensing tends to push the capabilities of GIS with regard to modeling and/or simulation to their limits very quickly (see, for example, Aranoff *et al.*, 1987). At some stage, the entire software design must be rethought (Jackson and Mason, 1986). Some companies have adopted such an integrative approach, and the results look promising (e.g., Herring, 1987).

A popular approach to basic functionality has been for companies which specialize in GIS software to collaborate with companies which specialize in image processing systems on data exchange formats, at the lowest level, or on some form of tandem processing (raster on one side, vector on the other) at a higher level (see Figure 2a and 2b). A similar approach is often found in companies which handle both image and cartographic data, but which have always done so as separate products. The providing of a common user interface is often done with no fundamental change in either software package. The use of data exchange formats, while functional, is cumbersome. Tandem processing, from the point of view of researchers in remote sensing, is more useful, but many of the operations which one would like to perform are still difficult (e.g., integrated spatial modeling combining vector and pixel information).

Furthermore, one of the basic limitations of many commercial systems is that they lack the kind of extensibility through programming tools which are presently available, for example, with DBMS systems using fourth-generation languages. Some systems provide rudimentary programming tools, but geographic information systems are often so complex structurally that programming additions is extremely difficult and time consuming for most users to make the attempt. The kind of flexibility offered by fourth-generation languages or non-procedural languages in DBMS is highly desirable to manipulate spatial entities and should be a goal of GIS developers over the next few years.

Task-Oriented Integration

Aside from such basic functionality and its extensions into tandem processing, a combination of research in private industry, government, and academia has led to high levels of integration for certain specific problems, for the most part related to extracting cartographic features from imagery. This progress has been facilitated by a number of recent developments including (1) software and hardware advances in GISs (Dangermond, 1988; Frank, 1988; Croswell and Clark, 1988); (2) the availability of high resolution satellite data in digital format such as SPOT's High Resolution Visible (HRV) and Landsat's Thematic Mapper (TM); and (3) new developments in automated information extraction, especially the application of image matching techniques for Digital Elevation Model (DEM) generation (Swann *et al.*, 1988).

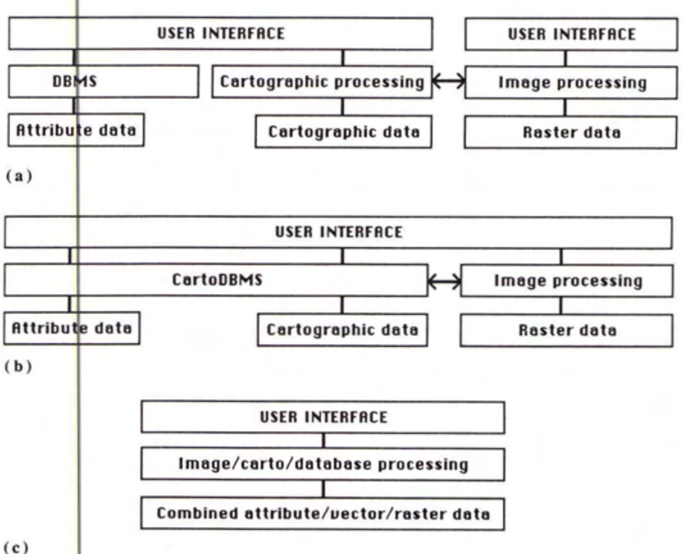

FIG. 2. (a) Stage one in the integration of image analysis with existing GIS technology: Two software modules with only data exchange formats linking them. (b) Another possible stage in the integration of image analysis with existing GIS technology: Two software modules with a common user interface and simultaneous display. (c) Stage three in the integration of image processing with GIS technology: One software unit with combined processing. This constitutes full integration, and is the long-term goal.

Satellite image data especially from Landsat TM and SPOT HRV have been shown to be suitable for base map production and map revision tasks at scales which were previously considered impossible for remote sensing applications (Rose *et al.*, 1986; Dowman, 1987; Welch and Ehlers, 1988b). This promises greater reliability for map information, i.e., lower "meta-uncertainty" (uncertainty about uncertainty) (Bédard, 1987), contained within GISs because errors are known and tracked throughout the map generation process where traditionally digitized maps contain "errors" which are often "hidden" or simply unknown.

Another application of integration which is being explored is terrain visualization. Satellite imaging, combined with a DEM, can be used to produce realistic perspective views of the ground for planning and environmental impact analysis (Gugan, 1988). By using video recording techniques, it is feasible to simulate passage through the terrain by foot, vehicle, or aircraft (Muller *et al.*, 1988).

DEM generation is one of the most successful areas of integration. Ehlers and Welch (1987) in one of the first stereocorrelation experiments undertaken with real satellite data, achieved a root-mean-square error (RMSE) in Z of ± 42 metres with sidelapping Landsat TM images. At the very weak base-to-height (B/H) ratio of 0.18, this Z error is equivalent to a planimetric correlation error of ± 0.3 pixels, confirming that correlations to better than ± 0.5 pixels are feasible with real data. Similar results in correlation accuracy have been recorded for SPOT stereo data (Simard *et al.*, 1988; Vincent *et al.*, 1987). With more favorable base-to-height ratios and the 10-metre pixels for SPOT, RMSE(Z) values range from ± 6 metres to ± 18 metres. These accuracies allow the generation of DEMs and ortho-images at scales of 1:50,000, from which further topographic information for GIS applications can be derived.

An application in which considerable integration gains have been achieved is that of change detection. Remote sensing offers greatly enhanced capability to GIS in updating map information on a regular basis. For example, Ehlers *et al.* (1989) demonstrated that SPOT data could be used in a GIS environment for regional growth analysis and local planning at a scale of 1:24,000. It was shown that SPOT image data yield accuracies for growth detection as high as 93 percent. Once incorporated into a GIS, the spatial growth pattern can be readily analyzed (Jadkowski and Ehlers, 1989). Change detection in forestry by means of integration of cartographic and remote sensing data has been demonstrated by Goldberg *et al.* (1985) and Goodenough *et al.* (1987) using a knowledge-based approach.

Some gains have been achieved in using GIS vector information as an aid to image segmentation (Ait Belaid, 1989; Ait Belaid *et al.*, 1989; Edwards and Beaulieu, 1989). Ait Belaid experimented with integration of cartographic data with multispectral image data (SPOT MSS) as a guide to segmentation over an agricultural site containing very small plots of land. He was highly successful, achieving classification accuracies and surface area accuracies on the order of 90 percent. Edwards and Beaulieu (1989) combined segmentation results from filtered and unfiltered airborne radar data in a GIS, using overlay techniques. In this preliminary study, they successfully located clear cuts in a forest scene on an automated basis.

Finally, the last few years have seen increased concern for modeling in GIS (Itami, 1988; Burrough *et al.*, 1988). The use of GIS for simple two-dimensional modeling using standard overlay procedures is now widespread (Berry, 1987). Extension to three-dimensional spatial and dynamic modeling is crucial for applications in several disciplines (e.g., marine science, climatology, geology, soils modeling) (Davis and Davis, 1988; Burrough *et al.*, 1988).

In summary, a basic functionality of data exchange formats has been made commercially available by numerous companies.

An extended functionality using tandem vector/raster processing has begun to emerge on the market place. New commercial systems designed expressly around data integration are also beginning to emerge. Research gains on the non-commercial side are centered around specific tasks in three areas: generating maps from image data, increasing the "realism" of cartographic representation (e.g., visualization), and using map data as auxiliary knowledge to improve image analysis. The automated extraction of cartographic information from satellite imagery (both stereoscopic and monoscopic) has been achieved by means of pattern recognition software, greatly increasing the capability of remote sensing as a data input tool for geographic information systems. Change detection is another successful application of remote sensing imagery as data input to GIS. Terrain visualization is a promising task. The use of GIS databases as a guide to segmentation and modeling has attracted some interest, but progress has been much slower in this area. This is partly due to the relatively recent availability of segmentation algorithms and the relative inaccessibility of modeling capabilities in GIS. Most current GIS are simply not designed to allow dynamic modeling to be piggy-backed onto existing structures.

Based on the experience gained from the preceding experiments and case studies, we outline a strategy for system integration in the following section. It should be noted that several research initiatives of the National Center for Geographic Information and Analysis (NCGIA) recently funded by the National Science Foundation will be dealing with such issues (Simonett *et al.*, 1988). Most directly involved will be the research initiative, "Remote Sensing and GIS," to begin in 1990. It is anticipated that papers such as this one will initiate discussions on the research agenda for this initiative.

TOWARDS A LONG-TERM STRATEGY OF INTEGRATION

As a first step towards seeking a long-term strategy of integration, we will examine the major stumbling blocks which have been encountered to date. They may be divided into two groups, technical and institutional, although both are interrelated.

TECHNICAL IMPEDIMENTS TO INTEGRATION

The so-called raster/vector dichotomy has confounded many attempts at integration. Remote sensing has been almost completely oriented towards a raster approach to data and analysis, while GIS software has tended to be vector oriented (although there exist also raster-based systems). From the perspective of GIS users, it is recognized that there are advantages and disadvantages to both data representations. Remote sensing users, on the other hand, while recognizing the merits of vector representation for cartographic information, have largely concentrated on raster analysis for image processing. There are good reasons for this: the CPU processing burden for image analysis is sufficiently high that raster data structures are the only feasible choice on low speed hardware platforms. Furthermore, because detectors produce raster digital information directly, raster processing seems "natural." There is nothing sacred, however, about raster processing, even on the remote sensing side, and vector processing of imagery is actually used in some applications. For example, Edwards and Beaulieu (1989) have used segmentation polygons and the spatial analysis capabilities of GIS for higher level image interpretation.

More generally, research on human vision and perception has led to a model of spatial information extraction, object recognition, and predicate manipulation that is constructed as a three-level integrated raster-vector processing system (Marr, 1982) (Figure 3). At the first level, gray values (raster data) are processed (low-level) from which structures (features) can be extracted and manipulated as symbolic descriptors (mid-level). At the highest level, knowledge based information often coupled with spatio-

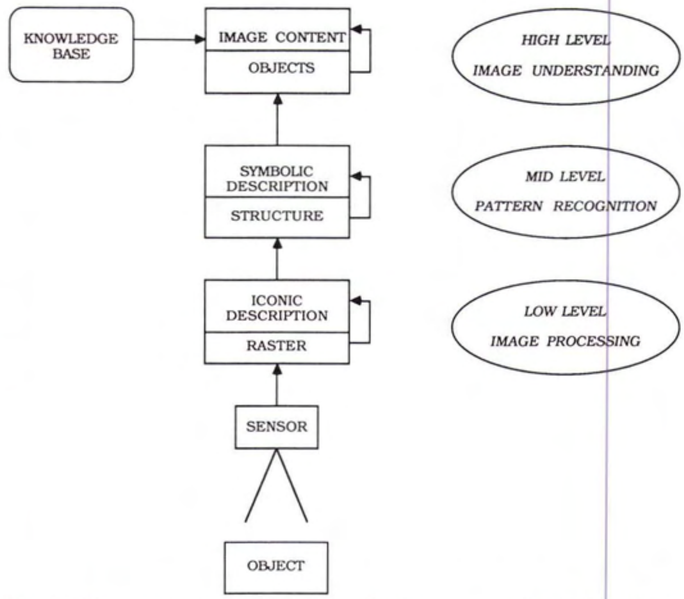

FIG. 3. Vision concept of information extraction from an image as a three-stage process.

temporal models gives a predictive description (image understanding) of the "imaged" object (Pentland, 1985).

This may give rise to hierarchical image analysis systems for remote sensing in which mid-level and high-level information can be stored as vectors and/or objects rather than as gray values. Finally, data structures based on raster and vector representations are not the only possibilities. Quadtree and other tesselations (e.g., Voronoi diagrams, cell graphs) of the image plane are also possible data structures, as are constraint derived surface representations such as are currently being explored for computer vision (Samet, 1984; Frank and Kuhn, 1986; Gold 1987; Terzopoulos, 1988).

A second technical obstacle is that geographic information systems rely on fairly uniform and pre-determined data. They tend to be removed from the raw end of data collection. For typical GIS applications, the data needed are defined and then collected. For remote sensing applications, however, a set of data is typically collected and the user has to decide how to use it. This orientation has several consequences. Tracking errors in the data is much in harder GIS because of this separation from data collection. Furthermore, the management of information inside the GIS tends to be oriented towards the regular availability of the necessary data. In remote sensing, on the other hand, it is difficult to separate data collection from data processing. Data collection is uneven and data coverage is very far from being uniform.

It has been argued that remote sensing is essentially a data acquisition technology, and hence that its role is limited to serving as a data input tool to GIS. We note, however, that remote sensing includes also data processing technology (see the definition of remote sensing given by ASPRS in the column "What *Photogrammetric Engineering and Remote Sensing* is" in every issue of *PE&RS*). Image data from a wide variety of different wavelength regions and spatial resolutions and at irregular time intervals must be combined to generate a cohesive model of the territory viewed. Indeed, the very basis of GIS technology is to model the territory in such a way that parameters useful to the user can be extracted. The integration of remotely sensed data requires that the GIS be based on deeper, more complete models of the territory. The fact that most GIS today are based on a more superficial model is indeed one of the major stumbling blocks to improved integration of remotely sensed imagery into GIS technology. Its solution probably involves rethinking the data structures of most existing GIS.

Both these differences (the raster-vector dichotomy and the issue of data uniformity) are rooted in the following fact: image data and cartographic data represent information about the world using two different concepts of space, which might be called "object-based" and "field-based." Cartographic data usually fill an "empty" Euclidean two-dimensional space with objects (e.g., transportation features, houses, lots) whereas remote sensing separates a non-empty space into a tiling of raster elements (pixels), that is, a field representation. These pixels, for example, represent reflectance values of objects at certain spectral wavelengths. Without further processing and additional information, however, these objects cannot be identified in the image data. Cartographic data, on the other hand, are obtained by abstracting some information about the world and discarding the rest. Image data, while involving some level of abstraction (selection of certain spectral regions, time intervals, etc.), are a lower form of information: the interpretation of this information remains to be done. Cartographic data are data where much of the interpretation has already been carried out after the data collection process; only the results are stored. Integration of remote sensing and GIS will largely depend on the ability to understand and conceptualize the transition from one representation to another (Figure 4) (Bruegger *et al.*, 1989).

One area that has already had some limited success is the abstraction of cartographic data from image data using the automated techniques discussed earlier. This is illustrated in Figure 5 where we note that the relationship between attribute and cartographic data is also one of abstraction. Hence, the development of spatial information systems from information systems has involved the incorporation of spatial information at a lower level of abstraction. It is true that much attribute data comes from other sources than cartography, just as some cartographic data will never be acquired from remotely sensed imagery (e.g., income distribution maps, etc.).

Nevertheless, the abstraction relationship still holds as a general rule. In Figure 5, we also show the extension of the integration of data at lower levels of abstraction to the inclusion of surveying data in a raw form (e.g., so-called measurement-based information systems; Buyong and Frank, (1989) and Onsrud and Hintz, (1989) such as we might expect to occur as surveying becomes more and more automated. A total information system, according to this view, would be a GIS extended to accommodate and manage remotely sensed imagery and robotic measurements as soon as such information could be made available to the system.

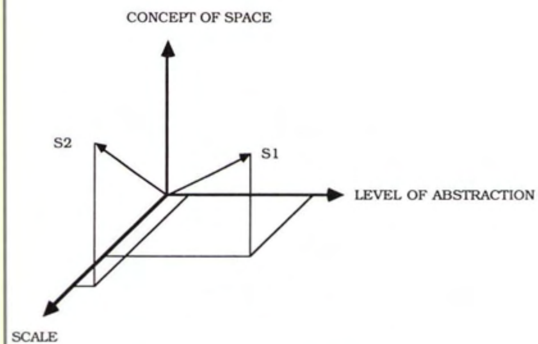

FIG. 4. Example for different representations of spatial information in Geographic Information and Image Processing systems. Every realization of a representation may be described as a point in a discrete space. The representations may vary in several aspects such as concept of space, level of abstraction, or scale which are represented as orthogonal axes of a "representation space." Other representation axes may include level of uncertainty and accuracy or temporal abstraction to create higher order representation spaces. Some transformations from one realization of representation to another (e.g., from S1 to S2) may be reversible, whereas others may be not.

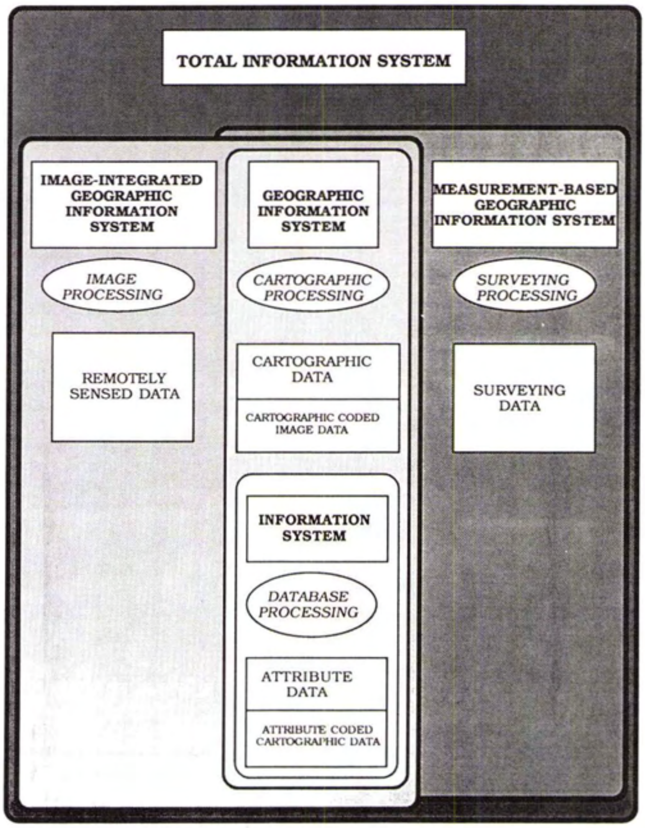

FIG. 5. Diagram showing the evolution of information systems towards incorporating and managing data at lower levels of abstraction. Note that lower level information may be left implicit, or it may, for reasons of efficiency and speed, be coded explicitly at higher levels of abstraction. Hence, for example, early information systems made spatial information available by coding it explicitly as attributes in the database.

INSTITUTIONAL CONCERNS FOR INTEGRATION STRATEGIES

On the institutional side, two groups of users with different needs are presently active clients of both image processing systems and GIS. First, there are the decision-makers, those who need a pool of information sufficiently "global" to guide sensitive or strategic development and management of the land and our natural resources. These users generally work with a restricted area (e.g., city, county, or country) or are involved in a restricted task (e.g., providing building permits). Second, there are the research scientists, those oriented towards increasing our understanding of the Earth as a global system. In government, private industry, and academic institutions there are also groups in-between, because decision-makers rely on scientists for much of their information about the world. For many decision-making groups a heavy-duty "spatial" database, along with personnel who are competent at making the necessary connections and drawing up the appropriate statistics, is quite usable in the present context of these organizations. In fact, most current geographic information systems have been designed with such groups in mind; hence, it is not surprising that their needs are met.

Research groups have different requirements, however, especially in terms of spatial and temporal modeling. A database is by no means sufficient. A spatial database is seen as just a potential component in the sophisticated spatial and temporal modeling of non-linear systems. The vast majority of research problems involving the use of spatial and temporal data cannot be attempted using the current state of the art. For example, problems involving time evolving, dynamic interchanges between spatial elements and/or "thematic" elements such as modeling forest ecology subsystems or marine temperature and currents modeling require more sophisticated systems. To the extent to which groups within the cartographic and remote sensing communities align with management needs or with scientific research needs, perceptions of the role and value of currently available geographic information systems differ. For example, a GIS for marine areas would require a relatively low spatial resolution but would have to address temporal variability and the three-dimensional nature of its environment. A GIS for cadastral applications would require higher spatial resolution but could be viewed as essentially static and two dimensional. These functional differences are probably more fundamental than reported differences between the cartographic and remote sensing communities (e.g., Green *et al.*, 1988).

A second consequence of this difference in orientation between the two user communities is that GIS software is conceived by managers to be a part of a larger information system which includes "a combination of elements (data, equipment, procedures, users) organized around a common geographic base and dedicated to a particular goal" (Bédard, 1983); that is, a system which includes the information resources of the organization itself. Many scientific users, on the other hand, tend to see only the software tool itself, or are independent of the organizational aspects of such systems.

A third, potential group of users of more sophisticated and integrated GISs is the general (i.e., non-expert) public (and/or scientists working outside their field of expertise). The non-expert needs a GIS and/or image analysis system which is sufficiently sophisticated to be able to suggest to the user which are the important or relevant relationships and which are not. Also required is an interface to GIS that makes information readily accessible to those not trained in computer usage.

While there is no such GIS capability presently available, and probably will not be for some time to come, awareness of such a long term goal exists in both communities. Image interpretation in remote sensing is that area which seeks to abstract higher-level information from images (e.g., to identify houses directly by shape rather than so-called "urban areas" by traditional classification techniques). Image interpretation is frequently implemented using knowledge bases, but it relies on lower-level segmentation techniques which usually produce very "noisy" information. Cartographic information can be used to decrease the "noise" of such segmentation, and hence increase the "interpretability" of the resulting images (e.g., Ait Belaid *et al.*, 1989). On the GIS side, this awareness takes the form of examining user interfaces, looking at the questions of natural language processing, and studying the possibilities of spatial analysis techniques (such as the ability to handle "fuzziness") which are not presently incorporated in GIS (see, for example, Mark *et al.* (1987)). Knowledge-based GIS systems are also being studied (Smith *et al.*, 1986; Robinson and Frank, 1987).

In order to meet these different but convergent needs, a three-stage integration process is outlined. This incorporates the existing capabilities of commercial GIS in a natural framework which permits one to see the long term goals clearly.

First Level Integration Avenues ("Separate but Equal")

First level integration strategies include the following points:

- simultaneous display of GIS (usually vector) data and remotely sensed (raster) images;
- the ability to move the results of low level image processing (e.g., thematic maps, extracted lines, etc.) to the GIS, allowing for the assignment of attribute values to the "themes" and for the collection of basic statistics;
- the ability to move the results of GIS overlays between images and vector data to image analysis software. This is particularly useful for geometric registration of the images to a common (map) base; and
- the ability to move the results of GIS spatial analyses to image analysis software for support and validation of the image.

First level integration is generally achieved using some sort of data exchange format between existing GIS and image analysis systems (see Figure 2a).

Second-Level Integration Avenues ("Seamless Integration")

More advanced geographic information systems should be designed to permit tandem raster-vector processing (Figure 2b), still based, however, on the two separate space representations discussed earlier. Such systems would involve for the most part straight-forward extensions of existing capabilities of GIS in the following areas:

(a) entity-like control over remote sensing image components (e.g., themes);
(b) capability to incorporate GIS (vector) data directly into image processing. For example, the vector data can be rasterized as an "image plane" and incorporated directly into traditional classifications or segmentation algorithms. It can be combined with segmentation while retaining its vector-like properties, or it can be used as "knowledge" to guide image interpretations of a previously segmented image. These operations require the control capability of (a);
(c) ability to accommodate (spatially, radiometrically, spectrally, and temporally) inhomogeneous data input in a coherent manner;
(d) ability to handle time (e.g., to handle both irregular time intervals, to infer events by interpolation between known items, and to compensate for time differentials between image acquisition and map dates);
(e) ability to accommodate hierarchical entities (e.g., "house" at one level, "block" at another, "city" at another). This is necessary for both the hierarchical segmentation of images and map generalization procedures;
(f) capability to analyze errors (both random and systematic);
(g) ability to generate simulations combining cartographic data and image data and temporal evolution ("what if" simulations, visualizations, dynamic modeling, etc.).

Whereas existing commercial GIS have some of these capabilities, no single system is currently capable of handling all these tasks. Object-oriented systems seem particularly interesting for efficiently handling many of these functions (Herring, 1987; Egenhofer and Frank, 1989).

Total Integration

So-called "seamless integration" (see the previous section) still constitutes two systems complementary to each other but interwoven, and all current attempts at such systems confirm this observation. Although based on different concepts of space, the two technologies are not as distinct as is usually perceived.

The raster-vector dichotomy alone is a false dichotomy: it is only valid at low processing levels. At higher processing levels (i.e., higher levels of abstraction), a vector representation may seem more appropriate, while at lower levels some form of tiling seems more useful. Total integration requires something more, however. A single "deep" model of the real world should underly all information in the GIS. From such a model, the different space representations may be derived. Flexible handling of both object-based space representations and field-based space representations of this model is also fundamental. For example, the ability to abstract objects from field information, and the ability to reconstitute field information from an object description, are essential to achieving such flexibility. Space representation (object versus field) is a deeper characterization of GIS than data structure (vector versus raster). Indeed, a field-based representation could be implemented either as a set of contiguous (vector) objects (e.g., a DEM composed of TIN) or as a raster tiling (e.g., a grid-based DEM). Likewise, an object-based representation can be handled either in a vector or raster mode. A geographic information system should accommodate both types of information at different hierarchical levels (see Figure 5).

Such a GIS would be a candidate for a total information system (see Figure 2c). Indeed, it would need to address such questions as an "integrated" query language or query structure. There is a great deal of interest these days in spatial extensions to Structured Query Language (SQL), and to user interfaces which accommodate sophisticated query functions (Egenhofer and Frank, 1988; Herring *et al.*, 1988). There is no reason why this work could not be extended to include image-oriented query functions as well. Just as spatially extended SQL queries engage spatial analysis software to extract information which is not explicitly coded in the database, an "image-integrated" SQL query might engage image analysis software to extract image information not explicitly recorded in the cartographic data structures.

Furthermore, the view of GIS as an integrated system incorporating data, equipment, procedures, and users involves a more complete understanding of information and its uses than the view of GIS as "only a software tool," and the scientific community can benefit considerably from adopting this approach – after all, scientific goals are centered around understanding the Earth as a system. The long term goal of the scientific community is really nothing more than the ultimate GIS: a planetary, also called global, geographic information system (see, for example, Bliss and Reybold (1987) or Kineman and Clark (1987)). Benefits of integrated remote sensing/GIS would extend to Earth scientists concerned with modeling the physical, biological, and chemical cycles of the system Earth (Butler *et al.*, 1986).

The remote sensing community recognizes the need to understand the data collection and calibration process. The GIS community can, and probably must, adopt such an approach in the long-term. Already, data collection techniques in geomatics which use robotic vehicles and instruments are being developed and used. The use of robots and robotic vision algorithms and technology may lead the way to more sophisticated image understanding systems for remote sensing. Geographic information systems will have to adapt to such new technologies for data collection and input. A total system means reclaiming the data input process as an integral part of the functionality of the GIS. The effort to include remote sensing now in GIS provides the opportunity to learn how to track error, how to deal with inhomogenous data, etc., which will become part of other data collection processes for GIS.

Finally, neither the remote sensing community nor the GIS development community have solved the problem of incorporating the temporal dimension in their respective analyses. This will have to be addressed before a fully integrated GIS technology can mature. Other research topics include the three-dimensional aspect of spatial information, especially for Earth and marine sciences. Researchers in the GIS and remote sensing domains have to collaborate on this problem, because the answer probably lies somewhere in the middle ground between the two domains. The kind of fundamental work on data structures necessary to develop a totally integrated GIS lends itself naturally to addressing the question of accommodating temporal change and 3-D aspects.

Ultimately, today's geographic information systems and today's remote sensing image analysis systems are both aspects of single data collection and analysis systems containing data at different levels of representation. The long term goal of integration is not "seamlessness," but "unity." If and how this can be realized remains an open question. A lot of work will have to be done, especially in the area of fundamental geometric data structures and the integration of vector and raster processes in a hybrid structure. But realization of such long-term goals can help orient today's research.

CONCLUSIONS

In this paper, some of the successes achieved to date in integrating GIS and remote sensing have been examined, both in the commercial sphere and in academic and government directed research. Several of the problems which continue to hamper improved integration were identified. The solution to these problems probably lies in the recognition that cartographic and image data constitute spatial information at different levels of representation, just as is the case when comparing attribute and cartographic data. Data structures, data collection and management technologies, and institutional responses to these data are all impacted by such a recognition. This view led to the identification of three possible levels of integration: a basic level of separate but interfaced GIS and image analysis systems; an intermediate level of "seamlessly" interwoven systems, sharing a common user interface and incorporating various forms of tandem processing; and an advanced level of a single data collection and analysis system.

We see GIS and remote sensing as one entity concerned with handling and analyzing geographic data. The more or less separated GIS and remote sensing communities have to accept that both need each other. The integration of these technologies will inevitably lead to a synergistic approach to spatial data handling, i.e., the final system would have *more* capabilities than just the sum of the two. It is envisioned that future systems will include measurement-based GIS and digital photogrammetric workstations ("total information system"). Due to the limitation of space for a technical paper, we have only discussed the technical and institutional impediments for GIS and remote sensing integration. We are, however, fully aware of the fact that there are others such as *educational* impediments that well deserve a complete paper of their own.

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