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Integration of Remote Sensing and Geographic Information Systems: Report of the Specialist Meeting (91-16)

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NCGIA

National Center for
Geographic Information
and Analysis

Initiative 12: Integration of Remote Sensing
and Geographic Information Systems

Report of the Specialist Meeting

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Specialist Meeting held at:
EROS Data Center, Sioux Falls, South Dakota

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Report of the Specialist Meeting

This report summarizes the planning meetings and preliminary work that led to the first Specialist Meeting for Initiative 12, Integration of Remote Sensing and Geographic Information Systems. It also provides a detailed synopsis of the highlights of the specialist meeting held in December 1990 at the EROS Data Center, Sioux Falls, South Dakota. Initiative 12 is led by Frank Davis, Jack Estes, and Jeff Star, all at the University of California, Santa Barbara.

Two planning meetings were held in preparation for the specialist meeting. Participants in the first planning meeting, held 17 May 1990 in Denver, Colorado, began to flesh out the components of jx and to begin to identify potential participants for the specialist meeting. Attendees included Bill Anderson (Ohio State U.), Bob Best (EG&G), Manfred Ehlers (U. Maine/NCGIA), Nick Faust (Georgia Tech and ERDAS), Dave Greenlee (USGS/EROS Data Center), Ross Lunetta (EPA Las Vegas), Tom Mace (EPA Las Vegas), and Dale Quattrochi (NASA Stennis Space Center), in addition to Davis, Estes and Star from UCSB/NCGIA. Based on both topdown and bottom-up examinations of the research interests of the attendees and their knowledge of the research needs of the area as a whole, a set of general areas of emphasis were developed. These included:

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*        Error Analysis (Lunetta)
*        Data Structures and Access to Data (Ehlers)
*        Data Processing Flow and Methodology (Davis)
*        Man-Machine Interaction (Fauso
*        Hardware Environments (Fauso
*        Institutional Issues (Lauer)
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Individuals were selected to help to organize and outline potential research topics within each of these areas; the coordinator is listed after each topic above. The group decided that drafts of position papers for each of the areas would be developed as starting points for discussion at the specialist meeting.

A second planning meeting was held at the Stennis Space Center, Mississippi on 1/2 August 1990. Attendees included Bill Anderson (Ohio State U.), Manfred Ehlers (U. Maine/NCGIA and ITC), Jack Estes (UCSB/NCGIA), Nick Faust (Georgia Tech and ERDAS), Dave Greenlee (USGS EDC), John Jensen (U. South Carolina), Ross Lunetta (EPA Las Vegas), Tom Mace (EPA Las Vegas), Ken MIGwire (UCSB/NCGIA), Dale Quattrochi (NASA SSC), Jeff Star (UCSB/NCGIA), Fran Stetina (NASA/GSFC), and Larry Tinney (EG&G). Observers at the meeting included Tony Lewis (LSU), Merril Ridd(Utah), Jack Hall (Houston Univ. Research Assoc.), and Gil Rochon (Dillard U.). We continued to flesh out the general areas that a research agenda must include, as well as a potential list of participants that would include a broad cross-section of discipline interests as well as application areas. We considered the preparation of position papers on five topics (based on the list from the previous meeting, but combining man-machine interaction and hardware environments into a new topic called future computing environments). Discussion also included the possibility of a special issue of Photogrammetric Engineering and Remote Sensing dedicated to the initiative. Tjis special issue would showcase the position papers which would flow from the specialist meeting. The group also discussed the desirability of sessions dedicated to the initiative at the March 1991 ACSM/ASPRS annual meeting.

The specialist meeting was held at the EROS Data Center, Sioux Falls, South Dakota, on 3/4/5 December 1990. Al Watkins, director of the EROS Data Center, opened the meeting with a general welcome and an overview of the research and production activities of the Center. This was followed by a presentation by Jack Estes, who described the background of the NCGIA initiative process, as well as the goals and operations of NCGIA in general. Jeff Star followed with discussions of GIS and Remote Sensing both separately and together, as well as a charge to the meeting for the following two and a half days.

After lunch, Don Lauer (USGS EDC) presented his paper on institutional issues. David Goodenough (Canada Centre for Remote Sensing) and Nancy Tosta (Teale Data Center) were discussants after this presentation, responding to some of the issues from Lauer's presentation from their own perspectives. Manfred Ehlers (U. Maine/NCGIA and ITC) then presented the paper he coordinated on data structures and access. Sud Menon (ESRI) and Terry Smith (UCSB/NCGIA) served as discussants for this paper.

On Tuesday, the meeting heard three more sets of presentations and discussion. Frank Davis (UCSB/NCGIA) presented the paper on processing flows. Chris Johannsen (Purdue) and Steve Guptill (USGS) served as discussants for this paper. Ross Lunetta (EPA Las Vegas) presented the paper on error analysis. Nick Chrisman (U. Washington) then presented some of his own work on error analysis, and Mike Goodchild (UCSB/NCGIA) then served as a discussant. Nick Faust (Georgia Tech and ERDAS) presented the final paper, on future computing environments. Jeff Star (UCSB/NCGIA) and John Gage (SUN Microsystems) served as discussants on this last paper.

On Wednesday, the meeting broke into five working groups, aligned with the five general topic areas of the presentations. In each of these working groups, the goal was to assemble a prioritized research agenda. After a break for lunch, the leaders of the working groups presented their findings. One specific change that emerged from the working groups was to change the focus of the data structures and access section to one of data models. At the end of the day, a small group convened in executive session to examine the next steps required to (1) prepare for sessions at the ASPRS/ACSM meeting in Baltimore in March 1991, and (2) prepare to revise the papers presented at the meeting as a submission to Photogrammetric Engineering and Remote Sensing. Additional discussion revolved around a future research monograph, as well as the interests of several meeting participants to spend time in residence at UCSB/NCGIA to work on priority research problems.

We thank all the participants for their hard work and attention span during these meetings, including those who were unable to attend the meeting in Sioux Falls. In particular, we acknowledge the staff at the EROS Data Center, who went far beyond the call of duty to make this meeting a success. A copy of the video tape of the meeting will be available at the UCSB/NCGIA office shortly.

At this time, papers based (at least in part) on the documents presented here have been revised and submitted to Photogrammetric Engineering and Remote Sensing, for a special issue tentatively scheduled for mid-1 991. We also look forward to the Baltimore 1991 ACSM/ASPRS meetings where NCGIA will convene special sessions on the integration of remote sensing and GIS, and the subsequent proceedings volume which will come from these sessions.

Following this introduction are the majority of materials presented and at the meeting, as well as the research priorities which were developed by the attendees at the working sessions. Each of the five topical areas is represented by the paper presented by the coordinator of the area, as well as viewgraphs and comments from the discussants where available. We also include a list of the attendees at the end of this document.

<div style="text-align: right">

Jeffrey L. Star
19 March 1991
Santa Barbara, California

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Introductory comments by John E. Estes, University of California, Santa Barbara/National Center for Geographic Information and Analysis

The National Center For Geographic Information and Analysis (NCGIA)

* idea proposed and discussed in 1984

* serious discussions in the federal government and in academia during 1986

* NSF Solicitation issues in June 1987

* Santa Barbara, Buffalo, and Maine form a consortium in July 1987

* 8 proposals (including 17 institutions) submitted in January 1988

* site visits in June 1988

* announcement in August 1988

* "official" start in November 1988

NCGIA:

Announcement - 8/19/88

Start date - 11/15/88

$1.1 million/year for 5 years
    * possible extension for 3

Consortium of:
    UCSB
    SUNY at Buffalo
    University of Maine

Reasons for consortium
    * advantages and disadvantages

The NCGIA has three sites:

* the University of California at Santa Barbara, which acts as the "lead" institution:

* the State University of New York at Buffalo; and

* the University of Maine (in Orono).

* Research and educational activities occur about equally at all three Centers

* The center at Santa Barbara performs various "central office" functions, including the publication of the Newsletter and of Technical Reports.

NCGIA Objectives:

Removal of impediments to use of GIS technology

Development of analysis and modeling

Development of social science applications

Improving supply of trained personnel

     * **need analysts more than technicians**

Research/education/outreach

Educational Concerns:

Lack of trained personnel at all levels;

New field - new discipline?

Need to introduce technology in new areas;

Need to stress conceptual in short term.

Education at the NCGIA

Educational activities include:
* the development of a one-year (two-semester or three-quarter) model curriculum of basic GIS concepts, techniques, and applications

* professional short courses and workshops held both on-campus and off, and training for GIS educators.

Educational Programs

* Core Curriculum Project

    - Curriculum Development

    - Testing and Evaluation Program

    - Offerings at UCSB

NCGIA Education Program:

Phase I - Core Curriculum:

3 courses, 25 modules, 75 lectures;

Beta test program 1989-90 25 participating schools;

Lab assignments, readings

Phase I - short courses:

Phase II projects 1989-90

Case study course;

Model GIS Labs;

University administrations.

Future Needs in Education:

The Academic GIS:

Conceptual Ideal;
Uses existing database, tools;
Open software;
Spatial database functionality.

Practical training:

Packaged courses
Community college level.

Outreach at the NCGIA

Outreach to all segments of the GIS/GIA community, both private and public sector, is an important aspect of the Center's activities.

Research at the NCGIA

Research at the NCGIA is undertaken primarily by means of Research Initiatives, or projects designed to fully investigate impediments to the more widespread implementation of geographic information systems (GIS).

Research Initiatives:

* are conducted at at least two and often three, of the NCGIA sites.

* are strongly interdisciplinary.

* normally include participants from industry, from government, from the NCGIA, and from other academic institutions.

Research Initiatives

* Research Initiatives are designed to take advantage of the Center's potential for new modes of research.

* This approach is based on enhancing interaction, not only between individual researchers but also between the academic, industrial, and government communities.

Research Initiatives Consist of Six Components

* Planning Phase.

* Specialist Meeting.

* Working Groups.

* In-Progress Seminars.

* National/International Conferences.

* New and Outgrowth Research.

Specialist Meeting

Center research on a specific topic is initiated by a meeting of one to two weeks' duration, at which perspectives on the topic are presented by specialists drawn from Center personnel, researchers from outside the Center, and other representatives of government and industry.

These meetings will promote cross-disciplinary exchanges, work out the agenda for the Research Initiative, and assign responsibilities to Working Groups.

Some multi-year initiatives will have annual Specialist Meetings.

Organization for the initial Specialist Meeting will occur during the initiative planning period.

Working Groups

Specific Commitments of time and resources are made for Working Groups which will conduct research for periods of six months to two years following the Specialist Meeting.

We assume that the largest commitments will be made by Center personnel (permanent faculty, visiting fellows, research assistants), but that in many cases research will be conducted jointly with other institutions, agencies, and firms.

Working groups will use a variety of modes of inquiry including seminars, computer modeling and prototyping, and empirical investigation.

In-Progress Seminars

Progress on Research Initiatives may be expanded through seminars of two to five days' duration.

Such seminars would bring together a group of scientists with differing views on a topic, both from within the NCGIA and from the outside.

Seminars may be organized to clarify an interdisciplinary effort to identify further research directions or to integrate and make available results from other areas of research with relevance to GIS research.

National/International Conferences

The fourth component of the Research Initiative model is a National or International Conference at which substantive findings are presented to a larger

We anticipate that many of these will be held in conjunction with other national and international meetings, and that these conferences will be a prominent feature of the NCGIA.

New and Outgrowth Research

Initiatives may lead naturally into long-term single-investigator projects of greater depth and specificity.

The involvement of graduate students in Research Initiatives will have considerable educational impact.

Doctoral dissertation research will be a very important part of this outgrowth research.

Many initiatives will also lead to applied research relevant to federal agencies, state and local governments, and the private sector.

Funding for such outgrowth research will be sought from the agencies involved.

Initiatives will usually conclude with descriptions of new problems which have been exposed, and thus influence the Center's long-term research plan.

Current Research Initiatives

Initiative 1:   **Accuracy of Spatial Databases**
(December, 1988)

Initiative 2:   **Languages of Spatial Relations**
(January, 1989)

Initiative 3:   **Multiple Representations**
(February, 1989)

Initiative 4:   **Use and Value of Geographic Information in Decision Making**
(May, 1989)

Initiative 5:   **Architecture of Very Large GIS Databases**
(July, 1989)

Initiative 6:   **Spatial Decision Support Systems**
(March, 1990)

Initiative 7:   **Visualization of the Quality of Spatial Information.**

Research Areas: Visualization, statistics, applications.
Leaders: Kate Beard (Maine) and Barbara Buttenfield (Buffalo).
Duration: October 1990 to 1992.

Initiative 8:   **Expert System for Cartographic Design.**

Research Area: Visualization; expert systems.
Leaders: Andrew U. Frank (Maine) and David M. Mark (Buffalo).
Duration: February 1991 to 1992.

Initiative 9: Institutions Sharing Spatial Information

Research Area: Social, economic, institutional issues.
Leaders: Hugh Calkins (Buffalo) and Harlan Onsrud (Maine).
Duration: Early 1991 to 1992.

Initiative 10: Temporal Relations in GIS.

Research Area: Spatial and spatio-temporal analysis.
Leader: Andrew U. Frank (Maine).
Duration: May 1990 to 1992.

Initiative 11: Space-Time Statistical Models in GIS

Research Area: Spatial and spatio-temporal analysis.
Leaders: David S. Simonett (Santa Barbara) and Joel Michaelsen (Santa Barbara).
Duration: October 1990 to September 1992.

Initiative 12: Remote Sensing and GIS

Research Area: Spatial analysis and spatial statistics.
Leaders: Jack Estes (Santa Barbara) and Frank Davis (Santa Barbara).
Duration: October 1990 to September 1991.

National Center For Geographic Information and Analysis
Initiative 12:   Remote Sensing and GIS

Specialist Meeting

EROS Data Center
Sioux Falls, South Dakota
3-5 December 1990

Co-Leaders

Frank Davis
Jack Estes
Jeff Star

History.

17 May 1990   Planning Meeting #5

Problems in the integration of RS and GIS
Bottom-Up and Top-Down
First set of topics and writing assignments

1-2 August 1990 Planning Meeting #2

Topics List
Writing Assignments
Invitations to Specialist Meeting

Future.

Revised position papers

Journal issue - PERS? Geocarto International?

March 1991 Symposium

Research ...

Monograph

__Remote Sensing__

1859:   Photographs from a balloon over the French countryside

1862:   Forestry mapping from aerial photography

1910:   Wilbur Wright's photography from an airplane

1920's: Systematic forestry mapping from aerial photography

1960:   TIROS 1

1962:   Mercury 8 astronauts photography Earth

1966:   Digital image analysis for agriculture

1972:   Landsat 1

1978:   Seasat

1982:   Thematic Mapper on Landsat 4

1986:   SPOT

Geographic Information Systems

1838:   Atlas to accompany the Second Report of the Irish
Railway   Commissioners

1890:   Herman Hollerith - punch cards for the US Census

1960's: Refinements in cartographic technique
            Digital Computers
            Quantitative Revolution in spatial analysis

1969:   Ian McHarg's Design with Nature

1970's: Rapid evolution of GIS applications

1980's: Commercialization of GIS

Uncertainty in GISs

* Garbage In/Garbage Out

* Accuracy vs. Precision

* Statistical Models

* It is easier to create data than to verify it.

Thematic Areas

Institutional Issues

Data Structures and Data Access

Processing Flow

Error

Future Computing Environments

Jeffrey L. Star

INSTITUTIONAL ISSUES AFFECTING THE INTEGRATION AND USE
OF REMOTELY SENSED DATA AND GEOGRAPHIC INFORMATION SYSTEMS

Prepared by
D. Lauer, J. Estes, J. Jensen, D. Greenlee, T. Mace,
for the NCGIA Specialist Meeting on
Initiative 12

December 1990

INSTITUTIONAL ISSUES AFFECTING THE INTEGRATION AND USE OF REMOTELY SENSED DATA AND GEOGRAPHIC INFORMATION SYSTEMS

1.0 Introduction

Remote sensing is a somewhat unique technology in that its transfer to users has been conditioned not only by the U.S. federal role, but governmental agencies around the world. This is true both in the development of the technology and in making it and its products available to the user community. Geographic information system (GIS) technology, while not as tied to federal level institutional constraints in its development, has none-the-less been influenced by the needs of the federal establishment and, indeed, the needs of governmental entities from local to international. Integration of remotely sensed data with geographic information systems has thus been, and, indeed continues to be, subject to a variety of institutional, as-well-as technical limitations (Estes, 1981). In this paper a number of key institutional issues affecting the use of integrated remote sensing and GIS technologies are addressed. It is important for the reader to understand that the list of issues presented herein and the research topics which flow from them are not intended to be exhaustive. They represent those institutional issues which the authors most often have confronted in their operations, research and development activities. Some of these issues are more generic than others. The authors hope that the material presented herein will stimulate expanded discussion and generate research on ways to eliminate or at least minimize institutional impediments to a fuller integration of remote sensing and GIS technologies.

1.1 Objectives of Paper

The primary objectives of this paper are to identify the institutional issues surrounding the technologies of remote sensing and GIS, and to suggest research which might be undertaken to develop an improved understanding of these issues. Colwell (1987) referred to these issues as 'deterrents"--that often create barriers to the adoption of modern remote sensing technology. Colwell identified these deterrents as overselling, overkilling, undertraining, underinvolvement, spurious evaluation, misapplication, timidity (sometimes known as gutlessness), inadequate infrastructure, inadequate understanding, and inordinate distrust. These and other deterrents or barriers, most of which are institutional in nature, are identified and several case studies are presented to help illustrate them. Another objective is to discuss institutional issues in a manner that explores the challenges facing the research community--which in turn might lead to a more effective overall research agenda for integrating and using remotely sensed data and GIS techniques.

1.2 Background

Extraordinary advancements have been made in recent years in the technical fields of remote sensing and GIS. These advancements are by-in-large the result of the deployment of new satellite sensor systems, the construction of large-area data base, the merging of image and cartographic data sets, and the development of innovative modeling algorithms for spatial analysis. The rate of development of remote sensing and GIS technologies, however, has increased much faster than the rate at which these same technologies have been understood, accepted, integrated, and used in an operational manner within an institutional context.

Strome and Lauer (1977) reported on a study done by Battelle Columbus Laboratories that found technologically advanced societies are unable to quickly transform new ideas into successful products. According to the Battelle study, the time-frame from year of first conception to year of first realization for the heart pacemaker, hybrid corn, and the oral contraceptive was 32 years, 25 years, and 9 years, respectively. The average time-frame for 10 innovations studied was 19.2 years. Just as Feigebaum has said it took artificial intelligence to become an overnight success, so too has remote sensing and GIS exploded some 20 years after the significant events in these fields in the early 1970's. The process of technology acceptance in any field is complex, so, normally, research results often require decades to achieve practical application. In the case of remote sensing and GIS, the complexity is enhanced due to the fact that the ultimate users of these technologies affiliate with nearly all types of institutions--including government (federal, state, local), industry (corporations, small businesses, consultants), and academia (teachers, researchers, extension specialists) (see figure 1). The land managers, resource specialists, or environmental scientists within these institutions often find that the barriers to accepting remote sensing and GIS, either taken separately or as an integrated technology are not always technical in nature, but rather can be attributed to the institutions themselves. Thus, a better understanding of institutional issues might lead to-their mitigation--and to improved success in the integration and operational uses of remote sensing and GIS.

Further complicating the topic of remote sensing/GIS integration are issues related to interdisciplinary barriers. Engineers often have difficulty talking with environmental scientists. Environmental scientists have difficulty communicating with computer scientists; who have difficulty relating with public officials; and, so it goes. While there are individuals who can successfully communicate across disciplines, the authors believe that there are not enough people with this special talent. Education, is one key here, but another is the realization that information transfer gaps do exist and that conscientious efforts must be made to close these gaps.

2.0   Institutional Issues

2.1   Data Availability

Hard to find data. A common complaint among users of remotely sensed and other forms of digital spatial data is that they, the users, often have a difficult time finding out what data sets are available. There are few catalogs that describe available digital cartographic data sets and their attributes. The Federal Interagency Committee for the Coordination of Digital Cartography (FICCDC), recently renamed the Federal Geographic Data Committee, has noted tha t most digital data sets are created for a particular purpose or to support a particular program (FICCDC, 1990). In both remote sensing and GIS, the creation and use of data sets often occur within the same program. Consequently, in most cases there is no need to advertise the availability of the data set. For a data set to be available to potential users outside the original program, requires a marketing effort. It requires a distribution mechanism and an institutional commitment to furnish the data in formats and media which may not have been required by the original program. It requires an institutional commitment to an on-going services program to help other users decide if the data set is useable for their purpose. It requires an institutional willingness to gauge the needs of users and to modify standard products to meet those needs. These service efforts demand resources which are usually not included in the original program. The required resources usually represent only marginal increases in the base program, yet the investment is usually not made. Only the largest programs in digital cartography, such as those under the direction of the U.S. Geological Survey (USGS) and the Bureau of Census, can justify an adequate product awareness activity.

Non-existent data. Jensen and others (1989) have identified certain critical remote sensor systems and/or data types which currently are not available, but are essential to the successful integration of remote sensing and GIS. They note, for example: 1) there are no 1 x 1 m to 5 x 5 m spatial resolution data from space sufficient to meet many of the urban mapping requirements which are becoming so important in this age of increased census and GIS use; and 2) on a global basis there will continue to be no remotely sensed data of any kind systematically collected for tropical regions of the world until a synthetic aperture radar (SAR) system is placed in orbit. Therefore, until a SAR is in place, precious little can be done in the integration of remote sensing and GIS for tropical regions of the world. Furthermore, the populations of these regions are often growing very rapidly and are in dire need of such data. These two examples are representative of the problem of non-existent data caused primarily by a lack of institutional commitments to the development of these types of sensor systems.

Data for global change research. Equally as critical in many ways is the fact that as yet no federal agency has accepted the responsibility to operationally produce data sets required to adequately support global change research. While the USGS and several federal agencies will provide U.S. data as input to the National Digital Cartographic Data Base, no agency has accepted or been given the mandate to produce these data sets for areas outside of the United States. This issue of data availability and responsibility for producing and making data available pervades the institutional issues discusses below. It is well understood that GIS's are data driven. This being the case, what data do we require, who will produce it, in what forms and in what time frames, at what costs certainly become critical issues.

Data Sharing. The FICCDC's User Applications Working Group has reported that there exists unrealized potential for iu 'ch greater sharing of federally produced digital spatial data (FICCDC, 1990). Cooperative actions (i.e., sharing) should be happening, but they are not. To the contrary, there are many reported examples of different agencies independently collecting or digitizing the same data sets. To a large degree, the original purpose of the FICCDC was to prevent duplicative digitizing projects--it was assumed that the only reason duplication of effort among different organizations occurs is because the parties are not aware that they both are doing the same thing. But, when the degree of awareness was increased, mainly through the efforts of the FICCDC, the situation persisted which would indicate barriers to data sharing must exists. The FICCDC's User Applications Working Group has set a task to identify these barriers.

The Working Group suggests that the barriers can be classified as either technical or institutional. Technical barriers concern the content, quality, and structure of a data set. They include the questions of media, format, and encoding--factors which must be considered by a receiving party before it can read and understand a digital data set.

Institutional barriers concern an organization's resistance to sharing data. Producing agencies often fail to put data into a form such that it can be widely used. Users are often unaware of the existence of potentially useful products. Users often prefer to digitize data from maps rather than share another party's digital data set while some data producers will assert a proprietary interest in data. Proprietary considerations often apply to data collected from private companies by the federal government. Some organizations are reluctant to announce digital products because of the uncertain status of the liability for accuracy of the data.

2.2   Data Marketing and Costs

Geographic and cartographic data. The FICCDC Working Group also noted that for a GIS manager, it may be more cost-effective, or at least more expedient, to digitize data from maps than to search out and assess suitable existing digital cartographic data sets. Most individual GIS managers cannot afford to spend much time searching out suitable data sets. However, if a federal agency establishes a product awareness program such as has been done by the USGS for its National Digital Cartographic Data Base, then the search for at least USGS data can be done quickly, and at minimal time and cost to the user. This is essentially the thrust of the work being done by the National Aeronautics and Space Administration (NASA) on the Master Data Directory at the National Space Science Data Center. This work is considered by many participating in NASA'S Earth Observing Systems (EOS) program to be critical in insuring effective use of EOS data for global change studies. Nevertheless, many organizations that produce digital cartographic data fail to take the extra steps necessary to establish a product awareness and marketing activity. From the viewpoint of local program managers, these activities are not part of their program responsibilities and, in times of tight budgets, they cannot afford to allocate resources to them. In such cases, there may be a reluctance to go beyond the objectives of the original program and make marginal investments to serve the common good. This reluctance is not likely to be overcome. The extra steps, and the benefits they would produce for the cartographic and GIS community, are not likely to occur unless institutions accept the responsibility for marketing their digital cartographic data sets.

Satellite remotely sensed data. Data marketing strategies and costs for satellite remotely sensed data are considerably different than the costs associated with the capture and distribution of digital cartographic data. In this case, the U.S. Government has transferred the nation's Landsat program to the private sector with the expectation that the program can be managed and operated on a commercial basis (U.S. Dept. of Commerce, 1980).

The underlying premise for commercializing the Landsat program was that in a reasonable amount of time, revenues would exceed costs, government subsidies would be eliminated, and a profitable commercial enterprise would flourish. Since revenues are to date a fraction of total program costs, heated debates occur among the various institutions over appropriate Landsat product prices. Early in the program, the USGS set product prices according to the Department of the Interior's (DOI) legislative guidelines--prices were based on the cost of reproducing the archived product, not on the high costs of acquiring raw data. Thus, in the 1970's, a satellite photographic image cost between $8 and $50, a digital multispectral scanner (MSS) tape cost $200, and annual revenues from data sales never exceeded $3 million (Pohl and Smith, 1979). As the National Oceanic and Atmospheric Administration (NOAA) planned for an operational system, it hypothesized that a 5- to 10-fold product price increase could in itself increase annual revenues over time to $30 to $40 million (U.S. Dept. of Commerce, 1980). NOAA further hypothesized that a 10 percent growth in sales per year plus a 5-fold increase in both product prices and foreign station data reception fees would generate annual revenues of $140 million by the year 2000.

Thus, in concert with the commercialization thrust, overall Landsat data prices have been increased first by NOAA, then by the commercial operator--the Earth Observation Satellite (EOSAT) Company, as shown in Table 1. Since 1980, prices of MSS and thematic mapper (TM) photographic products have increased by 1000 percent to 2000 percent and MSS digital tapes by 500 percent. TM digital tapes have increased in price by less than 200 percent. Also, EOSAT no longer charges fees for special acquisitions. Landsat data sales in the U.S. as a function of price history are shown in Table 2. Not surprisingly, as data prices increased, users became more selective of what they purchased, and units sold decreased (Watkins, 1989b; Pohl, 1988). In fiscal year 1976, the USGSIS EROS Data Center shipped almost 300,000 frames of Landsat photographic imagery (Austin and Rothenbuehler, 1989). Shipped frames dropped to about 125,000 by 1980, to 40,000 in 1985, and to less than 5,000 in 1989. The number of Landsat digital tapes shipped by the Data Center was about 3,000 in 1976, 4,000 in 1980, 6,500 in 1985, and more than 7,000 in 1989. (EOSAT also directly ships some photographic images and digital tapes from Lanham, Maryland, which are not included in the USGS figures.) Having fewer photographic images shipped from one year to the next is not surprising, since this has been the trend for several years. In the early 1980's, when photographic image prices averaged $15 to $20 per item, more than 100,000 items were shipped per year. For the 4,200 photographic images shipped in fiscal year 1989, the range in price per item was from $90 to $1,000. The EOSAT Company attributes at least some of this loss of market share to the availability of data from government subsidized foreign systems (i.e., Satellite Pour l'Observation de la Terre (SPOT) data) and from the U.S. Government's weather satellites (i.e., Advanced Very High Resolution Radiometer data) (Foley, 1989). These trends also show that Landsat data are now being purchased primarily by only a few government agencies and a number of aggressive corporations. Research facilities, academic institutions, educators, students, state and local governments, and the governments of less-developed nations are now purchasing considerably less data than they did a few years ago (Draeger, 1989; Voute, 1987).

Table 1.--Landsat product price examples.

Photographic Images

Year	Organ.	MSS B&W 10" Neg.	MSS Color 40" Print	TM B&W 10" Neg.	TM Color 40" Print
1980	USGS	$ 10	$ 50		
1982	NOAA	$ 35	$ 175	$ 35	$ 175
1985	NOAA	$ 40	$ 195	$ 80	$ 290
1985	EOSAT	$ 90	$ 350	$ 160	$ 500
1989	EOSAT	$ 90	$ 550	$ 300	$ 800
1990	EOSAT	$ 175	$1000	$ 550	$1500

Digital Tapes

Year	Organ.	MSS/CCT	MSS Acq. Fee	TM/CCT	TM Acq. Fee
1980	USGS	$ 200			
1982	NOAA	$ 650	$ 790	$2800	
1985	NOAA	$ 730	$1120	$4400	$1600
1985	EOSAT	$ 660	$1120	$3300	$1600
1989	EOSAT	$ 660		$3600	
1990	EOSAT	$1000		$3960	

(courtesy USGS, NOAA, and EOSAT)

Table 2.--Landsat data sales and price history.

Year	Film Items Sold	Average Film Price	CCT Items Sold	Average CCT Price
1980	128,433	$ 15	4,139	$ 200
1981	128,755	$ 15	4,351	$ 200
1982	115,025	$ 20	4,974	$ 250
1983	76,621	$ 30	5,599	$ 500
1984	34,964	$ 60	5,042	$ 500
1985	39,079	$ 60	6,704	$ 500
1986	19,061	$125	7,100	$1000
1987	12,388	$150	7,842	$1000
1988	9,088	$150	7,992	$1000
1989	4,206	$150	7,374	$1000

(from Watkins, 1989a)

The negative side of commercial civilian space remote sensing was a recurring theme at the meeting of Directors of National Remote Sensing Centers, sponsored by the United Nations Development Program's Economic and Social Commission for Asia and the Pacific (ESCAP), held in Shanghai, People's Republic of China in July 1988. In the opening session of the meeting, the Executive Secretary of ESCAP commented on the "... widespread concern about the increasing cost of obtaining remotely sensed data," and the need to "... explore the possibility of assisting member countries to obtain such data at more reasonable prices" (Kibria, 1988). Then, one director after another included a statement in his or her annual report that condemned current pricing policies for Landsat and SPOT data. For Indonesia, it was "...the unfavorable price relating to satellite imagery" (Irsyam, 1988); for Pakistan, "…the commercialization of satellite remote sensing systems and the increasing cost of space segment services could have an adverse effect on the development of remote sensing programs" (Mehmud and Mirza, 1988); and from Sri. Lanka, " ... paucity of funds has also limited the frequency with which air photography or satellite imagery could be obtained" (Berugoda, 1988). Even a recent report from People's Republic of China noted that if the costs of satellite imagery continue to remain so expensive, China and other countries in the region may have to abandon satellite remote sensing technology and return to the sole use of aerial photography (He, 1989).

Since the mid-1970's, the Regional Center for Services in Surveying, Mapping, and Remote Sensing in Nairobi, Kenya has provide training, user assistance, and project support services to the National Centers in east Africa. But, Hassan and Falconer reported (1986) that the computer tapes comprising one single Landsat TM scene cost the same in Africa as employing a competent car driver for 4 years. They also noted that if a country purchases the tapes, using precious foreign exchange reserves, multiple use of the data throughout that country or region is restricted by the condition of sale. Consequently, for the Nairobi Regional Center, or for any other regional and national remote sensing center in the Third World, to obtain satellite data exhibiting information about the extent and condition of Earth resources in its region, that center must ask for support from institutions within the industrialized nations to acquire the data that is in the hands of those advanced nations.

2.3   Equipment Availability and Costs

To properly integrate remotely sensed data and its derivatives into geographic information systems, users are subjected to the problem of merging two sets of technology. Some of the equipment and procedures are common to both, but a considerable amount of additional hardware and software may also be required. As users attempt to work from what they have to what they need, several problems are likely to occur. While these problems are common, they are also chronic and can be difficult to overcome if not fully understood. Below are listed some of the most common institutional hardware/software pitfalls:

Limited budget--a "chicken and egg" dilemma. All institutions will place constraints on available budget. With limited budget, it may be tempting to follow a course of action that involves acquiring hardware and software that can demonstrate GIS and remote sensing integration without having the capability (or capacity) to properly conduct project work. If pilot or demonstration projects employ different systems than the targeted operational capability, the transition to an operational system can be quite difficult. The use of inadequate systems with flashy outputs may serve to generate the needed budget support, but can also waste considerable time and money when hardware, software, and training costs are calculated. The obvious solution to this problem is to make certain that the first system is not a "throw away" acquisition. For example, one approach that has worked well is to use a workstation configuration for demonstrations, and then to augment that system with file servers, additional workstations, and shared output devices (e.g., plotters, film recorders) when an operational system has been justified.

Inadequate support staff. Software and hardware systems that are needed to conduct digital processing of remotely sensed data will require more time and effort to support than most users would acknowledge. On the other hand, adequate support for operating system and applications programs, and good engineering support for the specialized display and output devices, is critical. Even "turn-key" systems, while providing some efficiencies in the packaging of needed components, will require highly technical support at times. It is important that this support be factored into the institutional decision-making process. This is especially true of agencies that are geographically or institutionally isolated from good hardware support (e.g., developing countries). Countless hours have been wasted as users attempt to fill in for software or hardware experts.

Chasing the technology--a "tiger by the tail." The technologies of remote sensing and geographic information systems are continuing to progress rapidly, as they have for the last few years. This, of course, is good news. Unfortunately, there are very few hardware/software configuration standards to guide new users, and many times the interfaces between a new system and other systems that are required, lag far behind the development of analysis capabilities. One approach that has been taken by larger and more centralized institutions is to enforce a standard configuration. This has not always worked well, because it tends to stop the evolutionary process at a point in time when the system requirements are not even fully understood, much less the technological limitations. A more successful approach has been to concentrate on the interface technology, and to promote data sharing as a means to promoting mutually beneficial interchange of new technology.

Public domain software--the "free lunch." One of the most subtle of the institutional pitfalls that confront users is the promise of a "free lunch"-public domain software. With limited budgets, many institutions spend money on the hardware components of a

system, hoping that public domain software will provide adequate capabilities, at least in the short tem. This approach seems quite logical for a phased implementation. If the software is inadequate, it can be replaced at some future time (and with future funding sources). This is not true of hardware, this logic continues, which is likely to be much more difficult to completely replace.

The public domain approach can and does work at times, but only if: 1) the public domain software performs all necessary functions (not to be confused with functions that are "nice to have"), 2) the user can understand the software well enough to continue development until it performs adequately, or 3) the purpose of the system is for research and development, and not for an operational capability.

The public domain approach will fail when institutions (and users) fail to understand the fundamental nature of free software. Government sponsored developments will make the code available on a "what you see is what you get" basis. Promises of future enhancements and improved user support should be viewed with skepticism, as system developers will likely be assigned to new developments, or to support "paying customers" rather than providing improvements to software already released to the public domain.

The cost of failure in making public domain software perform operationally is generally larger than would be obvious. There is the cost for the replacement software, but also there is the time and effort spent in learning to use (and enhance) the software, and the time needed to relearn a new system. All this represents time that would be lost to performing operational tasks. The point to be made here is that the "free lunch" approach is not for everyone, and, in fact, users should be very cautious in employing public domain software for operational problem solving.

2.4 Certification, Standards, and Practices

Sources and magnitude of errors are major issues in the integration of remote sensing and GIS. Inconsistency and error can creep into a study which incorporates remotely sensed data and GIS techniques when: 1) the remote sensing or GIS analyst is not properly trained, or 2) the analyst uses improper methods. Much of this error may be removed if the analysts are certified an d use professional standards and practices. To highlight this condition, it is useful to compare and contrast a surveyor versus a remote sensing or GIS professional.

Surveyors must be certified (licensed) in the state in which they practice. While it is not always necessary to have a formal degree in surveying, the surveyor must have substantial apprentice experience and pass a standardized surveying examination (Dahlberg, 1990). When performing surveying they must use standardized practices, maintain meticulous notes, state the level of accuracy attained, and sign their work. Anyone using similar procedures and technology should be able to replicate the results with a high degree of accuracy. These conditions generally cause the public to have confidence in maps and engineering drawings produced by surveyors.

Unlike surveyors, remote sensing and/or GIS professionals do not need to be licensed or certified to practice. Most simply do the work and assume it meets generally accepted accuracy standards (whatever this means); or that the data is of sufficient currency and accuracy for a given use. In 1977 the American Society for Photogrammetry and Remote Sensing (ASPRS) initiated a voluntary certification program whereby remote sensing specialists and photogrammetrists could become certified photogrammetrists. As of September 1990, only 618 of the approximately 8,000 members of the society have become certified (7.7%). The Society is also developing criteria for recertification. There is no certification program for GIS specialists as of September 1990, although ASKS is in the process of developing a GIS certification program (Shrader, 1990). Therefore, almost anyone who has taken even a short course in remote sensing or GIS may conduct research and report the results as if they were well qualified.

In addition to the vast majority of practitioners lacking certification, there are no rigorously defined standardized practices. These should eventually be established for the use of remotely sensed data, e.g., for geometric registration and thematic classification. Similarly, while there exist specifications for the preparation and use of digital cartographic data (NCDCDS, 1988), standardized practices for the proper design and use of GIS should be established.

To prevent unqualified scientists from using nonstandard remote sensing and GIS practices, single or multiple societies must take charge of the certification process and work to develop personal certification and methodological standards and practices. Among the most logical societies are the American Society for Photogrammetry and Remote Sensing, the American Congress on Surveying and Mapping and the Urban and Regional Information Systems Association in the United States, and the Remote Sensing Society in England. The National Center for Geographic Information Analysis (NCGIA) should also take the lead in developing the GIS standards and practices. The personal certification and professional standards and practices must be constantly updated by the societies to incorporate improvements in logic, technology, and computation methods. This would hopefully make products derived from remote sensing and/or GIS analysis more consistent and increase their acceptance. The public then should have more confidence in products derived from remote sensing and GIS.

2.5   Education and Training

The status and content of remote sensing and GIS education and training in the U. S. is poorly understood. Only a few studies have attempted to document the status and content of the educational system and how it functions (Dahlberg and Jensen, 1986; Kiefer, 1988; Civco and Kiefer, 1990). Nevertheless, some general observations about institutional and programmatic shortcomings in the remote sensing/GIS educational system can be made.

Who performs the education and training? All too often a faculty member is conscripted into teaching remote sensing or GIS because they have had a single course in these areas and are by default the most literate on the subject within the department. Conversely, the ideal educational environment occurs when a professor who has a sound background in remote sensing and GIS is actively conducting remote sensing research and takes the time to translate the new knowledge which he or she is continually gaining into meaningful lecture material and laboratory exercises. In certain instances, students also have the opportunity to work side-by-side the professor conducting the research as research assistants (as opposed to teaching assistants who help with laboratories and grades papers). This interaction with the professor in the research environment educates students on how to approach and solve problems as apprentices. Also, research ethics are communicated to students. Well trained, certified professors (discussed in Section 2.4) will insure that erroneous misconceptions about remote sensing and GIS are not propagated and that inaccurate results are not produced when interpreting remotely sensed data.

Considerably fewer opportunities for assistance and training exist in less-developed countries, where the infrastructure necessary for making effective use of remote sensing and GIS technologies is often lacking. Part of the infrastructure needed in these countries is well-educated and highly trained personnel, which involves training of decision-makers, training of teachers, and the providing of training materials (Tauch and Albertz, 1988). In the case of satellite remote sensing, it is not clear under the current U.S. policies guiding the commercialization of Landsat whether educational cooperation with the Third World is a government, commercial operator, or joint government/commercial operator responsibility, or whether it is even considered an important institutional issue. What is clear, however, is that over the last few years there has been a significant decrease in U.S. sponsored education and training programs for less developed countries in the uses of commercially available satellite data.

The remote sensing specialist "mystic". Scientists who use remotely sensed data and GIS capabilities must: 1) have a systematic knowledge of the environment, 2) understand how remote sensing systems function, 3) know how to extract accurate information from remotely sensed data, 4) know how to structure the data in a suitable GIS, 5) know how to model or query the GIS data base to answer important questions, and 6) know how to communicate the results to others. Unfortunately, item number 1--a systematic knowledge of the environment--is often woefully inadequate. All too often students want to become remote sensing or GIS specialists without have a systematic area of study (e.g., soils, agriculture, forestry, wetland, oceanography, urban structure) to which the remote sensing or GIS can be applied. Although there are some successful remote sensing/GIS specialists who have no systematic knowledge of the environment, it seems that the most worthwhile research is conducted by persons well trained in a systematic area (Jensen, 1989).

Remote sensing and GIS analysts are poorly trained in field techniques. Remote sensing courses rarely cover how to conduct field investigations that are specific to a systematic body of knowledge, e.g., the grain size of a soil or how to use a sling psychrometer. In fact, most remote sensing courses rarely have the students venture into the field at all! Remote sensing courses in the future must teach students how to: 1) conduct specific types of field sampling (e.g., soil moisture, leaf area index, biomass) that support and calibrate the remote sensing data, 2) use spectroradiometers to measure the terrain in situ during the overflight (especially how to calibrated them), and 3) relate or model the in situ data with the remotely sensed data. Nationwide, remote sensing courses must improve the teaching of in situ data collection techniques which build upon other field techniques learned in the student's systematic study area (e.g., soil measurement techniques). This is an area of great significance which must be addressed.

Knowledge of fundamental photo interpretation principles. It is painfully obvious that people allowed to take digital cartography or GIS courses without having taken the introductory thematic cartography courses produces misleading and often cartographically inaccurate results. Similar disasters occur when persons are allowed to take digital image processing courses when they have never had a fundamental course in photo interpretation. It is imperative that a person progress from a knowledge of fundamental aerial photography, to more exotic sensor systems (thermal infrared, radar), and then and only then be allowed to begin to interpret an image using digital image processing techniques. This leads to the next observation, the analog versus digital dichotomy.

The analog versus digital dichotomy. During the 1970's and early 1980's there has been a substantial emphasis on digital image processing and digital GIS. During this time the art and science of photo interpretation remained relatively stagnant without much emphasis given to the development of new theory and knowledge. With the advent of high spatial resolution data (especially SPOT 10 x 10 m panchromatic and enhanced TM data when available), one will finds that these data contain information similar to that available from panchromatic aerial photography. Therefore, a new synergistic relationship is developing. For rural, agricultural, forestry areas, etc., data analyzed using digital image processing techniques may yield the best results. Conversely, for urban areas and

other environments which consist of high spatial frequency information, the data may be best analyzed by a human being who may or may not use digital image processing techniques. Thus, the final product which eventually ends up in a GIS data base often is a mixture of both analog and digital image processing techniques (Jensen and others, 1990). There will be increased awareness of the importance of visual photo interpretation techniques which will become just as important as the digital techniques. In fact, to have true expert systems in remote sensing then this is exactly how they must function (Jensen and others, 1989). Persons who only know how to do digital image processing will be severely handicapped as the higher spatial resolution remotely sensed data becomes available. Course offerings in visual image interpretation should take this future scenario into consideration.

The interface between remote sensing and GIS. It is advantageous for students who specialize in remote sensing to take courses in GIS and vice versa. More attention is needed in both remote sensing and GIS courses on how to integrate remote sensing into the GIS data base and GIS information into the remote sensing system (Gernazian and Sperry, 1989). This should not be a one-way street. Remote sensing studies can be improved substantially in certain instances when information from the GIS is incorporated as ancillary data in the classification or rectification process. Conversely, GIS data bases require timely, accurate information which often can only be provided from remote sensing. This synergistic relationship must be nurtured and taught more effectively. The ideal mechanism is a specific course on the integration of remote sensing and GIS.

Modeling and remote sensing. In the future, it will be important that geographers and others know how to model the remote sensing signal. This means that the student must know and understand in detail the nature of the incident electromagnetic radiation, how it interacts with the atmosphere, how it interacts with the terrain, and how it eventually interacts with the remote sensor system. Students must realize that if we can successfully model the interaction of energy with the atmosphere, terrain, and sensor system, then there is a high probability that we actually understand what is taking place. Fundamental courses in modeling must first be introduced as separate courses in geography (where approximately 50% of the remote sensing instruction takes place) and other disciplines. Then, remote sensing courses on how to perform modeling of the atmosphere, terrain, and sensor system energy interactions should be taught. There are currently only a few scientists in the United States who are adept at modeling the remotely sensed signal. This will be one of the great areas of retraining that must take place if current remote sensing professors and professionals desire to stay active in the field. Extension courses, short courses, and self-teaching will probably be the major mechanisms.

Remotely sensed data sets for education and training. An obvious negative impact of current institutional issues plaguing the U.S. civilian satellite land remote sensing program has been in the areas of education and training. Studies have shown that users, especially potential users, of satellite data are in general low on the "learning curve" for making maximum use of these data (Henderson, 1986; Maxwell, 1980). Some of the problems in education and training were noted by Estes (1980) at a conference among remote sensing educators held at Stanford University on June 26-30, 1978. He was tempted to call a well-trained remote sensing technologist a person who is "all things to all people," due to the breadth of physical, biological, and socioeconomic information embodied in the technology. Both user assistance and formal training opportunities related to satellite remote sensing are generally available in the U.S. and in most other developed countries (Dahlberg and Jensen, 1981; Estes, et al., 1980). One noticeable impact in this area, however, has been a decrease in the amount of Landsat data sold to colleges and universities. In 1976, customers in academia purchased from the USGS's EROS Data Center over 25,000 Landsat photographic images and 270 digital tapes for a total of $177,000 (Draeger, 1989). In 1988, they purchased only about 400 photographic images and 380 digital tapes for $330,000, a cost of approximately double the 1976 expenditure. Other factors besides data prices may have affected demand over this 12-year period, but there is little doubt that large price increases have drastically limited academia's access to Landsat data. Furthermore, there is very little sharing of satellite remotely sensed data taking place because of the copyright restrictions placed on data from SPOT Image and EOSAT. These companies have developed an initial image data base of a limited number of scenes which can be purchased at a nominal fee by academics (Barker, 1990; EOSAT, 1990). However, there needs to be a data bank set up by either the Remote Sensing Specialty Group of the AAG, the NCGIA, or some other entity which collects and catalogs analog and digital images from around the world which are to be used for instructional purposes. Dr. Paul Gray (1990), the President of MIT, recently said that, *Connections between academia and industry; both foreign and domestic, are crucial to the health of U.S. research, education, and competitiveness." This is one area where such connections are vital. Instructional remotely sensed data should be made available to academics for the cost of duplication. In order to do this, negotiations must take place with both SPOT Image and EOSAT to ensure the copyright is maintained.

A remote sensing core curriculum. Given these observations and recommendations, perhaps it is wise to suggest an undergraduate remote sensing education and training core curriculum (Civco and Kiefer, 1990). This curriculum would be agreed upon by representatives from academia, practicing resource managers, and professional societies (e.g., ASPRS, ISPRS, ACSM). For example, the NCGIA has developed such a core curriculum for education and training in GIS. The first draft of the three-part program, consisting of Introduction to GIS, Technical Issues in GIS, and Application Issues in GIS was completed in the summer of 1989 and has undergone extensive evaluation by educators during the 1989-1990 (Estes and others, 1990). The NCGIA curriculum represents a comprehensive set of lecture and laboratory materials and is an attempt to standardize introductory, technical, and applied training in GIS. Based on both the widely varying content of what is taught and the apparent success of the NCGIA program, it is perhaps desirable to suggest a similar core curriculum for remote sensing education, and in fact, the NCGIA curriculum can serve as a model

for the proposed remote sensing program. Civco and Kiefer (1990) suggest that the remote sensing core curriculum would first be concerned with the development of three specific courses which could be taught nationwide dealing with: Course One: Introductory Remote Sensing; Course Two: Advanced Remote Sensing; and Course Three: Case Studies in Remote Sensing. Additional courses would be developed to support the core curriculum.

2.6 Infrastructures

As noted above, institutional issues rather than technical factors usually govern the acceptance and operational use of remotely sensed data and GIS techniques. For any organization to make routine, operational use of digital spatial data, a viable infrastructure to support the use of that data and a capacity for internal problem solving are essential. When the first Landsat was launched in 1972, there was no infrastructure for implementing satellite remote sensing in any of the land management agencies of the U.S. Government, so there was little acceptance or understanding of Landsat technology. As a result, little use was made of the acquired data. Over about a ten year period, the necessary institutional infrastructures were constructed--managers were made aware, equipment was purchased, demonstration projects were conducted, and resource specialists were trained. Federal agencies eventually integrated this new space technology into operational land management programs. In DOI, for example, almost every bureau established a remote sensing coordinator and hired remote sensing experts. The USGS's EROS Data Center acted as a central facility in support of DOI's national remote sensing program, and today the Director of the Data Center chairs the DOI Remote Sensing Task Force--a coordinating body for current and future remote sensing activities within the Department.

Long-term technical and financial commitment. A crucial ingredient in the federal infrastructure described above is the long-term technical and financial commitment given to this new technology by federal agencies, e.g., DOI, NASA, and Environmental Protection Agency. Likewise, if digital spatial data are going to be accepted and used worldwide, a similar commitment must be made by the participating government organizations. A major component of a U.S. program for international cooperation using remote sensing and GIS technologies must include long-term technical and financial commitments that will allow for the establishment of the institutional frameworks, organizational infrastructures, and human resources needed in the developing regions of the world.

In one important respect, however, these institutional commitments need to be strengthened. That is, more resources need to be directed towards fundamental research on remote sensing/GIS integration. There are major barriers here. A number of funding agencies appear to feel that all the problems are solved. Others feel that perhaps private industry has the answers or will come up with them. A recent National Academy of Sciences report on "Spatial Data Needs: The future of the National Mapping Program" states:

> If ours is to be an information-based economy that is competitive on a global basis, there is a critical need for a coordinated and efficient national information infrastructure to facilitate the sharing and communication of information resources (Nat'l Res. Council, 1990).

One of the report's major recommendations is that the USGS's National Mapping Division should expand its current research activities in digital cartography, geographic information systems, and remote sensing and image processing. This statement is valid for a number of other federal agencies as well. Moore (1987) suggests that a viable solution for gaining increased involvement of developing countries (in this case, in using remotely sensed data in a GIS for hydrologic studies) must include ensuring continued data availability tied to programs that train developing country resource scientists and managers. He feels programs that financially support data purchases will provide a mechanism of creating an information explosion to the planners and managers of developing countries. Moore also notes that to use the information beneficially, integrated resource inventories, well-structured monitoring programs, and efficient information handling and management systems also must be established--which will require a major increase in international cooperation and financial support on the part of the U.S. and other developed nations. The enormous challenge in the developing parts of the world, according to Chagas (1984 and 1987), is for remote sensing and GIS technologists to develop new ways of integrating these new technologies with existing economic and cultural aspects of society in a manner that respects and builds upon local talent and existing institutional infrastructures.

Basic technology needs. As noted earlier, remote sensing and GIS are relatively advanced technologies. They require advanced equipment and skilled individuals with special training in interdisciplinary analyses as well as support staff with advanced training in computer science and electronics. An institutional infrastructure must be present to support and nurture an environment where appropriate equipment and staff exist as a base requirement for effective remote sensing and GIS integration. This infrastructure varies from items as basic to constant, 115v power sources and appropriate air conditioning to items as complex as high speed computer networks and the associated staff to support them. While these basic technology needs are usually met in developed countries, there are severe barriers to high technology implementation in developing countries..

Life cycle versus procurement cycle. Integration of remote sensing and GIS technologies requires sophisticated analytical photogrammetric and digital image processing workstations with GIS workstations. These workstations, largely the result of the introduction of Reduced Instruction Set Computing (RISC) technologies, are gaining capability at a rate greater than the speed at

which most procurement cyclescan be carried out. Standards that are written for the state-of-the-art at one point in time are easily eclipsed by advances in hardware and software during the procurement cycle. Additionally, for federal procurements, improvements in competing software and hardware may result in protests which delay procurements even further. In many cases, advances are impossible to anticipate, and procurements may be outdated even before final order. Institutions need to carefully weigh the costs and benefits of incorporating new software and hardware in a cycle that probably does not exceed 3 years. This is an especially difficult scenario for federal institutions, since their procurement and implementation cycle is approximately 3 years, as well.

Interdisciplinary work mechanisms. Remote sensing and GIS are essentially interdisciplinary in nature. Most organizations are formed along a disciplinary core (i.e., hydrologists, foresters, urban and regional planners, air quality specialists, etc.). Integration of these activities requires new infrastructures with a focus on the interdisciplinary nature of the technologies. Yet, disagreements over jurisdiction, funding, and responsibility often form barriers in addition to the technical barriers inherent in understanding and applying the technologies themselves (i.e., one may have to understand physics, computer science, statistics, cartography, engineering, and biological science to effectively integrate remote sensing and GIS in an ecological study).

Interagency/intergovernmental work mechanisms. As organizations become more institutionalized, they tend to view their own work as the "center." This results in attitudes, procedures, guidelines, and rules that tend to limit the free interchange of information. Examples of this are extreme Agency review cycles for scientific information, lack of common data dictionaries and classification procedures for mapping data, and perceived needs for the maintenance of data confidentiality. All of these factors tend to close down opportunities for cross-fertilization of ideas from institution to institution. Resources tend to be viewed as scarce items to be protected and directed only toward the goals and priorities of the "owning" organization. In the extreme, Landsat imagery purchased for a hazardous waste study may be prohibited from being used within the same organization for an ecological study, just because it was purchased with protected funds.

3.0   Discussion: The Landsat Example

The U.S. has exhibited undisputed technological leadership over the last 25 to 30 years in nearly all civilian space endeavors and especially in the field of Earth observations from space (Ride, 1987). This country performed most of the innovative research and development that led to the design, testing, and implementation of today's spacecraft, sensor systems, and data processing and analysis tools. Considerable efforts also have been expended by the U.S. on establishing mechanisms for disseminating data, developing applications, conducting training, and giving user assistance on a worldwide basis. Just as this technology started to show signs of maturity and other nations began making major commitments to their own systems, the U.S. Government chose to transfer its responsibility for civilian space remote sensing (i.e., the Landsat program) to the private sector.

In its 1975 report on practical applications of space systems, the U.S. National Research Council's Space Application Broad (1975) noted that the potential users of Landsat data are distributed throughout many fields of activity and many states, cities, industries and businesses, and thus do not constitute an aggregated "market" to which commerce and industry can easily respond. During the 1970's and early 1980's, the U.S. Government, particularly via NASA, DOI, and DOA, attempted to foster uses of space data in the Earth resource disciplines through an aggressive and often expensive technology transfer program. NASA supported such programs as University Grants, Regional Applications, Technology Application Center, and Applications Systems Verification Tests (Morain and Thome, 1989). In cooperation with DOA and NOAA, NASA also conducted several very large agricultural crop inventory and assessment projects. Likewise, DOI and DOA funded cooperative projects among sister bureaus, conducted training programs, and carried out a variety of application development efforts. As the market for space remotely sensed data was beginning to be understood, partly as a result of these government-sponsored technology transfer activities, the U.S. Office of Manager and Budget (OMB) continued to press hard for demonstrated favorable cost/benefit results.

Institutional issues have from the very beginning plagued national policy making in this program. Conflicts between the space agency (NASA) and the resource agencies (DOI, DOA) erupted when the program was being conceived. OMB opposed the program from the beginning and remains skeptical today. NOAA, with a mission geared not to land areas, but to the oceans and atmosphere, has overall management responsibilities for a satellite program that is directed at land resources. The Department of Defense and the intelligence community have continually raised questions and concerns over the civilian program's relationship to military satellite systems--raising the spectra of conflicts over national security. The EOSAT Company, the private operator of the Landsat program, is attempting to carry out a contractual obligation with NOAA as the U.S. Government continually reneges on the agreed-upon level of funding, resulting in multiple starts and stops in the building of any future satellites. NOAA, noting that revenues from Landsat data sales have remained essentially flat since 1985 (the last year of government operation), has accused EOSAT of: 1) making little apparent progress in addressing the market as a commercial venture; and 2) showing no willingness to put its own capital at risk to demonstrate good faith and confidence that commercialization can succeed (U.S. Dept. of Commerce, 1988). It sometimes appears that only one
institution is not involved in the fray, but rather is usually ignored--the disaggregated, highly diverse group, called the users. When asked about space remote sensing, users will agree that they want to see a stable program with long-term continuity of data.

Many of the institutional problems noted above were well documented more than 15 years ago (National Research Council, 1975), but little action was taken to correct them. Current and future policy making for the U.S. civilian satellite land remote sensing program will continue to suffer from inefficiencies until a mechanism is created that removes the institutional conflicts occurring within the U.S. Government, and between it and the private sector.

4.0   Summary and Conclusions

5.0   References

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Institutional Issues

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Objectives of Panel:

* Identify Institutional Issues
* Develop an Improved Understanding of the Issues
* Illustrate the Issues with Case Studies
* Explore the Challenges Facing the Research Community

Objectives:

* The Issues--Sometimes Called "Deterrents"
  - overselling   - misapplication
  - overkilling   - timidity
  - undertraining   - inadequate infrastructure
  - underinvolvement   - inadequate understanding
  - spurious evaluation   - inordinate distrust

                                          (Colwell, 1987)

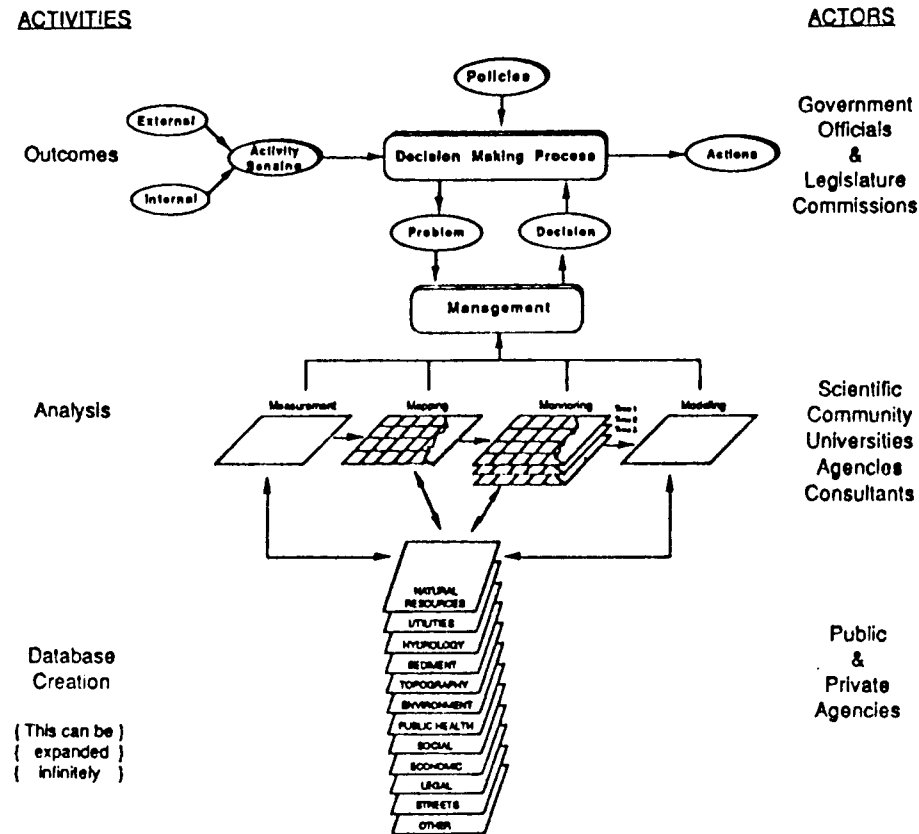## Background

* Rapid Technological Advancements
* Slow Acceptance
* Institutional Complexity
* A Decision Support System
* Interdisciplinary Communications

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REMOTE
SENSING
— AND —
GEOGRAPHIC
INFORMATION
SYSTEMS

INSTITUTIONAL ISSUES

BACKGROUND:

- A Decision Support System

(courtesy of D. Cowen)

Institutional Issues:

* __Issue #1__   Data Availability
* __Issue #2__   Data Marketing and Costs
* __Issue #3__   Equipment Availability and Costs
* __Issue #4__   Certification, Standards, and Practices
* __Issue #5__   Infrastructures

__Issue #1__   Data Availability

* Hard to Find Data
    - FICCDC (renamed FGDC) study results
    - Institutional Commitment (marketing, distribution, services, etc.)

* Non-Existent Data
    - DLG's and DEM's, land use/land cover
    - satellite data (3 to 5 m resolution, SAR, etc.)

* Data Sharing
    - awareness, resistance, proprietary, liability, etc.

* Data for Global Change Research

__Issue #2:__   Data Marketing and Costs:

* Geographic and Cartographic Data
    - cost effectiveness
    - expediency
    - Master Data Directory (NASA), National Digital Cartographic Data Base (USGS), and others

*   Satellite Remotely Sensed Data
        - commercialization of the U.S. civilian program
        - Landsat product prices
        - Landsat data sales
        - impacts of commercialization

Satellite Remotely Sensed Data
- Landsat product price examples (photographic)

Year	Organ.	MSS B&W 10" Neg.	MSS Color 40" Print	TM B&W 10" Neg.	TM Color 40" Print
1980	USGS	$ 10	$ 50		
1982	NOAA	$ 35	$ 175	$ 35	$ 175
1985	NOAA	$ 40	$ 195	$ 80	$ 290
1985	EOSAT	$ 90	$ 350	$ 160	$ 500
1989	EOSAT	$ 90	$ 550	$ 300	$ 800
1990	EOSAT	$ 175	$ 1000	$ 550	$ 1500

(Courtesy USGS, NOAA, and EOSAT)

Issue #2   Data Marketing and Costs

* Satellite Remotely Sensed Data
    - Landsat product price examples (digital)

Year	Organ.	MSS/CCT	MSS Acq. Fee	TM/CCT	TM Acq. Fee
1980	USGS	$ 200			
1982	NOAA	$ 650	$ 790	$ 2800	
1985	NOAA	$ 730	$ 1120	$ 4400	$ 1600
1985	EOSAT	$ 660	$ 1120	$ 3300	$ 1600
1989	EOSAT	$ 660		$ 3600	
1990	EOSAT	$ 1000		$ 3960	

(Courtesy USGS, NOAA, and EOSAT)

Issue #2   Data Marketing and Costs

* Satellite Remotely Sensed Data
    - Landsat data sales and price history

Year	Film Items Sold	Average Film Price	CCT Items Sold	Average CCT Price
1980	128,433	$ 15	4,139	$ 200
1981	128,755	$ 15	4,351	$ 200
1982	115,025	$ 20	4,974	$ 250
1983	76,621	$ 30	5,559	$ 500
1984	34,964	$ 60	5,042	$ 500
1985	39,079	$ 60	6,704	$ 500
1986	19,061	$125	7,100	$1000
1987	12,388	$150	7,842	$1000
1988	9,088	$150	7,992	$1000
1989	4,206	$150	7,374	$1000

(Watkins, 1989a)

Issue #3   Equipment Availability and Costs

* Limited Budget--a "Chicken and Egg" Dilemma
  - demonstrations vs. operations
  - upgradable workstation
* Inadequate Support Staff
* Chasing the Technology--a "Tiger by the Tail"
  - hardware/software configuration standards
  - system interfaces
* Public Domain Software--the "Free Lunch"
  - functionality, documentation, user friendly,
    maintenance, enhancements, etc.

Issue #4   Certification, Standards, and Practices

* Problems with Consistency and Errors
  - lack of training
  - use of improper methods
* Licensed to Practice
  - surveyors
* Voluntary Certification
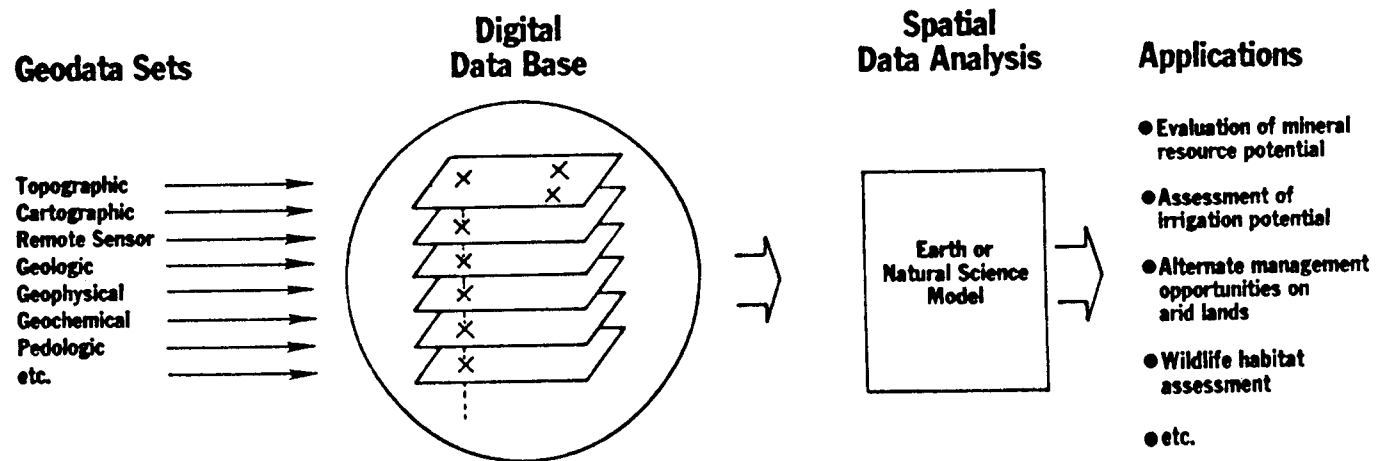 - photogrammetrists
* Methodological Standards and Practices

Issue #5   Education and Training

* Who performs the Education and Training?
* The Remote Sensing Specialist "Mystic"
* Training in Field Techniques
* Principles of Photo Interpretation and Thematic Cartography
* The Analog vs. Digital Dichotomy
* The Interface between Remote Sensing and GIS
* Modeling and Remote Sensing
* Remotely Sensed Data Sets for Education and Training
* A Remote Sensing Core Curriculum

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GEOGRAPHIC
INFORMATION
SYSTEMS

INSTITUTIONAL ISSUES

ISSUE #5 EDUCATION AND TRAINING:

- The Interface Between Remote Sensing and GIS

| Geodata Sets | Digital Data Base | Spatial Data Analysis | Applications |

Geodata Sets

Topographic
Cartographic
Remote Sensor
Geologic
Geophysical
Geochemical
Pedologic
etc.

Digital Data Base

Spatial Data Analysis

Earth or
Natural Science
Model

Applications

● Evaluation of mineral
resource potential

● Assessment of
irrigation potential

● Alternate management
opportunities on
arid lands

● Wildlife habitat
assessment

● etc.

Issue #6 Infrastructures

* Constructing Infrastructures
* Long-term Technical and Financial Commitments
* Understanding Basic Technology Needs
* Life Cycle vs. Procurement Cycle
* Interdisciplinary Work Mechanisms
* Interagency/intergovernmental Work Mechanisms

Constructing Infrastructures in Dept. of the Interior in the 1970's

- managers were made aware
- demonstration projects were conducted
- equipment was purchased
- resource specialists were trained
- remote sensing coordinators were established
- remote sensing experts were hired
- a Data Center was built
- a DOI Remote Sensing Task Force was formed

A Case Study--The Landsat Program:

* Undisputed Technological leadership?
* Innovative Research, Development and Applications?
* Aggressive Government sponsored Technology Transfer?
* Institutional Issues Plague National Policy
    - conflicts between NASA and DOA/DOI
    - management responsibility with NOAA
    - relationship to DOD/intelligence satellites
    - start-stop-start contract with EOSAT
    - users have been largely ignored

Summary of Institutional Issues:

* <u>Issue #1</u>   Data Availability
* <u>Issue #2</u>   Data Marketing and Costs
* <u>Issue #3</u>   Equipment Availability and Costs
* <u>Issue #4</u>   Certification, Standards, and Practices
* <u>Issue #5</u>   Education and Training
* <u>Issue #6</u>   Infrastructures

Conclusions

Institutional Issues are Mostly Administrative, Managerial, or Political...

Einstein was once asked, "How come there are so many geniuses in physics and so few, if any, in political science?" He answered, "I guess physicists work on easier problems."

(Katz, 1976)

Recommendations For A Research Agenda:

* Need to Evaluate the Management of Spatial Data within Public Institutions
* Need to Decide What Institutions Will Provide Which Data
* Need to Define Mechanisms for Improved Sharing of Data and Exchange of Information
    - information as a public good
    - value of multiple uses of information
* Need to Assess FICCDC (now FGDC) Effectiveness
* Need to Link Academic Research with Industrial Competitiveness
* Need Creative Consortiums Between Institutions
* Need to Upgrade University Facilities and Develop Core Curricula

Research Needs in Processing and Analysis of Remote Sensing and GIS Data

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INTRODUCTTON

The purpose of this paper is to identify and discuss some basic scientific issues and research needs in the joint processing of remote sensing and GIS data for environmental analysis. Over the past decade there has been an explosive increase in geo-referenced data and computer systems for spatial data handling. Our perspective is that of scientists attempting to take advantage of these data and new technologies to investigate real world environments, their conditions, problems, patterns and dynamics. In this sense, we approach GIS as a tool, or as Goodchild (1985) defined it, as:

"... a system that uses a spatial data base to provide answers to queries of a geographic nature (P.36)."

The type of spatial data base that we are concerned with is very large (e.g., 10^2 - 10^5 megabytes) and includes fundamentally different kinds of data, for example, a) multi-temporal and multiresolution digital images acquired from one or more satellite and aircraft platforms, b) gridded elevation data, c) digitized maps of terrain variables such as soil types, hydrography and vegetation cover, d) socioeconomic data (e.g., population density, zoning district), aggregated by political reporting units, and e) surface measurements of several environmental variables at scattered locations. Our queries of this database range from relatively simple (e.g., where? how much?) to extremely complex (e.g., what is the projected distribution of variable A at time T based on linked simulation models 1, 2 and P).

Much work has been devoted to overcoming the technical obstacles to joint processing of image and GIS data, the advent of an Integrated Geographic Information System (IGIS) capable of handling multiple data structures and supporting complex spatial analyses and user queries is fast approaching (Ehler et al. 1989; Faust et al., this issue). In contrast, scientific theory on the nature of the amalgamated data inputs and outputs of IGIS has been slow to develop. Some features of IGIS analysis, by which we mean joint analysis of remote sensing imagery and other digital spatial data, make interpretation of the outputs especially complex, for example:

- lack of explicit theory to guide spatial analysis of many earth surface processes;
- use of mixed data types that can vary in their structure, level of pre-processing and degree of human interpretation or generalization;
- multiple (and often poorly known) measurement scales, ranging from "points" to regular or irregular regions;
- unknown measurement errors for most variables;
- unknown spatial dependencies in data inputs and their propagation through to model outputs;
- limited capability for model sensitivity analysis;
- limited ability to verify or validate IGIS model outputs.

The research priorities identified here are tentative and intended to initiate discussion and debate among IGIS users. We do not attempt a full review of the literature on remote sensing and GIS, nor do we try to cover all of the research issues that must be addressed. Many important topics such as the integration of disparate data structures, analysis of large spatial databases, user-IGIS interfaces, and error analysis are the focus of other research initiatives by the National Center for Geographic Information and Analysis, and also treated elsewhere in this issue. Instead, we touch on a few topics related to IGIS data analysis and modeling and expand on two general topics that we believe are high priority areas for research: 1) data transformations and information flow in IGIS analysis, and 2) scale-dependence of IGIS data and products. The discussion here will be at a fairly high level of generalization. We believe, however, that a focusing and prioritization of research needs must occur as soon as possible both to coordinate research efforts and to guide the design of future hardware and software systems.

DATA PROCESSING AND INFORMATION FLOW IN IGIS ANALYSIS

IGIS analysis can be conceptualized as a flow of geographic data through a series of transformations into geographic information (Figure 1). Data flow in geographic information systems ultimately begins with geo-referenced measurements of the "real world," whether by sampling, survey or remote sensing. These measurements take several fundamentally different pathways to incorporation in a digital spatial database. Ground and survey measurements may be entered directly into the database, potentially carrying with them both measurement error and locational error, or they may be interpolated to make a map, in which case sampling and estimation errors must also be considered (Curran and Hay, 1986, Curran and Williamson 1986).

Analogue remote sensing imagery is usually converted to geographic information by human interpretation, whereas digital imagery is guided by human analysts but also depends on image processing and statistical algorithms (see Duggin and Robinove (1990) for a fuller treatment of information flow in remote sensing). Photointerpretation of imagery is a complex, interpreter-dependent process that involves both objective and subjective criteria (Estes et al. 1983). Automated or semi-automated digital image

analysis is also analyst-dependent, and the main difference may lie in the more uniform application of rules for information extraction across an image or series of images (Duggin and Robinove 1990).

The merging of ground, map and image data requires digitizing, data rectification and registration, each entailing additional transformations of the original measurement data. These include introduction of noise (e.g., locational and thematic errors), but also may involve more fundamental changes in the input data. For example, conversion of gridded elevation data to a Triangulated Irregular Network (TK for vector-based analysis changes the effective spatial scale of surface representation and the surface topology, with profound effects on modeling of topographic processes such as surface runoff or solar radiation (e.g., Theobald 1990).

Once compiled, the geographic database is used in analysis and modeling to derive new geographic information, which in turn may guide processing steps or serve as input to subsequent IGIS analyses. Efforts to relate processing flow to model output usually focus on this step, taking the form of an accuracy assessment or model sensitivity analysis. However, it is obvious that the quality of the new geographic information may depend as much on any of the preceding processing steps as on this last step, that is the joint analysis of the remote sensing and GIS data. Often the original measurement data and steps taken in developing the geographic database are not documented in sufficient detail to relate them to model output. This renders model testing and validation an extremely ad hoc process that, at its worst, can lead to misspecification of the modeling procedures in order to compensate for errors, biases or scale-dependencies introduced during database development. As the database and analytical products are used to guide the acquisition and processing of new data, geographic "misinformation" can become deeply embedded in the overall data processing flow.

Tracking the changes in geographic data during processing is clearly a formidable task, in part because of the wide variety of changes that can occur, including:

- value range
- precision (higher $\rightarrow$ lower)
- spatial or temporal resolution (higher -4 lower)
- type (numerical $\rightarrow$ ordinal $\rightarrow$ categorical $\rightarrow$ binary)
- structure (tabular $<\rightarrow$ vector $<\rightarrow$ raster)

For remote sensing data, transformations that occur in processing radiances into geographic information generally raise the information level of the data (Ehlers et al. 1989, Duggin and Robinove 1990). Additional transformations to remotely sensed data and those imposed on existing geographic data tend to lower the information content of those data.

Many of the important research issues in IGIS data processing can be posed in terms of the following questions:

> How do the accuracy, resolution, scale-dependence and predictive value of the information that flows from IGIS analysis depend upon the measurement and processing strategies used to derive that information?
> What is the appropriate mix of ground measurements, satellite measurements and existing cartographic information for modeling a particular process?
> What are the preferred processing strategies and algorithms for production and integration of digital geographic data?
> What methods should be applied or developed to track changes in the content, spatial and temporal properties of geographic data during data processing and analysis?

Our view, as illustrated by Figure 1, is that research into integrated processing of remote sensing and GIS data must consider the origin and evolution of those data, and therefore must be placed in the larger framework of geographic analysis, incorporating the theory and methods of mathematics and spatial statistics, cartography, remote sensing and GIS (Fisher and Lindenberg 1989). Relevant research issues range from those related to measurement and sampling of geographical variables to those concerned with geographic data storage, retrieval and display, to development of methods of spatial simulation modeling, verification and validation.

In principle, the relationships among cartography, remote sensing and GIS should be highly synergistic. Remote sensing allows the investigator to measure (at points in time) and monitor (in serial time frames) surface electromagnetic variation. GIS capabilities facilitate the organization of these measurements in time and space, and the cartographic database provides the informational template and context to model change and to infer processes linking associated spectral phenomena.

In practice, there are many poorly understood tradeoffs in coupling satellite data to existing thematic maps. Maps use points and lines to represent selected features of the environment in a highly abstracted and generalized fashion (Peucker and Crisman 1975). Map properties such as minimum mapping unit, degree of generalization, boundary accuracy, thematic accuracy are typically unknown and may vary considerably from one part of a map to another. Satellite data differ from traditional cartographic data in their consistency, high positional accuracy and high spatial resolution. These are quite complementary features, and there are many ways in which remote sensing and GIS data have been profitably merged, for example:

- use of satellite data to update and/or improve the positional accuracy of maps (e.g., Hill and Kelly 1987);
- use of GIS data to segment satellite imagery for improved image classification (e.g., Strahler 1981, Hutchinson 1982);
- calibration of satellite data and overlay on thematic maps for spatially distributed process modeling (e.g., Running et al. 1989).

On the other hand, joint analysis of satellite and map data such as topographic data or soils data carries the following costs:

- increased data volume and processing time;
- loss of precision and object-based representation of map information during vector to raster conversion;
- new cartographic error due to misregistration of image and map data,
- imposition of thematic map errors on satellite measurements;
- new cartographic error due to misspecification of the relationship between map classes and satellite data.
- unknown spatial attributes of output data in terms of their effective resolution, error structure,

The literature on integration of remote sensing and GIS is now well stocked with examples of integrated analysis of remote sensing and GIS data. None have systematically examined the full suite of transformations, information gains and losses that inhere in this integration. One transformation with potentially severe consequences in environmental modeling and analysis is the changes in the effective scale or resolution of output versus input information, as discussed in the next section.

SCALE-DEPENDENCE OF IGIS DATA AND OUTPUTS

By *scale* we mean the integral of space or time over which a measurement is made (Table 1). Nearly all surface processes are highly scale dependent, that is their magnitude or variability depends on the measurement scale. Each of the disciplines in the earth sciences recognizes *characteristic scales* for the processes it investigates. For example, atmospheric scientists distinguish microscale versus mesoscale processes as those occurring at length scales of 0.01-1000 m versus 10 - 1000 km, respectively (Oke 1987). Processes at different characteristic space and time scales are associated with different phenomena. For example, a hurricane is a feature of atmospheric circulation associated with mesoscale pressure gradients over a characteristic time scale of a few days. Characteristic scales thus define the space and time integrals with which a process can be monitored but also the characteristic dimensions of surface phenomena. Many natural systems exhibit hierarchical organization, with nested patterns and processes occurring over a wide range of characteristic space/time scales.

Environmental scientists using remote sensing and GIS data usually operate at multiple space and time scales wherein data density is a technical consideration. As illustrated in Figure 2 (modified from Townshend 1987), data density depends jointly on spatial and temporal resolution (and the spectral dimensionality of the sensor), so that data density decreases from the lower left to upper right comers of the diagram. Continuous increases in computing capacity have shifted the data volume threshold towards the lower left hand comer, allowing the investigation of processes operating at relatively fine space and time scales over increasingly large areas and with finer spectral resolution. Nevertheless, there are still very real practical limits to the spatial and temporal domain of remote sensing for regional and global analysis. These scales are still far coarser than the measurement scales of many kinds of biophysical data, for example small plot measurements of biomass or trace gas fluxes, or high time frequency of measurements of rapidly varying atmospheric properties such as temperature, humidity or cloud cover. A real challenge in the interfacing of remote sensing and GIS for earth science applications is the proper nesting of phenomena/process observations at multiple space and time scales to facilitate the linking of short-term, fine scale measurements and process models to long-term, broad scale measurement and modeling efforts. This is a key issue, for example, in the current international movement toward monitoring and modeling global change.

Spatial Scale of Remote Sensing and GIS Data

In principle, the hierarchical organization of natural systems ought to be explicitly defined and determined prior to data collection, processing and interpretation. In practice, the measurement scale of remote sensing and GIS data may be very ill-defined. Socioeconomic data are artificially aggregated to reporting units that vary in size and shape. The spatial scale of many ground measurements is often only approximately known. For example, what areas are integrated by a rain gauge or wind gauge at a meteorological station? For such "point" measurements, the actual measurement scale is less relevant than the size of the area that they represent, which depends on the time-varying spatial autocorrelation of the process. Only recently have earth scientists made explicit use of spatial autocorrelation theory in designing measurement and integration schemes for surface variables (e.g., Lovejoy and Schertzer 1985, Dancy et al. 1986, Oliver and Webster 1986, Curran 1988). and many processes and surface types have not yet been studied systematically. The measurement scale of maps produced from point data or from survey and image data is even less well specified (Goodchild 1980). The resolution of a map produced from interpretation of aerial photography may be defined by the *effective resolution element*, that is the size of the smallest object that can be reliably detected against a spectrally contrasting

background, but mapping is rarely done to that resolution. Resolution depends instead on the complex generalization process applied by the analyst. For this reason the effective scale of GIS data is sometimes described in terms of the *Minimum Mapping Unit* (MMU), but the actual MMU may vary both within and between maps as a function of map classes, terrain type and analyst.

The measurement scale of digital remotely sensed data is relatively well specified compared to other geographic data, but may still be quite uncertain. This scale depends on *image resolution*, which is the ground area covered by picture elements (*pixels*). Image resolution varies not only as a function of the sensor's Instantaneous Field Of View (IFOV), but also due to many other factors including the sensor point spread function, surface-sensor geometry, atmospheric conditions and data processing such as image rectification or enhancement (Billingsly 1983, Duggin 1985, Strahler et al. 1986).

It is obvious that the effective spatial resolution of data input to IGIS analysis is practically never well known. To the degree that the processes and phenomena under investigation are hierarchically scale-dependent, the outputs of IGIS analysis can suffer from artifacting and indeterminacy. Coordinated research is needed to address several related questions:

- What are the characteristic spatial and temporal scales and scale dependencies of earth surface processes and phenomena (notably in those related to the electromagnetic variation measured by satellite sensors);
- What are the *effective* measurement scales of GIS and remote sensing data, and how do these effective scales depend on data processing algorithms and overall data processing flow?
- How can multi-scale geographic data be integrated and linked in a statistically reliable fashion to facilitate hierarchical modeling of earth surface processes?

Existing research has addressed some aspects of these questions. For example, recent studies have identified scale-dependence in environmental variables such as topography (e.g., Mark and Aronson 1984, Mulla 1988), solar radiation (Dubayah et al. 1990), soils (Burrough 1983, Oliver and Webster 1987), vegetation (Woodcock and Strahler 1987, Davis et al. 1989) and land use (O'Neill et al. 1988, REFS). Work by Jupp et al. (1988, 1989) has examined how surface variation is regularized by imaging systems as a function of sensor resolution. Turner et al. (1989) have shown that there is considerable scale dependence in land use patterns, suggesting that in complex or spatially heterogeneous environments localized measurements at small spatial scales cannot be readily extrapolated to produce regional estimates. Of special relevance is the NASA FIFE (First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment) project, which was conducted between 1987 and 1989 over the Konza Prairie Long Tem Ecological Research Site near Manhattan, Kansas. FIFE was designed to study regional land surface climatology and to develop methods for deriving quantitative information about surface climate variables from satellite observations (Sellers et al. 1988) This is one of the first attempts to simultaneously acquire ground and remote sensing data over a range of measurement scales in order to explicitly examine how processses and patterns at small scales are related to those at larger scales. Preliminary data analyses have indicated the potential as well as the enormous complexity in scaling from ground to satellite measurements of surface biophysical properties (Sellers et al. 1990).

Studies like those just cited are improving our understanding of scaling properties of geographic variation. However, in the context of IGIS analysis, the most pressing need is for coordinated research that considers spatial scale-dependence of surface variation from the joint perspectives of process-oriented measurements, remote sensing and cartography.

To this point we have only discussed issues of scale in terms of absolute spatial scales of measurement and modeling. However, in joint processing of cartographic and remote sensing it is important to consider relative space and relative spatial scale as well. Absolute space is space as referenced to a euclidean coordinate system. The topology of elements within this coordinate system is determined by location, distance, direction, shape and geometry, as well as the size of the observation area (i.e., local, regional, global) (Meentemeyer 1989). In relative space, topology is defined by the spatial elements and processes under consideration, which may include non-Euclidean terms (Meentemeyer and Box 1987, Meenterneyer 1989). Relative scale, therefore, implies a transformation of absolute scales to relative scales where relative distance, direction and geometry are predicated on a functional relationship.

Remote sensing observes phenomena in a euclidean framework where it is relatively easy to to relate the position and size of various phenomena at one scale to those at another (for example, an image of surface albedo can be transformed from higher to lower resolution by simple image filtering). This is very different than the kind of operation one would use to simplify or reduce the scale of a vector representation of a variable such as watershed boundaries, where aggregation of sub-basins within a basin would be more appropriate. Thus GIS data may be appropriately treated in terms of either absolute or relative scales, depending on the overall structure of the database. For example, a GIS constructed to model watershed dynamics could contain gridded (i.e., remote sensing) data on land cover conditions within the watershed, but also contain information on water runoff or rates of infiltration within the watershed. Although these two cause-effect processes may appear close in absolute space (e.g., the identification of a specific type of land cover as a source of potential runoff), these factors may be very distant in relative space when time, rates, and interactions are considered (e.g., the rate of runoff as a function of the distribution of these specific land covers within the watershed basin). The appropriate mix of measurement scales in absolute space and relative space is especially problematic. For example, what is the appropriate spatial

resolution of satellite data for parameterizing the evapotranspiration component of a spatially distributed hydrologic model whose modeling units are regional drainage basins (which vary in size, terrain complexity,etc.)?

The distinction between absolute and relative space or spatial scales is closely related to the concept of *object-oriented* vs. *field-oriented* representation of geographic variation (Ehlers et al. 1989), and thus bears on a number of important research issues related to problems of data structure and to modeling using aggregated versus disaggregated spatial data. The preceding discussion should at least call attention to the complexity of determining the scale-dependencies of IGIS output, and underscore the notion that this output differs qualitatively from either satellite or map data.

Temporal Scale

As noted by Townshend and Justice (1988), the ability to detect changes in a surface identified over time with remote sensing depends on the spatial (geometric registration, resolution), spectral (band location and width), radiometric, and temporal (imaging frequency) properties of the sensor system. Of particular importance in assessing temporal change with remotely sensed data are the difficulties associated with instrument factors encountered in comparing images obtained by the same sensor. Changes in instrument function such as gain or offset and factors related to atmospheric or sun angle conditions have a destabilizing influence on temporal data sets. These characteristics are also confounded by prevailing local or regional environmental factors (e.g., seasonal, meteorological) that affect accurate comparison of temporal remotely sensed data sets. Inherent instrument problems or atmospheric influences are further exacerbated when comparing data sets from different sensors with varying EFOV's and spectral response characteristics at similar or different time periods (e.g., comparison of airborne multispectral data with Landsat TM and AVHRR data for detection of changes in vegetation indices). Additionally, high frequency variation in solar, atmospheric, and surface conditions (e.g., illumination, rapid changes in physiological response of vegetation) contributes noise that can perturbate analysis of multitemporal data (Davis and Simonett 1990).

Factors related to multiple spatial data also relate to the multitemporal domain and the integration of these data within a GIS environment. For example, temporal processes are both abstract (e.g., change in land cover conditions over time) and relative (e.g., the rate of change in crop maturity over time). Time as well as space may even be broken down into the more definitive constituents of continuous, discrete, or intermittent temporal extent. Processes may also be stationary or non-stationary, random, autocorrelated, or regular within the temporal domain. These relate back to the abstract or relative nature of the phenomena under observation and the ability of remote sensing to detect these phenomena. In essence, remote sensing remains as a point sampling technique for observation of processes in the time domain (Davis and Simonett 1990). The incorporation of multitemporal remote sensing data into GISs must recognize that detection of spatio-temporal change depends upon two primary factors:

- the radiometric contrast extant between temporal changes in landscapes or related phenomenon (i.e., how distinct or statistically separable is the spectral "signature" inherent to the target under observation);
- the manner in which temporal change of landscapes, earth processes or similar observable phenomena is distributed in space (e.g., how definitive are the changes in observable boundaries through time, what is the uniform or nonuniform distribution of the processes manifested on the landscape through time) (Townshend and Justice 1989).

In short, the problematic areas for integrating multitemporal remote sensing data into GIS architectures focus on both the vicissitudes of the remote sensing systems used and the phenomena under observation. The synoptic nature of remote sensing permits the detection of high intensity, short duration events such as floods or forest fires, but the temporal observation of slow or gradual change (e.g., impacts of acid rain on forest defoliation) are considerably more difficult to record using remotely sensed data.

Concluding Remarks

The trend in remote sensing over the past decade has been from empirically-based image classification, mapping and inventory to mom deterministic modeling of scene characteristics based on physical laws of radiative transfer and energy balance (Asrar 1989). Similarly, GIS analyses have grown increasingly sophisticated, moving from simple map overlay and relational models to spatially distributed simulation modeling. It is obvious that the progress made to this point and future developments in this area depend critically on hardware and software that facilitate the integration of remote sensing and GIS. As these technologies continue to improve, the power of IGIS analysis is increasingly limited by our understanding of the exact nature of the phenomena under investigation and their representation in spatial databases. At its worst, IGIS is a powerful technology that can be used to answer poorly posed questions by running misspecified models on improperly extrapolated data to generate output whose validity can never be tested. At best, the coupling of satellite measurements with other spatial data has tremendous potential for describing earth surfaces and predicting future conditions.

We have tried to show in the preceding discussion that impediments to the integration of multiple spatio-temporal remote sensing data are ensconced in both structural and conceptual foundations. Some of the difficult problems relate to defining appropriate

strategies for data acquisition and spatial modeling. This will require in-depth research on scale-dependence in surface features and the relationships of absolute and relative scale within a remote sensing context. As Meentemeyer and Box (1987) and Meentemeyer (1989) suggest, a "science of scale" (both spatial and temporal) may be required whereby scale problems are identified as explicitly stated variables in analysis.

Another set of problems relate to tracking and understanding the impact of data processing steps on output products. This requires tools for measuring spatial properties of input data such as spatial autocorrelation, 2-dimensional spectral analysis, block variance analysis, Monte Carlo resampling and cross-validation. What analytical tools should be included in an Integrated Geographic Information System? What are appropriate statistical approaches for analyzing IGIS products? At present, it appears that the more complex modeling efforts cannot be validated except in a piecemeal fashion, and thus sensitivity analyses will be the best method for assessing the robustness of model outputs. Thus user interfaces and analytical software need to be designed that facilitate sensitivity analysis of complex spatial models. Much can be gained simply through improved methods for the display and visualization of IGIS products. Simply developing better interfaces between image processing, GIS, database management, expert systems and statistical software will go a long way in improving analysis capabilities. Finally, to expedite the development of general methods in this area, we would recommend that a set of high quality, representative, real and simulated datasets be compiled and distributed to develop, test and validate different processing and modeling strategies.

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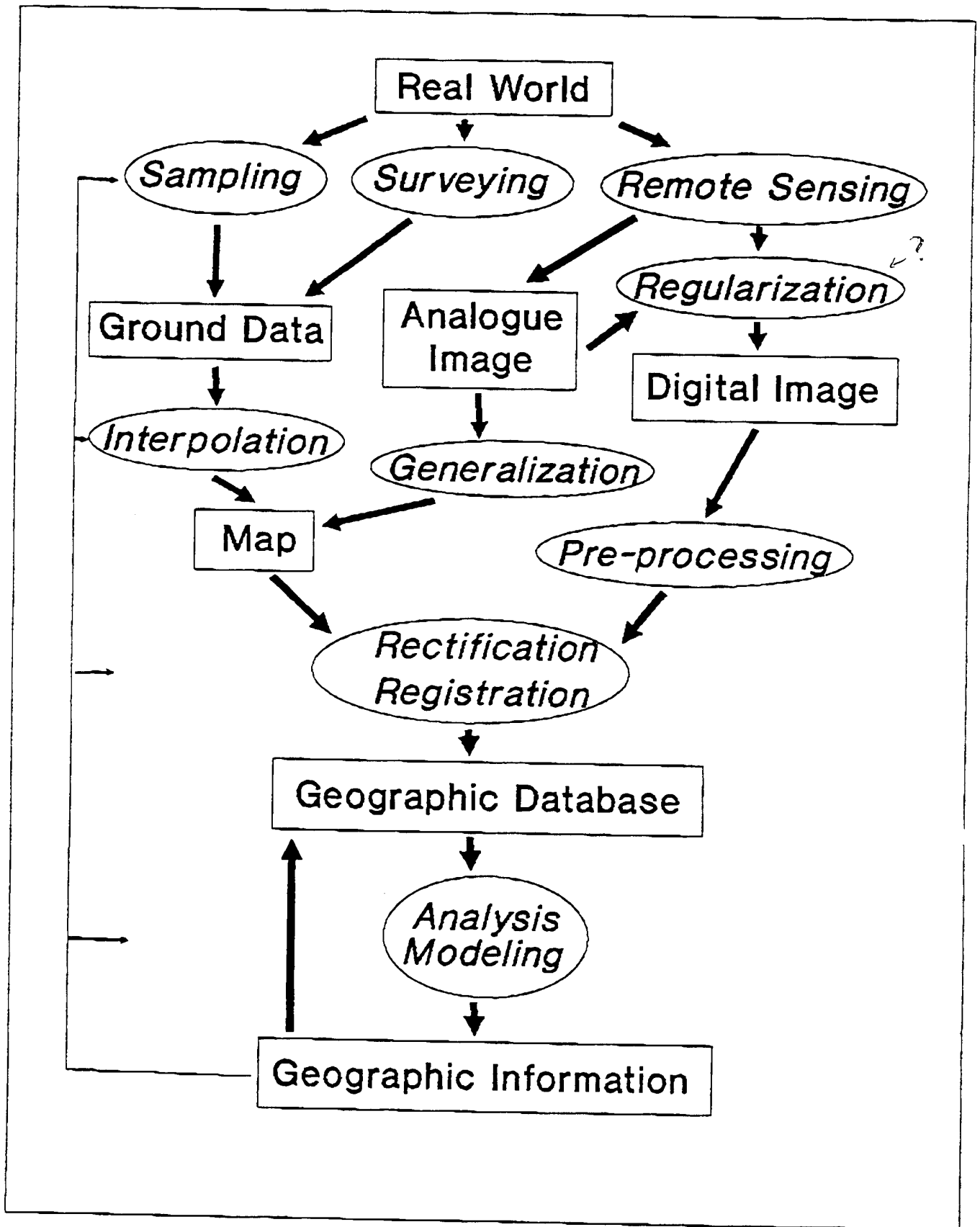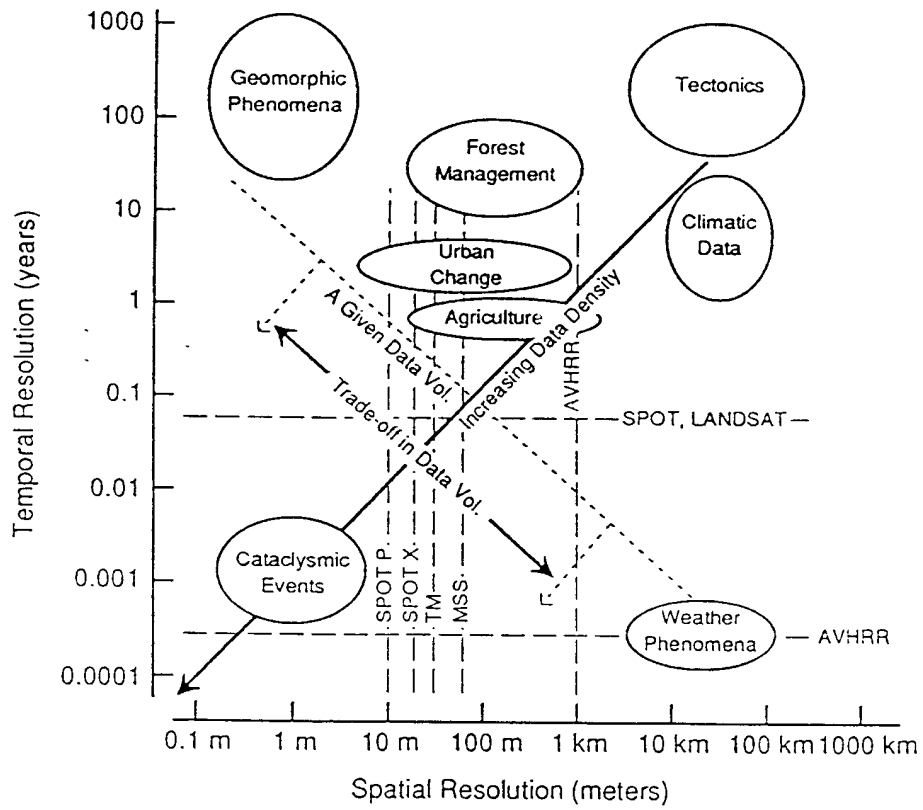
Figure 2

Viewgraphs presented by Frank Davis, University of California, Santa Barbara/National
Center for Geographic Information and Analysis

Data Processing
And
Information Flow
In
IGIS Analysis

IGIS Analysis Limited By:

* Understanding the exact nature of the phenomena under investigation

* Ability to observe and characterize the phenomena

* Techniques to model those observations in a digital spatial data base

Issues:

* Data observation and interpretation processes

* Continuous phenomena (fields)

* Discrete phenomena (objects)

* Data models

* Positional, temporal, and attribute resolution and accuracy

Prioritized Research Agenda

* Preferred methods to characterize the accuracy of observation of geographic phenomena

* Methodology for collecting and storing such accuracy data

* Error analysis of GIS data processes and results

* Enumeration of spatial data modeling techniques available and the appropriate application of each

* Methods of supporting multiple data models; conversion between models

* Variation of information content across methods of representation

* Better modeling of spatio-temporal change process

    - Temporal spectra analysis

* Analytical methods to work with multiple representation models

* Information surrogates

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INFORMATION
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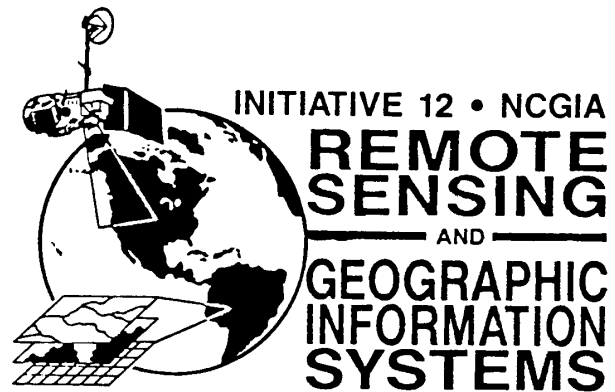
1. DATA ACQUISITION FOR REMOTE SENSING AND GIS

Remote Sensing is broadly defined as collecting and interpreting information about a target without being in physical contact with the object. Aircraft and satellites are the common platforms for remote sensing observations. The term remote sensing is commonly restricted to methods that employ electromagnetic energy (such as light, heat, and radio waves) as the means of detecting and measuring target characteristics. This definition of remote sensing excludes electrical, magnetic and gravity surveys that measure force fields rather than electromagnetic radiation. Magnetic and radioactivity surveys are frequently made from aircraft but are considered airborne geophysical surveys rather than remote sensing. As a source of geographic information, digital remote sensing represents more than a simple extension of conventional aerial photography, requiring fundamentally different approaches to the analysis of earth surfaces.

1.1. Remote Sensing Data Types

1.1.1. Raw Remote Sensing Data

Although often restricted to the acquisition of image data, the definition of remote sensing allows to include other sampling mechanisms (e.g. profiles).

Images

The most common form of data acquisition for remote sensing is the creation of twodimensional datasets (e.g. imagery). Depending on the recording device we can differentiate four principle recording mechanisms:

a)   Central perspective (the image is recorded in one extremely short time interval. Recording device is a camera in which a film is exposed (analog principle). Digital cameras employing two-dimensional arrays of CCD (charge-coupled devices) are being developed but have not reached operational status (max. dimension 2048 x 2048 sensors).

b)   Along-trade (line) scanner
A line scanner records one line of an image per recording step up to thousands of CCD sensors arrayed in a linear array. The image is isolated as a series of lines due to the forward motion of the recording platform (example: SPOT).

c)   Cross-track (mirror) scanner
Using a rotating or oscillating mirror, one single sensor can in principle create the total image. The rotation of the mirror is utilized to record one line, the forward motion of the platform is again used for the second dimension (example: Landsat MSS and TM).

d)   Active sensors (radar, sonar)
Active sensors transmit electromagnetic energy (sonar: acoustic) and record the energy reflected back to the sensor. Time difference and intensity of the backscattered signal are used to create an image. In general, remote sensing image data represent a two-dimensional sampling in space and a sampling in time.

The basic properties of a remote sensor can be summarized as:

- spectral coverage (spectral band locations)
- spectral resolution (spectral band width)
- spectral dimensionality (number of bands)
- radiometric resolution (quantization)
- instantaneous field of view (IFOV)
- angular field of view
- point spread function (PSF)
- temporal response function (Strahler et al. 1986)

Satellite sensors provide the opportunity for consistent multi-temporal measurements of large areas over time periods of days to decades. Sensor coverage and repeat interval are determined by platform altitude, angular velocity, orbital inclination relative to the equator and orbital orientation relative to the vernal equinox. Many optical sensors are placed in sun-synchronous near-polar orbits to achieve global coverage and consistent illumination geometry (e.g. Landsat, AVHRR). The repeat interval varies among these sensors

depending on their altitude and velocity. Others are placed in geosynchronous orbits to provide high frequency coverage of the same region (e.g. the GOES meteorological satellites).

Profiles

Profiles can be obtained in vertical or horizontal directions. Examples are temperature soundings in atmospheric remote sensing or laser/radar altimetric profiles of the terrain. Also, spectometers and radiometers can provide point or profile sampling.

Image cubes

Combining imaging techniques and spectometric measurements led to the development of imaging spectometers. A specified part of the electromagnetic spectrum is continuously sampled (i.e. without gaps and with extremely narrow bandwidths). Examples are AIS and the Eos sensors HIRIS and MODIS.

1.1.2. Interpreted Remote Sensing Data

Raster Image Data

Raster images from remotely sensed data are generally stored as fully represented scan lines (i.e. they are seldom compressed or run-length encoded) with a 6-10 bit range. Eight bits (range 0-255) is probably the most common representation as it can be represented by a byte on most computer systems.

Most sources of remotely sensed data (e.g. MSS, TM, AVHRR) are distributed as raw relative radiance values with only limited calibration. These data are often further calibrated by the end user (this is sometimes referred to as preprocessing) in order to correct for such effects as low sun angle, sensor striping, and different satellite platforms with the same sensor type. Image enhancement functions can be used in order to generate improved contrast, enhance edges, or eliminate systematic image "noise". As an alternative to enhancement, classification of the data using supervised or unsupervised (clustering) techniques provides a way to reduce the multispectral data into a single set of themes or classes. Classification effectively reduces the dimensionality of the raw sensor data to a single observation that can be labelled with a class name or some other descriptive attribute. Classification methods are well described in Swain and Davis, 1978, and Duda and Hart, 1973.

Digitized photography (e.g. digital orthophotography) can be created by scanning photography with off-the-shelf technology. Generally these data are scanned and converted from analog to digital (A/D conversion) into a 6-8 bit range. The technology exists to scan photography to any reasonable resolution down to film grains. Most photography exhibits a brightness falloff effect towards the edges of the image caused by the lend optics and this is called vignetting. A digital shading correction if often performed in order to correct for this source of unequal illumination.

Digitized photography that has been corrected for topographic effects and rectified to a standard cartographic projection is referred to as a digital orthophoto for orthophotoquad). This type of digital photography has the advantage that it is directly usable in GIS applications without the need for a) expensive (and error prone) manual transfer of interpreted themes to a standard map base, or b) the tedious (and error prone)(selection of control points and subsequent geometric correction and resampling process.

Vector Data

In remote sensing applications, vector data are required in a limited number of cases. In fact, many remote sensing systems immediately convert vector data to raster form in order to avoid the complexity of handling both data types. As a result, remote sensing systems are often inadequate to process vector data in the way they can be processed in more sophisticated vector GISs (e.g. topological structuring, vector overlay, vector buffer zone generation).

Some examples of the limited (and specialized uses of vector data structures in remote sensing applications are:

Training sets for classification

Some remote sensing systems that perform supervised classification methods use a vector polygon data structure to define 'training sets'. Training sets are areas of a known (and labelled) cover type that are used to "train" a classification program to identify all areas that are spectrally similar. A full polygon data structure is an efficient way to store the perimeter of the training set, when combined with spectral observations and class statistics that directly relate to the area. Once the class statistics have been generated, the vector representation is seldom used for subsequent processing. There are several good references for this procedure, including texts by Jensen, 1986, and Swain and Davis (1978).

Classification to theme polygons

The result of a classification procedure is a raster data layer that has a nominal class or theme associated with each output value. It is technically possible to convert these raster themes to vectors (usually polygons or topological arcs) but the sheer volume of most multispectral classifications will often inundate a GIS. The techniques for generalizing and reducing the value of data to be vectorized are less tried-and-true, and represent a fertile area for research and development. This is an important technique gap, as it represents the bridge between remote sensing classification technology and vector GIS. A good reference on this topic is Fosnight, 1989.

Ground truth and ancillary map data polygons

Remote sensing applications require that the data that are enhances or classified be related to an based on ground-based observations (sometimes called ground truth). These data are often mapped as polygons, and are then digitized as vector polygons or topological arcs. Subsequent to classification, it may be useful to relate the output to administrative or physiographic zones that are typically mapped as polygons. In addition, in the production of display and map outputs, it is often necessary to overlay ancillary data (e.g. roads, administrative units, cultural detail) in order to provide adequate reference for the cartographic display. In most remote sensing systems, these requirements are approximated with rasterized polygons and lines. This creates a difficult problem when output products require scale change or scale generalization. Rasterized lines and polygons are very difficult to reduce or generalize without unacceptable sampling or spurious replication. In these applications, data should be maintained in a vector form. Future remote sensing systems should take advantage of modem vector data handling tools.

Line feature extraction

It is possible to systematically enhance edges and line features in remotely sensed data using techniques such as edge enhancement or highpass filtering. These enhanced features can then be extracted from the image by binary thresholding into lines vs non-lines. With this raster representation of lines, it is then possible to convert to vector arcs using an 8-way connectedness rule, in the same way that raster linework is scan digitized from maps and then converted to vector arcs. A reference for these methods is Greenlee, 1987.

DEMs

The knowledge of elevation (relative or absolute) and information derived from this knowledge (e.g. aspect, slope) is often essential for GIS applications (e.g. watershed management, road planning, etc.). Interestingly, this information also plays a prominent role in the interpretation of remotely sensed data (e.g. improvement in classification and rectification accuracies). Consequently, terrain data are being used in both GIS and remote sensing systems. Since remote sensing is the primary source of this information, it will be discussed in the remote sensing section.

Terrain information can be provided in a number of formats. Most common formats are Digital Elevation Model (DEM) or Digital Terrain Model (DTM), contour lines, profile and spot height measurements. A DEM may be stored in a gridded format just like remote sensing image data with the digital number (DN) value representing elevation instead of radiance. Examples include USGS DEM files or Digital Terrain Elevation Data (DTED) files from DMA. Another DEM format which has become important in the context of GIS is that of a triangulated irregular network (TIN), a vector format. Profiles and lines are provided in vector format. Recently, the USGS has begun to offer hypsography (contours) in DLG format.

Primary data source for terrain information has been aerial photography coupled with photogrammetric processing. All organizations that are involved in the production of topographic information use the principles of stereophotogrammetry as backbone of their operations. With the advances in sensor technology (forward motion compensation, integration with GPS, INS), and photogrammetric hardware (analytical plotters) and software (bundle block adjustment, robust estimation), this technique has matured to a point where improvements will only be marginal in nature.

However, the photogrammetric line is still based on human interpretation, and efforts have been made since the early 50s to replace the operator by automated procedures. After a series of highly-specialized hardware devices (e.g. Gestalt Photomapper) attention over the last ten years has been focused on software based systems. The human operator is replaced by an image matching procedure in a digital environment. Analog images (photographs) have to be digitized Ion-line CCD, off-line scanner), whereas digitally recorded images (e.g. SPOT, CCD camera) can be used in the raw format. Earlier developments concentrated on the use of least-square based area or line correlation techniques, later developments included feature based matching procedures from recent advances in modelling the human stereo vision (computer vision systems) or combination of both techniques. Accuracy of stereomatchers; are reported to $\pm$ 0.025 - 0.3 pixels which, for example, amount to $\pm$ 2-5 m for stereo images from SPOT. The major

bottleneck in the automated production of DEMs is still the processing speed which today requires advanced SIMI) or MIMD hardware. With the advanbes in computer, sensor, and satellite technology, however, we might not be far away from operational automated processing of terrain data for large scales and large areas. It is interesting to know that Japan plans to launch an 8-meter resolution stereo-satellite in 1994 and that the USA and Japan are promoting satellite sensor systems with resolutions of 1-5 m.

Another primary source for terrain information is field measurements using conventional survey or Global Positioning System (GPS) technology. Especially the recent developments in GPS technology have made the accurate location and recording of x, y and z coordinates easier and faster than ever before. It is now possible to plot the course of a truck with a GPS receiver interfaced to a digital cartographic data base in real time.

However, most of the digital terrain information used in GIS comes from secondary (interpreted) data sources. The most common input is the manual digitization of contour lines from existing maps. In addition, optical scanners (CCDs, drum scanners) are employed to avoid the cumbersome, operator dependent, and slow manual digitizing. Scanned data, however, begin in a raster format and must be vectorized to be used in a vector-based GIS. Although automated procedures exist, extensive manual editing may still be required depending on the quality of the input material and digitizer. In recent years, mapping organizations have started to provide DEMs in gridded or contour format (e.g. USGS DEM or DLG) which come directly from the processing of raw data thus avoiding the double data conversion for GIS (e.g. raw data -+ map 4 digitized GIS data). It must be noted that the USGS is moving toward storage of terrain information in contour format only. DEMs would be created as needed.

There are good arguments in favor of storing the raw data. Having access to the original data provides the means of re-evaluating them either after refinement of the techniques or to check data of questionable reliability.

1.2. GIS Data Types

1.2.1. Raster Data

Although most (advanced) GIS are based on vector structures there are also good arguments in favor of raster structures for GIS. Many operations (e.g. overlays, spatial statistics, model integration) are simpler and faster in the raster than in the vector domain. Consequently, input of raster data in a GIS is essential for many systems. Possible sources for raster input include

    a)   classified remotely sensed data,
    b)   rasterized versions of vector (cartographic) data,
    c)   interpolated point or profile measurements, and
    d)   scanned maps.

Existing thematic maps may be scanned by electro-optical or electro- mechanical devices (e.g. CCD sensor, videocamera. and frame grabber, flatbed or drum scanner). The quality of the output and the amount of editing necessary to create 'sufficient' GIS layers depends largely on the quality of the map, the geometric and radiometric accuracy of the scanner, and the capabilities of the associated software. In principle, it is advisable to digitize map separates independently to avoid confusion between different classes. Automated recognition of cartographic symbols or text is not operationally performed, as of this writing.

The rasterization or binarization of vector-based GIS information is relatively straightforward. This process can be visualised as an equidistant grid that is placed over the input vectors, grid elements are then intersected with vectors and receive a nominal value (e.g. T). The remaining area is stored as containing no information and receive the value V. The data may be cleaned up to create features of 1-pixel width (thinning and skeletonizing). Other raster data may come directly from classified remote sensing images or from 2D interpolation procedures for point data.

1.2.2. Vector data

The most common data source for GIS comes from existing map data. Features of interest are manually digitized using digitizer tablets or large-format tables. The output depends mainly on the skill of the operator and the quality of the digitizer and its inherent accuracy.

Some semi-automated scanners imitate the line following approach used in manual digitizing. A CCD line scanner with a width of a few sensors is oriented perpendicular to the line to be digitized. By following the direction of strongest intensity, this line can be followed automatically. For contour lines, some devices can automatically select the next contour and repeat the process. The process, however, usually requires operator interaction to keep the instrument 'on-track' and to guide the device through line intersections as well as some post-processing. Despite these deficiencies, this process can speed up line digitizing for some highly complex lines (e.g. contours).

Direct input from digital cartographic data bases, CAD systems, or photogrammetric data files is usually possible through data exchange programs. Here, national and international standards have been developed or are evolving that allow data transfers between most of the cartographic/photogrammetric/CAD data files.

1.3. Other Data Types

1.3.1. Field Data

Remote Sensing and GIS must be related to, and calibrated with ground based measurements (e.g. field samples, ground truth).

Ground truth is usually obtained from field samples (rain gauges, transects, weather stations, soil probes, surveys, etc.), with the aid of existing maps or aerial photographs.

Calibration models relate sensor radiances to measured physical, biological or geometrical surface conditions on the ground. These models are of statistical nature and depend on interactions of sensor, atmosphere, and macro/micro surface parameter. They are inherently complex and sensitive to errors. The data needed for sensor calibration depend on the model itself (e.g. leaf area index for normalized vegetation index, soil moisture for radar interpretation) and may include point measurements, horizontal and vertical profiles, and generalizations (e.g. soil data).

1.3.2. Deterministic Model Data

Deterministic models are developed independently from GIS or remote sensing. They try to describe quantitatively the physical, chemical, biological, ecological, or economic structures and developments for regions of various size (e.g. global, nation, state, district, city, or block). They may be spatial, temporal, or spatio-temporal in nature. Remote sensing data may be used for model validation and GIS technology for visualization and interpretation.

Models may range from simple one parameter logarithmic growth models (for instance, algae bloom as a function of time) to complex atmospheric or weather models with a set of parameters. They can be ID, 2D, 3D or 4D in nature. Integration with models win tax the capabilities of remote sensing and geographic information systems.

1.3.3. Survey measurements

Survey measurements can be used to accurately relate GIS and remote sensing information to a geodetic coordinate system. Usually, survey data (including, for example, GPS measurements) are used to triangulate a geodetic network. Recent developments, however, stress the storage of raw survey data from which a network can be triangulated 'on the fly'. The advantage of such survey-based measurement system is that new measurements can easily improve such a network.

II. DATA STORAGE AND ACCESS

For GIS and remote sensing data to be stored in a readily usable form, they have to follow specified data structures. Structures for spatial data may differ in several ways from one another:

(a)   type of geometric data (point vs region);
(b)   object handling (non-fragmenting vs fragmenting);
(c)   division of space (regular vs data determined); and
(d)   retrieval (direct vs hierarchical).

The most common form of data structures in GIS and remote sensing are raster (region, fragmenting, direct, regular) and vector (region, non-fragmenting, direct, data determined) formats.

II.1. Raster Systems

Raster data systems tessellate space and assign each spatial element a unique value, thus providing explicit information for each location. Raster structures my include regular and irregular tessellations and hierarchical and direct models. They may be described as field representation, as opposed to object-based representations provided by vector structures, referring to the fact that fields are assigned object attributes in a raster model whereas objects are given locations and attributes in an object model.

Image files

The most common raster structure is a square lattice whose values are stored as 2D arrays in the computer. This structure essentially follows 'naturally' the structure of imaging devices in remote sensing or scanning devices for digitizing. Its advantages include simplicity; ease of display and processing, ease of data aggregation and overlay, and uniform cell size which allows multidimensional spatial analysis and modeling. It also allows the full radiometric: storage of the original data. A hierarchical structure for image files is the pyramid structure (bottom-up approach) which is a hierarchical structure of aggregated image layers. It has the advantage that feature search can be performed hierarchically and/or selectively at the required levels of resolution. Due to its complexity (multi-spectral storage, neighborhood operations) it has yet to be implemented in a commercial remote sensing system. It may, however, prove to be a valid model for the integration of remote sensing and GIS as it may facilitate a low level - mid level - high level system approach similar to those promoted in computer vision.

II.1.2. Other Raster Structures

Several methods of data compaction have been developed to store raster data more efficiently making use of coding and hierarchical structures (top-down approach). Coding structures usually make use of run-length encoding or block encoding schemes, where fields or blocks of pixels with the same value are stored only once. They are often used after optical scanning to reduce the amount of data that has to be transferred to a GIS or image processing system. The amount of data to be stored can be vastly reduced especially for binary images. Access and processing of encoded data, however, usually requires decoding.

Top-down hierarchical structures organize the data in so-called trees (quadtree, R-tree, hex tree, field tree, etc.). Hierarchical data structures require tessellations that can be recursively decompressed into similar pattern of smaller size. Advantages may include reduction of data storage and processing time, and a more object-like representation of surface variation.

II.2. Vector based systems

II.2.1. CAD Systems

Computer-Aided Design (CAD) systems are often compared with Geographic Information Systems (GIS) because they are readily available and relatively simple to operate. CAD systems handle points, lines, and areas (polygons), and have some similarities in terms of user interaction and data display. The data model for CAD systems is generally simpler than are needed for GIS applications. Normally the concept of feature topology is quite limited in CAD systems because very little is done that requires vertical integration or overlay and intersection of features from different layers or sources. In addition, while there may be several tabular or numeric attributes for the features maintained in a CAD system, they do not generally contain a comprehensive database management capability (DBMS) for attributes or (spatial entities).

II.2.2. Advanced systems

Topological arc

Systems that are based on topological arcs employ a data model that requires that polygons can be formed as needed from chains or arcs. Chains or arcs are made up of ordered line segments that begin and end on high-order nodes or line intersections. While these systems require complex algorithms for creating and maintaining topological structure, it tends to be a robust and comprehensive model for performing spatial analysis tasks. The storage of arcs is more efficient than full polygon encoding, but the cycling of polygons (e.g. to display a polygon or to calculate the area) requires the calculation of topological pointers (a list of arcs in a polygon).

Full polygon

Systems that employ a full polygon representation can be used for some GIS applications that require polygons to be cycled for display and analysis. In applications that require such operations as overlay, buffer zone calculation, or line generalization, the full polygon model is generally lacking. The principal advantage of this data model is its simplicity for display of polygons and their attributes. Because each polygon is stored without regard to adjacent polygons, it is possible to create and propagate errors in the spatial database that cannot be easily detected without special consideration (topological checking or validation).

Network

Systems that employ a network data model generally support different applications from topological arc and full polygon systems. In the network model, the arcs and nodes provide the spatial framework for describing flows and directions. Network analysis and display of flow through a network (e.g. hydrology, traffic, facility siting).

II.3. Hybrid Systems

Raster and vector data structures are clearly two rather specialized techniques for representing spatially referenced data. There has been a seemingly endless debate as to which is the most efficient structure from the point of view of space storage or from the point of view of applying various sets of procedures to the data.

There can be no clear answer to this debate, since the answer depends on a large number of factors, relating for example to the nature of the application and the distribution of the queries.

Rather than follow the lines of this traditional argument, it seems preferable to view the two data structures in a different manner, and to note that the main difference between them essentially relates to the degree to which the objects of interest have been made explicit in terms of the data.

In general, rasters provide a generic form of representation in which most objects and the spatial interrelationships between them are implicitly encoded.

A large collection of operators, typical of image processing, may be used to make the objects and their interrelationships more explicit. On the other hand, vector data structures typically represent an additional "layer" of processing on top of a raster structure (eg as in the digitizing and topology-producing processes) and objects are made explicit in terms of points, lines and polygons and their interrelations.

Hence it is of value to conceptualize a large family of representational schemes that are characterized in terms of the degree to which they explicitly encode information about the objects and relationships of interest.

It is clear that from some points of view, one is characterizing the degree of object orientation involved in the data structure.

The key reason for object orientation is to represent objects in a manner that a user in some application will find more efficient, in terms of representation and manipulation. Hence the essential tradeoff is the cost of processing in order to produce a more object oriented data structure versus the additional user cost if the preprocessing is not performed (this argument is of course subject to the usual caveats of the traditional view of the data structures in terms of space and time efficiency).

It is now generally agreed that most spatial database systems of interest to a large community of users should involve both raster and vector data.

Given the argument in the preceding paragraphs, it follows that the optimal mix of raster and vector should relate to the degree to which a user finds it worthwhile to perform vector preprocessing and to store the objects in a more explicit form. For example, in a spatial database system in which one is storing large amounts of image data relating to meteorological phenomena, it is clear that in general it is not possible a priori to process the data and to obtain polygonal representations of all objects that will be of interest to a general population of users, since the cost would be prohibitive even if one could decide upon or even define the objects of interest.

On the other hand, it might be of great value in such a system to a have a vector representation of certain important objects, such as the outlines of terrain features (eg coastlines).

While one can argue that a mix is probably the optimal solution, given the current state of spatial database technology, it is clear that there is no a priori optimal solution.

Issues that arise, therefore, include:

1. providing a DBMS that is capable of handling both types of data representation, and optimizing over their use;
2. providing facilities for converting from one representation to the other and for making objects that implicit in the raster form explicit in the vector form in a quasi-automated manner;
3. providing the user with a view in which, for some applications, the differences in the representation are transparent to the user;

More generally, however, a key issue is whether and how to support more general classes of data structures that support different degrees of object orientation, and the provision of a DBMS that supports the different representations in an efficient and transparent manner.

II.4. Data Archive Systems

Introduction: An archive system for spatial data, irrespective of the source of the data, has a number of requirements, including-

- volumetric efficiency of data storage
- stability of the media
- appropriateness of the user interface
- low cost with high performance

11.4.1. Media

Conventional removable magnet media have serious limitations as a means to archive large datasets, for long periods of time. Industry standard 9-track computer tapes have limited lifetimes (on the order of 5 years between maintenance), limited data storage (on the order of 100 Mbytes in a volume of 4500 cm3), restrictions on access modes (sequential, in contrast to random), and a relatively high cost to copy. In addition, while 9-track drives are available for a wide variety of computers and operating systems, they are expensive to purchase and to maintain. Other media may have a role to play in the integrated geographic information systems of the future.

The storage industry has recently provided two new tape formats that are becoming widely available. These are based on tape formats and transports used in mass-market entertainment systems: 4mm DAT (digital audio tape) and 8mm video tape. Each of these has excellent storage density (for example, 2 or more Gbytes in 200 cm^3 for 8mm tape), and intermediate costs for the drive and interface. Serious concerns in using these technologies include the serial nature of the medium, relatively slow I/O speeds (affecting copying time and cost), and lifetime of the medium.

CD-Rom disks are being used in a number of experiments as a means to store and distribute spatial datasets. While their lifetime is under debate, their ability to hold on the order of 600 Mbytes of data in 200 cm 3, their fundamentally random access nature, and extremely low cost to make copies (on the order of a few dollars each) make them very attractive. Mastering costs for producing a CD-Rom have dropped dramatically in the past 24 months, making it possible for smaller agencies to think about creating their own CD-Rom disks. Availability of low-cost drives for a wide range of computers and operating systems make these disks appealing as well.

There are at least three other optical disk technologies that must be considered as well. WORM (write once, read many) disks, erasable (often using magneto-optical technology), and video disks are all in use to varying degrees in the computer industry. WORM and erasable disks at this time are expensive (disks > $100, drives on the order of several thousand dollars), copying times are long, and standards to permit data written on a disk to be read on multiple systems are lacking. The precision of recalling data from video disks, a fundamentally analog medium, is perhaps not known. However, the low costs of players and duplication may make video disks extremely attractive for browse or other index datasets.

II.4.2. User Interface and Access

An important set of concerns for spatial data archives involve the ways in which users identify potentially interesting datasets, and then obtain copies of these datasets. The former includes modes of the user interface and information which describes the datasets. The latter includes consideration of distribution mechanism and media, price vs performance, and data format.

A number of studies have examined portions of the user interface to collections of spatial data. In general, these have shown a need for:

- graphics (an electronic map for specifying the spatial region of interest, for example)
- hierarchical levels of detail (perhaps including a general description of a collection, documentation of the kinds of information stored and how they were gathered, and a detailed inventory of the collection)
- browse (interactively accessible samples of the data, perhaps reduced in spatial precision as well as other characteristics)
- interactive query of data characteristics, with intelligent aids
- ability to store user profiles and use them to optimize its response in the future

Concerns about obtaining copies of the identified datasets typically revolve around more practical issues. These include:

- ability to request data in 'standard" formats
- ability to acquire documentation about the datasets, including information about other uses of the data and available software for processing
- distribution mechanism (electronic vs. delivery of media)
- cost (and cost trades between various mechanisms for delivery - time probably required to satisfy the request

III. KEY RESEARCH ISSUES

Although the potential for the integration of remote sensing and GIS is evident and some success has been achieved in several areas, improved integration of remote sensing and GIS require a number of research questions must be addressed. One key impediment to a total integration is the different concept of space that GIS and remote sensing are based on. Investigation of this topic is seen as a fundamental research question.

III.1.. Concept of space in GIS and remote sensing

GIS may be viewed as object-based data representations whereas remote sensing employs a field-based model. Other differences include

(a) level of abstraction;
(b) level of accuracy;
(c) scale;
(d) metric; or
(e) temporal abstraction.

Within this concept, there are several research issues which need to be addressed:

- Is there a unifying theory that would allow to see remote sensing and GIS as different representations in a 'model of space'?
- What are the predominant parameters in this representation model that differentiate GIS from remote sensing data structures?
- Is it possible to define transformations between the different representations?
- Do transformations without loss of informations exist? If not, can this loss be quantified?
- To what degree are these transformations reversible? If not, can an inverse transformation be approximated?

Note: Sometimes it may prove advantageous to formulate a 'statement of impotence', i.e. what cannot be achieved.

III.2. Data Conversion and Exchange

Based on, and partly parallel to, the research in 1) more specific questions concerning data acquisition, conversion and exchange need to be formulated.

- What are the requirements for remote sensing data (temporal, spatial and spectral resolution, timing, areas, etc.) to be incorporated in GIS applications (e.g. urban, regional planning, global monitoring, etc.)
- What data structures and data management strategies are appropriate for GIS guided image interpretation?
- What are the data exchange/conversion standards within GIS and remote sensing to provide best access to large distributed cartographic, GIS, and remote sensing data-bases? Are these standards appropriate?
- Are there alternate concepts for integration, i.e. information exchange rather than data transfer?
- Is there a need to set up an integrated test data set containing remote sensing data, cartographic data, field measurement data, and possibly model data?

III.3. Integrated Databases

Following the raster/vector discussion above, we make the additional comment that remote sensing systems and GIS are not fundamentally different, in the sense that users are interested in analyzing the objects and relationships that are encoded in some set of spatially referenced data.
This is particularly the case of raster-based GIS, hence the research problems in both RS systems and GIS are closely related.

There are several research issues of major importance:

1. Determining the user requirements with respect to the degree of object orientation required in a system that handles RS data, and deciding on the degree and nature of object orientation that is required in such a system in order to satisfy user needs.

2. Deciding whether a single DBMS architecture is the correct approach to follow, or whether a more modular approach is desirable, in which one can build a system of different components in order to handle the varieties of data models that one may be required by users to handle.

3. If a large DBMS is a reasonable approach, to design and implement a DBMS that can handle different data models in an efficient and (where necessary) transparent manner. Extensibility and efficiency are key issues for such a system.

III.4. Display and user interface

a) is possible to establish a consistent set of terms that can serve as a standard for GIS and RS systems? (Example: lines and samples in RS; lat and long, x and y, eastings and northings... in GIS) (Example: display is usually first quadrant Cartesian in GIS, fourth quadrant in RS).

b) is it possible to establish a complete and consistent processing treatment of features? (Complex polygons with island topology, rather than simple convex polygons only with no allowable inclusions in RS; more complete set of raster structures (byte, integer, real) and processing operations allowed in GIS).

III.5. Inventory and access to existing GIS and remote sensing data

a) can we develop (and facilitate widespread acceptance of) spatial data exchange standards?

b) can we define minimum standards for the encoding and digitizing of spatial data to minimize redundant data collection and inadequate quality control)?

c) are there databases that should be made available (or more convenient) to users? (e.g. DTED).

III.6. OTHER TOPICS

Today remote sensing and GIS mainly deal with 2D data structures. As the earth is essentially 3D, extensions of 2D models need to be studied. Also, integration of models may require higher dimensional data structures. Current GIS do not address the time domain whereas remote sensing is a sampling in both space and time. Specific research topics include:

- How can GIS and remote sensing data models be extended to handle 3D data (DEMs, geological data, atmospheric data, marine data, hydrological data, etc)? Possible approaches include independent layers, 2.5D, full 3D.
- How can time be treated in GIS and remote sensing data models (explicit parameter vs time samples).

O. Meta Comments

1)   a. What is appropriate focus of I12
           (i) institutional (?)
           (ii) large DB issues (?)

       b. Question of intersection of initiatives
           (i) NCGIA summary

2)   For DS and ACCESS

       a. 2 NSF panels:
           (i) DBS technology
           (ii) scientific DBs

       b. Raster GIS / RS system not fundamentally different

       c. Focus
           (i) uniform language that allows integration of concepts,
               procedures, data
           (ii) computational transparency principle

I. NSF DB Workshop

1. DBS technology (pull)

2. PAST:

       a) focus on business

       b) achievements
               high level QL
               theory / algs for optimization
               nomalization theory
               algs for tuple / page allocation
               buffer management
               indexing
               prototype DBMS

2. Next Generation

    a) drives: large spatial DB
                       CAD
                       GENOME
                       multimedia
                       Data Dredging

    b) new kinds of data - complex objects
                             - images

    c) new generation of QL's

    d) rule processing

    e) data - modelling

    f) scaling up

    g) parallelism

    h) tertiary storage

    i) long duration transactions

    j) versions

3. Heterogeneous / Distributed DB's

    a) semantic inconsistency / fusion

    b) browsing

    c) incompleteness / inconsistency

    d) mediators
             - need info sources between DB / User

    e) name services

    f) security

    g) site scale up

    h) transaction management

III. SCIENTIFIC DB

1. Main questions

2. Main issues

IV. PROBLEM AREAS

A. Concepts of space

    1. Explicit versus implicit 02

    2. Unifying idea of different geometrics based on sets

B. Data conversion / exchange

    1. Vector versus raster

    2. Compression

C. Integrated DB

    1.   a) User view : via LANGUAGE
              simplicity
              expressiveness
              efficient implementation
              semantics

        b) TD planning
              - user -> LANGUAGE -> reqirements

        c) DB / modelling system

        d) Declarative language

        e) typing facility

    2. Data modelling : relational
                          0 2
                          semantic
                          logic-based

    3. Single DBMS or modular?

    4. Content based search

    5. Indexing and updating of index

D. Display

    1. Standards and languages

    2. Interface

REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM DATA INTEGRATION: ERROR SOURCES AND ISSUES

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ABSTRACT

Remote sensing derived data are increasingly being utilized as a data source in geographic information systems (GIS). Remote sensing and GIS error associated with the data acquisition, processing. analysis, conversion, and final product presentation can have a significant impact on the confidence of decisions made using the data. This paper attempts to identify potential sources of error at each data integration process step, assess potential impacts of error propagation on the decision making process, and recommend priority error quantification research topics. There is an immediate need for the development and standardization of error assessment procedures and reporting conventions. Suggested error quantification research topic priorities include the development of more cost-effective remote sensing accuracy assessment procedures, development of field verification data collection guidelines, procedures for vector-to-raster and raster-to-vector conversions, assessment of scaling issues for the incorporation of elevation data in georeferencing, and development of standardized geometric and thematic reliability legend diagrams.

INTRODUCTION

With the proliferation of geographic information systems (GIS) in both industry and government for numerous management applications, there has been a tremendous increase in demand for remote sensing as a data input source to spatial database development. Remote sensing derived products are particularly attractive for GIS data base development because they can provide costeffective, large area coverage in a digital format that can be directly input into a GIS. Because remote sensing data are typically collected in a raster data format, the data can be cost-effectively rectified or converted to a vector or quadtree format for subsequent spatial data analysis or modeling applications (Reference

Although the use of remote sensing data for spatial data base development is increasing rapidly, our understanding of associated data processing errors, especially for integrating multiple spatial data sets, lags far behind. We need to clearly identify the types of error that may enter into the process, understand how the error propagates throughout the processing flow, and procedures need to be developed to better quantify and report the error using standardized techniques, ie., techniques for all spatial data users. Performing spatial data analysis operations with data of unknown accuracy, or with incompatible error types, will produce an output product of low confidence and limited use in the decision making process.

The process of integrating remote sensing data into a GIS usually includes the following analytical procedures: data acquisition, data processing, data analysis, data conversion, error assessment, and final product presentation. Error may be transferred from one data process step to the next and manifest in the final product, accumulate throughout the process in an additive or multiplicative fashion, or an individual process error can be overshadowed by other errors of greater magnitude. The potential sources of error which may enter a remote sensing data processing flow are illustrated in Figure 1. Although the typical processing flow is in a clockwise direction, bidirectional and cross-element processing flow patterns are possible. Data conversion usually occurs after data analysis. However, in some instances conversion may occur in the data processing step. Usually these conversions are in the form of raster-to-vector or vector-to-raster.

In theory, the amount of error entering the system at each step can be estimated. In practice, however, error is typically only assessed at the conclusion of data analysis (i.e. the final product), if it is assessed at all. Usually, the decision maker is provided graphic final products, statistical data. or modeling results with little or no information concerning the confidence of the information. This limits the confidence of the implemented decision(s). If remote sensing data is to continue as a viable geographic information data source, it is imperative that we improve our ability to quantify the error associated with the data, and monitor the error as it propagates through a GIS application. The following sections review the nature of the error which may be introduced and identify significant improvements which must be addressed.

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The sections in this paper are presented in order of the "typical" processing flow for incorporating remote sensing data into GIS's for spatial data analysis applications (Figure 1). Note that error is potentially introduced at each step, with the exception of the error assessment process. Although efforts can occur in the error assessment process, error is not introduced into the actual data products. The fact that error assessment is performed after, rather than before data conversion(s), is of significance. Because errors associated with data conversion processes are poorly understood, it is imperative that error assessment be performed subsequent to any data conversion process(s).

The objectives of this paper are to first identify the potential sources of error in the data processing flow for the integration of remote sensing data into GIS's. Secondly, discuss and illustrate the consequences of error in the decision making and implementation processes. Finally, recommend important research and development issues of critical importance to overcome error related impediments for the incorporation of remote sensing data products into GIS data analysis applications.
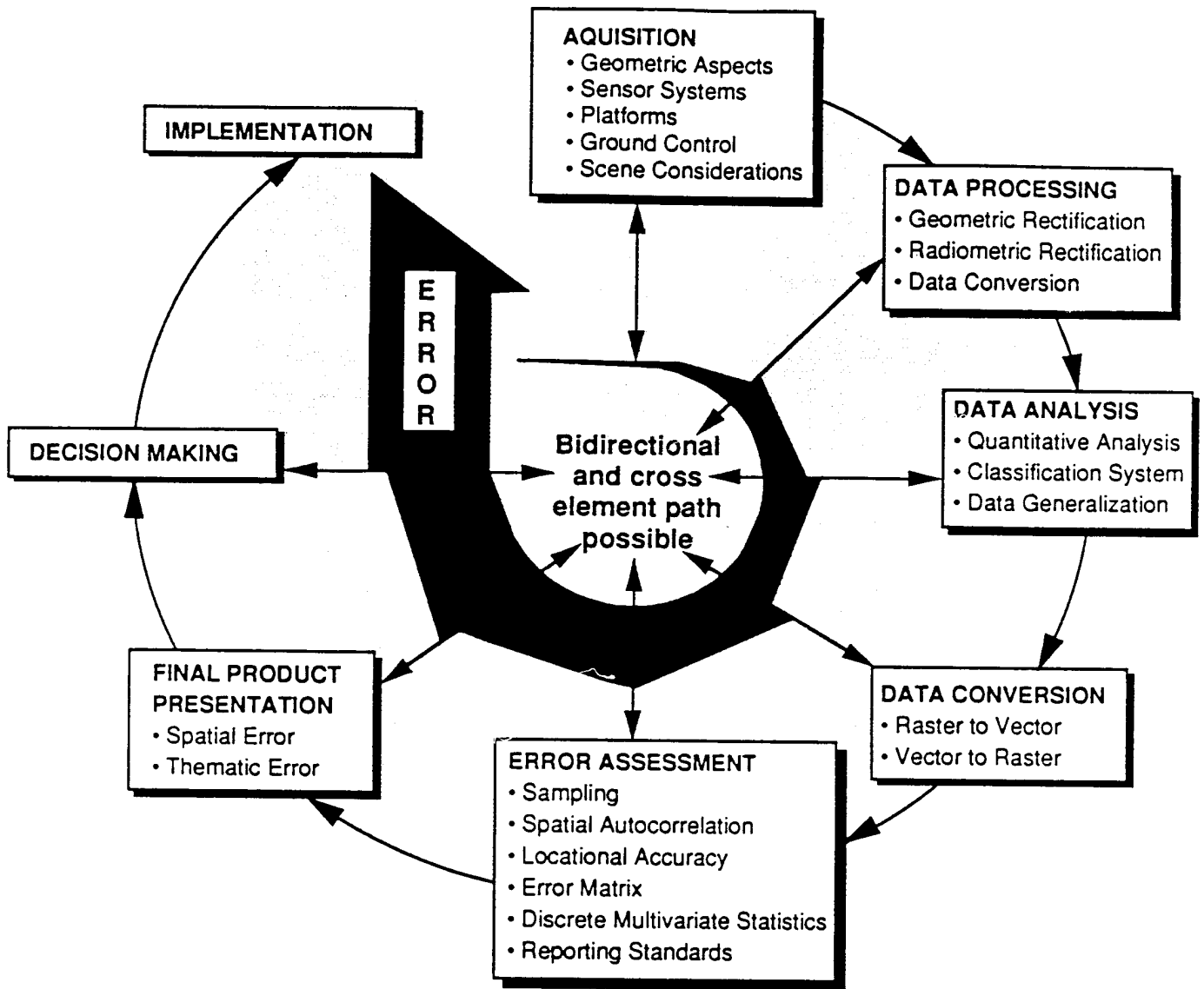
Figure 1. The accumulation of error in a "typical" remote sensing information processing flow.

DATA ACQUISITION ERROR

Environmental and/or cultural data may be acquired either by in situ or remote measurement. Some data acquisition errors are common to any form of data collection and may be introduced from a number of sources. Some of these sources cannot be controlled such as atmospheric conditions and the natural variability of the landscape. Conversely, other types of data collection error may be controllable such as geometric or radiometric error. Nevertheless, it is important to have an understanding of the type and amount of error possible from all data acquisition sources and to control it whenever possible. Extensive information may be found in the literature on many of the data acquisition error sources, e.g., Desachy et al., 1985; Duggin et al., 1985; and Salsig, 1990. Data acquisition errors will be briefly discussed in the following paragraphs, excluding those errors associated with natural and human variability.

Geometric Aspects

The processing of multiple data layers in a GIS database is predicated upon accurate spatial registration between data layers. Therefore, it is absolutely critical that all remotely sensed data be geometrically accurate and congruent with the GIS database. Modem photogrammetry is moving towards fully analytical techniques and digital image processing (reference_____). These photogrammetric developments have broad implications for remote sensing and GIS integration. They provide a sound and necessary mapping basis applicable to remote sensing imagery. The following discussion identifies some of the primary issues involved, such as basic geometric aspects of imaging, scene environmental considerations, platforms, and ground control.

Illumination geometry can affect image quality and subsequent analyses. ideally, illumination geometry is constant or nearly constant throughout an image. In practice, however, acquisition needs dictate a relatively wide instantaneous field-of-view (IFOV), resulting in a range of illumination- measurement geometries. Optical systems are dependent upon solar illumination. Solar elevation and azimuth conditions for aircraft acquisitions can significantly limit the duration of suitable acquisition windows (Reference

Maintaining constant image scale would facilitate image entry into a GIS. Scale variations are introduced by numerous factors, such as off-nadir viewing (tilt for aerial cameras) and terrain relief displacement. The IFOV of an imaging system also introduces scale variations, which are most pronounced in wide IFOV systems. Imaging geometry varies by sensor type and effects. A brief comparison of aerial cameras, multispectral scanners, and side-looking airborne radars illustrates this.

Sensor Systems

The design of conventional aerial camera systems provide a central perspective geometry and produces radial geometric effects. Most mapping systems have high quality lenses, filters, and image motion compensation to achieve film geometric stability during exposure. Camera systems are also periodically calibrated using well-defined standards that allow for correction of known geometric distortions. Gyro-stabilization can assure nadir-looking and correct orientation.

Multispectral scanner systems (MSS) are constantly imaging when in operation. This means that all platform motions during acquisition affect the image geometry (these motions are reviewed later). Also, there is no single nadir point in MSS imagery, but rather a "nadir line" that tracks the platform movement during data acquisition. Therefore, pixel size away from the nadir line varies as a fuction of the cosine of the look angle. Linear charge coupled device (CCD) "pushbroom" sensors eliminate many of the geometric efforts associated with MSS (American Society of Photogrammetry and Remote Sensing. 1980).

The active image formation process used by a side-looking airborne radar, or SLAR, necessitates a side-looking or oblique view of the terrain. Since SLAR systems continuously send and receive microwave signals, aircraft motions can significantly degrade image geometry. To improve image quality, SLAR antennae can be gyro-stabilized. Depending on the height of the terrain, and the look angle and direction, mountainous regions may be enhanced on radar imagery. Unfortunately, image foreshortening or "layover" may introduce serious geometric error which cannot be removed thus making these data of less value in a GIS. The lee side of mountains may be in radar shadow with no information of value. The goal is to acquire synthetic aperture radar (SAR) data with the ideal look angle and direction to minimize radar layover. Then the radar imagery can be rectified just like any other remote sensor data.

As briefly reviewed here, image geometry is dependent upon the image generation process involved. Attaining geometric fidelity at this stage is well developed in conventional photogrammetry, which is based on the use of vertical aerial photography. Many other types of remote sensing systems, however, involve continuous image generation processes; these processes are more susceptible to geometric distortions and may impede GIS integration. The geometric error introduced by each of these sensors must be quantified and removed prior to the entry of the remote sensor data in the GIS database.

Platforms

The stability of moving platforms has a major influence on the geometric fidelity of the remote sensing system. Conventional aerial photography has the advantage of nearly instantaneous film exposure using highly calibrated equipment Conversely, continuous imaging systems, such as scanners, are susceptible to geometric distortions due to platform motions.

The flight or orbital altitude of a remote sensing platform, in conjunction with the sensor's field-of-view and viewing direction, affect the imaging geometry considerations reviewed earlier. Of additional interest here is platform velocity and direction, and the orientation or attitude of the platform. Major distinctions for these parameters can be made between aircraft and satellite platforms. Aircraft platform motions have proven especially troublesome since turbulence can rapidly impact aircraft altitude and attitude.

Instantaneous aircraft altitude (z) and locational (x,y) information are essential if the remote sensing data are to be accurately rectified and placed in a GIS. A continuous record of (x,y,z) location allows for determination of ground speed and degree of pitch, roll, and yaw. A correction for high frequency platform motions can require solution of a complex pointing model on a per pixel basis. Such systems have been developed but are not yet widely used (Reference_____).

Promising trends are apparent in both locational and attitude measurement equipment for aerial platforms. Global Positioning System (GPS) technology provides an excellent basis for (x,y,z) location measurements. Similarly, compact and lower priced inertial navigation technology, such as laser ring and fiber optic gyros, are becoming available for attitude measurements.

Ground Control

The locational accuracy of rectified remote sensor data or final map products can be no better than the ground control upon which the rectification coefficients were based. In photogrammetry, control is established by using points whose positions are known in an objectspace reference coordinate system and whose locations can be positively identified in the imagespace. In addition to conventional survey techniques, procedures and issues such as photo markers, photo control extensions (e.g., aerotriangulation), datums, projections, and accuracy standards are well addressed (Reference_____).

Typical ground control for satellite and aircraft digital remote sensing products also make use of the relationship between object space (the ground) and image space coordinates. While fundamental root mean square error (RMSE) values are sometimes provided, standardized procedures for establishing and reporting image ground control accuracy have not been developed by the remote sensing community. To allow routine remote sensing data entry and use in GIS databases, such standards must be developed.

Ground control is necessary during the accuracy assessment of any thematic map. GPS technology will enhance field verification efforts by providing increased accuracy in determining ground coordinates. However, it will still be costly and impractical to assess the accuracy of all map feature boundaries using GPS. Standards and procedures for the use of GPS data in GIS will be a primary research topic in the years to come.

Scene Considerations

Several scene specific effects are routinely corrected for during photogrammetric mapping. For example, radial distortions due to atmospheric refraction can be calculated and remove for a standard atmosphere and earth curvature effects. These types of effects are more pronounced at the higher altitudes common for large area remote sensing surveys, but the effects can impact locational accuracy at even relatively low altitudes.

Whereas terrain relief and image displacement create problems when performing MSS analysis, conventional photogrammetry is well developed for the extraction and mapping of terrain elevation contours, or hypsography, based upon the principles of stereo image parallax. The accurate measurement and modeling of these effects is necessary for the preparation of planimetric basemaps, elevation contour maps, digital elevation models, and orthophotos.

Basic ground-level and atmospheric characteristics are pertinent to photogrammetry but often more developed for digital remote sensing applications. Examples include atmospheric absorption and scattering (Kaufman, 1988; Kaufman and Fraser, 1984; Singh, 1988), surface bi-directional reflectance (BDRF) properties (Lee and Kaufman, 1986), variable topographic illumination conditions, and the relationship between vegetation and climate (phenology) (Reference

An understanding of these characteristics and their impact on film and digital MSS products are important to the correct analysis and interpretation of these data types.

DATA PROCESSING ERROR

Geometric Rectification

Since the early 1960s it has possible to use digital image processing techniques were developed to geometrically rectify remote sensing data to a map projection (Reference_____). Simple polynomial-based algorithms have proven adequate for satellite imagery, where geometric distortions are minimal. Attitude motions common when collecting MSS data from aircraft platforms, however, make this approach acceptable on only small areas (Jensen and Christensen, 1983). Adaptive or discrete techniques such as finite element programs are required to remove the complex distortions that result from aircraft instability (Reference_____).

The Geometric correction of digital remote sensor data usually involves some type of resampling, e.g., nearest neighbor, bilinear, cubic convolution (Jensen, 1986). How these and other resampling algorithms affect the radiometric integrity of the data and its spatial appearance need to be more fully understood. Techniques to better automate or fine-tune geometric processing have been developed using different methods of multiple image spatial cross-correlation. However, broader application of these useful techniques requires development of more sophisticated image processing environments. Current software menu driven or "toolkit" approaches are too primitive and tedious for routine production processing. Photogrammetric techniques for differential rectification to remove relief displacement and achieve constant photo scale have led to orthophotography systems which are being well received in the GIS community. This approach provides images and/or photographs with map-like geometric characteristics. Similar processing is becoming populu for remote sensing imagery and necessary for GIS integration. (Ref. EOSAT + SPOT quads).

Radiometric Rectiflcation
(In Preparation)

Data Conversion

Processing of spatial data in image processing often involves some form of data conversion. It is possible to resample the data to such a degree that the geometric and radiometric attributes of the resampled data have a poor relationship with the original data. A good example would be cubic convolution resarnpling of Landsat 56 by 79 meter pixels to merge with 10 by 10 meter SPOT data. Another good example of resolution degradation during data conversion is when remotely sensed data is classified and then spatially filtered in order to increase classification accuracy. Once filtered, the spatial precision of resulting products may be reduced from that of the original measurements. Similarly, in GIS analysis of slope and aspect calculated from digital elevation models, the resulting value is representative of a neighborhood rather than being directly relatable to an individual pixel. These types of data conversions -must be catalogued, studied, and their cumulative impact quantified when incorporated into GIS.

DATA ANALYSIS ERROR

In the remote sensing/GIS processing flow outlined in this paper, data analysis involves the exploration of relationships between data variables and the subsequent inferences which may be developed. This stage of error accumulation will focus on the validity of statistical techniques. Difficulties in statistical analysis of spatially based environmental data sources involve the typical assumptions of the general linear model, compounded by the effects of spatial autocorrelation. Data analysis will also be subject to errors arising from variability in analyst expertise. Such variability may involve the choice of relevant predictive variables or the synthesis of new variables from multiple, correlated or uncorrelated parameters. The underlying nature of environmental data in classical linear regression is beyond the scope of this paper. However, a few examples of difficulties specific to spatial environmental data are provided.

Quantitative Analysis

Beyond the basic problems in sampling and regression model specification, environmental data commonly violate assumptions of independence for measured parameters and error variance. As a result, multi-colinearity may present a problem in, the case of regression modelling efforts (Montgomery and Peck, 1982). In this case, variance estimates for regression weights derived from ordinary least squares are inflated, resulting in potentially unstable values. Though better suited by weighted least squares estimation, regressed relationships in cases of correlated or changing error variance (heteroskedasticity) still provide problems in terms of efficient parameter estimation.

The tendency of adjacent or nearly adjacent samples to have similar values in environmental datasets, i.e., autocorrelation, may violate the independence of samples required in classical statistics. This may result in underestimated sample variance and inflated confidence estimates. The effects of autocorrelation in remotely sensed data sources have been examined by a few investigators, e.g., Woodcock et al., 1987; Jupp et al., 1988; Townshend and Justice, 1988. Techniques which are utilized include

semi-variogram. and block variance analysis. Methods should be developed based on these techniques to improve digital classifications, construct sampling methodologies, and/or deflate confidence estimates.

In terms of error accumulation, major impediments to the use of spatial data in the analysis phase arise from a lack of well documented methods and a lack of integrated statistical tools within existing software packages. The functions of many commercial software packages are organized in a hierarchical manner which leads an analyst through a logical processing flow. Flexible statistical tools need to be identified to take into account the particular difficulties of spatial environmental datasets and organized into a usable software environment. This would encourage adequate consideration of statistical assumptions in the development of more accurate information products.

In addition to statistical validity, the classic problem in GIS-based data analysis of misregistered polygon boundaries continues to plague us. Registration error might be seen as being somewhat distinct from the positional errors involved in the various independent data products. This distinction being that the resulting "slivers" cause logical errors of association in addition to being positionally inaccurate. The problems of cartographic overlay continue to be investigated and have recently been addressed by the National Center for Geographic Information and Analysis (NCGIA) as part of NCGIA Initiative 1: The Accuracy of Spatial Databases (Goodchild & Gopal, 1989). Proposed approaches to removing this hurdle in the processing flow have included attempts to deal with the boundary uncertainty using a statistically based buffer called the epsilon distance.

At this stage of the processing flow, where inference is being made between various types of data, the temporal nature of environmental data also becomes an issue. Errors which will occur due to the static representation of dynamic environmental parameters suggest that some method of assigning a lifetime to a dataset must be developed. To some degree this task is intractable due to the unpredictable or discontinuous nature of certain processes. For example, elevation data are generally considered stable within the time scale of database development, though natural and cultural processes are capable of making measurable changes in landscape morphology over short periods of time. However, certain products may correctly portray the landscape for long periods of time. For example, the multi-temporal composites of the normalized difference vegetation index (NDVI) derived from the AVHRR sensor, which are being compiled by agencies such as NASA Goddard and the EROS Data Center (USGS), represent continuous landscape processes which change throughout and beyond the period of measurement. Despite this difficulty, studies utilizing this information have found that periodic coverage of the NDVI data correspond well with certain environmental parameters (Tucker et al., 1983; Prince and Tucker, 1986). It is imperative that the temporal nature of remotely sensed phenomena be catalogued and judgements made concerning the optimum time period during which they are collected and their degree of longevity, i.e., when are the data obsolete?

Classification System

Classification systems themselves can be a significant source of error in the integration of remote sensing data into GIS's. Some of the potential sources of classification system induced errors are: the inability of classification systems to categorize mixed pixels, transition zones or dynamic systems; poorly defined or ambiguous class definitions; human subjectivity; and the lack of compatibility among different classifications systems used with both remote sensing and traditional data types.

Thematic data layers created using remote sensing data generally require the use of some type of classification system(s) to facilitate categorization of the data for subsequent GIS spatial data analysis. When dealing with mixed pixels or polygons and transition zones or dynamic systems, labeling inconsistencies will occur with all classification systems. This introduces an element of error which is particularly difficult to quantify.

Classification system induced error is of particular significance when dealing with natural systems. The fundamental under pinnings that natural-dynamic systems can be neatly categorized into "black boxes" does not hold. To make matters worse, the level of error related to the black box syndrome cannot easily be addressed. In a mixed pixel and transition or dynamic process situations, it is particularly important that detailed field verification data be collected to adequately describe the variation within a system to minimize classification system related error.

The problem of poorly defined or ambiguous class definitions is a common problem that often introduces an element of error. In dealing with either natural or man made (land cover or land use), there are an infinite number of situations that do not neatly fall under a specific class definition. If there is not a clear definition for a particular occurrence, there is a reasonable chance that inconsistence in labeling classes would occur leading to classification induced error. The better defined the classes and the more logical the classification scheme, the less classification induced error should result.

Often multiple thematic data sources are joined together or utilized as GIS coverages in a spatial data analysis process. Inconsistency in classification schemes can cause serious problems, rendering certain thematic coverages unusable in combination. A good example of this would be the Anderson et al. (1972) classification for use with remote-sensor data and the Cowardin et al. (1979)

classification of wetlands and deep water habitats. Because the two systems were developed on totally different schemes, wetland classes from one classification system are not directly convertible to the other. This potentially limits the use of data in these two classification systems, in combination.

Data Generalization

Data generalization is routinely performed during remote sensing analysis for two purposes; spatial resolution and spectral or thematic data reduction. Spatial generalization involves pixel resampling prior to analysis and resampling or grouping after analysis to meet a minimum map unit. As stated previously, resarnpling to a spatial resolution finer than the original data commonly results in substantial error. Spectral generalization may be performed by filters which either enhance certain features such as edges, or homogenize similar pixels. Since filters alter the original pixel values, errors such as accurate location of edges or loss of a spectrally similar yet unique resources may occur. Thematic generalization occurs after the classification process.

Post-classification data generalization takes on two forms, spatial and thematic. Thematic generalization is the grouping of classes to form meaningful categories. Since this is performed at the discretion of the analyst, bias errors may be introduced and information may be lost if the analyst does not recognize a unique resource. Another form of thematic generalization is the smoothing of a classified data set to remove any (salt and pepper) single classified pixels.

It is also common to resample a classified data set to a minimum map unit. For example, it may not be desirable for particular applications to generate a dataset with higher than an acre or hectare minimum map unit, especially if the dataset is large and data storage is a consideration. Also, with the recent trend of transferring raster-based remotely sensed data into a vector-based GIS, it is important to minimize the number of polygons which must be created in the vector form. Generalization of this form may result in inaccurate boundaries and the inclusion of small resources within a larger area resource class.

DATA CONVERSION ERROR

Raster to Vector and Vector to Raster Conversion

With the growing use of geographic information systems (GIS) and the need to incorporate digital remotely sensed data as a quick and reliable source of information, it was inevitable that data. would need to be converted between raster and vector formats (Figure 2). Raster format is simply data arranged as regularly spaced, equal sized grids. Satellite data and digital elevation models (DEMs) are common examples of raster data. These data are easily stored in a computer as a matrix of numbers. Vector data are more complex than raster data. Vector data maintain the true shape of a polygon using a series of arcs and nodes. Vector data are more aesthetically pleasing and are the preferred method of data display for most GIS thematic maps containing polygons. Additionally, most map products including the results of photo interpretation are generally represented in vector format.

Unfortunately, there can be significant error introduced either by converting from raster to vector format or from vector to raster format. The amount of this error depends on the algorithm used in the conversion process, the complexity of features, and on the grid cell size and orientation used for the raster representation. Failure to consider this potential error can introduce considerable problems into any analysis.
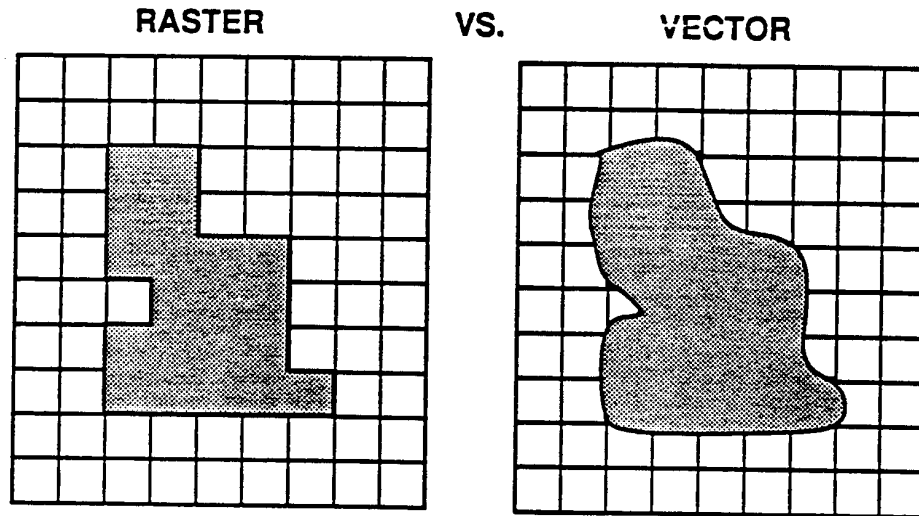
RASTER   VS.   VECTOR

Figure 2. A raster and vector representation of the same shape.

ERROR ASSESSMENT

Quantitative error analysis may be performed during any phase of data processing, including data acquisition. Ideally an error assessment is performed after each phase of the analysis. However, project funds and schedules rarely provide the opportunity to perform such a thorough error assessment. Typically in remote sensing projects, error assessments are only performed after completion of data analysis, and usually only address thematic and locational accuracy. Figure 3 illustrates a common approach used for remote sensing data error assessment. Locational accuracy typically refers to how well the georeferencing algorithms correctly placed pixels into a map coordinate projection, and not the accuracy of thematic or class boundaries.

Until recently, the idea of assessing the classification accuracy of remotely sensed data was treated more as an afterthought than as an integral part of most projects. In fact, even in the early 1980's many studies simply reported a single number to express the accuracy of a classification map. In many of these cases the accuracy reported was non-site specific, i.e., the locational accuracy was completely ignored. In other words, only the total amount of error per category was considered without regard for the location. If all the errors balanced out, a non-site specific accuracy assessment could yield very high but misleading results. In addition. most assessments were derived from the same data used to wain the classifier. Training and testing on the same data set results in overestimates of classification accuracy. Rigorous guidelines must be developed to insure that these fundamental non-spatial specific error assessment problems do not continue.
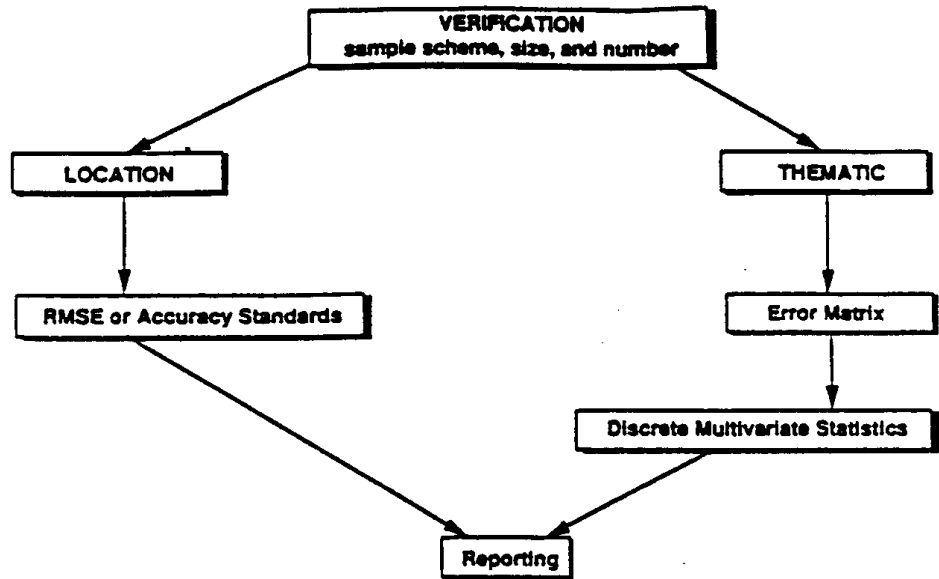
Figure 3. Error assessment flow chart.

Sampling

Sample size is an important consideration when assessing the accuracy of remotely sensed data which are to be used in a GIS. Each sample point collected is expensive and therefore sample size must be kept to a minimum and yet it is important to maintain a large enough sample size so that any analysis performed is statistically valid. Many researchers, (van Genderen et al. 1978; Hay 1979; Hord and Brooner 1976; Rosenfield 1982; and Congalton 1988b) have published the necessary equations and guidelines for choosing the appropriate sample size'

Sampling scheme is also an important part of an accuracy assessment Selection of the proper scheme is critical to generating an error matrix that is representative of the entire classified image. Poor choice in sampling scheme can result in significant biases being introduced into the error matrix which may over- or under-estimate the true accuracy. Researchers have expressed opinions about the proper sampling scheme to use (e.g., Hord and Brooner 1976, Ginevan 1979, and Rhode 1978). These opinions vary greatly and include everything from simple random sampling to stratified systematic unaligned sampling. Despite all these opinions, very little research has actually been performed in this area. Congalton (1988b) performed sampling simulations on three spatially diverse areas and concluded that in all cases simple random and stratified random sampling provided satisfactory results. Depending on the spatial autocorrelation of the area, other sampling schemes could also be used.

Spatial Autocorrelation

Spatial autocorrelation is said to occur when the presence, absence, or degree of a certain characteristic affects the presence, absence, or degree of the same characteristic in neighboring units (Cliff and Ord, 1973). This condition is particularly important in accuracy assessment if an error in a certain location can be found to positively or negatively influence errors in surrounding locations. Work by Congalton (1988a) on Landsat MSS data from three areas of varying spatial diversity (i.e. an agriculture, a range, and a forest site) showed a positive influence as much as 30 pixels away. Surely these results should affect the sample size and especially the sampling scheme used in accuracy assessment. Therefore, additional research is required to quantify the impact of spatially autocorrelated imagery or classification products when subjected to error evaluation procedures.

Locational Accuracy

In remote sensing, locational accuracy may be reported as the Root Mean Square Error (RMSE) resulting from the georeferencing algorithms which rectify images to map coordinates. The RMSE is the square root of the squared errors mean and reflects the proportion or number of pixel(s), plus or minus, that the image control points differ from the map or reference control points. However, the RMSE does not truly reflect the locational accuracy of all pixels within an image; the RMSE only addresses the control points. A simple procedure which may be used to better understand the overall locational accuracy of a georeferenced image has been developed by the Environmental Protection Agency (Norton, et al., 1990) for its Environmental Monitoring Assessment Program (EMAP). This procedure examines the average difference between ten noncontrol points in the image and reference map.

The most accurate means of examining locational accuracy is too costly to implement-, a ground survey with differential GPS.

Error Matrix

The most common way to represent the thematic or classification accuracy of remotely sensed data is in the form of an error matrix. An error matrix is a square array of numbers set out in rows and columns which express the number of pixels assigned to a particular category relative to the actual category as verified on the ground, see Figure 4 (Story and.Congalton, 1986). The columns usually represent the reference data while the rows indicate the classification generated from the remotely sensed data. An error matrix is a very effective way to represent accuracy because the accuracies of each category are plainly described along with both the errors of inclusion (commission errors) and errors of exclusion (omission errors) present in the classification.

The error matrix can then be used as a starting point for a series of descriptive and analytical statistical measurements. Perhaps the simplest descriptive statistic is overall accuracy which is computed by dividing the total correct (i.e., the sum of the major diagonal) by the total number of pixels in the error matrix. In addition, accuracies of individual categories can be computed in a similar manner. However, this case is a little more complex in that one has a choice of dividing the number of correct pixels in that category by either the total number of pixels in the corresponding row or the corresponding column. Traditionally, the total number of correct pixels in a category is divided by the total number of pixels of that category as derived from the reference data (i.e. the column total). This accuracy measure indicates the probability of a reference pixel being correctly classified and is really a measure of omission error. This accuracy measure is often called "producers accuracy" because the producer of the classification is interested in how well a certain area can be classified. On the other hand, if the total number of correct pixels in a category is divided by the total number of pixels that were classified in that category, then this result is a measure of commission error. This measure, called "users accuracy" or reliability, is indicative of the probability that a pixel classified on the map/image actually represents that category on the ground (Story and Congalton, 1986).

Figure 4. An example error matrix showing row, column, and grand totals, and the producer's and user's accuracy results (from Story and Congalton, 1986).

Discrete Multivariate Statistical Techniques

In addition to these descriptive techniques, an error matrix is an appropriate beginning for other analytical statistical techniques, e.g., the discrete multivariate techniques described by Congalton et al. (1983). These techniques allow for the comparison between classifications (i.e. error matrices) to test if one is statistically better than the other. These techniques also provide for standardizing the error matrices so that they can be directly compared without regard for differences in sample sizes. The error matrix is also appropriate input for the more established normal theory statistical techniques.

Reporting Standards

The two most common measures of thematic accuracy utilize binomial probabilities or Kappa coefficients of agreement. Binomial probabilities are based on the percent correct and therefore do not account for errors of commission or omission (Aronoff, 1985; Dicks and Lo, 1990). Conversely, the Kappa coefficient provides a difference measurement between the observed agreement of two maps and agreement that is contributed by chance (Congalton et al., 1983, and Hudson and Ramm, 1987). A Kappa coefficient of 0.90 may be interpreted as a 90 percent better classification than what would be expected by random assignment of classes. Advantages of Kappa are that its calculation takes into consideration off-diagonal elements of the error matrix (i.e. errors of omission or commission) and the conditional Kappa coefficients may be calculated for individual categories (Congalton et al., 1983, and Rosenfield and Fitzpatrick-Lins, 1986). Therefore, to standardize reporting procedures for static thematic maps, the error matrix must be present and include the percent commission error by category, percent omission error by category, total percent correct, number of points sampled, map accuracy (at the 95 percent confidence interval), and the Kappa statistic. Methods of assessing the accuracy of dynamic change detection maps are woefully inadequate and must be further researched (Martin, 1989; Haack and Jensen, 1990).

FINAL PRODUCT PRESENTATION ERROR

The goal of most remote sensing/GIS investigations is to produce a product which will quickly and accurately communicate important information to the scientist or decision-maker. This product may take many forms including thematic maps and statistical tables. This section identifies sources of geometric (spatial) and thematic (attribute) error in the final map products and statistical summaries.

Thematic maps produced using remote sensing and/or GIS procedures may contain static and/or dynamic information. A static thematic map is produced by analyzing information collected on a single date of observation while a dynamic map depicts the change which has occurred between successive dates of observation. There are a number of important issues which must be resolved in the creation of these static and dynamic thematic maps in order to reduce error which is communicated to the reader. A substantial amount of error can be removed if the reader is provided a complete cartobibliographic citation, i.e., the genealogy or lineage of the map product (NCDCDS, 1988). Methods for tracking processing flow for a particular data file exist in certain remote sensing software packages. The general approach has been to create a history file which lists all operations and parameters which have been applied to a dataset. An integrated solution to the tracking of processing flow is described by Lanter (1989). This approach involved the development of a program. written in the LISP language, which tracked the manipulation of data products in an ARC/INFO environment. The algorithm allowed automated backwards and forwards reconstruction of intermediate products between data inputs and information outputs. Ongoing research is focussing on the application of this technique to the modelling of error accumulation in GIS information products (Lanter and Veregin, 1990). Still other types of error can be reduced by simply using good cartographic design principles in the creation of map products, especially the legends. As will be demonstrated, a significant amount of work remains to be done to improve and standardize the information content of the thematic map products.

Geometric (Spatial) Error

As previously mentioned, geometric error in the final thematic map products may be introduced through the use of 1) different scale base maps over a region, 2) different national horizontal datum in the source materials, and 3) different minimum mapping units which are then resampled to a final minimum mapping unit. It is imperative that improved map legends be developed which include cartobibliographic: information on the geometric nature of the original source materials. This is the only way a reader can judge the geometric reliability of the final thematic map products. An example is shown in Figure 5, where the final thematic map was compiled from a digital elevation model (DEM) which had both "good and bad" data, from SPOT panchromatic data and USGS digital line graph transportation data. Note that the legend also identifies that the DLG vector data were resampled to 10 x 10 m and placed in a raster format. Additional information might include the root mean square error (RMSE) associated with the resampling procedures per dataset (Ford and Zanelli, 1985). All that is required in the legend is the topmost composite along with the text summary of data types. This type of cartographic bibliography helps readers to identify portions of the final thematic map which have reduced reliability. This should lead to improved decision making.
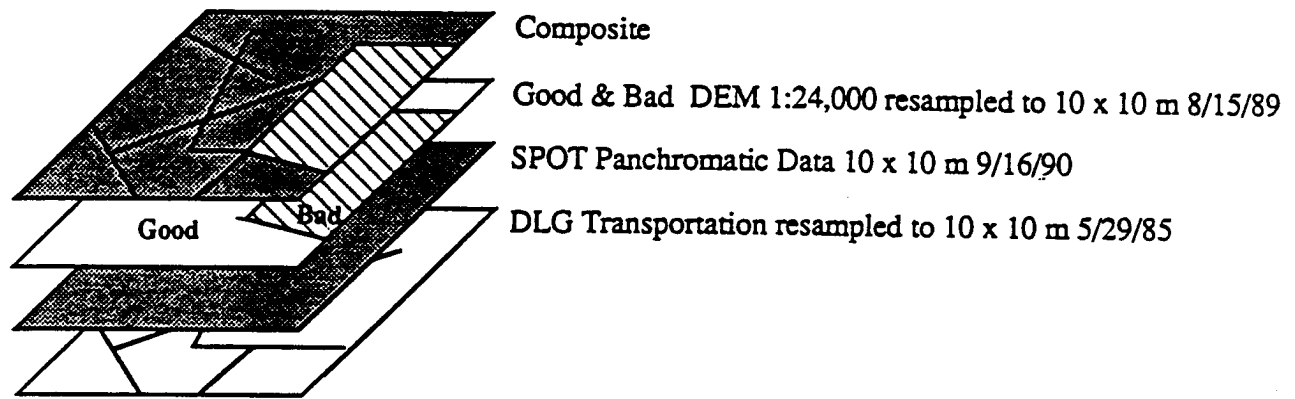
Composite

Good & Bad DEM 1:24,000 resampled to 10 x 10 m 8/15/89

SPOT Panchromatic Data 10 x 10 m 9/16/90

DLG Transportation resampled to 10 x 10 m 5/29/85

Good   Bad

Figure 5. Geometric reliability diagram summarizing datasets and degree of resampling.

Thematic (Attribute) Error

Diverse datasets obtained on different dates with different minimum mapping units may be used to educate a classifier or perform some other GIS analytical function. Newcomer and Szajgin (1984) and Walsh et al. (1987) suggest that the highest accuracy of any GIS output product is only as accurate as the least accurate file in the data base. Thus, although the final map may look uniform in its accuracy, it is actually an assemblage of information from diverse sources. It is important for the reader to know what these sources are through a thematic reliability diagram. For example, Figure 6 identifies the two sources of wetlands used to educate a classifier and the location of in situ samples used to assess map accuracy. Persons who map wetlands might be concerned that DLG wetland were used. Also, the diagram might reveal that the in situ sampling was spatially biased toward locations which were accessible only by boat. These two facts help the reader to determine the value of the final map product. There is a great need to standardize the design and function of thematic reliability diagrams.

Fundamental cartographic design principles must be followed especially when constructing the class interval legends for thematic maps. Gilmartin and Shelton (1989) suggest that too many class intervals and poor hue (color) selection yield poor cartographic communication on CRT displays. Since more and more of the remote sensing/GIS information are stored and displayed on CRTs and less on paper this a very important issue (Reis, 1990). Also, while progress has been made on static thematic map design, dynamic change detection maps often have extremely poor legends. Much research is required to construct meaningful change detection "from --- to--" legends which allow the reader to accurately determine what has changed.
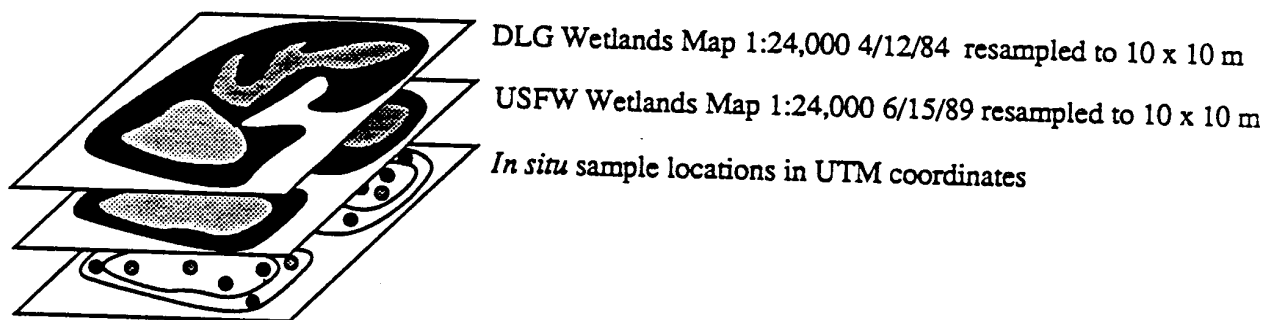
DLG Wetlands Map 1:24,000 4/12/84 resampled to 10 x 10 m

USFW Wetlands Map 1:24,000 6/15/89 resampled to 10 x 10 m

In situ sample locations in UTM coordinates

Figure 6. Thematic reliability diagram summarizing sources used to educate a classifier and perform error evaluation.

Many scientists are now overlaying image raster data with thematic vector data. This powerful technique provides an ungeneralized basemap which the reader can use to orient and appreciate the thematic vector data (Goodenough, 1988). Unfortunately, there are no standards about optimum display conditions for the background image (e.g. band selection, type of resampling, degree of contrast stretching) or the optimum design of the vectors (e.g. selection of contrasting color, degree of transparency). Research is required to standardize and improve thematic map products which incorporate a raster-vector integration.

DECISION MAKING

The decision maker is often presented with remote sensing/GIS derived map or statistical presentation products for use in the decision making process. In most situations, adequate information concerning the lineage of thematic data layers and associated thematic and geometric accuracies is not provided. Ideally, in addition to the above mentioned information, the decision maker needs an estimate of the overall accuracy and confidence of the data product(s) used in the process. However, GIS map and statistical data are being used by decision makers with little to no knowledge of the potential sources of error, and no information concerning the accuracy and confidence level of final presentation products.

There is a definite tendency among many decision makers to accept map products (including map derived statistics) as truth. Because many final remote sensing/GIS analysis products are presented in thematic map form, there is a tremendous potential for a decision maker to error by over estimating the accuracy and/or confidence of thematic remote sensing/GIS map products. It is imperative that the remote sensing and GIS communities educate the decision makers to better understand the potential error sources associated with remote sensing/GIS data products. As the decision makers become more knowledgeable of the issues related to data accuracy and confidence, they will begin to demand data concerning consumer accuracy be provided with all final presentation products.

One of the objectives of this manuscript is to provide an overview of the potential error sources for the incorporation of remote sensing data into GIS for spatial data analysis applications. The "typical" data processing flow organization used is intended to provide a straight forward overview of the error propagation process. The authors hope this presentation provides a better understanding of the remote sensing/GIS integration process to the decision maker. Decision makers and data analysts can no longer work in isolation if the use of remote sensing and GIS technologies are to become data sources on which decisions are based.

IMPLEMENTATION

Decisions based on data of substandard accuracy and/or inappropriate confidence levels, has an increased probability of resulting in incorrect implementation actions. The obvious implications of an incorrect implementation decision are an erroneous resource management action which can have serious consequences on the resource itself. This can result in the loss or degradation of the resource, adverse impacts on a particular ecosystem or ecosystem element, or potentially detrimental human health impacts, all of which can result in monetary or other adverse punitive actions.

As remote sensing/GIS derived products are increasingly being utilized as a basis for implementation decisions concerning resource management and regulatory issues, there is a high potential for an explosion in the number of litigation cases in the near and long term. A major challenge to the remote sensing and GIS communities will be the ability to adequately defend the accuracy and reliability (confidence) of products used by decision makers in implementation processes. The research and development issues recommended for priority attention in this manuscript will significantly enhance our ability to defend implementation decisions based on the use of remote sensing/GIS products with sound scientific criteria.

CONCLUSIONS

A considerable amount of research and development must be accomplished before error associated with remote sensing and GIS data integration can be adequately quantified and reported in standardized formats. A number of research topics have been identified based on the current needs of the user community to facilitate the use of remote sensing data products in geographic information analysis. This list is not presented as an exhaustive research topic overview. Instead it identifies critical research areas that should receive priority for research support on a national and international level.

1. Improve on existing remote sensing error assessment procedures. Current state-of-theart remote sensing error assessment procedures have been adapted for existing statistical procedures that were not specifically developed for spatial data. Although these techniques have been adopted and perform reasonably well for small areas, their application on regional and global scales are not economically feasible.

2. Assess/propose error reporting standards and lineage documentation. Over the past few years, the use of a confusion matrix for reporting classification accuracies has become common. However, comprehensive standards for reporting error have not been adopted by societies, agencies, etc. dealing with spatial data. There is a need to: 1) review the various error reporting mechanisms found in the literature; 2) refine existing and develop new error assessment procedures where needed; 3) evaluate error assessment procedures and recommend a set of standards for the GIS and remote sensing communities. This will provide a direct method for comparing the results from every research effort.

3. Field verification data collection procedures. The need for field verification or "ground truth" to assess the accuracy of remotely acquired data is well established. Peer-reviewed journals have published papers on sample size and scheme, and accuracy assessment procedures. However, the philosophy and general guidelines for acquiring good field data for map accuracy assessments has not been well addressed. For example, is it adequate to make observations and record labels or class names when in the field, or should more descriptive observations and measurements be made, or will the interpretation of small scale aerial photography provide the data needed for an accuracy assessment? Basic research needs to be performed and documented on the levels of accuracy associated with different forms of field verification.

4. Raster to Vector and Vector to Raster Conversion. The results of digital satellite image classification is a pixel by pixel label of the entire image. This data is easily stored in raster format but requires carefully administered steps to convert accurately to vector format. The difficulty lies in the huge number of polygons created if the data were converted to vector format. In the worst case scenario, each pixel in the image becomes a single polygon. Such a large amount of data quickly burdens even the Largest computer. Additionally, in many instances the desired result of image classification is not a pixel map but rather a polygon map of areas of similar characteristics. These polygons would approximate the result achieved by on-the-ground field visitation or more commonly by photo interpretation. It is therefore desirable to reduce the pixel by pixel classification to some smaller number of polygons, i.e. simplify the image.

Numerous rules have been set up to perform this procedure of converting raster data to vectors. However, the effects on shape, size, and accuracy of these polygons as compared to the original raster data have not been explored with any rigor. Therefore, it is critical that research be undertaken to explore the effects of the raster to vector conversion process for digital remotely sensed data. Methods of quantifying the change between vector to raster and raster to vector conversions must be developed. Only when the effects of performing such conversions are understood and quantified can these techniques be effectively employed.

5. The incorporation of elevation correction in georeferencing procedures. Additional studies need to be conducted to assess the relationship of elevation model scale and the degree of relief displacement in the georeferencing process. A critical component in the georeferencing process is the use of geodetic control. Guidelines and procedures need to be established for control requirements in the georeferencing process including procedures and guidelines for appropriate datum selection.

6. The development of standardized geometric and thematic reliability legends. Final map and statistical products must be designed and standardized to communicate information regarding the accuracy and/or reliability associated with the specific data products. This will require research to develop geometric and thematic reliability diagrams for remote sensing/GIS final products.

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Remote Sensing and Geographic Information System Data Integration: Error Sources and Issues

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Objectives:

Identify the potential sources of error in the "typical" data processing flow for the integration remote sensing data into GIS's.

Discuss the potential impacts of error propagation in the decision making and implementation processes.

Recommend priority error quantification research topics to overcome error related impediments for the incorporation of remote sensing data into GIS analysis applications.

Remote Sensing and Geographic Information System Data Integration: Error Sources and Issues
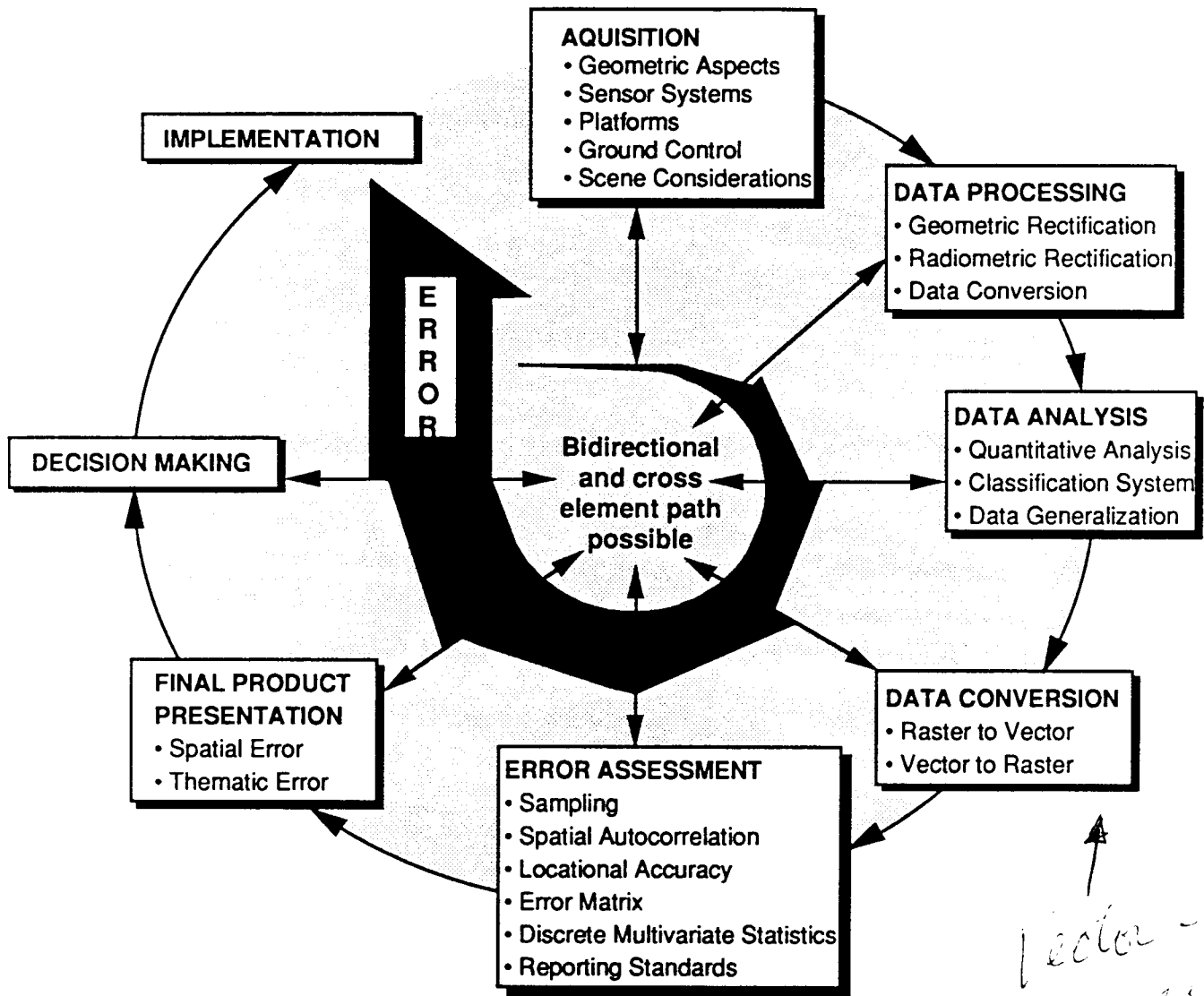
Figure 1. The accumulation of error in a "typical" remote sensing information processing flow.

Conclusions: Research Issues

1. Improve on existing remote sensing error assessment procedures.

2. Assess/ propose error reporting standards and lineage documentation.

3. Field verification data collection procedures.

4. Raster to Vector and Vector to Raster Conversion

5. The incorporation of elevation correction in georeferencing procedures

6. The development of standardized geometric and thematic reliability legends.

Acquisition

GIS processing of multiple data layers is predicated upon accurate spatial registration between layers.

For the processing of remote sensing imagery this includes consideration of both geometric and radiometric fidelity that result from a combination of factors such as:

Type of Sensor System
    (e.g., aerial camera, multispectral scanner, imaging radar)

    Spectral response range and sensitivity
    Illumination source (active vs. passive)
    IFOV and total FOV

Platforms

    Aircraft
    Satellite

Ground Control

    Survey techniques (growth of GPS)
    Visually interpreted

Scene Considerations

    Terrain
    Atmospheric conditions
    Seasonal and episodic conditions

Data Processing

Geometric Rectification

Systematic vs. non-systematic corrections
Manual vs. automated techniques

Radiometric Rectification

Sensor calibration
Atmospheric corrections
Scene characterization (surface effects, e.g., BDRF)

Data Resampling (Conversion)

Spatial resampling algorithms (e.g., bilinear, cubic convolution)
Spectral resampling

Data Processing/Analysis

Mathematical Logic

- Enforcement of data mixing constraints
- Variety of statistical techniques exist

Spatial Convolution

- Precision versus accuracy location & quantization
- Relationship to generalization
- Effect of filtering techniques on MMU

Multi-temporal Compositing

- Discrete views of a dynamic environment
- Develop approaches for dealing with uncertainty

Statistical Validity

Environmental data pose special problems for traditional statistical analysis
- Spatial autocorrelation
- Multi-collinearity

Data Product Generation

Categorical
- Training field validity, signature extension
- Band selection

Continuous Parameterizations
- Robustness of empirical relationships
- Bias, overconfidence

Error Assessment

- Choice of sampling scheme
- Efficiency of sample collection
- Bias, overconfidence

Improving Error Assessment

Class Specific Nature of Error

- Weak links between taxonomic divisions and spectral properties
- Patterns arising from class dependent error
- Understanding the interaction of case specific weighting functions and class dependent error

Covariance of Error Between Data Layers

- Error accumulation
- Spatial repercussions

The Boundary Challenge & Registration

- Positional error vs. logical error
- Bias due to undersampling of boundary zones
- Look to 11 research for related approaches such as Epsilon band

Remote Sensing and Geographic Information System Data Integration: Error Sources and Issues
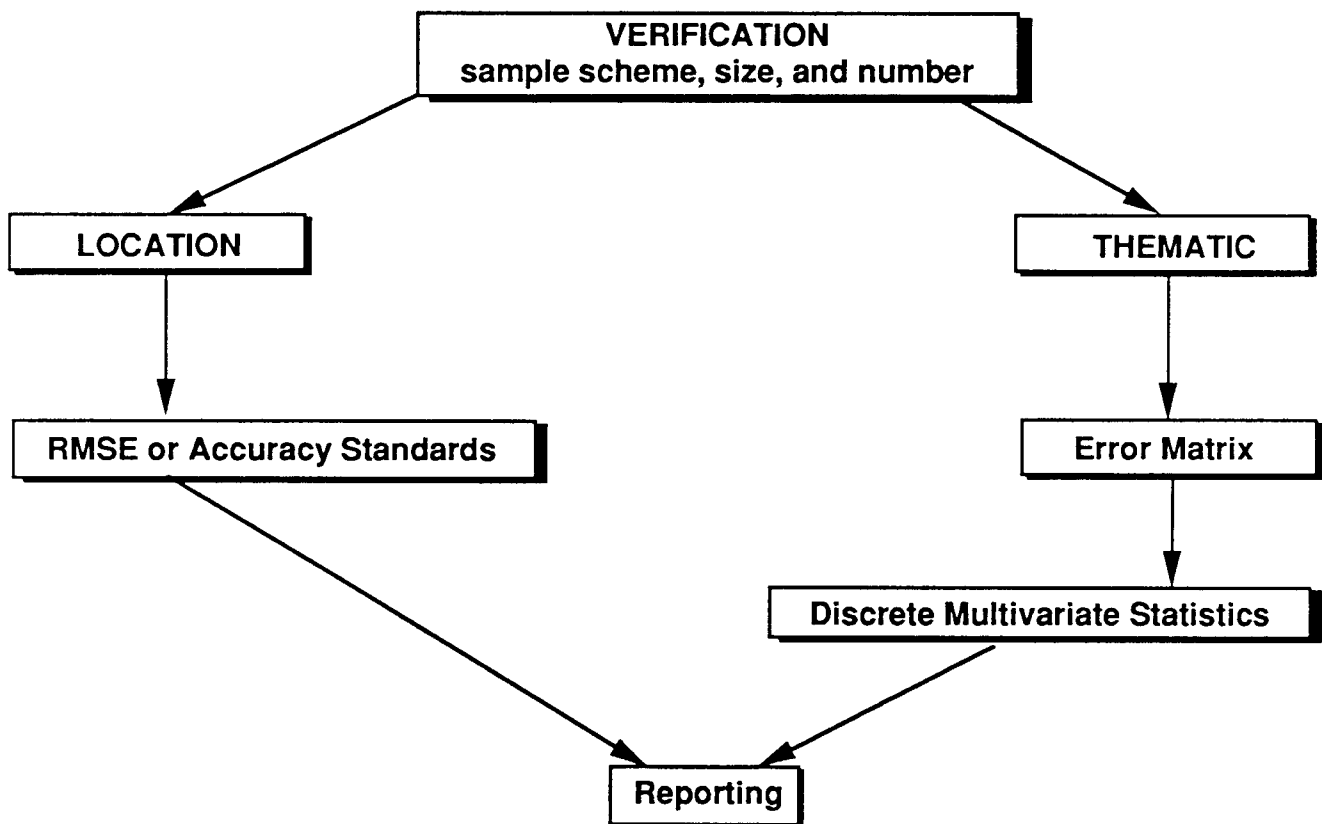
```
                    ┌──────────────────────────────────────┐
                    │          VERIFICATION                │
                    │  sample scheme, size, and number     │
                    └──────────────────────────────────────┘
                      ╱                               ╲
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         ┌────────────────────┐              ┌────────────────────┐
         │     LOCATION       │              │     THEMATIC       │
         └────────────────────┘              └────────────────────┘
                  │                                   │
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     │ RMSE or Accuracy Standards   │         │    Error Matrix    │
     └──────────────────────────────┘         └────────────────────┘
                    ╲                                 │
                     ╲                                │
                      ╲                  ┌─────────────────────────────────┐
                       ╲                 │ Discrete Multivariate Statistics │
                        ╲                └─────────────────────────────────┘
                         ╲                     ╱
                          ╲                   ╱
                        ┌──────────────┐
                        │  Reporting   │
                        └──────────────┘
```

Figure 3. Error assessment flow chart.

Definitions of Data Quality

Tradition in Mapping Sciences:

    * judgement of fitness integrated in cartographic decisions

    * conformance to expectations, *paternalist & centralist*
        fixed thresholds for position only - e.g.. US National Map Accuracy
        Standards "This map complies with National Map Accuracy Standards" =
        the producer thinks that the product would pass the test if tested.

New approach: US Proposed Standard for Digital Cartographic Data Quality

    * fitness for use - truth in labeling (user, not producer)

    * testing for all components of data quality

        Testing depends on models of information.

Components of Data Quality

        NCDCDS, SDTS

* Lineage
        records the source material and all transformations.
        mixtures must be explained.

* Positional accuracy
        ASPRS Standard for Large Scale Line Maps (for well-defined points)

* Attribute Accuracy

* Logical Consistency
        particular attention to definition of "Topologically Clean".

* Completeness

Model for Geographic Information
after Sinton

Dimensionality: time, space and attribute

To measure one, another must be fixed (no variation), and the third must be controlled (variation limited).

Time fixed, space controlled, attribute measured applies to raster, choropleth (collection units)

Time fixed, attribute (identity) controlled, measure space applies to vector structure for exhaustive categorical coverages

      perhaps the fixed element can become controlled

This model explains differences in tests.

Tests for Spatial Data

Topology: logical consistency of data structure

Point objects (and features surrounded by void):
      if identity is clear (well defined),
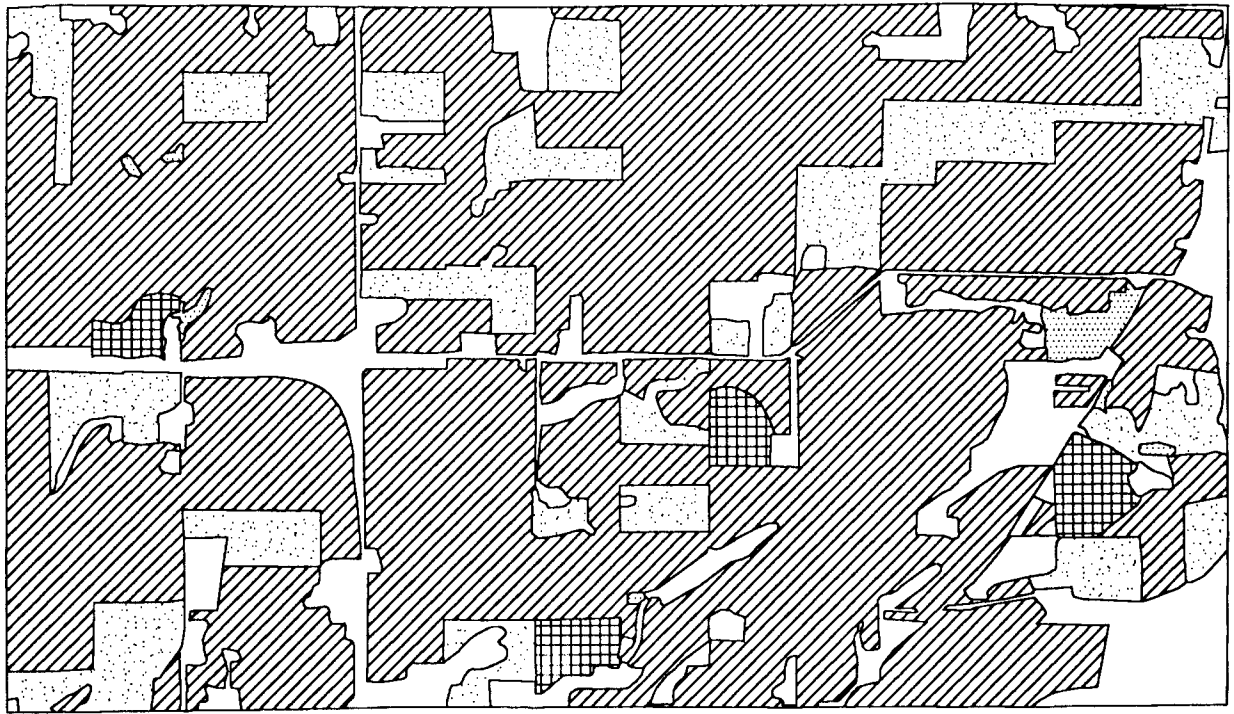   * paired observation, NMAS,RMSE ets.

Categorical coverages:
      - no direct pairing of observation
      * point sampling, tabulation in matrix
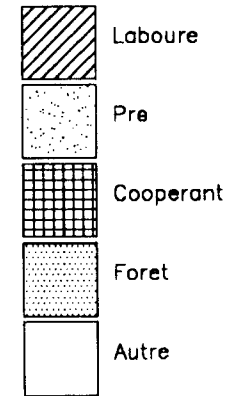   * Overlay of two sources, tabulation of areas in matrix

Continuous surfaces
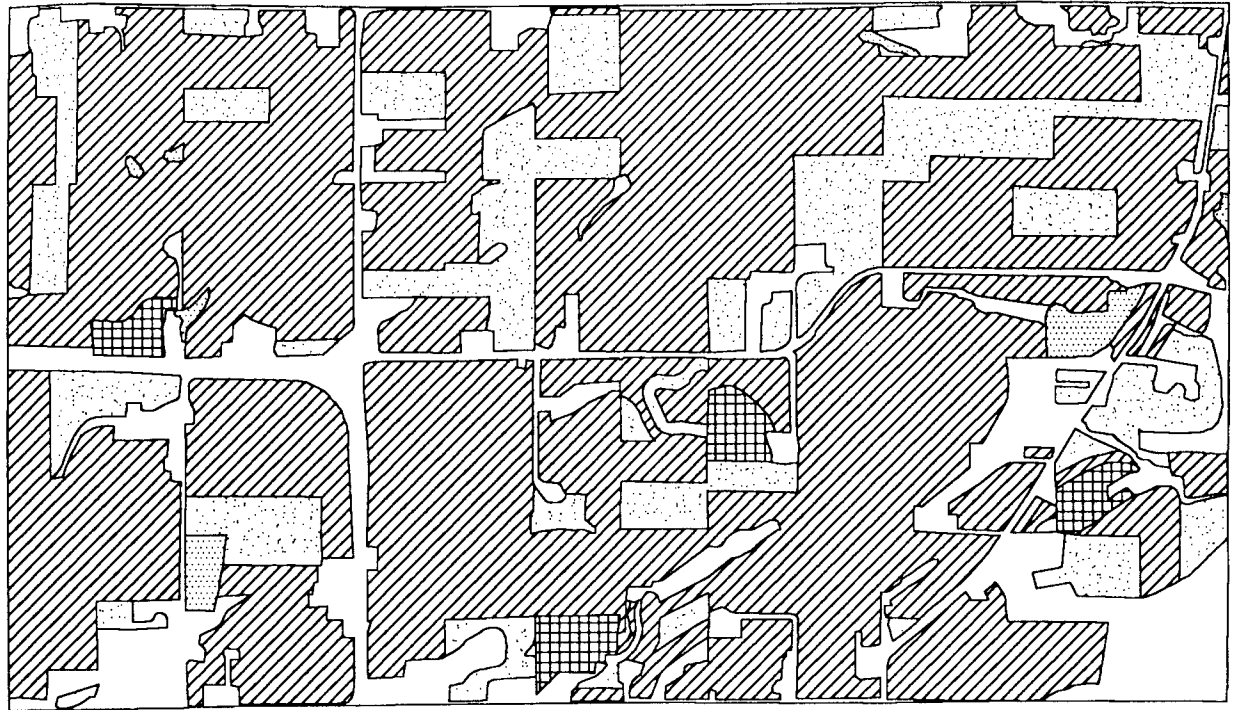   - pair observations for sampled points, RMSE
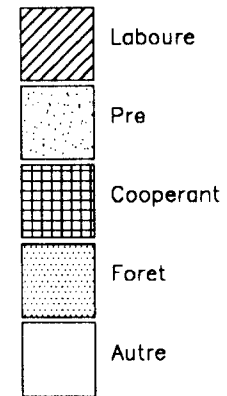
Other forms of data require other tests.

Utilisation
du Sol
Interp. 1

Laboure
Pre
Cooperant
Foret
Autre

Utilisation
du Sol
Interp. 2

	Laboure
	Pre
	Cooperant
	Foret
	Autre
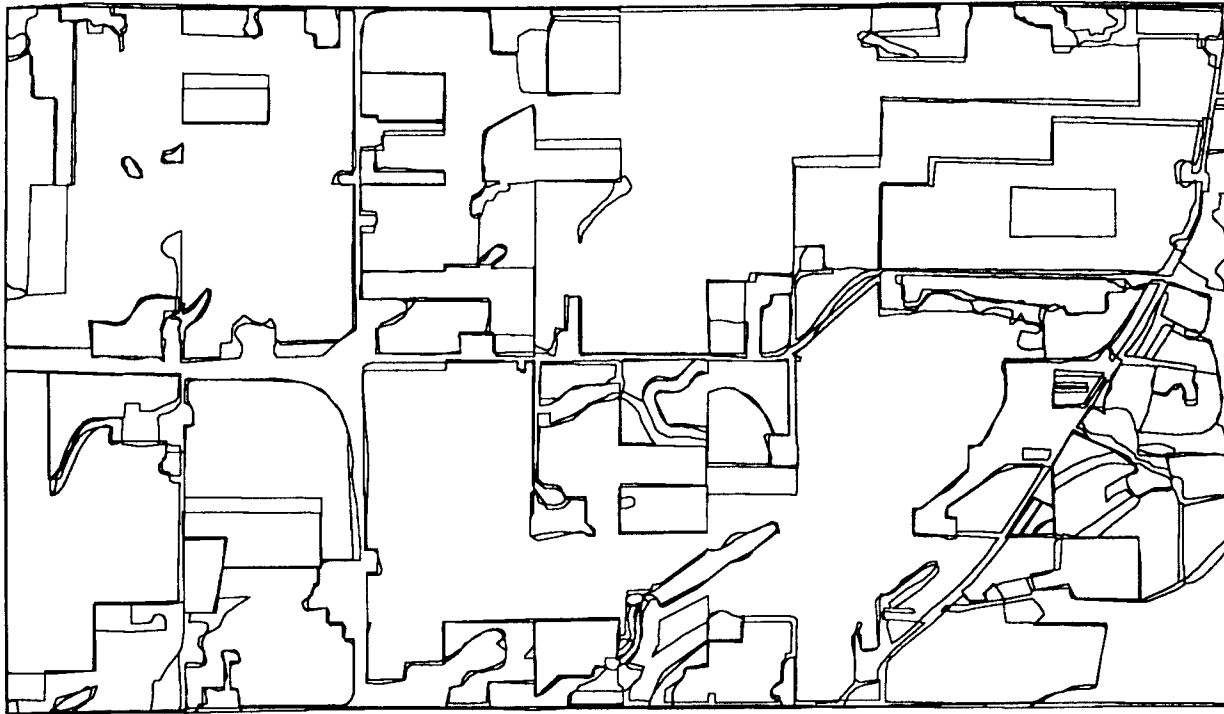
Error Matrix

Interp. 2

Interp. 1	Row Crop	Meadow	Coop.	Woods	Other
Row Crop	1110.9	82.5	.9	.8	57.8
Meadow	17.5	212.3	.04	.2	35.8
Coop.	4.0	3.6	32.6	.03	2.0
Woods	.9	.3		10.2	2.1
Other	32.7	11.6	.1	7.5	212.3

Figures in hectares
All errors, unfiltered

Diagnosis of Errors (not yet perfect)
Discrimination Errors

Interp. 1	Interp. 2 Row Crop	Meadow	Coop	Woods	Other
Row Crop	- -	38.5	.9	.8	44.3
Meadow	11.9	- -	.04	.2	31.8
Coop.	2.1	1.2	- -	.03	2.0
Woods	.9	.3	- -	- -	2.1
Other	19.5	7.9	.1	.09	- -

Identification Errors

Interp. 1	Interp. 2 Row Crop	Meadow	Coop.	Woods	Other
Row Crop	- -	44.0	- -	- -	13.5
Meadow	5.6	- -			4.1
Coop.	1.9	2.4	- -		
Woods				- -	
Other	13.2	3.7		7.4	- -

Figures in hectares
All errors, unfiltered
Map 4
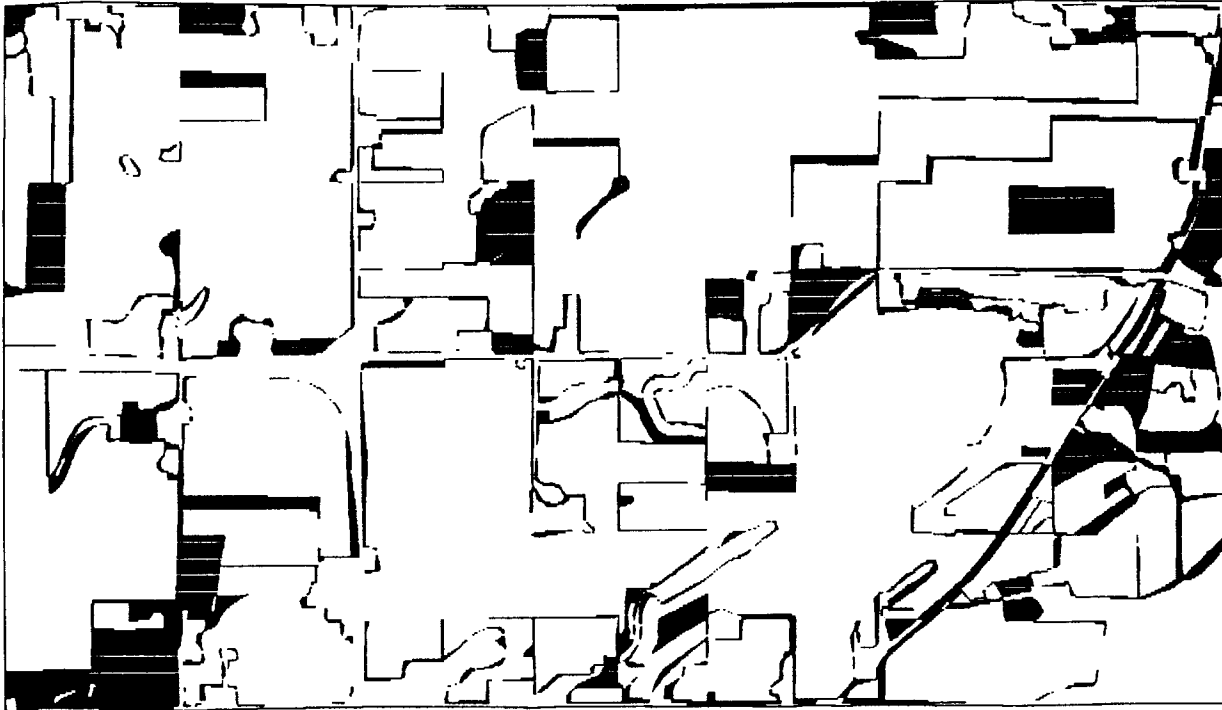
Resultat de
Superpositic

Different

Meme
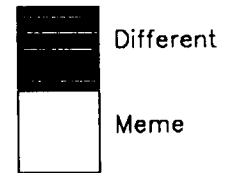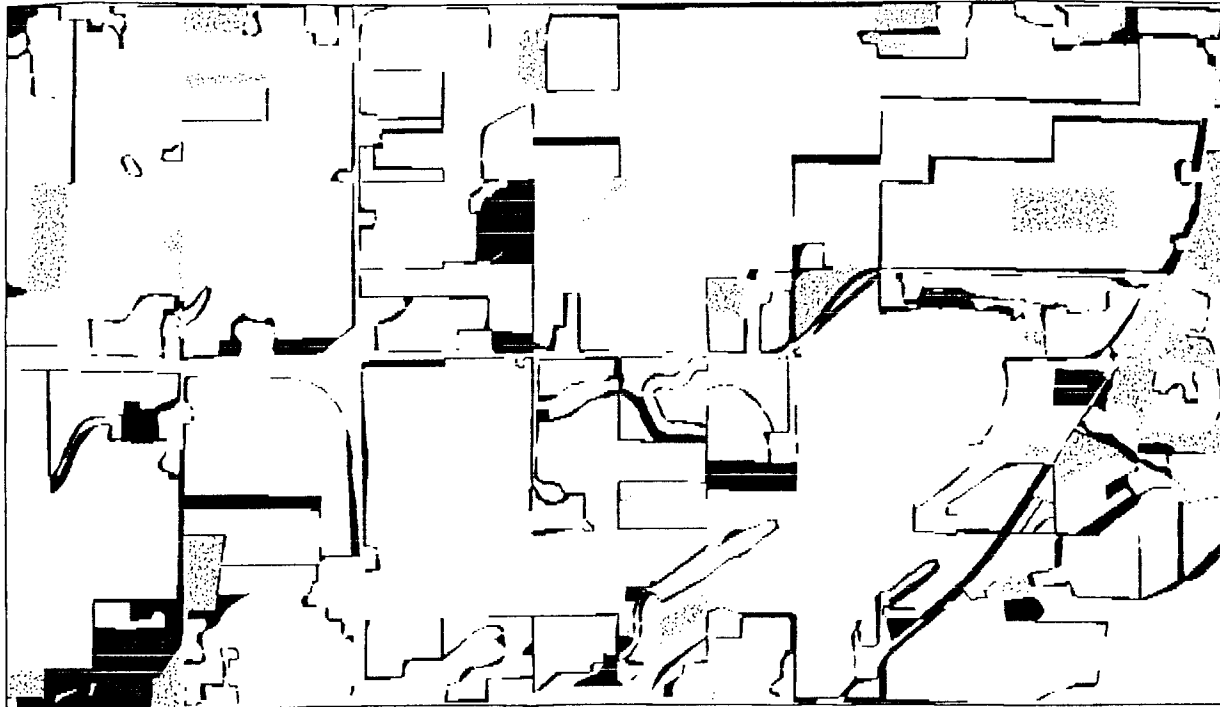
Classification
des Erreurs

Discrimination

Identification

Meme
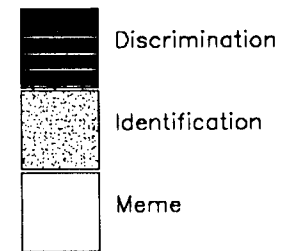
Sensitivity of Error to 20m Filter
Discrimination Error without filter

	Interp. 2				
	Row Crop	Meadow	Coop.	Woods	Other
Interp. 1					
Row Crop	- -	38.5	.9	.8	44.3
Meadow	11.9	- -	.04	.2	31.8
Coop.	2.1	1.2	- -	.03	2.0
Woods	.9	.3		- -	2.1
Other	19.5	7.9	.1	.09	- -

Discrimination Error after 20m epsilon filter (WHIRLPOOL)

	Interp. 2				
	Row Crop	Meadow	Coop.	Woods	Other
Interp. 1					
Row Crop	- -	15.4		.2	19.5
Meadow	6.5	- -			24.4
Coop.	1.7	.4			.4
Woods	.04	.1		- -	1.0
Other	18.0	7.9	.1	.04	- -

Figures in Hectares

Sensitivity of Error to 20m Filter
Identification Error without filter

	Interp. 2				
	Row Crop	Meadow	Coop.	Woods	Other
Interp. 1					
Row Crop	- -	44.0			13.5
Meadow	5.6	- -			4.1
Coop.	1.9	2.4	- -		
Woods				- -	
Other	13.2	3.7		7.4	- -

Identification Error after filter

	Interp. 2				
	Row Crop	Meadow	Coop.	Woods	Other
Interp. 1					
Row Crop	- -	61.2			21.5
Meadow	5.6	- -			7.8
Coop.	1.8	2.5	- -		.6
Woods				- -	.9
Other	18.0	7.9		7.6	- -

Figures in hectares

Discrimination Error and Translation (uniform registration error)

Discrimination Error from test

Interp. 2

Interp. 1	Row Crop	Meadow	Coop.	Woods	Other
Row Crop	- -	38.5	.9	.8	44.3
Meadow	11.9	- -	.04	.2	31.8
Coop.	2.1	1.2	- -	.03	2.0
Woods	.9	.3		- -	2.1
Other	19.5	7.9	.1	.09	- -

Result of translation experiment

Translated Interp. 1

Interp. 1	Row Crop	Meadow	Coop.	Woods	Other
Row Crop	- -	15.4		.2	19.5
Meadow	6.5	- -			24.4
Coop.	1.7	.4	- -		.4
Woods	.04	.1		- -	1.0
Other	18.0	7.9	.1	.04	- -

Movement = .8m towards the South
Figures in hectares

Paper Coordinated by Nick Faust, Georgia Tech.

Geographic Information Systems and Remote Sensing
Future Computing Environment

I. Introduction

The integration of image data into Geographic Information Systems (GIS) is one of those great ideas whose time has come. GIS systems have become accepted as a standard way of handling geocoded data sets and performing analyses on that data for multitude of applications. Historically, the major costs associated with the implementation of a GIS system is neither the necessary hardware or software, nor the personnel costs associated with the management of the system. The major costs of GIS have normally been in the gathering of the geocoded data. Recently, remote sensing (RS) images have been shown to be natural and cost effective means for update of GIS data sets (Sperry,1989, ERDAS, 1989). As we enter into the 1990's, the technologies for data entry, data storage, and data access, and data analysis will progress such that a new vision of GIS will be created with radically different constraints. The concept of real time modeling and interactive 3 dimensional query will change the way in which we deal with spatial data. These new insights will in part be due to major advances in computer technology and in part be due to the institutionalizing of the GIS/RS process into everyday decision making (Lang,1989).

Modern GIS analysis began in the middle 1970's at the Harvard School of Landscape Design with Carl Stenitz. A cell based model for growth management was developed under NSF funding for the Boston metropolitan area. The model, called GRID, was a complex model of spatial parameters including population distribution that was run in a batch mode on an IBM mainframe. Given certain spatial variables such as the implementation of zoning laws, the model was used to allocate projected population growth with a gravity distribution within Boston and its neighboring areas. The model was used in teaching planning and resource allocation techniques to graduate students in the School of Design. Because of the batch nature of the model, and its dependence on complex interactions, GRID was difficult to use in a 1 to 2 year graduate program. A student revolt led to the design of an somewhat interactive geographic analysis set of tools called IMGRID which allowed the exercise of the geographic analysis functions without being tied to the complex GRID model. GRID and IMGRID form the basis for most cell based GIS analysis systems. Early students in the Graduate School for Design include Jack Dangermond of Environmental Systems Research Institute (ESRI), Dana Tomlin of Yale, and Bruce Rado, Lawrie Jordan, and Steve Sperry of Earth Resources Data Analysis Systems (ERDAS) . ESRI developed a mainframe and minicomputer based grid analysis package and the first topologically based vector based GIS. Dana Tomlin developed the Map Analysis Package (MAPS), and ERDAS developed the first microcomputer GIS and Image Processing system. ESRI and ERDAS developed the first integrated capability for image processing, grid GIS analysis, and topological vector processing. Other packages, such as the Map Overlay Statistical System (MOSS), were developed with a basis of software developed at the State University of New York.

All of these systems were initially developed on mainframes, minicomputers, or microcomputers with a Von Neuman, or serial, architecture. As computer power has increased, GIS systems have become oriented towards a workstation environment where single workstations have the power of full mainframes of the past, and networks of workstations allow resource sharing and multiprocessing. The implementation of GIS systems to take advantage of the vast resources of the multiprocessing environment has yet to be fully realized. Supercomputing systems are currently implemented that perform complex viscous flow modeling, finite element integration, and 3 dimensional stress and heat flow modeling, but very little serious attention has been paid to the prospects for parallel implementation of GIS analyses.

Computer technology changed significantly from the 1960's to the late 1970's. Mainframes were being supplemented by minicomputers, and microcomputers were initially being introduced into the popular market. By the mid 1960's minicomputers (PDP 1, IBM 650) were being introduced by Digital Equipment Corporation (DEC) and International Business Machines (IBM) (IEEE Scientific Subcommittee) Scientific applications were becoming viewed as inherently different from business applications and new systems were being developed to met this market. Personal computers became available using the Zilog Z-80 and the Motorola 6800 chips in the late 19701s, and IBM introduced its personal computer in the early 1980's. The introduction and wide acceptance of the personal computer led directly into the concepts of networks and shared access which represent the state of the art in today's lower power computing arena.

During the 1970's, also, computer technology developed the first of the parallel processing (Illiac IV) and vector processing (CDC Star 100) systems. These systems signaled the emergence of supercomputers as a new class of computer. Techniques experimented with in the 1970's have led to commercial hardware and software implementation of parallel and vector processors. Mini-supercomputers, a lower cost and sometimes hardware specific implementation of supercomputer principles have become available in the 1980's for intensive computational power at a workstation.

Spatial display of GIS and Remote Sensing information has been another area in which computer technology has advanced greatly in the last two decades. In the early days of GIS and Remote Sensing, the only display media for spatial information were line printer maps and plotters, with subsequent manual coloring. Advances in computer graphics for Computer Aided Design and Computer Aided Manufacturing (CAD/CAM), Image Processing (IP), and Scientific Visualization have provided a sophisticated method for interpretation and display of geographic information that is only recently being employed by GIS/RS.

Objective

We are currently in the midst of massive changes in the computing environment that will affect all phases of GIS/RS integration. In this article, we will attempt to:

1) functionally identify the processes used in GIS/RS analysis
2) identify current impediments in the computing environment to rapid GIS/RS acceptance
3) identify trends in computing technology that will directly affect the GIS/RS systems of the future
and
4) suggest research thrusts that might be pursued to overcome these obstacles.

II. Identification of functions provided in GIS/RS integration

GIS systems in today's market may be conveniently be broken down into two types that are indicative of their inherent data structure. Raster GIS systems have multiple variables which normally are coded into cell or raster grids. Attributes for variables are normally coded to a grid cell value with a lookup to extended attributes. While data may be captured in either a raster or vector manner, data analysis occurs in the raster domain. Examples of such raster systems include ERDAS by ERDAS, SPANS by TYDAC, GRASS by the U. S. Army Corps of Engineers, and MAPS by Dana Tomlin.

Vector systems, on the other hand, capture data in vector f ormat, analyze data in vector format, and produce output in either vector of raster format. Generally, the data are either stored as whole polygons, lines, and' points, or in a topologic
structure of arcs and nodes (?????) . Attributes are coded to each basic representation and are generally stored in a relational database. Examples of current vector based GIS systems include ARC/INFO by ESRI, MOSS by Autometrics, and TIGRIS by Integraph.

The integration of Remote Sensing information into GIS occurs naturally in a raster GIS since both data structures are approximately the same. Integration into a vector system requires somewhat more effort, but it has been recently achieved by several GIS and Remote Sensing vendors, at least to the extent of updating vector information by using an image as a backdrop for vector editing (Sperry, 1989,ERDAS, 1989)

Basic image processing and analysis tools such as geometric correction and pattern recognition are expected to be available to preprocess remote sensing information into a form in which attributes are assigned to raster data instead of raw data values from spectral bands of multispectral imagery.

Once the Remote Sensing information is in a form that can be analyzed as a part of a GIS, systems with both data representations apply a number of the same functions, even though they are implemented in a significantly different manner. We will consider each of the basic functions of a GIS and discuss the differences in the implementation for vector and raster systems.

Information Display

Display of GIS/RS information is, of course, the most visible part of a GIS/RS system. The information must be provided to a user in a concise, and easy to understand manner so that he may be able to comprehend the potential complex relationships that may exist between multiple spatial variables. The techniques for GIS/RS display will tend towards using all of the capability available in a graphic display system.

Display of raw and processed Remote Sensing data normally occurs in a 'true color' mode in which raster images for three different variables (in this case, 3 spectral bands) may be assigned independently to the individual color guns of a display unit. Each variable normally can have up to 256 values (8 bits) in grey scale. Some RS imagery is captured with 10 bits (1024 levels) or 12 bits (4096 levels). A user defined, hardware scaling vector, Look Up Table (LUT) may be used to scale the input data into the desired 0-255 range. If the data occupies only a part of the potential 0-255 range, the LUT may also be used for dynamic enhancement of the, image. Some of the current workstations will allow display of true color imagery but do not allow the passing of the data through LUT's. Since a large part of Remote Sensing analysis involves the dynamic enhancement of true color' images, this architecture does not satisfy the GIS/RS users needs.

Raster GIS data variables may also be displayed in a true color mode, with the visual integration of the three primary colors of the display giving dynamic information showing a three layer analysis.

Normally, however, GIS raster variables are displayed in a pseudo color mode in which each GIS data value may be assigned a color value that is taken from either a set color palette or a user selectable combination of grey scales on the red, green, and blue primary color guns.

Since a modern graphics display system is a raster oriented device, vector data must be converted 'on the fly' into the raster domain for display. This function may be provided in software or hardware. Hardware implementations of vector plotting, clipping, filling, and shading generally operate in a display list manner in which the software display program loads vector data from a database into the local memory of the display which can be operated on by dedicated hardware processors.

In some current graphics displays, an overlay plane is available as well as the three 8 bit planes of the true color image. In most cases, this overlay plane will have from 16 to 256 colors which will mask the underlying image or gis file that has been placed into the true color memory. This overlay plane may be used to display vector information overlaid on true color Remote Sensing data or other GIS data that has been rasterized. The ability to simultaneously view image data and GIS vector information is crucial to the integration of GIS and Remote Sensing information.

When such an overlay plane is not available, extensive manipulation of images and display bits within a true color display system is necessary to provide a similar capability. often this manipulation results in degraded display times. For GIS/RS, the overlay plane is clearly desirable.

Attribute Handling

The simplest case of handling identifiers for raster GIS variables is a code that identifies the value of particular cell in the raster data set with a character string. Attributes for vector data are more complex in that single entities such a vectors may have multiple codes depending on directionality or its relationship to other neighboring entities. This coding is generally developed at the time of data entry via a text manipulation program and is usually carried along with the data variable in the same or an auxiliary file.

When analysis is performed on a number of GIS variables, the resulting attributes of the analysis file should indicate which variables have been combined, and which functions were applied to perform this combination. The resulting attributes may then be a simple concatenation of the input attributes, or it may be a user defined text attribute that describes the process. For example, the combination of soil, vegetation, slope, and land ownership may result in an analysis called 'suitability for siting of land fill areas' or it may contain a history of all processed that were applied without a meaningful description of the final result.

One of the basic GIS functions is the ability to display GIS data that satisfies a user selectable set of attributes. This capability assumes the function ability to search through all GIS data and select only those GIS variables for display that satisfy all of the given criteria. Attributes may be handled in a flat file manner in which the application program must perform an exhaustive character string search through concatenated attributes. This function can be performed relatively easily for a small number of variables and simple analyses, but may become impossible, or too time consuming for complex analyses. Next, attributes may be handled in a linked list manner, in which a pointer is kept in the analysis file that points to all input data sets as well as the input analysis attributes. This method is reasonably efficient, but requires the GIS/RS system to keep track of a myriad of pointers, as well as have the capability for deleting, editing, and updating these pointers. A third method uses the tools available with a commercial Relational Data Base Management System (RDBMS) to keep track of multiple attributes for GIS variables and resulting analysis variables.

Vertical Analysis

In a raster based GIS/RS system, a vertical analysis is implemented easily. A vertical analysis allows the user to combine numerical attributes of a number of independent GIS/RS variables into a resulting analysis variable. Each input GIS/RS variable is preprocessed with user input to create a numeric value that represents each raster cell's relative importance to others within its own GIS layer for the desired analysis.

Once the numeric scaling has occurred for each input GIS/RS variable, 'a weighted sum of the variable's values for each raster cell is calculated and finally scaled by the user for final output. As mentioned above, the attributes are normally either lost with the only attribute being defined by the user for the analysis output, or they are concatenated to form a more complex textural description of the combination process. In some cases, both final attribute user definition and concatenation occurs.

The vertical analysis above, may be described as a 'point' process in which each raster cell within a GIS/RS database is considered without respect to adjacent values with the same variable or other variables. Image Processing techniques utilize similar 'point' functions. A 'point' function allows the value of each raster cell in one variable to be processed with a mathematical function with respect to the same raster cell in another GIS/RS variable. The mathematical operations may include :'+', '-', ' / ','*' as well as any other legitimate function such as sin or cosine, logarithms, or exponentials. In the case discussed above, the operator was '+'.

Ratios between GIS/RS variables can be handled by 'point' functions with an operator of '/'.

Masking of GIS/RS variables may be handled by preprocessing the values within one variable to have binary values of 0 and 1 and then performing a 'point' operation with an operator of '*'.

Logical operations may be handled in a 'point' function mode with additional operators of: 'AND', 'OR', 'XOR', and 'NOT'.

Vertical raster functions are functionally identical to normal image processing functions used on Remote Sensing data sets. Ratios and linear combinations (weightings) of multispectral bands are often used functions for enhancement of multispectral imagery.

Vector GIS/RS operations for vertical analysis are substantially more complex than raster vertical operations. To perform vertical operations on vector data, a set of algorithms for point, line, and polygon overlay must be executed. Logical functions, such a union and intersection of polygons, point inside polygon, vector intersection, and clipping must be performed on all data entities within each of the variables with respect to all entities in the second data variable. Clipping and windowing functions hopefully reduce the complexity of the analysis, but normally, substantial portions of each data variable must be processed. Most of these functions involve floating point logic, and are thus extremely time consuming. For analyses in which two simple GIS/RS variables are overlaid, the process may go fairly fast. However, after a number of combinations have been performed, the number of possible intersections for subsequent analyses may become prohibitive with the current implementation of technology. For simple variables, the storage of the GIS/RS variable in vector format provides a large compression in the amount of memory and disk space. For the storage of complex variables and the results of complex analyses, however, the vector file will often exceed the storage necessary for storage of the file in raster form.

Attributes in a vector system may be stored either in a linked list form, which again must be managed by the application program, or they may be stored in a RDBMS as discussed above. A typical inquiry of such a system might be : find me all areas with at least 60 % pine forest, within Jasper County, containing a stream, with a size of 10 acres or more, and a cost of less than $2000 per acre. Polygonal areas may be defined with multiple attributes, such as the percentage pine cover, ownership, cost per acre, soil type, etc. These attributes may be searched along with multiple attributes from other GIS variables to find candidate areas. The solution to such a request requires several polygon overlays as well as a search into a relational data base management system for attributes satisfying the request.

If data are stored in an arc/node representation, then directionality and right and left attributes must be dynamically interpreted to form polygonal areas, and access their attributes. Access to the attributes may require a search command with the supporting RDBMS.

Proximity Analysis

Proximity analysis is one of the more powerful tools of GIS/RS systems. A proximity variable is one whose values represent the spatial distance of any point from a data value specified as a search criteria. For example, in a land cover classification, a proximity analysis may be required to show the distance away from all water classes. The resulting GIS file will not have anything to do with the coincidence of a test pixel with any other land cover class, but it will include the Euclidean distance of any point from the specified criteria, in this case, the existence of water in the land cover classification.

This technique is extremely useful in assessing the relative spatial importance of a specified search class with respect to user specified criteria for an analysis. For example, in a siting problem, nearness to a water body may be an important factor. The best circumstance might be those areas directly adjacent to a water body, but the importance of a site might be only marginally less if it is less than 100 meters from water. It also might be acceptable if it is within 200 meters, since site modifications might be easily made to provide direct water access.

Proximity to certain criteria is often used as a weighting criteria in a subsequent vertical analysis.

Vector proximity analysis usually entails the definition of a buffer zone area defined by lines and/or polygon features showing areas a certain distance away from a specified criteria. The buffer zone may be used as a mask in a polygon overlay of vector data.

Neighborhood Operations

Neighborhood operations are those functions in raster analysis i-n which the resulting value or class for a cell at position (x,y) depends not only on cells at the same (x,y) location from different variables, but also on the cell values within a certain distance of the (x,y) location in all data variables. This neighborhood in raster analysis may be symmetric (a 3 x 3 window of cells surrounding the (x,y) cell, a 7 x 7 window, etc.) or it may be asymmetric (a 3 x 10 cell area). A neighborhood operation may be as simple as computing the sum of all values within the designated box, or it may be as complex as the dynamic computation of the mean, mode, median, maximum, and minimum of the box and zeroing values less than zero and greater than 10. The neighborhood function may also be performed on logical variables to indicate presence or absence of a specific criteria.

A neighborhood function may create more than one output variable that represent different functions applied to the window. For example, slope and aspect may be computed using the same window on digital elevation data. Some common neighborhood functions that are applied to GIS/RS data sets are:

    average value
    minimum value
    maximum value
    mean value
    median value
    mode value
    AND, OR, NOT logical functions
    slope
    aspect
    coincidence
    absence
    diversity

Neighborhood operations are also common in image processing. While the functions are approximately the same, and the implementations are equivalent, the names of the functions often differ. For example, texture analysis of images uses neighborhood functions to define first, second, and third order moments that can be thought of as higher derivatives of an image surface within the specified window.

Convolution filtering is another enhancement process used in image processing that uses a neighborhood window approach. A user specifies the size of his window (3 x 3, 7 x 7, etc) as above, however, the user is then required to input a set of coefficients for each of the n x n elements of the neighborhood. The convolution algorithm then computes the resulting output cell's value as the sum of each cell's value within the window multiplied by the user specified coefficient for that (x,y) location within the window and then divided by the number of cells in the window. For example, if a user were to specify all coefficients to be equal to 11s, then the resulting value would be the average cell value within the window. This result would be called a low pass filter in image processing terminology. Low spatial frequency information within the image is saved and high frequency information is thrown away.

Low spatial frequency information may be demonstrated by a grey scale image in which the value in the image varies slowly from the left side of the image to the right. thus the grey scale only goes through one cycle of black to white in the entire image. In contrast, a high spatial frequency image is one with many black to white reversals across the image. The highest spatial frequency image possible is represented by a checkerboard image that changes from black to white in every adjacent cell. This highest frequency in an image is called the nyquist frequency, and the spatial frequency is n/2 where n is the total number of pixels across an image. Most images contain neither all low frequency nor all high frequency information within them. Most images contain many spatial frequencies of information, and the above convolutional filtering techniques may be used to enhance certain spatial frequencies and suppress others. Normally high frequency enhancement is applied to Remote Sensing digital data to sharpen edges and make the image more interpretable.

By specifying different coefficients, a high pass filter may be generated. This filter saves only high spatial frequency information at the expense of low frequency information. By using other variations of coefficients, other filters such as band pass and directional filters may be implemented.

Since most polygon overlay operations are boolian in nature, there does not seem to be an equivalent function to neighborhood processing in raster GIS and Remote Sensing images. As mentioned above, however, proximity masks may be used to extract regions within a specified distance of a selected value.

Time Based Operations

In many of the more sophisticated GIS/RS applications, time series events form a methodology for studying changes over a period of time. Since a GIS system is based on the same spatial coordinate. system regardless of the acquisition date of the data set, procedures may be used to study spatial changes over a period of time.

The simplest application of time based analysis is the use of data from two different time periods to detect differences that are present from one date to another. This technique, called 'change detection' in normal remote sensing analysis can be used with imagery or GIS data entered from base maps of varying dates. Change detection is simply the identification of the fact that the map/image has changed spatially over time. A more detailed form of change detection allows the quantification of how much change has occurred over the period, and which GIS classes have changed into which new classes. For example, in Remote Sensing analysis, it is often advantageous to know what classes have had a change, and into what other classes are the changes placed. This change detection can also be used as a check on classification accuracy, since the probability of going from one class to another (ie. forest to urban) may be high in one case but very low in another (ie. urban to forest).

The more complex case of time series analysis has to do with trend analysis and prediction of a particular spatial distribution of GIS/RS classes given the prior spatial distributions of classes in a number of preceding data sets or years. In this case, it is insufficient to determine that a change has taken place. It is necessary that one develop a model for how these changes have occurred over time and to make the model so robust that it can predict future results based on specific assumptions in the model parameters.

Modeling can be thought of as a complex association of rules that allow the prediction of future events based on the past history of events. Spatial modeling may involve a high level decision making strategy which may rely of political, economic, and resources based criteria. Most spatial models employ the use of a GIS/RS system to manage the geographic information and the spatial interactions between information data sets. Current models may predict population growth and distribution, watershed run-off, or economic trends based on the availability of resources. The most complex model of them all, in today's use of spatial data, is the modeling of the global environment. The state of the environment has so many variables that operate in three dimensions as well as time, the forth dimension, that it is unlikely that man will be able to accurately produce a successful predictive model in the near future. On the other hand, research into well defined three dimensional time series analyses will continue to provide insights into the environment that could someday be. the basis of a fully predictive model of the global environment.

Vector Raster Conversion

Vector to raster conversion is traditionally the easier of the two conversions between data representations. Normally, vector to raster conversion occurs by simply performing polygon fill logic on individual polygons, lines, and points within a database and writing the raster version of a polygon into a raster image buffer. If all polygons and all of the raster image buffer fit into memory, then the task is efficient. If, on the other hand, enough memory cannot be allocated, the procedure must operate on a polygon by polygon basis and an image block basis. Virtual memory normally will eliminate the need for the user to have to manage this partitioning, but disk space accesses will invariably cause longer run times.

One of the principal problems with vector to raster conversion is deciding what to do with the multiple attributes that may have been assigned to the polygons in the analysis or data entry phases.

Raster Vector Conversion

Raster to vector conversion normally requires a number of user intensive steps to define polygons that will fit into a topologically structured vector network. Initially, clustering or clumping GIS algorithms may be used to define contiguous regions with the same GIS/RS value. The boundaries of the regions may be formed by segmentation algorithms that normally operate on the detection and chaining of edges, or the growing of regions within the raster data set. The perimeter of the regions thus constitute the initial 'polygon' region. Algorithms for smoothing to remove the jagged pixel edges and thinning, to remove short vectors along a consistent path, must be run iteratively until the final vector file is acceptable. Next, the assignment of attributes to vectors, points, nodes, etc. must be assigned in at best a semi-automated manner. The process from raster to vector representations is normally an extremely difficult process. No current totally automated manner is known by the author that can perform without exhaustive preprocessing of the raster input data sets.

III. Computing Technology

Advances in computing technology have been so rapid in the last decade, that it is difficult to evaluate the many alternatives offered in today's and tomorrow's market for high speed interactive computing. The above functions describe the algorithms and techniques which are at work in the current generation of GIS/RS systems. The next decade of computing promises much more in the

individual power of computers and the synergistic capability of distributed networks. Jack Dangermond, President of ESRI predicted that for geographic analysis in the next 10 years, 'CPU's capable of processing 1000 MIPS will be common in large organizations and greater processing power will be packed into compact, less expensive systems. '(Dangermond,1988). I endorse Jack's progressive view, and will try to discuss the alternatives that are available for GIS/RS in the near to mid term future. It is possible that with the emerging technologies in the computing, user interface, and visualization areas, the concept of how GIS/RS analyses are performed will be totally redefined.

Single Processor Computation Power

One of the most dramatic areas of change in the overall computing environment that affects GIS/RS systems is in the raw computation power of computing systems. Initially we will look at changes that have occurred in single Central Processing Unit (CPU) architectures, and later we will expand to consider multiprocessing and special purpose architectures.

The 1960's saw the development of a number of mainframe computer architectures with sophisticated supporting operating system and applications software. These machines were designed to respond to needs both from the scientific community (NASA, etc), the oil exploration community (seismic analysis), and the Department of Defense as well as needs from a growing business community (IEEE Scientific Supercomputer Committee, 1989). The speed and power of these computers lay in the extensive instruction sets, and the ability to perform complex instructions in the lowest level clock cycle time for the computer hardware. The cycle time was also related to the speed of access of memory. A major advantage of a mainframe was that a single computer system could support a large number of users with little degradation in service. Multi-user support requires a sophisticated operating system and a management strategy for setting priorities between users. Large computational loads and high priority processing on such systems could cause the system to be ineffective as a multi-user system.

Differing physical implementations of memory were being developed, with the standard random access memory in the 1960's being core memory. In the 1970's Metal Oxide Semiconductor (MOS) memory was. introduced with faster access times but only volatile storage (the memory had to be refreshed by the computing system). Static Random Access Memory (RAM) did not have to be refreshed, but was slower and more costly than the MOS implementation.

The density at which memory can be stored in computer chips has increased radically, over the past few years with 64 kilobits, 256 kilobits, and now 1 megabit may be stored on a single chip. This storage density also translates in faster access times for memory, reducing one of the limitations on computing speeds.

Different vendors, throughout the 1960's and 1970's, produced general purpose computers with different word lengths and instructions sets. For example, the IBM 7000 series and the 360 and 370 series used 32 bits as its internal word length, the Harris series used 24 bit wordlengths, the Control Data Cyber series used 60 bits, and the Univac 1100 series used 36 bits. The word length selection was made by each vendor in the design of computing specific hardware to optimize the number of instructions that could be executed per second, and the capability of each individual instruction. one standard by which the raw power of computer systems may be gauged is the number of million instructions per second that can be executed by that machine (MIPS). Data access is also normally handled in terms of data words with the same number of bits. In some cases, the ability was created to execute an instruction and fetch data in the same cycle time. Each computer manufacturer had a different number of storage registers and accumulators that acted as temporary storage while a complex instruction was being executed. These companies strategies for hardware design and implementation and high power software environments led to an abundance of proprietary systems with little commonality.

Minicomputer systems also became available in the 1960's in response to the high costs required for mainframe processing. While the costs were less than mainframes, the performance also was less. Early minicomputer systems such as the DEC PDP 8 and used an 8 bit cpu, with later generation minicomputers such as the DEC PDP 11, Data General Nova, and Hewlett Packard 3000 used a 16bit CPU. The shorter wordlengths resulted in less complex instructions that could be executed in one clock cycle of the system. More complex instructions could be implemented in multiple cycles. In the mid to late 1970's minicomputers expanded their power, speed, and software and hardware sophistication by including 32 bit cpu's in minicomputer systems. DEC's VAX and DG's eclipse/MV systems were developed in the early 1980's with a speed of approximately 1 million instructions per second, which was approximately equivalent to the larger mainframe computers being used for scientific tasks.

In the 1970's the market for a small computer, known as a microcomputer became viable, first for computer hobbyists, and later for business and scientific applications. Mainframe architectures and later, minicomputer systems had been introduced with relatively sophisticated operating systems and high speed serial processing, the micro computer, first and 8 bit cpu (Zilog Z80, Motorola 6800, and Intel 8086), was intended to have a simple operating system and a relatively slow processing rate (<. 1 mip). As time has progressed into the 19801s, however, microcomputers have extended their capabilities with 16 and 32 bit cpu's. The simple operating systems such as CPM have given way to more complex and general purpose ones. The integration of multiple functions into

one computer chip, a microprocessor, caused an explosion in the system development. The microvax system from DEC, achieved approximately the same speed of the VAX 11/780 series machine, but at a fraction of the initial and ongoing maintenance costs.

During the 1980's we have seen a dramatic reduction in the differences in capabilities of mainframe, minicomputer, and microcomputer systems. Minicomputer systems have achieved mainframe speeds and most of their capabilities, and microcomputer systems are becoming the focus for a distributed processing strategy that is altering the whole concept of computing.

It should be pointed out that mips is only a rough measure of comparison of the speeds of different computer systems. The computers ability to perform computations along with memory accesses and reading and writing to input/output (i/o) devices is what one one like to measure for a particular application code. Other standards currently exist which test the computers speed on various mixtures of computation, memory access, and i/o processes. For problems needing intensive floating point calculations, a more realistic standard is MFLOPS, which is discussed below.

In 1977 Apple introduced its first entry into the microcomputer market with an easy to use graphically oriented system which became popular because of its power and low cost, especially in education.

The major change in the acceptance of the microcomputer that propelled microcomputer systems into high visibility was the introduction in 1981 of the IBM Personal Computer based on an Intel 8086.computer chip. Almost all microcomputers became known as PC's, and the market penetration into all walks of life was initiated. IBM extended the PC's capability initially with the Intel 80286, a 16 bit processor, and then a Intel 80386, a 32 bit processor. Motorola products in this time period included the M68000, the M68010, M68020, and the M68030. These chips became the cornerstone of a number of third party microcomputing systems that pointed towards a tailored application environment, or a sophisticated development environment.

In an about face from the trend of having longer word lengths to give more power and speed, the Reduced Instruction Set Computer (RISC) was introduced in 1986. The RISC computers achieve high speeds by optimizing the implementation of only a few instructions of the more complex systems. A 32 bit wordlength was used, then, to provide faster data access, and to combine multiple instruction executions in a clock cycle. The state of the art in speed for single processor systems is the MIPS R2000,R3000, R4000, and R6000 RISC chips used in Silicon Graphics and STARDENT products as well as the SUN SPARC RISC chip. Depending on the clock speed for these chips, these RISC processors show a performance of between 8 and 30 MIPS. Most of the workstations in today's market use these two chips as their basis. IBM, on the other hand has recently developed its own RISC chip with very attractive speed figures of between 30 and 50 MIPS. Other vendors are also in the process of releasing similar speed systems.

Thus, in the time span between the development of the VAX 11/780 minicomputer and the present, we have gone from a realizable speed of 1 mip to approximately 50 on current generation single cpu workstations.

New generation serial processors include the intel dedicated graphics processor called the 82786 and its follow-on general purpose i860. A graphics processor seeks to offload are graphics processing from the host into the high speed special purpose processor. The i860 product boasts 33 MIPS and 66 MFLOPS and is today being embedded into many imaging and graphics products (Keller,1990). Because of the speed of the new generation cpu chips, new memory technology was needed to prevent memory bottlenecks. The Video RAM chips allow direct refresh of video screens from solid state memory, and take the load of memory management from the cpu.

Several companies have invested in the development of their own custom silicon processors to achieve greater speeds. Vitek developed its image computer in silicon to provide the processing power of 300 MIPS. The system is programmable and may be used for many applications, from image processing to scene rendering.

Vector Processing

Vector processing is the basis for most 'supercomputer' systems in the last decade. Scientific computing has a need for fast computation using floating point or greater precision. A vector processor is generally a single controlling processor which sequences a long data vector through a number of 'pipelined' stages. A pipeline operation, as the name suggests, is the process by which a complex operation is broken into a number of independent sub steps that can be implemented sequentially. Each step in a pipeline operation may be handled by a dedicated processing element (an adder, multiplier, etc) and the results passed as input directly to the next processing element. Each step within an operation such as a vector multiply may also be broken down into simpler functions such as fetch, add, and store. Each operation in this sequential process has an inherent execution time, and the total time for processing the first element of a vector is the sum of the individual execution times. However, once the first vector element has exited the first sequential step and entered the second step, the second vector element is entered into the first step. After the sequential pipeline is full, the time for processing a vector element is equal only to the time taken by the longest of the individual sub steps. For long vectors,

therefore, the pipeline processor gives significant speedups. For short vectors, however, the speedups may be much less, and in some cases, may not justify the use of a vector pipeline operation.

Vector pipelining assumes that the same operation is being applied to a large amount of data. The control and execution of the next instruction is sequential in nature, but the CPU must know whether the last batch of data has passed through the total pipeline. A timing interrupt or message passing strategy must provide this information.

Vector Supercomputing

Vector pipelining was introduced in the late 1960's early 1970's on the Control Data STAR 100 , the Texas Instruments Advanced Scientific Computer - TI-ASC, and the Cray-1 (Cragon, 1989), (August,1989). These systems were legitimately known as supercomputers. A performance measure for floating point operations based on a set of computer programs known as Linpack was developed by Dongarra (Dongarra, 1987) to measure the effectiveness of such computers with the measure computed in millions of floating point operations per second (MFLOPS) . The Cray 1S supercomputer was evaluated as having a performance of 12 MFLOPS. Current supercomputer vector architectures have greatly expanded the power of floating point computation, with the Cray X-MP having a performance measure of 235 MFLOPS per processor with up to 4 processors. Other competing supercomputer systems have the performance measures below (IEEE Scientific Supercomputer Subcommittee, 1989):

System	MFLOPS per processor	Max processors
1) Cray-2	488	4
2) Cray Y-MP	333	8
3) CDC/ETA 10g	133	8
4) IBM 3090S	1710	1
5) Hitachi S-820-80	3000	1
6) NEC SX 2	1300	1

New systems in design will have up to 5.5 and greater MFLOPS performance per processor, however these supercomputer systems still fall into the category of 'big ticket' items with price tags of 10-30 million dollars per system.

The currently available workstations, with 30 to 50 mips, will normally have a floating point performance of between 4 and 10 Unpack MFLOPS. These are the systems that will be applied most directly to GIS/RS problems in the near future.

Vector Array Processors

One method that can be used to add more floating point performance to a workstation or stand alone CPU is by addition of a detached vector array processor. Common array processing systems include those by Floating Point Systems, Mercury Data Systems, CSPI, and SKY. Normally, these systems will be attached through direct plug into the bus of the workstation or through a parallel input/output channel. For maximum performance, a direct memory access (DMA) interface is necessary to minimize data transfer bottlenecks.

Array processors are normally implemented through intense vector pipelining, so only problems that can be approached in a way to guarantee long vectors will be efficiently implemented. If short vectors are used, there is a danger of spending more time transferring data than actually operating on the data. The efficiency of an array processor implementation of a particular problem is inversely proportional to the amount of time that the array processor spends idle.

Parallel Processing Power

When multiple cpu's or vector processors are linked together, the major differentiation between systems relates to the method of synchronization between the various processors and their memory. For a synchronous system, all operations are coordinated

through a timing clock. The vector processing architectures shown above depend explicitly on timing to send the input data stream to multiple processors and various subparts of a pipeline. Multiple processors may operate through local memories or a global memory that is shared by all processors. If a processing algorithm needs only data that is not needed by any other processor, local memory may be used since communication across processors is minimized. If, however, an algorithm is implemented that requires that data be shared between processors, a complex addressing scheme must be used to avoid collisions in memory access and update. If four processors need to access the same memory location, then care must be taken to lock out other processors during the instant that data are being read and to allow the next processor to read the memory as soon as it is available. If the algorithm is allowed to modify the contents of memory, the relative access order of the multiple processors could determine the final value. This result would be clearly undesirable.

SIMD

Another kind of synchronous parallel processing environment is the Single Instruction, Multiple Data (SIMD) systems (Duncan, 1990). For this type system, multiple processors are required to execute the same instructions on multiple data streams. Image processing systems have been designed to take advantage of this architecture, and the same kinds of SIMD systems may be applied to most GIS/RS data sets. Synchronous timing is used to move data in and out of a SIMD system and to move data within the system.

Two dimensional and three dimensional arrays of processors can be assembled with mesh and crossbar methods of memory addressing. For a two dimensional array, a single processor may be assigned to operate on each picture element (pixel) of an input image and to write the results into an output pixel array if there were no data dependences on the output value from another processor. If such data dependences did exist, the problem would not be applicable to SIMD synchronous processing.

SIMD processors may operate on complex or floating point values or they can operate on single bit values. one bit operations such as masking may be applied by a huge array of one bit processors such as the Loral Massively Parallel Processor (MPP). In an image with (x,y) locations for individual pixels, an N x N array of processors may be used to perform logical and arithmetic functions on N x N image pixels. The CM-2 from Thinking Machines Corporation has a stated benchmark of 2500 MIPS or 2500 MFLOPS for a large matrix multiply in double precision and a 3500 MFLOPS for the same operations in floating point (Ref Thinking Machines Corp., 1987)).

Image array processors have been implemented in a SIMD mode in which multiple processors operate independently on a number of individual image pixels. If the operation to be performed involves not only point operations (those which act on a single (x,y) image pixel with multiple layers of information) but also area operations (the output pixel's value is dependent not only on the (x,y) pixel's value, but also its neighbor's values), a memory access system must be employed to assure that no memory address conflicts arise. If the data to be processed is only available to individual processors through local memory, a mechanism must be employed to avoid boundary effects due to local memory boundaries. If the memory available to all processes is global, then only direct memory conflicts will potentially cause access problems.

Associative memory may be used to store data words based on the word content rather than the location in an input array. The advantage of using associative memory rises when it is desired to search a large amount of data for a particular character or data pattern. An associative memory word usually has a large number of bits. Multiple processors then can search through associative memory in a bit by bit-match mode to find the condition satisfying the specified requirements. SIMD systems can be used to implement associative processing.

'Systolic architectures (systolic arrays) are pipelined multiprocessors in which data is pulsed in rhythmic fashion from memory and through a network of processors before returning to memory' (Duncan,1990). Systolic systems are SIMD systems that combine pipelining and parallel processing to optimize the processing that may happen to an individual element without significant degradations to performance by i/o. Many operations may be performed on the data without requiring intermediate storage of the temporary results.

Convex Computer Corp. implements a SIMD vector and scalar processor based on RISC architecture.

MIMD

Multiple Instruction, Multiple Data (MIMD) computer systems are the classic case that most of us think of when parallel computing is discussed. MIMD systems have multiple processors which may operate on different instructions and differing data. MIMD machines do not have synchronous timing with the same instruction being performed; therefore, a sophisticated intercommunication scheme is necessary to tell each processor when to execute its instruction and on which data set to operate.

Asynchronous processing allows each processor to perform a number of different operations on its own local data without concern of the neighboring processors. Each processor acts alone, but when it finishes its process, it must notify the other processors.

Message passing between adjacent nodes on the architecture is normally the method by which one processor talks to its neighbors. This is normally considered as loose coupling between the processors and memory (Hornstein, 1986) (Since these systems employ local memory only, local memory to local memory transfers are necessary to update the state of the overall process.) The topology of the MIMD architecture may employ a ring, mesh, tree, or hypercube structure. The hypercube structure may be represented by the Intel Personal Supercomputer or the NCUBE/10 system.

A global memory is another alternative to be considered when discussing MIMD systems. This alternative leads to a tightly coupled state between processor and memory. The constraints on dynamic update of the shared memory involve constant checking, especially when the memory is in the process of being updated by one process, and at the same time being accessed by another processor. Bus contention can be handled by only having one bus to memory. When a processor is using the bus for memory access, the bus will not respond to other requests until the initial request is satisfied. Other memory access systems have a dedicated memory access path to a memory cache. Multiple switching logic is implemented in the BBN Butterfly processor as a method of memory access control. Other tightly coupled systems include the Alliant FX/8, the Sequent Balance 8000, and the Concurrent 3200 MPS (Duncan,1990).

For an optimum implementation, an N processor architecture would represent a speedup factor of N over the serial implementation of the same algorithm. In practice, this is almost never the case since the complex message passing and testing logic will provide some inefficiency in the application of the N processors. The optimum case for a parallel system, whether synchronous or asynchronous, is to be able to use 100% of the capability of all processing elements.

MIMD processing is especially applicable to 'coarse grained' parallelism in which an application may be broken down into functional sub units that then can be implemented on a number of processors. This is a high level parallel structure that may have one system performing totally different operations than another processor. For example, in image processing, one set of processors may perform edge enhancement and detection while another will perform edge chaining to for polygons. The vector chaining procedure in this case cannot happen before the edge operations have been completed. A message must be passed from the processor performing the edge operations to all other processors saying that the results of the edge operation are available for further processing.

In some cases MIMD may be combined with SIMD processors to form a hybrid parallel processing scheme. One of the implementations involves a tree structure topology in which higher level MIMD processors send messages to SIMD subservient processors which then operate on multiple data in a synchronous mode.

Two other advanced MIMD architectures are dataflow and reduction (Duncan,1989). A dataflow system continually scans to see if all. of its operands are available. Once the operands are complete from one or more other processors, the instruction is executed. A token data flow system acquires tokens that are passed from completing processes and stores them until a check can be made as to whether the token matches the requirements as one of the operands for its own execution.

A reduction process, on the other hand, executes a process when its results are necessary for the execution of another process. This 'demand driven' strategy involves a clear idea of the data necessary for a particular operation, and where the sources of that data reside.

Parallel Processing Software

One of the greatest challenges in parallel computing is the development of the software that will allow full use of the hardware capabilities of the new hardware systems. Most of the new systems are trying to avoid the development of special languages for implementation of applications code and instead rely on optimization of Fortran an C code. SIMD systems have been developed with reasonably efficient parallelizing compilers since the synchronization between processors is a vital part of the architecture. MIMD systems, on the other hand, often have to have special tailoring of the application program to achieve speedups. For example, in MIMD programs, the software developer must identify variables and sections of the code that must be kept in global memory with sophisticated access lockout protection. other portions of the code may have variables in local memory that do not affect the other processors.

Transputers were designed along with the Occam programming language to allow efficient concurrent execution of loosely coupled processes with extensive message passing along one way paths. A transputer may only address other transputers to which it has a direct connection. Occam is a special purpose parallel language which seeks to optimize the performance of loosely coupled parallel systems (Dinning,1989).

A parallel system may have 'coarse grained' or 'fine grained I parallelism in its software implementation. Coarse grained parallelism involves the identification of whole code segments such as functions, expressions, or do loops that can be assigned to multiple processors. Fine grained parallelism, on the other hand requires the definition of individual variables that must be shared between processors. MIMD machines require a detailed understanding of the application code, and often require a rewrite of the applications to adequately take advantage of the parallel hardware. The implementation of an algorithm on parallel hardware may be divided into a number of processes. A heavy weight process such as the operating system may occupy resources and have high priority while 'threads', or lightweight processes such as message passing may also be implemented. There may be a number of threads within a process, each sharing memory and resources. Threads are one implementation of fine grained parallelism (Feitelson, 1990)).

Custom Designed Silicon Chips

Another method of obtaining significant speedups in operation involves the design and implementation of special purpose chips that may be dedicated to a specific processing task. These chips, known as ASIC chips (Application Specific Integrated Circuits), have been designed for a number of applications including image processing, communications, and synthetic scene rendering. Silicon Graphics developed their proprietary 'shading engine' and 'transformation engine' for application in the simulation and visualization markets. We have seen above that the VITEK image processor has a dedicated, programmable, custom chip for performance of high speed computations on image data (Keller,1990). The technology advances in recent years have allowed great expansion of the number of integrated circuits that may be place on a chip. Very Large Scale Integration (VLSI) and VHISC (?) are being used for implementation of more and more complex processes.

IV. Display Technology

The concept of value for any GIS/RS system lies in its ability to display geographic information in a meaningful way to a manager, technical specialist, or student. Display technology has changed greatly in the last decade, with new advances bringing on lower cost and more practical methods of information presentation. Hardcopy as well as softcopy displays are valuable as a media for GIS/RS information. In the past decade changes in display technology have followed several paths. First, for softcopy true color image display, the technology has moved from a 256 x 256 image, through a 512 x 512 image, to a standard 1024 * 1024. 1024 displays now cost the same or less than the first 256 x 256 displays. A number of new workstation displays are greater than 1024 in resolution, but in many cases allow 512 and 1024 windows within the workstation display area for true or pseudocolor images. Pseudocolor or greyscale displays with eight or 10 bits of color are commonplace on the least expensive personal computers. Integration of the capability of capturing images from a video source created the dilemma of saving and displaying images at video resolution (NTSC - 540? x 480) while having a greater display resolution. The advent of animation techniques on mini, micro, and workstation hardware also brought up the reverse problem of how to store information from 512 or 1024 images in video format. Current software and hardware on windowing workstation systems allow the creation of video windows within the workstation and the sending of image information out to a NTSC format device.

Image processing systems, in addition to having 'true color', or 24 bit, displays also normally have more image memory planes than are displayable by the red, green, and blue color guns of a Cathode Ray Tube (CRT). These extra image memory planes may be used for computational scratch pad memory, or they can be used to hold other image spectral channels, or other GIS layers. Since these memories are automatically refreshed, instantaneous display of a number of frames of information is possible.

New display technology has resulted in the creation of stereo image displays by use of alternating fields on a 60hz display or by using polarization. Glasses are normally necessary to achieve the stereo perception necessary for detailed air photo interpretation and elevation extraction. Other new stereo viewing techniques are being investigated to achieve stereo viewing without glasses. Holographic displays of GIS/RS information has interesting potential, but has not yet been proven practical.

For animation purposes, it is necessary to be able to record a sequence of video frames on a frame by frame basis on suitable device that will allow for real time playback of the sequence. It is not necessary that the individual frames be computed in real time for most applications. Technology for recording of video or digital information onto a media for real time playback has also advanced greatly in the last decade. High quality video editing systems such as those used for broadcast TV have the capability of single frame editing, and adding one frame at a time to one inch video tape. Unfortunately high quality video equipment is often prohibitively expensive. If animation frames can be generated on video tape, they may then be transferred to video disk by an expensive disk mastering process. The advantage of video disk is that once the master video disk is made, many copies may be made at low cost.

Another method that may be used for animation is the optical Memory Disk Recorder (OMDR) which is a Direct Read After Write (DRAW) or 'Write Once' technology. Information may only be recorded once in each position in the OMDR. The recorded image is then permanently on the OMDR and may not be recorded over. This type of system is often used for archiving images. In a DRAW system, a user may record frames from his rendering system in a frame by frame manner by converting the RS170 RGB signals from a reasonable quality color monitor to a NTSC signal through a converter and recording the video directly on the OMDR.

A user than is able to play his video frames back from the OMDR in real time. OMDR systems with DRAW technology are now within the ten thousand dollar range.

New technological advances now have resulted in the development of optical disks with limited read/write capability. These systems may also be recorded in a frame by frame manner and may be played back in real time.

V. Identification of Technology Limitations

While the advances in computing technology have been spectacular in the last decade, the realization of its full potential for GIS/RS processing and analysis is yet to be realized. For full acceptance of GIS/RS systems into the everyday management process, the systems will have to provide data access and analysis solutions in 'real time', not simply 'near real time'. The real time processing must apply to relational access to multiple attributes for a geographic database class, as well as complex overlay processing to answer 'what if' questions,

A manager must be able to postulate questions to a system through a user interface that does not require sophisticated computer knowledge and to receive an answer in text, numeric, or graphic terms instantaneously. Expert and Learning systems must be used to develop systems capable of learning a particular application and providing tailored default answers and processing streams. For example, the user should be able to input a Landsat image tape and have the system dynamically enhance the data, geometrically correct the data, classify the data by means of a layered classifier, and then load the data into a GIS, all by specification of only a few parameters at the beginning.

The most important limitation of all to widespread GIS/RS acceptance is the cost of initially entering geographic and attribute information into a database, and the cost of continuous updating of the data. Some steps have been taken towards a limited satisfaction of the availability of geographic data sets with the service provided by several vendors and applications companies of assembling a number of the data variables necessary for a GIS/RS system for a particular geographic area

VI. Recommendations for GIS/RS future computing research

* Investigation of discrete GIS/RS functions to determine speedup potential from pipeline and parallel computing

* Determine advantages/disadvantages of SIMD vs MIMD for GIS/RS

* Investigate potential of Expert Systems for simplification of the interface to non-scientific users

* Determine speed vs cost issues in practical application of GIS/RS (Institutionalization cross issue)

* Investigate the advantages/disadvantages of the development of a low level GIS toolkit that may be called by superior planning/modeling programs.

* Investigate the practicality of performance of GIS/RS functions 'across a heterogeneous network.

* Investigate the practicality of dynamic compression/decompression of GIS/RS data on the fly

* Investigate the implementation of vector GIS functions (polygon overlay, masking, etc) on parallel systems.

* Develop standards and generic algorithms that would allow for automatic conversion of raster scanned data to polygons

* Investigate the application of 'Learning Systems' to GIS/RS analysis and user interface.

* Investigate methodologies and implementation for real time raster GIS/RS analysis using SIMD and vector hardware.

* Investigate the usefulness/ application of stereo displays for three dimensional update of raster/vector integrated data

Viewgraphs by Nick Faust, Georgia Tech.

Integrated Geographic Information Systems (IGIS)

GIS and Remote Sensing
Future Computing Environment

Objectives:

1. Functionally Identify Processes used in IGIS

2. Identify Current Impediments to Rapid IGIS Acceptance

3. Identify Trends in Computing Technology Affecting IGIS

4. Suggest Research Topics to Further IGIS Acceptance

IGIS Functions (Raster and Vector):

* Display/Interpretation

* Attribute Handling

* Analysis

* Data Conversion

* Modeling

Attribute Handling

1. Flat File - Linked List

2. Relational Database Management System (RDBMS)

3. Object Oriented / Frame Based

Display Technology

1. Physical Resolution
   - a) VGA
   - b) 512
   - c) 1024
   - d) 2048

2. Color Resolution
   - a) 8 - 12 bits monochrome
   - b) 8 - 12 bits psuedocolor
   - c) 24 bits RGB (8 bits per color gun)
   - d) RGB + 8 bit graphics plane

3. Stereo Viewing
   - a) Red / Blue view of offset images on standard CRT
   - b) Interlaced images / shuttered glasses
   - c) Color based 3d viewing
   - d) Mechanical mirror stereo display

IGIS Analysis Functions

1. Vertical Indexing / weighting

2. Neighborhood Analysis

3. Time Series Analysis

Vertical Analysis

1. Linear Weighting of IGIS Layers

2. Rations / Change Analysis

3. Masking

4. Logical Functions

Neighborhood Operations

1. Proximity Analysis

2. Texture Analysis

3. Contiguity analysis

4. Differentiation (slope)

5. Filtering

Time Series Analysis

1. Trend Analysis

2. Change Detection

3. Model Development

4. Prediction Model

Data Conversion

1. Raster to Vector

2. Vector to Raster

3. Vector to Vector

4. Raster to Raster

Modeling

1. 1,2,3 and 4 Dimensional Models

2. Explanation / Interpretation of Raw Data

3. Generalization / Prediction

Computer Architectures

1. Serial Processing

2. Parallel Processing

3. Pipeline Processing

4. Network Multiprocessing

Serial Processing

1. Full Word Instruction Length
   * 8, 16, 24, 32, 60, 64 Bit Processors

2. Reduced Instruction Set Processors
   * MIPS R2000-R6000
   * SPARC

3. Operating Systems
   * UNIX
   * Proprietary

4. Programming Languages
   * Fortran
   * C
   * Pascal

Parallel Processing

1. Single Instruction / Multiple Data (SIMD)
   * Array Processors
   * Bit Plane Processors
   * Byte Plane Processors
   * Massively Parallel Processor

2. Multiple Instruction / Multiple Data
   * BBN Butterfly
   * Data Flow
   * Reduction

Pipeline Processing

* Segment Algorithm into discrete steps that can occur sequentially

* Implement Algorithm on a Time Sequenced Hardware System

* Do Not Allow Pipeline to be Emptied

Parallel Processing Software

1. Multi-processing UNIX / Proprietary OS

2. Parallelizing Compilers
   a) Course grained
   b) Fine grained

3. Resource Sharing Capability
   a) files
   b) memory

4. Busy Checking Implementation

5. Conflict Resolution

Parallel Processing Fundamentals

* Local vs Shared Memory

* Dynamic Modification of Data

* Problem Segmentation

* Timing Control and Sequencing

User Interface to IGIS

* Standardized ' LOOK and FEEL'

* Expert Systems Front End

* Learning Systems using Neural Nets

IGIS Current Limitations

1. Serial Processing too slow for:

    a) Classification
    b) Geometric Correction
    c) Proximity Calculation
    d) Data Base Access
    e) Polygon Overlay

2. High Speed Implementations often do not respect data integrity

3. Marginally successful Automatic Parrallelizing Compilers

4. immature Network Capability / Strategy

    a) Low data rates over standard telephone lines
    b) Compression / decompression techniques / hardware coming
    c) Implementation of multi-cpu processing strategy across networks is lacking

5. User Interface Needs Significant Improvement using Expert Systems

IGIS Look to the Future

* Realtime Interactive Analysis

* Learning Systems Build User Interface

* Instant Access to Voluminous Data Sets

* Automatic Fine Grain Parallelizing Compilers

* Integration of Parallel, pipeline, and ASIC

* Global Data Network

* Graphical Analysis Tools

* Dynamic Visualization

Recommendations for Further Research

* Investigation of Discrete IGIS Functions to Determine Speedup Potential from Pipeline and Parallel Computing

* Determine Advantages / Disadvantages for SIMD vs MIMD

* Investigate the Potential of Expert Systems for Tailoring the User Interface to Non-scientific Users of IGIS

* Determine Speed vs Cost Issues in Practical Application of IGIS (Institutionalization Cross Issue)

* Investigate the Advantages / Disadvantages of the Development of a Low Level IGIS Toolkit that may be called by Superior Planning/Modeling Programs

Challenges for the Future

- Making knowledge about the system more available and accessible to the user

- System power continues to increase at decreasing cost-per-unit-of-processing. But at the same time, we make additional demands on the power of the systems for sophisticated user interfaces, more complex algorithms and visualization techniques, and larger datasets. Does the power increase through time necessarily keep pace with our increasing needs?

- The model for much of today's science is that of collaboration and coordination. Do the systems of the future make these easier?

- When we role a workstation into a user's office to replace a terminal, do we assume that the system management functions which are necessary to run a workstation are provided automatically, or is there another level of training and overhead that we impose on the user?

NASA's Earth Observing System

5 Space Platforms (in the current baseline)

Monitoring Sensors vs. low-duty-rate target of opportunity sensors

Multiple Agencies, Multiple Nationalities

Approximately 1 Terabyte of data per day for 15 years

EOS Data and Information System (EOS-DIS):

Expensive

Distributed - hundreds to thousands of users, at least 7 major archive sites

"One Stop Shopping" - a user views a single, integrated system, irrespective of how it is truly implemented

It will endure for 2 or more decades

Approximately 3 Terabytes of data per day for 15 years.

Data includes Non-EOS, Non NASA datasets

Algorithm Migration from the users to the centralized data processing facilities.

Institutional Issues

Problem: What are Institutional Constraints to the Management and Use of Spatial Data?

Organizational Structures

a) Define Models and Identify Incentives for Forming Creative "Consortia"

* among levels of government
* among academic/industry/government sectors
* among professional organizations, etc.

b) Explore optimum intra-organization structures (where does the work really get done?)

* Data
* Hardware
* Standards
* Education and Training

Data

a) Evaluate how spatial data are used in the decision-making process.

b) Evaluate how spatial data are managed in the public sector

c) Evaluate how institutions provide spatial data.
* open versus restricted access
* information as a public good
* freedom of information/public records acts
* value of multiple uses of information

d) Define mechanisms for improving sharing of data and exchange of information.

Hardware

a) evaluate the integration of remote sensing and GIS in different equipment environments including Supercomputers, Mainframes, Minicomputers, Workstations, PC's, and Laptops.

* advantages and limitations of each environment
* assess environments for optimal technology use

Standards

a) define common geoprocessing language for interdisciplinary use

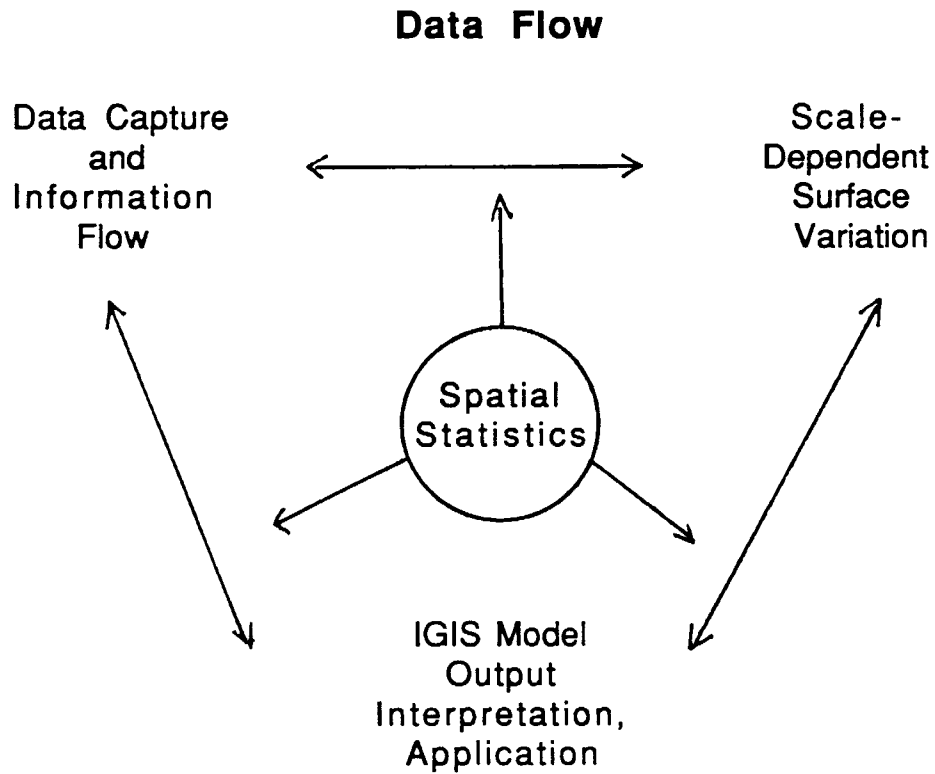b) explore methods for developing and documenting standard procedures.

Education/Training

a) explore options for enhancing CORE Curricula for other purposes

* integration of remote sensing and GIS
* project definition
* technology implementation for public agencies

b) explore options for creating and distributing teaching modules in CD-ROM format.

Preamble

1)   Earth surface variation

-    Dynamic in space and time
-    Multi-scaled patterns and processes
-    space-time hierarchies

1)   Multiple measurement scales (cont.)

-    measurement/instrumentation needs to facilitate
     extrapolation across scales (e.g. airborne video,
     imaging systems)

-    appropriate mathematical/ statistical models to
     describe scale-dependence of IGIS data

-    How to apply these models to define appropriate
     mixture of ground, map and image data to study
     processes and phenomena over large areas at low
     spatial resolution, variable temporal resolution?

2)   RS/GIS

-    Tools for measuring, monitoring, mapping and
     modeling earth surface variation

-    Limited to "fixed" spatial/temporal resolution

-    Limited measurement variables

-    Operate within constraints of geodesy,
     cartography, environmental optics, imaging science

Data Flow

Data Capture
and
Information
Flow

Scale-
Dependent
Surface
Variation

Spatial
Statistics

IGIS Model
Output
Interpretation,
Application

2)   Data Transformations in IGIS Processing

-    Change in Radiometric Integrity during processing
flow?

-    Appropriate Geodetic/Cartographic Measures to
assess changing locational precision and accuracy
during   information processing

-    Methods for Georeferencing and Co-registration of
Multi-resolution Data in IGIS?

[*   Modeling strategies using mixed data types?]

Data Structures/Access

1) Language for multiple data models - integrated functions for remote sensing and GIS   [I-5]

   for definition and manipulation of spatio-temporal objects (phenomelogical, data,   ...)

   focus on language between user and system [not interface]

   "theory of space"

   driven by specific application

   leading to such efficiency issues as bottom-up processing, geometric optimization, typing

2) Metadata (Data dictionary, data description, directory)

   Lineage   [I-1, Error Group]

   Error

   Data directory

   Content based Search

   Semantic compatibility and data fusion over distributed databases

3)   Multiple Data Models & Conversion

Design of data models, operators, algebra

*   conversion and hybrid operators (appropriateness,
        loss of information, errors)
*   requirements based on applications

Prototyping

*   extending existing systems (e.g. Starburst)
*   Test data sets

4)   Data Standards   [outside NCGIA]

*   Data exchange and Access
*   Data collection and reporting

Error Analysis

General Statement

Methods of accuracy assessment have been developed in both RS and GIS. However, these methods are incomplete and inadequate for integration of the two technologies. Users of integrated GIS and RS are consequently unable to assess the uncertainty present in their data and analytic results.

Statement of Problems (1)

Need to review what is known about characteristics of positional error in remote sensing, evaluate the adequacy of the knowledge for IGIS and, if necessary, extend. This research effort should involve photogrammetry, there are similar needs to review and improve knowledge of radiometric errors and associated correlation structures, and to review knowledge of positional, thematic and temporal errors in GIS.

Statement of Problems (2)

Need to develop methods and procedures for tracking data lineage through remote sensing processing and IGIS analysis, methods for documenting procedures, and methods for reporting the errors introduced at each step. The ultimate objective should be a measure of error on every IGIS product, so that the tradeoffs between alternative data sources can be evaluated.

Statement of Problems (3)

Need to extend, adapt and evaluate the appropriateness of Veregin's I-1 error taxonomy to IGIS, and the proposed SDTS quality statement.

Review current methods of evaluating and expressing classification accuracy and extend to better meet the needs of IGIS. Specific topics include separating uncertainty of detection from uncertainty of classification, and determination of the covariance structures of uncertainties.

Statement of Problems (4)

Investigate the spatial structure of error in an integrated remote sensing classification - e.g. how are errors related to proximity to polygon boundaries

Explore links between cartographic generalization and classification, data reduction and data cleaning.

Statement of Problems (5)

RS and GIS can be crudely oversimplified as raster - and vector - based views. We need to develop error models which have meaning in both areas, and thus allow information on uncertainty to be transferred between the two technologies.

Future Computing Environments

1) Impediment:

GIS and Remote Sensing Systems are too complex for many users; impeding wider acceptance.

Research Need:

Examination of methods to effectively embed domain specific expert knowledge into systems, automated assistants, learning systems, CASE tools, neural networks.

2) Impediment:

Current IGIS User Interfaces are inadequate

Poor information comprehension, limited computer assisted analysis, education and speed

Research Need:

Improved user interfaces incorporating

* Dynamic visualization including: 3D and 4D,
* Scene simulation, training materials

3) **Impediments:**

Inflexibility of existing GIS/RS systems

* ability to redefine links
* ability to dynamically create new data structures
* maintaining history or lineage information
* error characterization and tracking
* redefine user interface for an application or user

Research

Application of object-oriented software and systems

Graphical object-oriented design

4) **Impediments:**

Algorithms based on assumptions which are not supported by GIS/RS data.

Users do not select appropriate analysis strategies.

Research:

Specific algorithm development for GIS/RS integration.

Knowledge-based guidance and advice.

Explicit consideration of time - identification of temporal change,

5) **Impediments:**

Scaling

Field Data

Research:

... make sure that it appears elsewhere...
Rule-based generalization.

6) **Impediments:**

Costs
Communication
Collaboration

Research:

Sharing system capabilities
Sharing knowledge
Multimedia mail and conferencing
(digital, voice, video...)

7) **Impediments:**

Speed (vs. cost...)

Research:

Optimization of the end-to-end processing flow
including hardware/software/wisdom/data
structures.

8)   **Impediments:**

Data Capture costs
Availability

Research:

On-board processing for specific applications

9)   **Impediments:**

Creating new functionality - an IGIS toolkit

Research:

Automated generation of software, user interface, etc. via graphics

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