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

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ABSTRACT: Data derived from remote sensors are increasingly being utilized as a data source in geographic information systems (GIS). Error associated with the remote sensing and GIS data acquisition, processing, analysis, conversion, and final product presentation can have a significant impact on the confidence of decisions made using the data. The goal of this paper is to provide a broad overview of spatial data error sources, and to identify priority research topics which will reduce impediments and enhance the quality of integrated remote sensing and GIS data. Potential sources of error will be identified at each data integration process step, impacts of error propagation on the decision making and implementation processes will be assessed, and priority error quantification research topics will be recommended. Suggested priorities for error quantification research topics include the development of standardized and 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 applications, there has been a tremendous increase in demand for remote sensing as a data input source to spatial database development. Products derived from remote sensing are particularly attractive for GIS database development because they can provide cost-effective, large area coverage in a digital format that can be input directly into a GIS. Because remote sensing data are typically collected in a raster data format, the data can be cost-effectively converted to a vector or quadtree format for subsequent analysis or modeling applications (Lee, 1991).

Although the use of remote sensing data for spatial database development is increasing rapidly, our understanding of associated data processing errors, especially for integrating multiple spatial data sets, lags far behind. Performing spatial data analysis operations with data of unknown accuracy, or with incompatible error types, will produce a product with low confidence limits and restricted use in the decision making process. Although some research has addressed spatial error (Veregin, 1989a), 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 develop procedures to better quantify and report the error using standardized techniques, i.e., techniques for all spatial data users.

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 unknown to the analysts until it manifests in the final product, error may accumulate throughout the process in an additive or multiplicative fashion, and individual process error(s) 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 displayed in a clockwise direction, bidirectional and cross-element processing flow patterns are possible. For example, 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-raster (e.g., resampling pixel size) 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 that can be placed in the information. This limits the confidence in the implemented decision(s). 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 that may be introduced and identify significant improvements that must be addressed.

The objectives of this paper are first, to identify the potential sources of error in the data processing flow for the integration

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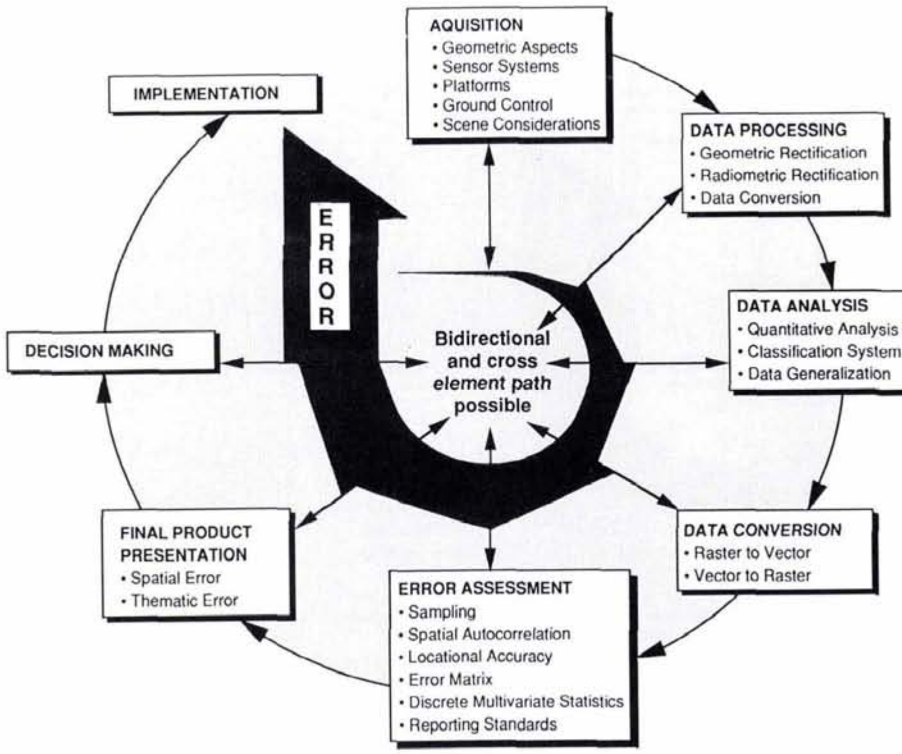


FIG. 1. The accumulation of error in a "typical" remote sensing information processing flow.

of remote sensing data into a GIS; second, to discuss and illustrate the consequences of error in the decision making and implementation processes; and, finally, to recommend important research and development issues to overcome error-related impediments for the incorporation of remote sensing data products into GIS data analysis applications.

## DATA ACQUISITION ERROR

Environmental and cultural data may be acquired by either *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, such as atmospheric conditions and the natural variability of the landscape, cannot be controlled. Conversely, other types of data collection error, such as geometric or radiometric error, may be controlled. One of the most difficult sources of error to quantify is human subjectivity during data analysis and interpretation. 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, excluding those errors associated with natural and human variability, will be briefly discussed in the following paragraphs.

### GEOMETRIC ASPECTS

The processing of multiple data layers in a GIS database is predicated upon accurate spatial registration between data layers. Therefore, it is critical that all remotely sensed data be geometrically accurate with the same cartographic projection as the GIS database. Modern photogrammetry is moving towards fully analytical techniques and digital image processing (ISPRS, 1986; Hood *et al.*, 1989). 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 (Richards, 1986).

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 total field-of-view (TFOV), resulting in a range of illumination measurement geometries. Passive systems are dependent upon solar illumination. Solar elevation and azimuth conditions for aircraft acquisitions can significantly limit the duration of suitable acquisition windows (Brew and Neyland, 1980).

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 instantaneous field of view (IFOV) of an imaging system also introduces scale variations, which are most pronounced in wide TFOV systems. Imaging geometry varies by sensor type and effects. A brief comparison of sensors such as aerial cameras, multispectral scanners, and side-looking airborne radars illustrates this issue.

### SENSOR SYSTEMS

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

Multispectral scanner (MSS) systems 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 continuous sequence of nadir pixels that tracks the platform movement during data acquisition. Pixel size away from the nadir line varies as a function of the cosine of the look angle. "Pushbroom" imaging systems with linear charge-coupled-device (CCD) sensors eliminate many of the geometric errors associated with MSS mirror motions (Slama, 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. Because 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 and therefore provide 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. Ideal look angle and direction is dependent on land feature orientation and project goals. Then the radar imagery can be rectified just like any other remote sensor data.

As briefly reviewed here, image geometry is dependent upon the sensor involved. The ability to attain geometric fidelity 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 should be quantified and removed or adequately minimized 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. As just noted, conventional aerial photography has the advantage of nearly instantaneous film exposure using highly calibrated equipment. Conversely, continuous and line imaging systems, such as video cameras and 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 because 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 (Gibson, 1984; Gibson *et al.*, 1987; Reimer *et al.*, 1987; Rickman *et al.*, 1989; Till, 1987).

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 (Case, 1989). 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 object-space reference coordinate system and whose locations can be positively identified in the image-space. 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 for photographic applications (Wolf, 1974).

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 geometric accuracy have not been developed by the remote sensing community. To allow routine remote sensing data entry and use in GIS databases, such standards should be developed and adopted.

Ground control is necessary during the field accuracy assessment of any thematic map. The 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 are and will continue to be a primary research topic.

### Scene Considerations

Corrections for several scene specific effects are routinely performed during photogrammetric mapping. For example, radial distortions due to atmospheric refraction can be calculated and removed for a standard atmosphere and Earth curvature effects (Slama, 1980). 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 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). 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 been possible to use digital image processing techniques to geometrically rectify remote sensing

data to a map projection. 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 *et al.*, 1983). Adaptive or discrete techniques such as finite element programs are often required to remove the complex distortions that result from aircraft instability.

The geometric correction of digital remote sensor data usually involves some type of resampling, e.g., nearest neighbor, bilinear, or 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 generally 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 popular for remote sensing imagery and necessary for GIS integration.

#### 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 resampling of Landsat 56- by 79-metre pixels to merge with 10- by 10-metre SPOT data. Another example of resolution degradation is when remotely sensed data are classified and then spatially filtered to remove heterogeneous "noise" in the classification. 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 and studied and their cumulative impact quantified when incorporated into GIS.

### DATA ANALYSIS ERROR

In the remote sensing and GIS processing flow outlined in this paper (Figure 1), data analysis involves the exploration of relationships between data variables and the subsequent inferences that may be developed. This stage of error accumulation focuses on the validity of statistical techniques. Difficulties in statistical analysis of *spatially* based 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 spatial data in classical linear regression is beyond the scope of this paper. However, a few examples are provided.

#### Quantitative Analysis

Beyond the basic problems in sampling and regression model specification, spatial data commonly violate assumptions of independence for measured parameters and error variance. As a result, multi-collinearity may present a problem in the case of regression modeling 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 spatial data sets, i.e., autocorrelation, may violate the independence of samples required in classical statistics. This problem 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.* (1988), Congalton (1988a), Jupp *et al.* (1988), and Townshend and Justice (1988). Statistical techniques which are not significantly biased by autocorrelation effects include semi-variogram and block variance analysis. Methods should be developed based on these techniques and others to improve digital classifications, construct sampling methodologies, and deflate confidence estimates.

In terms of error accumulation, major impediments to the analysis of spatial data arise from a lack of well documented methods and a lack of integrated statistical tools within existing software packages. Many commercial software packages are organized in a hierarchical manner with limited statistical options, e.g., a choice of only one or two classifiers with limited user-established parameters. As a result, inexperienced analysts may blindly follow the software hierarchy using default options without thinking about what is happening to the data. Flexible statistical tools need to be identified to take into account the particular difficulties inherent to spatial data sets 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 be a plague. Registration error might be seen as somewhat distinct from the positional errors involved in various independent data products. This distinction is that the resulting "slivers" cause logical errors of association in addition to positional inaccuracy. 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 and 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 ecological data also becomes an issue. Errors which will occur due to the static representation of dynamic ecosystem components suggest that some method of assigning a lifetime to a data set 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. An example of this is a multitemporal composite of the normalized difference vegetation index (NDVI) derived from the AVHRR sensor. These data are being compiled by agencies such as NASA Goddard and the EROS Data Center (USGS) and 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 a GIS. Some of the potential sources of errors induced by classification systems are the inability of classification systems to categorize mixed classes, transition zones, or dynamic systems; poorly defined or ambiguous class definitions; human subjectivity; and the lack of compatibility among different classification 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.

Error induced by classification systems is significant when dealing with both natural and anthropogenic systems. The fundamental foundation 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 mixed, transition, or dynamic process situations, it is particularly important that detailed field verification data be collected to adequately describe the variation and minimize classification system related error.

The problem of poorly defined or ambiguous class definitions is common and often introduces an element of error. In dealing with either natural or man made features (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 inconsistency in labeling classes would occur, leading to 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 inconsistency 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 combined use of data in these two classification systems.

### 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 produce a minimum map unit. Resampling to a spatial resolution finer than the original data commonly results in substantial error. Spectral generalization may be accomplished by filters which either enhance certain features, such as edges, or homogenize similar pixels. Some filters preserve edges while reducing noise. However, because some filters may alter the original pixel values, error such as accurate location of edges or loss of a spectrally similar yet unique resource may occur.

Postclassification data generalization takes on two forms, spatial and thematic. Thematic generalization is the grouping of classes to form meaningful categories. Because 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. Spatial (or cartographic) 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 data set with higher than an acre or hectare minimum map unit, especially if the data set 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 maintain the true shape of a polygon using a series of vertices connected by (implied) straight lines. Vector data are the preferred method of data display for most GIS thematic maps due to the smooth line and edge appearance. Additionally, most map products, including the results of photointerpretation, 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 size of this error depends on the algorithm used in the conversion process, the complexity of features, and the grid cell size and orientation used for the raster representation. Failure to consider this potential error can introduce considerable problems into any analysis.

## 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

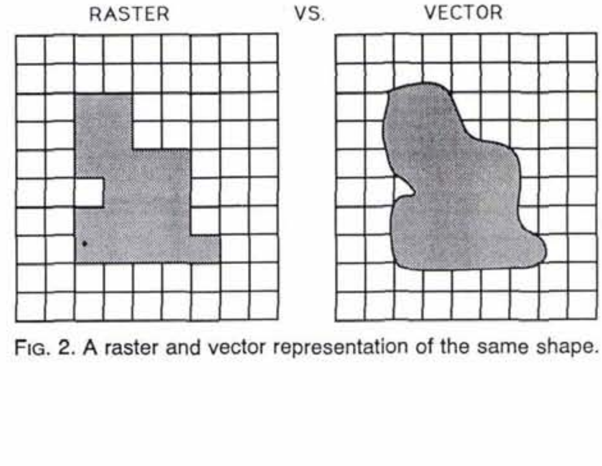


FIG. 2. A raster and vector representation of the same shape.

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.

The classification accuracy of remotely sensed data is more often assessed as an afterthought than as an integral part of most projects. In the past, many studies simply reported a single number to express the accuracy of a classification map. In many cases accuracy was reported as nonsite-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 nonsite specific accuracy assessment could yield very high but misleading results. In addition, assessments have commonly been derived from the same data used to train 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, nonspatial, specific error assessment problems do not continue.

### SAMPLING

Sample size is an important consideration when assessing the accuracy of remotely sensed data. Each sample point collected is expensive and, therefore, sample size must be kept to a minimum; yet it is important to maintain a large enough sample size so that any analysis performed is statistically valid. Many researchers (van Genderen and Lock, 1977; Hay, 1979; Hord and Brooner, 1976; Rosenfield, 1982; Congalton, 1988b; Fukunaga and Hayes, 1989a, 1989b) have published the necessary equations and guidelines for choosing the appropriate sample size.

An important part of an accuracy assessment is the sampling scheme used. Selection of the proper scheme is critical to generating an error matrix that is representative of the entire classified image. Choosing a poor sampling scheme can result in significant biases being introduced into the error matrix which may over- or underestimate the true accuracy. Researchers have expressed opinions about the proper sampling scheme to use (e.g., Hord and Brooner, 1976; Ginevan, 1979; 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 may also be appropriate.

### 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., agricultural, range, and forest sites) 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) that is derived from the georeferencing algorithms that rectify images to map coordinates. The RMSE is the square root of the mean squared errors 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 and only with respect to the map. The most accurate means of examining locational accuracy, a ground survey with differential GPS, is generally too costly to implement.

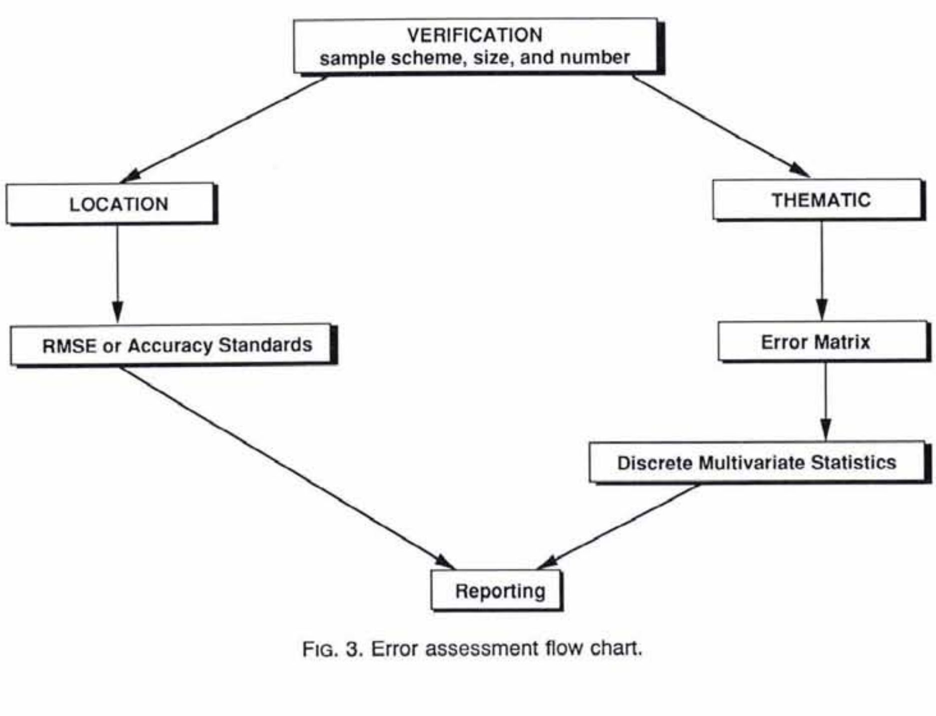


FIG. 3. Error assessment flow chart.

### 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 that expresses the number of pixels assigned to a particular category relative to the actual category as verified on the ground (Story and Congalton, 1986) (see Figure 4). 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 pixels (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 "producer's 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 "user's accuracy" or reliability, is indicative of the probability that a pixel classified on the map or image actually represents that category on the ground (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.

| | | Reference Data F | W | U | row total |
|---|---|---|---|---|---|
| Classified Data | F | 28 | 14 | 15 | 57 |
| | W | 1 | 15 | 5 | 21 |
| | U | 1 | 1 | 20 | 22 |
| column total | | 30 | 30 | 40 | 100 |

Land Cover Categories

F = forest
W = water
U = urban

Sum of the major diagonal = 63

Overall Accuracy = 63/100 = 63%

Producer's Accuracy

F = 28/30 = 93%
W = 15/30 = 50%
U = 20/40 = 50%

User's Accuracy

F = 28/57 = 49%
W = 15/21 = 71%
U = 20/22 = 91%

Fig. 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).

### 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; 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; 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 a specified 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, in press).

## FINAL PRODUCT PRESENTATION ERROR

The goal of most remote sensing and GIS investigations is to produce a product that will quickly and accurately communicate important information to the scientist or decision maker. The 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 GIS procedures may contain static and 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 that is communicated to the reader. A substantial amount of error can be removed if the reader is provided with a complete cartobibliographic citation, i.e., the genealogy or lineage of the map products (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 listing all operations and parameters that have been applied to a data set. An integrated solution to tracking process 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 focusing on the application of this technique to the modeling 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 thematic map products.

### Geometric (Spatial) Error

As previously mentioned, geometric error in final thematic map products may be introduced through the use of (1) base maps with differing scales, (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 USGS digital elevation model (DEM) which had both "good and bad" data, from SPOT panchromatic data, and from USGS digital line graph (DLG) transportation data. Note that the legend also identifies that the DLG vector data were resampled to 10 by 10 m and placed in a raster format. Additional information might include the root-mean-square error (RMSE) associated with the resampling procedures per data set (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 and should lead to improved decision making.

### Thematic (Attribute) Error

Diverse data sets 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 database. 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 known what these sources are through a thematic reliability diagram. For example, Figure 6 identifies the two sources used in a supervised classification of wetlands and the location of *in situ* samples used to assess map accuracy. Persons who map wetlands might be concerned that DLG wetland data 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 any thematic map product derived using these source materials. 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. Because more and more remote sensing and 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.

Many scientists are now overlaying image raster data with thematic vector data. This powerful technique provides an ungeneralized base map which the reader can use to orient and appreciate the thematic vector data (Goodenough, 1988; and Jensen *et al.*, 1990). 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 and GIS derived maps 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. In addition, the decision maker needs an estimate of the overall accuracy and confidence of the data product(s) used in the process. However, decision makers are provided with little or no knowledge about 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 and GIS analysis products are often presented in thematic map form, there is a tremendous potential for a decision maker to err by overestimating the accuracy and confidence level of thematic remote sensing and GIS data products. It is imperative that the remote sensing and GIS communities educate decision makers to better understand the potential error sources associated with remote sensing and GIS data products. As the decision makers become more knowledgeable about the issues related to data accuracy and confidence, they will request that more data concerning data accuracy be provided with all final presentation products.

## IMPLEMENTATION

Decisions based on data of substandard accuracy and inappropriate confidence levels has an increased probability of implementing incorrect actions. The obvious implications of an incorrect decision are erroneous resource management actions which can have serous consequences for the resource itself.

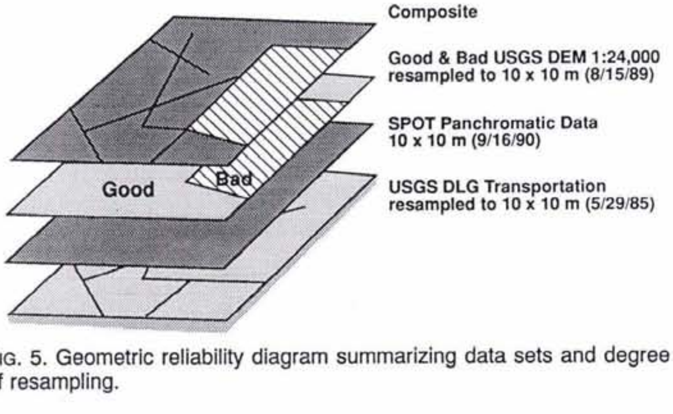


Fig. 5. Geometric reliability diagram summarizing data sets and degree of resampling.

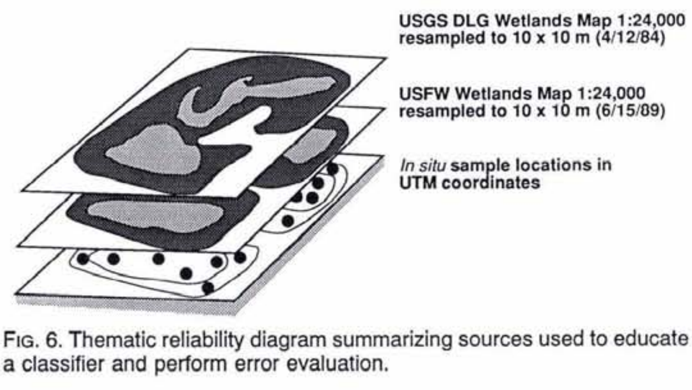


Fig. 6. Thematic reliability diagram summarizing sources used to educate a classifier and perform error evaluation.

These consequences 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 may result in monetary or other adverse punitive actions.

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

## CONCLUSIONS

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

(1) *Assess and propose error reporting standards and lineage documentation*. Only recently have reporting standards been proposed which include a data quality report for the transfer of spatial data and products. There is a need to (1) evaluate error classification (Veregin, 1989b) and the proposed spatial data transfer standards - SDTS (NCDCDS, 1988); (2) refine and extend the proposed SDTS to meet error assessment reporting objectives; (3) develop new error assessment procedures where needed; and (4) recommend appropriate refinements or additions to the proposed SDTS for the remote sensing and GIS communities. The ultimate goal of standardized error reporting is to provide an evaluation method for the appropriateness of GIS products derived from remote sensing for specific applications and to facilitate comparison of various research results.

(2) *Improve on existing remote sensing error assessment procedures*. Current state-of-the-art remote sensing error assessment procedures have been adapted from 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 to regional and global scales are not economically feasible. Because existing techniques only report overall class accuracies, the spatial distribution of error is not evaluated. Techniques need to be developed for assessing the spatial structure of error in an integrated remote sensing classification product, e.g., how are errors related to polygon boundaries.

(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 on 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; 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 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. These data are easily stored in raster format but difficult to convert to vector format. The difficulty lies in the huge number of polygons created if the data were directly converted to vector format. In the worst case scenario, each pixel in the image would become a polygon. Such a large amount of data would quickly become uneconomical. 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 photointerpretation. 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 control 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 has 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 accurately employed.

(5) *Locational data error characteristics*. Additional information is required on remote sensing locational error characteristics and the correlation between locational and classification errors. More knowledge is needed on the characteristics of alternative remote sensing platforms and how advances in global positioning system (GPS) technology will improve remote sensing data locational accuracy.

The incorporation of elevation correction in georeferencing procedures for both aircraft and satellite remote sensing data is critical to achieve acceptable locational accuracy for incorporation into a GIS. Additional studies need to be conducted to assess the relationship of elevation model scale and the degree of relief displacement in the georeferencing process. Another 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 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 reliability associated with the specific data products. This will require research to develop geometric and thematic reliability diagrams for remote sensing and GIS final products.

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