A DEPENDENCY MATRIX TO ASSIST IN THE VISUALIZATION OF GEOSPATIAL IMAGE QUALITY

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ABSTRACT:

Professionals of various backgrounds have recognized the value that the use of geospatial imagery can add to their analysis. They take advantage of the widespread availability of data in vast image collections. Images in these collections are of various quality, which should be communicated to the users to prevent misuse of information. Visualization of data quality has itself proven to be a valid method to communicate the quality of images to users conducting geospatial analysis. In order to visualize quality, researchers have identified data attributes that hold quality information, and several quality visualization projects followed in its wake. This work concentrates on investigating the dependencies between data quality attributes in geospatial image data. We develop a binary dependency matrix that illustrates dependencies between quality attributes. Then a second, qualitative matrix is populated to describe the dependencies between the attributes in more detail. From this we derive the impact that the discovered dependencies have on quality visualizations. These visualizations would benefit from a formal description of dependencies between data quality attributes, enabling the automatization of the data quality visualization process. The conclusions drawn from the exploration of dependencies can enhance the communication of data quality when they are incorporated into the visualization design.

KURZFASSUNG:

Durch moderne Datenerfassung steht eine große Zahl von Luft- und Satellitenbildern zur Verfügung, die sich zur räumlichen Datananalyse anbieten. Diese Bilder unterscheiden sich in ihrer Qualität. Für eine optimale Nutzung sollten GIS Nutzer auf die jeweiligen Qualitätsmerkmale aufmerksam gemacht werden, da die Verwendung von Daten mit ungeeigneter Qualität die Resultate der Analyse negativ beeinflussen kann. Die Fachwelt ist sich einig, dass sich die Methode der Visualisierung besonders zur Kommunikation der Datenqualität eignet. Zur erfolgreichen Visualisierung müssen Datenattribute identifiziert werden, die Qualitätsinformationen vermitteln. Unsere Arbeit untersucht diese Attribute der Datenqualität auf ihre Abhängigkeit. In einem ersten Schritt entwickeln wir eine binäre Abhängigkeitsmatrix die zeigt, zwischen welchen Attributen eine Abhängigkeit besteht. Der zweite Schritt besteht aus einer Erweiterung der Abhängigkeitsmatrix, in der die Details der Abhängigkeiten qualitativ beschrieben werden. In der darauffolgenden Analyse diskutieren wir die Konsequenzen, die diese Abhängigkeiten zwischen Datenattributen auf die Qualitätsvisualisierung haben. Das Wissen, das durch die Analyse der Abhängigkeitsmatrix gewonnen wird, kann die Kommunikation der Datenqualität verbessern, was zu der Verwendung von geeigneteren Bildern und somit zu verbesserten Resultaten der Bildanalyse führt.

1. INTRODUCTION

Today's advances in remote sensing give us more data about our world than ever before. The lower cost of acquisition and abundance of storage space makes it possible to store these satellite images in geospatial image collections that can be remotely accessed. This situation enables a variety of users to take advantage of images in geospatial image databases. Professionals with backgrounds as varied as forestry, city planning, and disaster management, just to name a few, rely on geospatial images to assist in finding the solution to their problems.

The advantages that the abundance of geospatial images offer are offset by the problems that this same abundance causes. Due to the sheer volume of images users might become overwhelmed. Image databases may contain multiple data of the same area that differ in quality attributes such as resolution, currency, and others. It becomes difficult to choose appropriate data for various tasks. Especially professionals that are not experts on geospatial imagery, but use images only as a supporting tool for their analyses can become confused in choosing the images that are best suited for their task. Choosing images that do not have the correct attributes can lead to sub-par results and can even cause errors in the outcome of the analysis.

We need to educate users, make them aware of the problem, and assist them in selecting the right images. For this we have to communicate the image quality to the user in an easily understandable way. Multiple ways to communicate data quality exist, such as tabular listings of metadata, narrative descriptions, and visualization. Of these methods, visualization has often been hailed as a valid and proven tool for quality communication especially useful for geospatial data (Beard and Mackaness, 1993; van der Wel et al., 1994). The advantages of using visualization are that the visual channel can transport a lot of information at the same time, and it is the primary sensory input channel for most people (Beard and Buttenfield, 1999). This is especially true of users working with satellite images, since they are skilled in absorbing information from images.

In order to visualize image data quality one has to follow these steps: First one has to decide on data attributes that convey quality information. Discussion on which data attributes show valid quality information specifically for geospatial data can be found in the literature, and we are discussing relevant pieces in the next section. Secondly, one has to decide on the visualization method. A successful method helps users to see the quality of the available data at one glance and shows it clearly enough for everybody to understand. One example is previous work on developing visualization methods for geospatial image quality (Schlaisich et al., 2004). When working on these two points, researchers have to take care to not overlook the dependencies between selected quality attributes. Interactions between attributes can influence the outcome of the data quality visualizations which makes them inaccurate or incorrect and might confuse the user or send a wrong message.

The core of this paper provides a description of attribute dependencies, specializing on quality attributes in geospatial imagery. This will help to visualize image data quality, especially enabling the automatization of the generation of visualizations. The value that our research on quality attribute dependencies contributes lies in the formal description of these dependencies, which will enable researchers to incorporate them into their quality visualizations and consequently produce more accurate visualization models. In addition, the formalization of the dependencies contribute to making an automatization process possible, that will make it easier for users to perceive the data's usefulness and applicability.

Our approach to the problem is as follows: First we identify the attributes that are most useful for conveying image data quality. We base our selection on attributes that were listed as valid geospatial data quality attributes in other projects in the literature and in the US Spatial Data Transfer Standard's (SDTS) section on data quality (NIST, 1992). The quality attributes that we chose to convey the overall image data quality are: *positional accuracy*, *scale*, *resolution*, *completeness*, *consistency*, and *currency*. Then we formalize the dependencies between the attributes and draw conclusions on the impact these dependencies have on quality communication. A binary matrix introduces dependencies between quality attributes. In a qualitative matrix we explore these dependencies in greater depth, and derive the consequences for quality visualization.

This work is not concerned with determining or deciding on the quality of geospatial images in image collections. We assume that this information is given, since it would exceed the scope of this work to produce quality information. A considerable body of literature is available on this topic. As an introduction the following collections of articles are recommended: (Foody and Atkinson, 2002; Zhang and Goodchild, 2002)

The remainder of this paper is structured as follows: section two discusses literature that is relevant to our work. In section three we introduce data attributes that communicate data quality, and argue why we chose the ones that we use to show geospatial image quality. Section four introduces and discusses the dependency matrices that show the dependencies between quality attributes and derives consequences from these interactions. Conclusions and future work follow in section five.

2. RELATED WORK

Recent years have shown a substantial rise in literature on data quality in general and specifically in geospatial data quality. In the 1990ies researchers recognized that data quality issues influence the outcome of GIS and other spatial analysis and that some form of quality information should be conveyed to end users (Beard, 1997; Buttenfield and Beard, 1994; McGranaghan, 1993). Soon it became obvious that the nature of spatial data lends itself perfectly to the communication of quality parameters by visualization in the form of images and graphics. As a result, the call for visualization of data quality surfaced (Beard and Mackaness, 1993; van der Wel et al., 1994). The US National Center for Geographic Information and Analysis devoted a lot of energy to explore this area and spearheaded a research initiative on "Visualization of the Quality of Spatial Information" (Beard et al., 1991), and work on improving the communication of spatial data quality has been ongoing until now (Devillers and Beard, 2005).

Data quality visualization is a multi-disciplinary research effort. Along with professionals in the fields of geography and GIS, researchers in computer science, statistics, and others are working on developing suitable ways to communicate data quality. Even though a lot of progress has been made, the results are not satisfactory yet and additional research in the area of visualizing geospatial data quality has to be done. This was shown in a recent interdisciplinary workshop titled 'Toward Improved Visualization of Uncertain Information' (Board on Mathematical Sciences and Their Applications, 2005), where the importance of research in the field of uncertainty visualization was emphasized. Furthermore, the participants of the workshop concentrated on quality communication of large data sets such as the image collections that we deal with in this work. In a valuable survey paper MacEachren et al. (2005) discuss various approaches to visualizing uncertainty in different research fields, tie together the work that was done, and identify research challenges that present themselves today, which have to be solved in order to convey geospatial data quality in a way that is easy to understand.

To work with image quality, the term quality itself and related terminology has to be investigated. In the literature a substantial number of expressions are used to describe data quality, including quality, error, reliability, uncertainty, validity, accuracy, vagueness, precision, and fitness for use. Sometimes these terms are applied ambiguously. In the following we list how various terms are used in relevant publications.

The term *quality* is used as an umbrella-term that covers all aspects of the issue. It is used by practically everybody in the field (Beard, 1997; Veregin, 1999). The use of the term *error* is also widely used, and there is broad consent on what the word describes when used for image data, namely the difference between true value and the value stored in the database (Hunter and Goodchild, 1995). *Reliability* can be defined as the level of confidence a data provider has that the data are correct (Evans, 1997).

The term *uncertainty* is used in various ways, one being that the resolution of the data does not allow a user to make an assured decision about the content of the data. For example, pixels in remotely sensed images might contain uncertain information because of sub-pixel mixing or sensor sampling bias (Bastin et al., 2002). Worboys and Duckham (2004) use the term uncertainty to describe the doubt that users have about the right use of data. In this sense it is a measure that describes the state of mind of the user.

Other terms that are used to describe different outlooks on data quality are *validity* (Goodchild et al., 1994), and *accuracy* (Veregin, 1999). *Vagueness* describes the impossibility to determine the exact location or boundary of an object in space (Duckham et al., 2001). For example ‘the East of Maine’ is a vague area in that its boundaries are not exactly determinable. *Precision* denotes the exactness with which the measurement is made that led to the entry in the database (MacEachren, 1992). An overall phrase that is used frequently is *fitness for use*. It indicates whether the data has the specifications that the users need to solve their task (Paradis and Beard, 1994).

3. QUALITY ATTRIBUTES

This section discusses the data attributes that we identified as being pertinent to quality communication for geospatial image data. Since the goal of our research is to visualize geospatial image data quality, we select attributes that are specific for raster data. Most work in the area of quality attribute selection has been geared towards vector data.

Metadata contain a wealth of information about the data at hand. From the attributes that are typically described by metadata information we selected the ones that convey data quality, and more specifically, those which pertain to geospatial image quality. Our goal has been to display the optimum number of essential data attributes, avoiding redundancies which could confuse the user. We based our selection on the US Spatial Data Transfer Standard’s (SDTS) section on data quality (NIST, 1992), which is quite consistent with the data quality parameters that are used by the GIS community (Veregin, 1999).

A lot of research has been done on the quality of vector data. This a laudable development, but the work on raster data quality has lagged behind. Our work wants to counterbalance this trend. In the selection of quality attributes we started with the ones that proved valid for vector data, but adjusted them for raster data. Consequently, we do not use lineage, one data attribute that is relied on heavily for vector data, since it describes how the data was modified over the course of its existence, but raster data are normally not heavily modified. On the other hand, we added the attribute of resolution to our selection, since it is a very important quality measure for raster data.

Accordingly, to visualize the quality information of geospatial image data we selected the following data attributes: positional accuracy, logical consistency, completeness, scale, resolution, and currency, which we describe in the following:

Positional Accuracy: In the generally accepted definition, accuracy of spatial data describes how much the data deviates from a certain model or from reality. A point in an image does not necessarily lie exactly in the place where it is shown, but depending on its positional accuracy it can lie anywhere within an area around its displayed position.

Resolution: For geospatial image data resolution is an important quality measure. Digital images are stored in the form of raster data of a certain resolution, e.g. a single pixel can cover a ground area of 1x1km, 30x30m, or 0.6x0.6m. Resolution is hardware-dependent. It relates to sensor specifications in the case of digital images, and the granularity and settings of the scanner in the case of digitized photographs. The difference in information detail and quality that images of various resolutions offer is clear. Different resolutions are useful for different tasks, but users have to be aware of the impact that resolution has on the usability of the data.

Scale: The scale of an image describes the correspondence between image space and the captured ground area. This geometric relationship is dependent on the selected flight mission parameters such as flying height and camera focal length. It is primarily applicable to aerial photographs on film. In digital images with the ability to zoom in and out, it is a measure of the detail of features that is recognizable in the data.

Completeness: Completeness communicates whether data is present. Data might be missing completely for some areas, for example in cases where there have been no flight missions to produce aerial photographs. Also, parts of a picture can be missing due to cloud cover.

Currency: The currency of data is defined as the time between the production of images and the date of a query. Information on currency can be a decision factor for users. Several applications ask for the most recent available data, while other users may be looking for older data or specific time series for change detection.

Logical Consistency: Logical consistency checks if data are contradicting each other. The visualization of the results of these checks can be a powerful warning sign for users. For example, a satellite image with 5m resolution and a currency of 1972 should raise an inconsistency flag.

4. DEPENDENCIES BETWEEN ATTRIBUTES

This section introduces the dependency matrix that we developed. It lists the dependencies that exist between the attributes and discusses the impact that these dependencies have on the visualization of data quality. As a first step we populate a binary dependency matrix. Subsequently, we expand the matrix by qualitatively describing the dependencies between attributes. This qualitative dependency matrix is discussed and in the end of the section we describe how the dependency matrix can help in the generation of quality visualizations.

4.1 Binary Dependency Matrix

The matrix in Table 1 describes the dependencies between the selected quality attributes *logical consistency*, *positional accuracy*, *completeness*, *scale*, *resolution*, and *currency*, in a binary way, i.e., it only denotes if a dependency between two attributes exists or not. The X in the main diagonal denote attribute dependencies on themselves, which are naturally given, and which are of no interest to us. The matrix is symmetric and the table lists only the upper half to avoid duplication.

We determined dependencies between:

- positional accuracy – scale
- positional accuracy – resolution

- scale – resolution
- resolution – currency

	logical consistency	positional accuracy	completeness	scale	resolution	currency
logical consistency	x	no	no	no	no	no
positional accuracy		x	no	yes	yes	no
completeness			x	no	no	no
scale				x	yes	no
resolution					x	yes
currency						x

Table 1. Binary Dependency Matrix

The other pairings of quality attributes do not entail dependencies. Logical consistency per se does not depend on any of the other attributes. In some instances inconsistencies can arise when values of quality attributes are in disaccord with each other, such as in the aforementioned example of an older satellite image with impossibly low resolution. But these cases do not warrant defining a general dependency between logical consistency and one of the other attributes.

The fact that there are no images available for a certain area or that parts of images are obstructed does not have any influence on the positional accuracy of features in the image, therefore positional accuracy and completeness have no dependencies. Furthermore, completeness does not depend on the scale, resolution, or currency of an image. Unlike resolution, the scale of an image is not dependent on the time it was taken, since advances in technology over time did not make a difference in the scale in which an image can be taken.

A dependency is entered into the matrix only if it exists directly between the two attributes. In some instances the dependencies between two attributes can make other attributes dependent on each other, but the second pair of attributes is still listed as independent. An example for this would be that there is no direct dependency between positional accuracy and currency, but there is dependency between positional accuracy and resolution, and resolution and currency.

Developing the binary dependency matrix is a valuable first step to understanding dependencies between quality attributes. It shows where dependencies arise and warns of combinations of attributes that might cause problems.

4.2 Qualitative Dependency Matrix

Table 2 shows the dependency matrix with a short version of the qualitative dependency descriptions. As in the binary matrix, only the upper half of the symmetric matrix is populated. In the following we elaborate on the dependencies between the quality attributes.

Positional Accuracy – Scale: It is a long-known truth of cartography that the smaller the scale of a map is, the lower is the positional accuracy of features that can be observed on a map. The same holds true for spatial data in digital form, including geospatial images. For digital data one has to note that the scale, and therefore the positional accuracy of the displayed image, can be manipulated on-screen by zooming, but there is still a specific scale and positional accuracy inherent in the stored data.

Positional Accuracy – Resolution: The dependency between these two attributes is very similar to the one between positional accuracy and scale. An image of high resolution can naturally show high positional accuracy. The lower the resolution of an image is, the lower is the positional accuracy of features that can be detected.

	logical consistency	positional accuracy	completeness	scale	resolution	currency
logical consistency	x	no	no	no	no	no
positional accuracy		x	no	lower accuracy at smaller scale	lower accuracy at lower resolution	no
completeness			x	no	no	no
scale				x	resolution implies certain scale - scanning of photo introduces resolution	no
resolution					x	higher resolution possible in newer images
currency						x

Table 2: Dependency matrix with qualitative descriptions

Scale – Resolution: The attributes of scale and resolution both describe similar characteristics of an image. As was stated above, resolution is hardware dependent, and scale is dependent on the characteristics of the flight mission. In digital images these two attributes are intertwined in the following way: the notion of scale was originally used as an attribute for aerial photographs. With the advance of digital imagery, aerial photographs are added to digital image collections. In the resulting scanning process the scanner introduces resolution to the image. On the other hand, raster images of a certain resolution should be viewed at their corresponding display scale to avoid giving the user the illusion of more detail in the image than is actually present. When using multiple images of various resolutions in GIS analysis, one has to take care that the implied scale of the images is compatible with the operations that are applied, to avoid a situation of 'comparing apples with pears'.

Resolution – Currency: The dependency between resolution and currency is driven by technology. The advances in sensor development over time make higher resolutions possible. Consequently, the highest possible resolution of older satellite images is lower than the highest possible resolution of more recent images.

4.3 Consequences for Quality Visualization

As was established before, professionals using geospatial analysis would benefit from knowledge about the quality of the data that is available to them. Some previous projects that used visualization methods to communicate data quality are: work on quality information for risk management decisions (Davis and Keller, 1997), visualizing uncertainty in multi-spectral remotely sensed imagery (Bastin et al., 2002), visualization of the reliability of water quality data (Howard and MacEachren, 1996), and visualization of image quality in distributed spatial databases (Schlaisich et al., 2004). These projects use a limited number of quality attributes between which dependencies might exist.

Data quality visualizations that show multiple attributes together might introduce an unwanted dynamic into the display. The previously described dependencies between quality attributes must be taken into account when developing a visualization method. The knowledge that we gained until now will lead to a formalization of the attribute dependencies, which in turn will enable an automatization of the data quality visualization process.

5. CONCLUSIONS AND FUTURE WORK

The wide availability and large number of geospatial image data offers users new ways to analyze spatial data. Data at hand is captured in various degrees of quality, which should be communicated to the end user. An effective way to convey geospatial data quality is by the means of visualization. This paper emphasizes the importance of quality visualization and develops a dependency matrix for quality attributes that can help the development of these visualizations.

The used quality attributes are *positional accuracy*, *logical consistency*, *completeness*, *scale*, *resolution*, and *currency*. The selection is geared towards raster data in order to cater to geospatial images. In a first step, a binary dependency matrix is developed. The matrix recognizes dependencies between positional accuracy and scale, positional accuracy and resolution, scale and resolution, and resolution and currency. There are no dependencies identified between the other attribute pairings.

In a further step, the dependency matrix is progressed from the binary state to further describe the nature of the dependencies in a quanlitative dependency matrix. The results from this expansion are as follows: Lower resolution or smaller scale result in lower positional accuracy. More current images have the potential for higher resolution. The resolution of an image implies a certain scale.

The aforementioned dependencies between quality attributes can influence the quality visualizations in a negative way. Therefore, they need to be taken into consideration when designing a method for geospatial data quality visualization.

Even though this research focuses on image data the resulting dependency matrices can be used in the broader context of spatial data in general. Furthermore, our selection of quality attributes is not absolute, and the matrices could be further populated by using additional attributes as they emerge.

In future work we will concentrate on expanding the dependency matrix to include formalizations of the dependencies. This will make it easier to incorporate our findings into quality visualizations, enabling the generation of automated visualizations, which is the final step in the course of this work on data quality.

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