DEALING WITH UNCERTAINTY IN LARGE-SCALE SPATIAL DATABASES

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ABSTRACT

This experimental study addresses the issue of uncertainty inherent in large-scale spatial databases. A contemporary Spanish large-scale topographic database, compiled according to the current standards, is used to examine uncertainty patterns and propose practical solutions for their communication. A set of specific, inexpensive and explanatory visualisations is developed for each of the data quality categories within an uncertainty typology proposed by Thomson et al. (2005). The resultant visualisations offer a compact and direct view of uncertainty aimed at novice users and provide means to deal systematically with uncertainty inherent in spatial databases. The disadvantage of this approach includes the necessity of arbitrary decisions for metadata classification.

A concept of global visual uncertainty indicator (G-VisUI) is introduced as an extension to visualising individual categories of data quality. The G-VisUI provides an immediate ‘overview’ of the overall quality of the database with the ability of alerting users to local variations and anomalies. However, the strategy for visualising G-VisUI is still immature and requires further research and testing.

INTRODUCTION

Over the past two decades, there has been a significant growth in the analysis and processing of geo-referenced data. Digital databases have become the ultimate source of spatial information and the main source of data for geographical interpretation and analysis. However, these databases often contain spatial information of poor or insufficient quality. Error is frequently introduced through data compilation methods and later propagated by various spatial operations. This introduces uncertainty and ultimately creates a need for its communication.

Visualisation provides a valuable approach for communicating uncertainty information in a spatial environment. Its use of visual means to represent spatial relationships that cannot be detected by other forms of expression (e.g. textual, verbal or sonic) is a clear advantage. Visualisation engages the principal human information-processing ability, that associated with vision (Buttenfield and Mackaness, 1991; MacEachren et al., 1992).

Visualisation of uncertainty is particularly useful when spatial data are used in decision-making processes, where the implications of using uncertain information may be significant. It is also an important consideration when assessing suitability of data for geographic information systems (GIS) operations or for a particular application.

Visualisation of uncertainty associated with geo-referenced information has been a subject of increasing attention from researchers over the last decade. It has been greatly influenced by the National Center for Geographic Information and Analysis (NCGIA) Research Initiative on Visualisation of Spatial Data Quality (Beard et al., 1991). The Initiative played a significant role in addressing a need for exploration, development and evaluation of visual techniques to communicate data quality issues.
Following that, McGranaghan (1993), MacEachren (1994) and van der Wel *et al.* (1994) compiled a list of potential visualisation tools that are available for representation of data uncertainty. Other authors developed specific visual techniques and applications, such as animation (Fisher, 1993), interaction (Lucieer and Kraak, 2004; MacEachren *et al.*, 1993), a modified HIS (hue, intensity, saturation) colour system (Hengl, 2003; Jiang *et al.*, 1995), virtual depth-based representations (Clarke *et al.*, 1999), opacity and ‘squares’ (Drecki, 2002), or sonification (Krygier, 1994) to represent uncertainty. Majority of these visualisations are centred on the use of cartographic visual variables and their extensions (such as e.g. opacity, size or clarity), while others utilise sophisticated computer-based applications or geovisualisations (e.g. Lucieer and Kraak, 2004; Slocum *et al.*, 2003) and virtual environments (e.g. Clarke *et al.*, 1999).

To date, many uncertainty visualisations are developed in a research or academic environment, which often makes them expensive both in terms of time and capital outlay. They primarily focus on the exploration of uncertainty patterns and often target analysts or expert users of spatial data. They usually centre on visualisation of a single category of data quality (such as accuracy or lineage), rather than deal with uncertainty in a systematic and comprehensive way. In the case of a commercially operated geospatial agency this approach is prohibitive from the perspective of economic principles, inadequate with regards to target audience, and limited due to the selective approach in communicating data quality information.

This paper centres on the development of inexpensive and explanatory uncertainty visualisations aimed at novice users. It begins with a brief discussion of a typology for visualising uncertainty based on Thomson *et al.* (2005). The research attempts to contribute to this typology by matching the developed uncertainty visualisations with data quality categories. The discussion of data characteristics and profiling end users is included to explain the criteria by which the selection of uncertainty visualisations was undertaken. The actual development stage focuses on the implementation of uncertainty representations suitable for use commercially. The global visual uncertainty indicator (G-VisUI) is proposed to inform users about the overall quality of the database, including local variations and so called ‘hot spots’ in data quality.

It seems relevant to mention, that in a commercial environment it is rare to specifically inform users about the uncertainty associated with the supplied data, particularly in a graphic form. Therefore, this study is experimental and, by permission, uses commercial data stored within a corporate database often obtained specifically for this research.

### A FRAMEWORK FOR VISUALISING UNCERTAINTY

The initial efforts on formalisation of uncertainty visualisations resulted in the development of Spatial Data Transfer Standard (SDTS)(NIST, 1990). The categories of data quality in the SDTS include lineage, positional accuracy, attribute accuracy, logical consistency and completeness. Currency, although not regarded as a data quality category within SDTS, has its place in the uncertainty visualisation framework (Beard *et al.*, 1991; Beard and Mackaness, 1993). Furthermore, a recent study on uncertainty typologies for geo-referenced information suggests inclusion of further categories, namely precision, credibility, subjectivity and interrelatedness, as well as combining positional accuracy and attribute accuracy into accuracy category (Thomson *et al.*, 2005). The following list gives brief definitions for each category (all quotes from Thomson *et al.*, 2005).

- **completeness:** extent to which information is comprehensive
- **consistency:** extent to which information components agree
- **lineage:** conduit through which information passed
- **currency:** temporal gaps between occurrence, information collection and use
- **credibility:** reliability of information source
- **subjectivity:** amount of interpretation or judgement included
- **interrelatedness:** source independence from other information
- **accuracy:** difference between observation and reality
- **precision:** exactness of measurement

This paper attempts to contribute to the framework by matching specific visualisations with the proposed uncertainty categories. A challenge of dealing with uncertainty is undertaken for all categories within the above typology.

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1. The above categories can be put into a matrix, whereby each category of uncertainty is matched with a distinction among location (position), attribute and time components of data (MacEachren, 1994; Thomson *et al.*, 2005), thus removing a need for separate categories of the positional and attribute accuracy. For examples refer to paper by Thomson *et al.* (2005).
DATA CHARACTERISTICS

At Aurensis s.l., a Spanish geospatial service provider, one of the main productions focuses on urban and topographic medium- to large-scale mapping (in a form of spatial databases), as well as orthophotomaps and other geo-referenced image-based products. The target scale of these products ranges from 1:500 to 1:100 000. The three main sources of data include: base maps obtained from other sources (mainly digital databases, but also hard-copy maps), high resolution aerial photography or satellite imagery, and information obtained from rigorous field checks.

The urban and topographic spatial databases are generated using high precision photogrammetric techniques in conjunction with other sources, such as already processed digital products, externally generated spatial databases, hard-copy maps and field checks. Examples of the corporate database features include roadways, parcel boundaries, buildings, contour lines, curbs and manholes. Sometimes, laser technology is used for very detailed terrain modelling or to capture and process architectural details into inventory databases for cultural heritage protection agencies. Most of the data is captured and processed in 3D with full attribution and according to client specifications.

Currently, the communication of data quality information to the customers is limited. It includes a statement of nominal scale, e.g. 1:10 000 and a percentage of “visible” features that meet prescribed data quality measures (usually 90%). In the case where some features cannot be identified in the field or some technical or equipment errors occur, a written report is supplied with coordinates of these features or descriptions of the affected areas. There is no practice of providing graphic representations of uncertainty to the customers.

The above data characteristics and data quality reporting, although described here with reference to Aurensis s.l., are relevant to any geospatial service provider specialising in the provision of large-scale spatial databases.

For this experimental research a mapping project that involves development of a large-scale (1:10 000) topographic digital database for the Province of Burgos in central Spain has been selected. The Province is divided into approximately 550 quadrangles of long 5° x lat 2.5° each with Aurensis s.l. being responsible for mapping almost 60% of the area (Fig 1). For each quad in the Burgos Mapping Project (BMP) relevant metadata information has been collected enabling preliminary processing of uncertainty information.

![Figure 1](image.png)

**Figure 1.** Burgos Province in northern Spain with 1:10 000 quadrangles marked and area covered by the BMP shown in grey.
END USER CHARACTERISTICS / PROFILE

The customer base of Aurensis s.l. includes local authorities, mainly the planning and transportation departments, port and airport authorities, as well as cultural heritage protection agencies and private companies. Supplied large-scale urban and topographic databases are largely used by planners and decision-makers for land information, policy development and allocation of resources. Such customers have limited experience in dealing with uncertainty inherent in geospatial databases and can be broadly characterised as ‘novice users’.

Novice users’ ability to comprehend uncertainty information associated with spatial databases cannot be compromised by complex visualisations. Therefore, explanatory representations seem to be a preferred option. It requires uncertainty visualisations to be compact, direct, easily understood and relevant to the users’ ‘reading’ abilities.

DEVELOPMENT OF UNCERTAINTY VISUALISATIONS

Aurensis s.l. is a commercially driven private geospatial enterprise. A substantial technological investment both in terms of equipment and expertise for the development of uncertainty visualisations is prohibitive from the perspective of economic principles. Therefore, a modest approach in developing inexpensive solutions has been adopted. This philosophy is also relevant for the incorporation of uncertainty visualisations into any standard commercial product.

Development of explanatory visualisations that provide compact, direct and easily understood information about uncertainty could be a challenging task. The characteristics of the target audience (‘novice users’), that these visualisations are aimed for, need to be taken into account. Furthermore, providing ‘separated’ visualisations (MacEachren, 1992), whereby data can be easily separated from the uncertainty information, is of particular importance. Customers usually prefer data that can be easily manipulated according to their specific needs without the necessity of dealing with ‘embedded’ uncertainty information (like in bivariate representations). A challenge of representing uncertainty within the data quality framework is to be undertaken for all categories in the proposed typology (Thomson et al., 2005). Lastly, developed visualisations are to complement and not duplicate the current uncertainty reporting methods.

Initially, the above criteria prompted an adoption of a ‘traffic light’ approach to visualise data quality categories for the Burgos Mapping Project (BMP). For each quadrangle, an arbitrary decision had to be made, using 3-step ordinal scale, with regards to the quality of data for each category of uncertainty. However, some categories were difficult to classify using just three steps. For example, subjectivity deals with the experience of analyst performing spatial operations. In the case of the BMP, there were two analysts, one with over 4 years and the other with over 12 years experience. It is clear that both analysts are sufficiently qualified, but it seemed appropriate to give the latter one higher ranking. Under 3-step scenario, the former analyst would then need to be classified as ‘average’ which seemed inappropriate. Therefore, careful examination of data prompted to replace the 3-step scale with a 5-step scale, where the following colour hue distinctions were determined: green for ‘very good’ quality of data, green-yellow for ‘good’, yellow for ‘average’, orange for ‘poor’ and red for ‘very poor’. Quadrangles for which there are ‘no data’ or for which representation of a particular category is ‘not applicable’ are shown in grey.

Development of uncertainty representations for each uncertainty category is described in detail and a clear description of available metadata is given below. It seems appropriate to mention that the BMP has been compiled to the highest quality standards and the discussed uncertainty spectrum is almost entirely within the accepted threshold. What falls outside the threshold is highlighted (in orange or red colour – ‘poor’ or ‘very poor’) and communicated to the client in a form of a separate written report.

Completeness
Completeness deals with issues of missing information. In other words it informs about the extent to which data is comprehensive (Thomson et al., 2005). In the case of the BMP, it is expressed by the status of the updating process and carries a binary relationship of ‘updated’ and ‘not yet updated’. Completed quadrangles are shown in green and those where updating is in progress (April 2005) are shown in red (Fig 2).

Consistency
The degree to which there are no contradictory relationships in the database is expressed by consistency (or logical consistency). Since the BMP required compilation of data from various sources, it is essential to merge these data in a seamless and consistent fashion. The degree of positional, attribute and temporal ‘agreement’ between these sources is analysed by calculating the percentage of error between the ‘edges’ of juxtaposed quadrangles. When error is lesser than 10%, a ‘very good’ score is given. A ‘good’ score is recorded when error is higher than the 10% threshold, but
lesser than the accepted standard. The resultant map shows areas of high consistency in green colour, while quadrangles with lower consistency are marked in green-yellow (Fig 3).

![Map showing completeness and consistency categories](image.png)

Figures 2 and 3. Representation of completeness and consistency categories of data quality in the BMP.

**Lineage**

Lineage is a record of processes applied to source data or to information stored in a database. In the case of the BMP, processing of the source information is subject to various operations in order to meet the required mapping standard. They include geometric correction, fusion of information across neighbouring areas, homologation of database structure and updating. Those quadrangles, for which source information required all of the above operations, carry the highest degree of uncertainty (marked in yellow on Fig 4). This is caused by the necessity of using the largest number of steps in data processing as well as by the type of processing involved. Application of homologation process without updating produced better quality results (green-yellow quadrangles) because the source data were already current. The highest degree of certainty was achieved by using homologation, fusion (for some areas only) and updating operations (shown in green on Fig 4). These areas were processed using current high quality aerial photography.

**Currency**

Currency can be defined as a temporal difference between the time of enquiry and the time the data was processed. In any topographic mapping project, the use of most up-to-date information is critical. In the BMP, source information or supplementary materials are regarded as suitable if they are up to 3-4 years old. From the four sources of information used in the project, three met this criterion (aerial photography, orthophotomaps and supplementary topographic maps). They are marked as green on Figure 5. Older data are considered if they are useful in the updating process, such as another set of supplementary topographic maps from 1999. This dataset is shown in green-yellow colour (Fig 5).

**Credibility**

Credibility deals with the reliability of information and is often related to the experience of an analyst (Thomson et al., 2005). In the case of the BMP, there are two analysts working on the project. Although both of them are very experienced with over 4 years and over 12 years experience respectively, it seemed appropriate to give the latter one higher ranking. Areas processed by analyst with over 12 years experience are marked in green and quadrangles processed by the analyst with over 4 years experience are shown in green-yellow colour (Fig 6).

**Subjectivity**

Subjectivity refers to the amount of interpretation or judgement included in the data (Thomson et al., 2005). In photogrammetry, image interpretation is a common but often subjective task used in data collection and processing for topographic mapping. Urban areas are usually subject to higher uncertainty associated with data interpretation because they are more complex. For example, an object can be interpreted as a small house (permanent dwelling category) while in reality it is a temporary storage structure (temporary storage category). Rural areas are subject to lower uncertainty. Their interpretation is mainly concerned with land use, which is easier to interpret and classify. As a consequence,
Interpretation quality in the BMP is shown as less certain – more subjective (green-yellow colour) for urban areas and as more certain – less subjective (green) for rural areas (Fig 7).

**Figures 4 and 5.** Representation of lineage and currency/timing categories of data quality in the BMP.

**Figures 6 and 7.** Representation of credibility and subjectivity categories of data quality in the BMP.

**Interrelatedness**

Interrelatedness deals with the issue of source independence from other information (Thomson *et al.*, 2005). It is particularly useful in the news media or intelligence information assessment where a story needs to be verified whether is genuine or not. Since all source information for the BMP were obtained from authoritative sources, such as the Junta de Castilla y León (Government of Castilla y León), interrelatedness is uniform for the entire project. Consequently, representation of this category of data quality is expressed by green colour for all mapped quadrangles (Fig 8).
Accuracy

Accuracy refers to the degree of conformity between the description of an object in reality and its description in a database, and it can be matched with a distinction among positional, attribute and temporal characteristics of data (MacEachren, 1994; Thomson et al., 2005). Accuracy is heavily dependent on the quality of source information. The BMP uses several sources of information for data verification, each produced with a different level of accuracy but according to the current high standards. Digitised hard copy maps were defined as most uncertain due to the media instability (affected by humidity, temperature, etc.), digitisation process and attribute encoding. Quadrangles verified using these maps are shown in orange colour on Figure 9. Digital database obtained from the Consejería de Medio Ambiente (Department of Environmental Protection, Government of Castilla y León) received higher ranking as being originally fully digital and rigorously checked (green-yellow on Fig 9). The most certain were digital databases obtained from the Consejería de Fomento (Department of Promotion, Government of Castilla y León) for their currency and strict procedures used in their creation. Quadrangles verified using these databases are shown in green colour (Fig 9).

![Figures 8 and 9. Representation of interrelatedness and accuracy/error categories of data quality in the BMP.](image)

Precision

Precision is defined as the exactness of measurement (Thomson et al., 2005). In photogrammetry, precision is often associated with the parameters of the aerial camera or equipment used in photogrammetric processing. In the case of the BMP, all data requiring aerial photography or any photogrammetric products were captured and processed using the same state of the art equipment. Therefore, all quadrangles are shown in green (Fig 10), as they are produced to the highest standard.

GLOBAL VISUAL UNCERTAINTY INDICATOR (G-VisUI)

As an extension to visualising individual categories of data quality, a single view of ‘combined’ uncertainties seems to be a logical consideration. This study introduces the concept of a global visual uncertainty indicator (G-VisUI). The G-VisUI informs about the ‘overall’ quality of the database, alerting customers to the local variations and so called ‘hot spots’ in the database.

The simplest but also conservative approach in representing G-VisUI is to assume that the data certainty is as good as their most uncertain category and that all categories are of equal weighting. For example, if completeness is ‘very poor’ (red colour) for a particular quadrangle, this quadrangle will carry this score in G-VisUI regardless of how well it scored against other categories of data quality or how important the other categories are (in the view of a customer or a database supplier). In the case of ‘no data’, a particular quadrangle receives the lowest ranking scored for any of the remaining categories. Figure 11 shows G-VisUI for the BMP using the above criterion (Criterion 1).
Another, more liberal approach is to visualise G-VisUI based on average score received from all categories, but still treat all categories with equal weighting. For example, a quadrangle scoring ‘very good’ for three categories of data quality, ‘good’ for another three and ‘average’ for the remaining three categories will carry an overall score of ‘good’ in G-VisUI. In the case of ‘no data’ or ‘not applicable’ for a particular category, a quadrangle receives the lowest ranking (very poor) for calculation purposes. The G-VisUI for the BMP based on this criterion (Criterion 2) is shown on Figure 12.

It is easy to imagine coming up with several other approaches in visualising G-VisUI. Allocating weighting to the data quality categories is an obvious example. However, this falls beyond the scope of this research and is only briefly discussed in the next section.
DISCUSSION

The following discussion focuses on the implementation strategies concerned with visualisations of data quality categories. It also addresses the complexities and challenges associated with the introduction of a global visual uncertainty indicator (G-VisUI) for visualising ‘combined’ uncertainties in spatial databases.

Visualisations of Data Quality Categories

The uncertainty typology proposed by Thomson et al. (2005) and adopted for the BMP is relatively new. Since the project itself began prior to its publication, a systematic and comprehensive approach in collecting and processing of appropriate metadata to suit the adopted framework was difficult to accomplish. As a consequence, visualisations of some categories of data quality are compromised and not dealt with comprehensively. Therefore, interpretation of these visualisations needs to be undertaken cautiously. For example, accuracy focuses only on the quality of source information used in data verification and it doesn’t include any information on accuracy of attribute encoding or positional accuracy of objects in the database. Currency, on the other hand, is represented comprehensively, as it was possible to gather all temporal information concerning data sources, information processing and dissemination.

The ‘extended’ traffic light approach used in visualising individual data quality categories has several advantages. It provides easy to understand solution for novice users, because is based on commonly recognised diverging colour scheme. It is inexpensive and reasonably fast to develop. It can be easily incorporated into the database as extra layers, which allows separation of data and quality (‘separated’ relation). Lastly, it provides means to deal systematically (and potentially comprehensively) with uncertainty inherent in spatial databases.

The obvious disadvantage of the above approach is the arbitrary decision that is necessary to classify metadata into 5-step classification. It is particularly problematic where no clear guidelines are available for dealing with a particular category of uncertainty, such as interrelatedness or credibility. Even for purely quantitative categories, such as accuracy or precision, classification process could be biased, as there is often no clear consensus of what is acceptable and what is not with regards to data quality.

It is believed that developed visualisations, despite their deficiencies, are valid from methodological standpoint. They offer a systematic view of uncertainty across all data quality categories and they provide platform for more comprehensive studies of uncertainty.

Visualisations of G-VisUI

The proposal for a global visual uncertainty indicator (G-VisUI) as a solution to represent ‘combined’ view of uncertainty associated with a particular database is a valid consideration. However, the strategy for visualising G-VisUI is still immature and needs careful attention. Both approaches developed in this study have their limitations. The obvious disadvantage is the assumption that all data quality categories are of equal weighting. For example, this is particularly problematic in large-scale topographic databases, where some data quality categories (such as accuracy, consistency or currency) are traditionally considered as critical, while others have less relevance (such as credibility or subjectivity). The resultant visualisations are therefore biased as they don’t take into account data category weighting.

Furthermore, visualising G-VisUI based on average score approach has further limitations associated with the actual score computation. For example, in an extreme case a quadrangle scoring ‘very good’ for four categories of data quality, ‘average’ for one and ‘very poor’ for the remaining four categories will carry an overall score of ‘average’ in G-VisUI. This seems unacceptable as four ‘very poor’ scorings should disqualify this quadrangle from receiving an acceptable ranking. Therefore, G-VisUI currently poses more questions than answers and needs to be further researched and comprehensively tested.

CONCLUSIONS

A systematic and comprehensive approach in dealing with uncertainty inherent in spatial databases becomes increasingly pressing. This is particularly critical when spatial data are used in decision-making processes, where implications of using uncertain information may be significant. A contemporary large-scale topographic database,

\[\text{An introduction of a local visual uncertainty indicator (L-VisUI), which synthesise and visualise all data quality characteristics for a particular category (such as attribute encoding, positional estimation of an object, etc in the case of accuracy category) could provide a viable solution.}\]
largely used by planners and decision-makers for land information, policy development and allocation of resources, served as a source for exploration of uncertainty patterns.

In this experimental research a typology for visualising uncertainty proposed by Thomson et al. (2005) has been adopted as a base to develop a series of inexpensive and explanatory uncertainty representations for each of the data quality categories defined within this typology. The resultant visualisations provided a compact and direct view of uncertainty aimed at novice users. They were reasonably fast to develop, used a commonly recognised diverging colour scheme and provided the means to deal systematically with uncertainty inherent in spatial databases. However, the arbitrary decisions necessary to classify metadata into 5-step classification were an obvious disadvantage.

A global visual uncertainty indicator (G-VisUI) offering a single ‘combined’ representation of uncertainty in a database has been proposed as an extension to visualising individual categories of data quality. The G-VisUI provided immediate ‘overview’ across all data quality categories alerting users to local variations and anomalies. However, the strategy for visualising G-VisUI is still immature and requires further research and testing. These tests could be valuable as the development of uncertainty visualisations can be expensive both in terms of time and capital outlay. This is particularly significant in the case of a commercially operated geospatial agency, where economic principles apply.

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**BIOGRAPHICAL NOTES**

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