REPRESENTING GEOGRAPHICAL INFORMATION UNCERTAINTY: CARTOGRAPHIC SOLUTIONS AND CHALLENGES

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Representing geographical information uncertainty has been a subject of conceptual and applied research in geographical information science (GIScience) for over two decades. Although many solutions have been proposed, only some have actually been developed and even less comprehensively evaluated. An overwhelming number of these developments are focusing on some selected (or known) aspects of geographical information rather than supporting a comprehensive view of uncertainty.

Cartographic design theory and practice plays a significant role in finding and developing valid representations of geographical information uncertainty. For example, visual variables and their extensions, animations and interactive maps, haptic and sonic solutions have been proposed and developed. However, their systematic evaluation and assessment of their effectiveness in representing uncertainty is scarcely mentioned in cartographic literature.

This paper looks specifically at the cartographic design heritage as a source to derive valid solutions in representing geographical information uncertainty. It reports on the current state of affairs in assessing the suitability and effectiveness of cartographic solutions in representing geographical information uncertainty.

Cartographic Heritage in Representing Uncertainty

Cartographers are concerned with producing maps of a high and homogeneous degree of accuracy. Where that can not be accomplished they are using a variety of graphic or textual means to convey adequate information about uncertainty present on a map or its portion (Hunter and Goodchild, 1996; van der Wel *et al.*, 1994). Examples of textual means that are used to convey reliability measures include map accuracy standards, such as the National Map Accuracy Standard (Thompson, 1980) or the Instrukcja techniczna K-2 “Mapy topograficzne do celów gospodarczych” (Technical Instruction K-2 “Topographical Maps for Economy”) (GUGiK, 1980), and lineage statements documenting origin of data used, cartographic characteristics and processes involved.

There are several ways that uncertainty can be represented on maps. Many of them are widely accepted and utilised, although they have their limitations.

Reliability Diagrams

Reliability diagrams, usually placed on the map margins, are useful in showing information about the date of the survey, data used during the map compilation process, survey procedures, and variations in the map revision process (Hunter and Goodchild, 1996; McGranaghan, 1993).

Figure 1 presents a simple reliability diagram from a Polish topographic map of the Tatra Mountains published by Wojskowy Instytut Geograficzny (Military Geographical Institute) in 1937 (WIG, 1937). Only source data used to compile this map and date is given. Unfortunately, it can only be assumed that all the source maps were of the same kind (topographic) and of a good standard, as this important information is not given.

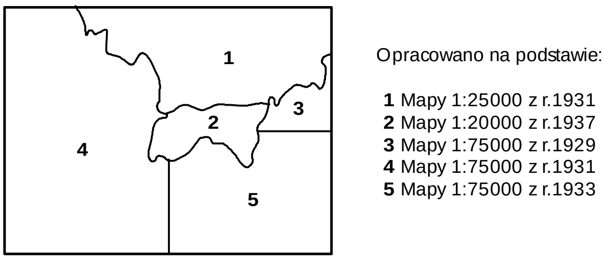

Figure 1. A reliability diagram showing data sources and dates. Source: WIG, 1937.

The New Zealand topographical map contains a reliability diagram that shows the "mapping methods" used to draw this map (NZ Lands and Survey, 1973). Survey procedures, data sources and dates are shown (Fig 2), giving a good understanding of the overall reliability of this map. However some terms, such as "Existing Survey Records" are ambiguous, and do not specify what these records are.

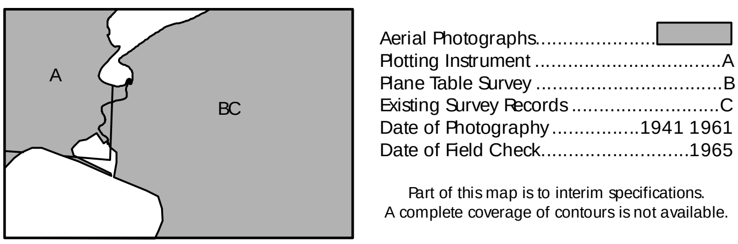

Figure 2. A reliability diagram showing survey procedures, data sources and dates. Source: NZ Lands and Survey, 1973.

Another example of a reliability diagram is included in the New Zealand Geological Survey Miscellaneous Series Map, where the entire map is divided into "responsibility sectors" for different geologists and researchers that undertook their field inspections in this area (Bishop *et al.*, 1990). This method however, does not convey the map reliability information directly to the reader, it is rather aimed at a narrow group of experts with extensive knowledge in the discipline.

A reliability diagram added to the margin of LHQ (Australia) Cartographic Company map of New Guinea is an example, where reliability information about an entire map is presented directly and in a manner, that is understandable even for novice users (Kraak *et al*., 1995; van der Wel *et al*., 1994). The map is divided into five levels of accuracy, where each class is complemented with a textual description of the accuracy:

- Accurate: for shape and position, some doubt regarding village position
- Reliable: from oil company traverses and German map
- Fairly reliable: from plans of doubtful accuracy
- Unreliable: from many conflicting plans of doubtful accuracy
- Very sketchy: from sketch plans

It is worthwhile to note, that the highest accuracy level represented on this map would not meet any accuracy standard for modern topographical maps.

All of the above examples of reliability diagrams are concerned with the positional accuracy of data. McGranaghan (1993) gives an example of complex reliability diagrams where lineage and attribute accuracy are also shown. It is an interesting approach to deal with the representation of accuracy measures, where double or multiple diagrams are used to convey uncertainty. An interesting extension of this idea is presented by Goodchild *et al*. (1994b) where multiple displays are introduced to visualise the original data and a number of fuzzy classification displays indicating membership probabilities at the same time.

Labelling and Symbolisation

Uncertainty associated with map features (point, line, area) could also be expressed by the use of labels. An example of nominal distinction between features is shown on early 1940's maps of the American Geographical Society, where P.D. (positional doubtful) and E.D. (existence doubtful) labels were used (Hunter and Goodchild, 1996; McGranaghan, 1993). A numerical value to convey reliability of point symbols could also be employed (McGranaghan, 1993).

In representing positional accuracy of map features, the variation in feature character is frequently used. The Topographical Map of New South Wales could be an example, where horizontal control points are shown in three categories: landmark, approximate and other (Fig 3)(Central Mapping Authority of NSW, 1982). On the same map, variation in line character indicates uncertainty in depiction of contour lines, where a dashed line is utilised to represent approximate contours. Similarly, in the area feature category, lakes are shown as perennial, intermittent or dry, which convey some degree of uncertainty in the positional representation of lakes on the map.

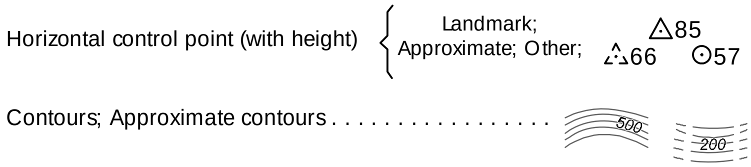

Figure 3. Symbolisation of reliability on a topographical map. Source: Central Mapping Authority of NSW, 1982.

This approach has a long tradition on geological maps to convey uncertain information associated with positional accuracy of rock faults and contacts. The New Zealand Geological Survey Miscellaneous Series Map (Fig 4), shows geological contacts and faults by four categories of line each representing different levels of accuracy (Bishop *et al*., 1990).

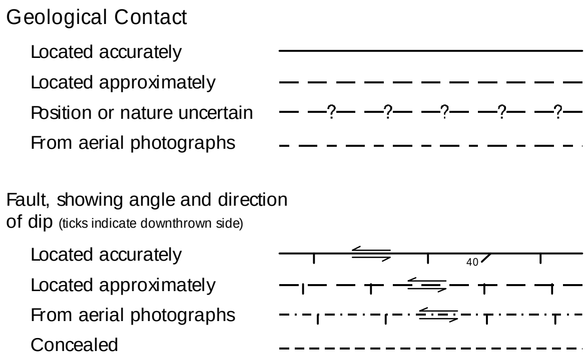

Figure 4. Representation of uncertainty of geological contacts and faults by different line symbols. Source: Bishop *et al*., 1990.

Other Methods

There is a range of other methods to visualise positional accuracy of map features. Accuracy at points could be represented either by circles or ellipses that vary in shape and/or size, or by vectors, where information about the direction of distortion forces could be illustrated (McGranaghan, 1993; van der Wel *et al*., 1994). In the case of circles and/or ellipses a value could also be employed to depict an ordinal or interval dimension of uncertainty.

The concept of utilising ellipses to show scale and conformity anomalies was formulated by Tissot. He introduced a graphic device called the *indicatrix* (error ellipse), to show areal and angular distortions that occur during transformation at various points on the map (Robinson *et al*., 1984; Salichtchev, 1984). Change in size and/or shape of the error ellipse, eg. during map projection transform, illustrates the magnitude of angular and/or areal distortion at a point as a consequence of this transformation (Fig 5).

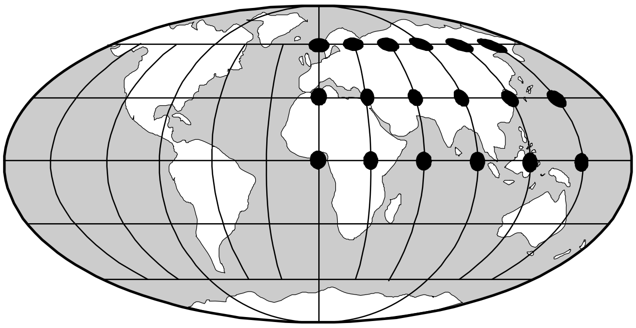

Figure 5. Example of Tissot's *indicatrix* used here to show the areal and angular distortion of the Mollweide projection.

The use of a grid is a similar approach to that of Tissot's *indicatrix*, but instead of an error ellipse it employs a grid to show positional error of map features. This technique is particularly useful in analysing projections of old maps (van der Wel *et al*., 1994).

Another method frequently used to convey uncertainty associated with positional accuracy is an isogram. It illustrates either maximum angular distortion, or maximum areal distortion at a point (Robinson *et al*., 1984; Salichtchev, 1984; van der Wel *et al*., 1994). An isogram is constructed by interpolating lines between points of equal distortion (isolines). Figure 6 shows the distribution of scale error for New Zealand topographical map series at a scale of 1:50 000 in New Zealand Map Grid (NZMG) projection (NZ Lands and Survey, 1986).

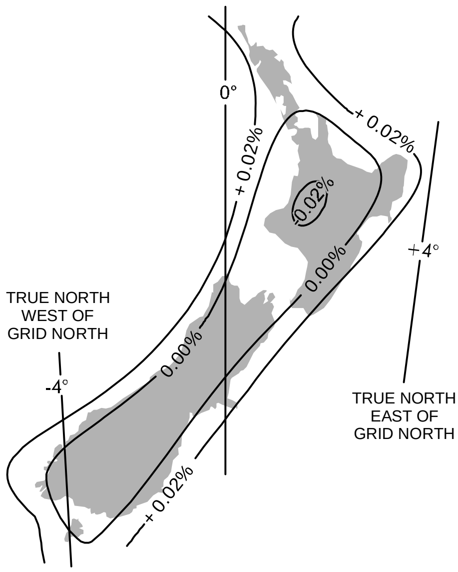

Figure 6. Scale error and convergence for the New Zealand Grid Projection. Source: NZ Lands and Survey, 1986.

Although the above pre-digital techniques provide a valuable tool in data quality assessment they also have a number of limitations. They tend to communicate uncertainty globally rather than locally and require a high level of skill and extensive knowledge (expert) from the map reader (Hunter and Goodchild, 1996). They focus on positional accuracy measures, while other components of data quality are often ignored, with the exception of lineage and currency. They also generally show discrete rather than continuous distribution of uncertainty where, for example, areas of a different level of reliability are represented by sharp boundaries (most of the reliability diagrams).

In effect, these traditional methods of representing uncertainty serve as a warning to attract the attention of the map reader to the possible variations from the "normal" situation (Hunter and Goodchild, 1996). This warning however is no longer sufficient especially in a digital environment, where immediate and more accurate estimates of uncertainty present in spatial databases are required. Therefore, new techniques had to be developed to meet these requirements.

Recent Cartographic Solutions in Representing Uncertainty

One of the important issues concerned with representation of uncertainty is the selection of appropriate characteristics for effective data displays. Currently there is a variety of graphics and computational hardware and software systems available that provide a vast selection of graphic solutions with different degrees of sophistication. However little is done to ensure the correct use of these solutions (DiBiase *et al*., 1992; Weibel and Buttenfield, 1992).

Visual Variables

A systematic approach to graphic symbolisation in cartography was first proposed by Bertin in his *Semiology of Graphics* (first published in French in 1967). Bertin (1983) identified seven primary visual variables. The original list includes *location* (*x* and *y* coordinate of the plane), *size*, (colour) *value, texture,* (colour) *hue, orientation* and *shape*. Supplementary variables such as (colour) *saturation, focus, opacity* or *arrangement* have been identified (DiBiase *et al*., 1992; Drecki, 2002; MacEachren, 1994; McGranaghan, 1993; van der Wel *et al*., 1994). Almost all of the above visual variables have been proposed as valid means to represent uncertainty, but only few were actually developed and even less evaluated.

The latter group include *size* (Drecki, 2002), *value* (Djurcilov *et al.,* 2002), *texture* (defined by the authors as *visual vibrations*) (Djurcilov *et al.,* 2002; Brown, 2004), *hue* (Djurcilov *et al.,* 2002; Drecki and Maciejewska, 2005), *orientation* (Pang, 2001), *saturation* (Buttenfield and Beard, 1994; Drecki, 1997, 2002; Evans, 1997), *focus* (also referred to as *texture, noise* or *speckles*) (Botchen *et al.,* 2005; Djurcilov *et al.,* 2002; Gershon, 1992), *opacity* (also referred to as *transparency*) (Cliburn *et al*., 2002;

Djurcilov *et al.,* 2002; Drecki, 1997, 2002) and *arrangement* (Djurcilov *et al.,* 2002; Kardos *et al.,* 2008).

Other authors mentioned such "variables" as *realism* (Gershon, 1998), *resolution* or *abstraction* (Ehlschlaeger, 1999; Goodchild *et al.,* 1994; MacEachren, 1994; McGranaghan, 1993; Trau and Hurni, 2007), *labelling* (Griethe and Schumann, 2005, 2006; McGranaghan, 1993) and *time* (McGranaghan, 1993). However, none of them have actually been developed or evaluated.

Static Representations

Apart from visual variables, many authors proposed or developed specific visual techniques to represent uncertainty associated with a particular scenario. They can broadly be classified as static or dynamic. The static techniques include *colour transformation, blending, 3D reliability surface, dazzling, complex symbols, shading, tessellation, multiple positions, squares, double displays, multiple displays* and *glyphs*. Again, many of these tools have been proposed, but only few were developed and even less evaluated.

The latter group include *3D reliability surface* (also referred to as *uncertainty surface*) (Davis and Keller, 1997; Drecki, 1997; Ehlschlaeger *et al.,* 1997; Rejeski, 1993), squares (Drecki, 1997, 2002), *double displays* (also referred to as *static comparison*) (Aerts *et al.,* 2003; Gooch and Chandler, 1999), *multiple displays* (Gibb *et al.,* 1999) and *glyphs* (Cliburn *et al.*, 2002)

Dynamic Representations

Dynamic representations of uncertainty are particularly useful in exploratory analysis of data. They play an important role in assessing data suitability for a particular use or application. Therefore, the dynamic representations received plenty of attention, especially in the last decade. The dynamic techniques include *animation, quality slider, hypermedia, squares, blinking, zooming, moving, fading, toggling, dynamic colour transformation* and *glyphs*.

The dynamic representations that were developed and some evaluated include *animation* (Davis and Keller, 1997; Ehlschlaeger *et al.,* 1997; Fisher, 1993; Gershon, 1992), *quality slider* (Drecki, 1997; MacEachren *et al.,* 1993), *interactive squares* (Drecki, 1997, 2002), *blinking* (Fisher, 1993, 1994a, 1994b, 1996; Drecki, 1997; Evans, 1997), *moving* (Fisher, 1996), *fading* (also referred to as *whitening*) (Hengl and Toomanian, 2006), *toggling* (Gershon, 1992) and *dynamic colour transformation* (Cliburn *et al.*, 2002).

Non-visual Representations

In context of data uncertainty, abstract sounds could be a valuable addition to visual methods (Fisher, 1994a; Krygier, 1994). An invisible "sound map" can provide uncertainty information without interfering with already busy visual display. In that way the crispness of original data can be maintained and uncertainty information can be accessed when desired. Click of the mouse at any point of a "sound map" would make a specific sound guided by its reliability, while dragging the cursor across would reveal a variety of sounds according to the variability of data uncerainty. However, sound is point specific which means that it reveals information only at particular position on a "sound map" where the cursor is pointing at. Consequently it is very difficult to develop a sound "image" that would provide a spatial representation of error distribution (Krygier, 1994). Therefore, abstract sound can be very useful in enhancing the visual techniques, but not alone.

Current State of Affairs in Cartographic Representations of Uncertainty

In this preliminary study, so far 40 papers on representing geographical information uncertainty have been examined. They come from two research domains, i.e. Geographic Information Science (GISci) and Information Visualisation (InfoViz). These papers have been published between 1991 and 2008 and form about 20% of all papers identified for this research.

It is interesting to note that the terminology describing either visual variables or specific visual techniques is not consistent. For example, visual variable of *focus* has at least three other names in GISci (*fuzziness, blurring* or *fog*) and further three in InfoViz (*texture, noise* and *speckles*), while *orientation* in GISci is often called *angle* in InfoViz. Similarly, the static representation of *multiple positions* is also called *layering*, while among dynamic representations, *blinking* has further four equivalent names, i.e. *twinkling, flickering, sequence* and *flashing*.

Among the representations involving visual variables, two that have been employed by the most authors were *saturation* (Buttenfield and Beard, 1994; Drecki, 1997, 2002; Evans, 1997) and *opacity* (Cliburn *et al.*, 2002; Djurcilov *et al.*, 2002; Drecki, 1997, 2002). Both representations have also been evaluated twice. *Focus* has also been used by three authors, all from InfoViz community (Botchen, 2005; Djurcilov *et al.*, 2002; Gershon, 1992), but no evaluation has been reported.

Djurcilov *et al.* (2002) developed six representations of uncertainty involving visual variables (*value, hue, texture, opacity, arrangement* and *focus*), but none of them have been evaluated. Drecki (1997, 2002) developed and evaluated two representations involving *colour saturation* and *opacity*. Cliburn *et al.* (2002) and Evans (1997) developed and evaluated representations based on *opacity* and *colour saturation* respectively.

Among static representations, *3D reliability surface* has been developed by three authors (Davis and Keller, 1997; Drecki, 1997; Ehlschlaeger *et al.,* 1997), but evaluated only once. *Double displays* technique also received attention by being developed by Aerts *et al.* (2003) and Gooch and Chandler (1999) and thoroughly evaluated by the former researchers. *Squares* (Drecki, 1997, 2002) and *multiple displays* (Gibb *et al.*, 1999) have also been developed and the former technique evaluated.

Drecki (1997) developed and evaluated two static representations of uncertainty, i.e. *3D reliability surface* and *squares*, while Aerts *et al.* (2003) evaluated *double display* technique.

Examining forty papers it seems that dynamic representations of uncertainty received the most attention. Clearly the *blinking* technique has been developed by most researchers (Drecki, 1997; Evans, 1997; Fisher, 1993, 1994a, 1994b, 1996). It is also a method that was evaluated the most (Drecki, 1997; Evans, 1997). Animation has been developed by three authors (Davis and Keller, 1997; Elschlaeger *et al.*, 1997; Gershon, 1992), while interactive squares, moving, quality slider, fading, toggling and dynamic colour transformation were developed once by Drecki (1997, 2002), Fisher (1996), MacEachren *et al.* (1993), Hengl and Toomanian (2006), Gershon (1992) and Cliburn *et al.* (2002) respectively.

The visual variables and several static and dynamic techniques provide a wide range of potential solutions to represent geographic information uncertainty. It seems that only small percentage of these solutions has been developed and even less empirically evaluated. Some evaluated techniques present contradictory results, such as positive report on the use of *saturation* in Evans (1997) and rather poor performance in Drecki (1997).

Little is still known how to relate these variables and techniques to the nature and sources of geographic information uncertainty (Drecki, 2007; MacEachren *et al.,* 2005). The research in finding taxonomy for graphical representation uncertainty is still progressing. Ideally, a link between types of uncertainty and ther graphic representation can be established.

Conclusions

This research looks at the cartographic heritage in representing geographic information uncertainty and briefly highlights more recent developments in this area. Forty papers (out of about 200 identified) have been processed from the perspective of assessing the development and evaluation of uncertainty representations. So far only a few variables and techniques have been developed and even less evaluated. This is unsatisfactory situation with regards to furthering our efforts in developing guidelines for representing uncertainty graphically.

The next step is to complete processing of all relevant papers and synthesise the outcomes. This will hopefully provides insights into gaps and niches in current approaches and methodologies. This might also lead to developing a relationship between nature and sources of geographic information uncertainty and its representation. Cartography will no doubt play an important role in these developments.

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