Proceedings XIII GEOINFO, November 25-27, 2012, Campos do Jordão, Brazil. p 11-22.

A Conceptual Analysis of Resolution

Auriol Degbelo and Werner Kuhn

Institute for Geoinformatics – University of Muenster
Weseler Strasse 253, 48151, Muenster, Germany
{degbelo, kuhn}@uni-muenster.de

Abstract. *The literature in geographic information science and related fields contains a variety of definitions and understandings for the term resolution. The goal of this paper is to discuss them and to provide a framework that makes at least some of these different senses compatible. The ultimate goal of our work is an ontological account of resolution. In a first stage, resolution and related notions are examined along the phenomenon, sampling and analysis dimensions. In a second stage, it is suggested that a basic distinction should be drawn between definitions of resolution, proxy measures for resolution, and notions related to resolution but different from it. It is illustrated how this distinction helps to reconcile several notions of resolution in the literature.*

1. Introduction

Resolution is arguably one of the defining characteristics of geographic information (Kuhn 2011) and the need to integrate information across different levels of resolution pervades almost all its application domains. While there is a broader notion of granularity to be considered, for example regarding granularity levels of analyses, we focus here on resolution considered as a property of observations. We further limit our scope to spatial and temporal aspects of resolution, leaving thematic resolution and the dependencies between these dimensions to future work.

Currently, there is no formal theory of resolution of observations underlying geographic information. Such a theory is needed to explain how, for example, the spatial and temporal resolution of a measurement affects data quality and can be accounted for in data integration tasks. The main practical use for a theory of resolution, therefore, lies in its enabling of information integration across different levels of resolution. Specifically, the theory should suggest and inform methods for generalizing, specializing, interpolating, and extrapolating observation data. Turning the theory into an ontology will allow for automated reasoning about resolution in such integration (as well as in retrieval) tasks.

The literature in GIScience has not reached a consensus on what resolution is. Here are some extracts from previous work, each touching upon a definition of resolution:

- "Resolution: the smallest spacing between two displayed or processed elements; the smallest size of the feature that can be mapped or sampled" (Burrough & McDonnell, 1998, p305).

- "Resolution refers to the amount of detail in a representation, while granularity refers to the cognitive aspects involved in selection of features" (Hornsby cited in (Fonseca et al. 2002)).
- "Resolution or granularity is concerned with the level of discernibility between elements of a phenomenon that is being represented by the dataset" (Stell & Worboys 1998).
- "Resolution: smallest change in a quantity being measured that causes a perceptible change in the corresponding indication" (The ontology of the W3C Semantic Sensor Network Incubator Group)[1].
- "The capability of making distinguishable the individual parts of an object" (a dictionary definition cited in (Tobler 1987)).
- "Resolution refers to the smallest distinguishable parts in an object or a sequence, ... and is often determined by the capability of the instrument or the sampling interval used in a study" (Lam & Quattrochi 1992).
- "The detail with which a map depicts the location and shape of geographic features" (a dictionary definition of ESRI[2]).
- "*Resolution* is an assertion or a measure of the level of detail or the information content of an object database with respect to some reference frame" (Skogan 2001).

This list exemplifies a variety of definitions for the term 'resolution' and shows that some of them are conflicting (e.g. the 2nd and 3rd definition in the list). The remark that "[r]esolution seems intuitively obvious, but its technical definition and precise application ... have been complex" made by Robinson et al. (2002) in the context of remote sensing is pertinent for GIScience as a whole. Section 2 analyzes some notions closely related to resolution and arranges them based on the framework suggested in (Dungan et al. 2002). Section 3 suggests that resolution should be defined as the amount of detail of a representation and proposes two types of proxy measures for resolution: smallest unit over which homogeneity is assumed and dispersion. Section 4 concludes the paper and outlines future work.

2. Resolution and related notions

In a discussion of terms related to 'scale' in the field of ecology, Dungan et al. (2002) suggested three categories (or dimensions) to which spatial scale-related terms may be applied. The three dimensions are: (a) the phenomenon dimension, (b) the sampling dimension, and (c) the analysis dimension. The *phenomenon dimension* relates to the (spatial or temporal) unit at which a particular phenomenon operates; the *sampling dimension (or observation dimension or measurement dimension)* relates to the (spatial or temporal) units used to acquire data about the phenomenon; the *analysis dimension* relates to the (spatial or temporal) units at which the data collected about a phenomenon

---

[1] See a presentation of the ontology for sensors and observations developed by the group in (Compton et al. 2012). The ontology is available at http://purl.oclc.org/NET/ssnx/ssn (last accessed: July 20, 2012).

[2] See http://support.esri.com/en/knowledgebase/GISDictionary/search (last accessed: July, 20, 2012).

are summarized and used to make inferences. For example, if one would like to study the change of the temperature over an area A, the phenomenon of interest would be 'change of temperature'. Data can be collected about the value of the temperature at A, say every hour; one hour relates to the sampling dimension. The data collected is then aggregated to daily values and analysis or inferences are performed on the aggregated values; this refers to the analysis dimension. This paper will reuse the three dimensions introduced in the current paragraph to frame the discussion on resolution and related notions. Although the roots of the three dimensions are in the field of ecology, they can be reused for the purposes of the paper because GIScience and ecology overlap in many respects. For instance:

- issues revolving around the concept of 'scale' have been identified as deserving prime attention for research by both communities (see for example (UCGIS 1996) for GIScience, and (Wu & Hobbs 2002), for ecology);
- both communities are interested in a 'science of scale' (see for example (Goodchild & Quattrochi 1997) for GIScience, (Wu & Hobbs 2002), for ecology);
- there exists overlaps in objects of studies (witness for example the research field of 'landscape ecology' introduced in (Wu 2006; Wu 2008; Wu 2012), and the research field of 'ethnophysiography' presented in (Mark et al. 2007));
- there are overlaps in underlying principles (Wu (2012) mentions for example that "[s]patial heterogeneity is ubiquitous in all ecological systems" and Goodchild (2011a) proposed spatial heterogeneity as one of the empirical principles that are broadly true of all geographic information).

One notion related to 'resolution' is 'scale'. Scale can have many meanings, as discussed for example in (Förstner 2003; Goodchild 2001; Goodchild 2011b; Goodchild & Proctor 1997; Lam & Quattrochi 1992; Montello 2001; Quattrochi 1993). Like in (Dungan et al. 2002), we consider resolution to be *one of many components of scale*, with other components being extent, grain, lag, support and cartographic ratio. Dungan et al. (2002) have discussed the matching up of resolution, grain, lag and support with the three dimensions of phenomenon, sampling and analysis. The next paragraph will briefly summarize their discussion. It will touch upon four notions, namely grain, spacing, resolution and support. After that, another paragraph will introduce discrimination, coverage, precision, accuracy, and pixel.

According to Dungan et al. (2002), grain is a term that can be defined for the phenomenon, sampling and analysis dimensions. Sampling grain refers to the minimum spatial or temporal unit over which homogeneity is assumed for a sample[3]. Another term that applies to the three dimensions according to Dungan et al. (2002) is the term lag or spacing[4]. Sample spacing denotes the distance between neighboring samples. Resolution was presented in (Dungan et al. 2002) as a term which applies to sampling

[3] The definition is in line with (Wu & Li 2006). Grain as used in the remainder of this paper refers to sampling (or measurement or observation) grain.

[4] The use of the term spacing is preferred in this paper over the use of the term lag. Spacing as used in the remainder of the paper refers to sampling (or measurement or observation) spacing.

and analysis rather than to phenomena. Finally it was argued in (Dungan et al. 2002) that support is a term that belongs to the analysis dimension. Although Dungan et al. (2002) limit support to the analysis dimension, this paper argues that it applies to the sampling or measurement dimension as well. This is in line with (Burrough & McDonnell 1998, p101) who defined support as "the technical name used in geostatistics for the area or volume of the physical sample on which the measurement is made". The matching up of resolution, grain, spacing and support with the phenomenon, sampling and analysis dimensions is summarized in figure 1.

Lam & Quattrochi (1992) claim that "[r]esolution refers to the smallest distinguishable parts in an object or a sequence, ... and is often determined by the capability of the instrument or the sampling interval used in a study". This definition points to two correlates of resolution. One of them relates to the sampling interval and was already covered in the previous paragraph under the term spacing; the second relates to the capability of the instrument, and is called here (after Sydenham (1999)) *discrimination*. The term discrimination is borrowed from the *Measurement, Instrumentation, and Sensors Handbook* and refers to the smallest change in a quantity being measured that causes a perceptible change in the corresponding observation value[5]. A synonym for discrimination is *step size* (see (Burrough & McDonnell 1998, p57)). Discrimination is a property of the sensor (or measuring device) and therefore belongs to the sampling dimension.

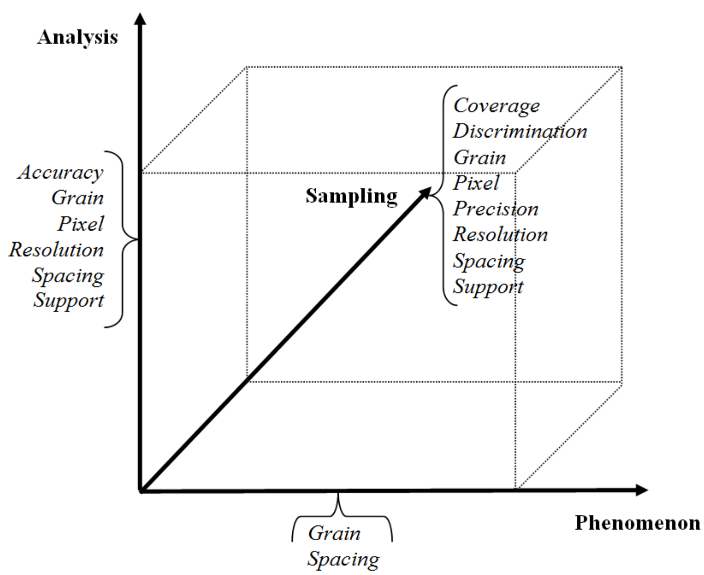

Figure 1. Resolution and related notions matched up with the phenomenon, sampling and analysis dimensions. The fact that some terms belong to several dimensions suggests that they need further disambiguation when used and this disambiguation takes place when the dimension which is referred to is made explicit (e.g. sampling grain or phenomenon grain instead of 'grain' alone).

[5] The definition is adapted and extended from (JCGM/WG 2 2008) and (Sydenham 1999).

Besides the discrimination of a sensor, coverage is another correlate of resolution. Coverage is defined after Wu & Li (2006) as the sampling intensity in space or time. For that reason, coverage is a term that applies to the sampling dimension of the framework (see figure 1). Synonyms for coverage are sampling density, sampling frequency or sampling rate. Figure 2 illustrates the difference between sampling grain, sampling coverage and sampling spacing for the spatial dimension.

Precision is defined after JCGM/WG 2 (2008) as the "closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions". Precision belongs therefore to the sampling (or observation) dimension of the framework. On the contrary, accuracy, the "closeness of agreement between a measured quantity value and a true quantity value of a measurand" (JCGM/WG 2 2008) is a concept which belongs to the analysis dimension. In order to assign an accuracy value to a measurement, one needs not only a measurement value, but also the specification of a reference value. Because the specification of the reference value is likely to vary from task to task (or user to user), it is suggested here that accuracy is classified as a concept belonging to the analysis level. The last correlate of resolution introduced in this section is the notion of pixel. The pixel is the "smallest unit of information in a grid cell map or scanner image" (Burrough & McDonnell 1998, p304). It is also, as indicated by Fisher (1997), the elementary unit of analysis in remote sensing. As a result, pixel belongs to both the sampling and the analysis dimension.

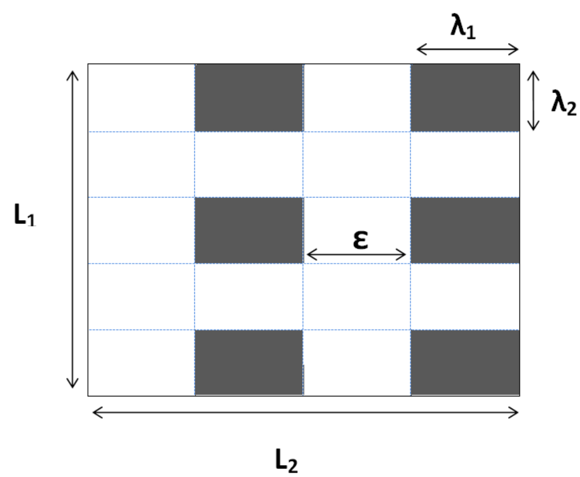

Figure 2. Illustration of grain, spacing and coverage for the spatial dimension (figure taken from (Degbelo & Stasch 2011)**). The extent is $E = L_1 * L_2$, the grain size is $G = \lambda_1 * \lambda_2$, the spacing is $S = \varepsilon$ and the coverage is C = Number of samples * grain size/extent = $6*(\lambda_1 * \lambda_2) / (L_1*L_2) = 3/10$.**

3. Proxy measures for resolution

The previous section has discussed various notions related to resolution and shown how these notions can be distinguished according to the framework suggested in (Dungan et al. 2002). This section proposes a complementary framework that can be used to link resolution and some of its related notions. The framework suggested in (Dungan et al. 2002) is valuable in the sense that it suggests care should be taken when using terms belonging to several dimensions as synonyms. Wu & Li (2006) mention, for example, that in most cases, grain and support have quite similar meanings, and thus have often been used interchangeably in the literature. Such a use is fine in some cases because, at the analysis or sampling level, the distinction between the two terms becomes blurred. On the contrary, the use of phenomenon grain and support as synonyms might not always be appropriate, since phenomenon grain might differ from analysis or sampling grain (= support).

3.1. A unifying framework for resolution and related notions

The framework suggested in this subsection aims at providing a basis to make compatible different views on (or definitions of) resolution in the literature. The framework has three dimensions: definitions of resolution, proxy measures for resolution and closely related notions to resolution. *Definitions of resolution* refer to possible ways of defining the term. *Proxy measures for resolution*[6] denote different measures that can be used to characterize resolution. It is the contention of the current paper that several proxy measures of resolution exist and the choice of the appropriate measure depends on the task at hand[7]. This argument generalizes what Forshaw et al. (1983), after a review of different ways of describing spatial resolution in the field of remote sensing, concluded:

> "No single-figure measure of spatial resolution can sensibly or equitably be used to assess the general value of remotely sensed imagery or even its value in any specific field".

Based on the analysis performed in (Frank 2009), we suggest two types of proxy measures for resolution. The data collection (or observation) process was analyzed in (Frank 2009) and it was shown that resolution is introduced in this process due to three factors: (a) a sensor always measures over an extend area and time, (b) only a finite number of samples is possible, and (c) only values from a range can be used to represent the observation. Two[8] types of proxy measures can be isolated from this: (i) proxy measures related to the limitations of the sensing device and (ii) proxy measures related to the limitations of the sampling strategy. The former type of proxy measures is concerned with the minimum unit over which homogeneity is assumed for a sample, the latter deals essentially with the dispersion of the different samples used during a data collection process. Finally, the last dimension of the framework suggested in this subsection, *closely related notions to resolution*, refers to notions closely related to resolution, but in fact different from it.

[6] A short introduction to proxy measurement can be found at (Blugh 2012).

[7] Proxy measures of resolution are also expected to vary from era to era. Goodchild (2004) points out that metrics of spatial resolution are strongly affected by the analog to digital transition.

[8] It is straightforward to see that factor (a) relates to (i) and factor (b) relates to (ii). Factor (c) relates also to (i) and is called the dynamic range of the sensor (see (Frank 2009)).

3.2. Using the framework suggested

Different authors have used different terms as synonyms for resolution in the literature. Resolution has been used as synonym for amount of detail in (Fonseca et al. 2002; Veregin 1998), level of detail in (Goodchild 2001; Goodchild & Proctor 1997; Skogan 2001), degree of detail in (Goodchild 2011b), precision in (Veregin 1999; Veregin 1998), grain in (Reitsma & Bittner 2003; Pontius Jr & Cheuk 2006), granularity in (Stell & Worboys 1998; Worboys 1998), step size in (Burrough & McDonnell 1998, p57) and scale in (Burrough & McDonnell 1998, p40) and (Frank 2009). This list of 'synonyms' for resolution will be used as input in the next paragraph to illustrate the usefulness of the framework suggested in the previous subsection.

To the *definitions of resolution* belong "amount of detail of a representation", "degree of detail" and "level of detail" of a representation. Step size and grain can be seen as *proxy measures for resolution*, concerned with the minimum unit over which homogeneity is assumed. Precision however is a *proxy measure for resolution*, related to the dispersion of replicate measurements on the same object. Additional examples of proxy measures for resolution are the size of the minimum mapping unit[9], the instantaneous field of view of a satellite, the mean spacing and the coverage. Granularity, accuracy and scale are *closely related terms to resolution.* Stating that 'scale' is a closely related term to 'resolution' is in line with Dungan et al. (2002) and Wu & Li (2006) who argued that resolution is one of many components of scale. Resolution is also different from accuracy. The former is concerned with how much detail there exists in a representation. The latter relates to the closeness of a representation to the 'truth' (i.e. a perfect representation), and since there is no perfect representation, accuracy deals in fact with how good a representation approximates a referent value. Veregin (1999) points out that one would generally expect accuracy and resolution to be inversely related.

In line with Hornsby, cited in (Fonseca et al. 2002), this paper considers resolution and granularity to be two different notions. If both notions deal with amount of detail in some sense, they are different because granularity is a property of a conceptualization and resolution is a property of a representation. The following remark on granularity was made in the field of Artificial Intelligence:

> "Our ability to conceptualize the world at different granularities and to switch among these granularities is fundamental to our intelligence and flexibility".
> (Hobbs 1985)

Thus, in GIScience, granularity should be used while referring to the amount of detail in a conceptualization (e.g. field- or object-based) or a conceptual model (e.g. an ontology) whereas resolution should be used to denote the amount of detail of digital representations (e.g. raster or vector data). An objection can be raised against the definition of resolution as a property of data and not of sensors. However, such a restriction is suggested in this paper because of the following comment from the *Measurement, Instrumentation, and Sensors Handbook:*

[9] "The 'minimum mapping unit' defines the smallest polygon the cartographer is willing to map (smaller polygons are forcibly merged with a neighbor)" (Goodchild & Quattrochi 1997).

> "Although now officially declared as wrong to use, the term *resolution* still finds its way into books and reports as meaning discrimination" (Sydenham 1999).

In a nutshell: resolution applies to data, discrimination to sensors[10], and granularity to a conceptual model. The framework suggested as well as the different examples introduced in this section are summarized in figure 3.

4. Conclusion

As Kuhn (2011) pointed out: "An effort at the conceptual level is needed [in GIScience], in order to present a coherent and intelligible view of spatial information to those who may not want to dive into the intricacies of standards and data structures". This paper has attempted to fulfill this desideratum, focusing on resolution.

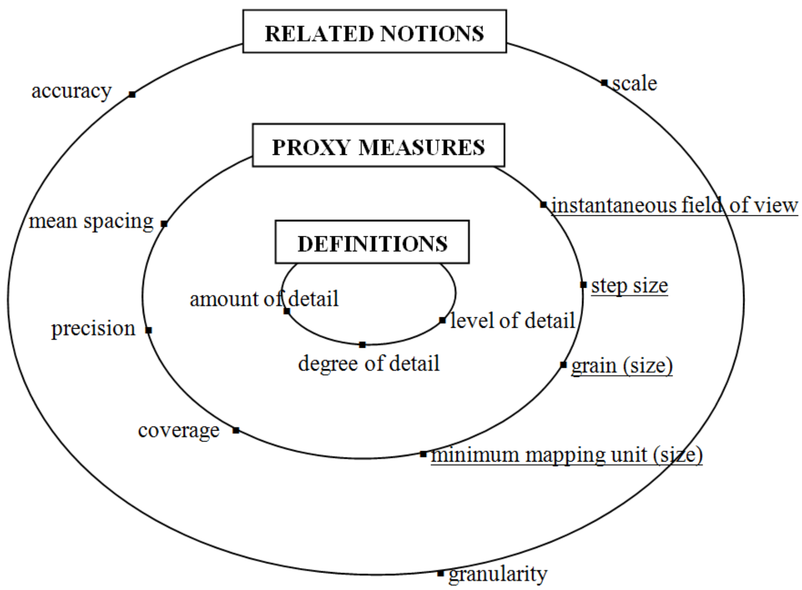

Figure 3. Possible definitions of, proxy measures for and notions related to resolution. Proxy measures dealing with the minimum unit over which homogeneity is assumed are underlined. Proxy measures not underlined characterize the dispersion of the samples used during a data collection process.

The three dimensions proposed in (Dungan et al. 2002), namely the phenomenon, sampling and analysis dimensions, were used to relate resolution and similar notions such as grain, spacing, coverage, support, pixel, accuracy, precision and discrimination. Resolution has been identified as a term that applies to the sampling and analysis dimensions rather than to phenomena. The paper suggests that resolution can be defined as the amount of detail (or level of detail or degree of detail) of a representation. It was

[10] The interplay between the resolution of a data (say an image) and the discrimination of the sensor (e.g. satellite which has produced this image) is not further investigated here.

also argued that two types of proxy measures for resolution should be distinguished: those which deal with the minimum unit over which homogeneity is assumed for a sample (e.g. grain or minimum mapping unit), and those which revolve around the dispersion of the samples used during the data collection process (e.g. spacing and coverage). Finally, the paper pointed to notions related to resolution but different from it (e.g. scale, granularity and accuracy). The second author, in his work on core concepts of spatial information, has meanwhile chosen granularity as the core concept covering spatial information, with resolution being the more specialized aspect referring to data (Kuhn 2012). The paper intentionally does not choose a particular definition of resolution, nor does it add a new one to the literature. Instead, the distinction between definitions of, proxy measures for, and notions related to resolution aims at making several perspectives on the term compatible.

The next step of this work will be a formalized ontology of this account of resolution. Such an ontology will extend previous ontologies of observations and measurements (e.g. (Janowicz & Compton 2010; Kuhn 2009; Compton 2011; Compton et al. 2012)) presented and applied in the context of the Semantic Sensor Web.

Acknowledgements

Funding from the German Academic Exchange Service (DAAD A/10/98506), the European Commission through the ENVISION Project (FP7-249170), and the International Research Training Group on Semantic Integration of Geospatial Information (DFG GRK 1498) is gratefully acknowledged. Discussions with Kathleen Stewart helped in the process of clarifying the distinction between granularity and resolution.

References

Blugh, A. (2012) Definition of proxy measures (http://www.ehow.com/facts_7621616_definition-proxy-measures.html; Last accessed July 31, 2012).

Burrough, P.A. & McDonnell, R.A. (1998) *Principles of geographical information systems*, New York, New York, USA: Oxford University Press.

Compton, M. (2011) What now and where next for the W3C Semantic Sensor Networks Incubator Group sensor ontology. In K. Taylor, A. Ayyagari, & D. De Roure, eds. *The 4th international workshop on Semantic Sensor Networks*. Bonn, Germany: CEUR-WS.org, pp.1–8.

Compton, M., Barnaghi, P., Bermudez, L., García-Castro, R., Corcho, O., Cox, S., Graybeal, J., Hauswirth, M., Henson, C., Herzog, A., Huang, V., Janowicz, K., Kelsey, W.D., Phuoc, D. Le, Lefort, L., Leggieri, M., Neuhaus, H., Nikolov, A., Page, K., Passant, A., Sheth, A. & Taylor, K. (2012) The SSN ontology of the W3C semantic sensor network incubator group. *Web Semantics: Science, Services and Agents on the World Wide Web*.

Degbelo, A. & Stasch, C. (2011) Level of detail of observations in space and time. In *Poster Session at Conference on Spatial Information Theory: COSIT'11*. Belfast, Maine, USA.

Dungan, J.L., Perry, J.N., Dale, M.R.T., Legendre, P., Citron-Pousty, S., Fortin, M.J., Jakomulska, A., Miriti, M. & Rosenberg, M.S. (2002) A balanced view of scale in spatial statistical analysis. *Ecography*, p.pp.626–640.

Fisher, P. (1997) The pixel: a snare and a delusion. *International Journal of Remote Sensing*, 18 (3), p.pp.679–685.

Fonseca, F., Egenhofer, M., Davis, C. & Câmara, G. (2002) Semantic granularity in ontology-driven geographic information systems. *Annals of Mathematics and Artificial Intelligence*, 36 (1), p.pp.121–151.

Forshaw, M.R.B., Haskell, A., Miller, P.F., Stanley, D.J. & Townshend, J.R.G. (1983) Spatial resolution of remotely sensed imagery A review paper. *International Journal of Remote Sensing*, 4 (3), p.pp.497–520.

Frank, A. (2009) Why is scale an effective descriptor for data quality? The physical and ontological rationale for imprecision and level of detail. In W. Cartwright, G. Gartner, L. Meng, & M. P. Peterson, eds. *Research Trends in Geographic Information Science*. Springer Berlin Heidelberg, pp.39–61.

Förstner, W. (2003) Notions of scale in geosciences. In H. Neugebauer & C. Simmer, eds. *Dynamics of Multiscale Earth Systems*. Springer Berlin Heidelberg, pp.17–39.

Goodchild, M. & Quattrochi, D. (1997) Introduction: scale, multiscaling, remote sensing, and GIS. In D. Quattrochi & M. Goodchild, eds. *Scale in remote sensing and GIS*. Boca Raton: Lewis Publishers, pp.1–11.

Goodchild, M.F. (2011a) Challenges in geographical information science. *Proceedings of the Royal Society A*, 467 (2133), p.pp.2431–2443.

Goodchild, M.F. (2001) Metrics of scale in remote sensing and GIS. *International Journal of Applied Earth Observation and Geoinformation*, 3 (2), p.pp.114–120.

Goodchild, M.F. (2011b) Scale in GIS: an overview. *Geomorphology*, 130 (1-2), p.pp.5–9.

Goodchild, M.F. (2004) Scales of cybergeography. In E. Sheppard & R. B. McMaster, eds. *Scale and geographic inquiry: nature, society, and method*. Malden, MA: Blackwell Publishing Ltd, pp.154–169.

Goodchild, M.F. & Proctor, J. (1997) Scale in a digital geographic world. *Geographical and environmental modelling*, 1 (1), p.pp.5–23.

Hobbs, J.R. (1985) Granularity. In A. Joshi, ed. *In Proceedings of the Ninth International Joint Conference on Artificial Intelligence*. Los Angeles, California, USA: Morgan Kaufmann Publishers, pp.432–435.

JCGM/WG 2 (2008) *The international vocabulary of metrology - Basic and general concepts and associated terms (VIM)*.

Janowicz, K. & Compton, M. (2010) The Stimulus-Sensor-Observation ontology design pattern and its integration into the semantic sensor network ontology. In K. Taylor, A. Ayyagari, & D. De Roure, eds. *The 3rd International workshop on Semantic Sensor Networks*. Shanghai, China: CEUR-WS.org.

Kuhn, W. (2009) A functional ontology of observation and measurement. In K. Janowicz, M. Raubal, & S. Levashkin, eds. *GeoSpatial Semantics: Third International Conference*. Mexico City, Mexico: Springer Berlin Heidelberg, pp.26–43.

Kuhn, W. (2012) Core concepts of spatial information for transdisciplinary research. *International Journal of Geographical Information Science*, (Special issue honoring Michael Goodchild), in press.

Kuhn, W. (2011) Core concepts of spatial information: a first selection. In L. Vinhas & C. Davis Jr., eds. *XII Brazilian Symposium on Geoinformatics*. Campos do Jordão, Brazil, pp.13–26.

Lam, N.S.N. & Quattrochi, D.A. (1992) On the Issues of Scale, Resolution, and Fractal Analysis in the Mapping Sciences*. *The Professional Geographer*, 44 (1), p.pp.88–98.

Mark, D., Turk, A. & Stea, D. (2007) Progress on Yindjibarndi ethnophysiography. In S. Winter, M. Duckham, L. Kulik, & B. Kuipers, eds. *Spatial information theory - 8th International Conference, COSIT 2007*. Melbourne, Australia: Springer-Verlag Berlin Heidelberg, pp.1–19.

Montello, D.R. (2001) Scale in geography N. Smelser & P. Baltes, eds. *International Encyclopedia of the Social and Behavioral Sciences*, p.pp.13501–13504.

Pontius Jr, R.G. & Cheuk, M.L. (2006) A generalized cross-tabulation matrix to compare soft-classified maps at multiple resolutions. *International Journal of Geographical Information Science*, 20 (1), p.pp.1–30.

Quattrochi, D.A. (1993) The need for a lexicon of scale terms in integrating remote sensing data with geographic information systems. *Journal of Geography*, 92 (5), p.pp.206–212.

Reitsma, F. & Bittner, T. (2003) Scale in object and process ontologies. In W. Kuhn, M. F. Worboys, & S. Timpf, eds. *Spatial Information Theory: Foundations of Geographic Information Science, COSIT03*. Ittingen, Switzerland: Springer Berlin, pp.13–30.

Robinson, J.A., Amsbury, D.L., Liddle, D.A. & Evans, C.A. (2002) Astronaut-acquired orbital photographs as digital data for remote sensing: spatial resolution. *International Journal of Remote Sensing*, 23 (20), p.pp.4403–4438.

Skogan, D. (2001) Managing resolution in multi-resolution databases. In J. T. Bjørke & H. Tveite, eds. *ScanGIS'2001 - The 8th Scandinavian Research Conference on Geographical Information Science*. Ås, Norway, pp.99–113.

Stell, J. & Worboys, M. (1998) Stratified map spaces: A formal basis for multi-resolution spatial databases. In T. Poiker & N. Chrisman, eds. *SDH'98 - Proceedings 8th International Symposium on Spatial Data Handling*. Vancouver, British Columbia, Canada, pp.180–189.

Sydenham, P.H. (1999) Static and dynamic characteristics of instrumentation. In J. G. Webster, ed. *The measurement, instrumentation, and sensors handbook*. CRC Press LLC.

Tobler, W. (1987) Measuring spatial resolution. In *Proceedings, Land Resources Information Systems Conference*. Beijing, China, pp.12–16.

UCGIS (1996) Research priorities for geographic information science. *Cartography and Geographic Information Systems*, 23 (3), p.pp.115–127. Available at: http://www.ncgia.ucsb.edu/other/ucgis/CAGIS.html.

Veregin, H. (1998) Data quality measurement and assessment. *NCGIA Core Curriculum in Geographic Information Science*, p.pp.1–10.

Veregin, H. (1999) Data quality parameters. In P. A. Longley, D. J. Maguire, M. F. Goodchild, & D. W. Rhind, eds. *Geographical information systems: principles and technical issues*. New York: John Wiley and Sons, pp.177–189.

Worboys, M. (1998) Imprecision in finite resolution spatial data. *GeoInformatica*, 2 (3), p.pp.257–279.

Wu, J. (2008) Landscape ecology. In S. E. Jorgensen & B. Fath, eds. *Encyclopedia of Ecology*. Oxford, United Kingdom: Elsevier, pp.2103–2108.

Wu, J. (2012) Landscape ecology. In A. Hastings & L. Gross, eds. *Encyclopedia of Theoretical Ecology*. University of California Press, pp.392–396.

Wu, J. (2006) Landscape ecology, cross-disciplinarity, and sustainability science. *Landscape Ecology*, 21 (1), p.pp.1–4.

Wu, J. & Hobbs, R. (2002) Key issues and research priorities in landscape ecology: an idiosyncratic synthesis. *Landscape Ecology*, 17 (4), p.pp.355–365.

Wu, J. & Li, H. (2006) Concepts of scale and scaling. In J. Wu, B. Jones, H. Li, & O. Loucks, eds. *Scaling and uncertainty analysis in ecology: methods and applications*. Dordrecht, The Netherlands: Springer, pp.3–16.