

Geospatial Big Data Handling Theory and Methods: A Review and Research Challenges

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Geospatial Big Data Handling Theory and Methods: A Review and Research Challenges

Abstract: Big data has now become a strong focus of global interest that is increasingly attracting the attention of academia, industry, government and other organizations. Big data can be situated in the disciplinary area of traditional geospatial data handling theory and methods. The increasing volume and varying format of collected geospatial big data presents challenges in storing, managing, processing, analyzing, visualizing and verifying the quality of data. This has implications for the quality of decisions made with big data. Consequently, this position paper of the International Society for Photogrammetry and Remote Sensing (ISPRS) Technical Commission II (TC II) revisits the existing geospatial data handling methods and theories to determine if they are still capable of handling emerging geospatial big data. Further, the paper synthesises problems, major issues and challenges with current developments as well as recommending what needs to be developed further in the near future.

Keywords: Big data, Geospatial, Data handling, Analytics, Spatial Modeling, Review

1. Introduction

Over the last decade, big data has become a strong focus of global interest, increasingly attracting the attention of academia, industry, government and other organizations. The term “big data” first appeared in the scientific communities in the mid-1990s, gradually became popular around 2008 and started to be recognized in 2010. Today, big data is a buzzword everywhere on the Internet, in the trade and scientific publications and during all types of conferences. Big data has been suggested as a predominant source of innovation, competition and productivity (Manyika et al. 2011), and has caused a paradigm shift to data-driven research (Kitchin 2014). The rapid growing flood of big data, originating from the many different types of sensors, messaging systems and social networks in addition to more traditional measurement and observation systems, have already invaded many aspects of our everyday existence. On the one hand, big data, including geospatial big data, has great potential to benefit many societal applications such as climate change, disease surveillance, disaster response, monitoring critical infrastructures, transportation and so on. On the other hand, big data’s benefits to society are usually limited by issues such as data privacy, confidentiality and security.

Big data is still not a clearly defined term and it has been defined differently from technological, industrial, research or academic perspectives (Chen et al. 2014). In general, it is considered as structured and unstructured datasets with massive data volumes that cannot be easily captured, stored, manipulated, analysed, managed and presented by traditional hardware, software and database technologies. Along with its definitions, big data is often described by its unique characteristics. In discussing application delivery strategies under increasing data volumes, Laney (2001) first proposed three dimensions that characterise the challenges and opportunities of increasing large data volumes: *Volume*, *Velocity* and *Variety* (3Vs). While 3Vs have been continuously used to describe big data, the additional dimension of *Veracity* has been added to describe data integrity and quality. Further Vs have also been suggested such as variability, validity, volatility, visibility, value, and visualization. However, these are met critically as they do not necessarily express qualities of magnitude. While it is true these further Vs do not directly contribute to understanding the “big” in big data, they do touch on important concepts related to the entire pipeline of big data collection, processing and presentation. Suthaharan (2014) even argued that 3Vs cannot support early detection of big data characteristics for its classification and proposed 3Cs: *cardinality*, *continuity*, and *complexity*. It is apparent that defining big data and its characteristics will be an ongoing endeavour, but it nevertheless will not have negative impact on big data handling and processing.

According to the arguable phrase “80% of data is geographic” (see discussions in Morais (2012)), much of the data in the world can be geo-referenced, which indicates the importance of geospatial big data handling. Geospatial data describe objects and things with relation to geographic space, often with location coordinates in

1 a spatial referencing system. Geospatial data are usually collected using ground surveying, photogrammetry and
2 remote sensing, and more recently through laser scanning, mobile mapping, geo-located sensors, geo-tagged
3 web contents, volunteered geographic information (VGI), global navigation satellite system (GNSS) tracking
4 and so on. Adopting the widely accepted characterisation method, geospatial data can exhibit at least one of the
5 3Vs (Evans et al. 2014), but the other Vs mentioned above are also relevant. As such, geospatial big data can be
6 characterised by the following, with the first four being more fundamental and important:

- 7
- 8 ▪ Volume: Petabyte archives for remotely sensed imagery data, ever increasing volume of real-time sensor
9 observations and location-based social media data, vast amount of VGI data, etc., as well as continuous
10 increase of these data, raise not only data storage issues but also a massive analysis issue (Dasgupta 2013).
- 11 ▪ Variety: map data, imagery data, geotagged text data, structured and unstructured data, raster and vector
12 data, all these different types of data – many with complex structures – calls for more efficient models,
13 structures, indexes and data management strategies and technologies, e.g., use of NoSQL.
- 14 ▪ Velocity: imagery data with frequent revisits at high resolution, continuous streaming of sensor
15 observations, Internet of Things (IoT), real-time GNSS trajectory and social media data all require matching
16 the speed of data generation and the speed of data processing to meet demand (Dasgupta 2013).
- 17 ▪ Veracity: much of geospatial big data are from unverified sources with low or unknown accuracy, level of
18 accuracy varies depending on data sources, raising issues on quality assessment of source data and how to
19 “statistically” improve the quality of analysis results.
- 20 ▪ Visualization: provides valuable procedures to impose human thinking into big data analysis. Visualizations
21 help analysts identifying patterns (such as outliers and clusters), leading to new hypotheses as well as
22 efficient ways to partition the data for further computational analysis. Visualizations also help end users to
23 better grasp and communicate dominant patterns and relationships that emerge from the big data analysis.
- 24 ▪ Visibility: the emergence of cloud computing and cloud storage has made it possible to now efficiently
25 access and process geospatial big data in ways that were not previously possible. Cloud technology is still
26 evolving and once issues such as data provenance – historical metadata – are resolved, big data and the
27 cloud would be mutually dependent and reinforcing technologies.

29 The increasing volume and varying format of collected geospatial big data pose additional challenges in storing,
30 managing, processing, analysing, visualizing and verifying the quality of data. [Shekhar, et al. \(2012, p. 1\)](#) states
31 that “the size, variety and update rate of datasets exceed the capacity of commonly used spatial computing and
32 spatial database technologies to learn, manage, and process the data with reasonable effort”. Big data tends to
33 hold people to expect more and larger hypotheses that grow faster than the statistical strength of data and
34 capacity of data analysis (Gomes 2014). Verifying the quality of geospatial big data and data products delivered
35 to end users is noted as one of the big challenges and becomes even more challenging in the quality control of
36 the delivered data products (see 2012 ISPRS Resolution, www.isprs.org/documents/resolutions.aspx). On the
37 other hand, fitness of uses or purposes appears more valid or should be advocated ([Mayer-Schönberger &](#)
38 [Cukier 2013](#)) in the context of big data.

40 The objectives of this paper are to (1) revisit the existing geospatial data handling methods and theories to
41 determine if they are still capable of handling emerging geospatial big data; (2) examine current, state-of-the-art
42 methodological, theoretical, and technical developments in modelling, processing, analysing and visualising
43 geospatial big data; (3) synthesize problems, major issues and challenges in current developments; and (4)
44 recommend what needs to be developed in the near future. Section 2 to 6 addresses objectives 1 and 2 of the 5
45 important areas related to geospatial big data handling methods and theories, which are the focus of various
46 Working Groups (WG) of ISPRS TC II. Related image analysis and processing topics, such as dimensionality
47 reduction; image compression; compressive sensing in big data analytics; content-based image retrieval; and
48 image endmember extraction, are not covered in this paper. Section 7 presents open issues and future research
49 directions of the three focus areas of TC II. Section 8 gives a summary and conclusions to the paper.

53 2. Collection of Geospatial Big Data

55 In recent years, along with the availability of new sensors, new ways of collecting geospatial data have emerged,
56 leading to completely new data sources and data types of geographical nature. Data acquired by the public, so-
57 called Volunteered Geographic Information (VGI), and data from geo-sensor networks have led to an increased
58

1 availability of spatial information. Whereas until recently, authoritative datasets were dominating in topographic
2 domain, these new data types extend and enrich geographic data in terms of thematic variation and by the fact
3 that it is more user-centric. The latter is especially true for VGI collected by social media (Sester et al. 2014).

4
5 Geospatial data collection is shifting from a data sparse to a data rich paradigm. Whereas some years back
6 geospatial data capture was based on technically demanding, accurate, expensive and complicated devices,
7 where the measurement process was itself sometimes an art, we are now facing a situation where geospatial data
8 acquisition is a commodity implemented in everyday devices such as smartphones used by many people. These
9 devices are capable of acquiring environmental geospatial information at an unprecedented level with respect to
10 greatly improved geometric accuracy, temporal resolution and thematic granularity. They are small, easy to
11 handle, and able to acquire data even unconsciously.

12
13 This data capture paradigm is similar to the situation in topographic data collection for digital terrain models by
14 capturing significant topographic points with morphological characteristics on the one hand (“qualified” points,
15 i.e., points with semantics)– as opposed to the collection of point clouds using LiDAR sensors or stereo
16 matching, leading to masses of “unqualified” points (Ackermann 1994). The first approach requires manual
17 selection and measurement and guarantees that the topographic reality can be interpolated from the sparse
18 measurements. The second approach assumes that the topographic reality is captured by the dense
19 measurements and can be reconstructed from them – thus the object formation and identification are shifted to
20 the analysis process.

21
22 In general, one can distinguish the following sensor configurations: (1) objects equipped with sensors moving
23 through space and capturing their own trajectories and the local environments: humans and moving devices such
24 as cars; and (2) static sensors constantly observing the (changing) environment. Today’s data acquired by these
25 new sensors and new stakeholders can be characterised as follows:

- 26
- 27 ▪ data streams,
- 28 ▪ arbitrary high density,
- 29 ▪ “close sensing” (Duckham 2013), i.e., the ability to measure many different dimensions of objects
30 characteristics, e.g., optical, acoustic, and mechanical features, and
- 31 ▪ different degrees of positional accuracy and reference, ranging from highly precise coordinates via
32 relative positions to information where there is no geometric reference or is only implicitly located by
33 location names.
- 34

35
36 There are many examples of data collections that may lead to geospatial big data sets. For example, from a
37 “social” perspective, over the last decade we have seen (through the rise of the so-called “smart city” concept)
38 the instrumentation of cities which are now providing vast amount of real-time data through the likes of smart
39 card ticketing systems, vehicle tracking devices, CCTV, toll systems, induction loops and other sensors. With
40 the rise of social media we are also seeing vast amounts of data (e.g., Twitter feeds), which can be geotagged
41 and used to assist in disaster management and emergency relief. From an “environmental science” perspective,
42 there are huge remotely sensed imagery repositories such as NASA’s Landsat repositories which provide
43 petabytes of geospatial data (Riebeek 2015). Capturing the urban environment is possible using a variety of
44 sensors. Cars (e.g., connected vehicles) are equipped with many sensors to aid the driver and enhance safety and
45 comfort. These sensors also capture the immediate environment of the car using front cameras, backwards
46 cameras, ultrasonic (for parking assistance), GPS, radar, rain-sensing wipers (Fitzner et al. 2013). The
47 information is stored on local systems and can be transmitted to the available infrastructure or other vehicles.

48
49 Another important example concerns the quality of data on health. Such data are routinely collected and stored,
50 e.g., with doctors or health centres. In particular in public health centres, however, the coordinates in space and
51 time may lack quality. The first reason is that health aspects are not always related to the location where the
52 person lives. The second reason is that the moment when he or she is visiting the health facility may not
53 correspond with the time of incidence. As an important reason we found that people avoid stigmatic
54 investigations, e.g., related to AIDS or other sexually transmitted diseases, thus giving a bias in routinely
55 collected datasets (Kandwal et al. 2010).

56
57 People, considered as “sensors”, can also help capture traffic or mobility related VGI style information. VGI
58 acquisition can be distinguished into participatory and opportunistic. Participatory data acquisition is conducted

1 in a conscious process by a user, who explicitly selects objects and their features and contributes this
2 information (an example is the OpenStreetMap, OSM). Opportunistic data capture occurs unconsciously, mostly
3 with no specific purpose – or even a completely different purpose. A prominent example is the exploitation of
4 mobile phone data to determine traffic information such as traffic jams. The capture of the spatio-temporal
5 phenomenon “traffic jam” is just a by-product of many users having switched their phones on when driving their
6 cars. With the recent emergence of smart cards, transport ticketing systems like the London Oyster card are
7 capturing the movement of millions of travellers which use the London Tube and railway system daily. A new
8 data point is created every time they register the location via swiping on or off a mode of public transport.
9

10 VGI has proven to be an essential data source, when ad-hoc information is needed as in a disaster context
11 (Goodchild & Glennon 2010). In those situations, it is important to get any information – even if it is not very
12 accurate. Thus, social media and services are considered as new information sources for example for early
13 response and crisis management (Fuchs et al. 2013). Fuchs et al. (2013) evaluated Twitter streams to detect
14 large scale flooding events in Germany. In a period of 8 months, approximately 6 million tweets had been
15 recorded. If the analysis concentrates only on the frequency, it was not possible to identify the events; however,
16 the inclusion of specific keywords, together with spatio-temporal clustering was able to detect some of the
17 events. A similar approach is reported by Dittrich and Lucas (2013). Huang et al. (2015) used millions of
18 location-based tweets to predict human movements. Other examples for the successful use of crowd-sourcing
19 data collection approach in the context of disasters, are the Haiti earthquake (<http://www.ushahidi.com/>), the
20 Queensland flood (McDougall 2011), as well as flood risk assessment (Poser et al. 2009). Invitation active
21 participation of users in the context of mapping has been reported by Frommberger et al. (2013).
22

23 It is worth noting that in the realm of geoscientific data, there is a wealth of new sensors and data sources, which
24 lead to large collections of diverse and “dirty” data (inaccurate, incomplete or erroneous data), which only gain
25 relevance by careful integration and fusion with complementary data (Van Zyl et al. 2009).
26
27

28 3. Quality Assessment

29
30

31 Geospatial data, being abstractions and observations of a continuous reality (Frank 2001), is by nature uncertain,
32 ideally time-stamped and often incomplete. Hence, geospatial big data, with its defining characteristics of being
33 large (voluminous), heterogeneous (variety), real-time processed (velocity), inconsistent (variability), and thus
34 also of variable quality (veracity), must suffer even more from uncertainty, asynchronicity, and incompleteness.
35 However, while certain effects on data quality are emphasized for geospatial big data, the phenomena to be
36 described are still the same. Thus, the known methods and theories of quality assessment are still applicable.
37

38 In geographic information science and technology, standardized methods have been developed in order to
39 assess, describe and propagate quality characteristics both quantitatively and qualitatively. Frameworks exist to
40 describe data quality from a producer's perspective, which then, in the hands of consumers, have to be translated
41 into fitness for purpose. These frameworks went into international standards, such as ISO 8402 (which is
42 generically about quality management: “Data quality is the totality of characteristics of a product that bear on its
43 ability to satisfy stated and implied needs”) or ISO 19157 (which is specifically about the quality of geographic
44 information: “Establishes the principles for describing the quality of geographic data. It defines components for
45 describing data quality, specifies components and content structure of a register for data quality measures,
46 describes general procedures for evaluating the quality of geographic data, and establishes principles for
47 reporting data quality”). The frameworks typically define quantitative measures of data quality, such as spatial,
48 temporal and thematic accuracy, spatial, temporal and thematic resolution, consistency, and completeness
49 (Veregim 2005), and in addition qualitative characteristics of data quality, such as purpose, usage, or lineage.
50

51 In the end, this approach to data quality assessment is descriptive about the data capturing process, stored in
52 separate metadata. But these data are used in decision making processes, and thus, the quantities and qualities of
53 the above frameworks require further analysis for propagation. In a spatial statistical context work has been
54 done by Van de Vlag et al. (2005) and Van de Vlag and Stein (2006) on natural objects and Kohli et al. (2012)
55 on slums. Frank (2007, p. 417), studying the ontology of imperfect knowledge, stated: “How do the
56 imperfections in the data affect the decision?”, but acknowledges that the decision making process is a black
57 box of unknown complexity. While still some quality descriptors, especially the quantitative ones, lend
58

1 themselves to functional error propagation, others – especially the qualitative ones – are still left to human
2 judgment. With the ad-hoc combination of data streams in geospatial big data collection and near-real-time
3 analytics, this traditional approach falls short both in collecting, aggregating or propagating metadata as well as
4 in human judgment of metadata. These challenges can be illustrated for example in the context of connected
5 urban transport introduced above:
6

- 7 ▪ The sheer volume of geospatial big data in transport arises from the large number of agents (vehicles,
8 people, and goods) on their way at any time. Furthermore, in order to be able to predict transport
9 demand or traffic, not only are real-time data required but also historic data. If the bandwidth of
10 communication channels forms bottlenecks, even with lossless compression, either the sampling rate or
11 the sampling size can be reduced (loss of details), or the computation can be decentralized (Duckham
12 2013), in which case a central instance would collect only aggregated data. Each of these solutions has
13 an impact on the quality assessment of the collected data.
- 14 ▪ The large variety of geospatial big data in transport (such as GNSS, inertial sensors, compass, wheel
15 sensors, radar, laser scanning, number plate recognition, induction loops, electronic toll or ticketing,
16 parking sensors, social media comments, citizen reports, to name only a few) to be combined in big
17 data analytics challenges error propagation models, which are based on a functional relationship.
- 18 ▪ The velocity of data, more often than not requiring real-time analysis for event management or near-
19 future prediction, does not allow for setting up proper error propagation, since disturbances in the
20 sensor or channel can only be detected in hindsight or from prediction models.
- 21 ▪ The variability of geospatial big data in transport, indicating inconsistency, stems from both the variety
22 between different data channels as well as the unreliability of any of these sources. For example,
23 volunteered geographic information can be inconsistent if the “citizens as sensors” (Goodchild 2007) or
24 “citizens as databases” (Richter & Winter 2011) disagree on their observations, are just not sampling a
25 particular phenomenon of interest (e.g., if a tree falls on a street and nobody is there to notice), or are
26 limited by lack of communication channels (e.g., a sensor is moving out of reach of WiFi/cell phone
27 coverage). In another example, satellite positioning has some well-known quality descriptors, but in
28 urban canyons, these measures vary with the location in the environment rather than the sensor, the
29 transmission channel or the time (Kealy et al. 2014). This dependency on location is non-linear and
30 difficult to predict.
- 31 ▪ The veracity of geospatial big data in transport indicates already that data is to be combined of very
32 different quality. This extends also to irregular sampling rates (both spatial and temporal), entry errors,
33 redundancy, corruption, lack of synchronization, or a variety of collection purposes (taxonomies,
34 semantics), to name a few.
- 35 ▪ Variability and veracity are closely tied to vulnerability, and vulnerability is perhaps the only aspect
36 that is in contrast to classic institutional databases, which are behind firewalls or even completely
37 disconnected (in safety critical applications). Since both big data collection and analytics require
38 connectivity, concepts are also required to deal with malicious contributions, attacks and theft, and
39 privacy. The latter is particularly true for geospatial data collected for tracking movements, and a
40 measure of quality would cater for protection of privacy while still guaranteeing some level of quality
41 of service (Anthony et al. 2007, Duckham & Kulik 2006).
42

43 Within geospatial big data in transport, a prominent example is research that observes the quality of
44 OpenStreetMap, which has become an open source for navigation services at a global scale. This research
45 focuses mostly on the completeness of OpenStreetMap (Haklay 2010, Mondzech & Sester 2011, Neis et al.
46 2012, Zielstra & Zipf 2010).
47

48 Typically, the value of geospatial big data (analytics) is seen in information for decision support. Analytical
49 methods such as data mining and machine learning enable only inductive reasoning on big data, i.e., detection of
50 global correlations, or predictions based on these correlations. In transport, an example is the early discovery of
51 traffic accidents. In these applications the traditional quality (from a provider or consumer perspective) has been
52 replaced by correlation coefficients (Miller & Goodchild 2014), well knowing that correlation is not necessarily
53 about causes or truth. Thus, validity or trust is traded for the velocity of information production.
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4. Data Modeling and Structuring

All the spatial data models, including the spaghetti vector data model, the network data model, the topological data model and the regular (raster) and irregular (Voronoi, k-d-tree, Binary Space Partitioning Tree, paving group, crystallographic group) tessellations based data models, can be used for handling geospatial big data. Nevertheless, there are some models that are more suitable for handling very large data sets and others that are less suitable for geospatial big data. As the network and topological data models need to store the connectivity (for the network and topological spatial data model) and the adjacency (for the topological spatial data model), they are not well suited for handling geospatial big data streams unless a very efficient spatial data indexing is making the update of the connectivity and/or the topology possible in real time. Since geospatial big data environments might have to relax accuracy constraints to satisfy the real-time constraint, irregular and especially regular tessellations are ideally suited to handle soft errors – geometric uncertainties in data that do not cause erroneous topology. Finally, as regular tessellations can be stored in matrices, they are subject to very parallelized vectorization algorithms. Nevertheless, the implicit topology of the regular tessellation (raster) spatial data model might not be desired topology in some applications that require small inaccuracies (e.g., collision detection for driver-less cars). In such cases, the only possible way to satisfy real time constraints is to use a spatial data indexing method that can maintain its performances with a big data stream being updated in real time. Current spatial data indexing methods cannot handle geospatial big data streams, because their efficiency gets lower as new spatial data streams go over the capacity of extension of the spatial data index (e.g., all the available locations for a hash function value get spent and the hash function needs to get updated or a tree must be rebalanced after a series of additions of data from the stream).

Spatial statistics is well suited to handle big data. It offers capabilities to summarize the data, and express measures of variation and uncertainty. The main concern, however, is that many of the processes and procedures are developed for smaller datasets. In particular, much of spatial statistical analysis is either done on datasets that are collected at a pointwise scale (such as field data, meteorological data, or administrative data) and of a relatively small content, or is focusing on the relatively large image data sets which have a very specific nature. Spatial statistics depends upon the notion of spatial (and spatio-temporal) dependence, and such dependence in turn depends upon the notion of distance between points. For n observations, including their coordinates in space or space and time, evaluating distances requires inspection of n^2 pairs of points, and here steps should be made to be able to do this efficiently. The current data structures as such are usually able to handle the big data as well, but most likely specific procedures have to be developed that are able to address issues that are relatively novel (such as combining data in the space-time domain) or that have to address specific questions and problems, i.e., to select data from a big data set for a particular model application. A particular way ahead may be that classification of the data into multiple classes is done in the form of metadata. In such a way it is possible to make the big data of relevance in a wide range of practical applications. This would require an improved database structure, and in particular a very much adaptive spatial statistical analysis procedure.

Some authors have already pointed out the necessity of parallel and distributed programming for handling the big data sets in the general context or even in the geospatial context (Lee et al. 2014, Shekhar et al. 2012, Shekhar et al. 2014, Wang et al. 2013). Others have pointed out the usefulness of functional programming concepts or languages such as Haskell Domain-Specific Language (Mintchev 2014), Map-reduce (Maitrey & Jha 2015, Mohammed et al. 2014), Data Flow Graphs (Tran et al. 2012), or self-adjusting computation (Acar & Chen 2013). However, there is a gap between the research works that advocate functional programming techniques but do not handle specifically geospatial data, and research works that focus on geospatial big data, but do not guarantee the absence of data races which are the races of different threads to gain access to the same data item in some shared memory Milewski (2009). The following sections discuss issues related to functional programming paradigms for big data streams and geospatial big data analytics in the context of big data modeling and structuring, and examines how geospatial data models and structures are adapted to big data.

4.1 Functional programming for big data streams

The main stumbling block for handling geospatial big data streams using parallel programming and the best reason for using functional programming is the concept of data races. A data race is a race between different threads that try to access the same data items, and relates to the notion of concurrency. Functional programming solves the problem of data races by strictly controlling the simultaneous access to mutable data. It has been

1 predicted that data races will produce the “downfall of imperative programming” (Milewski 2009). The main
2 advantage of Haskell (or other functional programming languages like Closure, Lisp, ML, Scheme) for big data
3 is its support of parallel computing and concurrency and the high performance of the most famous Haskell
4 compiler (GHC: the Glasgow Haskell Compiler): “applications built with GHC enjoy solid multicore
5 performance and can handle hundreds of thousands of concurrent network connections” (Mintchev 2014).
6

7 Domain Specific Languages (DSL) provide a solution to the key challenge of big data by making the “multi-
8 disciplinary collaboration as effective and productive as possible” and by offering the “required degree of
9 flexibility and control” and a domain-specific development completed on time possibly by non-software
10 developers (Mintchev 2014). The functional programming languages map and reduce functions are the basis of
11 the MapReduce programming model for processing big data sets by a distributed parallel algorithm. Maitrey &
12 Jha (2015) states “MapReduce has emerged as the most popular computing paradigm for parallel, batch-style
13 and analysis of large amount of data”, especially since Google adopted it.
14

15 **4.2 Geospatial big data analytics**

16
17 We can classify the techniques used for spatial data mining from different points of view: the assumptions that
18 these techniques pre-suppose and the “curse of dimensionality” that they exhibit or not. While parametric
19 statistics assume some probability distribution function or some spatial distribution, non-parametric statistics
20 only assume local smoothness. Functional analysis (e.g., wavelets) and homotopy continuation techniques
21 assume only the continuity of the functions involved. The “curse of dimensionality” (Juditsky et al. 1995) states
22 that the number of points needed to train machine-learning algorithms gets exponential with the dimension of
23 the search space. Statistical and machine learning techniques and even statistics based dimensionality reduction
24 algorithms do not lower the dimensionality of the problem in a deterministically exact way (Li et al. 2011).
25 Thus, they exhibit the “curse of dimensionality” (Juditsky et al. 1995). On the contrary, homotopy continuation
26 techniques are not subject to an exponential growth of the number of samplings (because they do not rely on
27 training with points) and the uncertainty of the modeling does not explode from one dimension to the next one,
28 as this has been shown in Musiige et al. (2013) and Musiige et al. (2011). This observation can be extended to
29 other functional analysis techniques as wavelets (Juditsky et al. 1995).
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32 As it can be conceived, in any attempt to process big spatial data streams in real time, one might be tempted to
33 ask if tolerating soft errors could be feasible, and to what extent. This was addressed in Carbin et al. (2013). If
34 we do not accept soft errors, then we need to rely on new High Performance Computing architectures to harness
35 the parallelism necessary to process geospatial big data streams in real time (Carbin et al. 2013). However, in
36 order to analyze and compare geospatial big data algorithms, we need benchmarks, so that the different
37 algorithms can have a common evaluation basis. Big data benchmarks (Shekhar et al. 2014, Shekhar et al. 2012)
38 have become one fundamental concept in studying geospatial big data.
39

40 Spatial databases research has intended to make query processing faster by designing spatial indexing methods,
41 which partition the search space in tiles (possibly irregular), so that the average query time will be concentrated
42 in one tile. The main challenge is to cleverly organize geospatial data in tiles through spatial data clustering that
43 will define optimal tiles and efficient paths (space-filling curves) through these tiles, so that the access to n-
44 dimensional data is done efficiently by referring to the location of the tile along that “space-filling curve”.
45 Several space-filling curves have been proposed in the literature. However, the Hilbert space-filling curve has
46 the advantage that the arc length between two consecutive tiles along the space-filling curve is constant (Ujang
47 et al. 2014). The main use and value of geospatial big data is to dig useful information from geospatial big data
48 sets (Wang et al. 2013, Wang & Yuan 2013, 2014).
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50 51 **5. Data Visualization and Visual Analytics**

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54 When several additional Vs are proposed in defining the big data (see Section 1 above), it is no surprise that the
55 terms *visualization* and *visual analytics* are frequently mentioned. There are many strong reasons for this with
56 the primary one being that some of our computational and statistical approaches do not scale – there is simply
57 *too much* data (Keim et al. 2013, Shneiderman 2014). Even smaller amounts of data in forms and tables are not
58 really human readable, thus the interactive and exploratory visualization environments help at the very early
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1 stages in dealing with big data in making sense of what the data actually contains (Cook et al. 2012, Frankel &
2 Reid 2008, Hoffer 2014). In other words, visualizations essentially enable humans to deal with big data where
3 machines along might fall short. Conversely, visual analytics approaches acknowledge the human shortcomings
4 as well and combine the powers of computational tools with powers of human visual sense-making (Choo &
5 Park 2013). Visualizations, therefore, are widely acknowledged as a part of analysis process (i.e., not only
6 communication), in which we can explore the data, and build hypotheses during this process (Zhang et al. 2012).
7 It is important to note that visualizations have been more commonly conceptualized as *communication* tools.
8 While this is true and visualizations are important in communicating hypotheses, results and ideas, in the case of
9 big data, we believe their role in *exploration* plays an even more important part. However, visualizations, while
10 often offered as remedies to the shortcomings of the computational methods, may not scale either. Big data
11 means many things to display; and it often results in very ‘busy’ displays, especially given the trend for
12 multiple-linked view displays that are popular in visual analytics and big data applications. Such requirements
13 can lead to information overload. It is important to note that human cognitive resources (such as the visual
14 working memory that is critical in processing visual information; or spatial abilities which are critical for how
15 well we can make sense of visualizations) are limited (e.g., Hegarty 2011, Hegarty et al. 2012). Novel
16 visualization designs are necessary, especially those informed by knowledge on human information processing,
17 perception and cognition.
18

19 In terms of novel design and visualization paradigms, the field witnessed many alternative approaches that are
20 constantly being proposed, even though many of them are not yet validated through empirical testing. Among
21 these approaches, the most dominant one appears to be the *multiple-linked views*, in which approaches such as
22 brushing and linking are used to allow the viewer to work with various visualizations at the same time
23 (Bernasocchi et al. 2012). Alternatively, summarization, clustering and highlighting approaches have been
24 proposed. Vision-inspired approaches, such as *focus+context* visualizations and *foveation* may provide
25 interesting new opportunities as they attempt to reduce the information load and are becoming more relevant
26 with the recent technological developments offering cheaper and better eye tracking solutions (Bektas &
27 Çöltekin 2012, Cockburn et al. 2008, Çöltekin 2009). Other approaches have also been proposed in the literature
28 taking advantage of technological developments such as *cloud computing*, *parallel processing*, *indexing* and
29 *querying* for real time utilization (e.g., Chen et al. 2014, Hoffman 2012, Liu et al. 2013, Lu et al. 2013).
30

31 Despite an influx of “new” solutions, we have also witnessed a rediscovery of a “not so new” system -- through
32 a strong coupling between geographic information systems (GIS) and big data. GIS is an unmatched and mature
33 toolbox for *data science* as its abilities to process spatial and non-spatial (attribute) data (even when they are not
34 perfectly structured) through computational as well as visual means. Some even called GIS and big data “two
35 parts of a whole” (Deogawanka 2014). Geographic information science and related domains such as remote
36 sensing and geoinformatics have been dealing with large datasets for a relatively long time, before the term big
37 data took momentum in science, popular culture and business (Çöltekin & Reichenbacher 2011). With the
38 advent of big data, other branches of geography have also shown great interest in utilizing big data for
39 addressing social (human geography) and environmental (physical geography) questions (e.g., Crampton et al.
40 2013, Goodchild 2013, Kitchin 2013, Steed et al. 2013, Wood et al. 2013).
41

42 One of the challenges is to be able to make such geospatial big data accessible to end users so that it can be used
43 to make real world decisions. Data visualization tools and techniques are therefore critical in providing windows
44 into such rich data so that it can be analyzed and interrogated by researchers, policy and decision-makers and
45 citizens alike. World Wide Web platforms, such as *geoportals*, provide an excellent means to deliver such
46 services. Portals provide access to geospatial data, and there has been significant momentum in creating
47 federated geoportal, which can access a window to a vast array of geospatial data sets. For example, the
48 INSPIRE Geoportal (<http://inspire-geoportal.ec.europa.eu/>) provides access to 10,000s of geospatial metadata
49 data records from across Europe. The INSPIRE Geoportal uses a visualization interface comprising of both a
50 map window and folksonomy tag cloud to assist users in navigating this rich geospatial data resource.
51

52 There has been an explosion of data available and as our planet continues to experience significant rapid
53 urbanization, there is an increasing need to access and visualize data which represents the dimensions of space
54 and place (see Straumann et al. (2014) for a distinction of the terms space and place). On this note, the rise of
55 *smart cities* has led to the instrumentation of cities with more real-time data and historical data being captured
56 and visualized (Cheshire & Batty 2012). Large-scale projects such as the Urban Big Data Centre (UBDC)
57 (<http://ubdc.ac.uk/>) and the Australian Urban Research Infrastructure Network (AURIN) (<http://aurin.org.au/>)
58

1 are endeavoring to develop “big data” visualization tools and techniques to support the realization of smart
2 cities. The challenge is to be able to provide not only such data visualization interfaces to researchers, but also
3 tools to support policy and decision makers, city planners and communities to be able to visually explore and
4 analyze this data to make better decisions in collectively planning our cities.
5

6 For example, addressing a rapidly urbanizing Australia, AURIN has developed a geoportal where over 1,800
7 datasets can be accessed and visualized. AURIN has deployed a federated data architecture which is metadata
8 driven (Sinnott et al. 2015). There are over 6 billion data elements that urban researchers, government policy
9 and decision makers can access via the AURIN portal (Pettit et al. 2014). This rich tapestry of “big data” across
10 the domains of health, housing, transport, demographics, economics and other essential areas provides coverage
11 across the major cities of Australia. Both *point in time* and *longitudinal data* are accessible via the AURIN
12 portal. Other examples show how geospatial big data is being used in practice in connection with multi-user
13 (collaborative) visualization environments in the context of geoportals for visualizing big data through work
14 being undertaken in Europe through INSPIRE and in Australia through AURIN.
15

16 Another “cutting edge” research area is the visualization of networks, such as transportation networks (Cheshire
17 & Batty 2012). In the London Oyster card case mentioned before in Section 2, there is a need to be able to
18 visualize individual and aggregated travel journeys to provide further insights in the travel behaviors of
19 commuters as they move through the city, and this, in turn, provides important information to transport planners
20 in optimizing timetabling and responding to events. Figure 1 illustrates a snapshot of a time sequence animation
21 of a typical weekday travel based on the Oyster card data.
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43 Figure 1 Oyster Card data for London Tube and train stations, animated for a day using 10 minute intervals
44 (Created by Oliver O’Brien (<http://oobrien.com/2013/03/londons-tidal-oyster-card-flow/>) (via Batty 2012)).
45

46 In addition, the real-time visualization of crowd-sourced big data from platforms such as Twitter can assist with,
47 for example, disaster management responses. The visualization of real-time data streaming from these sources
48 can provide emergency response team critical information on how to respond to events such as flood, fires and
49 other natural and human induced disasters. Visualization platforms such as Ushahidi
50 (<http://www.ushahidi.com/>) and Cognicity (<http://cognicity.info/cognicity/>) and the Peta Jakarta project
51 (<http://petajakarta.org/banjir/en/>) are such crowd-sourced platforms. In the latter, citizens can tweet the reporting
52 of floods particularly in the Monsoon season in the city of Jakarta, Indonesia.
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6. Data Mining and Knowledge Discovery

General big data analysis and traditional spatial data analysis and geo-processing methods and theories can all contribute to the development of geospatial big data analysis and processing. Statistical analysis, geo-computing, simulation and data mining methods and techniques can be used alone or together with other types of big data for discovering knowledge from geospatial big data. This section examines traditional knowledge discovery methods and resurgence of fractal analysis in dealing with geospatial big data.

6.1 Data mining and knowledge discovery

Knowledge discovery (KD) is concerned with mining and extracting meaningful patterns and relationships from large datasets that are valid, novel, useful and understandable (Miller & Hanz 2009). The field emerged in response to the need for methods applicable to data that violate the assumptions of traditional statistics. KD methods typically emphasise generalisation ability and predictive performance, which is particularly pertinent with spatio-temporal data because spatio-temporal datasets can provide rich information about how a process evolves over time. KD from spatio-temporal data enables us to create models that are able to predict future states of a process, so called the holy grail of science (Cressie & Wikle 2011). KD encompasses a range of spatio-temporal data mining (STDM) tools and methodologies for carrying out a set of tasks.

Perhaps the most conceptually simple KD technique is *Association rule mining* (ARM), which involves searching for associations in a dataset where an event X tends to lead to an event Y, where X is the antecedent and Y is the consequent (Agrawal et al. 1993). In the context of spatio-temporal data, ARM entails searching for the occurrence of an event Y in the spatio-temporal neighbourhood of another event X (Mennis & Liu 2005). Shekhar et al. (2011) describe some of the types of patterns that may be present in spatio-temporal data.

More traditional data analysis methods also come under the remit of KD. *Regression* is viewed as a data mining technique, but in truth its use in the spatial sciences and time series analysis predates the field of data mining. Regression models for spatio-temporal data emerged from the cross-pollination of ideas from time series analysis, econometrics and the spatial sciences. For example, the space-time autoregressive integrated moving average (STARIMA) model (Pfeifer & Deutsch 1980, Cheng et al. 2014), spatial panel data models (Elhorst 2003), Bayesian hierarchical models (Cressie & Wikle 2011) and space-time geostatistics (Heuvelink & Griffith 2010), amongst others. An important form of regression is classification, in which the outputs are class labels. As larger and more granular datasets have become available in recent years, the limitations of traditional statistical approaches in capturing nonlinearity and heterogeneity have been exposed. Therefore, some scholars have looked to the machine learning (ML) community for alternatives, first to artificial neural networks (ANNs) in the 1990s and more recently to kernel methods. Perhaps the most well-known and broadly successful machine learning (ML) method for classification and regression is the support vector machine (SVM), which uses kernels to carry out nonlinear regression or classification (Kanevski et al. 2009, Haworth et al. 2014). Recently, the Random Forest (RF) which is a method that combines multiple decision trees through bootstrapping has also gained popularity for classification (Cutler et al. 2007).

Other KD tasks include *anomaly detection*, also known as outlier detection, and *clustering*. Anomaly detection involves the identification of events or patterns in data different from what one would expect. Anomaly detection is inherently challenging as it requires a clear definition of what is considered to be normal and abnormal. In spatio-temporal processes, these definitions may evolve and change over time (Chandola et al. 2009). Accounting for these changes in different spatio-temporal processes is a key research challenge. *Clustering* is a form of unsupervised learning, which involves uncovering hidden structure in a dataset about which we know little. Clustering has wide applications in the spatial sciences, for example in geodemographic classification (Vickers & Rees 2007) and hotspot detection (Nakaya & Yano 2010). Although spatial clustering methods are well developed, spatio-temporal clustering (STC) is still an emerging research frontier. STC methods that are gaining popularity include ST-DBSCAN (Birant & Kut 2007) and space-time scan statistics (STSS) (Kulldorff et al. 2005, Cheng & Adepeju 2014).

The impact of ML methods on KD and STDM has been significant. ML methods are generally effective in tackling nonlinearity in spatial data, and can be modified to deal with the multi-scale issue and heterogeneity (Foresti et al. 2011). However, in many cases (especially kernel methods) their initial computation is expensive

1 if the number of data samples is large. Furthermore, if the statistical properties of a space-time series evolve
2 over time, models have to be retrained to reflect this. In the big data age where the ability to apply methods to
3 real time data streams is paramount, new ways of training traditional algorithms are needed. In ML, online
4 learning is used (Castro-Neto et al. 2009) and these types of approaches need to be integrated with more
5 traditional spatio-temporal analysis techniques. Parallel and grid computation can also be used to improve the
6 performance of KD methods (Harris et al. 2010). However, some issues cannot be solved with only
7 improvements in computational efficiency. For example, the principal problem in STC is to model how clusters
8 emerge, change, move and dissipate/disappear in time. This can be achieved retrospectively but is very difficult
9 to quantify in time critical applications. At what point does a cluster of crimes become a hotspot? Current
10 methodologies within KD and STDM are generally designed to analyse historical datasets but cannot adequately
11 deal with evolving properties of space-time data.

12 **6.2 Fractals emerged from big data**

13 Big data show incredible fractal structure, in which there are far more small things than large ones (Jiang 2015a,
14 Jiang & Miao 2015). There are several reasons for the emerging fractals. First, big data are usually emerged
15 from the bottom up or are contributed by diverse individuals, e.g., location based social media data, so they are
16 very diverse and heterogeneous. Second, big data are defined at very high spatial and temporal scales, which
17 enable us to observe fractal structure and nonlinear dynamics more easily. Third, big data due to the size are
18 more likely to capture a true picture of reality, and reality is no doubt fractal (Bak 1996, Mandelbrot & Hudson
19 2004). In these aspects, the emerging fractals differ from fractals seen on small data such as fractal cities (Batty
20 & Longley 1994). We argue that fractal geometry (Mandelbrot 1982), or complexity science in general, should
21 be adopted for big data analytics and visualization, and for developing new insights into big data.

22 Let us examine a working example to see how fractals are generated from tweets location data of the entire
23 world (Jiang 2015a, Jiang & Miao 2015). The data were sliced at different intervals, and in an accumulative
24 manner, which means that locations at t_1 are included in locations at t_2 . For each sliced location dataset, we
25 built a triangulated irregular network (TIN), and merged those small TIN edges (smaller than the mean of all the
26 TIN edges) as individual patches, which are referred as natural cities. Eventually, thousands of the natural cities
27 are emerged from the tweets locations. Figure 2 shows two natural cities near Chicago and New York at the four
28 time instants, and they are put in comparison with the generative fractal – Koch snowflake. The two natural
29 cities look very much like the snowflake, both sharing (1) the scaling pattern of far more small things than large
30 ones, and (2) irregular shapes or boundaries. On the other hand, the natural cities look a bit different from the
31 snowflake; the natural cities are developed from some irregular patches, which become further fragmented,
32 whereas the snowflake and its growth come from the regular triangle with a strict scaling ratio $1/3$. In other
33 words, the former is called statistical fractal, being statistically self-similar, while the latter called strict fractal,
34 being strictly self-similar.

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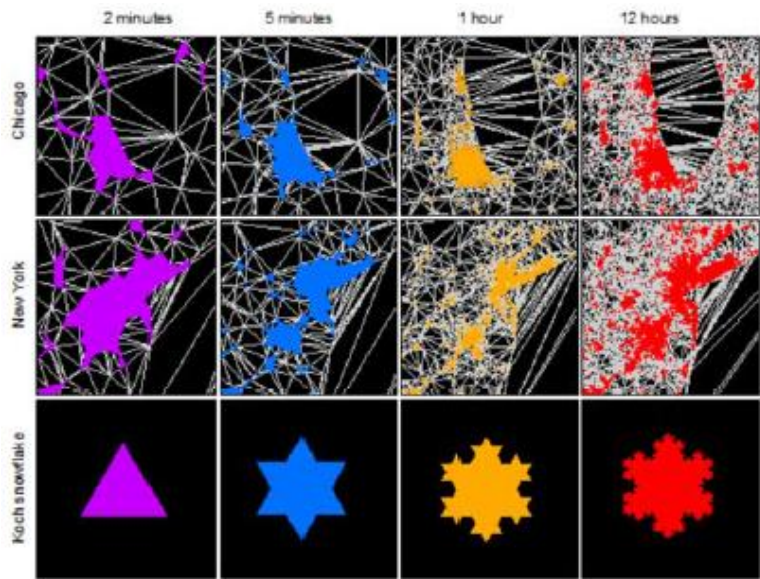
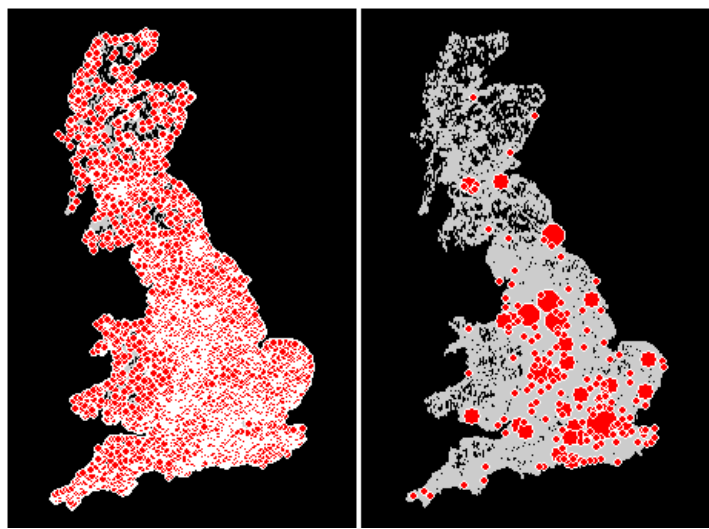


Figure 2 Fractals emerged from big data look very much like the generative fractal – Koch snowflake (Jiang 2015a)

What the example illustrated are not only fractals or natural cities generated from big data, but also a new, relaxed definition of fractals. A set or pattern is fractal if there are far more small things than large ones in it, or the scaling pattern of far more small things than large ones recurs multiple times (Jiang 2015b, Jiang & Yin 2014). The new definition is in fact developed from head/tail breaks (Jiang 2013) as a classification scheme for data with a heavy tailed distribution. The complexity of fractals can be measured by the head/tail breaks induced index – ht-index: the higher the ht-index, the more complex the fractal. Conventionally, complexity was captured by fractal dimension (Mandelbrot 1982), thus ht-index being an alternative index to fractal dimension. In comparison to conventional definitions of fractal, the new definition is much more intuitive and easier to understand, so that anyone can rely on it to see fractals. For example, society is fractal because there are far more poor people than rich people, or far more ordinary people than extraordinary people (Zipf 1949). It should be noted that the head/tail breaks method is not only for data classification, with which both the number of classes and class intervals are automatically determined, but also an efficient and effective visualization tool (Jiang 2015b). Figure 3 presents an example of visualization using the head/tail breaks; only part of the whole is shown to the right panel, but the part is self-similar to the whole, and thus the part reflects the whole.



1 Figure 3 Head/tail breaks as an effective visualization tool (Note: 16,000 natural cities (to the left) in UK
2 generated from a half million of points of interest look like a hairball, but their top 4 hierarchical levels clearly
3 show a scaling structure to the right.)
4

5 Fractal geometry represents a new way of thinking for geospatial analysis, and this is particularly truly for big
6 data analytics. Despite that Euclidean geometry has thousands of years of history, and serves as the foundation
7 of geospatial technologies, the essence of geography (both physical and human) is fractal. We therefore must
8 adopt fractal methods for developing new insights into big data. This fractal thinking is in line with Paretian
9 thinking (Jiang 2015b), which is in contrast to conventional Gaussian thinking. Statistically speaking, there are
10 far more small things than large ones, rather than more or less similar things. Given the scaling pattern or the
11 heavy tailed distribution, the head/tail breaks provide an effective means to derive an inherent hierarchy of
12 complex systems. This is the first step towards an understanding of geographic phenomena, i.e., to recognize
13 fractal structure of geographic systems. The next step is to further develop, through simulations, an
14 understanding of processes as to why the fractal structures exist. In this regard, a set of complexity modeling
15 tools have been developed such as cellular automata, agent-based modeling, and the sand pile model.
16

17 18 **7. Challenges, Open Issues and Future Directions** 19

20
21 This section presents the challenges and open issues based on the reviews in Sections 2-6 and outlines some
22 research directions in the three focus areas of ISPRS TC II (<http://www2.isprs.org/commissions/comm2.html>).
23

24 **7.1 Efficient representation and modeling for geospatial big data** 25

26 The main problem that spatial algorithms face in the context of real-time big data handling is that they cannot
27 wait until all the data are known, as it is the case in two of the major classes of spatial algorithms: the divide-
28 and-conquer or line/plane-sweep algorithms. Even though incremental algorithms are well-suited for handling
29 changing data sets, they are not well-suited for handling streams that cannot fit in the main memory of the
30 computer. Therefore, a new class of spatial algorithms has started to be designed and developed: spatial data
31 streaming algorithms (see e.g., (Hoffmann et al. 2007) and (Sharifzadeh et al. 2009)). However, any real-time
32 streaming algorithms must read an input stream, process it, and write the output stream in real-time. Among all
33 the tasks that have to be performed on computers or digital circuits, the tasks that are the slowest, i.e.,
34 communication over a network, must be minimized in order to satisfy the real-time constraint of big data
35 processing. Another implication of the constraint of real-time processing of big spatial data is to minimize the
36 amount of disk input/output, which is the second slowest task after communications over a network. For this
37 purpose, one needs to focus on the most compact data structures that will store spatial data using the smallest
38 amount of memory. Finally, as spatial data tend to be more complex than non-spatial data, the total CPU
39 running time is not negligible with respect to the disk input/output time. Thus, the parallelization of the spatial
40 algorithms will bring a non-negligible speed-up to the spatial algorithm. This means the spatial algorithms must
41 be distributed, parallelized and use the most compact spatial data structures so that the exchange of information
42 over a network and between the disk and the main memory are minimized and the CPU running time is also
43 minimized. This imposes a distributed parallel architecture where streams of data are processed in real time on
44 each unit controlling a sensor in order to transmit over the network only summary statistics and required results
45 for the other nodes in the computing environment. Such summary statistics that are relevant for sensors are
46 intervals, in particular the new measurements that change the intervals of measurements or the required results.
47 Interval analysis is a well-known method for computing bounds of a function, being given bounds on the
48 variables of that function, (see (Moore et al. 2009, p223) for an introduction to interval analysis). The basic
49 mathematical object in interval analysis is the interval instead of the variable. The operators need to be redefined
50 to operate on intervals instead of real variables. This leads to interval arithmetic. In the same way, the most
51 usual mathematical functions are redefined by an interval equivalent. Interval analysis allows one to certify
52 computations on intervals by providing bounds on the results. The uncertainty of each measure can be
53 represented using an interval defined by either a lower bound and a higher bound or a midpoint value and a
54 radius.
55

56
57 Furthermore, interval analysis is in conjunction with functional analysis, the most-well-suited framework to
58 model the uncertainty of geospatial big data. First, as observed by Juditsky et al. (1995), functional analysis
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1 methods like wavelets do not suffer from the curse of dimensionality that affects machine-learning as well as
2 parametric statistics (including multivariate statistics). Second, interval analysis allows one to model the
3 uncertainty of the input variables (like sensor observations) and the corresponding uncertainty of the functions
4 that are evaluated on these variables. The key challenge and open issue is to bridge the gap between the machine
5 learning and functional analysis communities by convincing the communities working on and with geospatial
6 big data to use functional analysis and interval analysis with a functional programming language. Unfortunately,
7 despite functional programming has made its way into other programming language paradigms, functional
8 analysis combined with interval analysis has not been so successful in making its way in applications of big
9 spatial data.

10
11 Four initial observations can be seen as the base for exploring further research directions. Firstly, functional
12 analysis methods like wavelets, homotopy continuation and interval analysis are much better suited than
13 parametric statistical methods to cope with the curse of dimensionality inherent in big spatial data that includes
14 many dimensions (each functionally independent physical value measured corresponds to one dimension and
15 each one of the coordinate systems component x, y and z corresponds also to one dimension). Secondly, pure
16 functional programming is very well suited for handling functions because pure functional programming does
17 not have (unlike impure functional programming and other programming paradigms) side effects in pure
18 functions, and functions are one of the two most fundamental concepts in any functional programming
19 language: functions and data types (see the seminal paper of Hughes (1989)). Thirdly, the main challenge in
20 spatial data handling, which is to certify the topological relationships and the uncertainty of any spatial data
21 modelling or decision-making by determining the uncertainties of all input variables, can be solved using
22 interval analysis. Finally, the lazy functional programming paradigm, which postpones the evaluation of
23 expressions until these expressions need to be computed in order to compute the final result (Hughes 1989), is
24 very well suited for fractals due to its ability to represent fractal recurrences and to compute only the fractal
25 components needed to compute the final result.

26
27 One future research focus in his area is to produce a locally distributed stream sensing, processing and
28 telecommunicating paradigm implemented using:

- 29 – new functional specification methods derived from ontologies, ontology mappings and their gluing into
30 ontology categories and their charts;
- 31 – functional analysis methods (decompositions of streams with interval enclosures of wavelets,
32 mathematical modelling in higher dimensional measure spaces from interval valued homotopies in
33 lower dimensional measure spaces);
- 34 – pure functional programming languages (see (haskell.org committee, 2015, Hughes 1989)) with:
 - 35 – visualization libraries (like Haskell and its OpenGL bindings and many specialized visualization
36 libraries),
 - 37 – parallelization and concurrency libraries (like the distributed MapReduce framework Holumbus or
38 OpenCL and OpenMP wrappers),
 - 39 – cloud computing libraries;
- 40 – functional programming inspired parallelisation and concurrency techniques.

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42
43 The architecture of any system based on this paradigm can be considered a fractal. Every sensor controlling unit
44 is responsible for collecting the big data streams, computing the statistics or any other desired result, generating
45 the triggers that will automatically update any computed result, visualization or decision making and
46 transmitting it to a lower-resolution data collecting node. Each local data-collecting node is responsible for
47 storing the streams of results and providing the desired visualization and assembling the partial decision taking
48 elements into a summarized decision taking from the neighbouring sensor controlling units. Each regional data
49 collecting node is responsible for storing the streams of results and providing the desired visualization and
50 assembling the partial decision taking elements into a summarized decision taking from the neighbouring local
51 data collecting nodes.

52
53 The other future research focus on new processing algorithms to handle large volumes of data through use of
54 functional programming languages is to design new streaming algorithms that:

- 55 – use the provably most compact geometric topology data structure that encodes all the ramifications (i.e.
56 the singular points of the skeletons of the objects),
- 57 – use CPU and GPU parallelization to harness the computing facilities wherever these lie (locally),
- 58 – use interval analysis to:

- 1 – represent uncertainty of streams of spatial data (Dilo et al. 2007), and
- 2 – to automatically generate the triggers that will react automatically once an input value in a stream
- 3 will make a change in any computed result, visualization or decision making;
- 4 – use wavelet decompositions for handling signals acquired by sensors,
- 5 – use fractals for handling spatial data that has components whose dimension is not an integer (the
- 6 Hausdorff-Besicowicz dimension of a fractal is not an integer, and thus, fractals can be used to model
- 7 phenomena that exhibit self-similarity),
- 8 – use interval valued homotopies to model or reconstruct functions in higher dimensional measure spaces
- 9 from measurements and reconstructions of functions from lower dimensional measure spaces,
- 10 reconstructing therefore higher dimensional measure spaces one dimension at a time,
- 11 – use categories to represent the functional dependencies between data variables and any computed result
- 12 or visualization or decision taking (like data types and functions in the Hask category), and a category
- 13 based Domain Specific Language computing library (like docon, see Mechveliani (2001)).

15 **7.2 Analyzing, mining and visualizing geospatial big data for decision-support**

17 Spatial statistical methods are in principle able to also include non-spatial big data. A typical example is the use
 18 of co-variables in a spatial interpolation procedure (Van de Kassteele & Stein 2006), or in a spatial point process
 19 modelling analysis. Such analyses commonly rely on assumptions, such as normality, independence, absence of
 20 noise in the explanatory data. With the advancements of big data, however, on the one hand the quality of the
 21 big data can be doubted, whereas on the other hand the speed of calculations is seriously affected. Hence, the
 22 procedures are at the moment not ready for the purpose, and serious pre-processing has to be done, for which the
 23 tools are not readily available. Some of the methods have been developed in the past, such as possibilities to use
 24 explanatory variables of a changing quality, but these are often rather complicated to use, and require substantial
 25 work to make them available for the purpose. As an example, one may think of Bayesian procedures, where
 26 prior distributions can be included into a likelihood function. These methods have shown an enormous power in
 27 spatial studies but their application on an automatic basis for big data may not be so easy and transparent to
 28 develop, implement and apply.

29 The main challenges in KD and STDM can be summarised around the first four Vs described in Section 1.

30
 31
 32
 33 *Volumes* of spatio-temporal data are ever increasing and some argue that traditional transactional database
 34 structures are becoming outmoded. Although this point is open to debate, research is taking place into how to
 35 best use new data storage and query architectures to deal with spatio-temporal data. For example, recent studies
 36 have used MapReduce programming models to parallelise data processing (Tan et al. 2012). Despite this,
 37 traditional SQL based spatial databases, such as PostGIS and Oracle Spatial, remain dominant in academia. If
 38 this trend continues, there is a risk that academic research will become disconnected from industry.

39
 40 Despite significant progress, challenges remain in developing predictive algorithms that can deal with the
 41 *velocity* of data arriving in real time. Geography has been a big data discipline since long before the term arose,
 42 dealing with large and complex problems like weather and climate modelling. Hence, geography has
 43 traditionally been forward thinking regarding the development of algorithms for dealing with large and complex
 44 datasets in a timely fashion. The discourse on parallel computing in geography began in the 1990s, leading to
 45 the emergence of the subfield of geocomputation (Cheng et al. 2012). However, parallelism is still far from the
 46 common practice despite enabling hardware being available in desktop computers. Most recent work has
 47 focussed on parallelising all or part of existing algorithms to improve computational performance. For example,
 48 Guan and Clarke (2010) developed a parallel raster processing library for use in cellular automata, and Guan et
 49 al. (2011) developed algorithms to parallelize elements of Kriging interpolation. Libraries for parallel
 50 geocomputation are also now beginning to emerge in open source software environments such as R (Harris et al.
 51 2010). Building on this, a greater focus needs to be placed on developing algorithms that are parallel in nature
 52 and can harness all types of parallelism. This is what Turton and Openshaw (1998, p. 1842) termed “Thinking in
 53 Parallel” in 1998, but is yet to be fully adopted in the research community.

54
 55
 56 *Variety* presents itself as an opportunity to the research community. We now have potentially many data sources
 57 of different types that can be used to analyse (and re-analyse) a diverse range of spatio-temporal processes.
 58 Traditional data providers such as governments, national mapping agencies and transport authorities are now

1 complemented by new data sources described in Section 2. However, an important and often overlooked
2 problems of KD in the spatial sciences is data *veracity*. Big data provides unprecedented volumes of data about
3 a broad range of human activities and physical processes. However, they are often collected on a fairly ad-hoc
4 basis when compared with traditional data sources, and usually must be repurposed to fulfil research objectives.
5 Initiatives such as OpenStreetMap have proven that crowd sourced data can compete with official sources in this
6 regard, but issues of sample representativeness and data collection design (or lack thereof) are still a concern. A
7 good example is Twitter, which has gained popularity in research communities recently, but under represents
8 certain groups, including the elderly and some ethnic minorities, and has an uneven spatio-temporal distribution.
9 Such datasets clearly have potential value alongside traditional demographic data such as censuses and cross-
10 sectional surveys (Longley et al. 2015). However, there is a trade-off between the spatial and temporal
11 granularity offered by these data and the certainty associated with any conclusions drawn from them. Personal
12 mobility data is another example; smartphone apps collect and store vast quantities of such data which have
13 considerable research potential, but this cannot be fully realised without proper validation and a clear
14 understanding of potential biases in the user group. This is coupled with difficulties in inferring activities from
15 raw, unlabelled mobility data (Bolbol et al. 2011).

16
17 Sampling is not a legitimate concept in the big data era, as argued by Jiang and Miao (2015). Big data tends to
18 take all or a large amount, and this data characteristic make big data different from small data which are often
19 sampled. Surely, social media data are oriented towards younger generations or those who have access to
20 Internet and social media, and not everyone has Internet access, in particular in developing countries. However,
21 the large data volumes enable big data to capture the true picture of all social media users, despite the fact that
22 not all people are involved in social media. All social media users can be a good proxy for studying real human
23 activities on the earth surface. In this regard, social media data are like maps, which do not represent everything
24 on the earth surface, but can be a good proxy of earth surface. Big data calls for new ways of thinking beyond
25 conventional thinking (Jiang 2015b, Mayer-Schönberger & Cukier 2013). For example, we tend to examine data
26 quality as we did in the small data era. Massive data should tolerate messiness. For navigation purposes, we
27 must make OSM data as precise and accurate as possible, in other words, the more precise and the more
28 accurate, the better. However, to examine whether there are far more small street blocks than large ones, we do
29 not need very good quality data, but need massive data with messiness instead.

30
31 Nonetheless, visualizing big data has some additional challenges; for example, visual analytics solutions
32 themselves may not scale: we need to consider how to deal with *information overload* on the viewer if we show
33 too many things at the same time (Choo & Park 2013, Ruff 2002). Applications in a large-scale geoportal like
34 AURIN have revealed there are significant challenges in being able to visualize large multi-dimensional
35 geospatial datasets via a browser. For this, thousands of years of cartographic expertise offers sound advice. We
36 should carefully generalize, e.g., emphasize the important while removing the unimportant, group the
37 information both thematically and perceptually, and pay attention to visual hierarchy when we design displays.
38 We should remember linking the good cartographic design principles to modern interaction design paradigms
39 (MacEachren et al. 2008, Schnürer et al. 2014, Slocum et al. 2008). Furthermore, researchers in the cartography
40 and geovisualization domain have taken a strong interest in cognitive and usability issues and much progress has
41 been made to understand how human capacity can enhance or limit our experiences with visual displays
42 (Çöltekin et al. 2010, Knapp 1995, Montello 2002, Roth 2013, Slocum et al. 2001).

43
44 Whilst the *smart city* and *big data* are hot topics of today (Batty 2012), there is also the challenge of how to
45 visualize the error and uncertainty inherent with big data sets such as crowd-sourced datasets and smart card
46 data (Cheshire & Batty 2012). In the realm of geospatial big data, there is also a need to effectively visualize
47 other types of massive data sets, such as LIDAR data or very large collections of remote-sensing data.
48 Visualization platforms such as PointCloudViz (<http://www.pointcloudviz.com/>), or Online LIDAR point cloud
49 viewer (<http://lidarview.com/>) specialize on Lidar data visualization. Similarly, there are efforts in organizing
50 remotely sensed imagery (Ma et al. 2014, Marshall & Boshuizen 2013).

51
52 Spatial statistics has always had good opportunities for visualizing spatial and spatio-temporal data, including
53 the uncertainties (see Rulinda et al. (2013) for an excellent example in the space-time domain). Their
54 opportunities are still present also for geospatial big data. In the past, such methods have also been applied to
55 non-spatial data, and there is apparently not a real problem to extend them towards big data. A critical issue in
56 all of spatial (or spatio-temporal) data is their relying on coordinates. Hence, also for non-spatial data there must
57 be an opportunity to assign coordinates, or equivalent, to the non-spatial data. Successes in the past have
58

1 typically considered class memberships to serve that purpose, bringing the non-spatial data towards the feature
2 space (Dilo et al. 2007).
3

4 **7.3 Quality assessment of geospatial big data from new sources** 5

6 Dealing with veracity in a scalable and timely manner has been identified as a substantial challenge (Saha &
7 Srivastava 2014). Behind this challenge is the lack of thorough knowledge of the data semantics when data that
8 is commonly called “dirty” (e.g., Chiang & Miller 2008) is collected and combined in an ad-hoc manner.
9 Accordingly, big data analytics has given up the closed-world assumption in favour of learning incrementally
10 under an open-world assumption. Thus, big data quality assessment has been characterized by the three stages of
11 discovering rules of data semantics, checking for inconsistencies based on currently known rules, and repairing
12 data near real-time (Saha & Srivastava 2014).
13

14 Geospatial big data collection, especially sensors’ data, is being captured in an automatic and unprecedented
15 way, which poses new opportunities and challenges. This in principle causes problems for a statistical analysis,
16 where statistical considerations such as optimal design or model based sampling are critical to make valid
17 statements. Big spatial data may be either largely irrelevant, as they are collected automatically and hence much
18 uninteresting repetition may occur, whereas big spatial data may be of a highly varying quality. They may be
19 precise, but too precise to be of use, they may be too abundant as the same object is over sampled, they may be
20 of a very poor quality as data may be at the nominal scale, where ratio-scale data might have been collected
21 elsewhere, or they may be inadequate for the specific purpose. At the moment, no adequate procedures seem to
22 be implemented to be able to harmonize the quality of spatial data for specific purposes. This will require a
23 significant effort in order to develop feasible solutions.
24

25 On the positive side, the large number of data sources allows us to acquire a “complete picture” of a spatial
26 situation, also including its dynamics. This is even more so, when different sensor data are integrated and fused,
27 allowing to also eliciting more than one aspect or feature of an object (Ebert et al. 2009). Due to the potential
28 high redundancy, it is possible to identify errors or blunders in the data and achieve higher accuracies even
29 though an individual sensor has a limited measuring quality.
30

31 As often no explicit semantics (or manual annotation of semantics) is given, automatic processes are required to
32 reveal it. This refers both to the object and its features, but also to the temporal characteristics.
33

34 Crowd-sourced data sets are often related to very detailed, i.e., large-scale phenomena. However, the level of
35 granularity (in space, time and semantics) is not always known. Hence, it is a challenge to determine this
36 granularity level from the sensor data. One option is to include explicit metadata about the sensor in terms of a
37 self-description. Another option is to infer the scale and granularity level by automatically relating it to other
38 sources of known granularity. This involves matching techniques at both the geometric and semantic levels.
39

40 In traditional sensors the quality (e.g., geometric accuracy) of the acquired data is given. This is not necessarily
41 the case with new data sources such as VGI data. As this data source is often user centred, questions of
42 reputation and trust have to be included to evaluate the quality.
43

44 **8. Conclusions** 45

46 This study reviews a variety of geospatial theory and methods used for traditional data but that can be extended
47 to handle geospatial big data. While there is no standard definition of big data, it can be considered as structured
48 and unstructured datasets with massive data volumes that cannot be easily captured, stored, manipulated,
49 analysed, managed and presented by traditional hardware, software and database technologies. Given these
50 unique characteristics, traditional data handling approaches and methods are inadequate and the following areas
51 were identified as in need for further development and research in the discipline:
52

- 53 ■ The development of new spatial indexing and algorithms to handle real-time, streaming data and to support
54 topology for real-time analytics.
55

- 1 ▪ The development of conceptual and methodological approaches to move big data from descriptive and
2 correlation research and applications to ones that explore casual and explanatory relationships.
- 3 ▪ The development of efficient methods to display data integrated in the three dimensions of geographic and
4 one dimension of continuous time. There is a strong need in understanding human capacity to deal with
5 visual information and identifying which visualization type is a good fit for the task at hand, and the target
6 user group. Furthermore, interdisciplinary studies and communication is important. The advances in
7 scientific visualization and information visualization are both beneficial to geographic visualization; but
8 geographic visualization has also a lot to offer to other domains. Novel visualization paradigms, especially
9 developed for big data tend to be information-rich (thus complex); therefore, we find that highlighting and
10 summarizing approaches should be further investigated. Additionally, and in relation to managing complex
11 visualization displays, technology research in terms of level of detail management remains important.
- 12 ▪ The development of novel approaches for error propagation so as to effectively assess data quality requires.
13 The challenge is not only the handling the many different types of data for real-time analytics, but rather the
14 ad-hoc combination of data streams in real-time, which may include the capture of the “whole” picture (or
15 “complete population”) instead of sampling a small portion of the whole population. In this case quick
16 assessments are preferable that may come out of varying the input data and simulating variability.

17
18 The paper also highlighted other general conceptual and practical issues. The relation between spatial statistics
19 and semantics and ontologies has been identified in the past, but requires further elaboration. Ontologies have
20 been identified, for example, for dunes and beaches in studies around 2005, whereas more slum ontologies have
21 been developed. The role of spatial statistics was related to the scale, the environment and the characterization
22 of specific variables. In particular, aspects of scale are important.

23
24 Privacy and security are equally important and key concerns especially in geospatial big data handling, which
25 may lead us into a “naked future” if not properly addressed. They are an essential part of geospatial big data
26 management, but are not covered here given the focus on this paper on data handling methods.

27
28 Big data presents both challenges and opportunities. This paper outlines some of these challenges from a
29 technical and conceptual perspective, and also provides priority areas that need to be addressed in the future.
30 Once big data research evolves and matures, the opportunities from leveraging big data for overall societal
31 management and decision-making become enormous.

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40 41 42 **Authors Contribution Statement**

43
44
45 Regardless of the listed order of the authors, all authors contributed equally by participating in discussions,
46 writing sections, revising corresponding sections and providing revision comments on the entire paper.

47 48 49 **References**

- 50
51 Acar, U. A., & Chen, Y. (2013). Streaming Big Data with Self-Adjusting Computation. *Proceedings of the 2013*
52 *Workshop on Data Driven Functional Programming - DDFP '13*, 15-18. doi:
53 10.1145/2429376.2429382
- 54 Ackermann, F. (1994). Digital Elevation Models - Techniques and Applications, Quality Standards,
55 Development. *IAPRS, 30/4*(Commission IV), 421-432.

- 1 Agrawal, R., Imieliński, T., & Swami, A. (1993). Mining Association Rules between Sets of Items in Large
2 Databases. *Proceedings of the 1993 ACM SIGMOD International Conference on Management of Data*,
3 22(2), 207-216. doi: 10.1145/170035.170072
- 4 Anthony, D., Henderson, T., & Kotz, D. (2007). Privacy in Location-Aware Computing Environments. *IEEE*
5 *Pervasive Computing*, 6(4), 64-72.
- 6 Bak, P. (1996). *How Nature Works: The Science of Self-Organised Critically* (1 ed.): Copernicus.
- 7 Batty, M. (2012). Smart Cities, Big Data. *Environmental and Planning B: Planning and Design*, 39(2), 191-193.
8 doi: 10.1068/b3902ed
- 9 Batty, M., & Longley, P. A. (1994). *Fractal Cities: A Geometry of Form and Function*. London: Academic
10 Press.
- 11 Bektas, K., & Çöltekin, A. (2012). Area of Interest Based Interaction and Geovisualization with WebGL.
12 *Proceedings of The Graphical Web Conference 2012*.
- 13 Bernasocchi, M., Çöltekin, A., & Gruber, S. (2012). An Open Source Geovisual Analytics Toolbox for
14 Multivariate Spatio-Temporal Data for Environmental Change Modeling. *ISPRS Annals of the*
15 *Photogrammetry, Remote Sensing and Spatial Information Sciences*, 1-2(2), 123-128.
- 16 Bolbol, A., Cheng, T., & Haworth, J. (2011). Using a Moving Window SVMs Classification to Infer Travel
17 Mode from GPS Data. *Proceedings of the 11th International Conference on GeoComputation*, 262-
18 270.
- 19 Carbin, M., Misailović, S., & Rinard, M. C. (2013). Verifying Quantitative Reliability for Programs that
20 Execute on Unreliable Hardware. *ACM SIGPLAN NOTICES - OOPSLA '13*, 48(10), 33-52. doi:
21 10.1145/2544173.2509546
- 22 Castro-Neto, M., Jeong, Y.-S., Jeong, M.-K., & Han, L. D. (2009). Online-SVR for short-term traffic flow
23 prediction under typical and atypical traffic conditions. *Expert Systems with Applications* 36, 6164–
24 6173. doi: 10.1016/j.eswa.2008.07.069
- 25 Chandola, V., Banerjee, A., & Kumar, V. (2009). Anomaly Detection: A Survey. *ACM Computing Surveys*,
26 41(3), 1-58. doi: 10.1145/1541880.1541882
- 27 Chen, M., Mao, S., & Liu, Y. (2014). Big Data: A Survey. *Mobile Networks and Applications*, 19(2), 171-209.
28 doi: 10.1007/s11036-013-0489-0
- 29 Cheng, T & Adepeju, M. (2014). Modifiable Temporal Unit Problem (MTUP) and its Effect on Space-Time
30 Cluster Detection. *PLOS ONE* 9(6), e100465.
- 31 Cheng, T., Haworth, J., Anbaroglu, B., Tanaksaranond, G., & Wang, J. (2014). Spatiotemporal Data Mining. In
32 M. M. Fischer & P. Nijkamp (Eds.), *Handbook of Regional Science* (pp. 1173-1193): Springer Berlin
33 Heidelberg.
- 34 Cheng, T., Haworth, J., & Manley, E. (2012). Advances in Geocomputation (1996-2011). *Computers,*
35 *Environment and Urban Systems*, 36(6), 481-487. doi: 10.1016/j.compenvurbsys.2012.10.002
- 36 Cheshire, J., & Batty, M. (2012). Visualisation Tools for Understanding Big Data. *Environment and Planning*
37 *B: Planning and Design*, 39(3), 413-415.
- 38 Cheng, T., Wang, J., Haworth, J., Heydecker, B., Chow, A. (2014). A Dynamic Spatial Weight Matrix and
39 Localized Space-Time Autoregressive Integrated Moving Average for Network Modeling,
40 Geographical Analysis. *Geographical Analysis*, 46: 75–97 DOI: 10.1111/gean.12026.
- 41 Chiang, F., & Miller, R. J. (2008). Discovering Data Quality Rules. *Proceedings of the VLDB Endowment*, 1(1),
42 1166-1177. doi: 10.14778/1453856.1453980
- 43 Choo, J., & Park, H. (2013). Customizing Computational Methods for Visual Analytics with Big Data. *IEEE*
44 *Computer Graphics and Applications*, 33(4), 22-28.
- 45 Cockburn, A., Karlson, A., & Bederson, B. B. (2008). A Review of Overview+Detail, Zooming, and
46 Focus+Context Interfaces. *ACM Computing Surveys*, 41(1), 1-31. doi: 10.1145/1456650.1456652
- 47 Çöltekin, A. (2009). Space-Variant Image Coding for Stereoscopic Media. *Picture Coding Symposium, 2009*
48 *(PCS 2009)*, 1-4. doi: 10.1109/PCS.2009.5167396
- 49 Çöltekin, A., Fabrikant, S. I., & Lacayo, M. (2010). Exploring the Efficiency of Users' Visual Analytics
50 Strategies Based on Sequence Analysis of Eye Movement Recordings. *International Journal of*
51 *Geographical Information Science*, 24(10), 1559-1575. doi: 10.1080/13658816.2010.511718
- 52 Çöltekin, A., & Reichenbacher, T. (2011). High Quality Geographic Services and Bandwidth Limitations.
53 *Future Internet*, 3(4), 379-396. doi: 10.3390/fi3040379
- 54 Cook, K., Grinstein, G., Whiting, M., Cooper, M., Havig, P., Liggett, K., . . . Paul, C. L. (2012). VAST
55 Challenge 2012: Visual Analytics for Big Data. *Proceedings of the 2012 IEEE Conference on Visual*
56 *Analytics Science and Technology (VAST)*, 251-255. doi: 10.1109/VAST.2012.6400529

- 1 Crampton, J. W., Graham, M., Poorthuis, A., Shelton, T., Stephens, M., Wilson, M. W., & Zook, M. (2013).
 2 Beyond the Geotag: Situating 'Big Data' and Leveraging the Potential of the Geoweb. *Cartography and*
 3 *Geographic Information Science*, 40(2), 130-139. doi: 10.1080/15230406.2013.777137
- 4 Cressie, N., & Wikle, C. K. (2011). *Statistics for Spatio-Temporal Data*: John Wiley & Sons.
- 5 Cutler, D. R., Edwards, T. C. Jr., Beard, K. H., Cutler, A., Hess, K. T., Gibson, J., & Lawler, J. J., 2007.
 6 Random Forests for Classification in Ecology. *Ecology*, 88(11), 2783-2792.
- 7 Dasgupta, A. (2013). Big Data: The future is in analytics. *Geospatial World*.
- 8 Deogawanka, S. (2014). Empowering GIS with Big Data. Retrieved May 4, 2015, from
 9 <http://www.gislounge.com/empowering-gis-big-data/>
- 10 Dilo, A., By, R. A. d., & Stein, A. (2007). A system of types and operators for handling vague spatial objects.
 11 *International Journal of Geographical Information Science*, 21(4), 397-426. doi:
 12 10.1080/13658810601037096
- 13 Dittrich, A., & Lucas, C. (2013). A Step Towards Real-Time Detection and Localization of Disaster Events
 14 Based on Tweets. *Proceedings of the 10th International Conference on Information Systems for Crisis*
 15 *Response and Management*, 868-872.
- 16 Duckham, M. (2013). *Decentralized Spatial Computing*: Springer Heidelberg.
- 17 Duckham, M., & Kulik, L. (2006). Location Privacy and Location-Aware Computing. *Dynamic & mobile GIS:*
 18 *Investigating change in space and time*, 3, 34-51.
- 19 Ebert, A., Kerle, N., & Stein, A. (2009). Urban social vulnerability assessment with physical proxies and spatial
 20 metrics derived from air- and spaceborne imagery and GIS data. *Natural Hazards*, 48(2), 275-294. doi:
 21 10.1007/s11069-008-9264-0
- 22 Elhorst, J. P. (2003). Specification and Estimation of Spatial Panel Data Models. *International Regional Science*
 23 *Review*, 26(3), 244-268. doi: 10.1177/0160017603253791
- 24 Evans, M. R., Oliver, D., Zhou, X., & Shekhar, S. (2014). Spatial Big Data: Case Studies on Volume, Velocity,
 25 and Variety. In H. A. Karimi (Ed.), *Big Data: Techniques and Technologies in Geoinformatics* (pp.
 26 149-176): CRC Press.
- 27 Fitzner, D., Sester, M., Haberlandt, U., & Rabiei, E. (2013). Rainfall Estimation with a Geosensor Network of
 28 Cars - Theoretical Considerations and First Results. *Photogrammetrie-Fernerkundung-Geoinformation*,
 29 2013(2), 93-103. doi: 10.1127/1432-8364/2013/0161
- 30 Foresti, L., Tuia, D., Kanevski, M., & Pozdnoukhov, A. (2011). Learning wind fields with multiple kernels
 31 *Stochastic Environmental Research and Risk Assessment*, 25(1), 51-66. doi: 10.1007/s00477-010-0405-
 32 0
- 33 Frank, A. U. (2001). Tiers of Ontology and Consistency Constraints in Geographical Information Systems.
 34 *International Journal of Geographical Information Science*, 15(7), 667-678.
- 35 Frank, A. U. (2007). Data Quality Ontology: An Ontology for Imperfect Knowledge. In S. Winter, M.
 36 Duckham, L. Kulik & B. Kuipers (Eds.), *Spatial Information Theory* (pp. 406-420): Springer Berlin
 37 Heidelberg.
- 38 Frankel, F., & Reid, R. (2008). Big Data: Distilling Meaning from Data. *Nature*, 455(7209), 30-30. doi:
 39 10.1038/455030a
- 40 Frommberger, L., Schmid, F., & Cai, C. (2013). Micro-Mapping with Smartphones for Monitoring Agricultural
 41 Development. *Proceedings of the 3rd ACM Symposium on Computing for Development*, 46.
- 42 Fuchs, G., Andrienko, N., Andrienko, G., Bothe, S., & Stange, H. (2013). Tracing the German Centennial Flood
 43 in the Stream of Tweets: First Lessons Learned. *Proceedings of the Second ACM SIGSPATIAL*
 44 *International Workshop on Crowdsourced and Volunteered Geographic Information*, 31-38.
- 45 Gomes, L. (2014, October 20, 2014). Machine-Learning Maestro Michael Jordan on the Delusions of Big Data
 46 and Other Huge Engineering Efforts. Retrieved May 4, 2015, from
 47 [http://spectrum.ieee.org/robotics/artificial-intelligence/machinelearning-maestro-michael-jordan-on-](http://spectrum.ieee.org/robotics/artificial-intelligence/machinelearning-maestro-michael-jordan-on-the-delusions-of-big-data-and-other-huge-engineering-efforts)
 48 [the-delusions-of-big-data-and-other-huge-engineering-efforts](http://spectrum.ieee.org/robotics/artificial-intelligence/machinelearning-maestro-michael-jordan-on-the-delusions-of-big-data-and-other-huge-engineering-efforts)
- 49 Goodchild, M. F. (2007). Citizens as Sensors: The World of Volunteered Geography. *GeoJournal*, 69, 211-221.
 50 doi: 10.1007/s10708-007-9111-y
- 51 Goodchild, M. F. (2013). The Quality of Big (Geo)data. *Dialogues in Human Geography*, 3(3), 280-284. doi:
 52 10.1177/2043820613513392
- 53 Goodchild, M. F., & Glennon, A. (2010). Crowdsourcing Geographic Information for Disaster Response: A
 54 Research Frontier. *International Journal of Digital Earth*, 3(3), 231-241.
- 55 Guan, Q., & Clarke, K. C. (2010). A General-Purpose Parallel Raster Processing Programming Library Test
 56 Application Using a Geographic Cellular Automata Model. *International Journal of Geographical*
 57 *Information Science*, 24(5), 695-722. doi: 10.1080/13658810902984228

- 1 Guan, Q., Kyriakidis, P. C., & Goodchild, M. F. (2011). A Parallel Computing Approach to Fast Geostatistical
2 Areal Interpolation. *International Journal of Geographical Information Science*, 25(8), 1241-1267. doi:
3 10.1080/13658816.2011.563744
- 4 Haklay, M. (2010). How Good is Volunteered Geographical Information? A Comparative Study of
5 OpenStreetMap and Ordnance Survey Datasets. *Environment and Planning B: Planning and Design*,
6 37(4), 682-703. doi: 10.1068/b35097
- 7 Harris, R., Singleton, A., Grose, D., Brunson, C., & Longley, P. (2010). Grid-enabling Geographically
8 Weighted Regression: A Case Study of Participation in Higher Education in England. *Transactions in*
9 *GIS*, 14(1), 43-61. doi: 10.1111/j.1467-9671.2009.01181.x
- 10 Haworth, J., Shawe-Taylor, J., Cheng, T., Wang, J. (2014) Local online kernel ridge regression for forecasting
11 of urban travel times. *Transportation Research Part C: Emerging Technologies* 46, 151–178.
12 doi:10.1016/j.trc.2014.05.015.
- 13 Hegarty, M. (2011). The Cognitive Science of Visual-Spatial Displays: Implications for Design. *Topics in*
14 *Cognitive Science*, 3(3), 446-474. doi: 10.1111/j.1756-8765.2011.01150
- 15 Hegarty, M., Smallman, H. S., & Stull, A. T. (2012). Choosing and Using Geospatial Displays: Effects of
16 Design on Performance and Metacognition. *Journal of Experimental Psychology: Applied*, 18(1), 1-17.
17 doi: 10.1037/a0026625
- 18 Heuvelink, G., & Griffith, D. A. (2010). Space–Time Geostatistics for Geography: A Case Study of Radiation
19 Monitoring Across Parts of Germany. *Geographical Analysis*, 42(2), 161-179. doi: 10.1111/j.1538-
20 4632.2010.00788.x
- 21 Hoffer, D. (2014). What Does Big Data Look Like? Visualisation is Key for Humans. Retrieved May 4, 2015,
22 from <http://www.wired.com/2014/01/big-data-look-like-visualization-key-humans/>
- 23 Hoffman, J. (2012). Q&A: The Data Visualizer. *Nature*, 486(7401), 33-33. doi: 10.1038/486033a
- 24 Hoffmann, M., Raman, R., & Muthukrishnan, S. (2007). Streaming algorithms for data in motion. *Lecture Notes*
25 *in Computer Science (including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in*
26 *Bioinformatics)*, 4614 LNCS, 294–304.
- 27 Huang, W., Li, S., Liu, X., & Ban, Y. (2015). Predicting human mobility with activity changes. *International*
28 *Journal of Geographical Information Science*. doi: 10.1080/13658816.2015.1033421
- 29 Hughes, J. (1989). Why Functional Programming Matters. *Computer Journal*, *Computer Journal*, *Computer J*,
30 *Comput J*, *Comput. J*, 32(2), 98–107. doi:10.1093/comjnl/32.2.98
- 31 Jiang, B. (2013). Head/tail Breaks: A New Classification Scheme for Data with a Heavy-tailed Distribution. *The*
32 *Professional Geographer*, 65(3), 482-494. doi: 10.1080/00330124.2012.700499
- 33 Jiang, B. (2015a). Head/tail Breaks for Visualization of City Structure and Dynamics. *Cities*, 43, 69-77.
- 34 Jiang, B. (2015b). Geospatial Analysis Requires a Different Way of Thinking: The Problem of Spatial
35 Heterogeneity. *GeoJournal*, 80(1), 1-13. doi: 10.1007/s10708-014-9537-y
- 36 Jiang, B., & Miao, Y. (2015). The Evolution of Natural Cities from the Perspective of Location-Based Social
37 Media. *The Professional Geographer*, 67(2), 295-306. doi: 10.1080/00330124.2014.968886
- 38 Jiang, B., & Yin, J. (2014). Ht-Index for Quantifying the Fractal or Scaling Structure of Geographic Features.
39 *Annals of the Association of American Geographers*, 104(3), 530-540. doi:
40 10.1080/00045608.2013.834239
- 41 Juditsky, A., Hjalmarsson, H., Benveniste, A., Delyon, B., Ljung, L., Sjöberg, J., & Zhang, Q. (1995). Nonlinear
42 Black-Box Models in System Identification: Mathematical Foundations. *Automatica*, 31(12), 1725-
43 1750. doi: 10.1016/0005-1098(95)00119-1
- 44 Kandwal, R., Augustijn, E.-W., Stein, A., Miscione, G., Garg, P. K., & Garg, R. D. (2010). Geospatial analysis
45 of HIV-Related social stigma: A study of tested females across Indian mandals. *International Journal*
46 *of Health Geographics*, 9(18).
- 47 Kanevski, M., Pozdnoukhov, A., & Timonin, V. (2009). *Machine Learning for Spatial Environmental Data:*
48 *Theory, Applications, and Software*: EFPL Press.
- 49 Kealy, A., Retscher, G., Toth, C., & Brzezinska, D. (2014). Collaborative Positioning: Concepts and
50 Approaches for More Robust Positioning. *Proceedings of the XXV FIG Congress 2014: Engaging the*
51 *Challenges Enhancing the Relevance*, 15.
- 52 Keim, D., Qu, H., & Ma, K.-L. (2013). Big-Data Visualization. *IEEE Computer Graphics and Applications*,
53 33(4), 20-21.
- 54 Kitchin, R. (2014). Big Data, new epistemologies and paradigm shifts. *Big Data & Society*, 1(1), 1-12.
55 doi:10.1177/2053951714528481.
- 56 Kitchin, R. (2013). Big Data and Human Geography Opportunities, Challenges and Risks. *Dialogues in Human*
57 *Geography*, 3(3), 262-267. doi: 10.1177/2043820613513388

- 1 Knapp, L. (1995). A Task Analysis Approach to the Visualization of Geographic Data. In T. L. Nyerges, D. M.
2 Mark, R. Laurini & M. J. Egenhofer (Eds.), *Cognitive Aspects of Human-Computer Interaction for*
3 *Geographic Information Systems* (pp. 355-371): Springer Netherlands.
- 4 Kohli, D., Sliuzas, R., Kerle, N., & Stein, A. (2012). An ontology of slums for image-based classification.
5 *Computers, Environment and Urban Systems*, 36(2), 154-163. doi:
6 10.1016/j.compenvurbsys.2011.11.001
- 7 Kulldorff, M., Heffernan, R., Hartman, J., Assunção, R., & Mostashari, F. (2005). A Space-Time Permutation
8 Scan Statistic for Disease Outbreak Detection. *PLoS Medicine*, 2(3), e59. doi:
9 10.1371/journal.pmed.0020059
- 10 Laney, D. (2001). 3D Data Management: Controlling Data Volume, Velocity, and Variety. *Application Delivery*
11 *Strategies*. [http://blogs.gartner.com/doug-laney/files/2012/01/ad949-3D-Data-Management-](http://blogs.gartner.com/doug-laney/files/2012/01/ad949-3D-Data-Management-Controlling-Data-Volume-Velocity-and-Variety.pdf)
12 [Controlling-Data-Volume-Velocity-and-Variety.pdf](http://blogs.gartner.com/doug-laney/files/2012/01/ad949-3D-Data-Management-Controlling-Data-Volume-Velocity-and-Variety.pdf)
- 13 Lee, K., Ganti, R. K., Srivatsa, M., & Liu, L. (2014). Efficient Spatial Query Processing for Big Data.
14 *Proceedings of the 22nd ACM SIGSPATIAL International Conference on Advances in Geographic*
15 *Information Systems - SIGSPATIAL '14*, 469-472. doi: 10.1145/2666310.2666481
- 16 Li, Y., Yan, D., & Liu, S. (2011). Dimensionality Reduction Algorithm Based on Density Portrayal. *Computer*
17 *Engineering*, 37(21), 138-140.
- 18 Liu, Z., Jiang, B., & Heer, J. (2013). ImMens: Real-Time Visual Querying of Big Data. *Computer Graphics*
19 *Forum (Proceedings of EuroVis '13)*, 32(3pt4), 421-430.
- 20 Longley, P. A., Adnan, M., & Lansley, G. (2015). The Geotemporal Demographics of Twitter Usage.
21 *Environment and Planning A*, 47(2), 465-484. doi: 10.1068/a130122p
- 22 Lu, Y., Zhang, M., Witherspoon, S., Yesha, Y., Yesha, Y., & Rishe, N. (2013). sksOpen: Efficient Indexing,
23 Querying, and Visualization of Geo-spatial Big Data. *Proceedings of the 2013 12th International*
24 *Conference on Machine Learning and Applications (ICMLA)*, 2, 495-500. doi:
25 10.1109/ICMLA.2013.196
- 26 Ma, Y., Wu, H., Wang, L., Huang, B., Ranjan, R., Zomaya, A., & Jie, W. (2014). Remote Sensing Big Data
27 Computing: Challenges and Opportunities. *Future Generation Computer Systems*. doi:
28 10.1016/j.future.2014.10.029
- 29 MacEachren, A. M., Crawford, S., Akella, M., & Lengerich, G. (2008). Design and Implementation of a Model,
30 Web-Based, GIS-Enabled Cancer Atlas. *The Cartographic Journal*, 45(4), 246-260. doi:
31 10.1179/174327708X347755
- 32 Maitrey, S., & Jha, C. K. (2015). *Handling Big Data Efficiently by Using Map Reduce Technique*. Paper
33 presented at the The 2015 IEEE International Conference on Computational Intelligence &
34 Communication Technology (CICT), Ghaziabad, IN.
- 35 Mandelbrot, B. B. (1982). *The Fractal Geometry of Nature*. New York: W. H. Freeman.
- 36 Mandelbrot, B. B., & Hudson, R. L. (2004). *The (Mis)behavior of Markets: A Fractal View of Risk, Ruin and*
37 *Reward*. New York: Basic Books.
- 38 Manyika, J., Chui, M., Brown, B., Bughin, J., Dobbs, R., Roxburgh, C., & Byers, A. H. (2011). Big Data: The
39 Next Frontier for Innovation, Competition, and Productivity.
- 40 Marshall, W., & Boshuizen, C. (2013). Planet Labs' Remote Sensing Satellite System. *Small Satellite*
41 *Conference*.
- 42 Mayer-Schönberger, V., & Cukier, K. (2013). *Big Data: A Revolution That Will Transform How We Live, Work,*
43 *and Think*. New York: Eamon Dolan/Houghton Mifflin Harcourt.
- 44 McDougall, K. (2011). Using Volunteered Information to Map the Queensland Floods. *Proceedings of the*
45 *Surveying & Spatial Sciences Biennial Conference 2011*, 13-24.
- 46 Mechveliani, S. D. (2001). Computer algebra with Haskell: applying functional-categorical-'lazy' programming,
47 *Proceedings of International Workshop CAAP-2001 (Dubna, Russia)*, 2001, 203-211; [http://ca-](http://ca-d.jinr.ru/confs/CAAP/Final/proceedings/proceed.ps)
48 [d.jinr.ru/confs/CAAP/Final/proceedings/proceed.ps](http://ca-d.jinr.ru/confs/CAAP/Final/proceedings/proceed.ps)
- 49 Mennis, J., & Liu, J. W. (2005). Mining Association Rules in Spatio-Temporal Data: An Analysis of Urban
50 Socioeconomic and Land Cover Change. *Transactions in GIS*, 9(1), 5-17. doi: 10.1111/j.1467-
51 9671.2005.00202.x
- 52 Milewski, B. (2009). Lock Options. *DR DOBBS JOURNAL*, 34(1), 28-31.
- 53 Miller, H. J., & Goodchild, M. (2014). Data-Driven Geography. *GeoJournal (Online First)*, 1-13.
- 54 Miller, H. J., & Hanz, J. (2009). Geographic Data Mining and Knowledge Discovery: An Overview *Geographic*
55 *Data Mining and Knowledge Discovery* (Second Edition ed., pp. 1-26): CRC Press.
- 56 Mintchev, S. (2014). User-Defined Rules Made Simple with Functional Programming. In W. Abramowicz & A.
57 Kokkinaki (Eds.), *Business Information Systems* (pp. 229-240): Springer International Publishing.

- 1 Mohammed, E. A., Far, B. H., & Naugler, C. (2014). Applications of the MapReduce Programming Framework
2 to Clinical Big Data Analysis: Current Landscape and Future Trends. *BioData Mining*, 7(1), 22. doi:
3 10.1186/1756-0381-7-22
- 4 Mondzech, J., & Sester, M. (2011). Quality Analysis of OpenStreetMap Data Based on Application Needs.
5 *Cartographica: The International Journal for Geographic Information and Geovisualization*, 46(2),
6 115-125.
- 7 Montello, D. R. (2002). Cognitive Map-Design Research in the Twentieth Century: Theoretical and Empirical
8 Approaches. *Cartography and Geographic Information Science*, 29(3), 283-304. doi:
9 10.1559/152304002782008503
- 10 Moore, R.E., Kearfott, R.B., & Cloud, M.J. (2009). Introduction to interval analysis (pp. 223): SIAM,
11 Philadelphia.
- 12 Morais, C. D. (2012). Where is the Phrase “80% of Data is Geographic” From? . Retrieved May 2, 2015, from
13 <http://www.gislounge.com/80-percent-data-is-geographic/>
- 14 Musiige, D., Anton, F., & Mioc, D. (2013). *RF Subsystem Power Consumption and Induced Radiation*
15 *Emulation*. (Ph.D.), Technical University of Denmark, Kongens Lyngby.
- 16 Musiige, D., Anton, F., Yatskevich, V., Vincent, L., Mioc, D., & Pierre, N. (2011). RF Power Consumption
17 Emulation Optimized with Interval Valued Homotopies. *Proceedings of the World Academy of*
18 *Science, Engineering and Technology*, 81, 147-153.
- 19 Nakaya, T., & Yano, K. (2010). Visualising Crime Clusters in a Space-time Cube: An Exploratory Data-analysis
20 Approach Using Space-time Kernel Density Estimation and Scan Statistics. *Transactions in GIS*, 14(3),
21 223-239. doi: 10.1111/j.1467-9671.2010.01194.x
- 22 Neis, P., Zielstra, D., & Zipf, A. (2012). The Street Network Evolution of Crowdsourced Maps: OpenStreetMap
23 in Germany 2007-2011. *Future Internet* 2012, 4(1), 1-21. doi: 10.3390/fi4010001
- 24 Pettit, C., Stimson, R., Nino-Ruiz, M., Moradini, L., Widjaja, I., Delaney, P., . . . Kvan, T. (2014). Supporting
25 Urban Informatics through a Big Data Analytics Online Workbench. *NSF Workshop on Big Data and*
26 *Urban Informatics*.
- 27 Poser, K., Kreibich, H., & Dransch, D. (2009). Assessing Volunteered Geographic Information for Rapid Flood
28 Damage Estimation *Proceedings of the 12th AGILE International Conference on Geographic*
29 *Information Science: Advances in GIScience*.
- 30 Richter, K.-F., & Winter, S. (2011). Citizens as Database: Conscious Ubiquity in Data Collection. In D. Pfoser,
31 Y. Tao, K. Mouratidis, M. A. Nascimento, M. Mokbel, S. Shekhar & Y. Huang (Eds.), *Advances in*
32 *Spatial and Temporal Databases* (pp. 445-448): Springer Berlin Heidelberg.
- 33 Riebeek, H. (2015). Big Data Helps Scientists Dig Deeper. Retrieved May 23, 2015, from
34 <http://earthobservatory.nasa.gov/Features/LandsatBigData/>
- 35 Roth, R. E. (2013). An Empirically-Derived Taxonomy of Interaction Primitives for Interactive Cartography and
36 Geovisualization. *IEEE Transactions on Visualization and Computer Graphics*, 19(12), 2356-2365.
37 doi: 10.1109/TVCG.2013.130
- 38 Ruff, J. (2002). Information Overload: Causes, Symptoms and Solutions (pp. 1-13): Harvard Graduate School of
39 Education's Learning Innovations Laboratory (LILA)
- 40 Rulinda, C. M., Stein, A., & Turdukulov, U. D. (2013). Visualizing and quantifying the movement of vegetative
41 drought using remote-sensing data and GIS. *International Journal of Geographical Information*
42 *Science*, 27(8), 1481-1496. doi: 10.1080/13658816.2012.723712
- 43 Saha, B., & Srivastava, D. (2014). Data Quality: The Other Face of Big Data. *Proceedings of the 2014 IEEE*
44 *30th International Conference on Data Engineering (ICDE)*, 1294-1297.
- 45 Schnürer, R., Sieber, R., & Çöltekin, A. (2014). The Next Generation of Atlas User Interfaces: A User Study
46 with “Digital Natives”. In J. Brus, A. Vondrakova & V. Vozenilek (Eds.), *Modern Trends in*
47 *Cartography* (pp. 23-36): Springer International Publishing.
- 48 Sester, M., Arsanjani, J. J., Klammer, R., Burghardt, D., & Haunert, J.-H. (2014). Integrating and Generalising
49 Volunteered Geographic Information *Abstracting Geographic Information in a Data Rich World -*
50 *Methodologies and Applications of Map Generalisation* (pp. 119-155): Springer Heidelberg.
- 51 Sharifzadeh, M., & Shahabi, C. (2009). Approximate voronoi cell computation on spatial data streams. *Vldb*
52 *Journal*, Vldb J, 18(1), 57–75. <http://doi.org/10.1007/s00778-007-0081-y>
- 53 Shekhar, S., Evans, M. R., Gunturi, V., Yang, K., & Cugler, D. C. (2014). Benchmarking Spatial Big Data. In T.
54 Rabl, M. Poess, C. Baru & H.-A. Jacobsen (Eds.), *Specifying Big Data Benchmarks* (pp. 81-93):
55 Springer Berlin Heidelberg.
- 56
57
58
59
60
61
62
63
64
65

- 1 Shekhar, S., Evans, M. R., Kang, J. M., & Mohan, P. (2011). Identifying Patterns in Spatial Information: A
2 Survey of Methods. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, 1(3),
3 193-214. doi: 10.1002/widm.25
- 4 Shekhar, S., Gunturi, V., Evans, M. R., & Yang, K. (2012). Spatial Big-Data Challenges Intersecting Mobility
5 and Cloud Computing. *Proceedings of the 11th ACM International Workshop on Data Engineering for
6 Wireless and Mobile Access - MobiDE '12*. doi: 10.1145/2258056.2258058
- 7 Shneiderman, B. (2014). The Big Picture for Big Data: Visualization. *Science*, 343(6172), 730-730. doi:
8 10.1126/science.343.6172.730-a
- 9 Sinnott, R. O., Bayliss, C., Bromage, A., Galang, G., Grazioli, G., Greenwood, P., . . . Widjaja, I. (2015). The
10 Australia Urban Research Gateway. *Concurrency and Computation: Practice and Experience*, 27(2),
11 358-375. doi: 10.1002/cpe.3282
- 12 Slocum, T. A., Blok, C., Jiang, B., Koussoulakou, A., Montello, D. R., Fuhrmann, S., & Hedley, N. R. (2001).
13 Cognitive and Usability Issues in Geovisualization. *Cartography and Geographic Information Science*,
14 28(1), 61-75. doi: 10.1559/152304001782173998
- 15 Slocum, T. A., McMaster, R. B., Kessler, F. C., & Hugh, H. H. (2008). *Thematic Cartography and
16 Geovisualization, 3rd Edition*: Prentice Hall.
- 17 Steed, C. A., Ricciuto, D. M., Shipman, G., Smith, B., Thornton, P. E., Wang, D., . . . Williams, D. N. (2013).
18 Big Data Visual Analytics for Exploratory Earth System Simulation Analysis. *Computers &
19 Geosciences*, 61, 71-82. doi: 10.1016/j.cageo.2013.07.025
- 20 Stein, A., Groenigen, J. W. v., Jeger, M. J., & Hoosbeek, M. R. (1998). Space-time statistics for environmental
21 and agricultural related phenomena. *Environmental and Ecological Statistics*, 5(2), 155-172.
- 22 Straumann, R. K., Çöltekin, A., & Andrienko, G. (2014). Towards (Re)Constructing Narratives from
23 Georeferenced Photographs through Visual Analytics. *The Cartographic Journal*, 51(2), 152-165. doi:
24 10.1179/1743277414Y.0000000079
- 25 Suthaharan, S. (2014). Big Data Classification: Problems and Challenges in Network Intrusion Prediction with
26 Machine Learning. *Performance Evaluation Review*, 41(4), 70-73. doi: 10.1145/2627534.2627557
- 27 Tan, H., Luo, W., & Ni, L. M. (2012). CloST: A Hadoop-Based Storage System for Big Spatio-Temporal Data
28 Analytics. *Proceedings of the 21st ACM International Conference on Information and Knowledge
29 Management*, 2139-2143. doi: 10.1145/2396761.2398589
- 30 Tran, N., Skhiri, S., Lesuisse, A., & Zimányi, E. (2012). *AROM: Processing big data with Data Flow Graphs
31 and functional programming*. Paper presented at the The 4th IEEE International Conference on Cloud
32 Computing Technology and Science (CloudCom), Taipei.
- 33 Turton, I., & Openshaw, S. (1998). High-Performance Computing and Geography: Developments, Issues, and
34 Case Studies. *Environment and Planning A*, 30(10), 1839-1856. doi: 10.1068/a301839
- 35 Ujang, U., Anton, F., Azri, S., Rahman, A. A., & Mioc, D. (2014). 3D Hilbert Space Filling Curves in 3D City
36 Modeling for Faster Spatial Queries. *International Journal of 3-D Information Modeling (IJ3DIM)*,
37 3(2). doi: 10.4018/ij3dim.2014040101
- 38 Umamaheshwaran, R., Bijker, W., & Stein, A. (2007). Image Mining for Modeling of Forest Fires From
39 Meteosat Images. *IEEE Transactions on Geoscience and Remote Sensing*, 45(1), 246-253. doi:
40 10.1109/TGRS.2006.883460
- 41 Van de Kasstelee, J., & Stein, A. (2006). A model for external drift kriging with uncertain covariates applied to
42 air quality measurements and dispersion model output. *Environmetrics*, 17(4), 309-322. doi:
43 10.1002/env.771
- 44 Van de Vlag, D., & Stein, A. (2006). Modeling Dynamic Beach Objects Using Spatio-Temporal Ontologies.
45 *Journal of Environmental Informatics*, 8(1), 22-33.
- 46 Van de Vlag, D., Vasseur, B., Stein, A., & Jeansoulin, R. (2005). An application of problem and product
47 ontologies for the revision of beach nourishments. *International Journal of Geographical Information
48 Science*, 19(10), 1057-1072. doi: 10.1080/13658810500032404
- 49 Van Zyl, T., Simonis, I., & McFerren, G. (2009). The Sensor Web: Systems of Sensor Systems. *International
50 Journal of Digital Earth*, 2(1), 16-30. doi: 10.1080/17538940802439549
- 51 Veregin, H. (2005). Data Quality Parameters. In M. F. G. Paul A. Longley, David J. Maguire, David W. Rhind
52 (Ed.), *New Developments in Geographical Information Systems: Principles, Techniques, Management
53 and Applications* (pp. 177-189). Hoboken, NY: Wiley.
- 54 Vickers, D., & Rees, P. (2007). Creating the UK National Statistics 2001 Output Area Classification. *Journal of
55 the Royal Statistical Society: Series A*, 170(2), 379-403. doi: 10.1111/j.1467-985X.2007.00466.x

- 1 Vlahogianni, E. I., Karlaftis, M. G., & Golias, J. C. (2006). Statistical Methods for Detecting Nonlinearity and
2 Non-Stationarity in Univariate Short-Term Time-Series of Traffic Volume. *Transportation Research*
3 *Part C: Emerging Technologies*, 14(5), 351-367. doi: 10.1016/j.trc.2006.09.002
- 4 Wang, S., Ding, G., & Zhong, M. (2013). On Spatial Data Mining Under Big Data. *Journal of China Academy*
5 *of Electronics and Information Technology*, 8(1), 8-17.
- 6 Wang, S., & Yuan, H. (2013). *Spatial Data Mining in the Context of Big Data* Paper presented at the The 2013
7 International Conference on Parallel and Distributed Systems (ICPADS), Seoul, KW.
- 8 Wang, S., & Yuan, H. (2014). Spatial Data Mining: A Perspective of Big Data. *International Journal of Data*
9 *Warehousing and Mining*, 10(4), 50-70. doi: 10.4018/ijdwm.2014100103
- 10 Wood, S. A., Guerry, A. D., Silver, J. M., & Lacayo, M. (2013). Using Social Media to Quantify Nature-Based
11 Tourism and Recreation. *Scientific Reports*, 3, 2976. doi: 10.1038/srep02976
- 12 Yan-yan, L., De-qin, Y., & Sheng-lan, L. (2011). Dimensionality Reduction Algorithm Based on Density
13 Portrayal. *Computer Engineering*, 37(21), 138-140
- 14 Zhang, L., Stoffel, A., Behrisch, M., Mittelstadt, S., Schreck, T., Pompl, R., . . . Keim, D. (2012). Visual
15 Analytics for the Big Data Era - A Comparative Review of State-of-the-Art Commercial Systems.
16 *Proceedings of the 2012 IEEE Conference on Visual Analytics Science and Technology (VAST)*, 173-
17 182. doi: 10.1109/VAST.2012.6400554
- 18 Zhu, XD, Huang, ZQ, Shen, GH, & Yuan M. (2009). Variable slide window based frequent itemsets mining
19 algorithm on large data streams. *Control and Decision*, 24(6), 832-836.
- 20 Zielstra, D., & Zipf, A. (2010). A Comparative Study of Proprietary Geodata and Volunteered Geographic
21 Information for Germany. *Proceedings of the 13th AGILE International Conference on Geographic*
22 *Information Science 2010*.
- 23 Zipf, G. K. (1949). *Human Behavior and the Principle of Least Effort*. Oxford, UK: Addison-Wesley Press.
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25
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