Further Insights into Geospatial/Geodetic Engineering

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This article is part of the Systems Engineering and Geospatial/Geodetic Engineering (GGE) Knowledge Area. It discusses in more detail a selected set of topics that a beginner in Geographic Information Systems (GIS) and science or a systems engineer adopting respective techniques might be interested in or should be aware of. Topics discussed include bodies of knowledge on geospatial technologies, various aspects associated with geographic data, and standardization in the geospatial domain.

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GIS related Bodies of Knowledge

The emphasis of the article Overview of Geospatial/Geodetic Engineering was to focus on to what extent systems and systems of systems are dependent on GIS related technologies and where potential interfaces or contributions are. In order to provide now an improved but still brief overview of which topics are related in general to geospatial and geodetic engineering and how broad the geospatial domain actually is, a high-level introduction into existing bodies of knowledge in the geospatial domain is provided here.

The work on a body of knowledge (BOK) for the geospatial domain actually goes back into the 1980s (cf. Kemp & Goochild 1991, cited in Stelmaszczuk-Górska et al. 2020), and since then at least two major workstreams have evolved. One in the United States that culminated first in 2006 with the publication of Edition 1 of the Geographic Information Science and Technology Body of Knowledge (GISTBoK) by the University Consortium for Geographic Information Science (UCGIS) (DiBiase et al. 2006). For the Geospatial Intelligence (GEOINT) discipline, a refinement was elaborated by the United States Geospatial Intelligence Foundation (USGIF). The UCGIS GISTBoK also formed the nucleus for the other workstream in Europe which started with the GI-N2K: Geographic Information – Need to Know project (Vandenbroucke and Vancauwenberghe 2016) that aimed to better reflect European aspects in a BOK and to provide an ontological structure of concepts and relationships (Hofer et al. 2020). The European workstream was then further pursued as part of the Earth Observation for Geoinformation project (EO4GEO) that refined and extended the work from GI-N2K

(Stelmaszczuk-Górska et al. 2020; Hofer et al. 2020).

UCGIS: Geographic Information Science and Technology Body of Knowledge (GISTBoK)

For the 2006 GISTBoK a hierarchical decomposition of the geospatial domain was conducted into 10 Knowledge Areas which were again divided into 73 Units and then into 329 Topics. There were over 1600 Learning Objectives listed in these topics. With the update that began in 2013 (Wilson 2014), there are also 10 Knowledge Areas in the current GISTBoK but they have changed partly versus the 2006 version. As of the beginning of 2022, there are 54 Units and 363 Topics. The current Knowledge Areas are:

- Foundational Concepts, with 7 Units and 35 Topics;
- Knowledge Economy, with 4 Units and 20 Topics;
- Computing Platforms, with 5 Units and 28 Topics;
- Programming and Development, with 5 Units and 23 Topics;
- Data Capture, with 8 Units and 35 Topics;
- Data Management, with 7 Units and 53 Topics;
- Analytics and Modeling, with 9 Units and 70 Topics;
- Cartography and Visualization, with 6 Units and 36 Topics;
- Domain Applications, with 44 Topics (with no categorization into Units); and
- GIS&T and Society, with 3 Units and 19 Topics.

It should be noted however that the GISTBoK is constantly evolving and for the latest version the respective GISTBoK online resource has to be checked. Additionally, a feature of this BOK is that many Topics are linked with respective citable articles providing insights into the subjects at hand. The UCGIS also provides at its web site (UCGIS BOK) information on open educational resources on GIS and GIScience.

USGIF: GEOINT Essential Body of Knowledge

Aside from the activities hosted by the UCGIS that were mainly driven by academia, the USGIF published in 2014 the first version of its GEOINT Essential Body of Knowledge that targeted the GEOINT discipline. Among other sources, it was based on the 2006 GISTBoK (DiBiase et al. 2006) but extending it where necessary to better reflect the broader needs of GEOINT and related industries. The second version (Brooks et al. 2019) was published in 2019 after an 18 months period of preparation with a survey in the GEOINT community involving various subject matter experts that interpreted the results of the survey. It serves as a guide to what skills are required in the GEOINT discipline and acts as a blueprint for respective Certified GEOINT Professional exams (Brooks et al. 2019; Baber 2018). The GEOINT Essential Body of Knowledge version 2.0 is divided into three parts. The first one is related to “Technical Competencies” with the following areas:

- GIS & Analysis Tools;
- Remote Sensing & Imagery Analysis;
- Geospatial Data Management; and
- Data Visualization.

The second part is related to “Cross Functional Competencies” which cover general skills like soft skills or common GEOINT knowledge and practices suitable for the GEOINT practitioner, whereas the third part looks at “Emerging Competencies”, like data science, machine learning techniques, virtual reality. artificial intelligence, and unmanned aerial platforms.

It is worth mentioning that, since 2015, USGIF also publishes the “State and Future of GEOINT Reports” on a yearly basis. These may also serve as a general reference on future trends in geospatial technologies.

Europe: The "GI-N2K: Geographic Information - Need to Know" and the "EO4GEO: Earth Observation for Geoinformation" BOKs

The GI-N2K project funded by the European Union's (EU) Erasmus Lifelong Learning Program and its BOK started as well with the 2006 GISTBoK (DiBiase et al. 2006) and had 10 Knowledge Areas. For these Knowledge Areas 63 sub-concepts were identified and further divided into 301 on level 3. However, in some instances level 3 was even further de-composed into level 4 and partly into level 5 concepts. At the end, 411 concepts were defined on these levels. Additional features that were provided with this BOK were curriculum design tools and a GeoWiki to enable discussion between experts.

The most recent development in European GIS-related BOKs is the EO4GEO BOK that continues and further develops as part of the Erasmus+ Sector Skills Alliance project EO4GEO the work conducted in the GI-N2K project. As Earth Observation (EO) and Geoinformation (GI) data sources, especially from the space sector, are gaining nowadays much more importance for data capture and updates of derivative data, the respective skills for data capture, information processing, standalone and combined analysis and associated applications need to be defined and matched or merged with the previous BOKs to reflect this change in academia, business and applications (Stelmaszczuk-Górska et al. 2020). An analysis revealed that "neither the American nor the European GIS&T (comment: Geographic Information Science and Technology) and GI-N2K BOKs include comprehensive information on EO" (Stelmaszczuk-Górska et al. 2020). Additionally, since there was a criticism that the previous BOKs were too much oriented along education driven by academia and too theoretical with a lack of practical aspects, an emphasis was made to “better align” the academically oriented EO4GEO BOK “with the business, professional, and industrial perspective” (Hofer et al. 2020) by analyzing a set of relevant business processes with regard to applicable concepts.

The EO4GEO BOK has at its highest level 14 subconcepts as follows:

- Analytical Methods, with 14 subconcepts;
- Conceptual Foundations, with 8 subconcepts;
- Cartography and Visualization, with 6 subconcepts;
- Design and Setup of Geographic Information Systems, with 4 subconcepts;
- Data Modeling, Storage and Exploitation, with 5 subconcepts;
- Geocomputation, with 4 subconcepts;
- Geospatial Data, with 4 subconcepts;
- GI and Society, with 6 subconcepts;
- Image processing and analysis, with 6 subconcepts;
- Organizational and Institutional Aspects, with 5 subconcepts;
- Physical principles, with 2 subconcepts;
- Platforms, sensors and digital imagery, with 4 subconcepts;

- Thematic and application domains, with 5 subconcepts; and
- Web-based GI, with 7 subconcepts.

Similar as with the GIN-2K BOK, there are partly also further levels below the subconcepts. In addition to the BOK, it provides an occupational profile tool, a job offer tool, a curriculum design tool, a BOK annotation tool, a BOK matching tool and other educational features. For the concepts, their names are given along with descriptions and references. A set of 5 relationships between the concepts is maintained, and skills explaining the practical use of the EO*GEO knowledge are associated with the concepts (Hofer et al. 2020). The BOK exploration is supported by a graphical tool.

Geographic Data and Metadata

Geographic Data

Geospatial data is actually the fuel needed for any type of geographic application, whether it might be only for visualization purpose, e.g. as background information for real-time situational awareness applications, or for advanced spatial analytics involving different data sources and specific analysis methods. A first categorization into the two fundamental concepts of geographic data has already been given in the SEBoK article Relationship between Systems Engineering and Geospatial/Geodetic Engineering. They are:

- Continuous fields, i.e. spatially distributed phenomena with no clear limits or boundaries and representing “the real world as a finite number of variables, each one defined at every possible position” (Longley et al. 2015). For the case that repeated pattern of positions is used, the term raster data is commonly used, especially for the case that an equidistant matrix pattern is used. However, a matrix could potentially have different resolutions in columns and rows, or theoretically also other regular patterns could be involved, such as hexagonal patterns, but these applications are very rare.
- Discrete objects or features, which are delimited by boundaries and potentially associated with a set of attribute data to describe them further beyond their spatial properties. This type of data is also termed vector data in a GIS context.

Beyond these two fundamental concepts, the different aspects that need to be considered for geographic data when designing a system using this data are very diverse and cannot be treated in full detail here. A selection of important key words coming from practical experiences to be considered when implementing GIS databases include:

- What data is actually needed (examples see below)?
  - At what scales shall the data be visualized, i.e. the level of detail needed.
  - Dimensionality: typical dimensionalities used in GIS technologies are:
    - 2D, describing the earth surface in a flat plane, like a paper map;
    - 2.5D, with a unique z-value to a position in the horizontal plane;
    - 3D, where all three dimensions are considered; and
    - Time dimension: for the case of 3D data then 4D, but as also the former 2 cases may have variations in time this is treated here as time dimension.
  - What are the critical infrastructures that need to be shown, such as transport networks?
- What standards need to be considered, such as feature catalogues, interface and data format standards, data acquisition standards etc.?
- What is the positional accuracy required for the geographic data? This is typically associated with data acquisition method to be selected and obviously with the costs involved.
- What is the level of semantic detail needed, e.g. how many feature attributes shall be captured for features / vector data and how big is the set of domain values from which they shall be selected?
- Are there complex topological relations to be captured and maintained, i.e. to establish connectivity for the vector data, for example, for routing applications or utility networks?
- Questions on updates:
  - How often does the data need to be updated? This is directly related to maintenance costs for the database, i.e. recurring costs to be considered, but also to availability of resources for the updates.

    - How shall the data be updated? Is it possible to use a central service for the data which is updated, i.e. can the responsibility for the updates be delegated?
    - What communication lines are used when data and updates are distributed in a system? Or is a service model the better choice as it realizes a single source of information principle? A systems engineers has to keep in mind that geographic data can reach considerable data volumes (depending on type of data terabytes and petabytes) that cannot be easily distributed over the air for example.
- What are the data sources that may or have to be used? How are bounding conditions on the use of the data?
    - Authoritative data from a spatial data infrastructure, from international or national governmental agencies (or even intergovernmental agencies), such as national surveys like the USGS or the British Ordnance Survey, or on an international level the United Nations.
    - Commercial data sources, such as satellite imagery service providers, or mapping service providers.
    - Open sources, from activities like the Open Street Map or Open Seamap initiatives.
    - Copyrights and Intellectual Property Rights associated with the data sources.
    - Classification of data.
    - Bounding legal conditions (e.g. export control laws and regulations for export of data, as for example some satellite image resolutions may have export restrictions).
    - Liability aspects for the data, especially for the cases of legal boundaries, i.e. national borders. This is of particular relevance when borders are under dispute between neighboring countries!

For implementation aspects again Tomlinson (2019) and Peters (2012) are referred to as well as the online successor to the latter text book, System Design Strategies.

Metadata for Geographic Data

Whereas the section above discusses aspects of geographic data itself, it is also of fundamental importance to make this data available to or detectable by potential users. This is done by describing the data by metadata and having the metadata available, for example in a catalog where users can search for it. Whereas the Dublin Core data set (ISO 2017; ISO 2019b) defined by the Dublin Core Metadata Initiative is now used to describe general items, for the special case of geographic data, a set of dedicated ISO standards has been developed (ISO 2014, with its amendments ISO 2018 & ISO 2022; ISO 2020d). As such, ISO 19115 "provides information about the identification, the extent, the quality, the spatial and temporal aspects, the content, the spatial reference, the portrayal, distribution, and other properties of digital geographic data and services" (ISO 2014).

Geocoding Systems, Localization and Geographic Search

One further particular aspect looked at here is how a spatial reference for a feature may be expressed. Certainly the most well-known way to describe a location technically or mathematically is by coordinates, either in 2 dimensions for the simple case of a plane, or in 3 dimensions or even adding a time dimension. Standardized ways to express geographic coordinates are covered by ISO 6709 (ISO 2009) but also Cartesian coordinate systems are in use. However, a spatial reference may also be given by other types of geographic identifiers where a location is expressed by a specific (sometimes non-numeric) code or name. A gazetteer is used to manage geographic identifiers, such as geographic names, e.g. names of states, provinces, or other geographically identifiable features such as lakes etc. Other codes in use are for example addresses (where it should be remembered that there are also different postal address types in use), country codes (ISO 3166-1, ISO 2020a) and codes of country principal subdivisions such as states and provinces (ISO 3166-2; ISO 2020b), but there are many other, sometimes application or domain specific or even commercially developed geocodes.

An example of a commercially developed and thus proprietary geococde is the What3words system that is even in use as a postal addressing system in some countries. By dividing the Earth's surface into squares of about 3 meters by 3 meters and assigning unique 3 ordered words to each of them, the codes for each location are established. There are, however, several other systems available, like Geohash or Mapcode, which have no license restrictions.

In general, geocodes may be categorized into non-hierarchical and hierarchical geocodes, while for the latter the accuracy of location position increases in a refinement/subdivision process, similar to adding more significant digits to a coordinate. A well-known dataset of geographic names often used in GIS applications is provided by geonames.org.

These codes can then also be used to navigate in a geographic display, i.e. by inserting a geocode one can jump directly in the display to the respective position or features (described by positions) associated with the code. In case the code is ambiguous (as it is sometimes the case for geographic names like city names) a disambiguation could be given, in order to clarify the selection. While this approach is mainly used to navigate in a display or to find a location, it should not be confused with the topic of efficiently searching in multidimensional spatial databases. This is not treated here as it relates to database management system design and implementation, including spatial indexing, for example with space filling curves.

Example: The United Nations 14 Global Fundamental Geospatial Data Themes

The set of geographic data to be used in a system will always be dependent on the purpose and goals of the system at hand, and therefore no general purpose structure can be provided here. Some examples of geographic data have already been given in the SEBoK article Relationship between Systems Engineering and Geospatial/Geodetic Engineering in the frame of Geospatial Aspects in Modeling and Simulation. In order to extend this for a better and broader overview of what may considered as relevant in general, the following list of geospatial data themes may serve as a first indicator. It has been elaborated as "The 14 Global Fundamental Geospatial Data Themes" by the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM 2019).

- Global Geodetic Reference Frame;

- Addresses, such as postal addresses, see above;
- Buildings and Settlements;
- Elevation and Depth, e.g. provided by Digital Elevation Models and Digital Terrain Models (DTM);
- Functional Areas, such as administrative or legislative areas;
- Geographical Names, e.g. geographic identifiers managed and provided by a gazetteer, see above;
- Geology and Soils;
- Land Cover and Land Use;
- Land Parcels, e.g. a cadastre or a land register;
- Physical Infrastructure, including industrial and utility facilities;
- Population Distribution;
- Orthoimagery, which is a special case of geographic imagery in orthogonal projection;
- Transport Networks, e.g. rails, roads, waterways and air transport routes associated potentially with connectivity relations; and
- Water, including rivers, lakes and marine features.

The UN-GGIM (2019) provides more insights and information into the themes, e.g. what standards are available and possible sources for data. In GIS where often multiple geographic data sets from different sources are processed in a combined way, these data sets are organized into a stacked set of layers which may be for example switched on and off individually for visualization purpose.

Standardization Organizations active in the Geospatial Domain

In the following selected international civil organizations are briefly introduced that publish standards related to the geospatial domain.

The Open Geospatial Consortium (OGC)

The Open Geospatial Consortium (OGC) was founded in 1994 and publishes open standards and specifications in the geospatial domain. The documents are created in a member-driven consensus process. The most successful standards are the Web Map Service (WMS; OGC 2006) and the Web Feature Service (WFS; OGC 2010), but

OGC has published about 70 implementation standards and about 20 abstract specifications.

OGC works closely with ISO TC211 (see next section), and some documents are jointly elaborated and published. For example, the above mentioned WMS is also an ISO standard (namely ISO 2005), as is the WFS (ISO 2010). Another example is the specification of the Geography Markup language (OGC, 2012; and ISO, 2015 & 2020a) that is published by both OGC and ISO. Special care has to be taken which version is published in which document since they are not necessarily published in the same versions at the same time. Besides the cooperation with ISO TC211, OGC has in addition other alliance partners, such as the Object Management Group (OMG), the Organization for Advancement of Structured Information Standards (OASIS), the Web3D Consortium, the World Wide Web Consortium (W3C), the International Hydrographic Organization (IHO) and the World Meteorological Organization (WMO) (both see below), and also with other ISO TCs.

Several companies well-known to the general public such as Amazon Web Services, Apple, Google, Microsoft, Oracle and SAP, and universities, governmental, inter-governmental and non-governmental organizations as well as individuals are members of the OGC at different levels of membership, summing up to more than 500 members.

ISO TC 211 “Geographic information/Geomatics”

The International Organization for Standardization (ISO) is certainly the best known international standardization organization in the world and is organized into technical committees which develop the standards. The Technical Committee (TC) 211 is related to “Geographic information/Geomatics”. TC211 has published more than 80 standards, most of them as part of the 191xx family of standards, including abstract specifications and interface standards together with the OGC. Several ISO TC211 standards are referenced in the list of references below. TC211 also maintains the Online Multi-Lingual Glossary of Terms (MLGT) at Geolexica that was used to define terms used in this Knowledge Area. Typically ISO standards are also promulgated as national standards, or as European standards from the respective European standardization organizations.

International Hydrographic Organization (IHO)

Founded in 1921 as the International Hydrographic Bureau and renamed in 1970 to the International Hydrographic Organization (IHO), IHO is an intergovernmental organization that standardizes and coordinates activities in the area of hydrography, nautical cartography and thus nautical charts to ensure initially and still primarily the safety of navigation. With the increasing interest in the marine environment, e.g. for the installation of offshore wind farms, the importance of the activities of IHO has even more increased as it publishes standards for the creation and exchange of digital hydrographic data (IHO 2020; IHO 2017a; IHO 2000, with its appendices) that may serve as a GIS base map layer, and also for the portrayal of data (IHO 2014). The way how hydrographic offices can support the creation of spatial data infrastructures by providing data for the marine environment is discussed in IHO (2017b). With the revision of its standards to adhere to ISO TC211 standards, IHO is now transitioning to the S-100 family of standards (IHO 2018).

World Meteorological Organization (WMO)

Originally founded in 1873 as the International Meteorological Organization and renamed in 1950 into the World Meteorological Organization (WMO), WMO is an intergovernmental organization and specialized agency of the United Nations. According to its mandate as described on its website, it provides the framework for international cooperation "in the areas of meteorology (weather and climate), operational hydrology and related geophysical sciences" and facilitates "free and unrestricted exchange of data and information, products and services in real- or near-real time on matters relating to safety and security of society, economic welfare and the protection of the environment." WMO defines several data formats for the exchange of weather information (WMO 2019 & 2021a/b).

Clearly the scientific background needed to create meteorological information goes far beyond of what is needed in standard GIS applications. From a GIS perspective, weather information may be treated as one or several information layer(s), and due to the typically required real- or near-real time information respective online interfaces have to be established with weather data providers, whether they are national weather services or commercial companies.

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