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# GEODATA IN SCIENCE – A REVIEW OF SELECTED SCIENTIFIC FIELDS

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## ABSTRACT

**Aim of the study**
Today, completely new forms of geo-information systems are becoming increasingly popular. New technological possibilities allow these systems to be adapted to the requirements and needs of societies. This paper is an extensive literature review of the use of geodata in various scientific fields, in STEM (science, technology, engineering, and mathematics) disciplines. However, as there is no universal agreement as to which disciplines are included in the STEM, the authors also included related fields such as geography or transport.

**Materials and methods**
Already a preliminary analysis of the Web of Science Core Collection database has shown that geodata is used very widely, in every scientific discipline analysed (with varying degrees of sophistication). The main objective of the paper is to provide a comprehensive analysis of the usage of geodata in five areas: bathymetric measurements, satellite geodata, aerial retrieved geodata, levelling networks, and GIS data.

**Results and conclusions**
The results showed the increasing availability of data that can contribute to a better understanding and management of our planet. Geodata as a tool is overly broad and general, and it is used or might be used in every discipline of science.

**Keywords:** science, data, geodata, STEM, research, GNSS, LiDAR, GIS, bathymetry, satellite

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## INTRODUCTION

Scientists have realized that the main essence and potential of the use of geodata is the need for a proper comprehension of the underlying concepts of time, scale, and space in the context of the Earth's framework. In spite of the fact that these concepts are presented and discussed in different media – from news to academic discussion – and typically without critical thinking, it is evident that the subject of geodata is not trivial at all (Awange et al., 2019).

Nowadays, the use of geopositioning techniques is omnipresent and such techniques are used on a daily basis. To be able to navigate either on land, water, or air, we use georeferenced data: the so-called geodata (Taha et al., 2021). The need for this type of data arises from the necessity to optimize logistics services, construction, agriculture, economic and social developments; and that is closely connected with the global navigation satellite system (GNSS) (Hotz, 2005). Determining position is now related not only to engineering fields of work but also to business administration, local administration such as city hall and other national and regional political administrations, which can reveal different patterns of developments and disparities obscured by various local agencies. The main characteristic of geodata is the process of assigning each statistical entity to a precise location on the Earth's surface (Apollo et al., 2021; Goodchild, 2013; Kampczyk and Dybeł, 2021; Ostermann et al., 2022).

One hot topic nowadays, which is sure to remain relevant in years to come due to social awareness, is climate change, the interrelated behaviour of which has encouraged different researchers from a wide variety of topics to work together towards solving a frequent problem. An urgent issue is to discern the complexity in the highly interconnected, evolving processes of the Earth's system, thus the need for integrated models to quantify these phenomena represents a demanding and arduous task that is related to terrestrial research.

The main aim of Earth Science (ES) is "to provide descriptions and explanations and, if possible, predictions of phenomena on the Earth and Earth-like planets" (Kleinhans et al., 2010).

Currently, we can benefit from long-term data sets that can be analysed in terms of different scientific disciplines such as chemistry, physics, geodesy, meteorology, atmospheric science, and many others, which can combine all of these data into a common geodata database to be able to relate and interconnect different regional and global events (Reid et al., 2009; Nistor and Buda, 2015; Banda et al., 2022; Mensah et al., 2022). Also, with the rapid advancement of remote sensing techniques and high-resolution sensors, abundant heterogenous environmental data are being generated as well as numerical models are developed, representing the ultimate evaluator for the validity of our understanding regarding Earth phenomena.

Another problem that arises is how, when and at what time interval these copious amounts of data can be provided to civil society. There is also a special need for geodata and for geographically referenced data to be obtained or provided in near real-time or even in real-time. The International GNSS Service (IGS) which since 1994 has provided high-quality, open-access GNSS data products, and its continued development to facilitate the implementation of a global reference frame for academic, scientific and commercial applications. It has been continually developing since, and generating an astounding amount of geodata that is addressed to the public (Johnston et al., 2015). As a result of the progress made by the IGS community, the Real-Time Service (RTS) was created to support real-time applications that require different types of geodata, enabling the use of the technique called precise point positioning (PPP) and related applications, which can be employed in disaster monitoring, determination of water vapour content in the troposphere, and time synchronization.

Geodata is a term used alternatively with geographic information, spatial information, geospatial information, geo-information, or location-based data (UN-GGIM, 2018). Geodata combines attribute information and location information (typically, coordinates on the Earth). A geographic coordinate system expressing longitude and latitude is used to assign locations to geodata. A projected x, y coordinate system may also be applied for this purpose (Kang-Tsung, 2018). Geospatial data constitute the most essential element of geographic information systems (GIS), which are used for storing, querying, analysing, and displaying the stored data. The concept of geodata in its modern interpretation refers to a wide variety of data and has definitely gone beyond earth sciences. The broad information provided by geodata may present details of phenomena above or below the Earth's surface. The geodata may include anthropogenic features, such as buildings, roads, paths, railways, and hydraulic structures, or naturally occurring phenomena, such as reservoirs and watercourses, plant formations, and soil. The geoinformation may also include information from other fields such as economics, sociology, management, and education, as well as transient phenomena (for instance, weather systems) (Goodchild, 2005). In order to achieve clarity of the broad information contained in the geodata, GIS principles must be applied. Most importantly, map layers representing different geospatial data must be spatially aligned. This means that the layers must be based on the same spatial reference. Geodata must be in numerical form (vector or raster) since they are used for spatial analyses. The spatial component of geographic information is conventionally recorded in one of two formats: raster or vector (Congalton, 1997; Lambin, 2001). The vector data model is based on points, lines, and polygons with a spatial reference frame – latitude and longitude. This model is used to represent spatial features with clear spatial locations and boundaries, such as roads, watercourses, parcels of land, or survey sites. Raster data models are composed of pixels or grid cells. Each pixel is assigned a value representing a spatial feature and a position denoted by a pair of (x, y) coordinates. Point features are assigned to individual pixels. Linear features are shown by a series of adjacent pixels, while polygon features are shown by sets of adjacent grid cells (Congalton, 1997). The assignment of raster values depends on the type of information. A distinction can be made between continuous rasters, where the value changes gradually (e.g., temperature, pollution), and discrete rasters, where pixels are assigned to different classes (e.g., land cover classes, vegetation). The raster format is not precise, but it has the advantage of having fixed cell locations. Therefore, a significant part of the data used in GIS is presented in this format. It allows for efficient manipulation and analysis in computational algorithms.

The resources of the Internet are the world's largest geodata library. Official statistics, geospatial information, satellite data, big data, and publicly sourced data are combined in various commercial and open databases. Data from these diverse sources should be accessible, interoperable, and standardised, so that their full potential can be exploited (UN-GGIM, 2015). For decades, the creation, maintenance, and distribution of geodata were entirely the domain of state survey offices and commercial companies. This was due both to the need for specialised surveying equipment, and to the cost of maintaining and distributing geodata (Elwood et al., 2012). The development of smart computing technology, widespread access to the mobile internet, and significant transformations of its architecture have changed public attitudes toward a wide variety of services. Mass access to mobile devices equipped with satellite navigation has made it easy and precise for society to generate and collect geo-information in various forms. Technological change is taking place simultaneously with societal changes. Making the basic functions of GIS tools available to the public has been termed the "democratisation of GIS" (Butler, 2006). Additionally, the rapidly developing public participatory approach to building publicly available geodatabases has come to be known as "public participatory GIS" (Sadler, 2016) and the "wikification of GIS" (Kamel Boulos et al., 2011). Thanks to rapid developments, the generation and sharing of several types of spatial information by the public is nowadays extremely widespread and is described as "Volunteered Geographic Information" (VGI). Although geodata from such sources may contain errors, in some cases this is the only available spatial information (Sini et al., 2020). Among the many platforms that enable the collection and use of VGI are the following: Google Earth, OpenStreetMap, GeoTagging Flickr, Wikimapia and Foursquare. VGI will not compete with and will not replace the data updating and maintenance activities of "conventional" GIS databases. However, it can be a low-cost and useful complement to databases of information and might be harnessed in a countless number of applications (see: Figure 1). Next to the voluntary acquired data there are commercial companies providing data available free-of-charge. These include Google street view, USGS Earth Explorer, and ArcGIS Open Data hub, among others (Biljecki and Ito, 2021; Hasan et al., 2022; Wang et al., 2023).

The authors also analysed the number of occurrences, and the fields in which the geodata were analysed. For this purpose, we searched for the phrase "geodata" from the Web of Science Core Collection in the "topic" field (including the title, as well as keywords and abstract if accessible in the WoS). Figure 2 shows a tree map of the top 10 search results with the topics that included geodata. This comprised 2,024 publications, and the main scientific categories in this field were Remote Sensing, Environmental Sciences, and Multidisciplinary Geosciences.

The article is an attempt to summarize the current state of science in the field of geodata. The term "geodata" nowadays refers to a much more comprehensive range of data than just those used in surveying, geodesy, and cartography. However, the common tools used by land surveying with a decreased level of accuracy are not in the scope of the review. To give but one example, satellite navigation positioning in our mobile phones or car navigation may be used for social studies (human behaviour or network), but in a narrowed scope, these data are not considered. To reiterate, this article explores the use of geodata in selected technical and natural sciences, with a particular focus on STEM (science, technology, engineering, mathematics) in 5 areas: bathymetric measurements, satellite geodata, aerial retrieved geodata, levelling networks, and GIS data.

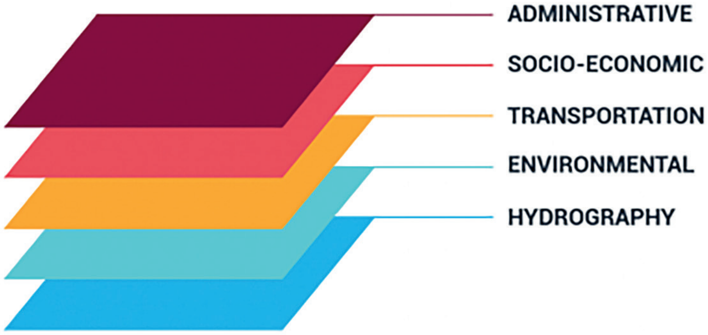


**Fig. 1.** Sample themes of geodata (source: https://gisgeography.com/what-is-geodata-geospatial-data/, accessed: May 5, 2023)

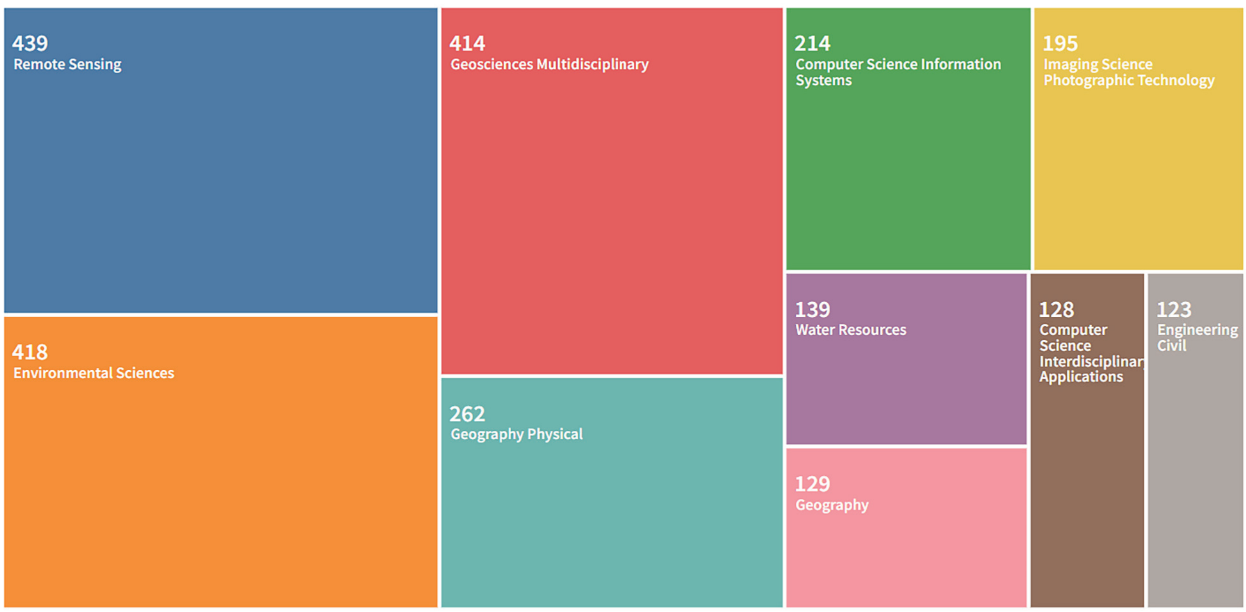


**Fig. 2.** Tree map of phrase "geodata" in Web of Science Core Collection database (source: https://www.webofscience.com, accessed: May 5, 2023)

Geodata can be described as interdisciplinary information set on many levels. Researchers from a variety of scientific disciplines obtain their geodata. There is a need of varied expertise and training in order to carefully plan and perform data acquisition, particularly if specific accuracy and density of data is needed. Post-processing and data transformation demands even more skill, and therefore it requires scientists and practitioners. Typically, where data acquisition is done by STEM practitioners, processing into usable format often requires help from cartographers, human perception experts, environmental experts, and even posologists, in order to create a useful and easy-to-understand set of geodata. Then the users of such data can be described as the entire scientific world since every branch of science and industry at some point will need some of those data. This is why in this paper we present geodata in the context of their interdisciplinary nature.

## SELECTED USAGE/APPLICATIONS

### Bathymetric measurements

Bathymetry is a branch of hydrology that deals with the measurement of depth and watercourses (Christ and Wernli, 2013). The results of bathymetric measurements marked on a waterbody map in the form of depth points make it possible to determine isobaths, i.e., isolines connecting points of the same depth, illustrating the shape of the bottom (NOAA, 2003). Based on the data provided by the General Bathymetric Chart of the Oceans (GEBCO), it should be stated that only about 20% of the world's ocean floor is explored (CCOM, 2020), despite the fact that the aquatic environment is one of the most dynamically changing regions on the Earth, in particular in the coastal zone (Yunus et al., 2019).

Bathymetric measurements are carried out using a variety of devices and measurement methods (Apicella et al., 2023) that should meet the requirements of the International Hydrographic Organization (IHO) S-44 standard (IHO, 2020). The most important of these include:

1. The tacheometric method, which consists in determining the location of the depth point based on the measurement of horizontal and vertical angles, as well as distances, most often made with the use of an electronic total station. This method is characterised by high accuracy of position measurement (< 1 cm). However, its main disadvantage is low coverage of the bottom, with measurements that depend on the depth to which a surveyor with a pole can go (Lane et al., 1994; Koljonen et al., 2013).
2. The geodetic method, which consists in entering the water to a given depth using a Global Navigation Satellite System (GNSS) receiver mounted on a pole. Similarly to the tacheometric method, it is characterised by high accuracy of position measurement (1–2 cm using a GNSS Real Time Kinematic or RTK receiver), and small coverage of the bottom with measurements (Salameh et al., 2019; C. Specht et al., 2019).
3. The hydrographic method that consists in bathymetric measurement using manned vessels, on which a measurement set comprising of a hydroacoustic device [MultiBeam EchoSounder (MBES) or Single Beam Echo Sounder (SBES)] and a positioning system [marine Differential Global Positioning Receiver (DGPS) receiver] is usually mounted. This method has a limited range of operation resulting from the depth of hydrographic vessels (approx. 1 m and more) and the installation of echosounder transducers on their bows. For practical purposes, we can safely assume that no bathymetric measurements to a depth of 1 m are conducted using the hydrographic method. In addition, we need to remember that this type of hydrographic survey is associated with large financial outlays (Popielarczyk and Templin, 2014; C. Specht et al., 2016).
4. Satellite Derived Bathymetry (SDB), which consists in determining the waterbody depth by measuring the light intensity using high-resolution multispectral images (0.5–2.5 m) from DubaiSat, IKONOS, QuickBird, WorldView satellites, or moderate resolution multispectral images taken from Landsat satellites (Salameh et al., 2019). Undoubtedly, the advantages of satellite bathymetry include the lack of costs associated with the implementation of hydrographic surveys, the significantly shorter time of their performance compared to traditional methods, or the possibility of conducting research in remote and inaccessible areas (see: Figure 3). The disadvantage of the SDB method is the unsatisfactory depth measurement accuracy (down to several meters), which is largely

dependent on the water transparency (Kasvi et al., 2019; J. Li et al., 2019).

5. Airborne LiDAR Bathymetry (ALB)/Airborne Laser Hydrography (ALH), which consists in determining the waterbody depth by measuring the time difference between the moments of receipt of two pulses recorded by on-board sensors of a manned aircraft (Szafarczyk and Toś, 2023). The advantage of ALB/ALH systems is full coverage of the bottom with measurements; however, their accuracy depends on the water transparency (Guo et al., 2022). Research conducted by (Su et al., 2020) has shown that these systems do not meet the accuracy requirements for the most stringent guidelines of IHO hydrographic surveys (i.e. for them to be exclusive and special). The disadvantages of ALB/ALH systems include low resolution, which depends to a considerable extent on local hydrometeorological and hydrological conditions, as well as significant financial outlays for research.
6. Unmanned Surface Vessel (USV), which are remotely controlled vessels, radio-controlled, enabling hardware integration with a GNSS receiver and a MBES or a SBES, intended for hydrographic surveys of lakes, port basins, rivers, and small water reservoirs . The main advantage of USVs is their small draft (10–20 cm in some cases). Thanks to this, unlike manned hydrographic vessels, they can perform bathymetric measurements in shallow waterbodies with a depth of up to 1 m with an accuracy required for the most stringent guidelines of IHO hydrographic surveys (exclusive and special) (M. Specht et al., 2020).
7. Unmanned Aerial Vehicle (UAV), which are aircraft that is capable of flying without a pilot on board. Therefore, the flight of the aircraft must be carried out autonomously, pre-programmed or by using remote control (Gupta et al., 2013; Lewicka et al., 2022). Flying drones are characterised by high availability, high manoeuvrability, and small size and

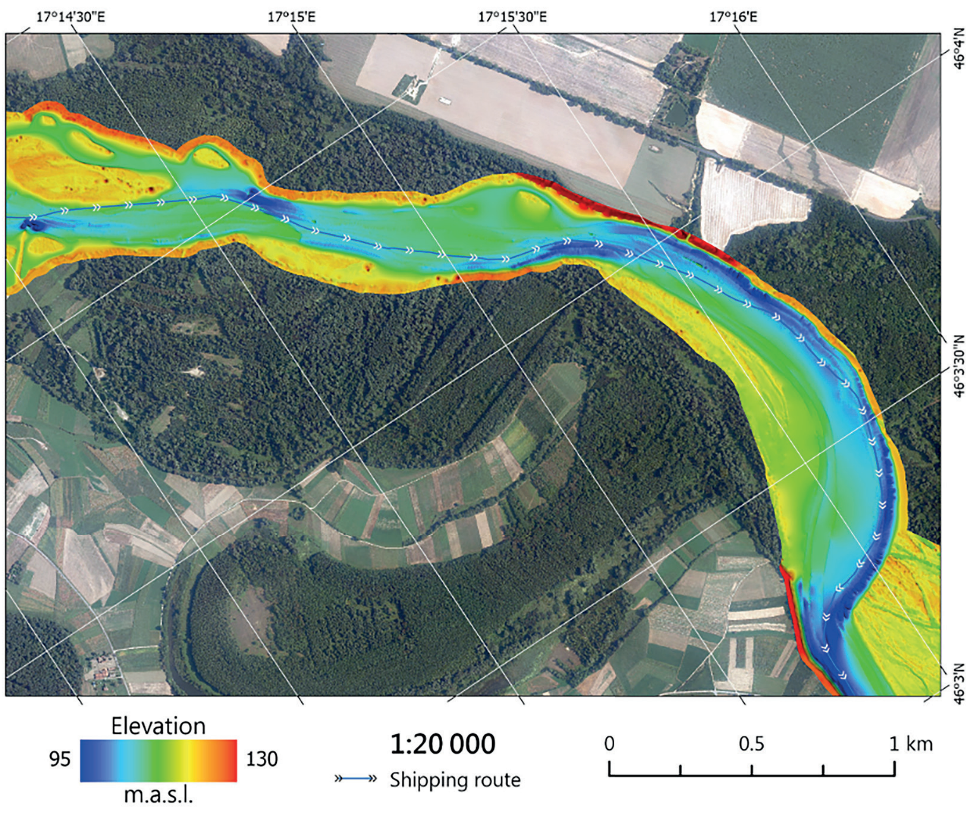


**Fig. 3.** Model of the depth and course of a river using bathymetric surveys (Halmai et al., 2020, p. 17)

they also enable complex photogrammetric measurements, thanks to the possibility of mounting high-resolution digital cameras or 3D laser scanners on them (Burdziakowski, 2020; Gonçalves and Henriques, 2015). Recently, there has been an increased interest in photos taken by UAVs for determining the depth of shallow waterbodies using the Structure from Motion (SfM) technique. The latter consists in providing three-dimensional scenes, using a series of temporal RGB images and georeferenced information. The conducted research proves that the methods based on the SfM technique do not meet the accuracy criteria required for the most stringent guidelines of IHO hydrographic surveys (exclusive and special) and depend to a large extent on water transparency (M. Specht et al., 2022).

**Satellite systems**

GNSS (Global Navigation Satellite System) systems are now the basis for GNSS positioning, such observations being based on geodata (Leick et al., 2015) in addition to the ready-to-use coordinates in a given coordinate system based on a global rotational ellipsoid model, most commonly WGS-84 (Xie et al., 2021). However, satellite data also includes other systems such as InSAR (Interferometric Synthetic Aperture Radar) or LiDAR (Light Detection and Ranging) (Benoit et al., 2015):

1. GNSS systems also have geodata associated with reference systems other than ECEF (Earth-centred, Earth-fixed), such as Kepler orbit elements (see: Figure 4) used to determine the coordinates of satellites, ultimately in the ECEF system (Eshagh et al., 2007; Maciuk, 2016).
2. In addition, observations of navigation systems are carried out based on code and phase measurements (Wang et al., 2021; Zhao et al., 2022). This type of data is developed in post-processing. Based on that, together with the coordinates of the satellites, the position of the receiver is determined (Su et al., 2020).
3. Recently, an absolute positioning method called PPP (Precise Point Positioning) has become increasingly popular and is based on several precision products such as satellite orbit files and clock correction files, which, when properly processed, can provide an accuracy down to one centimetre (Wielgosz et al., 2019; Kazmierski et al., 2020; Ai et al., 2021).
4. Space RADAR is an SAR (Synthetic Aperture Radar) technique for observing the Earth. A radar signal is sent towards the Earth at a specific angle. During recording, information on the scattering rate of the wave and its phase when it reaches the receiver is logged, and the recorded radar waves are formed into SAR images. Depending on the location of the radar antennas on the satellite, the acquired SAR images can be processed in three ways:
   a. across track interferometry – where two antennas are installed on the satellite perpendicular to the direction of flight, used to build a digital terrain model (Geudtner et al., 2002),
   b. along track interferometry – where two antennas are installed on the satellite parallel to the direction of flight, used to determine the speed of moving objects (Chapin and Chen, 2008),
   c. repeat pass interferometry – where only one antenna is installed on the satellite, and observations of a given area are made from the same place on the orbit, but at certain time intervals (Dillon and Myers, 2015), which makes this method the most suitable for studying deformations occurring on the ground surface (Farolfi et al., 2019).
5. InSAR (Interferometry SAR) is a method for processing SAR image data (Goldstein et al., 1988). It uses the phase differences of radar signals from two microwave SAR image observations of the same area. From this, an image of the differences in these phases between the two SAR images is generated. After processing, a single file is produced presenting the differences in the form of interferometric fringes shown in Figure 5. The resulting image then needs to be calibrated to the target coordinate system in which the analyses will be performed (Peyret et al., 2008; Witkowski et al., 2021).

   The interferometric method for measuring subsidence growth has found wide application in underground (Spreckels, 2023). n order to improve the accuracy of the interpretation of interferometric bands, attempts are being made to use Deep Transfer Learning (Franczyk et al., 2022). The PSInSAR (Permanent Scatterer Interferometry) method is based on the analysis of entire sets of interferograms, in which areas of the terrain are searched for those that retain excellent quality signal reflection on all interferograms from a given set. In this way, it is possible to observe the height changes of only these points (Escayo et al., 2022; Kopeć et al., 2022).

6. Space LiDAR is a technique for measuring data from space. Depending on the design of the laser-based measuring instrument, the data collected by satellites will measure different physical features of the Earth and its atmosphere. The LiDAR ATLAS (Advanced Topographic Laser Altimeter System) collects photon-counting data for topographic measurements (Baban and Niţă, 2023), but at the same time can be used for AGB (Above Ground Biomass) measurements (Silva et al., 2021). The current limitations of space LiDAR are the density of the data and of the time of acquisition as well as the area covered. In the case of the ATLAS project, an ICESat-2 satellite gathers data exclusively about the polar regions. The six-beam, three-array system allows for taking an elevation measurement every 70 cm along the satellite's ground path; however, the paths are about 90 m wide. Also, since this is originally a four-year mission, currently in progress for almost five years, the data has not been obtained at the same time, therefore, averaging over the five-year period of glacier and land height is necessary.

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G04 2019 03 14 04 00 00 1.330170780420e-04 7.275957614183e-12 0.000000000000e+00
    9.800000000000e+01-1.718750000000e+00 4.639836124941e-09 2.148941747752e+00
-1.881271600723e-07 3.355251392350e-04 8.245930075645e-06 5.153800453186e+03
    3.600000000000e+05-1.676380634308e-08 5.171400020311e-01 1.490116119385e-08
    9.601921900531e-01 2.187187500000e+02-1.736906885738e+00-8.044977962767e-09
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    4.000000000000e+00 6.300000000000e+01-8.847564458847e-09 8.660000000000e+02
    3.553500000000e+05 4.000000000000e+00
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**Fig. 4.** GPS Navigation Messages – Example (source: https://files.igs.org/pub/data/format/rinex_4.00.pdf, accessed: May 5, 2023)

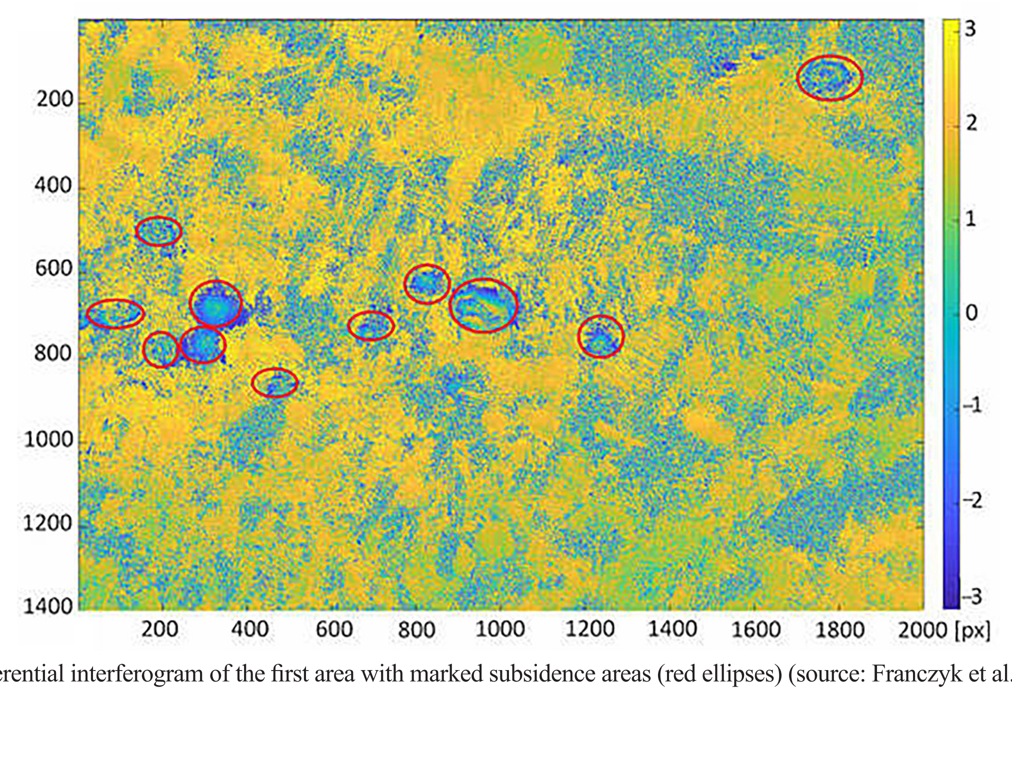


**Fig. 5.** Differential interferogram of the first area with marked subsidence areas (red ellipses) (source: Franczyk et al., 2022, p. 8)

**Aerial retrieved geodata**

Acquisition of geospatial data with use of UAV (Unmanned Aerial Vehicles) is becoming increasingly important in the context of its use in geodesy and cartography. It can be noted that the greatest development of this type of geodata acquisition methods took place in the second decade of the twenty-first century (Berra and Peppa, 2020). This is due to wide availability of modern technologies, thanks to which the users have easier access to low-cost aircraft, sensors, and software that allows the production of map products previously reserved for aerial surveys (Fabris et al., 2023). It can be concluded that small, unmanned vehicles, including airborne vehicles, are like a breath of fresh air in the field of geodesy – aerial photogrammetry. The increasing use of UAVs for the purposes of geodata acquisition can be attributed to a number of factors such as progressively lower cost of sensors and their miniaturization (Taddia et al., 2020), lower cost of UAVs, high accuracy of cartographic products obtained using sensors and COTS UAVs, and the possibility of accessing dangerous or hard-to-reach areas. In a certain way, UAV photogrammetry is a supplement to satellite data because it allows one to collect data regardless of meteorological conditions such as cloudiness. Because of this, the data collected locally by UAVs can be supplemented from satellite geodata resources. However, due to the principles of operation of UAVs, they also generate a number of problems, e.g. technical limitations caused by short battery operation (up to 60 minutes but several times less when flying with a high power demanding sensor), no possibility to move in strong wind, no resistance against atmospheric precipitation, the fact that surveys can only be carried out locally (a small area is processed), the long duration of calculations in the case of thousands of collected photos, and aviation regulations that do not allow drones to be operated over certain areas (critical infrastructure, zones in vicinity of airports, rivers, oceans etc.; for an example, see Figure 6) (Iizuka et al., 2018).

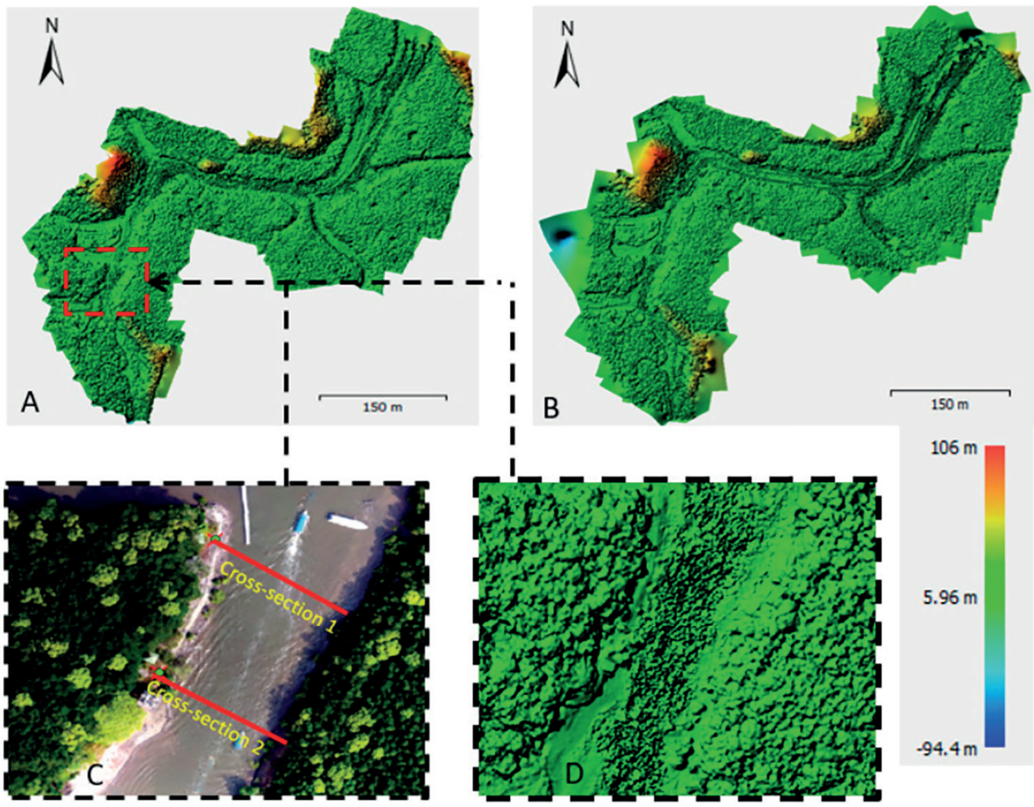


**Fig. 6.** Sample usage of a UAV for monitoring water level changes (source: Mohamad et al., 2019, p. 8)

It is also worth mentioning that there is one more branch distinguished by other features, namely high-altitude photogrammetry carried out by high-budget agencies and private companies in possession of aircraft equipped with optoelectronic heads or drones with airframes capable of similar tasks (Kovanič et al., 2021). They have unique features that make this type of method suitable for collecting large-area data with lower resolution requirements. Admittedly, in most cases, aerial photogrammetry is immune to the limitations of low-altitude photogrammetry implemented by UAVs. Airplanes conduct their missions photogrammetrically with greater resistance to meteorological conditions, and the range of the mapped area is limited to the technical capabilities of the aircraft (usually a few hours). High-altitude photogrammetry is well suited to mapping coastal areas. It is also used to create models of objects that, due to the occupied area (e.g., mountain ranges), cannot be measured using UAVs (Child et al., 2020; Pulighe and Fava, 2013).

Another branch that is undergoing dynamic development is the use of LiDAR's to acquire spatial data (ALS – airborne laser scanning). The principle of LiDAR measurement is to determine the time and angle of the laser beam emitted from the device mounted on the UAV or aircraft. After appropriate transformation of the aircraft orientation angles from the INS and the angle of the beam sent from LiDAR taking into account the high-precision position coefficients from the GNSS RTK system on which the airplane is located, the coordinates of the point on which the laser beam falls can be determined (Attila and Hajnalka, 2015). The INS sensors have a considerable influence on the accuracy of LiDAR data. However, in recent years there has been a major development of this type of device and their miniaturization, which allows for the construction and use thereof in low-cost aerial measurements. Sensors of this type require excellent quality INS systems mounted on the drone in order for their measurements to be accurate. The final product of airborne LiDAR's measurement is a terrain representation in the form of a dense point cloud with defined XYZ coordinates, which after processing becomes a DTM. The files are saved in the LAS format and, in addition to the point coordinates, they contain information about the class of the point and the intensity of the signal reflection, among other things (Glowienka et al., 2017). The points can also be assigned RGB values (corresponding to the colours blue, green and red), extracted from aerial photographs (He et al., 2022; Lombardi et al., 2022). Measurements of this type are used to model flood zones (B. Li et al., 2021), determine the condition of forests (G.W. Huang et al., 2014; Morsdorf et al., 2017), and model 3D objects (Roca et al., 2014).

The incremental SfM (Structure from Motion) method is the most commonly used method of acquiring three-dimensional spatial data from UAVs. The SfM method is based on the following stages: acquisition of overlapping geotagged images, key point extraction, key point matching, and bundle adjustment (Javadnejad et al., 2020). The final products of the image processing are DTMs, dense point clouds, and orthomosaics. Although this method has been used for many years, it is still being improved and developed. One of the main factors that have influenced SfM research is the use of artificial intelligence and machine learning methods (Agrafiotis et al., 2019; Eskandari et al., 2020; Mohan et al., 2021). The work focuses on examining the accuracy of current solutions depending on the research area, the environmental conditions, and the type of an unmanned aerial vehicle used for measurements (Sanz-Ablanedo et al., 2018; Iheaturu et al., 2020; Deliry and Avdan, 2021; Walker et al., 2021; Casella et al., 2022).

In recent years, many sensors have been miniaturized in such a way that they can be used on UAVs and so that their price allows for the implementation of solutions on a mass scale. Usually, when acquiring spatial data, UAVs use COTS sensors such as photogrammetric cameras, LiDAR, and SAR radars. Table 1 summarizes the use of cameras and LiDAR, and their domains in geospatial measurements in recent years.

### Levelling networks

Levelling points provide a height component of the datum. This dimension is related to the gravity of the Earth, which is a resultant of acceleration: gravitational, centrifugal, and from other sidereal objects (Moon, Sun). Therefore, height benchmarks (points) are established using field measurements by precise spirit levelling and gravimetry. The collected data are subject to rigorous adjustment and are characterized by accuracy, usually presented in mm/km of levelling. After this process, the points form a levelling network.

**Table 1.** Cameras, LiDAR and their domains in geospatial measurements in recent years

| UAV platform | Sensor type | Method | Application | Accuracy (RMSE) [m] | Source |
|---|---|---|---|---|---|
| DJI-P4RTK | CMOS 20 MP | SfM | Costal mapping | 0.052–0.025 | (Iizuka et al., 2018) |
| DJI-P3P + GPS+ RTK Topcon Hiper Lite | CMOS 12.4 MP | SfM | River Restoration Monitoring | 0.03–0.085 | (Evans et al., 2022) |
| Custom pixhawk based drone | Sony Alpha 5100 24 MP | SfM | Flood assessment | NA | (Jiménez-Jiménez et al., 2020) |
| DJI-Matrice 300 RKT | P1 45 MP | SfM | Sensor testing | 0.014 | (Urban et al., 2021) |
| Dji Phantom 4 Rtk & Dji Mavic 2 pro | CMOS 20 MP | SfM | Mapping & research | 0.014 - | (Nota et al., 2022) |
| Dji Matrice 300 RTK | DJi Zenmuse L1 LiDAR | LiDAR survey | Sensor testing | 0.038 | (Urban et al., 2021) |
| Dji Matrice 300 RTK | DJi Zenmuse L1 LiDAR | LiDAR survey | Facade and roof mapping | 0.12 | (Teppati Losè et al., 2022) |
| Dji Matrice 600 pro | Velodyne Vlp-32C | LiDAR survey | Costal mapping | ~0.07 | (Lin et al., 2019) |
| Custom made (low cost) | Hokuyo UTM-30LX | LiDARsurvey | Platform testing | 0.05 | (Z.C. Huang et al., 2018) |

Source: own elaboration

Traditionally, each country has its own levelling network based on different height systems, reference tide gauges, permanent solid Earth tides, and other standards. Since the nineteenth century, the academy has postulated the idea of a uniform vertical system (Liebsch et al., 2015; Rülke et al., 2013). The unification process has proceeded slowly, and it is still ongoing. One milestone was the adoption (in 2008) of a regional unified system (EVRF2007) and its inclusion in the INSPIRE Directive as an official recommendation for EU countries to implement (European Commission, 2013). Since then, the work has sped up and countries are implementing the pan-European height frame, usually during vertical network modernisation (Borowski et al., 2023) (see: Figure 7).

Table 2 shows examples of network average errors after adjustment in mm per kilometre of levelling. The sources with mgpu (milli geopotential unit) were omitted. In the table above, data from the Soviet Union (and Russian Federation) is lacking due to the authors' inability to access the sources. The first period (before WWII) shows errors higher than 1 mm. In the 1970s, the accuracy down to 0.8 mm/km was achieved. Today, this accuracy is lower (about 0.9). The decrease in the obtained accuracies, despite the simplification of the data collection process (electronic levels), is partly due to:

a) the lack of need for higher accuracies;
b) the pressure of cost-effectiveness.

Currently, the network is being developed as a mix of archival and new observations. The latter are reduced and performed when needed, for instance when the network point (benchmark) is destroyed.

The analysis of Table 2 shows, that the spirit levelling method has reached its limits (Cvetkov, 2023). The trend is therefore to emphasise the use of satellite levelling, based on a simple formula:

$$H = h - N \tag{1}$$

where:

- $H$ – physical height, orthometric or normal ones;
- $h$ – geometric height, based on GNSS measurements;
- $N$ – undulation – the distance between the ellipsoid and geoid/quasi-geoid;

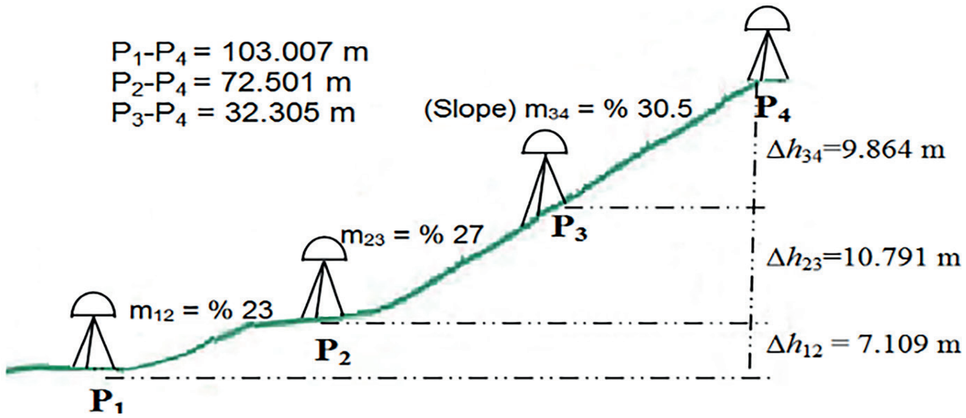


**Fig. 7.** The surveying profile of sites and height differences derived from geometric levelling (source: Erenoglu et al., 2012, p. 651)

**Table 2.** The national levelling network with its average error after adjustment

| Country | Measurement Campaign/ Network Name /Height reference frame | Years | Average error [mm/km] | Source: |
|---|---|---|---|---|
| Croatia | APL | 1874–1913 | +3.27 | (Rožić, 2001) |
| Finland | First Levelling | 1892–1910 | +1.29 | (Kääriäinen, 1966) |
| Poland | Amsterdam | 1926–1937 | +1.04 | (Wyrzykowski, 1993; S. Łyszkowicz and A. Łyszkowicz, 1998) |
| Finland | Second Levelling | 1935–1955 | +0.60 | (Kääriäinen, 1966) |
| Croatia | I.NVT | 1945–1963 | +1.33 | (Rožić, 2001) |
| Poland | Kronstadt’60 | 1947–1950, 1953–1955 | +0.78 | (Wyrzykowski, 1993) |
| Croatia | II.NVT | 1970–1973 | +0.79 | (Rožić, 2001) |
| Poland | Kronstadt’86 | 1974–1982 | +0.84 | (Kowalczyk and Rapinski, 2012) |
| Poland | PL-KRON86-NH | 1974–1982, 1997–2003 | +0.91 | (Kadaj, 2018) |
| Finland | N2000 (Third Levelling) | 1976–2003 | +0.86* | (Saaranen et al., 2021; Cvetkov, 2023) |
| Germany | DHHN92 | 1980–1985, 1992 | +0.88 | (Arbeitsgemeinschaft der (Vermessungsverwaltungen, 2023) |
| Malaysia | PLN | 1985–2000 | +1.14 | (Ses and Mohamed, 2009) |
| Poland | Kronstadt 2006 | 1997–2003 | +0.88 | (Gajderowicz, 2005; Kowalczyk and Rapinski, 2012) |
| Poland | PL-EVRF2007-NH | 1999–2012 | +0.91 | (Kadaj, 2018; Somla, 2018) |

* closing error of the levelling loops

Source: own elaboration

The formula (1) shows that accuracy is strictly dependent on GNSS measurements ($h$) and model of difference between ellipsoid and geoid/quasi-geoid ($N$). The first part might be established even down to sub-millimetre, when the point is placed on GNSS permanent station antenna, whereas the second element's accuracy is significantly lower. One of the most important tasks for geodesy, as science, is to improve it. Therefore, the models of geopotential are developed, using terrestrial, airborne, or satellite (Champ, GRACE, GOCE) gravimetry (Pail, 2023). The results (over 170 models, e.g. Pavlis et al., 2012; Bruinsma et al., 2014; Kvas et al., 2021) are published in the International Centre for Global Earth Models website (Ince et al., 2019). The key factor is to standardise the assumptions for each of them. Adaptation of the International Height Reference Frame (Mäkinen, 2021), introduced the mean tide as a base of the Global Geopotential Models (GGM) (Ince et al., 2019). By using the same tidal concept, fitting the GGMs into levelling networks should be more accurate, and it should produce a better-tailored geoid/quasi-geoid to height datum (Godah, 2013; Kaloop et al., 2022). This situation provides another opportunity to use GNSS observations in ordinary surveying work, that until recently had been reserved only for spirit levelling or total station. On the other hand, GGMs also provide a possibility for levelling networks to bypass terrain obstacles (Banasik and Bujakowski, 2018).

Despite the limits of precise spirit levelling and the development of GGM, we believe that levelling networks will remain in use for the near future (in the perspective of several decades). Most likely, however, with reduced total length, they will be limited to the main lines (backbone), for example, connecting a network of GNSS permanent stations (Borowski, 2015).

## GIS data

Regardless of the variety of goals and terms, there are a number of analogous functions, procedures and algorithms operating in all systems, using methods such as distance assessment, comparing the co-occurrence of geographical objects, presenting their distribution, etc. (Basista and Balawajder, 2020). This orientation to the processing of location-related data is an inseparable element of any geoinformation system. The concept of a "computer map" (numeric, digital) is commonly used, but in the operational definitions of GIS (Geographic Information System) systems, the term "visualization of geographical data" is used, and this applies not only to maps on a computer screen or their printouts, but also aerial photographs or satellite images with overlaid cartographic symbolism of maps and mounted reductions of photographic images of the Earth's surface (orthophotomaps) or graphic charts depicting phenomena that are difficult for remote sensing equipment to capture (economic, social, etc.) (Balawejder et al., 2021). The organizational (institutional) aspect is noticed in geoinformation systems as well. It is a point of view that separates the technology and software from the data, and from how the information is organised and made available (Kukulska-Kozieł et al., 2019). It is therefore necessary to make a clear distinction between systems that are sources of information for databases, versus databases and software as such. In the digital economy, it is estimated that the value-added chain is moving towards information distribution systems at the expense of the value of the information itself. The organization sharing, operating and visualization, as well as metainformation and geoinformation itself are just as important. In this way, computer software is only a potential tool or a set of tools for creating geoinformation systems as integrated systems composed of one or more computer programs cooperating together, organized in such a way as to enable users to access and process information continuously (currently often in an ICT network or an IoT idea), serving clearly defined purposes. On the other hand, the ways and methods of processing data about the geographic objects themselves and the purposes of the systems differ significantly. As a result of the analyses, we have conducted, 12 areas of application of computer systems that use Geodata for their work were distinguished:

1. GIS/AM – automated mapping – supporting cartographic works; it is an automatic cartography tool (Aghaloo et al., 2023; Bagheri, 2023).
2. GIS/CAD – computer aided design – computer aided design in areas such as urban planning or landscaping. Systems called SCAD (spatial CAD) hold and process data in geographical reference systems, using various editing, visualization and presentation techniques. As a rule, they also conta-

in AM subsystems (Cooper et al., 2020; Olszewski et al., 2021; Aghaloo et al., 2023; Bagheri, 2023).
3. GIS/DOC – document processing – systems that enable information processing from source documents (maps, photos, satellite images, data files), as well as statistical surveys or geodetic documents (Foster-Martinez et al., 2020; Droj et al., 2021; Olszewski and Wendland, 2021; Aghaloo et al., 2023; Bagheri, 2023).
4. GIS/DSS – decision support systems. From the beginning, GIS has been a research and policy tool oriented towards monitoring, analysis, simulation, and planning. An interesting review of DSS can be seen in (Ramírez-Cuesta et al., 2020; Ghunowa et al., 2021; Talari et al., 2022; Cimburova et al., 2023).
5. GIS/EXP – expert systems – diagnostic, specialized systems, using a broad range of knowledge and suggesting possible variants of solutions within a specific (albeit narrow) field (Ramírez-Cuesta et al., 2020; Ghunowa et al., 2021; Talari et al., 2022; Aghaloo et al., 2023; Bagheri, 2023).
6. GIS/FM – facility management – systems supporting management and planning in the field of broadly understood infrastructure and public services (Ramírez-Cuesta et al., 2020; Olszewski and Wendland, 2021; Talari et al., 2022; Aghaloo et al., 2023; Cimburova et al., 2023).
7. GIS/IMAGE – earth image processing – specialized data processing systems about the Earth's surface, primarily related to the analysis of images obtained using remote recording techniques (Ramírez-Cuesta et al., 2020; Bagheri, 2023; Cimburova et al., 2023).
8. GIS/LIS – land information systems – they are a tool of a legal and administrative nature (the term "SIT" – land information system has become popular in Poland) (Aghaloo et al., 2023; Cimburova et al., 2023; Cooper et al., 2020; Foster-Martinez et al., 2020; Ghunowa et al., 2021; Ramírez-Cuesta et al., 2020).
9. GIS/MODEL – spatial modelling – is a tool for universally understood analysis and spatial modelling. Digital modelling may concern both the intensity of processes (e.g. development of the transport network) and objects (e.g. projection of a three-dimensional image of a fragment of land onto a monitor screen) (Cooper et al., 2020; Foster-Martinez et al., 2020; Ghunowa et al., 2021; Ali et al., 2023; Bagheri, 2023; Cimburova et al., 2023).
10. GIS/SA – spatial analysis – this is most closely related to research methods used in geography (Cooper et al., 2020; Droj et al., 2021; Ghunowa et al., 2021).
11. GIS/STAT – geostatistics – systems for processing and displaying (geo)statistical data (Cooper et al., 2020; Droj et al., 2021; Ali et al., 2023).
12. GIS/VISION – animation systems – systems using computer animation technology to depict geographic data (Cooper et al., 2020; Foster-Martinez et al., 2020; Droj et al., 2021; Cimburova et al., 2023).

When we expand our literature review, we may see numerous and broad new applications of GIS in everyday life and societal challenges. A summary of the state of the art is shown in Table 3.

In practice, most geoinformation systems perform only a few selected functions and these depend primarily on the purpose for which a given system had been constructed. This variety of goals and functions has led to universal systems using the term "toolbox" to describe a set of loosely related procedures for processing geographic data, e.g. the Spatial Design Network Analysis (sDNA) toolbox for 3D spatial network analysis, especially street or path or urban network analysis (Cooper et al., 2020). An essential component of GIS is a digital geographic database. It consists of two parts containing two diverse types of data about location (spatial data) and related to the characteristics of geographical objects (non-spatial attributes). The database is distinguished by the fact that it has its own procedures, independent of the geoinformation system. It can be located inside, which means that access to it is possible only through a geographic information system, or outside. In the latter case, it is a separate program that communicates only with GIS. Often, however, solutions are used in which location data and object identification are stored in an internal database, and other data in a database external to GIS, while the geoinformation system provides access to them. Currently, completely new forms of geoinformation systems are gaining popularity, adapted to the needs of society and technological possibilities, such

**Table 3.** A summary of the state of the art in the context of specific areas of application

| No. | 1. | 2. | 3. | 4. | 5. | 6. | 7. | 8. | 9. | 10. | 11. | 12. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GIS areas | AM | CAD | DOC | DSS | EXP | FM | IMAGE | LIS | MODEL | SA | STAT | VISION |
| (Talari et al., 2022) | | | | x | x | x | | | | | | |
| (Cooper et al., 2020) | | x | | | | | | | x | x | x | x |
| (Olszewski et al., 2021) | | x | x | | | x | | x | | x | | |
| (Bagheri, 2023) | x | x | x | | x | | x | | x | | | |
| (Cimburova et al., 2023) | | | | x | | x | x | x | x | | | x |
| (Foster-Martinez et al., 2020) | | | x | | | | | x | x | | | x |
| (Ramírez-Cuesta et al., 2020) | | | | x | x | x | x | x | | | | |
| (Ghunowa et al., 2021) | | | | x | x | | | x | x | x | | |
| (Droj et al., 2021) | | | x | | | | | | | x | x | x |
| (Aghaloo et al., 2023) | x | x | x | x | x | x | | x | | | | |
| (Ali et al., 2023) | | | | | | | | x | x | | x | |

Source: own elaboration

as, for example, Digital Agora as a model of a social and geodatabase platform for virtual debates (Olszewski and Wendland, 2021) or Qualitative Geographic Information Systems (QGIS) which refers to an array of methodological efforts to incorporate into GIS more qualitative data (Bagheri, 2023).

An additional sub-field of GIS concerning spatial data processing is historical GIS (HGIS). It is focused on accessing and making available pre-computer era data e.g., maps, sketches, notes or any other analogue documents. In general, two branches can be discerned: (a) adapting old documents to modern requirements and disclosing them in digital format (e.g., geoportals); (b) data extraction, often of limited spatial quality, for the analysis of historical phenomena. The first deals with the transformation of old map (Bacior, 2023; Banasik and Borowski, 2021), aero photographs (Kuna, 2022) or both (Kuna and Kowalski, 2020), prepared in less accurate coordinate systems, cartographic projections or datums, into currently used ones. The results are usually presented in geoportals, which may cover areas from areas (e.g., a city) to worldwide (Table 4).

**Table 4.** Examples of historical map geoportals

| Name | Area coverage | Source |
|---|---|---|
| David Rumsey Collection | Worldwide | [davidrumsey.com] |
| Arcanum | Europe | [maps.arcanum.com/en] |
| Historical Topographic Maps – Preserving the Past | State area – USA | [davidrumsey.com] |
| National Library of Scotland | State area – UK | [maps.nls.uk/geo] |
| Historisch GIS Fryslân | State area – the Netherlands | [www.hisgis.nl] |
| Maps and historical boundaries of the Silesian province | Regional – Silesian Province | [geoportal.orsip.pl/gis] |
| HGIS Lublin | Local – city of Lublin | [teatrnn.pl/miejsca] |

Source: own elaboration

The second method is focused on the analysis of a specific phenomenon, for which the extraction of archival documents provides information about the space and place. A milestone in this approach is the project of the Holocaust Geographies Collaborative (Knowles et al., 2014).

## CONCLUSIONS

Geodata is information relating to geosciences in the broadest term, i.e., fields that use spatial data, which is now most often collected and stored electronically. These data can include topographic information, satellite data, land surface data, maps, satellite images, climate data, geological conditions, and many others (Coetzee et al., 2020; Karmaoui et al., 2023). Geodata are collected and processed by various organizations, institutions, companies, universities, etc. (S. Li et al., 2016). This type of data is very important for many fields, such as Earth science, architecture, urban planning, engineering and environmental protection, agriculture, mining, tourism, and many others (Schwartz-Belkin and Portman, 2023). Before the advent of geodetic technologies, collecting and processing of geographic data was time-consuming and expensive. With modern geospatial technologies such as GPS, LiDAR and UAV, geodata collection and processing has become easier, more accurate and more efficient (Shafapourtehrany et al., 2023). Every year, geodata becomes more accessible and the number of people using this data increases. Over time, collected geodata is becoming increasingly accurate and detailed. The data covers an increasing number of fields, and in addition to collecting only basic data, it presents, among others, the results of the analysis of this data. Currently, geodata is usually made available for free or, due to the costly method of acquisition, for a fee. Government agencies usually provide data free of charge (Quarati et al., 2019), for the purpose of infrastructure projects or scientific research. In contrast, private companies or corporations collect and process geodata for later resale. The increasing amount of shared data can have a positive impact in terms of preventing global threats, e.g., social or environmental. Integration and harmonization of data from various sources will be a good basis for the sustainable development of cities, countries, continents, and the world.

Geodata is being used currently by everyone, from google maps users to pilots of space shuttles. It is one of the most interdisciplinary datasets available since it allows experts from different field to both contribute, and more importantly, to use them. Future development of acquisition methods and processing techniques will only make this bond stronger, and representation of geodata more universally accessible.

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## GEODANE W SŁUŻBIE NAUKI – PRZEGLĄD WYBRANYCH DZIEDZIN WIEDZY


### ABSTRAKT

**Cel pracy**

Obecnie coraz większą popularnością cieszą się zupełnie nowe formy systemów geoinformacyjnych. Nowe możliwości technologiczne pozwalają dostosowywać je do wymagań i potrzeb społeczeństwa. Niniejszy artykuł przedstawia obszerny przegląd literatury na temat wykorzystania geodanych w różnych dziedzinach nauki, głównie w dyscyplinach STEM (nauka, technologia, inżynieria i matematyka). Ponieważ jednak nie ma powszechnej zgody co do tego, które dyscypliny zalicza się do STEM, autorzy uwzględnili również dyscypliny pokrewne, takie jak geografia czy transport.

**Materiał i metody**

Już wstępna analiza bazy Web of Science Core Collection wykazała, że geodane są wykorzystywane bardzo szeroko (choć w różnym stopniu szczegółowości i zaawansowania) niemal w każdej analizowanej dyscyplinie naukowej. Celem niniejszego artykułu jest przede wszystkim kompleksowa analiza wykorzystania geodanych w pięciu obszarach: pomiary batymetryczne; geodane satelitarne; geodane pozyskiwane z powietrza; sieci niwelacyjne; wreszcie dane GIS.

**Wyniki i wnioski**

Wyniki wykazały rosnącą dostępność danych, które mogą przyczynić się do lepszego zrozumienia naszej planety i skuteczniejszego nią zarządzania. Geodane mają jako narzędzie szerokie i ogólne zastosowanie, dlatego są lub mogą być wykorzystywane w prawie każdej dyscyplinie naukowej.


**Słowa kluczowe:** nauka, dane, geodane, STEM, badania naukowe, GNSS, LiDAR, GIS, batymetria, satelita