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AG EDITOR

REVIEW

# Digital Photogrammetry and Geographic Information Systems: A Review

## Fotogrametría Digital y Sistemas de Información Geográfica: revisión del tema

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**ABSTRACT**

Photogrammetry is an essential technology for the analysis and measurement of objects in geospatial space using photographs. This method is divided into several categories: analog, analytical, aerial, terrestrial, and digital photogrammetry, each with specific applications in geography, architecture, and more. Digital photogrammetry has revolutionized the field by integrating specialized software to process images and generate accurate geospatial information. Its applications include the creation of topographic maps, point clouds, and 3D models used in cartography and agriculture. Likewise, the Structure from Motion (SfM) technique allows for the creation of high-resolution 3D models using unmanned aerial vehicles (UAVs). This approach has facilitated data collection at a lower cost and with greater accuracy, excelling in situations where access is difficult. Furthermore, the importance of geodesy, which studies the shape and dimensions of the Earth, has been emphasized as a fundamental pillar for understanding the geographic environment. On the other hand, cartography, which has evolved from paper representations to digital solutions, plays a crucial role in modern geoinformatics, providing tools for analysis and decision-making. Advances in drone technology and GIS software have enabled greater versatility in the collection and analysis of geospatial data, supporting diverse sectors, from urban planning to environmental conservation.

**Keywords:** Cartographic Mosaic; Photogrammetry; Cartography.

**RESUMEN**

La fotogrametría es una tecnología esencial para el análisis y medición de objetos en el geoespacio mediante fotografías. Este método se divide en varias categorías: fotogrametría analógica, analítica, aérea, terrestre y digital, cada uno con aplicaciones específicas en geografía, arquitectura, y más. La fotogrametría digital ha revolucionado el campo al integrar software especializado para procesar imágenes y generar información geoespacial precisa. Entre sus aplicaciones destacan la creación de mapas topográficos, nubes de puntos, y modelos 3D utilizados en la cartografía y la agricultura. Asimismo, la técnica Structure from Motion (SfM) permite obtener modelos 3D de alta resolución utilizando vehículos aéreos no tripulados (VANT). Esta aproximación ha facilitado la recolección de datos a un costo más bajo y con mayor precisión, destacando en situaciones donde el acceso es complicado. Además, se ha enfatizado la importancia de la geodesia, que estudia la forma y dimensiones de la Tierra, como un pilar fundamental para la comprensión del entorno geográfico. Por otro lado, la cartografía, que ha evolucionado desde representaciones en papel a soluciones digitales, juega un papel crucial en la geoinformática moderna, proveyendo herramientas para análisis y toma de decisiones. Los avances en tecnología de drones y software SIG han permitido una mayor versatilidad en la recopilación y análisis de datos geoespaciales, apoyando diversos sectores, desde el urbanismo hasta la conservación ambiental.

**Palabras clave**: Mosaico Cartográfico; Fotogrametría; Cartografía.

## INTRODUCTION

Background SFM (Structure From Motion) digital aerial photogrammetry has become a valuable technique in engineering and spatial design, facilitating the capture of geospatial information. This methodology has evolved from aerial photogrammetry in airplanes since the 1950s.(1)

Digital Photogrammetry SFM is an advanced technique that uses computational algorithms to reconstruct objects and landscapes from digital images captured from different angles and positions in three dimensions. It is based on photogrammetric and stereoscopic principles, taking advantage of image variations to calculate objects' depth and three-dimensional shape.(2)

A key element of SFM Digital Photogrammetry is identifying and matching visual features between images, such as corners or edges. This allows the calculation of the three-dimensional position of prominent points in the scene and the position and orientation of the cameras used to take the images. This process is performed using triangulation and optimization algorithms.(2)

Once the three-dimensional structure has been reconstructed, dense point clouds representing the surface of the object or landscape are generated, enabling the creation of accurate and detailed 3D models. This technique is applied in various areas, including topographic mapping, monitoring of environmental changes, documentation and reconstruction of archaeological sites, and urban planning and infrastructure design.

Stereo triangulation is a fundamental aspect of SFM Digital Photogrammetry. It is based on the principle of parallax to determine the three-dimensional position of points in a scene from two-dimensional images captured from different locations and angles. Control points with known three-dimensional coordinates are established and used to calculate the position of other points in the scene.

Various algorithms and computational methods, such as feature matching algorithms to identify matching points in the images and 3D reconstruction algorithms to calculate the three-dimensional coordinates from the two-dimensional coordinates, are used to implement stereo triangulation. The combination of geographic information systems (GIS) with this SFM technology allows for a relatively fast mapping of the study area, covering all its typologies, such as relief, vegetation, and watercourses.

This technique is currently used in many parts of the world because it can obtain information with precision and time efficiency. The following will present several examples of the use of these technologies.

The authors Rubén Sancho Gómez-Zurdo, David Galán Martín, Beatriz González, Rodrigo Miguel Marchamalo Sacristán, and Rubén Martínez Marín, in their report entitled 'Application of DRONE Photogrammetry to Deformational Control of Structures and Terrain,' analyze the viability of the use of drones by evaluating their resolution, accuracy and validation in comparison with other techniques. They describe in detail the Structure From Motion photogrammetric technique, which is used to create accurate orthophotographs and 3D models without the need for prior knowledge of the positions and angles of incidence. In addition, they use precise control points, and their drones have an integrated RTK system, which ensures a high degree of accuracy. An outstanding example is the monitoring of an arc-gravity dam, which shows a deformation accuracy of ±2 mm for the structure. This confirms that drone photogrammetry can be effectively applied to the deformation monitoring of concrete dams.

For their part, Felipe Buil Pozuelo, M. Amparo Núñez Andrés, Roger Ruiz Carulla, Nieves Lantada Zarzosa, in their study(3) 'Influence of 3D Models on the Determination of Families of Discontinuities in Rock Massifs'., three focus on the characterization of discontinuities in the rock massif, to identify the potentially unstable outlet volume, necessary for the evaluation of the danger of rock falls. The study area is Pala de Morrano (Aiguestortes NP). Through photogrammetric flights from aerial platforms (RPAS and helicopter), two 3D models were generated, and a third one from ground coverage. The data were completed with a TLS (Terrestrial Laser Scanning), which was assumed as ground truth. The characterization was performed with the Fast Marching plugin of Cloud Compare on these models.

The generated models have significant completeness, above 95 %, where the combination of terrestrial and helicopter, without occlusions (98 %), stands out. They concluded that, for the set objective of obtaining the families of discontinuities, all the photogrammetric models are valid. The terrestrial photogrammetric model is the most similar to the one obtained with the TLS, being optimal on a cost-benefit basis, followed by the one generated by multi-copter photogrammetry.

In the report 'Topography of a Physical Model of Urban Drainage from the Structure From Motion Photogrammetric Technique,' the authors Regueiro-Picallo, M.; Sañudo, E.; Anta, J.; Puertas, J.; Suárez J. from the University of Coruña,(4) Water and Environmental Engineering Group (GEAMA), A Coruña, Spain, four present visualization techniques as an innovative tool to solve some complex problems of experimental hydraulics in a simple and generally low-cost way.

This study presents a case of the SFM technique being applied to reconstruct the surface of a physical model of urban drainage. A detailed surface mesh with a resolution of 5 mm and a relative error of ±2,5 % concerning conventional topographic techniques was obtained from an image sweep for use in 2D rainfall-runoff transformation models.

The research work of the authors Yandri José Lalangui Jaramillo and Belizario Amador Zárate Torres on 'Evaluation of the Digital Terrain Model Obtained Using Photogrammetry Techniques with UAV and GNSS Techniques Applied to Road Projects in Medium Vegetation Areas,'[5] had the objective of obtaining a digital surface model of mountain roads using an uncrewed aerial vehicle (UAV). At an altitude of 100 m, a UAV took images every two seconds and these were processed in SFM software.

A digital terrain model was configured using photogrammetric techniques, and the results were compared with the differential GPS-derived digital terrain model.

The digital models turned out to be similar because there is a variation where vegetation is dense. They would reduce the margin between these two types of surveys so that topographic surveys can be achieved without cost to the environment.

The research paper by authors Muhammad Hamid Chaudhry, Anuar Ahmad, and Qudsia Guizar six on 'Impact of Unmanned Aerial Vehicle Topographic Parameters on Urban Land Mixed-Use Surface Modelling'[6] argues that a large amount of data and high computational cost mainly characterizes uncrewed aerial vehicles (UAVs) as a surveying tool. However, this research explores the use of a small amount of data with less computational cost for more accurate three-dimensional (3D) photogrammetric products by manipulating UAV surveying parameters, such as flight line patterns and image overlap percentages.

In Pix4DMapper, 16 photogrammetric projects were processed with perpendicular flight plans and a 55 % to 85 % lateral and frontal overlap variation. For georeferencing and accuracy assessment of the UAV data, 10 ground control points (GCP) and 18 control points (CP) were used. The comparative analysis incorporated the median of tie points, the number of 3D point clouds, the horizontal/vertical mean square error, and large-scale topographic variations.

The results indicate that a higher frontal overlap increases the median number of tie points and that an increase in lateral and frontal overlap results in a higher number of point clouds. It was also found that the horizontal accuracy of 16 projects varies from ±0,13 m to ±0,17 m, while the vertical accuracy varies from 0,09 m to ±0,32 m. The lowest vertical mean square error did not correspond to the highest percentage overlap.

The trade-off between UAV topographic parameters can result in high-accuracy products with less computational cost. The Urban DesignLab[7] presents a report, 'GIS as a tool for Urban Planning,' which provides planners, surveyors, and engineers with the tools they need to design and map their neighborhoods and cities. Visualization, spatial analysis, and spatial modeling are the most commonly used GIS functions in mapping.

With GIS, a city's physical, social, and economic data can be stored, manipulated, and analyzed. Planners armed with this resource can then use the spatial query and mapping functions of GIS to investigate the city's situation. GIS can help identify conflict areas between development and the environment using the map overlay procedure. Using the multi-layer mapping function of GIS, the municipal government can visualize many things, such as quality agricultural land, surface water, flood frequency, and land at high risk from erosion or topographical features.

A work of great relevance and importance for our research purpose is the one that precisely combines the use of drones with GIS, which we refer to below.

The authors, Qiuxi Li and Tracy Deliberty,[8] explain in their report 'Integrating drones, participatory mapping and GIS to enhance resiliency for remote villages' that Indigenous communities in developing regions are affected by frequent disasters and the erosion of their culture under pressure from modernization. Notably, their efforts to reduce risk have been hampered because these communities lack a sufficiently detailed map of their territories.

This study uses drone imagery, participatory methods, and GIS to generate the first publicly accessible infrastructure and resource dataset for Indigenous communities in Southwest China. The maps produced enable data-poor Indigenous communities to be aware of the fire risk to their homes, the state of preservation of historic buildings, and potential economic resources such as tourist attractions.

The expected end product of these efforts is to build resilience in these communities, which is valid for hard-to-reach communities around the world. This is for disaster prevention, economic planning, and the all-important cultural preservation that sustains their identity as an ethnic group.

With the possibilities provided by these tools for the capture and presentation of spatial data, it is feasible to create the municipal cartographic base of the Dominican Republic and/or update the existing ones. For these reasons, we will take the opportunity to review and/or update the one that was made on the occasion of the Urban Development Plan of the municipality of San José de Ocoa.

The municipality of San José de Ocoa, which belongs to the new province of the same name, contains the urban center of the same. The town was founded in 1805 by inhabitants from Baní. Fifty-three years later, in December 1858, it was raised to the municipality status and belonged to the province of Santo Domingo. Later, in 1895, it was transferred to the province of Azua de Compostela. However, when the province of Peravia was created in 1944, San José de Ocoa was placed as a municipality of this province.

Law 66-00 made San José de Ocoa a province on 6 December 2000. Therefore, it is the youngest province of the 32 that make up the Dominican Republic. Pedro E. Sosa Veras, the Urban Development Plan of the Municipality of San José de Ocoa, was carried out between 2014 and 2015. In it, all the buildings, roads in the urban area, and waterways, among other information, were inventoried, and 74 municipal development projects were presented.

Currently, the country's municipalities do not have a cartographic base in which they can search with a few clicks for any information related to their productive components, with a complete description of a given unit, such as the use of a given area, whether it is institutional, medical, commercial, surface area, cadastral designation that includes parcel data, cadastral district, registration number, among others.

The only information available to them separately is that provided by Google Maps, and they do not have Geographic Information Systems that provide them with the detailed attributes mentioned in the preceding paragraph. In this sense, the research work will cover this wide range of the urban area's component units, including the mentioned attributes.

The lack of this information among the country's municipal governments diminishes the potential for private investment in suitable locations and also makes it difficult to control the economic and demographic development of these provinces.

### Importance

Cartography is an essential tool for the planning and sustainable development of cities and municipalities, as it provides detailed information on the geographical location of natural resources, existing infrastructure, and urban and rural areas, among other relevant aspects. However, on many occasions, existing cartographic information is outdated, incomplete, or inaccurate, which hinders decision-making and the efficient implementation of public policies. According to our experience, 95 % of the municipalities in the Dominican Republic lack a cartography that would allow them to develop their municipal development and territorial management plans.

Urban mapping is essential for effectively planning and managing territorial development in the Dominican Republic's municipalities. A workflow model that integrates Unmanned Aerial Vehicle (UAV) technology and Geographic Information Systems (GIS) can significantly improve mapping data collection and updating efficiency and accuracy.

## DESARROLLO

### Photogrammetry

Photogrammetry is a technology that makes it possible to analyze and define an object's shape, size, position, and dimensions in geospatial space, for which measurements are taken on photographs of the object under study.[2]

The types of photogrammetry that exist are:

#### *Analog Photogrammetry*

Analog photogrammetry was the first technique to be developed. Balloons or airplanes with cameras mounted on the underside captured images of the areas of interest. These photographs were printed and studied to analyze the objects' shape, size, position, and dimensions.

#### *Analytical Photogrammetry*

Analytical photogrammetry is the second technique to be developed. It uses mathematical models to analyze physical objects in photographs. This technique arose from the need to study objects in orthophotos. The advent of computers and the inclusion of the Internet facilitated its advancement, allowing photogrammetry data to be sent and processed efficiently. Digital photogrammetry is intertwined with analytical photogrammetry.

#### *Aerial Photogrammetry*

Aerial photogrammetry involves using space-based devices like satellites to capture images. These devices offer high quality and accuracy due to their cameras' good resolution. It does not refer to direct human action to take orthophotos but to the use of advanced photographic mechanisms.

#### *Terrestrial Photogrammetry*

In terrestrial photogrammetry, the photographic devices are at ground level and are not raised in the air. This technique allows detailed images of objects and areas to be captured from the earth's surface.

#### *Digital Photogrammetry*

Digital photogrammetry combines technology, science, and art. It uses specialized software to capture, manipulate, and process aerial and terrestrial images. Its calculations are based on advanced mathematical and geometric functions, and the interpretation of photographic images and electromagnetic and radiant energy models is considered an art.

Digital photogrammetry gained momentum with the advent of computers and the inclusion of the Internet, which facilitated data transfer. Creating software to improve and reduce data processing has been crucial in its development. This technique allows accurate and rapid geographic information, enabling real-time decision-making, especially in emergencies.[2]

**Applications of Photogrammetry**

To use photogrammetry, a flight plan must first be designed, and shots must be planned. The images are processed by programs that orientate the photos to work correctly with them. From these images, topographic maps, point clouds, meshes, or virtual drawings of reality are created, which are helpful for 3D printing.[9,10]

Photogrammetry is used in sociological and socio-demographic analysis, cartography, orthophotography, architecture, agriculture, and visual watershed studies. Based on real-time photographs of reality, it provides accurate and reliable data that is valid for topographic and location surveys.[1]

Digital photogrammetry is aided by software such as the following:

*Agisoft Metashape*

This software contains more tools. It starts processing digital images that can be exported to other GIS or used for different purposes, such as cultural heritage, measurements, visual effects, etc. The most important feature is that it can measure distances, volumes, scatter meshes, etc.

*Pix4D photogrammetry solution*

This program can process and take images. Pix4D can be found for Android and iOS mobiles for image processing and designing drone flight plans. Some of Pix4D's tools allow the analysis of earthworks, image optimization, infrastructure management, point clouds, elevation models, and many, many more processes.

Technological advances will increase the value of photogrammetry. It is worth remembering that a few years ago, orthophotos had to be taken by aircraft, which considerably increased the cost of these processes. But in recent years, drones have been introduced, which has led to a significant decrease in costs.

*SFM technique*

The Structure from Motion (SFM) technique is an automated photogrammetric method with high resolution and low cost compared to other techniques. The process is based on the principles of classical stereoscopic photogrammetry, meaning that the 3D structure is achieved by superimposing the optical images captured at the different viewpoints.[11]

However, SFM originates from the development of computer vision and automatic image correlation algorithms (CAI). It differs from conventional photogrammetry in that the scene geometry, camera positions, camera orientation, and deformations are determined using computational calculations.The SFM technique allows obtaining a set of XYZ coordinates, or 3D point clouds, with additional information from the RGB channels. This geometric and optical information can be used for the supervised extraction of parameters characterizing the relief or detecting changes between acquisitions carried out remotely at different times.[12]

**High Spatial Resolution Photogrammetry Using the Structure of Motion Method (SfM) and Unmanned Aerial Vehicles (UAVs)**

The Structure from Motion (SFM) method provides a relatively inexpensive alternative to LIDAR for producing high spatial resolution photogrammetry. This 3D modeling technique relies on human vision to reconstruct three-dimensional structures from 2D images projected on the retina.[13] The SFM method generates a point cloud of points that can be used to produce a 3D photogrammetry image of a site's spatial resolution.

This method generates a dense point cloud from photographs, which is then processed to obtain a topographic model (DTM) or a digital elevation model (DEM). Using this method reduces costs and the need for specialized equipment, as it only uses standard digital cameras and an automated image processing package, which can be freely available.[14]

The integration of the SFM method with the use of uncrewed aerial vehicles represents a viable alternative for the generation of high-precision photogrammetry. Uncrewed Aerial Vehicles (UAVs) are vehicles that can fly autonomously, i.e., they are piloted remotely. These vehicles have evolved a lot since the last decade, initially used almost exclusively for military purposes. However, their applications have expanded in geomatics, representing a breakthrough in the collection of imagery used in the SFM method.

Using uncrewed aerial vehicles has advantages over human-crewed aerial vehicles, such as lower operating costs, greater safety, flexibility in planning, and greater proximity to the area to be imaged, improving the resolution of data for the SFM method.

The use of high-resolution aerial imagery has essential applications in fields such as geology, agriculture, and hydrology, among others, such as the monitoring of vegetation phenology, high spatial resolution topography in very rugged terrain, as in the present case, and the characterization of hydrological basins.[15]

The present work aims to integrate low-cost aerial platforms with the SFM image processing method to

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generate high spatial resolution photogrammetry and carry out the municipal mapping of San José de Ocoa. We created an orthophoto with a GSD resolution of less than 5 cm and a terrain elevation model with a GSD of 30 cm.

**Uncrewed aerial vehicles**

Umanned Aerial Vehicles (UAV), or Unmanned Aerial Systems (UAS), are aerial vehicles flying without a human crew. It is correct to point out that World War II's first uncrewed vehicles were used as drones, e.g., V1 bombers, and for training anti-aircraft gun operators. However, the term UAV was introduced at the end of the 20th century to be used for radio-controlled aircraft, exhibiting all the characteristics of autonomy.

Uncrewed Aerial Vehicles (UAVs) are the latest innovation that integrates conventional aerial vehicles and satellites in capturing remotely sensed data. Currently, these vehicles are remotely controlled from a ground station by an operator or programmed by computer to maintain a predetermined route at a pre-set altitude, according to the purpose of their flight.(16)

Their use for commercial purposes, such as aerial photography, has been steadily increasing. Since these vehicles do not have the operational limitations of pilots and can perform risky or high-difficulty missions without compromising anything other than the flying device itself, these activities are quite cost-effective.

**The Best Drones on the Market for Photogrammetric Work**

The selection of the best drone for photogrammetric surveys depends on several factors, such as budget, required accuracy, the scale of the project, and terrain conditions. Here are some of the best drones recommended for photogrammetric surveys, considering their capability, accuracy and reliability:

*DJI Phantom 4 RTK*

- Features: Incorporates an RTK (Real Time Kinematic) positioning system with centimeter accuracy. It has a 20 MP camera with a mechanical shutter.
- Advantages: High accuracy, easy to use, good value for money.
- Recommended use: Medium to large-scale projects.

*DJI Matrice 300/350 RTK*

- Features: The industrial platform can carry multiple sensors, including photogrammetric cameras and LIDAR sensors. Integrated RTK positioning system.
- Advantages: Versatility, robustness, ability to perform long-range missions in adverse conditions.
- Recommended use: Large and complex projects, difficult conditions.(17)

*senseFly eBee X*

- Features: Fixed-wing with interchangeable camera options, including high-resolution photogrammetric cameras. Flight time up to 90 minutes.
- Benefits: Coverage of large areas in less time and high accuracy.
- Recommended use: Large topographic surveys and agricultural and environmental monitoring projects are also recommended.

*Parrot Anafi USA*

- Features: 32x zoom camera, thermal camera, and GNSS system for precise positioning.
- Advantages: Compact, lightweight, good value for money.
- Recommended use: Surveys in urban areas, search and rescue missions.

*WingtraOne*

- Characteristics: Vertical take-off and landing (VTOL) drone with high-resolution camera capabilities. Coverage of up to 400 hectares per flight.
- Advantages: Ability to cover large areas quickly, accuracy, and efficiency.
- Recommended use: Large-scale projects and extensive terrain surveys.

*Trimble UX5 HP*

- Features: Fixed-wing with a high-resolution camera and GNSS system for precise positioning.(17)
- Advantages: Accuracy, long flight capability.
- Recommended use: Detailed topographic surveys and infrastructure projects.

**The types of DRONES or UAVs currently available for photogrammetric work**

Various kinds of drones are used for photogrammetric purposes, each with specific characteristics that make them suitable for different projects. The main types of drones for photogrammetric surveys are:

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*Fixed Wing Drones:*

- Characteristics: They have a similar structure to conventional aircraft, with fixed wings that provide lift.
- Advantages: Longer flight range, ability to cover large areas in less time, efficient energy consumption.
- Disadvantages: It requires space for take-off and landing and is generally more expensive.
- Examples: senseFly eBee X, Trimble UX5 HP, WingtraOne.

*Rotary Wing Drones (Multi-rotors):*

- Characteristics: Equipped with multiple rotors (usually 4 to 8), they can take off and land vertically.[18]
- Advantages: Stationary flight capability, increased maneuverability, and ease of operation in restricted areas.
- Disadvantages: Flight time and coverage are reduced compared to fixed-wing drones.
- Examples: DJI Phantom 4 RTK, DJI Matrice 300/350 RTK, Parrot Anafi USA.

*Vertical Take-Off and Landing (VTOL) Fixed Wing Drones:*

- Characteristics: Combine the characteristics of fixed-wing and multi-rotor drones, which can take off and land vertically but fly like a fixed-wing.
- Advantages: Versatility of operation, ability to cover large areas, and not requiring large spaces for take-off and landing.
- Disadvantages: Generally more complex and expensive.
- Examples: WingtraOne, Quantum Systems Trinity F90+.

*Hybrid Drones:*

- Characteristics: Combine elements of different drone types, such as fixed and rotary wings or VTOL capabilities with fixed wings.
- Advantages: Versatility and flexibility in different types of missions.
- Disadvantages: Can be more complex to operate and maintain.
- Examples: Delair DT26X, Skyfront Perimeter.[18]

**Geodesy**

The term Geodesy, from the Greek γη (‘earth’) and δαιζω (‘to divide’), was first used by Aristotle (384-322 BC) and can mean both ‘geographical divisions of the earth’ and the act of ‘dividing the earth,’ e.g., between landowners. Geodesy is a branch of geosciences and engineering.

The Greek mathematician, astronomer, and geographer Eratosthenes of Cyrene (276 BC to 194 BC) was the first to estimate the circumference of the earth, obtaining a radius of 6267 km. This is quite similar to the modern calculation of 6378 km, considering the limitations of the time.

Geodesy is one of the oldest sciences cultivated by man. Its objective is the study and determination of the shape and dimensions of the Earth, its gravity field, and its temporal variations. It is a science-based on physics and mathematics. It forms the geometrical basis for other branches of geographical knowledge, such as topography, cartography, photogrammetry, navigation, and engineering of all kinds or for military purposes and space programs.[19] It is also related to astronomy.

Itis also related to astronomy and geophysics. This science is divided into two parts:

Higher geodesy or geodesy proper, divided between physical and mathematical geodesy, tries to determine and represent the figure of the Earth in global terms.

Practical geodesy, or topography, studies and represents smaller parts of the Earth where the surface can be flat. Geodesy is basic in determining the position of points on the Earth’s surface, and one of its greatest utilities, from a practical point of view, is that its techniques make it possible to represent very extensive territories cartographically.

It deals with the survey and representation of the shape and surface of the Earth, global and partial, with its natural and artificial forms. Geodesy is also used in mathematics for measurement and calculation on curved surfaces. Methods similar to those used on the Earth’s curved surface are used. Geodesy provides, with its theories and its results of measurements and calculations, the geometrical reference for the other geosciences as well as for geomatics, Geographic Information Systems, cadastre, planning, engineering, construction, urban planning, aerial, maritime and land navigation, among others, and even for military applications and space programs.

Higher geodesy or theoretical geodesy, divided between physical geodesy and mathematical geodesy, tries to determine and represent the figure of the Earth in global terms; Lower geodesy, also called practical geodesy or topography, surveys and represents smaller parts of the Earth where the surface can be considered flat. For this purpose, we can consider some auxiliary sciences, such as cartography, photogrammetry, compensation calculation, and the Theory of Observational Errors, each with various sub-areas.

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In addition to the disciplines of scientific geodesy, several technical disciplines deal with problems of the organization, public administration, or application of geodetic measurements, e.g., systematic mapping, land cadastre, rural sanitation, engineering measurements, and geoprocessing.[20]

**Theoretical Geodesy**

The observation and description of the gravity field and its time variation are currently considered the problems of most significant interest in theoretical geodesy. The direction of the gravity force at a point, produced by the rotation of the Earth and by the mass of the Earth, as well as the mass of the Sun, the Moon, and the other planets, and the same as the direction of the vertical (or plumb line) at some point. The direction of the gravity field and the vertical direction are not identical. Any surface perpendicular to this direction is called an equipotential surface.

One of these equipotential surfaces (the Geoid) is the surface that most closely approximates the mean sea level. If the gravity field within a spatial coordinate system is known, the problem of determining the terrestrial figure is solved for a given time. This gravity field also undergoes alterations caused by the rotation of the Earth and the motions of the planets (tides).

In accordance with the rhythm of the ocean tides, the earth's crust also undergoes elastic deformations due to the same forces: the terrestrial tides. For a hypothesis-free geoid determination, gravimetric measurements are required first—in addition to astronomical measurements, triangulations, geometric and trigonometric leveling, and satellite observations (Satellite Geodesy).

**Pysical Geodesy**

Most geodetic measurements are applied on the earth's surface, where points of a triangulation network are marked for planimetric determinations. With the exact methods of mathematical geodesy, these points are projected onto a geometric surface, which must be mathematically well-defined. For this purpose, a rotation ellipsoid or reference ellipsoid is usually defined. Several ellipsoids were previously described for the needs of just one country, then for continents, and today for the entire globe, first defined in international geodetic projects and the application of the methods of satellite geodesy. In addition to the planimetric reference system (triangulation network and the rotation ellipsoid), there is a second reference system: the system of equipotential surfaces and vertical lines for altimetric measurements.

According to the geodetic definition, the height of a point is the length of the line of verticals (curve) between point P and the geoid (geodetic height). The height of point P can also be described as the difference in potential between the geoid and that equipotential surface containing point P. This height is called the geopotential height. Compared to metric or orthometric heights, geopotential coordinates have the advantage that they can be determined with high accuracy without knowledge of the geoid's shape (leveling). For this reason, geopotential coordinates are often used in leveling projects of large areas, such as continents, as in the case of the 'Single European Altimetry Network compensation.'

If there is a sufficient number of planimetric and altimetric points, the local geoid of that area can be determined. The area of Geodesy that deals with the regional or global definition of the terrestrial figure is generally called Physical Geodesy for that area or its sub-areas. Terms such as Dynamic Geodesy, Satellite Geodesy, Gravimetry, Astronomical Geodesy, Classical Geodesy, and Three-dimensional Geodesy are also used.[20]

**Geometric Geodesy**

Determines the shape and dimensions of the earth in its geometric aspect and the determination of point coordinates on its surface.

*Geodetic astronomy*

To determine the coordinates on the earth's surface from measurements of the stars.

*Spatial geodesy*

This allows us to determine the coordinates from measurements performed by artificial satellites (GNSS, GPS, DORIS, etc.) and their relationship with the definition of reference systems.

*Microgeodesy*

It allows us to measure the deformations of civil works or land extensions through high-precision geodetic techniques.

**Importance of Geodesy**

With high-precision GNSS instruments, measurements can be obtained using geodesy to record millimetric movements over long periods. This allows us to detect small movements and changes in the earth that could represent an imminent danger.

Taking this into account, it is correct to point out that the importance of this information serves to ponder, review, carry out, or determine uses as varied as described below:

Erthquake damage is crucial because it can quantify the rupture of the ground surface and identify possible future hazards that the detachment of earth or rocks may cause.

Volcanic deformation. This study of the structure beneath the earth's surface makes it possible to predict volcanic eruptions.

Gravity. Measures the gravity of the earth's surface and establishes the gravitational pull, which is used to establish global sea level.

Multipurpose Cadastre. Determines the location, extension, and orientation of properties, providing precise information about the territory, thus favoring the improvement of public policies about the increase of access to the right to property of the population.

Land Management Plans provide accurate information for analyzing the territory's transformation process and determining the order's limits and restrictions.

Environment. Supports monitoring areas of environmental interest to establish identification and delimitation processes for sustainable territorial development.[21]

**Cartography**

A word derived from the Latin charta, which translates as 'map,' and the suffix -graph, which derives from the Greek graphein meaning 'to write.'

Cartography is the science of drawing and studying geographical maps. Although quite ancient, its origins cannot be pinpointed exactly because the definition of a map has changed over the years.

In the past, maps were drawn on the ground, whereas today, satellite technologies are used. Several sources state that Thales of Miletus was responsible for the creation of the first cartographic representation of the planet Earth and that Aristotle was the first to calculate the angular tilt of the Earth with respect to the equator.

Various murals and engravings dating back several millennia before our era are considered to be the earliest maps and, thus, the first evidence of cartography. The Greeks, Romans, Chinese, Arabs, and Indians are some civilizations that developed maps in antiquity. Specifically, a mural painting called 'The Admiral's House' has been identified as the first cartography. It is characterized by being made inside a community living in a coastal area in 1600 BC.

Throughout history, there have been many other cartographic examples that were important in their time and today are considered authentic jewels, such as the map of the ancient Sumerian city of Nippur, which, according to the studies carried out, would belong to the period between the 16th and 12th centuries BC. Chinese maps made of silk dating from the 2nd century BC were discovered in excavations carried out in the 1970s in the area of Mawangdui. Ancient maps with distinctive constellations, such as the Polar Bear, were made in India. Tabula Rogeriana. These are a set of cartographies by the Arab Muhammad al-Idrisi in 1154, whose subjects are Africa and the Indian Ocean area.[22]

*Tes of Cartography*

Catography can be divided into two main types: general cartography and thematic cartography. General cartography deals with producing maps aimed at the wider public, with various references, e.g., a world map or a map of a country.

O the other hand, thematic cartography specializes in maps of specific topics, such as the corn crops in a province or the predominantly Latino neighborhoods in New York.

Another distinction can be made between topographic maps (which reflect the elevation of the terrain) and topological maps (simplified maps that do not focus on geographic detail or scale but instead on the information they disseminate).

*Map*

The concept of a map comes from the Latin term mappa. A map is a drawing or outline that represents a swathe of territory on a given two-dimensional surface.

Maps allow a person to locate himself in a territory. For example, a man arriving for the first time in Santo Domingo can have a map with the streets and places of interest in the capital so as not to get lost.

The first maps were flat charts (latitudes were represented with a constant scale as if the Earth were flat). The invention of devices such as the compass and the quadrant contributed to more accurate maps. Technology has played a major role in the advancement of cartography. From telescopes to scanners, satellites to computers, numerous inventions have helped to improve map-making and analysis.

Cartographers use symbols and colors to provide as much information clearly as possible. The amount of data is determined by the scale chosen for representation; the larger the space to represent a region, the larger the

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amount of data.

*Weather Maps*

Many maps match what they want to show us and the objective they intend to cover. Weather maps are of daily use. They are documents that represent the meteorological phenomena, fronts, and pressure that will prevail in a specific period of time in a specific area of the world. With this map, we can find out about the temperatures and weather conditions that will occur in our city, like those presented on the news.

*Other types of maps*

Teachers in the educational field also use another kind of map to help students understand a topic being addressed in class more clearly.

ther very important are the concept maps, which are a kind of summary, of union of concepts, which allow students to understand much better and in a schematic way what is being taught. We also have didactic maps, which have an instructive and pedagogical mission.[23]

Within this same line would be the historical maps, which are used to make known a series of relevant events and historical facts.

*Digital Cartography*

This science deals with digitizing, storing, retrieving, and representing geographic maps. It encompasses the use of technologies in cartography and geospatial applications. Technological advances have significantly increased its relevance and the application of techniques in Geography, Topography, Geoprocessing, etc.

The aim of this science is to provide aesthetic and geographic maps of high detail and accuracy for use in various areas of knowledge. Digital cartography has grown significantly in recent years, as with the advancement of data analysis and artificial intelligence, it has become easier and easier to collect and analyze the most diverse information about an area of interest.

The main maps produced with this technology are relief maps, orthomosaics, point clouds, contour lines, aerial images, vectorized maps, and land surface maps. These maps provide important information for many areas, such as strategic planning, data analysis, and land identification.

Digital mapping provides fundamental tools to help us understand the world around us. It can organize and provide visual and geospatial information quickly and efficiently, enabling surveying and engineering professionals to make accurate and reliable decisions.

It is a fundamental part of communication in various projects, allowing people to follow its evolution and share information in real-time. It helps generate a better understanding of geographic data and provides a visual representation of that data, facilitating the creation of models for analysis.

Digital mapping is also essential for developing geographic maps that provide detailed information on terrain features such as relief, vegetation density, water sources, and other natural features. These maps plan urban and rural development strategies and provide information on natural resources and risk areas.

It is correct to infer that digital mapping is of great importance for disciplines such as surveying, civil engineering, agriculture, mining, environmental engineering, and solar energy. As it provides information for the development of any project, it plays a major role in urban planning, monitoring and conservation of environmental preservation areas, creation of solar plants, and many other areas.

Digital mapping offers numerous advantages in obtaining visual and georeferenced data, monitoring, measuring areas, calculating distances, and analyzing altimetry. The use of digital maps improves information accuracy, increasing the effectiveness of decision-making.

Digital mapping also contributes to the verification of geographic patterns, providing a better understanding of the local environment. It also allows the creation of more detailed maps that are easier to update, enabling effective management of geospatial data.[24]

Digital mapping allows for the agile and intuitive production of a range of maps, such as orthomosaics, digital terrain models, contour lines, point clouds, heat maps, and 3D models.

All these products are essential for monitoring and analyzing geographic data and obtaining visual information. Digital mapping also allows interaction between users and products, providing a database of the area of interest that can be manipulated in software such as ArcGIS Pro, QGIS, AutoCAD, and Civil 3D, among others.

The potential and objectives of each digital mapping product can be seen in issues such as the ortho mosaic, a digital map composed of several orthophotos joined and superimposed on a particular area, similar to a jigsaw puzzle. It is a powerful tool that provides georeferenced visual information. In other words, each photo that makes up the orthomosaic has geolocation data, making it easier to take measurements and collect points of interest. To generate an orthomosaic, the drone images must be processed in specialized software.

The digital terrain model (DTM) and digital surface model create representations of altimetry data for an area of interest. Each uses different filters to represent the terrain elevation data. So, while the digital surface model represents the ground elevation and all features above it, such as buildings and trees, the DTM excludes these objects and only represents variations in ground elevations. Both DTM and DSM files result from the automatic processing of images from drone mapping.

A contour line is formed when each contour line connects several points of the same height on a terrain. Contour lines are parallel lines that allow the visualization of the altitude levels of terrain and possible irregularities on its surface.

Contour lines provide a three-dimensional view of the topographic profile of the surveyed area. This makes it easy to identify terrain features such as mountainous areas, slopes, differences in altitude, and exit points.

The point cloud is able to recreate surfaces and structures through a large group of georeferenced points, as with other maps, this data is obtained through drone mapping and image processing. Through this cloud, it is possible to obtain various information such as elevation, depth, and location. And since each point represents a small piece of information, the denser the cloud, the closer it is to reality. In other words, the more points = the more information.

Te 3D model is created from the point cloud as a base. Through its rendering, it is much easier to generate a complete view of the area of interest. Some professionals use this map to follow the evolution of constructions, present projects, and predict shadows on solar panels. This type of product can be manipulated in software such as Cinema 4D, Global Mapper, Revit, and Wavefront.

The right tools for digital mapping offer the best image quality, loading speed, and presentation. The two main technologies for creating digital mapping products include drone mapping and cloud-based image processing.

With these two tools, you can obtain superb mapping results in an intuitive, agile, and accurate way at a more affordable cost than other alternatives. Just follow the three steps below: aerial mapping flight with drone, Drone image processing, and manipulation and analysis of the data obtained.

Although Google Maps can be used, its images are often outdated or do not have ideal image quality. Therefore, it is essential to use software designed for digital mapping. Digital mapping provides access to important geographic data that can be used to create interactive maps, offering the opportunity to extract relevant information.

We load the maps into software that accepts the generated file extension to extract the data and use it as a basis for a project. For example, ortho mosaic, contour, and digital terrain models can be manipulated in QGIS or AutoCAD.

Sebera possibilities exist, and a complete list of software compatible with all the cartographic products seen so far can be consulted.

Maps generated with digital cartography are versatile and have diverse applications, so it is essential to consider the needs and objectives pursued.

**Geographic Information Systems**

A geographic information system (GIS) describes and categorizes the Earth and other geographies to display and analyze spatially referenced information. This work is primarily done with maps.

The purpose of GIS is to create, share, and apply useful map-based information products that support organizations' work and to create and manage relevant geographic information.

Maps represent logical collections of geographic information as layers.

Interactive GIS maps are an effective way to model and organize geographic information in the form of thematic layers. They also provide the primary user interface for using geographic information.

In both interactive and printed formats, maps play a special role in GIS and are a central part of its operation.

A new type of map, the GIS map, is much more than a static cartographic presentation. It is an interactive window to all geographic information and descriptive data and to rich spatial analysis models created by GIS experts.

GIS maps are used to publicize and share GIS, compile and maintain GIS content, design and organize geographic information through thematic layers, obtain new information through geoprocessing, visualize, summarise, analyze, compare, and interpret the analytical results, and share geographic information for use on the Web.

Maps are a central part of how GIS works. In a GIS, the map is the interface. The following are some examples that illustrate how GIS maps are used in different organizations.[25]

**GIS maps are used for communication and understanding**

Maps are used to communicate and convey large amounts of information in an organized way. Humans think spatially, so when viewing a map, we can associate map locations with real-world phenomena and interpret and grasp essential information from the detailed content displayed on each map visualization.

**GI Maps as Tools for Identifying Patterns**

Mps are used to discover and investigate patterns, such as the characteristics of a population within a city or the antelope migrations between their winter and summer habitats. In GIS, interactive online maps are used to compare data reports from various entities and changes in phenomena over time.

The maps convey patterns visually. For example, one map shows the age distribution of populations in different parts of the southern Dominican Republic. Darker colors represent areas with older populations. You can click on an entity on the map to show the age distribution of the selected block group. In this way, you use the map as a window to large sets of geographic and tabular information. GIS maps provide interactive reporting of the underlying information on the map.

This is a key point. GIS maps provide interactive reporting of the underlying information, not just lists of attributes but graphs, reports, photographs, and virtually any relevant content (e.g., a link to a website). Defining how entities are reported and what is accessed through a map entity is one of the essential specifications that must be designed and captured when creating a GIS map. GIS maps combine effective visualization with a robust analysis and modeling framework.

**GS Maps Enable New Information Through Analysis**

Te GIS map becomes a window to rich analytical results. It is primarily used to enter and run analysis models and display their results as a new map layer. Analysis is related to working with and evaluating a model's results. It is performed using the reporting, visualization, and entity animation capabilities described above.

A heat map can show criminality. For example, warmer colors represent higher crime incidence. Another map might show predicted malaria outbreaks in Africa, with darker colors representing a higher predicted density of malaria cases.

You can have a map showing three routes used to optimize travel time between stops for three vehicles in a fleet. Organizations that use network analysis to optimize vehicle routes can save 20 % or more on annual delivery costs.

Spatial analysis is one of the most interesting and remarkable aspects of GIS. With it, GIS users can combine information from numerous independent sources and obtain entirely new sets of data (results) by applying a large and sophisticated set of spatial operators. GIS professionals use geoprocessing to program their own ideas to produce these analytical outputs, which are then applied to a wide variety of problems.

**GIS Maps are Used to Communicate and Report States**

On the Web, maps can communicate status and keep teams abreast of events. GIS information is dynamic and frequently updated in the case of many layers. Dynamic maps effectively give everyone a standard view of the latest information.[24]

A widespread application of GIS uses operational dashboards that present data sources and the status of a particular set of activities. The layers of information in the dashboards are targeted to a specific audience and their operational needs and allow them to work more efficiently and responsively.[25]

Maps allow for the compilation and editing of entities and other data managed and maintained in geodatabases. Primarily, the map is used to bring the data into the GIS. The best GIS maps for editing feature the specific types of entities you want to add to your maps, relevant attribute properties, and editing tools.

ArcGIS allows users to define and share these editing properties as part of a layered design.

Maps help communicate ideas, plans, and design alternatives. Effective layered visualization, combined with interactive entity reports, is an important mechanism for visualizing, communicating, and understanding various alternatives.[26]

Maps are convenient and helpful for displaying geographic information. Quality maps help GIS users to communicate and share geographic information (Arcgis.com, 2024).

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