ELIA QUIRÓS ROSADO

Introduction to Applied Photogrammetry and Cartography for Civil Engineering

UNIVERSIDAD DE EXTREMADURA

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GENERAL INDEX

PROLOGUE

Civil engineers, throughout their careers, should handle cartographical information, which is mainly obtained by photogrammetry techniques. This work aims at practically introducing the digital aerial photogrammetry technique, with the purpose of sharing the methods used to obtain cartography to plan their work.

Mathematical formulation is not under the scope of this work, since, in my view, it has little to contribute to civil engineers and there exist very complex treaties aimed at more specialised readers in the field.

This short text begins by outlining some basic cartography concepts, focusing on reference systems, which are changing nowadays and should be known by civil engineers before working with cartographical data.

The text's fundamental part focuses on digital photogrammetry, and by emphasising once again on its simplicity, it aims at explaining, from my professional experience, all the work process from the moment when a photogrammetric flight is requested until digital cartography arrives into the hands of engineers to work on it, with its accuracies and precisions.

Therefore, this work is intended to provide help to civil engineering professionals when valuating and handling cartographical data which, to a greater or lesser degree, would be the basis for their work.

Elia Quirós Rosado

THE CONCEPTS OF
GEODESY AND CARTOGRAPHY

Chapter I
GEODESY

1. THE CONCEPT OF GEODESY

Geodesy is the science that studies and determines the shape and dimensions of Earth, its gravitational field and its temporal variations.

Geodesy can be divided into two major branches:

Superior Geodesy or Geodesy:

This branch is the part of Geodesy that aims at determining and representing Earth in global terms.

Practical Geodesy or Surveying:

This branch is the part of Geodesy that studies and represents smaller portions of Earth where the surface can be considered flat.

Based on the study of Earth, according to a mathematical concept, Geodesy studies both the shape and the dimensions of Earth. Additionally, its gravitational field and its temporal variations are also studied, conforming to the definition of the term Geodesy. These two last concepts would be included in the field of Physics.

Following this last reasoning, Geodesy can be divided into two types:

- *Physical Geodesy* (Gravitational field): this first type studies the Earth's gravitational field by hypothesising about mass distribution models or by measuring gravity on the surface.

  This type of Geodesy postulates the Geoid (*Figure 1*) as a figure that defines the Earth's shape.

Mathematical Geodesy (Earth's shape): This second type studies the Earth's shape by determining the coordinates of check points located over the Earth's surface by using a fixed and valid reference system for the whole Earth.

This second type defines the Ellipsoid (*Figure 2*) as a figure that defines the Earth's shape.

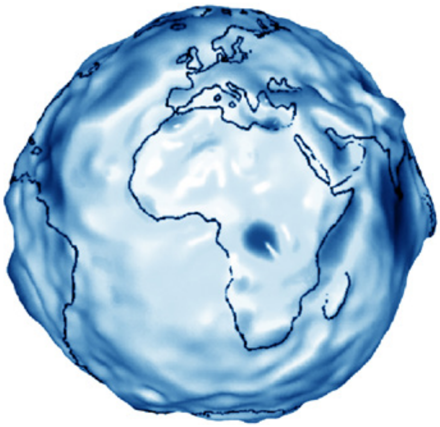

Figure 1. Geoid: Surface of Altimetric reference. (source: European Spatial Agency)

Figure 2. Ellipsoid: Surface of planimetric reference.

2. BRANCHES OF GEODESY

There exist different branches within Geodesy.

- GEODETIC ASTRONOMY: Determination of geographic coordinates and of azimuths of certain directions by means of astronomical methods, which are independent from any hypothesis regarding the Earth's shape.
- GEOMETRIC GEODESY: The observation data is compiled from the angles and distances' measurement on the Earth's surface. It is crucial to be knowledgeable of the geometry of the ellipsoid of revolution.

- DYNAMIC GEODESY: Devoted to the determination of the variations that take place in the check points' coordinates. Such variations are temporary, secular, regular or of a rough nature, and can take pace globally, locally or regionally.

3. DIVISIONS OF GEODESY

Regarding the length of the geodesic study, Geodesy can be divided into three categories:

- GLOBAL GEODESY: Internationally practiced and coordinated by whole Earth.
- REGIONAL GEODESY: Practiced independently in each country, with the purpose of solving cartographical and geographical problems of the nation.
- TOPOGRAPHIC GEODESY: Aims at specifying the details of a particular surface of small dimensions, being this surface considered either flat or spherical, depending on its dimensions.

4. OBJETIVES OF GEODESY

- To establish and maintain national and global three-dimensional networks' control (*figures 3, 4 and 5*), taking into account the movements of the tectonic plates.

Figure 3. National Geodesic Network.

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Figure 4. European Geodesic Network.

Figure 5. Global Geodesic Network.

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- To measure and represent geophysical phenomena like Earth tides, poles (*figure 6*) and crusts movements, etc.

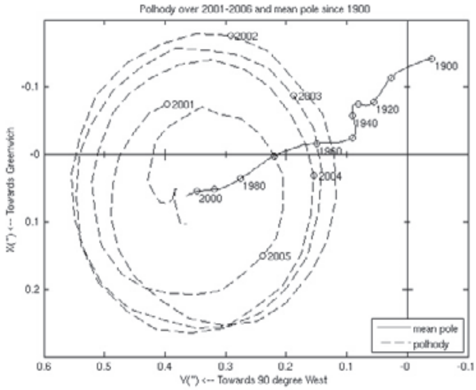

Figure 6. Pole movement (source: NASA JPL)

- To determine the gravitational field and its temporal variations, gathering data that delimit the geoid's shape, as shown in *figure 7*.

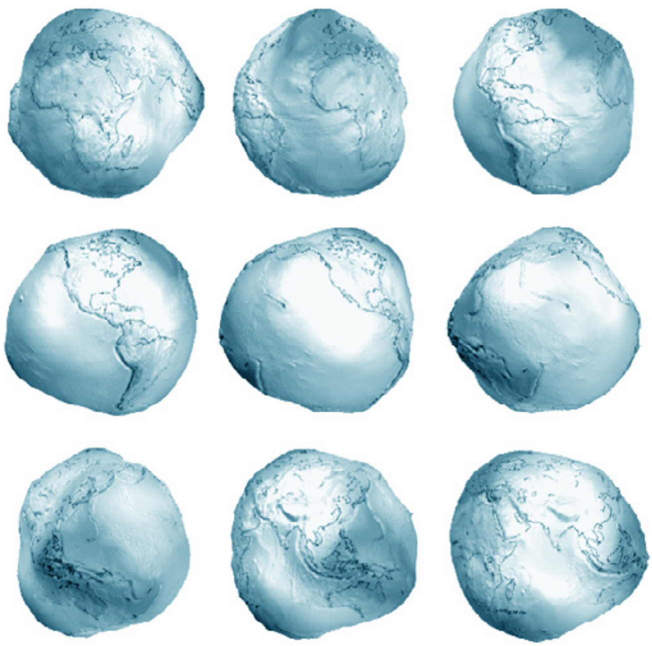

Figure 7. EIGEN-CG01C Geoid.

5. PHYSICAL GEODESY

Earth has a unique shape. There does not exist any other geometric figure with the same shape.

Seas and oceans occupy 70,80% of Earth. The average sea level is considered the role model surface to measure heights. This average measurement is the best approximation to the Earth's real shape.

The average sea level depends on the irregularities that the gravitational field may have, which alter its shape. Water aims to achieve stability and tends to follow an equipotential surface of gravity.

On this basis, the so-called figure ***Geoid*** is introduced, being defined as:

> *"The most similar equipotential gravimetric surface to the average sea level and its continuation underneath the continents"*

Therefore, the geoid would be the balanced surface of the oceans that are subjected to the gravitational pull and to the centrifugal force caused by rotation and the translation of the planet so that the gravity direction is perpendicular in all locations.

Geoid is the geometric location of the points that are at equilibrium under these forces' action:

– Forces of gravitational attraction of the other points in the surface of the Geoid.
– Forces of gravitational attraction of the rest of the solar system bodies in the Solar System.
– Centrifugal force, as a result of the Earth's rotational movement.

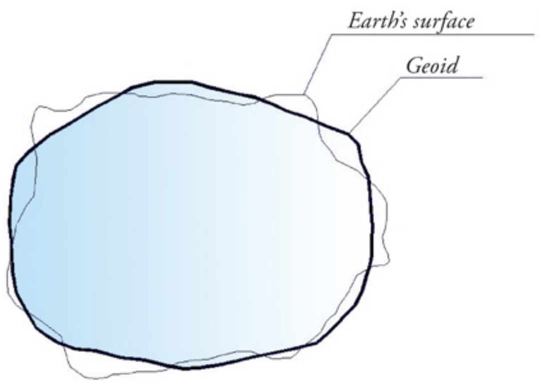

Figure 8. Adjustment of the Geoid to the real Earth's surface.

In fact, it is an irregular surface, as it can be seen in *figures 7* and *8*, which has protuberances and hollows due to the irregular distribution of the gravitational pull in the Earth's mass.

The geoid's shape can be determined by using two methods:

- Classical methods: gravimeters that observe the periodical variations that take place in the module or gravity magnitude.
- Current methods: Satellites that observe elements' signals that are not directly associated with Earth, like GRACE, GOCE…

6. MATHEMATICAL GEODESY

Mathematical Geodesy studies the Earth's shape by determining the points' coordinates located over the Earth's surface, by using a fixed and valid reference system for the whole Earth.

Its most remarkable characteristics are:

- It measures angles and distances over the Earth's surface.
- It takes mathematical models as surface references.
- It determines the parameters of those models.

When calculating locations, distances, etc. across the Earth, it is necessary for those mathematical calculations to be made over a specific surface that follows certain mathematical laws.

Geoid does not meet those needs; therefore, an arbitrary mathematical surface closely adapted to the geoid's shape is used.

The **Ellipsoid** is the simplest geometric shape that conforms to the Earth's real shape. Over this shape, angle, position and distance calculations can be made.

An ellipsoid of revolution is an ellipsoid that turns around its minor axis and generates a shape with surface.

Within Geodesy, two types of ellipsoid can be distinguished, as it can be seen in *figure 9*:

- Global Ellipsoids: Those that are close to the whole Earth's shape. They are compelled to coincide with the Earth's axis of inertia. They are also known as geocentric ellipsoids.

– Local Ellipsoids: They are adjusted to a specific area of Earth. They are merely used in that part of the Earth's surface.

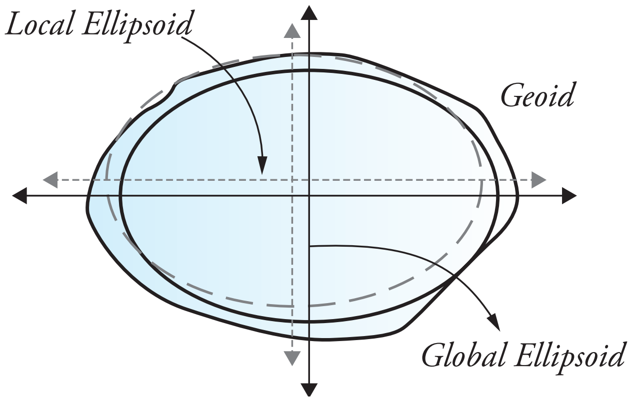

Figure 9. Differences between a Local and a Global Ellipsoid.

The parameters of an ellipsoid of revolution would be the ones shown in *figure 10*, and they are defined as:

a: Semi-major axis (Equatorial): length from the centre of the Earth's mass to the Earth's surface, measured along the equator.

b: Semi-minor axis (Polar): length from the centre of the Earth's mass to one of the poles.

f: Flattening factor: relation that exists between the magnitude of the major and the minor axis.

$$f = 1 - \frac{b}{a}$$

Eq. 1: Flattening factor

Given that this value is usually too low, there is a tendency to use the inverse flattening:

$$\alpha = \frac{1}{f}$$

Eq. 2: Inverse of the flattening factor.

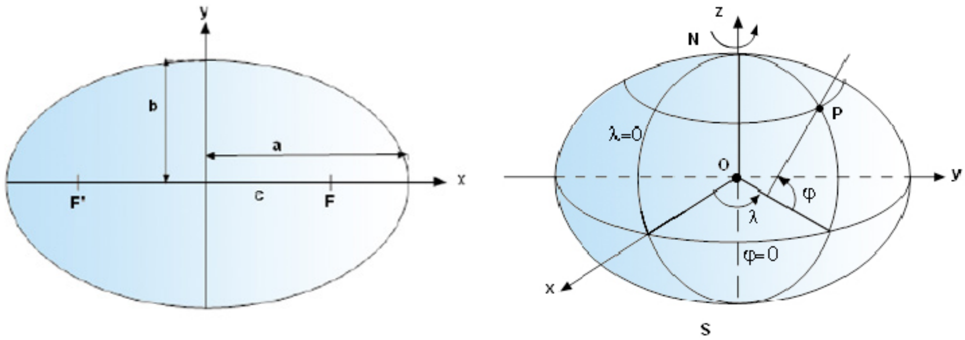

Figure 10. Parameters of an Ellipsoid of revolution.

Some of the ellipsoids used both in the past and nowadays, are the ones shown in *table 1*:

Nombre	a (m)	b(m)	1/f
Australian National	6,378,160.000	6,356,774.719	298.250000
Bessel 1841	6,377,397.155	6,356,078.963	299.152813
Clarke 1866	6,378,206.400	6,356,583.800	294.978698
Clarke 1880	6,378,249.145	6,356,514.870	293.465000
Everest 1956	6,377,301.243	6,356,100.228	300.801700
Fischer 1968	6,378,150.000	6,356,768.337	298.300000
GRS 1980	6,378,137.000	6,356,752.314	298.257222
International 1924 (Hayford)	6,378,388.000	6,356,911.946	297.000000
SGS 85	6,378,136.000	6,356,751.302	298.257000
South American 1969	6,378,160.000	6,356,774.719	298.250000
WGS 72	6,378,135.000	6,356,750.520	298.260000
WGS 84	6,378,137.000	6,356,752.314	298.257224

Table 1. Most common Ellipsoids

It should be highlighted that some of them belong to the so-called local ellipsoids, and others to the group of global ellipsoids. They have been defined for their use in certain areas of the Earth (*figure 11*).

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The ellipsoids that can be used in our geographic location are the following:

- ***International 1924***, also known as Hayford's Ellipsoid: it is the reference ellipsoid for the ED50 system, which remained valid in Spain until 1st January, 2015. It is the local ellipsoid to which the European coordinates relate.
- ***GRS 1980***, also known as GRS-80: it is the Global ellipsoid that is taken as a reference in the ERTS-89 system. Even though it is a global ellipsoid, it can only be applied to the European continent.
- ***WGS 84***: it is the global ellipsoid used by the WGS84 system. The GPS systems work with this ellipsoid, which is used globally over the whole Earth's surface.

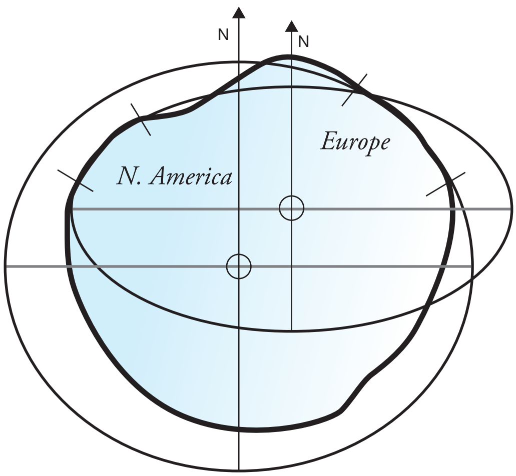

Figure 11. Differences between two regional ellipsoids, a global and a local one.

7. RELATION BETWEEN THE GEOID AND THE ELLIPSOID

The distance between the Ellipsoid and the Geoid in a particular location is known as the Geoid undulation in that location (*figure 12*).

Depending on where that distance is measured, it could be either positive or negative, depending on whether the ellipsoid is under or over the geoid respectively. Moreover, its value varies spatially, as it can be seen in *figure 13*.

$$N=h-H$$

Eq. 3: Geoid undulation

Being,

N the Geoid undulation
h the height or ellipsoidal height
H the height above the geoid or orthometric height.

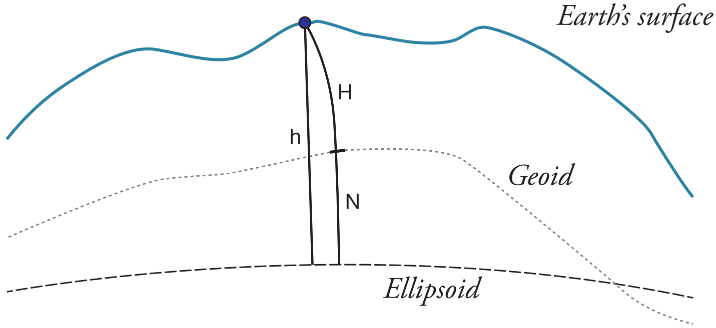

Figure 12. Geoid undulation.

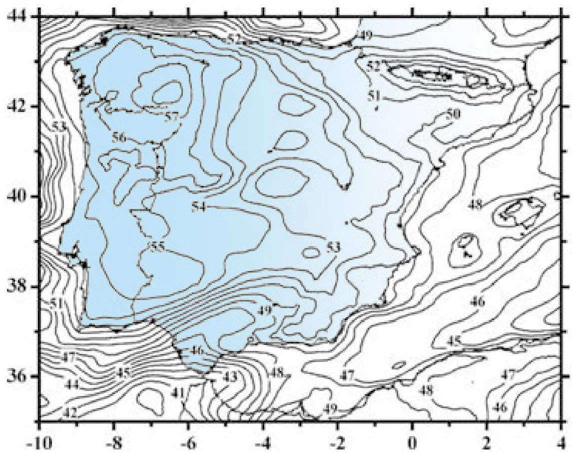

Figure 13. Geoid undulation's values in Spain.

The GPS measurement system provides us with coordinates that refer to WGS84, therefore, the height it measures is an ellipsoidal height. Nevertheless, the heights that are measured when making a geometric levelling are orthometric heights, being the latter the ones that appear in all the Official Cartography. In that way,

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when GPS[1] measurements are made, the measured heights should be transformed into orthometric, by adding or subtracting the Geoid's undulation, depending on the place where we are located.

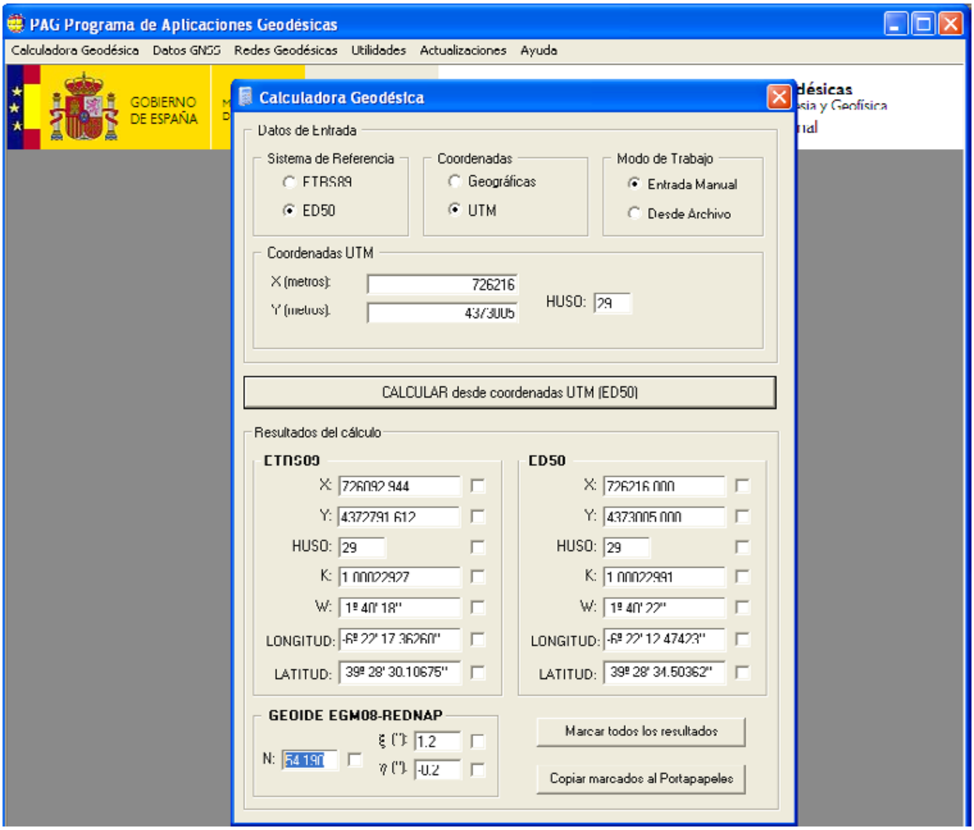


Figure 14. NGI's geodesic calculator.

A very useful resource is the Geodetic Applications Programme of the Spanish NGI[2]. As it can be observed in figure 14, by introducing the coordinates of a point, it gives us the undulation in that geographic location.

In our geographic location, the official undulation value of the geoid EGM08 for the peninsula regarding Hayford's Ellipsoid (ED50) is 54,190m.

1 Global Positioning System
2 National Geographic Institute

Chapter 2:
REFERENCE SYSTEMS

1. REFERENCE SYSTEMS

A **reference system** consists on a group of models that are necessary to describe the positions and movements of celestial bodies, including Earth (celestial systems), or of bodies that are on Earth (terrestrial systems)

Origin, scale, orientation and main plane should be defined.

A reference system is **Inertial** if it is at rest or if it moves at constant speed with regard to the rest of the universe. Therefore, it is considered to be fixed in space.

There are two main levels of reference systems:

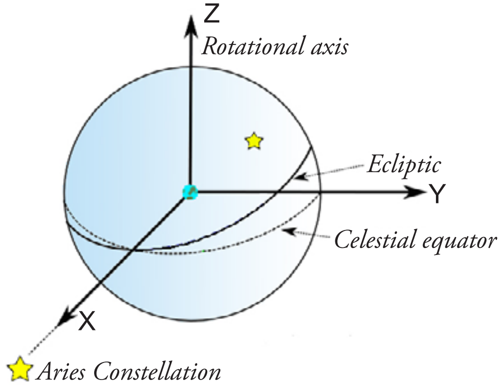


Figure 15. Celestial Reference System

- **Celestial Reference Systems** (CRS[3]): they are quasi-inertial systems used to locate the positions of celestial objects like stars. The direction of the terrestrial rotational axis remains approximately constant regarding such objects and allows definitions of the reference system to be made. As it can be seen in *figure 15*, its main plane is the Equator, the Z axis is on the direction of the terrestrial rotational axis. The X axis

[3] Celestial Reference System

towards the Aries constellation, and the Y axis creates a direct trihedron with the two latter. Its origin is the Earth's mass centre.

– **Terrestrial Reference System** (TRS[4]): They are systems that are tied to Earth and they rotate together. They are non-inertial. Their main plain is the Equator, as it can be seen in *figure 16*, the Z axis is in the direction of the terrestrial rotational axis, the X axis is in the direction of the intersection between the Greenwich meridian and the Equator, and the Y axis creates a direct trihedron with the previous ones. Its origin is the Earth's mass centre.

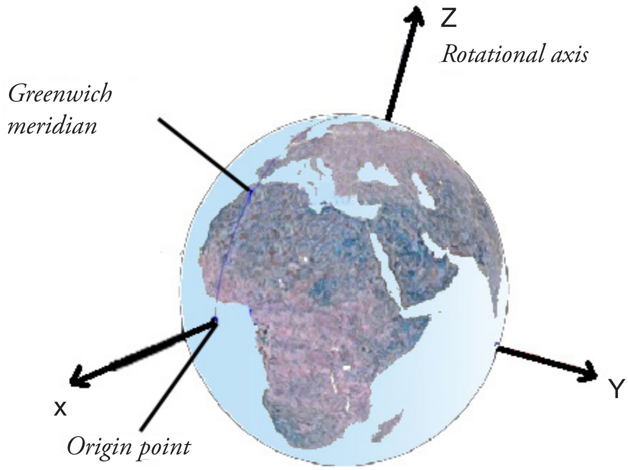


Figure 16. Terrestrial Reference System.

2. FRAMES OF REFERENCE

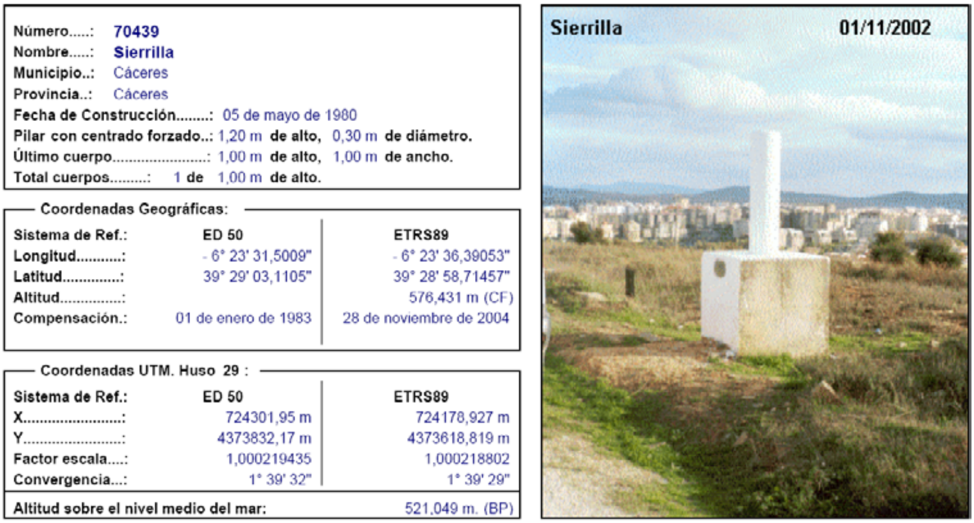
A frame of reference is the realisation of a reference system.

Frames of reference consist of the coordinates of the control points, the techniques applied in their observations, and the calculation methods the coordinates are obtained with. They are usually realised as shown in *figure 17*.

Each reference system is associated with its corresponding frame, but in some cases, the same point can serve as a frame for different systems (*figure 18*).

4 Terrestrial Reference System

Figure 17. Geodesic vertex that belongs to a reference system.



Número.....: 70439
Nombre.....: Sierrilla
Municipio..: Cáceres
Provincia..: Cáceres
Fecha de Construcción........: 05 de mayo de 1980
Pilar con centrado forzado..: 1,20 m de alto, 0,30 m de diámetro.
Último cuerpo.......................: 1,00 m de alto, 1,00 m de ancho.
Total cuerpos.........: 1 de 1,00 m de alto.

Coordenadas Geográficas:

Sistema de Ref.:	ED 50	ETRS89
Longitud...........:	- 6° 23' 31,5009"	- 6° 23' 36,39053"
Latitud..............:	39° 29' 03,1105"	39° 28' 58,71457"
Altitud...............:		576,431 m (CF)
Compensación.:	01 de enero de 1983	28 de noviembre de 2004

Coordenadas UTM. Huso 29 :

Sistema de Ref.:	ED 50	ETRS89
X.........................:	724301,95 m	724178,927 m
Y.........................:	4373832,17 m	4373618,819 m
Factor escala....:	1,000219435	1,000218802
Convergencia...:	1° 39' 32"	1° 39' 29"

Altitud sobre el nivel medio del mar: 521,049 m. (BP)

Figure 18. Geodesic vertex with coordinates of two reference systems (source: NGI).

3. TERRESTRIAL REFERENCE SYSTEMS

3.1. European Datum 1950 (ED50) reference system

This reference system comes from the compensation of the geodetic networks that the USA carried out by that year in order to achieve unified cartography for all the Allied Countries after the Second World War.

Hayford's ellipsoid or International 1924 was taken as the origin for the latitudes in the Equator and for the lengths in the Greenwich Meridian.

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The origin point (**fundamental astronomical point**) on which transportations of the calculated positions of the other points that constituted the framework could be made, was, as it can be observed in *figure 19*, the Potsdam Observatory (Germany).

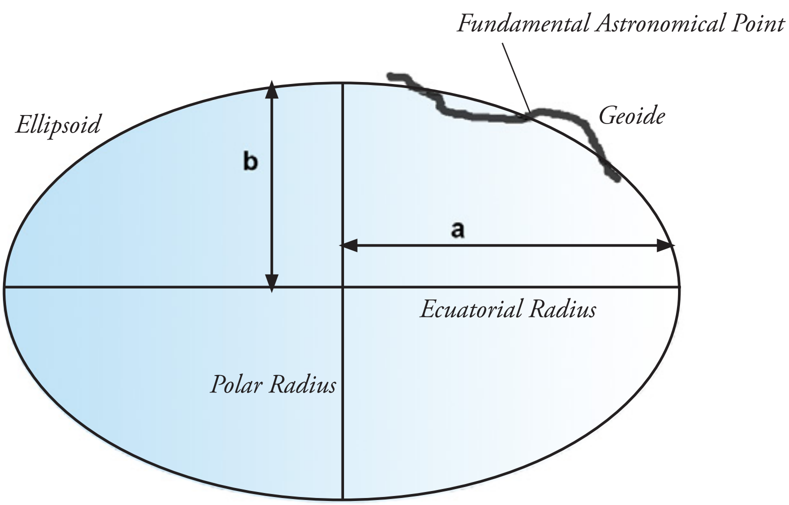

Figure 19. Fundamental Astronomical Point.

This reference system is adapted to Europe. Therefore, it is a local reference system. Its ellipsoid, as it is shown in *figure 20*, is displaced by about 230m regarding the centre of the Earth's mass.

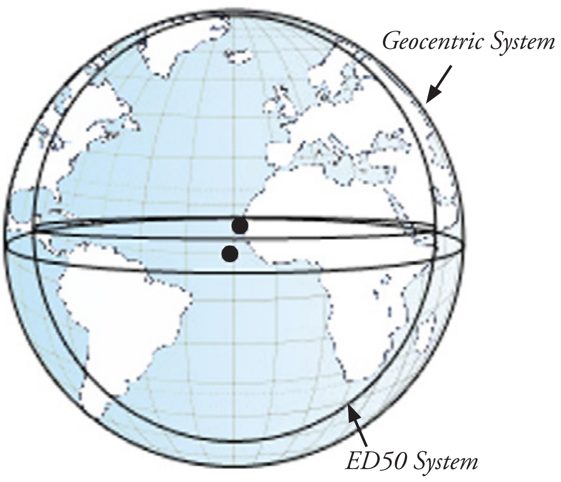

Figure 20. Disposition of the ED50 system in relation to a Geocentric system.

3.2. European Terrestrial System (ETRS89)

The necessity of a very precise reference system for Europe meant the creation of a terrestrial reference system known as EUREF.

The first realisation of the network was called EUREF89, and its correspondent reference system is ETRS89, which is the official system to which European cartography should refer to.

Figure 21. ETRS89 framework distribution.

Being all its station in the European plate, its movements are joined; thus, they remain relatively stable.

This system has as a reference ellipsoid the GRS80, which is almost identical to WGS84.

According to a Royal Decree published in 2007, this system is adopted as the official one to create cartography.

http://www.boe.es/boe/dias/2007/08/29/pdfs/A35986-35989.pdf

Such Royal Decree establishes a transitional period until 1st January 2015, and from that date onwards, all cartography will be produced using this system.

The frame of reference of the ETRS89 system consists of approximately 200 stations distributed along the European plate as it is shown in *figure 21*, and they have time-invariant coordinates.

It should be noted that, in the particular case of the Canary Islands, given that they are located on a different tectonic plate, a different reference system called REGCAN has been adopted. As in the case of the peninsula, this system has been adopted as the official and unique one since January 2015.

3.3. World Geodetic System 1984 (WGS84)

This is a Global Terrestrial reference system, which has a reference ellipsoid whose axis and origin are the same as those of the ETRS89 system.

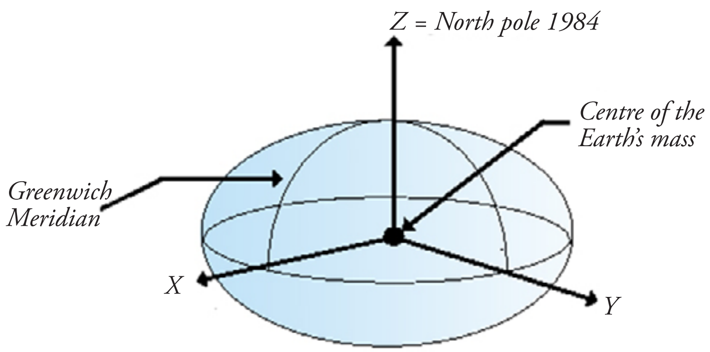

Figure 22. WGS84 system

Its origin is the centre of the Earth's mass, the Z axis is the 1984's direction of the North pole, the X axis is the direction of the intersection between the Greenwich meridian and the Equator, and the Y axis is the direction that is created by the direct trihedron (*figure 22*).

Its frame of reference was initially determined by the position of a set of 10 stations, as it is shown in *figure 23*. Five of them are the ones in charge of controlling the satellites in the GPS constellation.

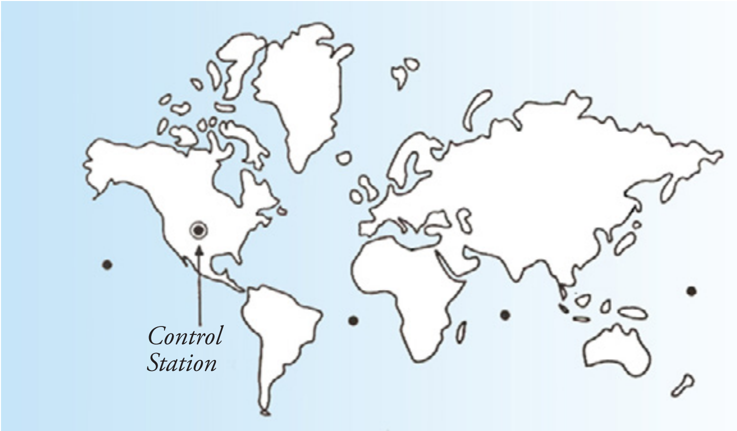

Figure 23. Initial disposition of the WGS84 seasons.

More stations were included afterwards.

4. TRANSFORMATION BETWEEN REFERENCE SYSTEMS

Measuring by GPS, XYZ cartesian coordinates referred to the centre of the WGS84 ellipsoid are obtained. An example of such coordinates is shown in *figure 24*.

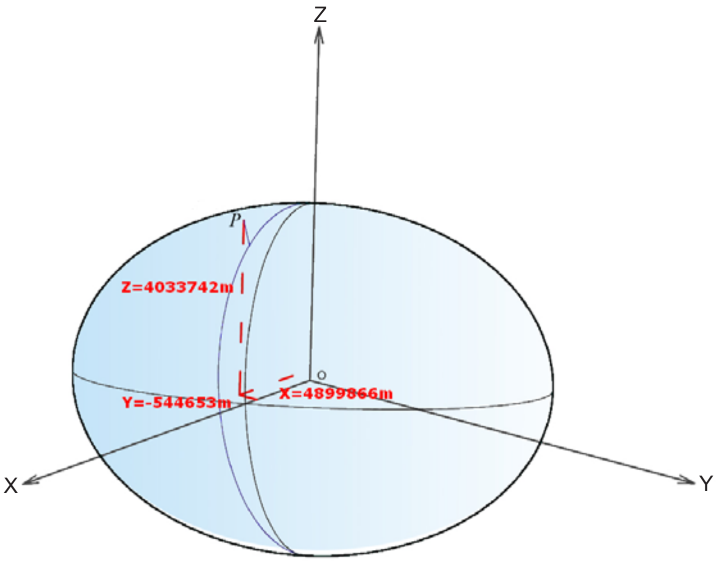

Figure 24. WGS84 Cartesian coordinates of a point.

Until January 2015, the ED50 and ETRS89 reference systems remained valid. After that date, the ETRS89 has been the unique reference system.

All these years are providing a margin for the conversion of all the old cartography into the new system. Thus, it is necessary to study a transformation between the coordinate systems ETRS89 and ED50.

Moreover, as it has previously been said, in the event that the coordinates are obtained by GPS, the initial result obtained is of WGS84 three-dimensional coordinates that do not belong to our official system and they are not projected. In that way, a transformation between this system and the other official ones is necessary.

4.1. Transformation WGS84-ED50

This transformation consists on a conformal three-dimensional transformation.

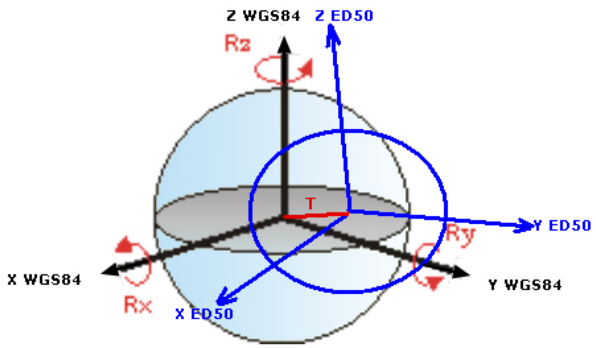

Figure 25. Transformation of WGS84-ED50 coordinates.

$$ED50 = T + (1+\Delta) \cdot R \cdot WGS84$$

Eq. 4: Transformation of WGS84-ED50 coordinates.

Being:

T for the vector of translations: $T = (Tx, Ty, Tz)^T$.
Δ for the scale factor.
R for the rotation matrix, which is a function of the rotation of the three axes.

There are 7 variables (three components of the vector T, the scale factor, and the rotations of the three axis XYZ). For each point, three equations would be created; thus, a minimum of three points with known coordinates in both coordinate systems is needed to solve the equations.

The system is solved by the least squares, since coordinates of four points are usually measured in both systems, and in that way, there is redundancy and verification for the obtained parameters to be the correct ones.

The work mode in the fields usually measures WGS84 coordinates of four geodetic vertexes whose ED50 official coordinates are known. In that way, it is possible to know the coordinates in both systems, and the parameters of transformation of the coordinates used for GPS measurements inside the polygon defined by the 4 geodetic vertex is obtained. An example is shown in *figure 26*, in which it is possible to observe how the parameters of transformation obtained by the measured vertex would affect all the surface inside them.

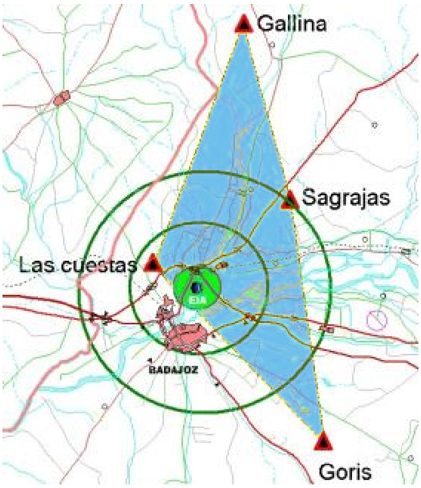

Figure 26. Example of how data is gathered for the WGS84-ED50 transformation.

Such parameters have a limited temporal duration.

If the project that is going to be carried out does not need to be very precise, the use of standard parameters such as the ones provided by local, regional or even national authorities could be considered. For instance, the generic parameters for the whole Iberian Peninsula provided by the IGN are the following:

Terms for Translation	Ax = 131.03	Ay = 100.25	Az = 163.35
Terms for Rotation	Rx = -1".244	Ry = -0".019	Rz = -1".144
Scale-correction factor:	9.39 ppm		

Table 2. Parámetros de transformación para la Península Ibérica

It is important to highlight the need for caution when using them, given that the estimated accuracy for the positions obtained by applying these parameters coincide with 70 cm of the RMSE[5] towards the N/S, 71 cm of the RMSE towards the E/W, and 43 cm of the RMSE for the altitude.

4.2. ED50-ETRS89 transformation

This transformation cannot be modelled by a mere transformation of 7 parameters, if there is a wish to implement its scale, given that there exists a distortion which is difficult to be absorbed.

In that way, the parameters that describe the transformation between the two systems are the jointly obtained from: "*conformation + distortion model*" (*figure 27*).

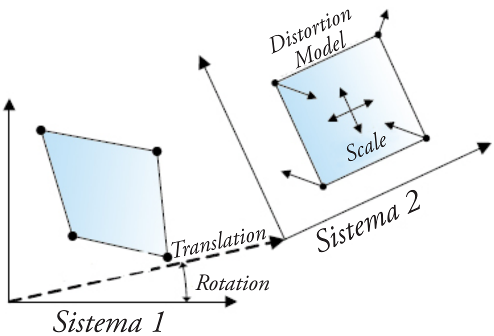

Figure 27. "Conformation + distortion model" transformation

The NGI has modelled such transformation by the so-called minimum curvature gridding whose value differences depending on the geographic location can be seen in *figure 28*.

[5] Root mean square error

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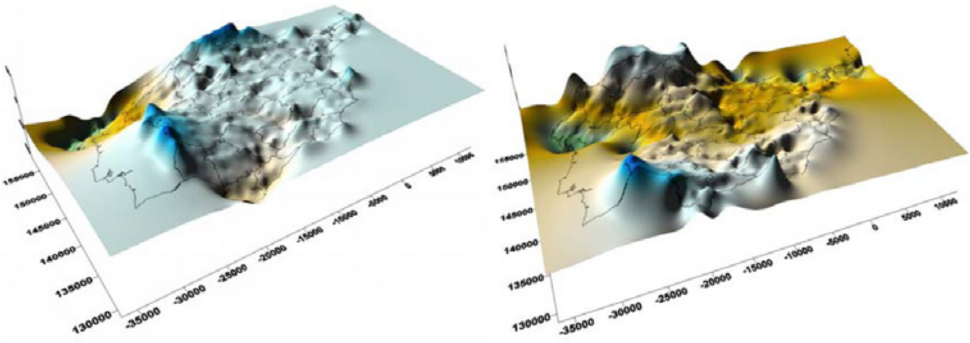

Figure 28. Minimum curvature gridding depending on the length (left) and height (right) (Source: NGI)

This gridding is implemented in calculation programmes by the *.gsb file provided by the NGI.

http://www.ign.es/ign/layoutIn/herramientas.do#DATUM

Three types of elements could be transformed:

a. Transformation of Isolated Points

The NGI geodetic applications programme is recommended (*figure 29*).

b. Transformation of Vectorial Cartography

The transformation is no longer that simple, as, depending on the geographic extension that needs to be transformed, the distortions effect is subjective.

There are different softwares that can do it, provided that the file that contains the official *.gsb grid is internally loaded

Some examples are:

FME. http://www.safe.com/fme/key-capabilities/coordinate-reprojection/

Autocad map. http://www.youtube.com/watch?v=rm8ke5zfdkA

Gvsig. http://www.gvsig.org/web/docusr/acceso-editores/funcionalidades/extension-jcrs-gestion-de-sistemas-de-referencia-de-coordenadas/transformaciones/transformacion-por-fichero-rejilla/?searchterm=transformaci%C3%B3n%20sistemas%20de%20coordenadas

Arcmap. http://www.sinfogeo.es/blog-geomatica.html/item/19-arcgis-cambio-datum.html?tmpl=component&print=1

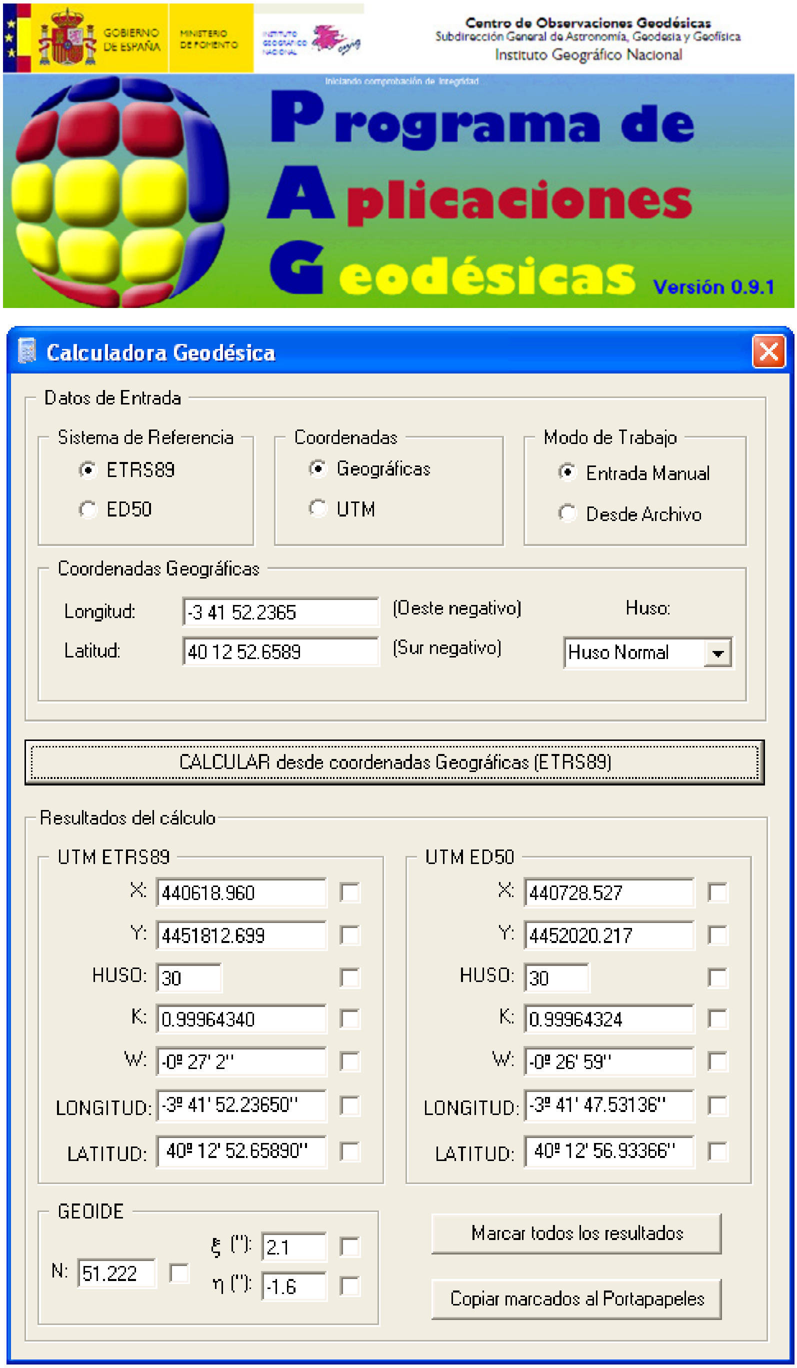

Figure 29. Coordinates transformation by the use of the geodetic calculator

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c. Transformation of Orthophotographs

There are discrepancies between the different authorities regarding how to carry this transformation out.

The most convenient software is the one provided by Castilla la Mancha's SDI (Spatial Data Infrastructure).

http://ide.jccm.es/pnoa/

This application transforms the orthophoto by using three methods:

- By the central point
- By a rectangle defined by two points
- By an enclosure defined by an shp polygon.

The desired bootstrap method can be selected from the following options:

- Nearest neighbour search
- Bilinear interpolation
- Bicubic interpolation

Chapter 3
CARTOGRAPHICAL PROJECTIONS. UTM

1. CARTOGRAPHICAL PROJECTIONS

A **Cartographical Projection** is a biunivocal correspondence between the points on the Earth's surface and the points in a plane known as projection Plane.

Given that any point in the sphere is defined by its geographical coordinates (λ, φ) and any point in the plane is defined by its cartesian coordinates (X, Y), there are endless relations between (λ, φ) and (X, Y). Each of these endless relations will be a cartographical projection system.

The purpose is to project the shadows of the meridians and parallels on a surface that can become flat and deformation-free (cylindrical (*figure 30*) or conical).

Figure 30. Cylindrical projection.

2. TYPES OF PROJECTION

Projections can be classified according to:

- The characteristics they retain: Some of them retain the angles, others the distances…
- The auxiliary surface used to project (*figure 31*): a cylinder, a cone or a plane.

– The tangency of the additional surface (*figure 33*): the tangency can be traced by a meridian, by a parallel, by the poles…

– The point from which they are projected (*figure 32*): this can be located inside the sphere, on its surface or far away from it.

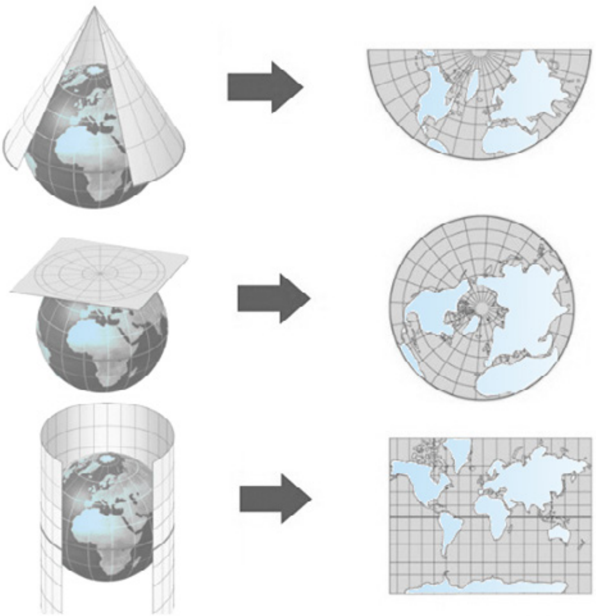

Figure 31. Types of projection according to the additional surface that is used.

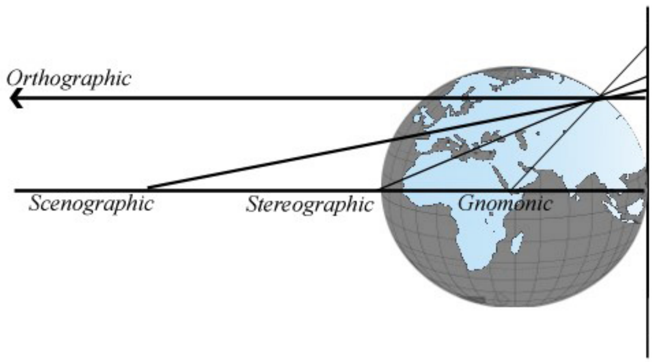

Figure 32. Types of projection according to the point from which they are projected.

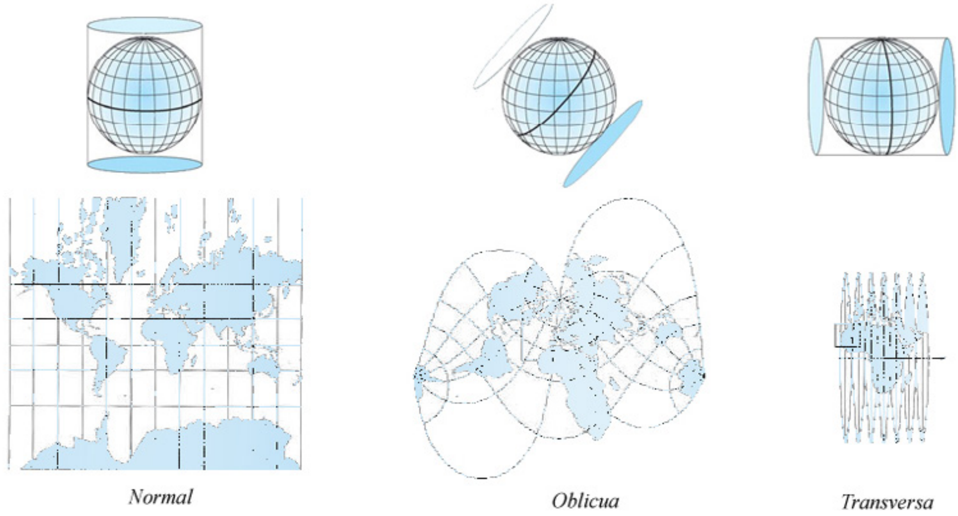

Figure 33. Types of projection according to the location of the tangency.

3. UTM PROJECTION

The 1071/2007 Royal Decree specifies that:

> "For terrestrial, basic and derived cartography, at scales larger than 1:500.000, the ETRS-Transversal Mercator coordinates reference system is adopted."

This means that the measures should be taken by using the ETRS89 reference system and, subsequently, they should be projected on the cylinder of the UTM[6] projection.

The UTM projection is a cylindrical projection where the axis of the cylinder is located in the Equatorial plane, and the cylinder is tangential to a meridian known as the prime meridian.

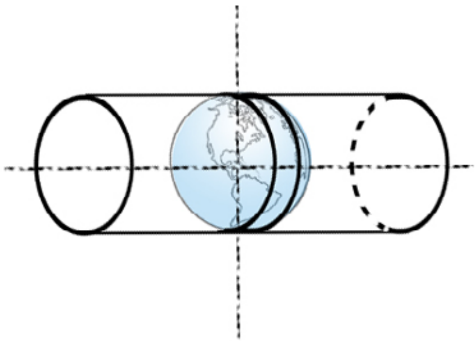

Figure 34. The cylinder arrangement in the UTM projection.

[6] Universal Transversal Mercator.

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As it can be seen in *figure 34*, when projecting and unfolding the cylinder, the Y axis is the prime meridian and the X axis is the generatrix tangent to the cylinder's Equator.

A UTM zone can be defined as the geographical positions that occupy all the points between two meridians. In the case of UTM, the UTM zones comprise 6º of longitude, and they are located as it is shown in *figure 35*:

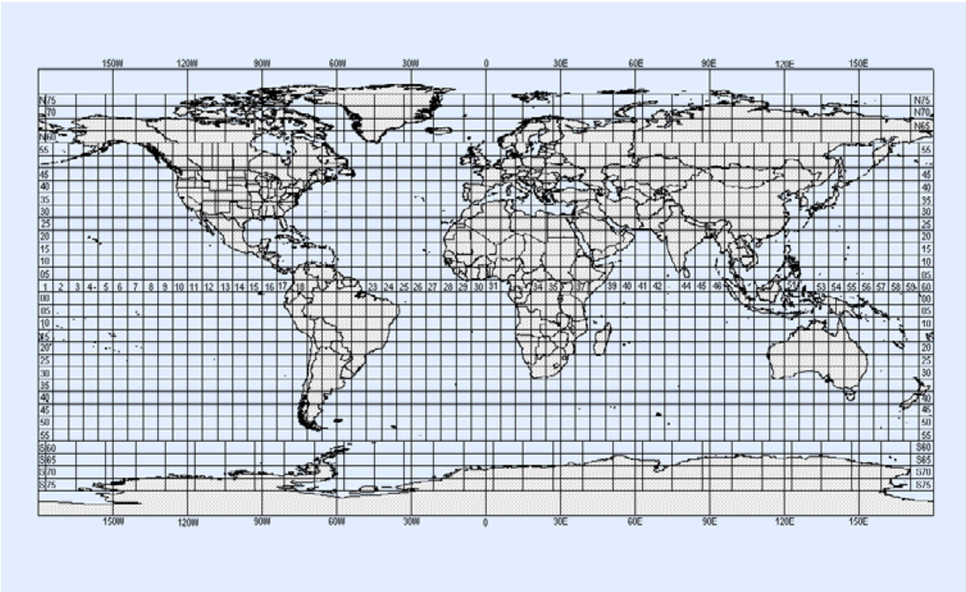

Figure 35. Global distribution of UTM zones.

3.1. Advantages of the UTM projection

The UTM projection system has the following advantages over other projection systems:

- It preserves the angles.
- It does not distort large surfaces (under 80º latitude).
- A point is easily reachable.
- It has universal applications.

3.2. UTM zones

Initially, the network was created zone by zone, using different cylinders to create each of the UTM zones. Each cylinder was tangent to the central meridian of each UTM zone (*figure 36*).

Such cylinder's disposition made the line of the central meridian the only one conserving the distances between its points (equidistant line).

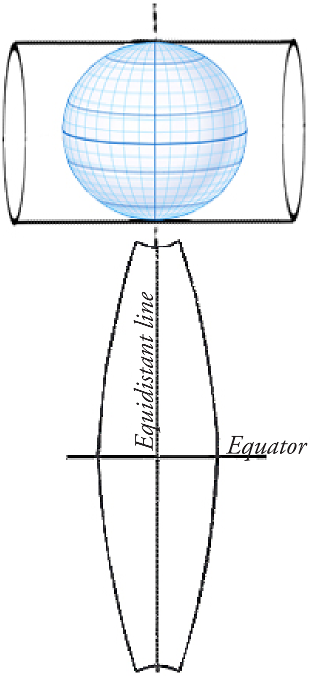

Figure 36. Initially tangent cylinder to the central meridian.

To prevent the distortion of the lineal magnitudes from increasing when the distance to the central meridian increased, the position of the cylinder was changed until it was secant by the extremes of the UTM zones' meridians, as shown in *figure 37*.

Thus, only two lines can be considered to be straight: the central meridian and the Equator. In the case of the central meridian, the distances are not preserved.

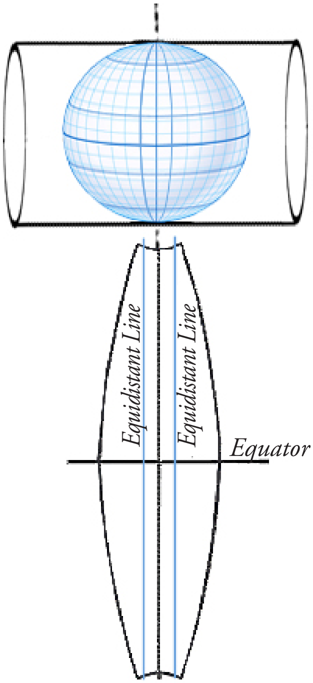

Figure 37. Secant cylinder to the extreme meridians of the UTM zones.

3.3. UTM coordinates

The origin of the coordinates of the system **is different for each UTM zone**, being located in the intersection between the central meridian of each of them and the equator.

As illustrated in *figure 38*, such intersection does not adopt 0,0 coordinates, which would be the logical, but, in the case of X, that point adopts the value of 500000m to avoid negative coordinates, and in the case of Y, it adopts the value of 0 for the North hemisphere and of 10000000m for the South hemisphere.

Consequently, there would be 60 points along the Earth with the same coordinates. Hence the importance of always defining the number of the UTM zone when defining the UTM coordinates, since, otherwise, this situation might be misleading.

In the case of the Iberian Peninsula, there are three UTM zones in which the coordinates can be located according to *figure 39*.

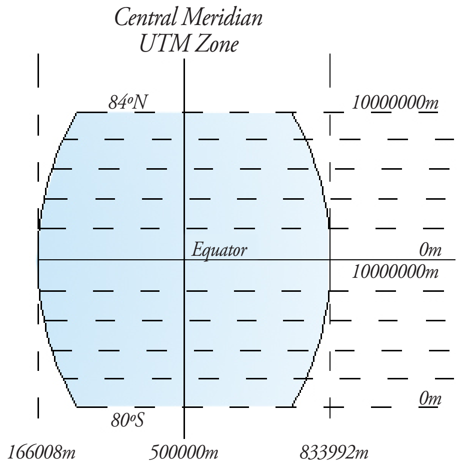

Figure 38. UTM coordinates of zone 30.

Figure 39. UTM zones of the Iberian Peninsula.

3.4. Overlapping grids

Only one line of the UTM zone coincides with the direction of the Geographical North, being this line the central meridian of the UTM zone.

In all the remaining points of the UTM zone there is an angle between the direction of the Geographical North and the North of the UTM Grid. Such angle is known as **Grid Convergence**, which can be of different quantity and sign depending on the UTM zone (*figure 40*).

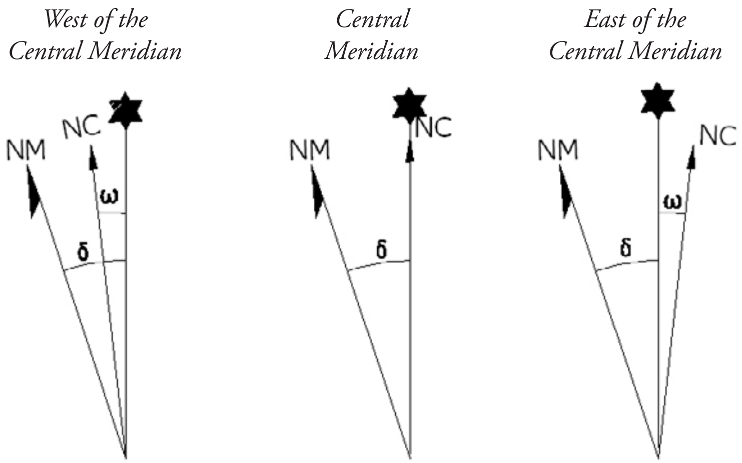

Figure 40. Location of the convergence of meridians depending on their position in the UTM zone.

Observing the graphics in *figure 40*, the Magnetic North does not vary since in our longitude it is always located to the west of the Geographical North, as shown in *figure 41*.

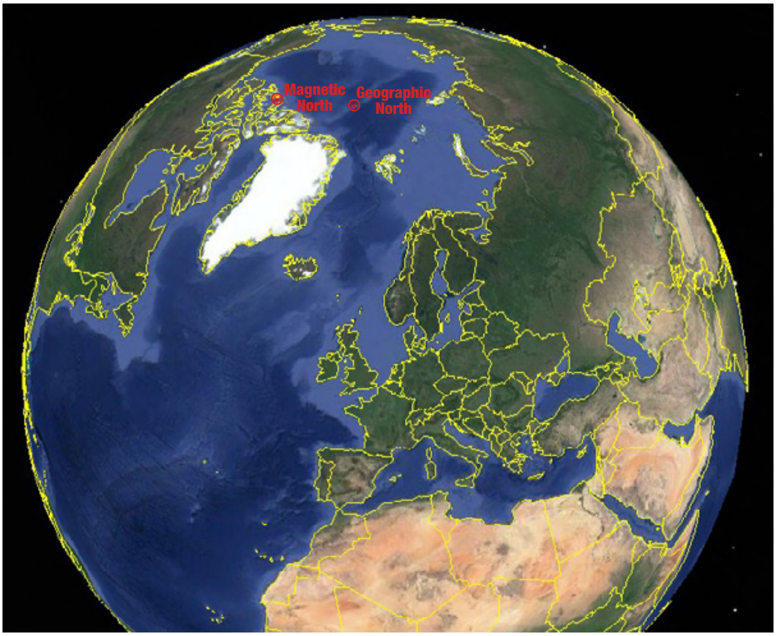

Figure 41. Location of the Magnetic North in 2009.

3.5. Duplication of coordinates between the extremes of two consecutive UTM zones

In the boundary meridian of two UTM zones there is always a duplication of coordinates, *figure 42* is an example.

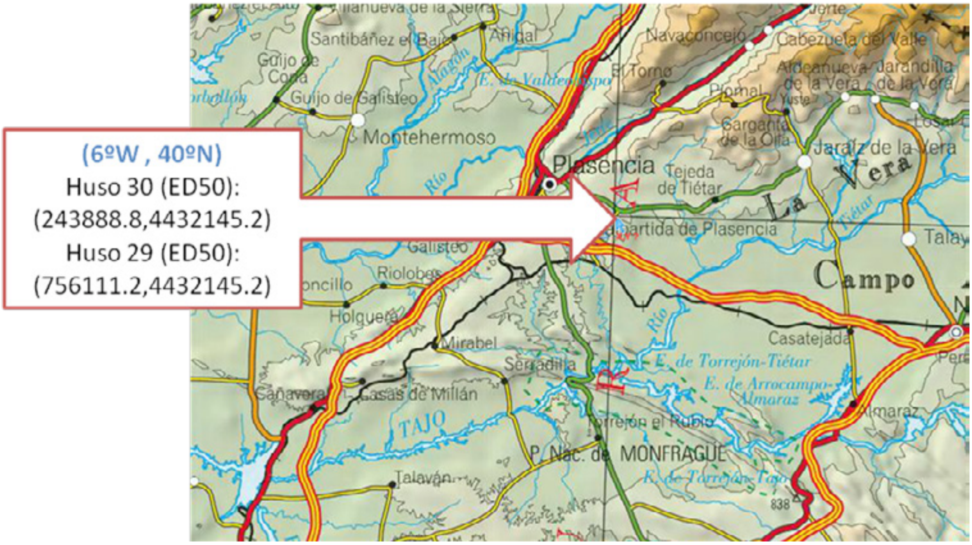

Figure 42. Duplication of the meridian coordinates between the 29 and 30 UTM zones.

If it were the case that a project of, for example, a road, would go through two different UTM zones, the whole project would commonly be referred to the zone that includes most of the surface of the project. The part of the project that is referred to a zone that does not match, enters a process called "forced coordinates".

Such forced coordinates cannot be extended extensively, since further we go, the more that UTM errors of projection increase.

In these cases, some authorities require the duplication of cartography, in order to refer the whole project to both UTM zones.

APPLIED DIGITAL PHOTOGRAMMETRY

Chapter 1

INTRODUCTION TO PHOTOGRAMMETRY. STEREOSCOPIC VIEW.

1. PHOTOGRAMMETRY

Photogrammetry is, according to Bonneval, the technique that has the aim to study and to provide a precise definition of the shape, the dimensions and the position in the space of any object by using, essentially, measurements taken at a single or at multiple photos.

Etymologically, the word "Photogrammetry" refers to the metrics of what is written by using light. It is, at its core, the science used by photography to take measurements, and its application is extensive to many fields of knowledge.

There exists another technique that also uses aerial photos, the so-called Photointerpretation, which is devoted to the detailed study of photos with the objective of analysing phenomena of very different claims.

Nevertheless, Photogrammetry does not interpret phenomena, it generates highly accurate maps by measuring photos.

Finally, Photogrammetry could be defined as the science that elaborates maps or planes on the basis of photos taken under certain specific determinants.

Figure 43. Aerial Photogrammetry.

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The most widespread of its possible branches is **Aerial Photogrammetry** (*Figure 43*), which, drawing from aerial photos taken under geometrical determinants, allows maps to be created accurately and with agility.

For rustic lands, the profitability limit to choose between a photogrammetric project and a GPS one could be of approximately 200 ha. In the case of urban land, the profitability limit would decrease substantially. However, it depends on the scale, accuracy and characteristics of the land in question.

2. FUNDAMENTAL ELEMENTS OF PHOTOGRAMMETRY

The choice of the **photograph's scale** depends on the scale of representation (the scale of the plane that is going to be represented) and the size of the objects that are supposed to be detected; this is the first problem that needs to be solved.

The relation between the photograph's scale (*Mb=1/mb*) and the scale of the plane (*Mk=1/mk*) that is supposed to be obtained through photogrammetric methods, comes from the abacus in *figure 44*.

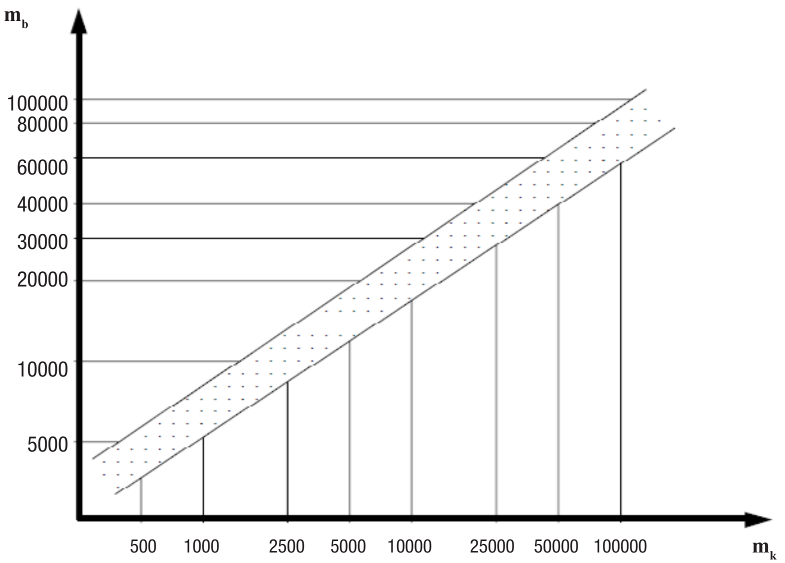

Figure 44. Relation between the photograph's scale and the cartography's scale.

Such photograph's scale limits the detection of the objects' size. Considering that the limit for visual perception is 0.2mm, if we observe through image magnification appliances, the limit becomes 0.02mm, so that each scale would give us a different minimum size of the objects (*Table 3*).

1:5,000	1:10,000	1:20,000	1:30,000
0.10 m	0.20 m	0.40 m	0.60 m

Table 3. Minimum size of an element detected with a restitution element.

The next elements that need to be taken into account are the **focal length** of the camera and the **flight altitude**.

The focal length is an inherent fact of the camera that is used in the flight. Such magnitude is a calibrated datum that corresponds to the distance from the optical centre of the lens to the focal plane where the image is captured. This topic will be dealt with in greater depth in subsequent chapters.

The flight altitude is determined by the two previous magnitudes

$$Mb = \frac{1}{mb} = \frac{c}{H} \Rightarrow H = c\ mb$$

Eq. 5: Relation between the photograph's scale and the flight altitude.

As shown in *figure 45*, such height (H) is the average height above the ground, which has nothing to do with the flight altitude above sea level H_0 (altimeter data).

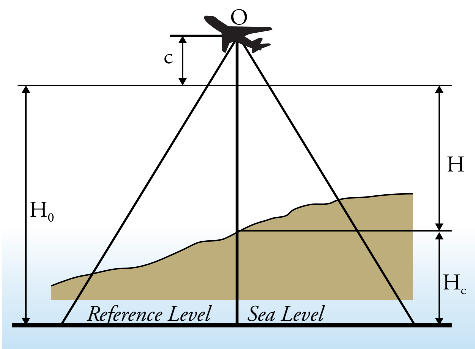

Figure 45. Flight altitude above sea level.

3. BASIC PRINCIPLE OF PHOTOGRAMMETRY

The basic principle of photogrammetry is the radial motion that a point undergoes in the reference frame due to its altitude.

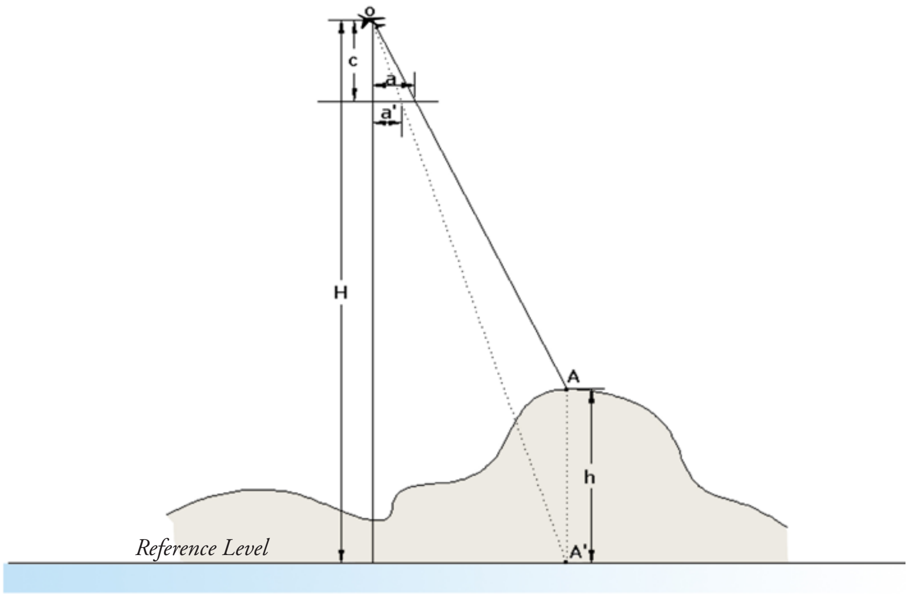

Figure 46. Motion of a point due to the relief.

Considering *figure 46*, the height of the point above sea level can be calculated as follows:

$$\frac{H}{a} = \frac{h}{a - a'}$$

Eq. 6: Height above sea level

Therefore, the height of the point above the reference level is:

$$h = \frac{a - a'}{a} \cdot H$$

Eq. 7: Height above reference level

4. STEREOSCOPIC VIEW. PARALLAX

Natural stereoscopic view is based on the capacity of humans to appreciate reliefs. To this effect, each eye captures an image of the same object and in the brain, they are combined through a mental process, generating a single relief image (*Figure 47*).

Artificial stereoscopic view consists of an imitation of the natural one, in which the observer is not in front of the object. Instead, two images are observed, taken from different perspectives (*Figure 48*), leading to the relief's view.

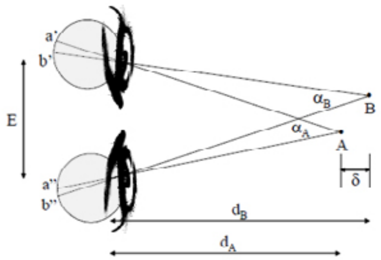

Figure 47. Natural stereoscopic view.

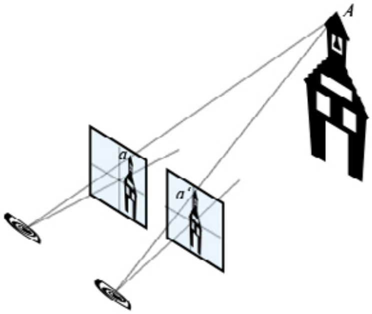

Figure 48. Artificial stereoscopic view.

The technique of photogrammetry is based on the stereoscopy's principle so that, by using images of the land taken from both perspectives, it is possible to reproduce its relief. *Figure 49* best reflects this principle.

Figure 49. Stereoscopic principle of photogrammetry.

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4.1. Procedures for artificial stereoscopic view

Starting with two photograms of the same zone taken from two different perspectives (photogrammetric overlap between two stereoscopic pairs) it is possible to observe the relief in the following ways:

a. By observation, using lines of *convergent vision*: this method is the most convenient one. Each eye observes a photogram depending on the following methods:

   a.1. **Anaglyph** (*Figure 51*): by means of glasses with complementary colours to the images shown in the screen it is possible for each eye to see just its corresponding image.

   a.2. **Polarisation**: it is the most widely used method in digital restitution. The screen has polarisation filters that deviate each image to the correct eye.

      a.2.1. Polarisation using **a screen** (Figure 51).

      a.2.2. Polarisation with **two screens** (Figure 52).

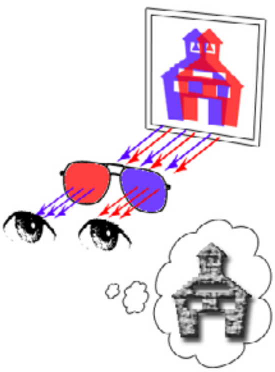

Figure 50.
Stereoscopy using anaglyph.

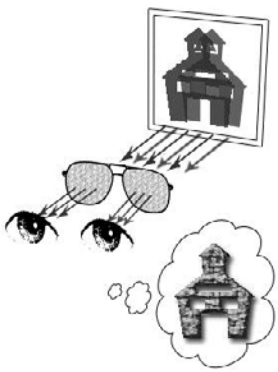

Figure 51.
Polarisation stereoscopy by using one screen.

Figure 52.
Polarisation stereoscopy by using two screens.

b. By observation, using lines of *parallel vision* (*Figure 53*). It is more consuming than the convergent method. This method was used in the past with pocket stereoscopes.

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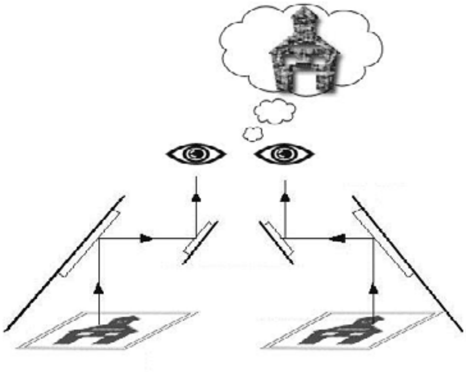

Figure 53. Parallel stereoscopy.

c. By *temporal separation* of the images (*Figure 54*): by means of active glasses, the images are shown alternatively in the screen. Such alternation is synchronised with the glasses that cover the eye that does not correspond so that the image is not observed. This method is more tiring for the sight than the others.

Figure 54. Stereoscopy by temporal separation.

4.2. Stereoscopic parallax

Parallax is defined as the difference in the position of a point in the image in two photographs due to the change of position of the camera when the photographs were taken.

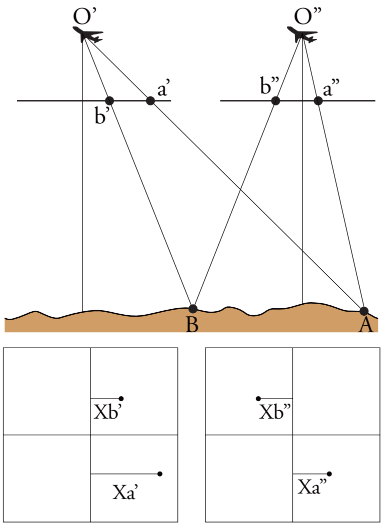

Figure 55. Stereoscopic parallax.

Following *figure 55*, the parallax derives from the following:

$$Pa = xa' - xa'' \qquad Pb = xb' - xb''$$

Eq. 8: Parallax.

In this way, it is possible to deduce the height of each point regarding the reference plane:

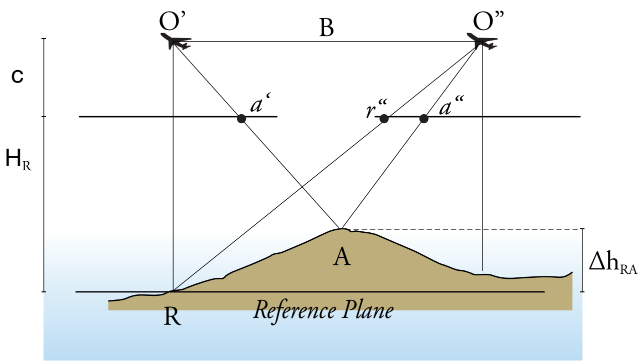

Figure 56. Relation between the parallax and the height.

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$$\text{Following } \textit{figure 56} \quad \frac{H_R}{B} = \frac{c}{P_R} \quad \text{being} \quad P_R = xr''$$

Eq. 9: Relation between the reference level and the parallax.

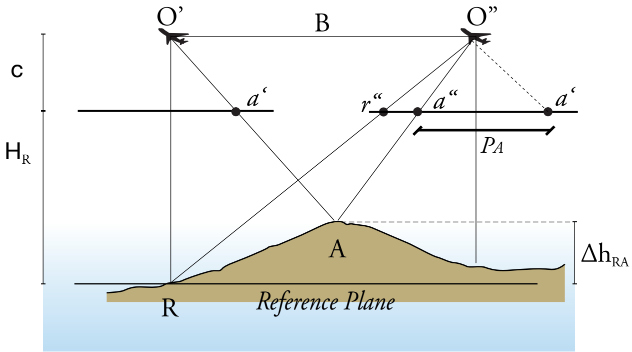

Figure 57. Relation between parallax and height.

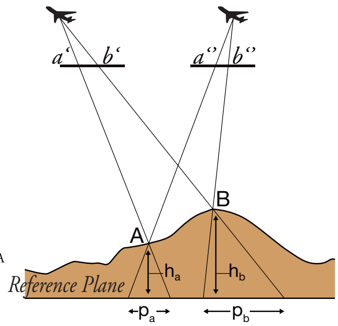

Figure 58. Relation between parallax and height.

Therefore, observing *figure 57*, point A can be established from the following relation:

$$\frac{H_A}{B} = \frac{c}{P_A} \quad \text{being} \quad P_A = xa' - xa''$$

Eq. 10: Relation between height and parallax.

What we aim to obtain is the increase in height that exists between the reference level and point A, being this amount:

$$\Delta H_{RA} = \frac{H_R \cdot \Delta P_{RA}}{P_A}$$

Eq. 11: Height of a point in relation to the reference level.

As shown in *figure 58*, the parallax of any point is directly related to the raise of a point, and it is greater for higher elevations than for low elevations, maintaining a constant viewing angle.

5. CLASSIFICATION OF PHOTOGRAMMETRY

Photogrammetry can be classified according to the following aspects:

a. According to the *instruments* used:

a.1. **Analogical Photogrammetry** (*figure 59*): analogical photograms are measured by using an analogous equipment.

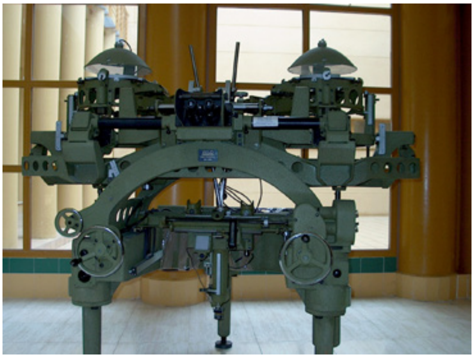

Figure 59. Analogical stereoplotter.

a.2. **Analytical Photogrammetry** (*figure 60*): analogical photograms are measured by using computer methods.

Figure 60. Analytical stereoplotter.

Figure 61. Digital stereoplotter.

a.3. **Digital Photogrammetry** (*figure 61*): digital photograms are measured by using photogrammetric digital systems.

b. According to the *distance to the object*:

b.1. **Space Photogrammetry** (*figure 62*): measurement with satellite imagery.

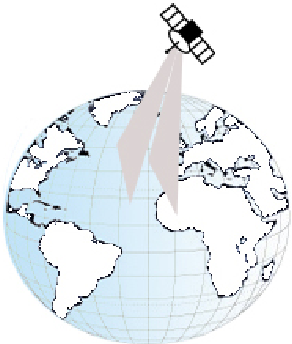

Figure 62. Space Photogrammetry.

b.2. **Aerial Photogrammetry** (*figure 63*): measurement with aerial photograms.

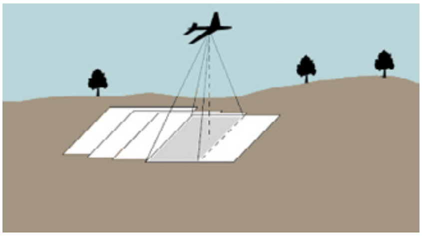

Figure 63. Aerial Photogrammetry.

b.3. **Terrestrial Photogrammetry** (*figure 64*): measurement with photograms obtained from the Earth's surface.

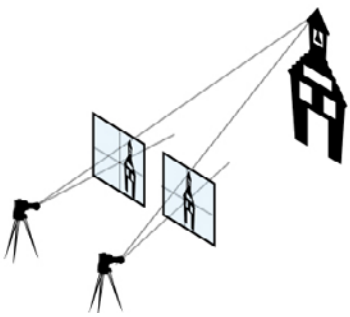

Figure 64. Terrestrial Photogrammetry.

6. ADVANTAGES AND DISADVANTAGES OF PHOTOGRAMMETRY IN RELATION TO CLASSICAL SURVEYING.

The first advantage was explained in the previous section and it is related to the economic issue, even though it always depends on the area to be surveyed.

Some other **advantages** include:

- Faster projects in the restitution phase. It should be noted that sometimes the photogrammetric flight is delayed if the weather condition is not adequate.
- If the field is difficult to access, photogrammetry is the appropriate technique, because access to the whole field is not needed. It would only be necessary to visit those areas where the ground control points are located.
- Continuous record of the whole field. All the details of the field would be registered in the photograph. Yet, via a surveying project, only the coordinates of the measured points would be available, which would be limited with regard to the whole field.

The only **disadvantage** of surveying maps through aerial photogrammetric methods is:

- The concealment of elements as a consequence of vegetation. If the field has too much vegetation, the view of elements below it is impeded. In this case, the register of the coordinates of those elements is necessary, as well as the measurement of such elements by using classical surveying.

7. PHOTOGRAMMETRY APPLICATIONS FOR CIVIL ENGINEERING

Within the general framework of Engineering, there are four main action groups that use photogrammetry:

a. Communication channels.
   Used for the layout of roads.
b. Territorial planning.
   Used for urban and spatial planning.
c. Hydrography.
   Used for the study of basins, dams' deformations, etc.
d. Execution of land movements.
   Used to measure Earth movements.

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Chapter 2:
DIGITAL PHOTOGRAMMETRIC IMAGE

1. BACKGROUND

Nowadays, nearly all photogrammetric images have a digital format, due to the fact that digital photogrammetry has achieved great popularity these days.

Digital images are such either naturally (if they have been captured by a digital sensor) or because they have been transformed into a digital format by using a photogrammetric scanner.

Figure 65. Photogrammetric scanner.

For that reason, this chapter will focus on that type of image by describing both its structure and its treatment.

2. DIGITAL IMAGE

A **digital image** is a bi-dimensional matrix where each minimum unit of information is a pixel with column and row coordinates (*i,j*). Each pixel has a value known as Digital Number (DN), which is represented by a grey level in a screen (*figure 66*).

This digital image composition corresponds to an image with only one band; in other words, it is composed of just one matrix, and it would be displayed on greyscale.

Nevertheless, colour images (RGB), as shown in *figure 67*, are composed of three matrixes: the first one for colour red, the second one for green, and the third one for blue.

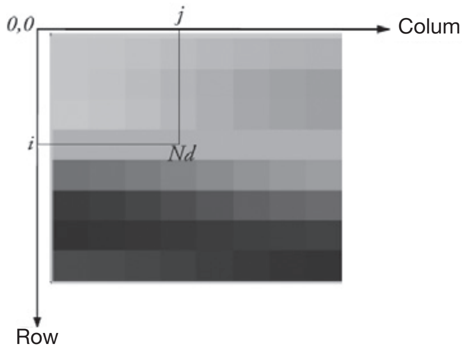


Figure 66. Digital image.

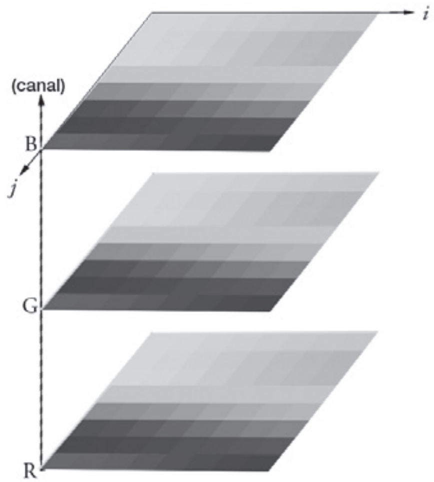


Figure 67. RGB digital image.

The storage of these images is trebled in space, because each matrix has its own digital levels.

2.1. Characteristics of digital images

a. Resolution

The quality of a digital image depends on the pixel's size, which is the **resolution**. If that size is too large, the image loses information, but, on the contrary, if the size is too small, the image would have high quality, with the drawback of, in addition, needing a lot of storage space.

The resolution is expressed in pixels per inch (*ppi*) or dots per inch (*dpi*).

In the case of aerial images, the resolution is called spatial, and it has direct correspondence with the size of the pixel in the ground (GSD[7]). *Figure 68* shows graphically what the term GSD means.

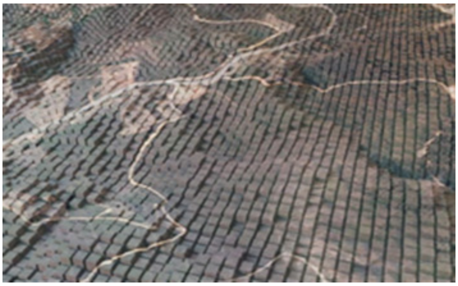


Figure 68. GSD.

b. Dimension

The **dimension** of the image indicates the width and the height of the image. It is usually expressed in centimetres, inches or pixels.

c. Colour depth

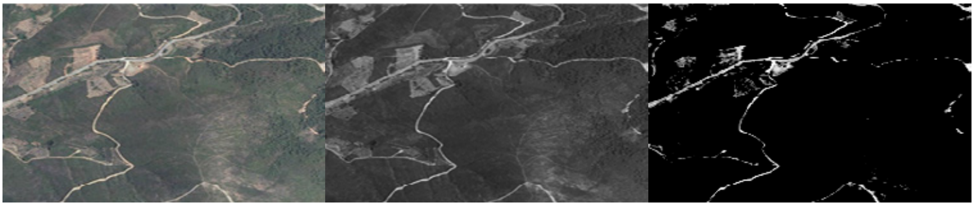
The colour **depth** corresponds to the number of bits used to describe the colour of each pixel.

As shown in *figure 69*, the greater the depth, the more colours that would appear in the image. The relation between the number of colours and the depth is expressed in the following table.

Depth	Colours ($2^{n^o b}$)
1 bit	2
4 bit	16
8 bit	256
16 bit	65,536
32 bit	4,294,967,296

Table 4. Depth of colour

[7] Ground Sample Distance.



8bits RGB 8 bits 1 band 1 bit 1 band

Figure 69. Depth of colour.

2.2. File size

The **size** of the file is the amount of memory needed to storage the image's information.

The number of bits needed to storage it depends on the resolution of the length, width and depth of colour.

$$\text{Size} = R^2 \text{x } L \text{ x } W \text{ x } D$$

Eq. 12: Size of an image (bits)

R= Resolution (*ppi*)
L and **W**= length and width (*inch*)
D= Depth of colour

In addition, the size of the image will be tripled if it is stored in colour.

One of the drawbacks of digital images is related to the necessity of having a large storage volume, given the amount of available information. It should be noted that a photogrammetric project without high dimensions is composed of numerous images.

3. IMAGE COMPRESSION

To overcome the drawback of the large volume of information that a digital image needs to be stored, the images **compression** technique reduces the storage space.

One must be cautious about compressing images, especially in photogrammetry, as some compression algorithms generate irreparable losses of information that reduce the quality of the image.

Compressing an image involves reducing the amount of unnecessary data to represent the digital image. This technique is based on the elimination of all redundant data in the image. The more redundancy in the image, the more compression it can suffer.

The image shown in *figure 70* has 1 bit (B/W):

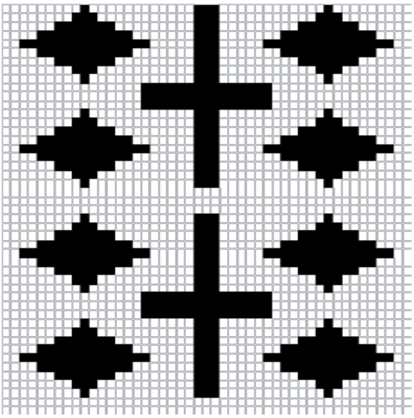


Figure 70. Example of a b/w image to compress.

The first row of the image would have the following values:

WWWWWWWWWBWWWWWWWWWWWWBBBWWWWWWWWWWWWWBWWWWWWWWWW

Without compressing it, it would need a memory of 47 bits just to store this row.

However, it would be possible to reduce the number of bits by expressing it in the following manner:

9W1B12W3B12W1B19W

In this way, only 17 bits would be needed to store the same row.

Redundancy has been eliminated. This redundancy consisted in the number of times that the same value was repeated in neighbour pixels in the same row.

A concept that needs to be mentioned is the **rate of compression**, which refers to the relation that exists between the original image and the compressed one. For instance, a 1.5:1 rate of compression means that the original image occupies 1.5 more space than the compressed one.

The greatest difference that exists between compression algorithms is that some of them lose information to reduce even more the size of the file. These are the so-called *Lossy Compressors*. When decompressing a compressed image to display it in a screen, these algorithms are not able to reproduce it exactly as if it were the original image; thus, they suffer a loss of information. This loss is minimum and the human eye cannot perceive it. In the cases when the metric of the image is its main utilisation, it is impossible to use this type of algorithms.

In the case of photogrammetry, the only algorithms that should be used are *lossless compressors*, so that even if they do not really reduce the size of the images, they conserve their integrity, which is essential to conserve, in addition, their metric attributes.

3.1. Discrete cosine transformation (DCT)

This compression method uses the JPG format, and it is a lossy compression algorithm.

The DCT is capable of gathering most of the information in a few transformed coefficients. In this way, those few coefficients just need to be codified to obtain a good representation of the whole image.

The objective of the DCT is to translate intensity variations into frequency components with the final purpose of eliminating high frequencies (the human eye is not very sensitive to them) while conserving low frequencies:

- High frequency component: intense brightness changes in small areas.
- Low frequency component: minor brightness changes in big areas.

As the image is divided into 8x8 pixel blocks and the DCT is applied to blocks and not to the whole image, it is possible to separate the blocks. By making consecutive compressions, the separation between them can be observed, as shown in *figure 71*.

Figure 70. Effects of the consecutive jpg compression in an image.

3.2. Lempel Ziv Welch (LZW)

This is a lossless compression algorithm used in formats like GIF or TIFF, and it consists in:

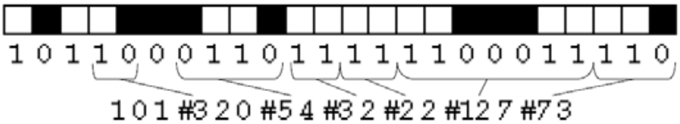


Figure 71. LZW compression

When a stream of pixels is similar to a previous one, it is substituted by two-value codes: the corresponding steps in the process and values that have been repeated.

3.3. Discrete Walavet transformation (DWT)

The format used is the ECW, patented by the trading house ERViewer.

This algorithm represents the image according to the concept of multi-resolution (*Figure 73*). It iteratively decomposes the original image generating series of images (2x2 sub images) with half of the resolution in each level.

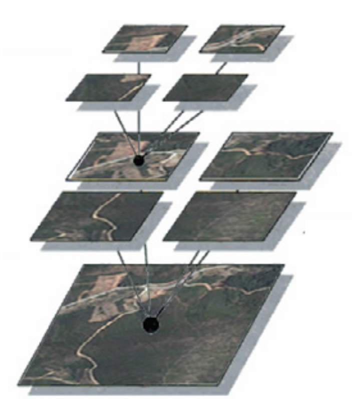


Figure 73. TDW compression.

The compression level of the image is determined by the user and the maximum level will be codified, with a code more reduced than the original image.

The algorithm can reproduce the original image after decompressing it, only until a certain level of decomposition of the image. In this way, it would be a lossless compression algorithm until a compression rate of 2:1 or 3:1. For major compressions there would be losses.

4. PYRAMID OF IMAGES

A **pyramid** of images is a tool used by the vast majority of digital instruments because it saves time in many phases of the calculation process.

The pyramid of images is not a compression technique, but a reduction method for the calculation processes and, therefore, for the information volume with which the instrument works.

The pyramid is based on multiresolution. The base of the pyramid would be an image with its original resolution and, subsequently, images with lower resolutions are stored in the memory consecutively.

In a pyramid shaped image, the search processes, as shown in *figure 74*, are carried out from lower resolutions to higher resolutions, without the need to explore the whole image.

Figure 74. Progressive search in a pyramid of images.

5. GRAPHIC FORMATS OF DIGITAL PHOTOGRAMMETRIC IMAGES.

The **format** is defined as the standard method used to organise and store the data of the image.

Not all the standard formats of the images are used in photogrammetry, and, conversely, some photogrammetric formats are not used in other fields.

The most widely used formats in photogrammetry are the following:

TIFF: compressed or non-compressed, it is the most commonly used format in photogrammetry.

ECW: with a small compression ratio, it is used especially in the generation of orthophotos.

SID: compressed format similar to ECW.

And all the characteristic formats of the digital photogrammetric system, such as RSW (Photomod), PIX (PCI geomatic), IMG (Erdas imagine) …

6. DIGITAL TREATMENT OF IMAGES

Before the photogrammetric process starts, images can undergo a pre-process with the aim of improving their visual quality.

Some concepts need to be defined beforehand in order to comprehend what the digital treatment of the images consists of.

6.1. Histogram of an image

The **histogram** of a grey-scale digital image is a discrete function that serves as a guide for the value placed on the probability that a certain grey level has to appear. This function will provide, for all grey values, a global description of the image's appearance.

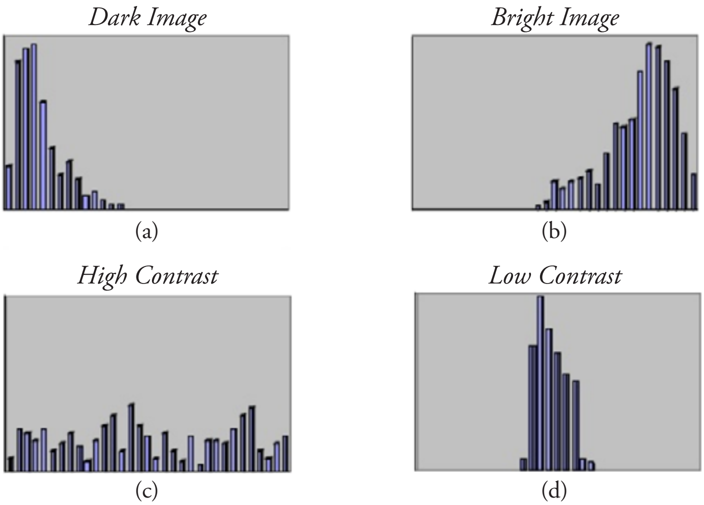


Figure 75. Histograms.

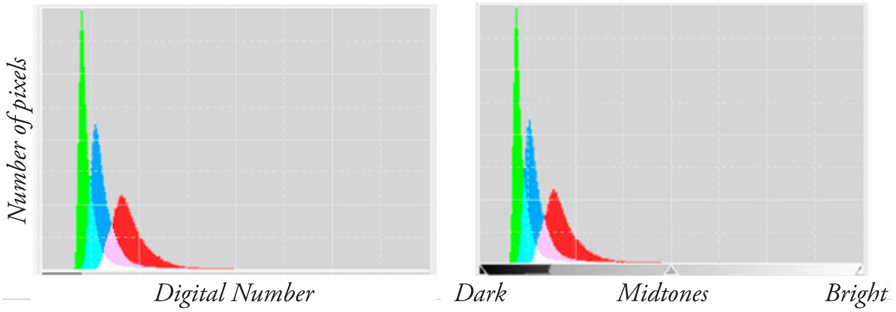


Figure 76. Histograms of three channels.

Each image has its own histogram. Yet, as a general rule, an image is considered to have good contrast if its histogram occupies almost all the tone range. Thus, the corresponding image to histogram (c) of *figure 75* would be the image with better distribution of values.

An RGB image would be represented by its corresponding histogram in each of its channels (*Figure 76*).

The most widely used techniques for digital treatment to process images are the following:

6.2. Image enhancement techniques

Histogram equalisation is an operation devoted to the uniform distribution of grey levels between the pixels of the image. This process gives higher digital level of the output image to the most frequent digital levels in the input image. Consequently, in the enhanced image, grey levels that occupy the majority of grids in the original image are more contrasting. In general, a better distributed histogram is obtained, with better separation between the most frequent DN of the image.

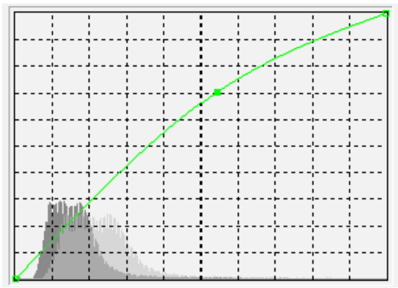


Figure 77. Management of a histogram with colour curve.

Some of the tools used to enhance the images have the capacity to work with colour curves or grey levels. Curves as the one shown in *figure 77* make the transformation of histograms with high precision possible, due to the fact that several check points can be set from anywhere in the histogram.

Thus, each manipulation of the curve will have an effect on the image:

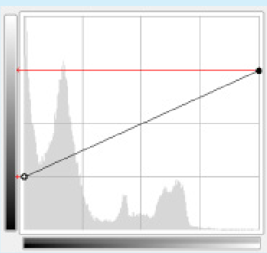
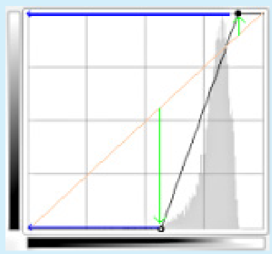
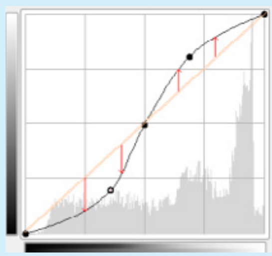
		
Make the curve more horizontal: the contrast is reduced.	Make the **curve more upright:** the contrast is increased.	**Curve the line:** the lights and shadows are incremented, but the contrast is slightly lower.

Table 5. Possible changes in the histogram of an image.

6.3. Filters

A **filter** is a mathematical process that consists in isolating interest components by reinforcing or softening the grey level special contrasts that are integrated in an image. In other words, the aim is to transform the original digital levels of each pixel so that they either look like or differentiate from their neighbours.

As shown in *figure 78*, a filter consists in a matrix that moves through the whole original image and that takes into account the values of the neighbour pixels to assign the *DN* of the pixel in the filtered image.

Depending on the type of matrix used to filter the original image, the effects would be different in the filtered image.

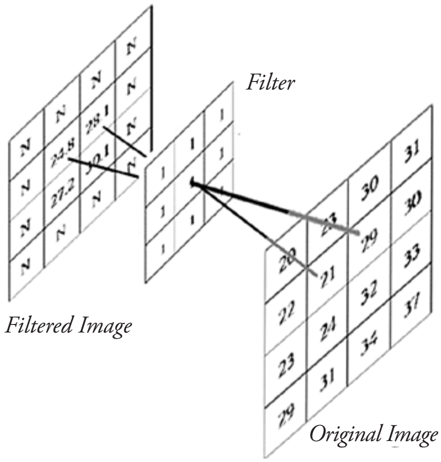


Figure 78. Matrix filter.

a. Smoothing and low pass filters

These filters are used to make the image blurry and also to reduce the noise. The purpose is to assembly the grey levels of each element to the contiguous ones, obtaining a smoothing of background noises.

Among the smoothing filters we find: median filter (*Figure 79*), average, blur and gaussian blur (the value of each point is the result of the average of the adjacent values on both sides of that point using different scales).

b. Enhancing and high pass filters

They are used to enhance the contrast in the photograph and to intensify blurred details (*Figure 80*).

Some of these filters are sharpen, to sharpen edges, Sobel (it calculates the gradient's intensity of an image in each pixel)…

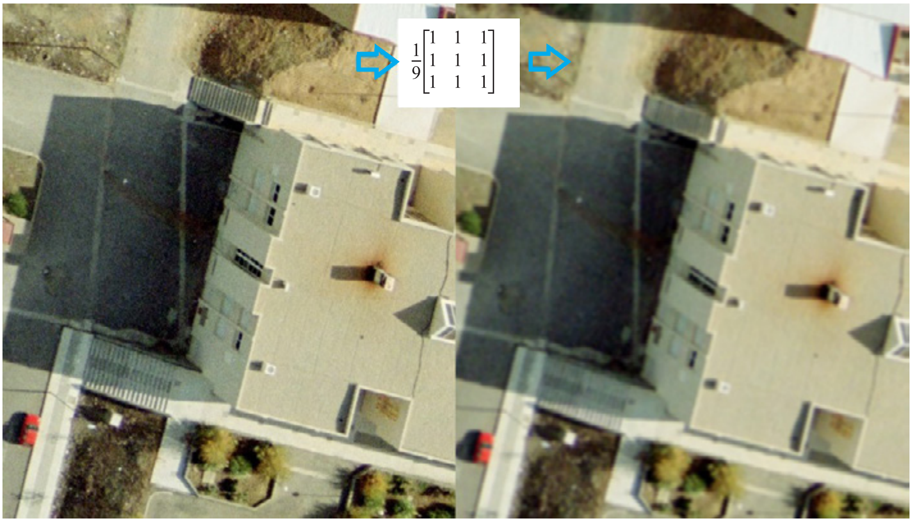


Figure 79. Example of a smoothing filter.

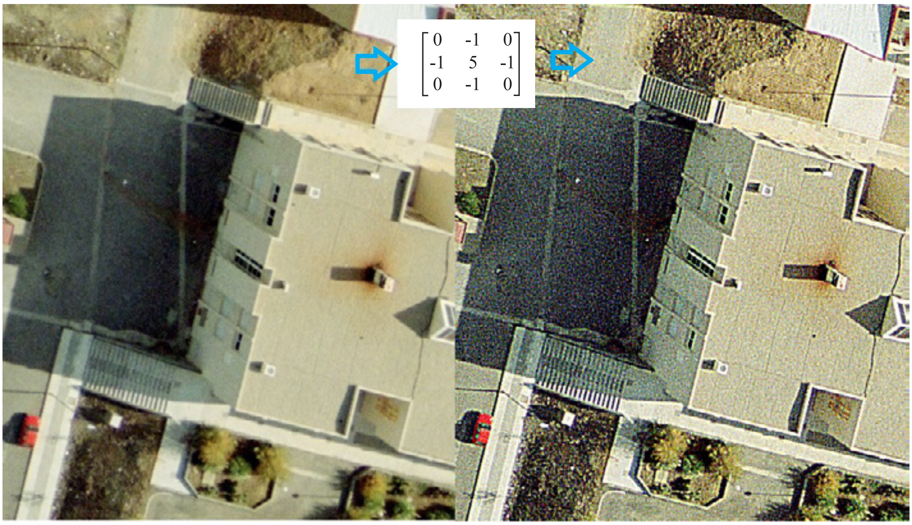


Figure 80. Example of an enhancing filter.

6.4. Types of enhancements allowed in photogrammetry

Photogrammetric images can be improved, but they can only be manipulated to a certain extent. Retouch cannot be overused because an excessive manipulation could mean a falsification of the original metric data.

Take as an example the corresponding section of the enhancement of the technical conditions to elaborate cartography using photogrammetric methods.

> "*The used unit for the radiometric equilibration should be the working area.*
>
> *Chromatic continuity should be guaranteed in all the sheets of the working area ("continuous orthophotograph") for the three provided RGB bands, preserving the natural colour without dominants.*
>
> *Hot spot*[8]*, vignetting and any other effects that deteriorate the image's quality will be eliminated from the photograph.*
>
> *Images with saturation over 0.5% for each band in the extremes of the histogram will not be admitted.*
>
> *If necessary, after the orthophotograph's information, digital treatment techniques can be applied in moderation to improve the quality such as contrast enhancement, colour balance, sharpen edges filter or any other improvements if they are appropriate*".

Figure 81. Vignetting of the images (source: Racurs).

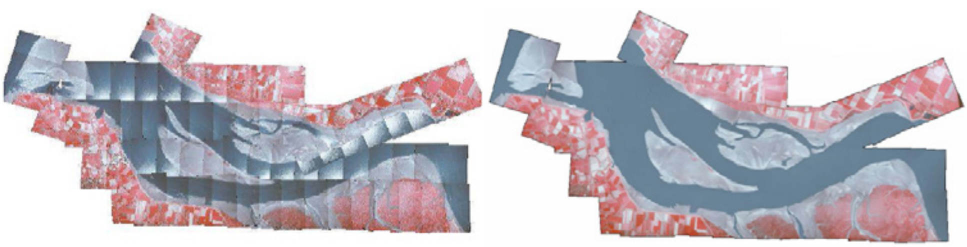


Figure 82. Effects of the sun reflecting on the water (source: Racurs).

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8 Hot spot: considerably clearer area compared to the rest of the image (*figure 82*).

Chapter 3
PHOTOGRAMMETRIC CAMERAS

1. INTRODUCTION

The photogrammetric camera is a fundamental element in the photogrammetric process. Matrix cameras, which are calibrated and have a geometry that produces optimal and reliable results, are used in this process.

Aerial analogical cameras have been used until present days, yet they are becoming outdated. That is why they are being substituted by a new generation of digital cameras.

Nevertheless, both types of cameras will be studied so that, subsequently, they are compared and their advantages and disadvantages are detailed.

2. PHOTOGRAMMETRIC ANALOGICAL CAMERAS

Photogrammetric analogical cameras are those cameras in which the image is instantly registered in a photographic film.

2.1. Components of analogical cameras

The three main parts of cameras can be distinguished in figure 83 and are the following:

- **Store or magazine**: it contains the film and its corresponding advance mechanisms and it assures that the film remains flat during exposure.
- **Body**: it connects the magazine with the lens assembly.
- **Lens assembly**: it stores the optic system, the diaphragm, the shutter, the filters… The intersection of the optic axis with the focal plane indicates the position of the *principal point* of the image.

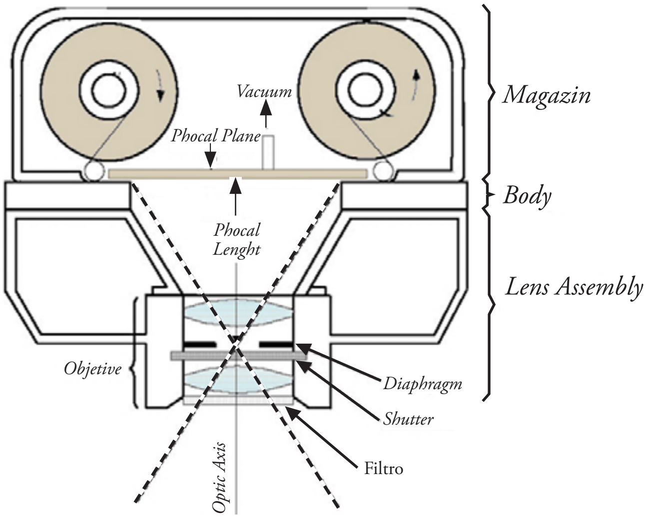

Figure 83. Components of a photogrammetric analogical camera.

The cameras are located in the plane over a **frame** that usually allows the correction of the orientation and the levelling of the camera.

The last generations of frames have a **stability** platform (F*igure 84*), that registers the spins of the camera during the flight, correcting its verticality and a **FMC**[9] system that reduces its apparent motion and the image blurring, moving the camera towards the back. This FMC is essential the lower the height of the flight is and the greater the speed of the plane is.

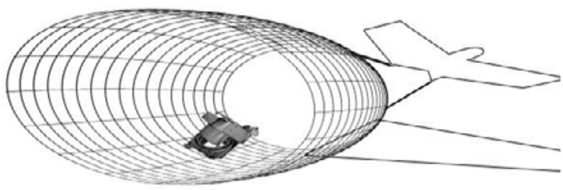

Figure 84. Platform of the camera in the plane.

Analogical cameras have a standard format of 23x23cm, and they contain in their focal plane a frame where the following are represented:

9 Forward Motion Compensation.

a. **Fiducial marks** (*figure 85*): they are essential to begin the photogrammetric process with the internal orientation of the photograms. There are, usually, 8 fiducial marks, 4 in the corners and 4 in the central parts. They have exact coordinates in the coordinate system of the image, being this one of the datum included in the calibration certificate of the camera.

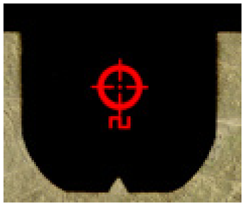

Figure 85. Fiducial mark.

The **fiducial centre** of the image is defined as the intersection point of the lines that connect the fiducial marks.

The fiducial centre and the main point do not necessarily coincide. This displacement is indicated in the calibration parameters of the camera.

b. **Marginal information**: as it can be seen in figure 86, there usually appears some information about the name of the project, the responsible organism of the project, the date and time when the picture was taken, the name of the camera, the calibrated focal length, the scale of the photogram, the strip number, the photogram number, the approximate height and the spherical level in some cases.

Figure 86. Analogical photogram.

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3. DIGITAL CAMERAS

In a digital camera, the focal plane is substituted by a sensor with tiny photocells that register the image (CCD[10]).

The form of disposal of the CCD gives rise to two types of digital photogrammetric cameras.

3.1. Linear cameras

The camera has three parallel lines of 12K[11] sensors, transversal to the flight direction. These lines have different inclinations: fore, nadir and aft position, as shown in *figure 87*.

As these cameras are digital, they can collect information from different parts of the electromagnetic spectrum, not just in the visible part.

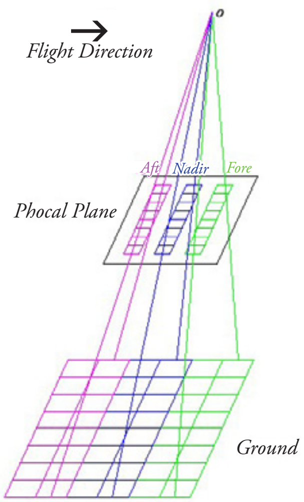

Figure 87. Linear digital photogrammetric camera.

Thus, once a strip has been done, three continuous bands of images (*Figure 88*) are obtained, which are composed by each of the lines captured by the sensors.

10 Charge-Coupled Device
11 Kilobyte

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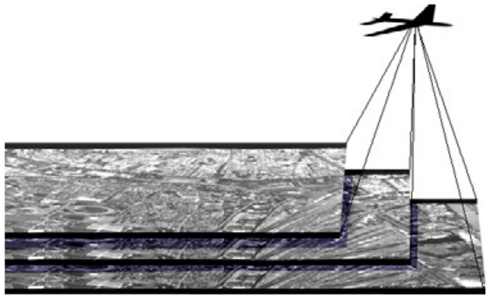

Figure 88. Photogrammetric shot of a strip with a linear image.

Therefore, an advantage of this type of cameras is that the whole ground appears in three images. This register involves the capture of all the points under the guidance of the nadir direction of the plane (*figure 89*). When capturing the whole ground vertically, the generation of truthful orthophotographs is favoured. These photos will be dealt with in chapter 5, as raised elements will not appear out of place in the photograph.

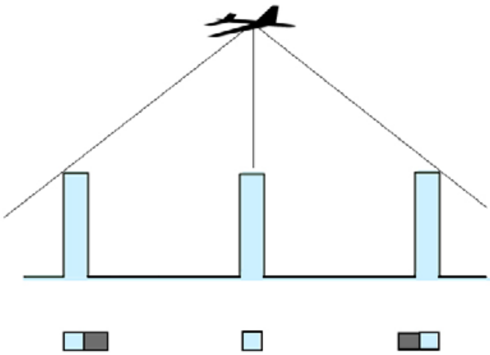

Figure 89. Displacements of non-nadiral points.

Nevertheless, each line has its own projection centre, and it cannot be considered as a photogrammetric shot with typical geometry. This aspect considerably complicates the calculations of the photogrammetric process. Hence, this type of cameras need to be complemented by a GPS (*figure 90*) and by INS/IMU[12] that registers the data and coordinates of each line.

[12] Inertial system /Inertial Measurement Unit

In addition, the photogrammetric instruments have to be prepared to work with this atypical type of geometry, premise that almost all instruments fulfil nowadays.

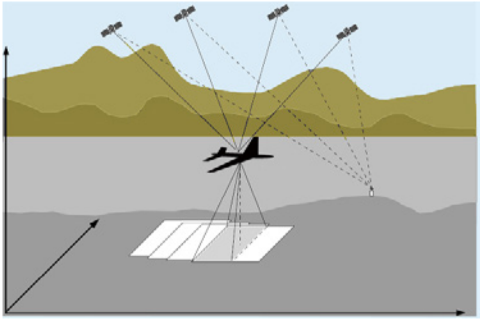

Figure 90. GPS during the flight.

Figure 91. Leica ADS40 camera. (Source: Leica Geosystems)

The linear camera par excellence is the one shown in *figure 91*.

3.1. Matrix cameras

Figure 92 shows that this type of sensors are similar to aerial analogical cameras regarding their composition. Matrix cameras have 1Kx1K sensorial elements (1024x1024 pixels), 2Kx2K, 3Kx2K, 4Kx4K, 4Kx7K, 7Kx9K, 5Kx10K, 9Kx9K. Among them, the most common ones are 3Kx2K and 4Kx4K, which, similar to the linear ones, can also record in other ranks of the electromagnetic spectrum.

These sensors have GPS and INS systems during the flight, yet it is not indispensable for them to have these systems, as it happened in the previous case, due to the fact that the geometry, as shown in *figure 94*, is

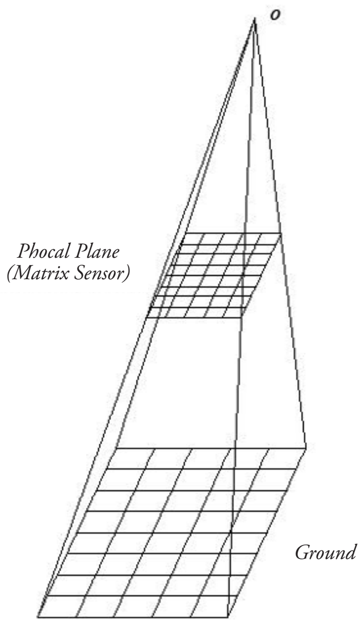

Figure 92. Geometry of a photograph taken with a digital matrix camera.

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similar to an analogical camera. In this figure 94 it is possible to observe that, despite of the fact that they are multi-objective cameras, the geometry is still the usual one.

One of the most updated matrix cameras is the one shown in figure 93. It combines various objectives in its focal plane, producing partial matrix images that unite in a complete image of 17310 x 1131 pixels.

Figure 93. Vexcel's Ultracam XP camera. (Source: Vexcel Corporation)

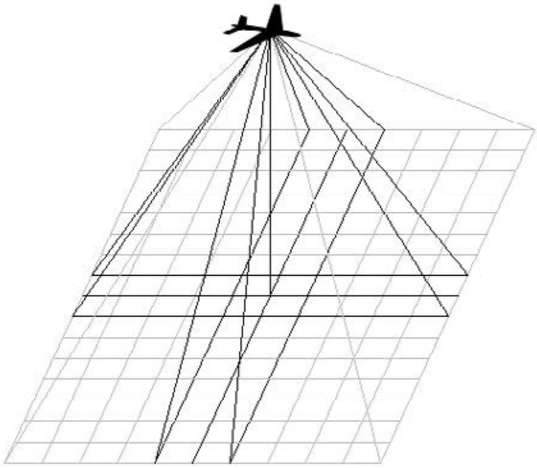

Figure 94. Photogrammetric shot with a multi-objective matrix.

4. COMPARISON BETWEEN BOTH CAMERAS

The advantages of digital cameras over analogical cameras are many. The main advantage is that, as they do not need to be digitalised to work with digital photogrammetric instruments, a process in which geometric and radiometric errors are keen to appear is avoided. These errors could alter the quality of the resulting photogrammetric products. Less important issues would be the susceptibility of the negatives over the years, the need of an appropriate storage, etc.

Within the digital format, the edition of the camera is a complicated issue. Nevertheless, such edition is not commonly carried out by the user, but by the company that has been chosen for the photogrammetric flight. Each company usually works with just one type of camera.

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Find below the advantages and disadvantages of both systems.

Linear cameras:

Advantages	Disadvantages
Continuous record of the whole land from three points of view.	GPS system: dependent on ground stations within 30 km.
Better resolution (*Figure 95*).	The objective should remain open at all times.
They do not need a lot of radiometric correction.	It is necessary to implement a new workflow (stereoscopic models no longer exist) and new software.

Table 5. Advantages and disadvantages of linear cameras.

Matrix cameras:

Advantages	Disadvantages
Its geometry is similar to analogical photographs.	Lower resolution
They do not need GPS systems.	

Table 6. Advantages and disadvantages of matrix cameras.

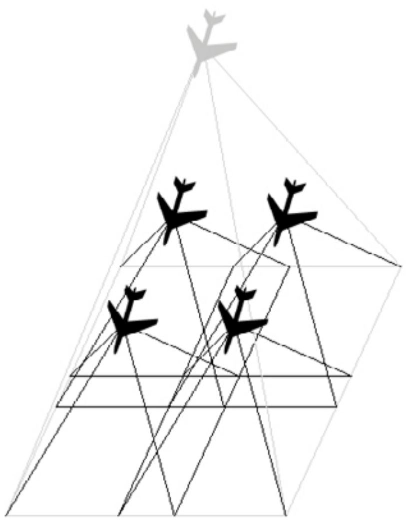

Figure 95. Advantage of linear cameras over matrix cameras.

Chapter 4
PHOTOGRAMMETRIC PROCESS

1. BACKGROUND

As explained in the previous chapters, nowadays, photogrammetry is carried out through digital procedures in most of the cases. Thus, this chapter focuses on explaining the digital photogrammetric process that differs, in some phases, from old analytical procedures.

2. INTRODUCTION

The **photogrammetric process** entails all the consecutive phases that lead to the production of cartography from photographs which are, in general, aerial.

The process begins taking photographs in the area, and ends obtaining three-dimensional coordinates of the area. These coordinates, later, result in different products such as cartographical planes, digital elevation models, orthophotographs…

This process involves field and cabinet work. The errors and accuracies in each phase are accumulated along the whole process. In this way, the quality of the final result depends on the quality of each phase.

3. DIGITAL PHOTOGRAMMETRIC PROCESS

The **main problem of photogrammetry** is the reconstruction of photograms in the same position at the time when the photograph was taken, so that, by geometric analogy, it is possible to measure three-dimensional coordinates of the field captured in the overlapping area.

Initially, the input data are two or more digital photograms. Yet, in addition, it is necessary to obtain field coordinates of points with the aim of, on the one

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hand, guiding the work in a concrete reference system and, on the other hand, obtaining the accuracy so that the quality of the final product is guaranteed.

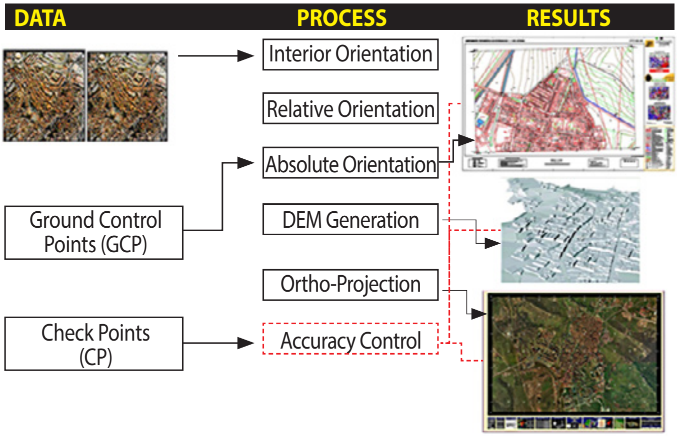

Figure 96. Phases of the digital photogrammetric process.

3.1. Interior orientation

In digital photogrammetry, **interior orientation** is a transformation process from pixel (row, column) coordinate system to camera's coordinates expressed in mm and referred to a 3D cartesian system, which has its origin in the projection centre of the camera. The difference between the two coordinate systems is illustrated in *figure 97*.

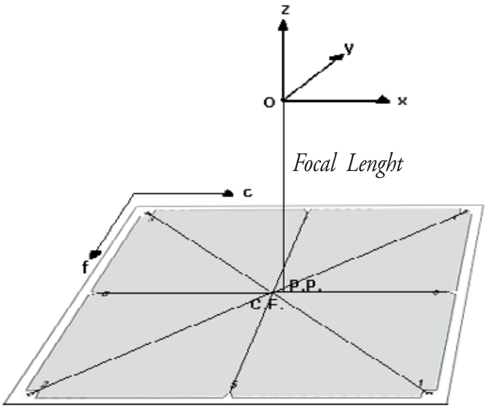

Figure 97. Coordinates transformation in interior orientation.

Additionally, the following errors are corrected in this process:

- The **principal point** does not coincide with the fiducial centre (in the case of analogical photographs) (*figure 98*).

Figure 98. Fiducial centre and main point.

- The **photogrammetric film has been deformed** (in the case of analogical photographs).
- **Objective distortions.** All the objectives have distortions (*figure 99*), which are quantified by the calibration certificate of the camera. In some cases, it is positive, and in other cases, it is negative.

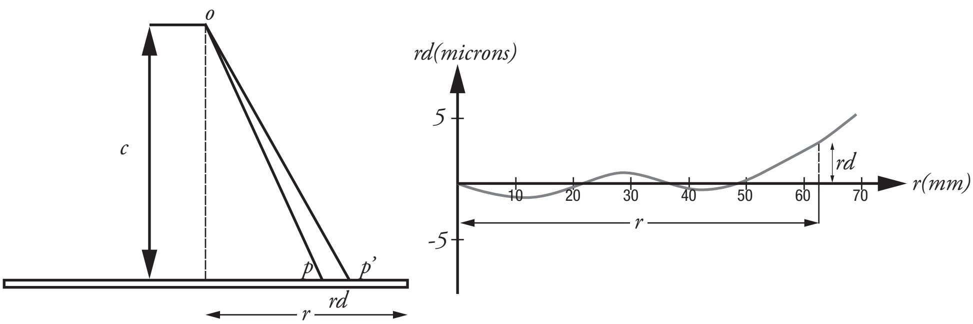

Figure 99. Effects of the distortions in the objective.

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– **Atmospheric refraction.** As it can be seen in *figure 100*, it makes the point's image appear in the photograms further from the centre than it should be.

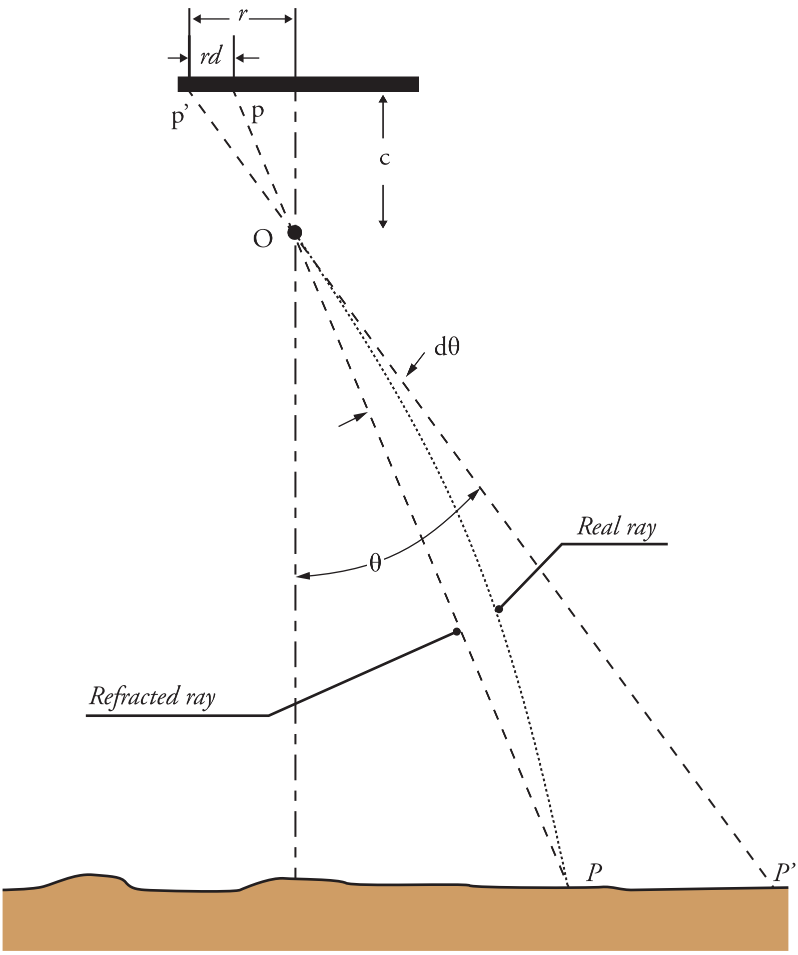

Figure 100. Effect of atmospheric refraction.

– **Terrestrial sphericity.** It moves the points closer to the centre of the photogram, as illustrated in *figure 101*.

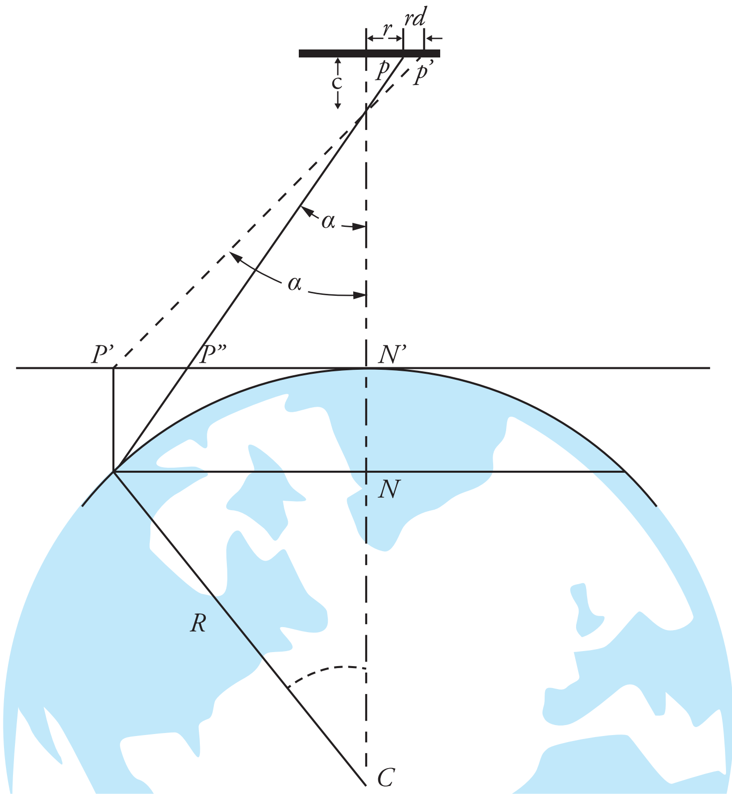

Figure 101. Effect of terrestrial sphericity.

The process that has to be followed in interior orientation should be different depending on whether the images are analogical or digital.

a. Interior orientation with analogical cameras

The interior orientation of images taken with this type of camera has two steps.

- Firstly, the calibration data of the camera are introduced:
- Calibrated focal length.
- Distortions of the objective.
- Coordinates of the fiducial marks in the coordinate system of the camera.

Later, the coordinates of the fiducial marks are measured using the image's coordinate system.

In this way, it is possible to know the coordinates of the fiducial marks in both coordinate systems. In the case of pixels coordinate system, because they are measured, and in the case of cameras, because the calibration certificate indicates them.

Figure 102. Standard patters for fiducial marks.

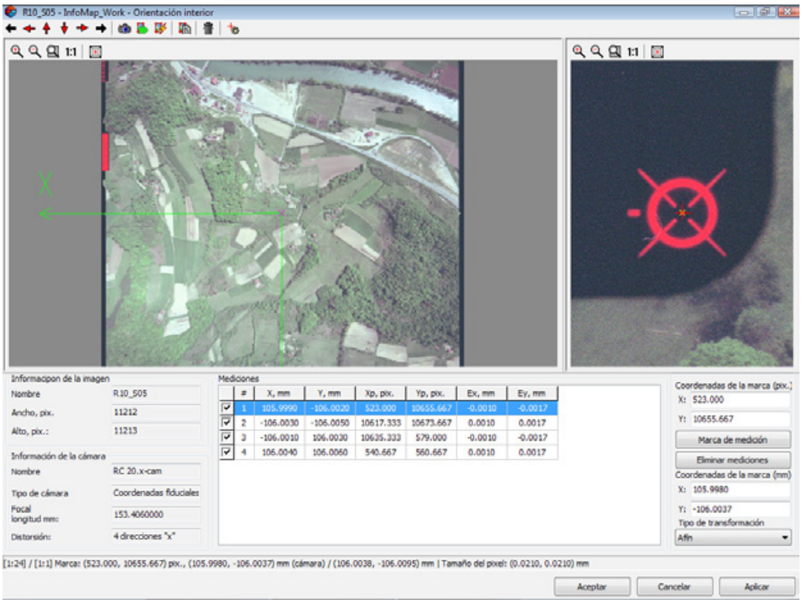

Figure 103. Digital interior orientation process.

With both sets of coordinates (*Figure 103*), the transformation parameters between the two systems are calculated, and then applied to the whole image.

This transformation can be either affine or projective. The mathematical difference between them will not be dealt with in this section, as there exist plenty of projects

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in which they are explained in detail. The user has to choose between one of them depending on the accuracies and precisions that are required.

The measurement of the fiducial marks in the latest digital photogrammetric instruments is **automatic**. In the vast majority of cases, the computer has patterns of the fiducial marks and it locates them using automatic correlation techniques. Some standard patterns are shown in *figure 102*.

In other cases, interior orientation is not automatic, given that the operator is in charge of indicating the centre of each fiducial mark.

Interior orientation is considered **semiautomatic** if the operator manually indicates only the fiducial marks of the first photograph in the project. If the operator manually indicates all the marks in all the photographs, it is considered **manual**.

b. Interior orientation with digital cameras

Regarding images taken with digital cameras, interior orientation consists merely in determining the position of the photograph's main point with respect to the centre of the digital image (row, column).

These images lack of fiducial marks and the process is completely automatic. The calibration parameters of the camera are the only thing that have to be determined (*Figure 104*).

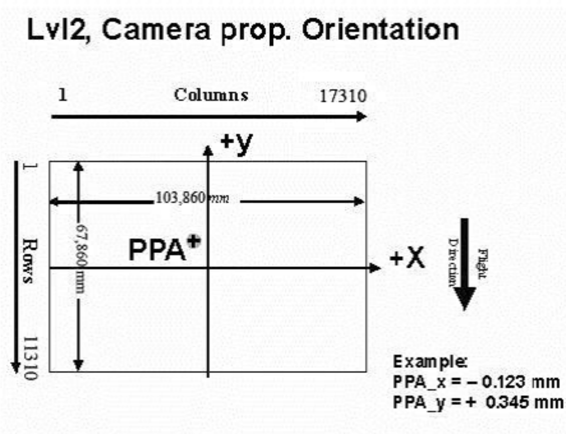


Figure 104. Interior orientation with digital cameras.

3.2. Relative orientation

Relative orientation is the phase of the process in which stereoscopic images are geometrically related, giving rise to the stereoscopic model (*figure 105*).

In this phase, homologous points in each photograph are identified (*figure 109*), so that, afterwards, the bundle can be reconstructed and the model generated.

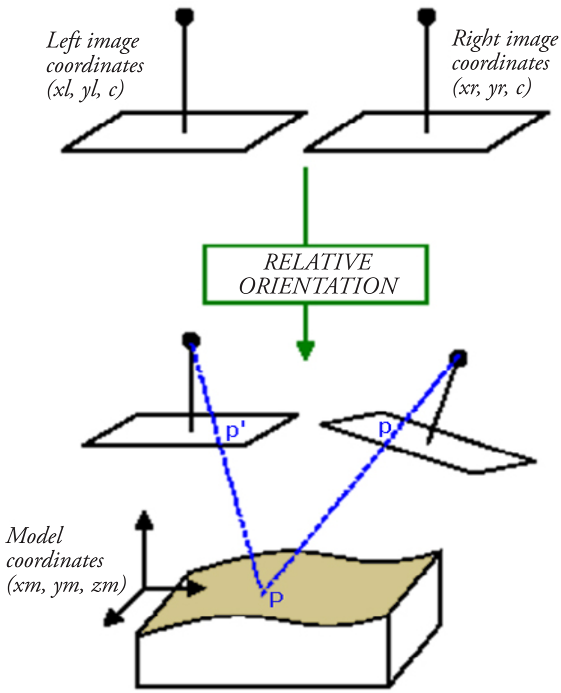


Figure 105. Relative orientation.

The bundles' reconstruction is carried out by the **coplanarity condition**, which forces both projection centres, homologous points and the Earth's point to encounter in only one plane, as shown in *figure 106*.

Relative orientation is carried out appropriately if all the homologous vectors interact. The minimum number of intersection points (tie points) necessary for the formation of the model is 6, which should be distributed as shown in *figure 107* according to *Vön Grüber.*

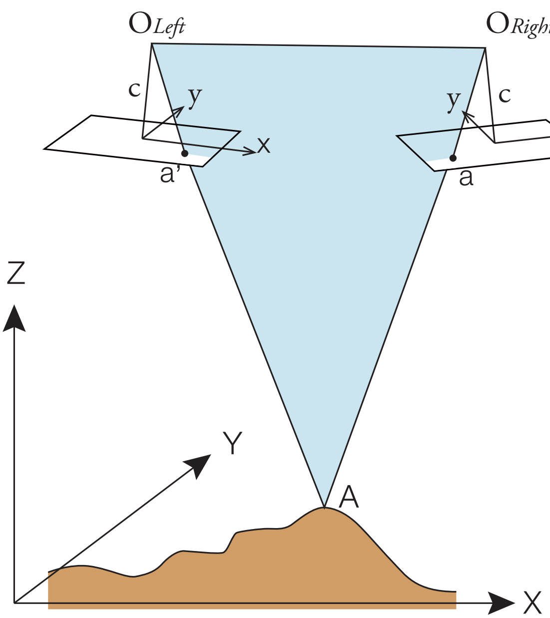


Figure 106. Coplanarity condition.

If identified manually, this is the minimum number of points in each photograph.

Digital photogrammetric instruments have the possibility of carrying out this process automatically, through correlation techniques. If the process is automatized, the number of **double points** should be increased in *Vön Grüber*'s distribution (*figure 108*).

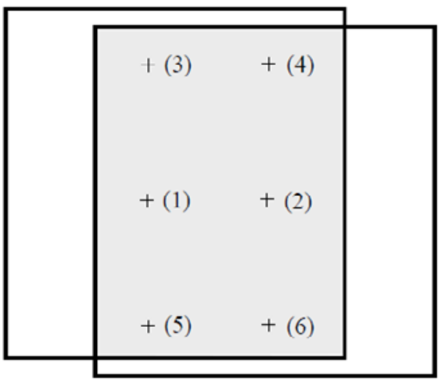


Figure 107. Vön Grüber's distribution.

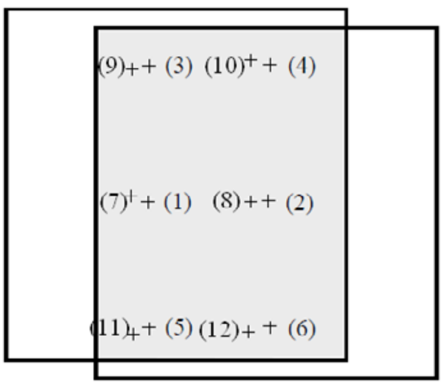


Figure 108. Vön Grüber's distribution in automatized relative orientation.

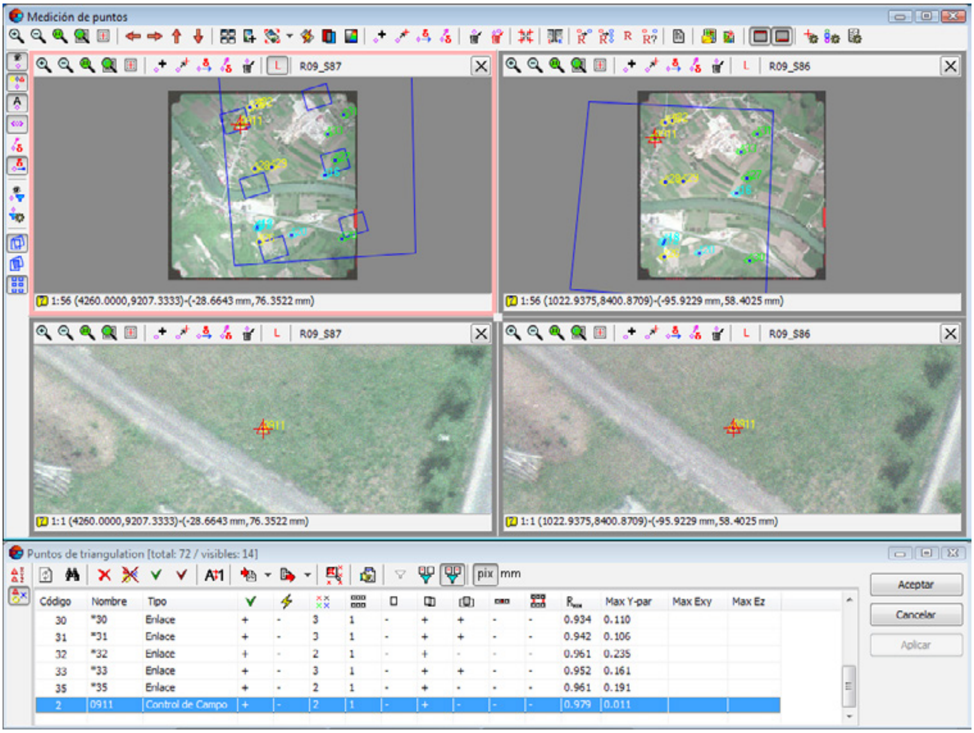


Figure 109. Digital relative orientation process.

Even though the process is automatized, it requires the operator's exhaustive inspection, given that depending on the correlation technique, sometimes the points chosen by the automatic correlator are not the adequate (*figure 110*). For instance, points in the elements' shadows, in moving cars…

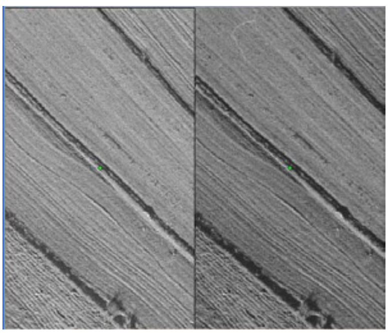


Figure 110. Homologous points.

3.3. Absolute orientation

Absolute orientation consists in levelling, scaling and moving the model to its real space position, as shown in *figure 111*.

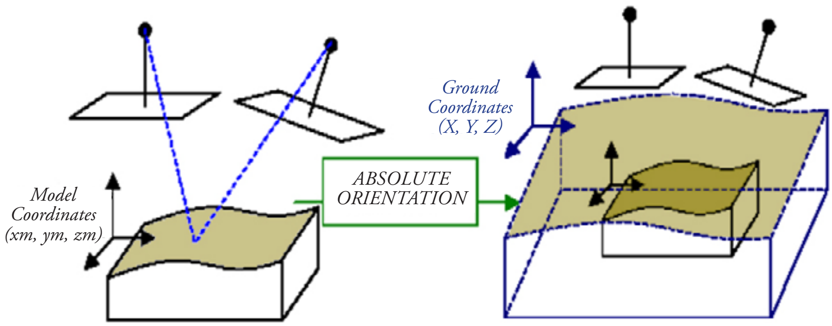


Figure 111. Absolute orientation.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \lambda \cdot [R] \cdot \begin{bmatrix} x_m \\ y_m \\ z_m \end{bmatrix} + \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix}$$

Eq. 13: Absolute orientation transformation.

To do so, a set of n≥3 numbers should be known, both in the model's coordinate system and in the field's coordinate system.

Each point would generate, consequently, 3 equations and there would be 7 unknowns to be solved.

In practice, at least 4 ground control points are used to, possibly, solve the system through least squares and, in this way, to control the exactitude of this phase.

Ground control points

The points needed for the absolute orientation are the so-called **ground control points**, which are taken in the field using the coordinates of the system that will be used to hand in the final project.

These ground control points should be well distributed along the model and they should have the following characteristics:

- They should be identifiable in all the photograms they appear.
- They should be stable details in the field.
- The area where they should be has to be identified prior to going to the countryside, so that the distribution requirements are complied.
- They should allow the operator an appropriate floating point mark placement in the model's identification process.
- They should have an appropriate size for the photograph's scale, as outlined in the first chapter. If it is an artificial point that has been put in the ground, its minimum size could be halved.

The perfect distribution of ground control points is shown in *figure 112*, in which the disposition if there existed different strips is presented.

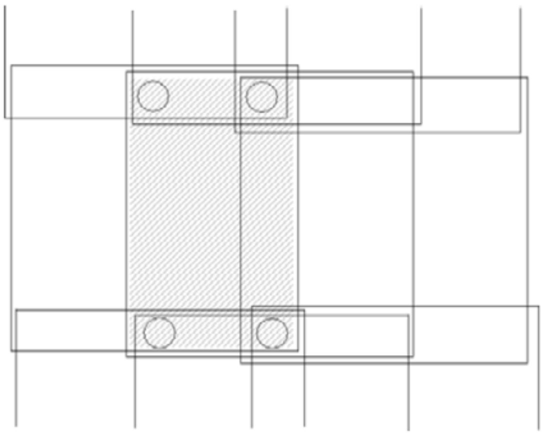


Figure 112. Perfect distribution of ground control points.

Each point should be numbered using a unique denomination that refers to the number of the photogram they belong to, the strip in which they are, and their own number.

Nowadays, the GPS technique is used to obtain ground control points coordinates in the field. Therefore, once the documents are submitted to the photogrammetric operator, apart from handing in an outline of the points (*figure 113*) and a list of the coordinates, the calculations used to obtain the coordinates of the points in the reference system of the project are also submitted.

POINT DESCRIPTION.

Near to the traffic island and close to the road, it can be distinguee a black dot that is a drainage manhole. The ground control point is located in the centre of the flap. Its elevation is referred to the floor level.

	X	Y	Z
COORDINATES	278005.543	4444440.420	523.099

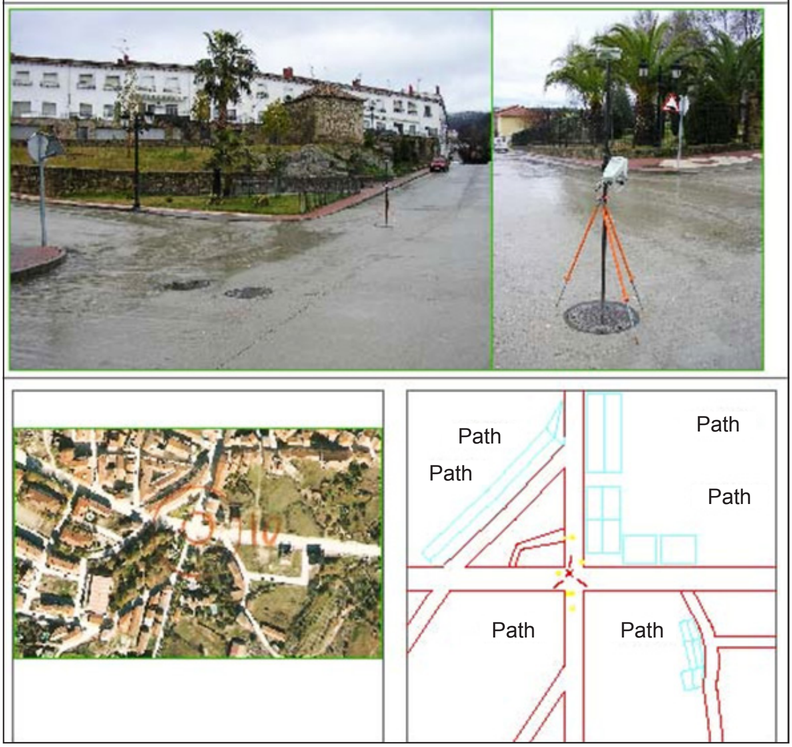
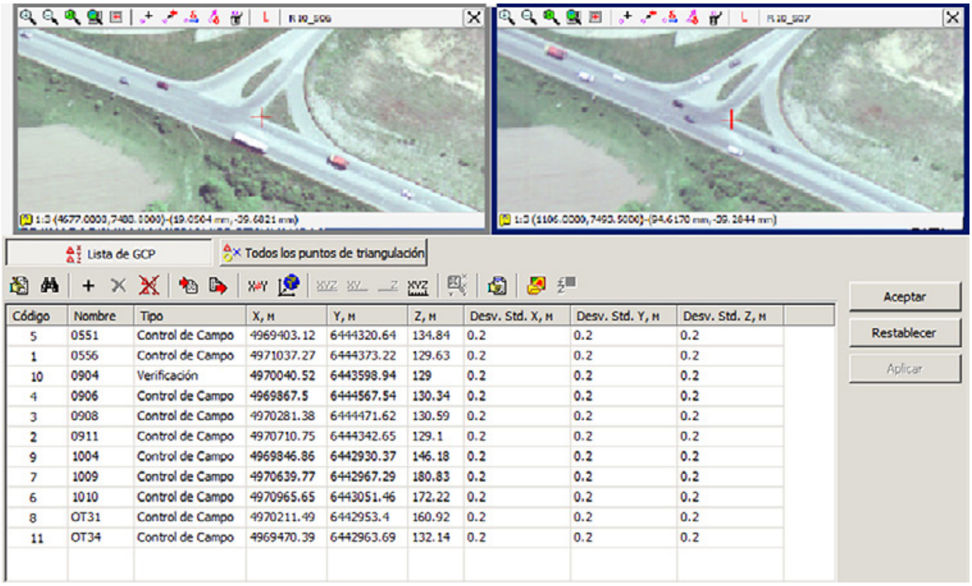


Figure 113. Ground control points' report.

Once the coordinates of ground control points are known, they should be identified in the photographs they appear. Using these well-defined coordinates, it is possible to calculate the parameters of the transformation. The finished process can be observed in *figure 114*.



Código	Nombre	Tipo	X, m	Y, m	Z, m	Desv. Std. X, m	Desv. Std. Y, m	Desv. Std. Z, m
5	0551	Control de Campo	4969403.12	6444320.64	134.84	0.2	0.2	0.2
1	0556	Control de Campo	4971037.27	6444373.22	129.63	0.2	0.2	0.2
10	0904	Verificación	4970040.52	6443598.94	129	0.2	0.2	0.2
4	0906	Control de Campo	4969867.5	6444567.54	130.34	0.2	0.2	0.2
3	0908	Control de Campo	4970281.38	6444471.62	130.59	0.2	0.2	0.2
2	0911	Control de Campo	4970710.75	6444342.65	129.1	0.2	0.2	0.2
9	1004	Control de Campo	4969846.86	6442930.37	146.18	0.2	0.2	0.2
7	1009	Control de Campo	4970639.77	6442967.29	180.83	0.2	0.2	0.2
6	1010	Control de Campo	4970965.65	6443051.46	172.22	0.2	0.2	0.2
8	OT31	Control de Campo	4970211.49	6442953.4	160.92	0.2	0.2	0.2
11	OT34	Control de Campo	4969470.39	6442963.69	132.14	0.2	0.2	0.2

Figure 114. Absolute digital orientation.

3.4. Exterior orientation (relative and absolute in one step)

In some digital photogrammetric instruments, both relative and absolute orientation processes are carried out in just one step. The model is not calculated and, automatically, the coordinates transformation parameters are obtained from the system of the camera to the system of the ground.

That is why the **co-linearity condition** is applied, as it is shown in figure 115. it makes the projection centre, the image point, and the projected Earth's point to meet in the same straight line.

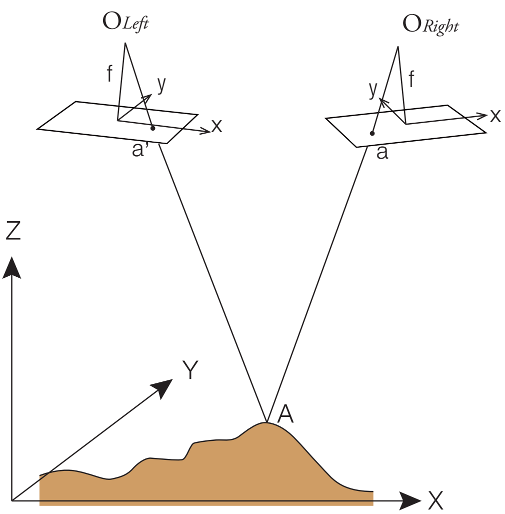


Figure 115. Co-linearity condition.

3.5. Aerotriangulation

Aerotriangulation is the process carried out in photogrammetric projects with the aim of reducing the number of ground control points in the land.

In large-scale projects, the number of ground control points is incremented and the cost of data collection is high. Aerotriangulation reduces the number significantly.

In addition, most of the work is done in the cabinet, so that the delays as a consequence of the weather conditions are reduced.

The basis of aerotriangulation is that once the photogrammetric pair is perfectly oriented, it is possible to transfer the points' land coordinates to the next model, so that they do not need to be taken in the ground. This method is known as **aerotriangulation through independent models**.

However, the so-called **bundle aerotriangulation** model is more widespread and it adjusts the whole strip at a time.

Lately, with the implementation of GPS flights and inertial sensors, the number of ground control points needed to adjust appropriately a photogrammetric block has been reduced. The GPS registers the coordinates of the projection centre of each photograph, despite of the fact that a support in the land is still necessary because this technique is not polished yet. The GPS and the camera work independently and the data is gathered at different intervals (*figure 116*).

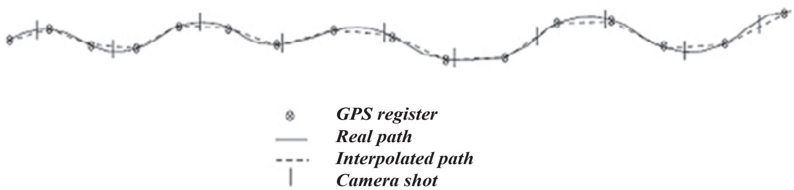


Figure 116. Discoordination between the data gathered by the camera and the GPS.

Furthermore, the difference between the GPS antenna and the camera is difficult to specify because, as it can be seen in *figure 117*, the stability platform moves the camera constantly with regard to the antenna.

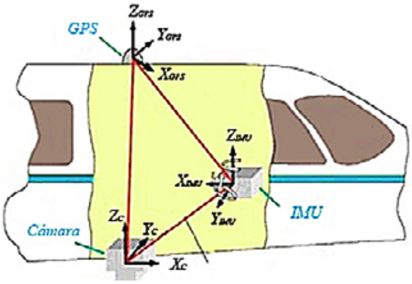


Figure 117. Difference between the GPS antenna and the camera in the plane.

Distribution and number of ground control points

The most widespread method is bundle aerotriangulation, which, drawing from a GPS flight, takes double points in the corners of the block and a point for each two models in the overlapping area between strips.

This distribution follows the assumption that aerotriangulation's exactitude depends on the ground control points of the block's extremes, while interior points have a very small incidence in planimetry, but they have an influence in altimetry.

Following this pattern and taking *figure 118* as an example, for a 14-photogram's flight in two strips, 11 ground control points would be necessary. If the whole block had been calculated without triangulation, 4 points would have been needed per model, which would mean 48 ground control points.

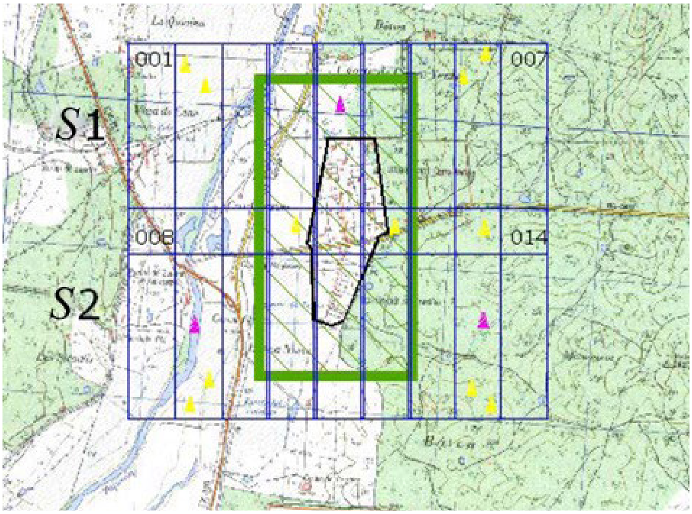


Figure 118. Distribution of the ground control points and check points in a GPS aerotriangulation flight.

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Once the coordinates are found, the operator will have to measure a minimum of 12 focal points in each overlapping area between pars, as shown in the figure where there appeared double points in *Vön Grüber*'s area.

Also, **check points** (magenta in *figure 118*) will be taken in the ground, and they should not interfere in the aerotriangulation's calculation. They can be used to prove the calculations. Their distribution will be: one point in the centre of the strips for odd strips, and two in the extremes for even strips.

4. ALLOWABLE ERRORS IN THE DIGITAL PHOTOGRAMMETRIC PROCESS

As mentioned at the beginning of this chapter, errors in the photogrammetric process are accumulated in its consecutive phases. At the end of the whole process, a control should be carried out to verify the quality of the data obtained. Nevertheless, each phase should have met the minimum exactitude requirements for the process to be accurate (*figure 119*).

Each phase should fulfil exactitude conditions:

- **Interior orientation**: if the photogram has been captured by an analogical camera and scanned afterwards, the maximum mean error should not exceed one pixel.

  If the image has been taken by a digital camera, it is inappropriate to specify the tolerance, given that interior orientation is automatic and the operator does not need to intervene.

- **Relative orientation**: planimetric tolerance is different from the altimetric one, being:

$$E^{xy}_{mean} = \sqrt{2} \cdot 0.5\ pxl$$

$$E^{Z}_{mean} = \frac{f}{b} \cdot E^{xy}_{mean}$$

Eq. 14: Maximum errors in relative orientation.

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– **Absolute orientation**: the acceptable mean error is different planimetrically and altimetrically:

$$E^{xy}_{mean} = 0.2\text{mm} \cdot M_K$$
$$E^{Z}_{mean} = 0.15mm \cdot Equi$$

Eq. 15: Maximum errors in absolute orientation.

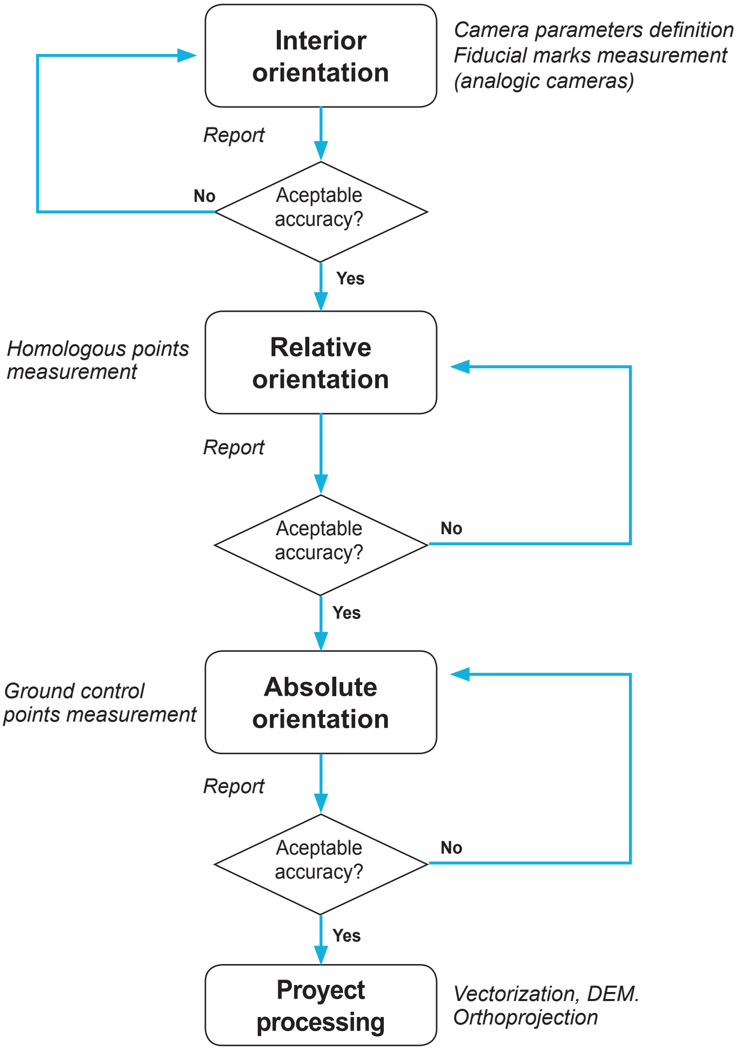

Figure 119. Control in the photogrammetric process.

5. POSITION QUALITY CONTROL OF THE DIGITAL PHOTOGRAMMETRIC PROCESS

Although the whole process should be controlled phase by phase, as it was specified in section 4, a quality control using external data that has not interfered in the process should be carried out. For this purpose, check and ground control points will be used.

An **error** can be defined as the difference between the measured value and the real value. From these values measured in the check points, considered "true values", the following statistical aspects will be obtained, and, then, they will be compared with the tolerances and the photogrammetric process will be accepted as valid or not.

– Mean error:

$$EM = \frac{1}{n} \sum_{1=n}^{n} e_i$$

Eq. 16: mean error

– Standard deviation:

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=n}^{n} (e_i - EM)^2}$$

Eq. 17: Standard deviation

Tolerances for possible standard deviations of errors obtained with check points have to be distinguished by whether they are planimetric or altimetric.

Tolerances for planimetric standard deviations:

– Measurement of a digital point:

$$\sigma_{xy} \leq \frac{1}{3}\, píxel \cdot Mb$$

Eq. 18: Digital measurement error of a point

– Measurement of an Earth's point:

$$\sigma_{XY}$$

Eq. 19: Error when taking planimetric coordinates

Therefore, the maximum planimetric standard deviation would be:

$$\sqrt{\sigma_{xy}^{2} + \sigma_{XY}^{2}}$$

Eq. 20*:* Maximum planimetric standard deviation

Tolerances for altimetric standard deviations:

In this case, it depends on the B/H relation (photographic base/height of flight) and on the planimetric accuracy when measuring the digital point:

The standard altimetric deviation in digital measurement is:

$$\sigma_{z} \leq \sigma_{xy}$$

Eq. 21: Standard altimetric deviation in digital measurement

Taking into account the deviation of the point to measure it in the land, the maximum altimetric standard deviation is:

$$\sqrt{\sigma_{z}^{2} + \sigma_{Z}^{2}}$$

Eq. 22: Maximum altimetric standard deviation

6. PHOTOGRAMMETRIC RESTITUTION

Once photogrammetric orientations are concluded and the exactitudes have been checked, it is possible to obtain the three-dimensional register of the land.

Restitution is the process in which metric information is extracted from the stereoscopic model with the help of a fixed index according to the principle of the floating point mark.

The instrument used for orientations and the measurement and register operations is known as **photogrammetric station**.

The principle of the floating point mark consists in two marks - which are set on two homologous points - that are merged into only one photograph (one mark) once the orientations are correctly made. In addition, this mark would be at the same height of the point over which it is set.

In this way, the photogrammetric operator will be placed on all the elements in the land and a register of their three-dimensional coordinates will be obtained, as it can be appreciated in *figure 120*.

This restitution process has as a result vector cartography, which is the first product derived from the photogrammetric process.

Figure 120. Photogrammetric restitution.

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Chapter 5
PHOTOGRAMMETRIC PRODUCTS

1. INTRODUCTION

As noted in the previous chapter and without going into detail, the three main products obtained from the photogrammetric process (*figure 121*) are the following:

- Vector maps obtained through restitution.
- Digital models of the ground.
- Orthophotographs.

They have not been mentioned at random, but, with a few exceptions, it is necessary to generate certain products before the others because their creation depends on the first products.

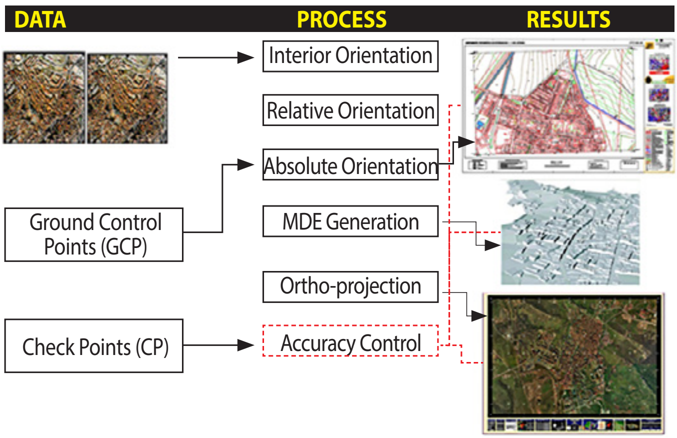

Figure 121. Phases of the digital photogrammetric process.

2. VECTOR MAPS OBTAINED FROM RESTITUTION

Vector maps obtained through restitution are products manually elaborated by the photogrammetric operator.

The operator represents, through the principle of the floating point mark and in a three-dimensional way, the elements depending on the map or final plane's scale.

Thus, as shown in *figure 122*, it is not necessary for the elaboration of 1:10.000 cartography to represent more than the blocks of the urban centres. However, the divisions between the houses should be represented to correctly represent a 1:1.000 plane.

Figure 122. 10.000 and 1.000 scales representations.

Altimetrically, the operator also makes contour lines. To do so, the floating mark rate will remain fixed and the operator will traverse the terrain placing the floating mark constantly. This walk will mould the shape of the contour line.

Many digital photogrammetric stations have automatic correlation systems, which are capable of automatically making contour lines. Nowadays, this process has not been fully developed yet and the curves taken with this automatic process need a long editing process to repair the errors caused by surfaces including objects on it, which do not belong to the land. This makes it more worthwhile to make the curves manually from the beginning.

The equidistance of contour lines is subject to not only the cartographic scale, but also to the relief that has to be represented. In an over steep ground, sometimes there is not enough space for contour lines, and, on the contrary, in low-lying areas sometimes the curves are scarce.

For an average relief, the following table can be taken as a guide:

Scale	Equidistance (m)
1:50,000	20
1:25,000	10
1:10,000	5
1:5,000	2
1:1,000	1
1:500	0.5

Table 7. Most popular *equidistances*

2.1. Restitution's quality

The first product obtained in the restitution is the so-called draft, which should be **checked** and **edited** to create the plane or final map.

Firstly, a revision of the possible errors that could have appeared is conducted. Most digital photogrammetric stations have routines to control their quality and to detect errors such as:

- Right junction between elements and contour lines.
- Lack of contour lines.
- Intersection between contour lines.
- Hydrology's altimetric errors.
- Closed polygonal elements.
- Topological errors.
- Etc.

Once the errors have been checked, it is time for the edition. In this phase, toponymy takes place and a distinction will be made between, for example, the different types of roads (local roads, regional roads, …). Depending on the scale of the final product, a revision of the field (with the aim of identifying and finding the elements that have been concealed by buildings or surfaces including objects on it) should be needed.

Revision and edition processes have been completed, and this first photogrammetric product is finished.

3. DIGITAL ELEVATION MODELS

Digital Terrain models[13] are a set of numerical data that describes the spatial distribution of a certain Earth's characteristic.

Different DTM can be created, but, in this case, the following models are going to be distinguished:

- **DEM**, Digital elevation model (*figure 123*): numerical data structure that represents the spatial distribution of the land's surface height.

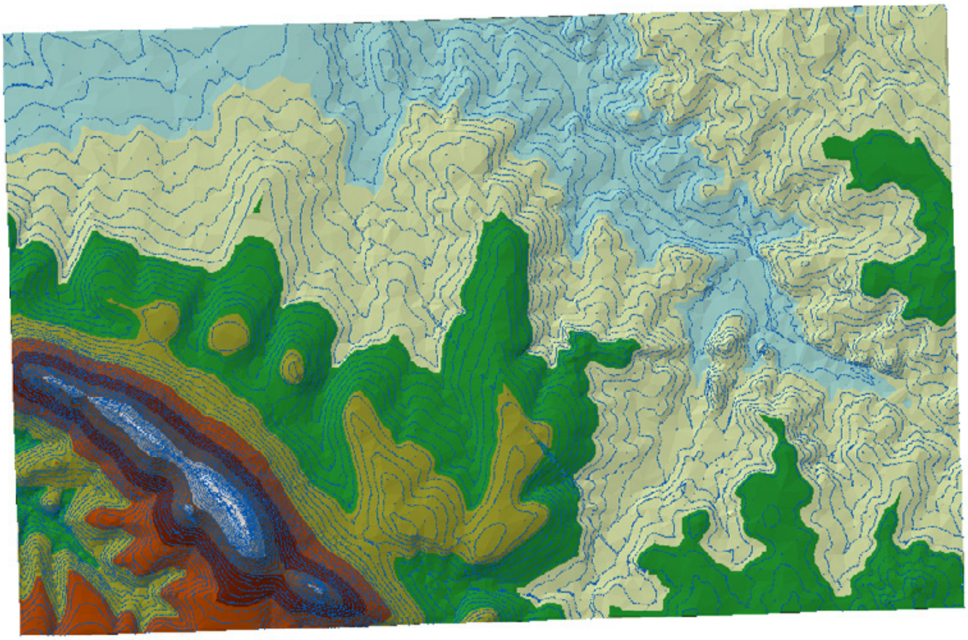

Figure 123. DME.

- **DSM**, digital surface model (*figure 124*): this model includes the heights of surfaces including objects on it, such as buildings, trees…

[13] DLM

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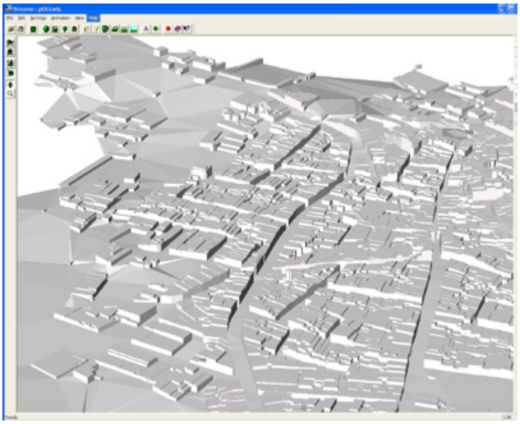

Figure 124. DSM.

3.1. DEM data structure

In general, the basic data item in a digital elevation model is an enclosed point, defined by a list composed by the height's value (Z), accompanied by the corresponding values of X and Y.

Conventional maps use contour lines to represent the land's surface, but DEM can be, mainly, of two types:

– **Vector DEM:** based on geometrical entities and, apart from the already mentioned contour lines shown in *figure 123*, it is also important to mention TIN[14] as vector information models (*figure 125*).

Figure 125. TIN.

– **Raster DEM** (*Figure 126*): based on the terrain's representation using regular and constant matrix structures. Its structure corresponds to the one of a digital image, in which each pixel shows the average elevation value of the ground on its surface.

[14] Triangulated irregular network

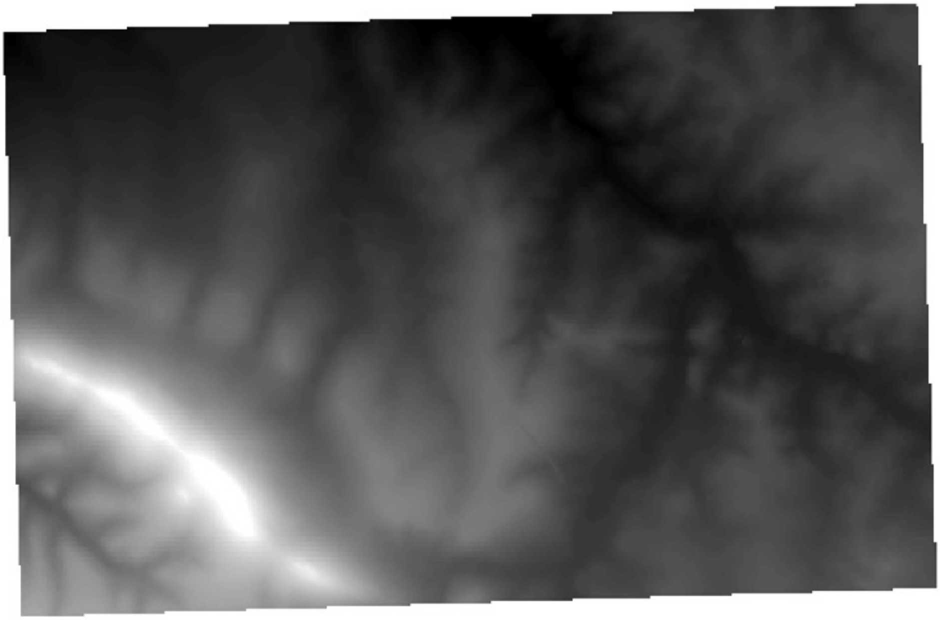

Figure 126. Raster DEM.

3.2. DEM generation methods

DEM, in the photogrammetric field, can be obtained through different methods.

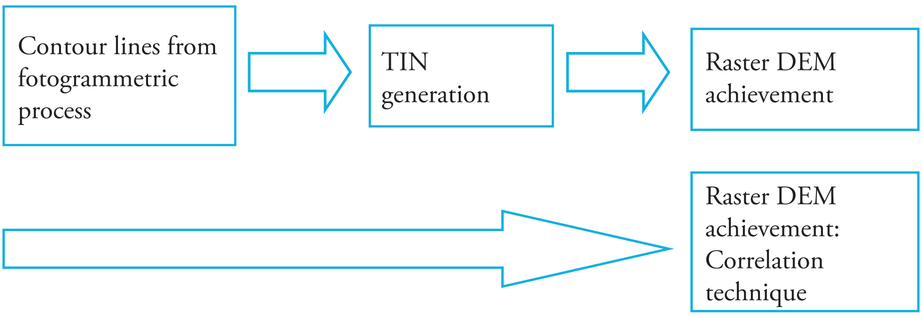

Figure 127. Methods to obtain DEM.

The chart in *figure 127* shows that the first option is carried out on the basis of the previous phase's result. The DEM is obtained "manually" and the result is usually guaranteed because contour lines have been revised and edited by an operator.

The only process that should be taken into account is the **interpolation** method (figure 128) that is going to be used, because it is required when changing from a TIN format to a raster format.

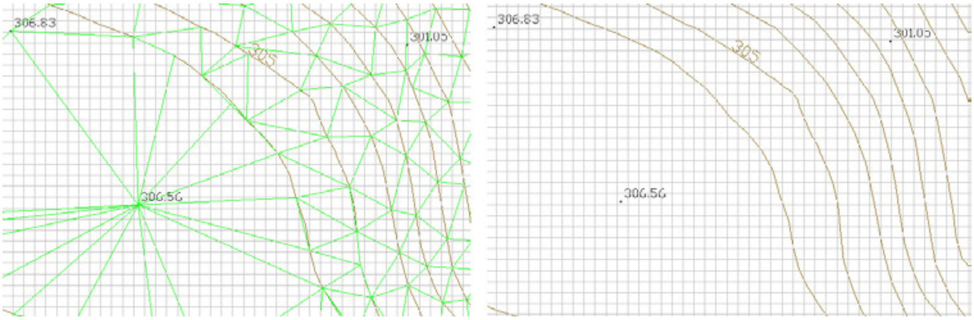

Figure 128. Interpolation.

In *figure 127*'s second case, the model is carried out automatically from the oriented photograms.

The types of matching or correlation depend on the area or on the element.

– **ABM**[15]: this type of matching compares grey levels in the pattern along the search window. This process can be observed in *figure 129* and is the one used in automatic interior orientation to search fiducial marks.

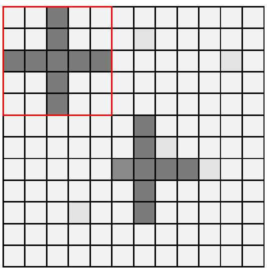

Figure 129. ABM.

[15] Area Based Matching

– **FBM**[16]: this type of matching extracts shapes out of the images (using filters) and it compares them (*figure 130*).

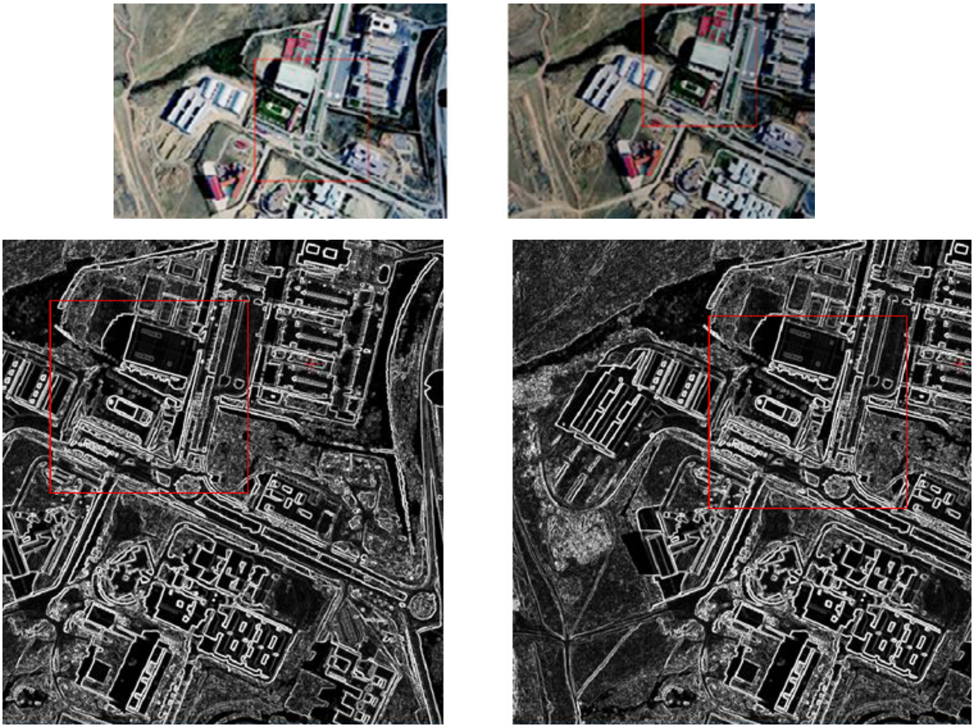

Figure 130. FBM.

This image matching process seems simple at first, but it has to face several problems such as surfaces including objects on it or the different appearance of a same element in different photographs. An example is shown in *figure 131*. The same building's cornice is completely different regarding number and intensity of pixels in the two images, so an automatic correlator would have difficulty in identifying it is the same element.

Another problem of automatic DEM is that, as they do not include division lines, the generated model needs an edition process to eliminate altimetric errors that will undoubtedly appear.

[16] Feature Based Matching.

If the output format chosen for our model is DEM, a points' filtering process is necessary to eliminate all surfaces including objects on it like buildings, vegetation…

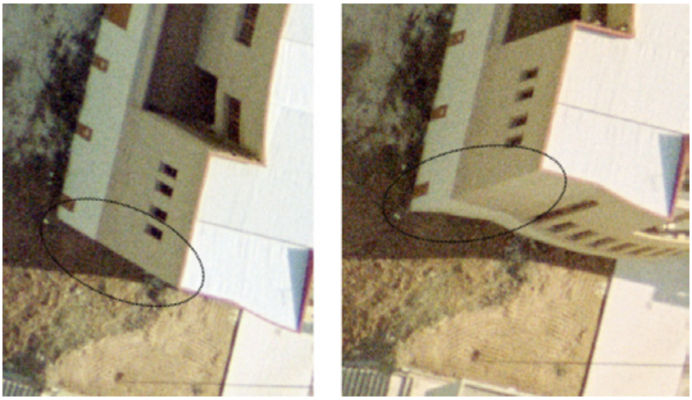

Figure 131. Matching problems.

Being our model obtained through any of the options in *figure 127* and with the aim of measuring the exactitude of the process, an error control should be carried out through the points devoted to this cause (*figure 123*).

Altimetric tolerance establishes that 90% of them should have errors less than a quarter of the equidistance, depending on the scale. The remaining 10% could vary half of the value of the equidistance.

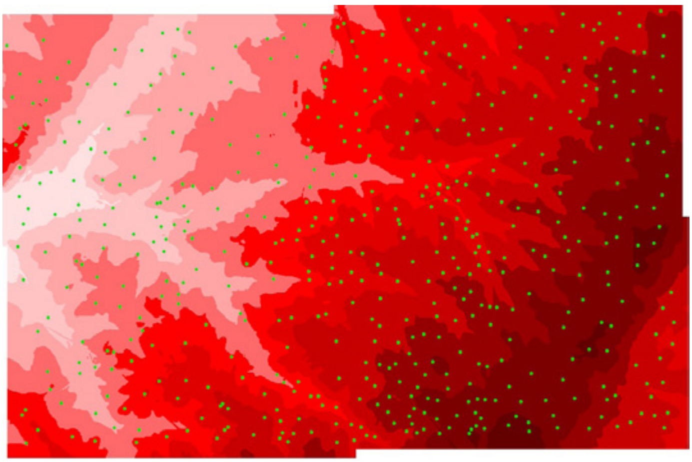

Figure 132. DEM control.

4. ORTHOPHOTOGRAPHS

A fundamental difference between two similar terms should be clarified because they are photogrammetric processes that differ in methodology and results.

4.1. Image rectification

Rectification (*figure 133*) is a photogrammetric technique that changes the conic projection of a photograph into an orthogonal projection.

Its main advantage is to obtain of a uniform scale, and the consequent measurement possibility.

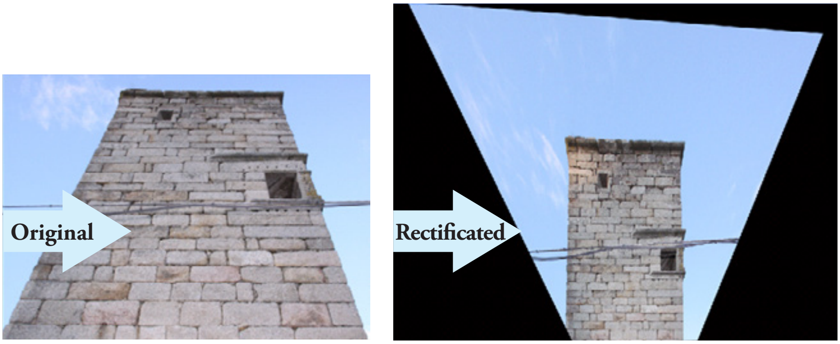

Figure 133. Rectification's result.

4.2. Orthoprojection

Orthoprojection (*figure 134*) is the photogrammetric method through which accurate photomaps are obtained. These maps have the deformations that appeared in the photographic image as a consequence of the relief and the inclination of the photograph corrected through differential rectification of the original photograph. To this effect, DEM is necessary.

In the case of aerial photogrammetry, the digital orthophotograph's generation is as summarised in *figure 135*.

Figure 134. Orthoprojection's result.

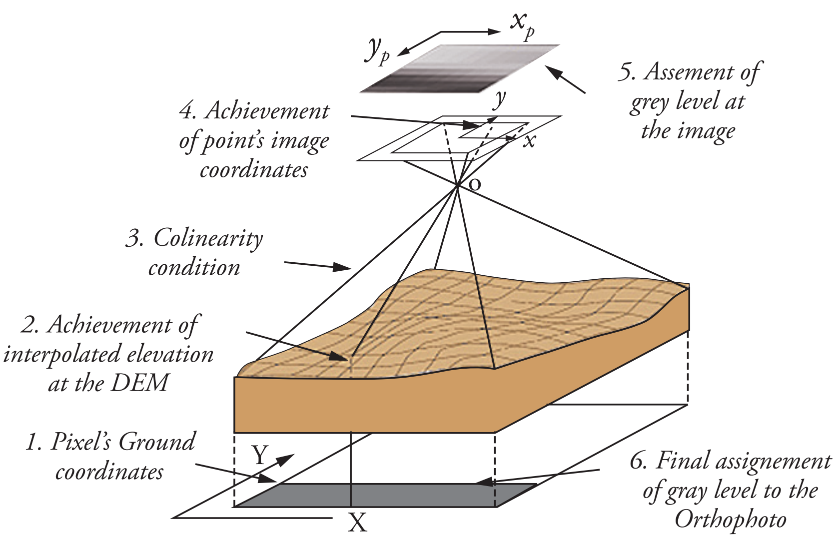

Figure 135. Phases of the orthophotograph.

Per each ground's pixel, its Z coordinate is obtained in DEM. Once this rate is known, and using the collinearity condition, the grey level of the corresponding pixel in the original photo is discovered, and it will be used in the orthophotograph.

In this process, the grey levels that are going to be represented need to be interpolated in some areas because the position given by the collinearity condition does not necessarily need to be the exact centre of a pixel in the original photograph.

The most commonly used interpolations are:

- **Nearest-neighbour interpolation** (*Figure 136*)**:**

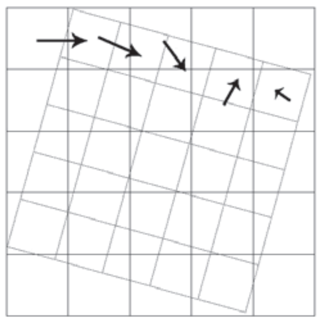

Figure 136. Nearest-neighbour interpolation.

– **Bilinear interpolation:** it takes the average of the four nearest pixels to the original image (*figure 137*).

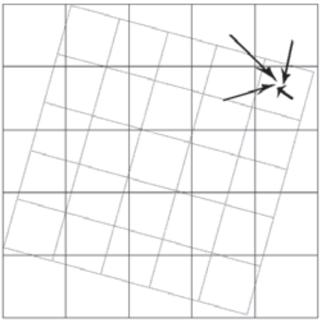

Figure 137. Bilinear interpolation.

– **Bicubic interpolation:** it considers the 16 nearest pixels (*figure 138*).

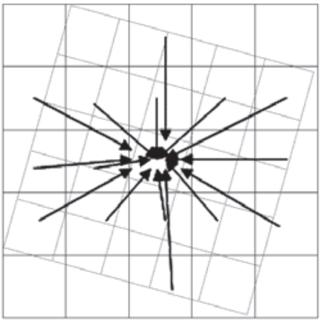

Figure 138. Bicubic interpolation.

5. TYPES OF ORTHOPHOTOGRAPHS

Orthophotographs made using DEM are the most common ones and they are known as "**conventional orthophotographs**". This type of orthophotographs have some problems regarding the correct representation of surfaces including objects on it. For example, as it can be seen in *figure 139*, the buildings seem to be laying down because they belong to radial areas of the photograph. We must remember *figure 89* in chapter 3, where it was possible to observe the displacement of surfaces including objects on it when they were not captured by the camera in a nadiral position.

That is why coordinates or distances of surfaces including objects on it should not be measured in conventional orthophotographs.

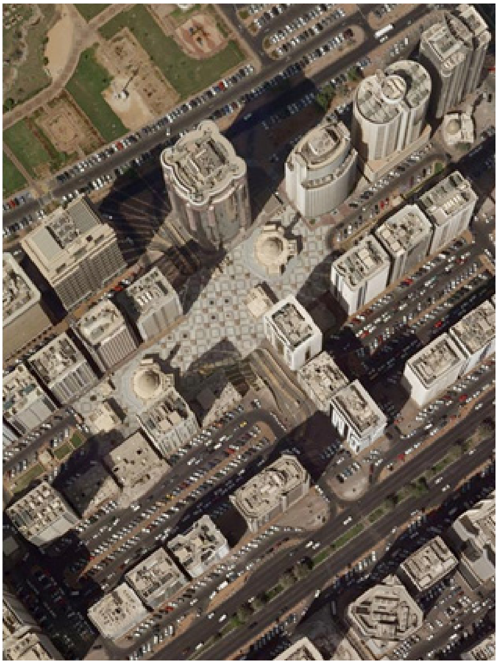

Figure 139. Conventional orthophotographs.

Additionally, the displacement of surfaces including objects on it can lead to noteworthy visual effects when two adjacent conventional orthophotographs are put together. *Figure 140* shows that the attachment of two orthophotographs has been done in the middle of an avenue; thus, the buildings in both sides of the avenue have different perspectives.

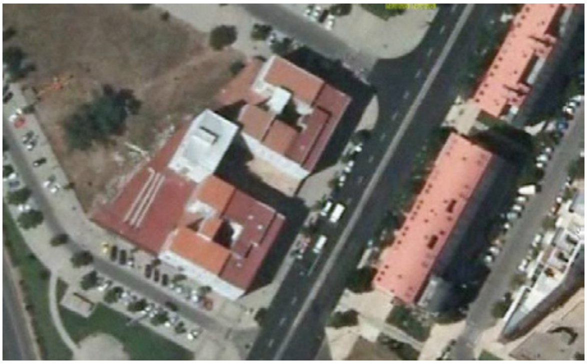

Figure 140. Errors due to perspective difference.

Nowadays, the new format of orthophotographs has been extended, the so-called "***true orthophotographs***".

This type of orthophotos follows the DSM instead of the DEM. This takes into account the height of all surfaces with objects on it and the results are more accurate, as shown in *figure 141*.

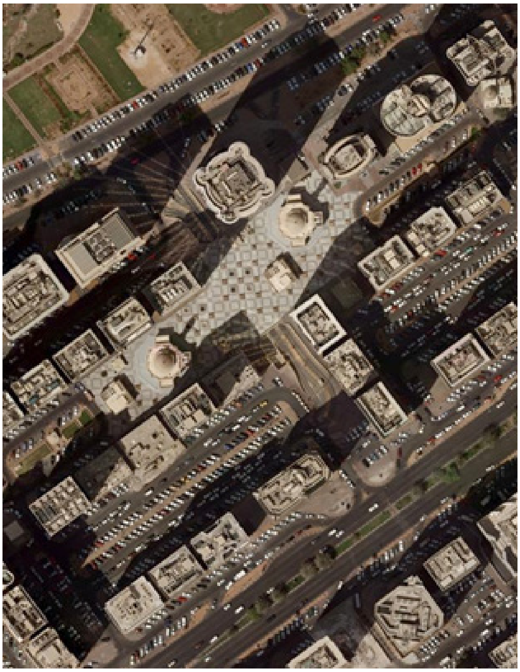

Figure 141. True orthophotograph.

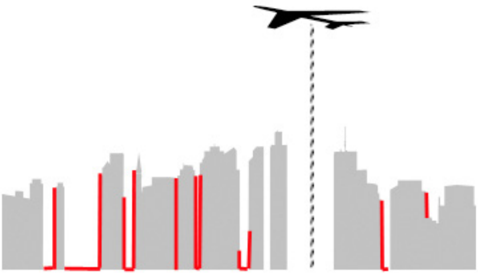

Figure 142. Spaces in the conventional process.

The process of producing true orthophotos is more laborious than conventional orthophotos and it requires not only more side lap between the flight photograms, but also a LiDAR flight to properly obtain the DSM.

Figure 143. True orthophoto's generation.

The spaces that need to be covered in *figure 143* make the flight with more overlapping necessary, so that the area is photographed from different points of view.

6. ORTHOPHOTOGRAPHS' MOSAIC

The fact that a photogrammetric flight consisting of many photographs is needed to cover the work area makes a mosaic of all the necessary orthophotos generated to take an orthophoto of the whole area.

Radiometric calibration is essential in this phase, and it is based on the fact that histograms must be equal in the overlapping areas between contiguous orthophotographs, which implies that a total radiometric adjustment of both images needs to be done until they coincide.

Even though the photographs have been radiometrically corrected, when they have to be connected, the difference between the photograms can be noted; hence, the process should not be carried out automatically, because the results would not be visually correct.

The right approach is to manually indicate union polylines between photograms that follow elements in which the radiometric difference cannot be appreciated.

Figure 144 is an example. The top image shows the result of not limiting the photograms unions through lines that follow natural elements. At the bottom,

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we find the result of having drawn the red polyline that follows the route of a communication channel. The aesthetic improvement can clearly be seen in the final product.

Figure 144. Correct delimitation of the orthophotograms' union lines (source: Racus).

Figure 145. Errors when connecting surfaces with elements on it.

Figure 146. Correct union delination between orthophotos.

In addition, that polyline is needed in conventional orthophotos not only to minimise radiometric errors, but also, in the case of constructions that go through cutting lines, to eliminate geometric errors that arise from the perspective difference of the surfaces with elements on it. An example is shown in *figure 145*.

The solution is to define, manually, the union, so that it does not go through any building, as shown in *figure 146*.

7. ORTHOPHOTOGRAPHS QUALITY

The final **visual result** of the completed orthophoto needs to be supervised, as there frequently exist some errors, primarily derived from the DEM's quality and they are not visible until the orthophoto is generated.

The first error that tends to appear is the image's "drag" (*figure 147*). This is usually because the DEM has a height local error and the photograph is forced to be stretched so that it fits. As a result, the orthophoto is deformed in that area.

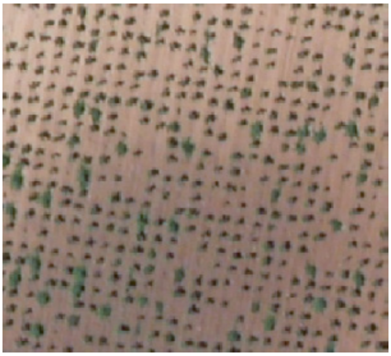

Figure 147. Drag of the image in the erroneous DEM orthophoto.

Another frequent error, similar to the previous one but produced in surfaces with elements on it, is the following one. If the orthophoto is conventional, it is based on the DEM, which, as it has already been mentioned, does not take into account surfaces with objects on it and, sometimes, these surfaces are not correctly represented, as it can be seen in *figure 148*.

Figure 148. Deformations caused by the DEM's errors.

Finally, the **geometric quality** of orthophotographs needs to be highlighted. This quality is, in short, the main quality of orthophotographs. For assessing this quality, check points should be used comparing their planimetric situation with regard to the one illustrated in the orthophoto (*figure 149*).

Figure 149. Example of a quality control of the orthophotograph.

The planimetric tolerance of the project establishes that 90% of the well-defined points will not differ from their true position 0.2 mm in the scale of the map.

Chapter 6
FLIGHT PROJECT. TECHNICAL SPECIFICATIONS.

1. INTRODUCTION

Throughout the career of a civil engineer, photogrammetric flights will probably be needed to obtain cartography in an accurate scale to design the project.

This chapter has been developed to address this issue. The aim of this chapter is to outline the elements needed in the technical specifications, from the necessary requirements in the execution of a flight to the quality that is necessary in the final products we are going to work with.

2. PHOTOGRAMMETRIC TECHNICAL SPECIFICATIONS

Photogrammetric technical specifications establish all the premises that have to be fulfilled by the company in charge of the photogrammetric project when going through all the phases of the photogrammetric process.

It should be reminded that the ultimate objective of photogrammetric projects is to obtain all or some of the photogrammetric objects that were mentioned in the previous chapters. For this reason, the sequence of the photogrammetric technical specifications should be the photogrammetric workflow.

The parts of the technical specifications are usually the following:

2.1. General Conditions

Firstly, the reference system in which the coordinates for the project are going to be obtained has to be detailed, especially nowadays.

As it was said in the first part of this book, this is a transition period between official reference systems. This premise forces us to decide between any of these two systems –ETRS89 or ED50– to which our project can be referred to.

The most logical thing would be, apparently, to use the ETRS89 system, but sometimes, having cartographic data of the area in the old system makes it necessary for the project to be carried out by using the old ED50 system. Nevertheless, this second option is not recommended because it would be better to transform old data from ED50 to ETRS89, as it was mentioned in chapter 2 in the first part of the book.

Another element that has to be clearly identified in this section is the scale of photogrammetric products that are going to be needed. Such scale will limit, subsequently, general accuracies and tolerances.

In this section, the size, shape and location of the area that is going to be mapped should be specified. The planning of the photogrammetric flight will largely depend on its dimensions and shape.

2.2. Flight conditions

In this section, there should be identified:

- *Types of cameras to be used*: if digital cameras are required or if analogical cameras are still admitted. In the last case, it would be necessary to specify the type of scanner used to transform from flight negatives to the digital format afterwards.
- *Resources the plane needs to have in the flight*: for example, if the plane is required to have a GPS or if, on the contrary, it is not necessary.
- It is of the utmost importance to define the geometry of the flight, in other words, the end lap (between consecutive photograms) and side lap (between strips). We recall that the most common end lap is the 60% one, but if one wants to obtain true orthophotographs, the overlap should be implemented. The side lap tends to be of, approximately, 25%.
- *Flight conditions* such as the time of the flight or the position of the sun should be specified to avoid shadows in surfaces with objects on it.
- *Presentation format of digital files*: apart from digital files with original formats, duplicates with reduced formats will be required and the type of compression algorithm that will be used.

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A fundamental part of the project is the flight's planning. This planning is not usually included in the technical specifications, but in an annex. That is why, this topic will be dealt with further on and, similar to the technical specifications, a section will be completely devoted to this issue at the end of the chapter.

2.3. Ground control surveying conditions

Gathering the data and processing ground control points is known as "flight ground control".

Apart from measuring the necessary points to carry out whether the aerotriangulation or the placement of stereoscopic models independently, coordinates of a series of points are measured so that they are identifiable in the photographs and they do not interfere in any of the process phases. These will be the so-called check points.

In this part of the technical requirements, the number of ground control points that need to be taken should be specified. For this reason, there should be stated if there is going to be aerotriangulation or not. In addition, if the plane has GPS, the number of points would be reduced.

The number and distribution of ground control and check points depends on the number of photographs needed to overlap the whole area, so a total number is not usually indicated, but a number based on the number of photographs.

In this section, it should also be mentioned how the outlines of the ground control points are going to be handed in, and all the calculations from gathering the data to obtaining coordinates in the final reference system.

It is important to specify planimetric and altimetric tolerances that all the measured points have to follow because the exactitude of the final result depends on their accuracy.

2.4. Restitution and cartography conditions

This section focuses on the specification of both the tolerances that errors committed in the photogrammetric orientations have to follow, and the tolerances and technical specifications of the first photogrammetric product that was mentioned in previous chapters.

Regarding orientation tolerances, they will be specified for interior, relative and absolute orientation phases, bearing in mind the errors that are accumulated in each phase.

With reference to cartography, the format in which the final result wants to be obtained needs to be specified, paying attention to the types of lines, colours, thickness, etc.

If this part of the technical specifications is well defined, the cartographic result will be more complete. For example, there is a difference between specifying that all roads are represented in red and with a continuous line, and detailing that national roads will have a thickness of 2 units and highways a thickness of 3 units, and, furthermore, each of them should be in different layers.

The type of quality control that is going to be carried out to final cartography should also be detailed.

2.5. DEM and orthophotographs conditions

As it has already been mentioned, to take orthophotographs, a DEM or a DSM, depending on the type of orthophoto that will be generated, has to be carried out properly in advance. Thus, the type of orthophoto is the first thing that should be specified.

If a conventional orthophoto is required, the DEM requirements are fewer. Usually, raster models with the ASCII format are requested, so that any program can open them. In addition, a file with the breaklines is used for the DEM. This raster model can be useful later on to work in a SIG without the need of generating one by ourselves from contour lines of cartography.

If a true orthophoto has been requested, then, the flight geometry section should be highlighted because it requires more stereoscopic overlap. Additionally, data collection with LiDAR is usually required for the DSM to be more precise. This, together with a more laborious orthophoto generation, can increase the cost of the project.

In this section, a DEM or DSM control is required before taking the orthophotograph and, afterwards, the tolerances that orthophotos should follow should also be specified.

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The premises regarding radiometric corrections that should be made to the photograms to generate the final mosaic tend to be indicated in this section as well. One should be cautious in this sense, as not too many manipulations should be allowed because they can cause quality loses in orthophotos.

Finally, the format of the digital files and, if the project is too large, which compression formats are desired, will also be specified.

3. FLIGHT PLANNING

The planning of a photogrammetric project can be divided into three phases:

- ***Flight planning*** that has to be followed to take all the aerial photos that will be used in the project.
- ***Terrestrial control planning***, as well as the execution of all surveying tasks that satisfy the accuracy required by the project.
- ***Estimated costs*** associated with the project.

The main condition in the whole flight planning is obtaining an appropriate photographic coverage with a minimum of photographs, in a way that each part of the field, however small it may be, should be stereoscopically covered. In other words, all the surface should be covered in overlapping areas, both contiguous photographs of a flight path and overlapping areas of neighbour flight paths.

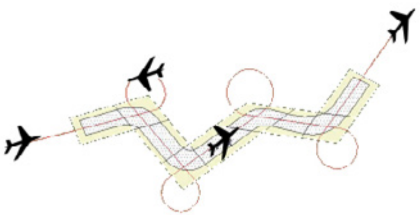

Figure 150. Flight project of a linear layouts.

As it can be seen in *figure 150*, in the case of civil linear works, geometry of a linear layout can complicate the capture of a photogram in terms of all areas having stereoscopic overlap.

3.1. Initial data

The available initial data are: the geometry of the area that is going to be overflown, and the scale of the cartography we want to make.

From this data, we should plan the flight by calculating the number of necessary photographs and their disposition so that all the desired surface can be restituted.

3.2. Flight characteristics' calculation

Some of the premises mentioned in previous chapters will be reminded.

Firstly, the scale of the final product should be taken into account to know which scale should be used to measure the ground when taking the photogram (*figure 151*).

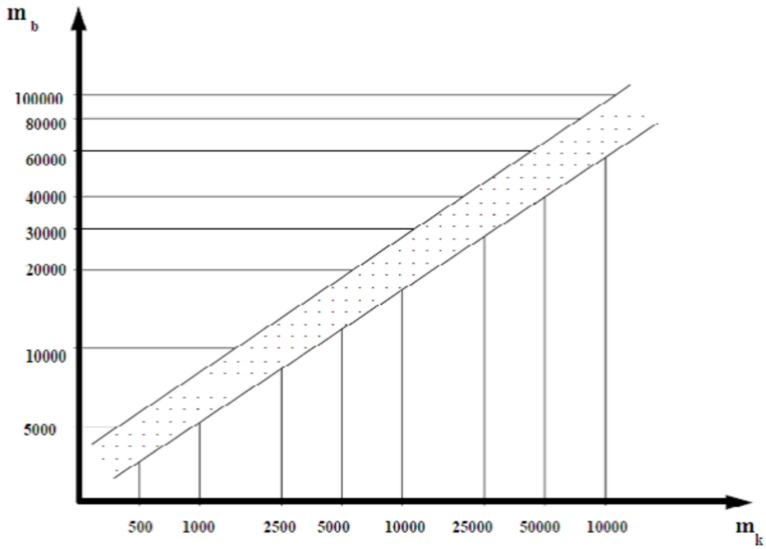

Figure 151. Relation between photographic and cartographic scale.

The second datum that has to be obtained is the height of the flight, which is linked to the camera's focal length. We cannot choose this datum, but we have to adapt ourselves to the cameras of the company in charge of the photogrammetric flight. Once this datum is known, we can obtain the flight's height over the ground (*figure 152*):

$$Mb = \frac{1}{mb} = \frac{c}{H} \Rightarrow H = c\ mb$$

Eq. 23: Relation between the scale and the flight's height.

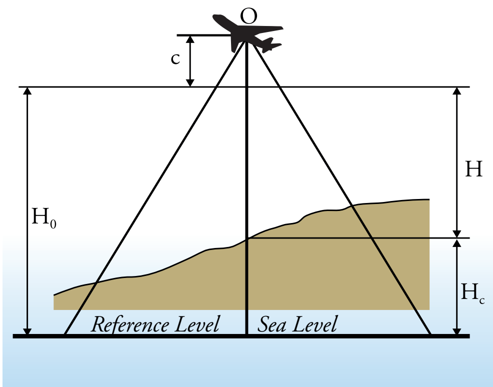

Figure 152. Flight's height above sea level.

According to the end lap and side lap that have been stated in the technical specifications, S_1 and S_2 dimensions of the stereoscopic models will be obtained (*figure 153*) as well as their overlap between strips (*figure 154*).

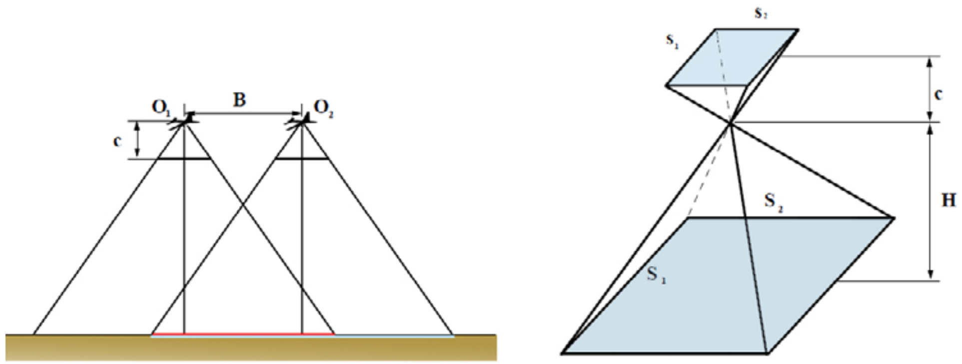

Figure 153. Photograph's dimensions.

$$S_1 = mbs_1 \qquad S_2 = mbs_2$$

Eq. 24: Photogram's size on the field.

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The distance travelled by the plane between photographs is known as "Base" and is obtained as follows:

$$B = S_1\ (1-p) = s_1\ mb\ (1-p) = s_1\ mb \left(1 - \frac{p\%}{100}\right)$$

Eq. 25: Base

Side lap refers to the distance between strips and is determined by the following parameters:

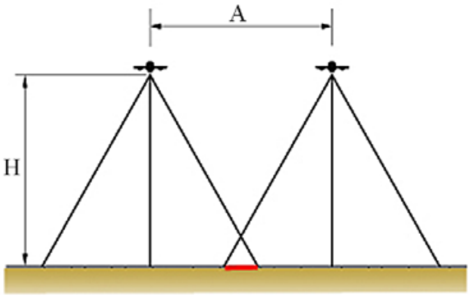

Figure 154. Side lap.

$$A = S_2\ (1-q) = s_2\ mb\ (1-q) = s_2\ mb \left(1 - \frac{q\%}{100}\right)$$

Eq. 26: Distance between strips

If the working area is regular or if it may resemble a regular polygon, as the one in *figure 155*, then, the strips would be parallel.

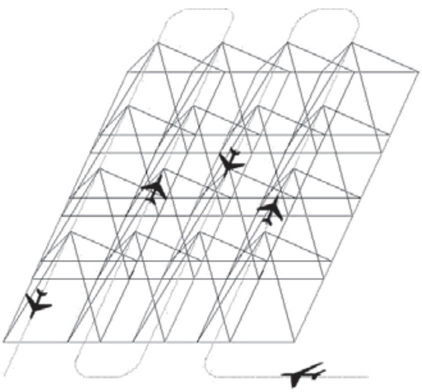

Figure 155. Flight scheme in a regular area.

Notwithstanding, if the area of the project has an irregular shape, or if it is long, narrow and not aligned with cardinal directions as the one in *figure 156* (riverbeds, layouts of new roads, coastlines, etc.) it is uneconomic to fly in North-South or East-West directions because the strips obtained would have few useful photograms. In this case, it is evident that we should fly parallel to lines of major longitudes, but being careful to cover the strips changes sufficiently.

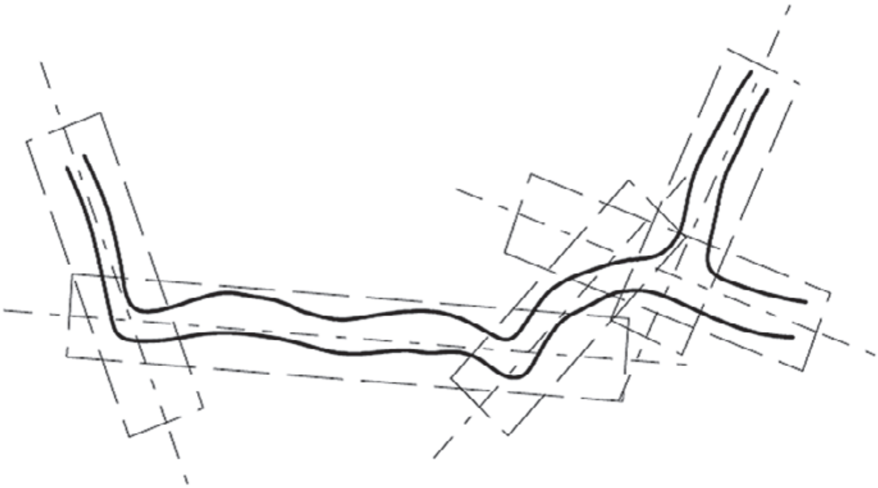

Figure 156. Flight scheme in an irregular area.

Now, the number of photographs needed to cover the whole area will be calculated in detail, following *figure 157*'s geometry.

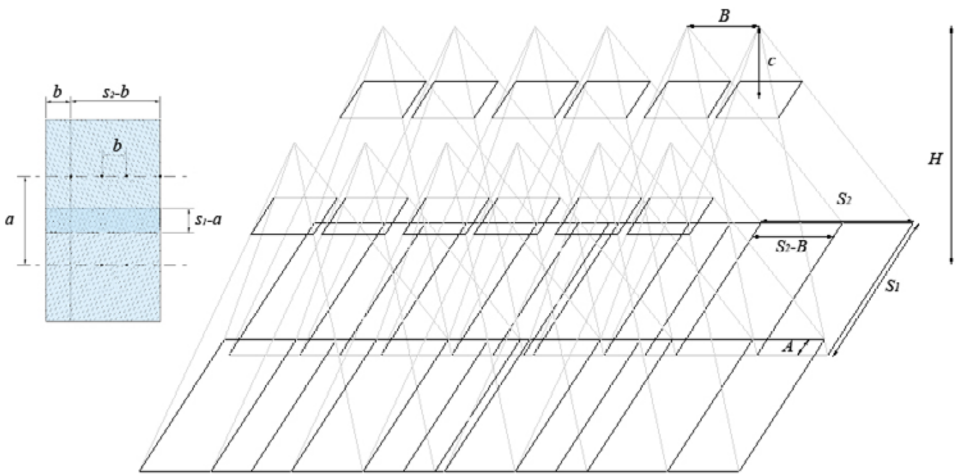

Figure 157. Photograms disposition to calculate the total number of photographs.

The number of photographs in each strip "n_p" is:

$$np = \frac{Lp}{B} + 1$$

Eq. 27: Number of photographs in each strip

The number of strips "n_q" is:

$$nq = \frac{Lq - S}{A} + 1$$

Eq. 28: Number of strips

Finally, the total number of photographs is:

$$tnp = n_p \text{ x } n_q$$

Eq. 4: Total number of photographs

Some aspects of other phases such as the information volume needed to store all the photographs, the number of ground control and check points in the field will depend on this number. That is why it should not be overvalued nor undervalued, because the real costs of the project can differ from the estimated costs due to a wrong planning.

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Chapter 7
FUTURE OF PHOTOGRAMMETRY; LIDAR AND SPACE PHOTOGRAMMETRY

1. LIDAR

In Photogrammetry, LiDAR[17] is necessary when a DSM with greater accuracy is going to be created; either because we want to make a True Orthophoto or because we need a more accurate DEM or DSM.

LiDAR makes reference to a system that uses electromagnetic radiation at optical frequencies of the visible and near infrared (*Figure 158*), being able to perform distance measurements.

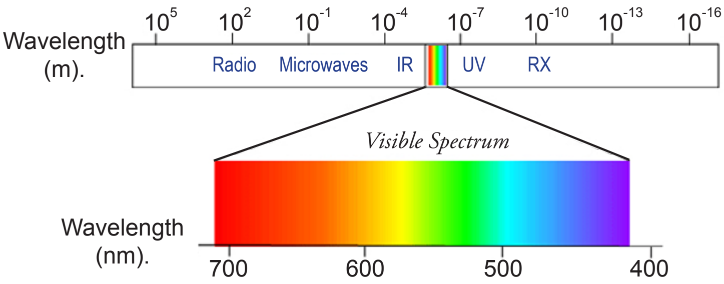

Figure 158. Electromagnetic spectrum.

The airborne LiDAR is an active system based on a sensor that transmits and receives a laser pulse. It can be installed on airplanes or helicopters. Nowadays, this technology is replacing classical photogrammetric methods for high-precision DSM, because it gets lower costs and shorter lead times, while accuracies of about 15 cm in elevation and higher density of point measurements are obtained.

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17 Light Detection and Ranging

The operation of LiDAR system consists in a scanning sensor that emits laser pulses and measures the time these pulses take to reach the Earth's surface and to return up to the sensor. It has the same running than the distance measurement of a total topographic station.

In the plane, a GPS system is installed, so that position coordinates are calculated (*Figure 159*). To increase the positioning accuracy of the instrument, a GPS device is also installed on ground. After the flight, GPS data of the airline is combined with GPS on ground, and accuracies of 5 cm are obtained in the instrument position. The inertial navigation system is also connected, as in a conventional photogrammetric plane.

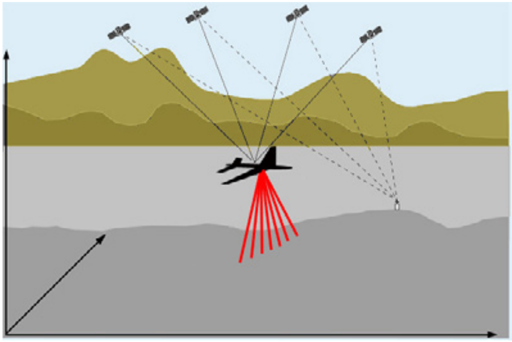

Figure 159. LiDAR flight disposition.

Firstly, all laser emissions are sent out in a unique direction, but there is a rotating mirror that deflects them to both sides of the plane with a configurable opening angle. In this way, a scan of a particular land strip is made, and its width depends on the flying height.

By combining all this information (distance measured with the laser, angle of the mirror that performs the scanning, exact position of the instrument with GPS and inertial navigation system), we can obtain the measurement of the land's height with an accuracy of 15 cm in Z coordinate.

The different performances of the earth field depending on its characteristics can be distinguished. When the laser beam hits the ground, it acts differently. See *Figure 160*:

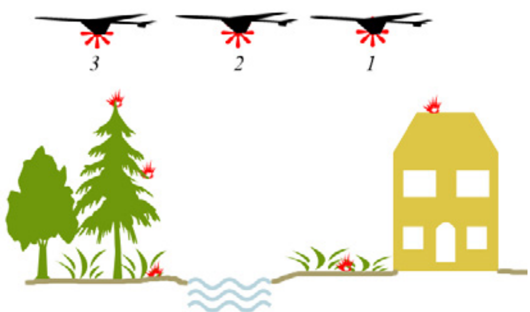

Figure 160. LiDAR performances in different surfaces.

In a *solid surface* (buildings, land, etc.), the beam is reflected without any problem and then it goes back to the plane.

On *water*, the laser beam undergoes a specular reflection and it does not return to the plane, so that no information is obtained, appearing a gap that must be interpolated from the heights of the surrounding surfaces or other available bathymetric data.

In the case of *vegetation*, the beam hits firstly with the top of the tree. At this point, part of the beam is reflected and goes back to the plane, but as it is a non-solid surface, another part of the beam passes through the vegetation until it reaches the ground and returns to the plane. The system saves the coordinates and heights of all the received pulses.

1.1. Advantages and disadvantages of LiDAR

The main advantage, which has already been mentioned, is the ability to obtain a DSM, with an accuracy of decimetres, and with a lower cost than using conventional photogrammetric techniques.

One of the advantages of LiDAR technology is the possibility of measuring, for each pulse, the first and last rebounding of the beam that go back to the plane. This allows measuring the height of the ground in areas which are completely covered with vegetation, and which are not possible to be measured with conventional techniques such as photogrammetry.

The achievement of the DSM is almost direct. The only operation to be performed, in most cases, is the relative orientation of the flight strips, or the georeferentiation into a given reference system.

The flight can be performed some more days a year. As it is an active sensor, it does not need any sunlight and it can fly during the day, at night or even with high clouds. As we have seen, in conventional photogrammetry, a certain height of the sun and completely clear days are needed.

However, LiDAR presents two limitations. Firstly, data collection of points not belonging to the Earth field as vegetation, buildings, electric lines, etc. is difficult. The treatment used is filtering the elements that do not belong to the Earth, to go from DSM to DEM; this process is done manually by identifying and removing points. Currently, some algorithms are being studied to make this process more automatic.

The second disadvantage is the lack of information from the visible spectrum. We do not get an image as usual, which makes it difficult to identify the terrain's elements. This is a disadvantage because, although the laser provides the intensity of the reflected rays, it is difficult to identify the elements they correspond to. Therefore, it is appropriate to combine these data with digital photo sensors, which arrange information in visible bands.

In this way, the future goal is to combine the information acquired by both sensors: LiDAR information, which delivers high geometric accuracy, and aerial photography information, which provides continuous information of the earth field, and good metric information.

1.2. Technological applications of LiDAR

The main applications in civil engineering in which LiDAR technology is often used are:

- **Mapping for flood studies:** one of the main applications is performing hydrological and flood studies with LiDAR. For this type of work, very accurate measurements of the ground heights are needed. So far, all these works were made by photogrammetry, which entailed high costs and long lead times. LiDAR technology can measure large areas at lower cost and shorter deadlines. Furthermore, it has a height measurement per terrain square meter, whereas in classical photogrammetry, in flat areas, contour lines are plotted widely separated and when interpolating, the DSM would not be so accurate.
- **Applications in urban areas:** another main application of LiDAR technology is the measurement of urban areas to plan telecommunication networks, detection of illegal constructions, emergency plans, engineering applications and other GIS applications (*Figure 161*).
- **Applications in the maintenance of electric power lines:** If the LiDAR instrument is installed in a helicopter, so that it can fly lower and slower, we can measure electric power lines with greater accuracy, as shown in *Figure 162*.

  In this case the first rebound corresponds to the height of the wires and the last one to the terrain's height. In this way, the trees that are dangerously close to cables can be located and, therefore, they must be cleared. Also, illegal constructions, that are closer than the allowed distance, can be detected.

Currently, many projects are inventorying power lines so that emergency helicopters (fire fighters, emergencies) can fly in an accurate and safer way at night if required by means of this type of mapping.

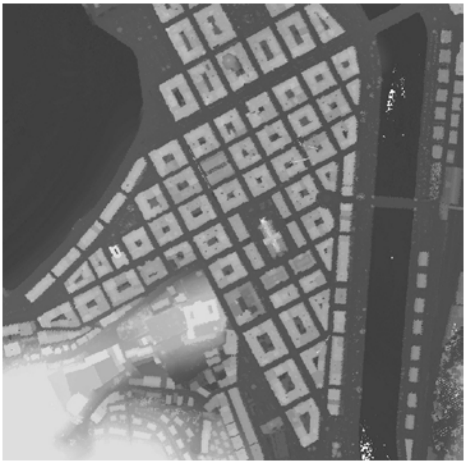

Figure 161. LiDAR applications in urban areas. (Source: Dielmo 3D S.L)

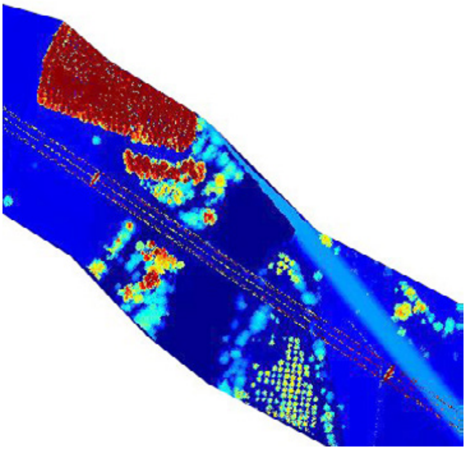

Figure 162. LiDAR application in the maintenance of electric power lines (Source: Dielmo 3D S.L)

– **For engineering projects:** Mapping for civil engineering projects: roads, railways, etc. For noise maps, inventory, accurate estimation of the Earth's movements, 3D visualization and other GIS applications.

2. SPACE PHOTOGRAMMETRY

Nowadays, it is possible to perform photogrammetry from images captured by sensors located in satellites.

The performance of photogrammetry using satellite imagery has advantages and disadvantages. For example, spatial data have lower spatial resolution, which seems obvious since the flying height is very different. This impedes the use of satellite images for detailed mapping scales, although it demonstrates the possibility of extracting information from l: 100,000 scale to even 1:5,000 scale. This problem could be compensated by its large terrain coverage, the periodicity of the shots, the high spectral resolution and the availability of, in some cases, triple stereoscopic data (one nadir scanning and two oblique scannings).

The geometry of photogrammetry using space sensors differs from conventional photogrammetric shots and it is similar to linear digital cameras, which were presented in Chapter 3.

As we have seen, stereoscopy is necessary to obtain Z coordinate or terrain elevation. Images taken by some satellites are stereoscopic because they perform simultaneous scans (two or three): one vertical, and one or more oblique ones.

2.1. Types of Stereoscopic geometry

Stereoscopic oblique geometry can be made in two ways: transversal or longitudinal.

In the case of transverse stereoscopic geometry, the images are obtained from two consecutive orbits. This geometry means that the sensor is capable of rotating laterally (perpendicular to the orbital path). This type of geometry was the first to be used in specific spatial data and it is used by the SPOT satellite. Other satellites using this type of geometry in stereoscopy are the CBERS, ADEOS, KOPSAT-1, RESOURCESAT. Its main drawback is the time difference between the images because it may take one or more days for the satellite to pass through consecutive orbits, and the difference greatly affects the image radiometry. This means that there is a clear trend towards longitudinal stereoscopic geometry.

Longitudinal stereoscopic geometry can be achieved through different ways, as shown in *Figure 163*, and it depends on the number of available sensors. Therefore, this stereoscopy can be achieved through:

- *Longitudinal stereoscopy with a single sensor*: the device rotates forward or backward. These sensors can also rotate laterally.
- *Longitudinal stereoscopy with two sensors*: usually one has a nadir position and the other is oblique.
- *Longitudinal stereoscopy with three sensors*: It has one zenithal sensor and two oblique ones, one forward and a backward one. In this case, three stereoscopies could be obtained by combining sensors (backward -zenithal, forward-zenithal, forward-backward) and, therefore, it is possible to increase the reliability of the process.

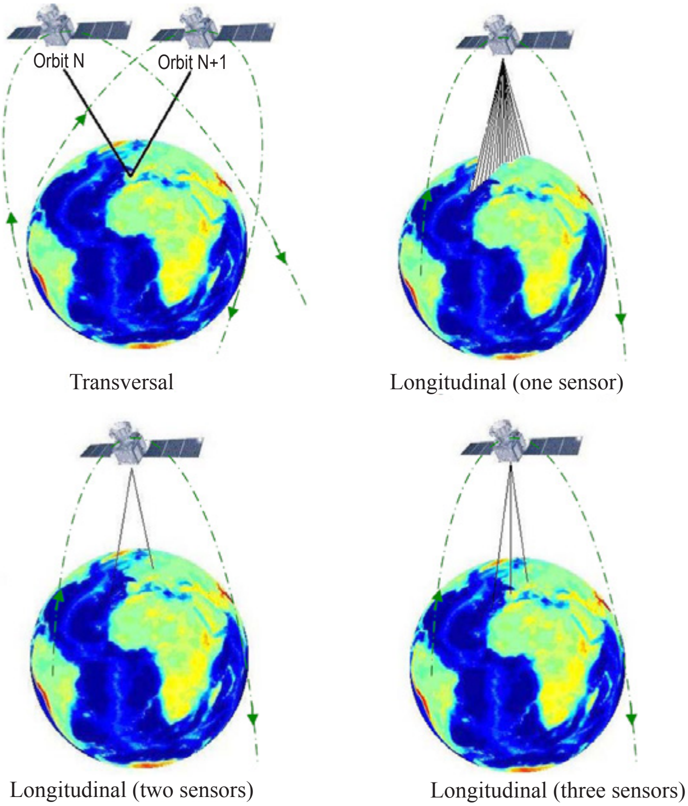

Figure 163. Satellite Stereoscopic geometry types.

The advantages or disadvantages that may occur only differ in one aspect: if all images are taken from a single sensor, there are unique calibration parameters and unique data inherent to the optical sensor. However, the disadvantage is that viewing angles may not be the expected ones, since they are obtained with a rotating motion sensor. On the other hand, the advantages and disadvantages of the stereoscopic images taken with more than one sensor are complementary to those indicated for a single sensor. Thus, the geometry of the shot is ensured, since the sensors are mounted and calibrated in position, but the disadvantage arises when the same optical systems are not acquired by two or three images, depending on whether we have double or triple stereoscopy.

Stereoscopic satellites

The first satellite capable of taking stereoscopic images was the SPOT satellite. Afterwards, a long list of them have been developed, summarized in table 8. The table shows the spatial resolution of each one and the scale of the derived final map.

Sensor	Spatial Resolution (m)	Cartographic scale
QuickBird	0.7	1: 2,400
EROS A	1.8	1: 25,000
ES Ikonos Orbview 3	1	1: 10,000
IRS P5	2.5	1: 5,000
Spot 5	5	1: 25,000
MOMS-2P	6	1: 25,000
Kompsat 1	6.6	1: 25,000
ADEOS	8	1: 50,000
Aster	1.5	1:100,000
Cbers	20	1: 50,000

Table 8. Cartographic scales of stereoscopic satellites.

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