Height Reference for Parcels and Land Objects for the 3D Cadastres Structuring

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SUMMARY

This paper describes the distinct existing systems to reference the height of objects and its possible applications in the structuring of 3D cadastre. It discusses advantages and inconveniences in the utilization of each one of them for the positioning of terrestrial objects in space.

Hypotheses based on similar studies of cases in 3D cadastre are analyzed, without the pretension of covering the totality in the same manner. The developed theory is applied to position apartments that are part of private residential buildings (3D parcels) and elements of road work (3D land objects), demonstrating the correlations between the distinct systems of heights.

It is possible to conclude from the results that the ellipsoid of revolution is the most appropriate reference surface for 3D parcels and generally all 3D land object heights. Furthermore, for certain territorial 3D objects, it may be necessary to utilize an equipotential surface to reference their heights.

Regarding the precisions required for the positioning and sizing of the plots and 3D objects, it is concluded that both must be carefully analyzed and defined in the cadastral legislation. It is not possible to set a single precision for all, parcels and land objects, since the accuracies depend of the function of the cadastral object.

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1. INTRODUCTION

The 3D cadastre must register land objects precisely in space and time, identifying and locating them geometrically as volumes, at a given time. A 3D registration allows relating land objects, or parts thereof, repositioning them in retrospect, projecting modifications and analyzes the influence of new objects, even before they exist through the construction of prospective scenarios.

The 3D cadastre, beyond the land object measures, must have the three coordinates of a sufficient number of points to spatially locate any object as a block. The number of points of georeferencing will depend on each case and will be defined by the professionals according to their criteria and experience, so that the precision parameters established by the standard of the cadastral framework and the measurement date, are guaranteed.

The planimetric positioning of territorial objects presents no difficulty once the geodetic reference system is established, however, the definition of the most suitable reference surface to determine heights, is still under discussion.

Navratil & Unger (2011) argue that to use geometric leveling in estimating ellipsoidal height differences it is necessary to know the deviation from the vertical. This statement is true but it is very general in nature since in practice it depends on the accuracy required and the extension of the area to be covered.

2. HEIGHT SYSTEMS FOR 3D CADASTRES

A **reference surface** is the element from which the heights are measured. To establish it, it is necessary to set different parameters. Planes, ellipsoids of revolution and the equipotential surfaces are the most commonly used.

A **horizontal plane** is the simplest reference surface, geometrically easier to understand for users. Its spatial position is defined as normal to the vertical by an origin point, and the heights of the other points are measured along perpendicular lines. Since in general a **vertical by a point** is considered as the direction of the earth's gravity passing through the point, perpendicular lines to the reference plane and the vertical do not necessarily coincide. In this sense, the heights are valid only for small areas as 1 km away from the origin point because further than that, altimetry error is of the order of 8 cm due to the earth's curvature.

An ellipsoid of revolution is a surface reference of a mathematical nature. Its center, orientation, semi-major axis, and flattening are chosen such that their approach to the geoid is maximized.

An **equipotential surface** or level surface is always perpendicular to the vertical, and since the vertical direction is influenced by the distribution of land masses and movement, this surface is uneven. Normally the **geoid** is taken as equipotential reference because it is the surface that best adapted to mid sea level on a global scale.
The distances of the points in space to the reference surfaces are named **heights**, even though in the geodetic language they are frequently referred to as **levels**.

Since the equipotential surfaces are not parallel, the result of a geometric leveling will depend on the path covered. Figure 1 demonstrates that the distance along the vertical between the equipotential surfaces W_A and W_B is not the same when measured in A, or is measured in B or if it follows the path through successive stations of level following a specific itinerary. Varying the itinerary may change the result. The ambiguity of the coordinates obtained leads to the denomination of **gross heights**.

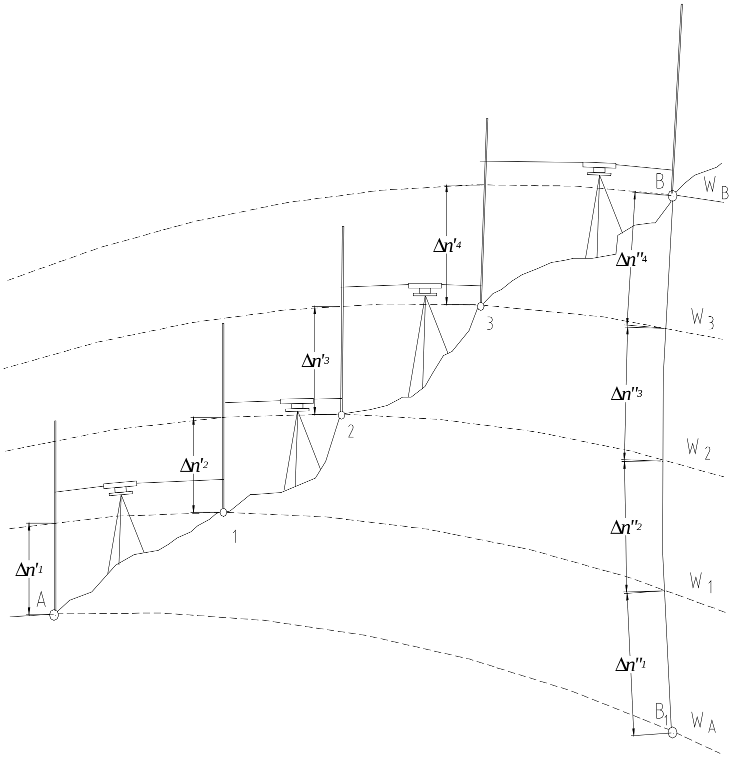
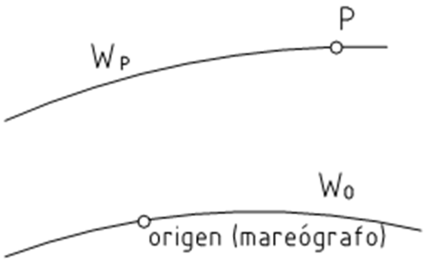


Figure 1. Distances between equipotential surfaces

Level concept may also be associated with the concept of gravitational potential, since points located at higher altitudes have a lower gravitational potential. Considering the geoid as equipotential surface of reference with potential W_0 (tide gauge origin), the **geopotential level** of point P is defined as the difference between the potential in W_0 and the potential of the level surface that pass through P (W_P).



$$C_P = W_0 - W_P$$

Geopotential levels rigorously determine the direction of water runoff between the points and the value obtained for any point, it is independent of the way utilized and so, in any case, a unique result shall be obtained.

The geopotential levels do not represent a longitude, but instead the work necessary to transfer a unit mass from the origin 0 to a point P. This latter feature means that, in practice, their use is not convenient for land surveying.

To circumvent this limitation, **dynamic levels** can be used. Huerta (2001) defines them as the ratio between the geopotential levels and a value of constant gravity. Thus, the resulting values are expressed as distances. Ordinarily the value of normal gravity is used on the ellipsoid at 0 m altitude and latitude of 45°.

$$\cot a\, din\acute{a}mica = C_P^{din} = \frac{C_P}{\gamma_0^{45}}$$

The dynamic levels have a common feature with geopotential levels: points of equal elevation belong to the same equipotential surface. Although expressed in units of distance, this feature creates a result insensitive to the convergence of the level surfaces. To determine the dynamic geopotential or dynamic levels, it is necessary to perform a geometric leveling, measuring at the same time the acceleration of gravity (g).

With a clear understanding of the concepts of dimensions, we turn to the concepts of heights, which are used for positioning of 3D objects.

The **orthometric height** (H) of a point on the Earth's surface is the distance between that point and the reference equipotential surface (geoid) measured along the vertical direction. This height is obtained from the geopotential level considering an average value of g, which would determine the distribution of mass between the point in question and its projection (according to the vertical) above the geoid. This, in fact, is impossible, but it can be supplemented satisfactorily by a calculation using known parameters.

The **normal height** is determined from the normal gravity rather than a mean value of g, that is, it comes from a calculation that considers a model established for the Earth's gravitational field. The normal height is a value that differs little from the orthometric height (generally a few centimeters), and defines a new reference surface called **quasi-geoid**. We can assert that, the separation between the geoid and quasi-geoid varies (taking extreme cases) between few centimeters and just over a meter. Obviously, for the surface of oceans the geoid and the quasi-geoid concur.

The **ellipsoidal height** (h) is the distance between a point in space and the surface of the ellipsoid, measured along the normal to the ellipsoid. The Global Navigation Satellite System - GNSS allow this height to be recognized with necessary precision, even up to a few mm.

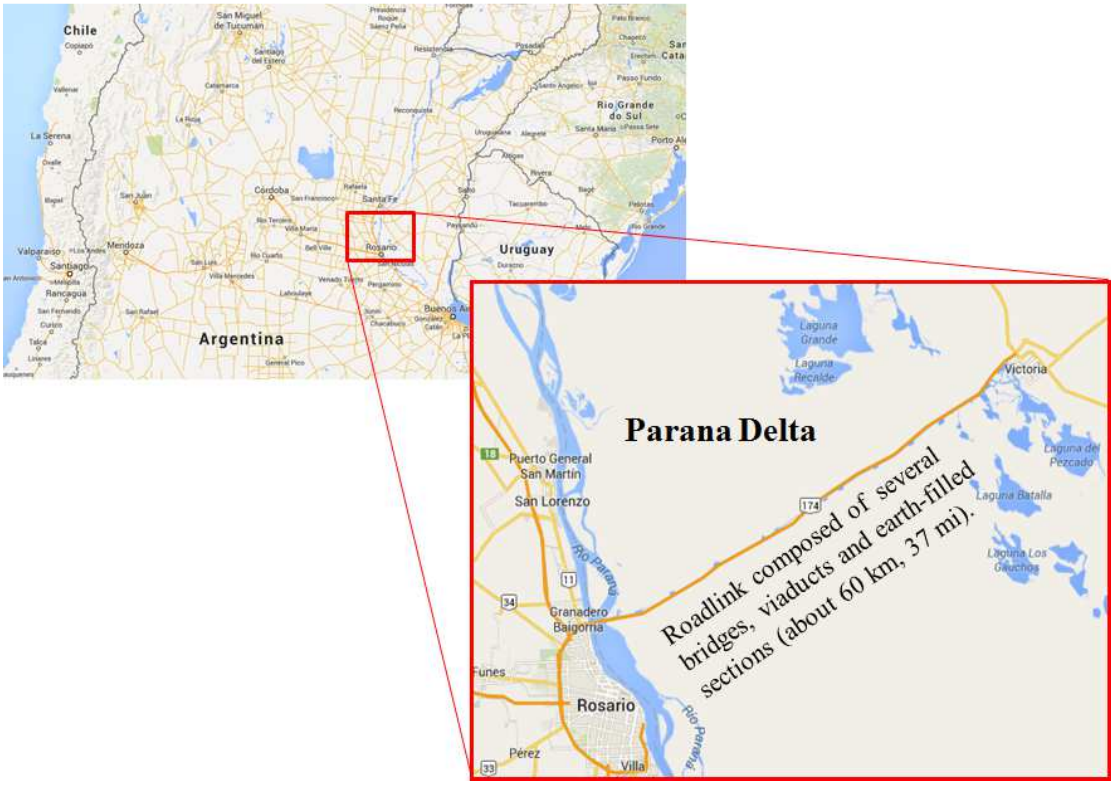
By linking h and H from the same point it is possible to relate the geoid and the ellipsoid through the **geoid undulation** (N), where N = h - H.

In fact, even when the vertical of the point and the normal to the ellipsoid are not exactly coincidental they are so close and their diversion does not affect the calculation of N.

In areas whose radius does not exceed a few dozen kilometers, it is possible to acquire local geoid models to correlate the orthometric heights with ellipsoidal heights. This strategy can be applied in the construction of a tunnel, positioning with satellite at the ends (only) and geometric leveling inside; or in a road construction work built over a water surface which prevents the geometric leveling (except at the ends). Appealing to a clever combination of geometric leveling, satellite positioning and geoid modeling, the results can be satisfactory to the spatial positioning of these two land objects.

This solution was applied during the road construction effort of linking the Argentine cities of Rosario and Victoria, crossing the Paraná River delta being 60 km (37.28 miles) wide. When the work commenced, an extraordinary flooding covered the entire area, making it almost impossible geometric leveling.

The ellipsoidal and orthometric heights on both heads were measured in their respective values of N were determined. Gravity was also measured at various points and appealing to a global geoid model, it was possible to calculate the variation of N (that is, a geoid profile) along the trace of the work. Following this strategy, it was possible to obtain orthometric heights at any point of the trace based on the satellite positioning satisfying a tolerance of 10 cm, which was verified after completion of construction.



Roadlink composed of several bridges, viaducts and earth-filled sections (about 60 km, 37 mi).

Figure 2. Location of area of study in Argentina
Source: Google maps

2.1 Models of geoid and permanent stations GNSS

To relate ellipsoidal and orthometric heights it is possible to use transformation models called "geoid models", from which it is possible to obtain N. These models can be obtained from the information of geodetic points located in the area with both heights (h, H). An example of this type is the Model of Geoid of city Rosario developed in 2006 - MGR06 presented in Figure 3.

The relationship between ellipsoidal and orthometric heights can also be determined from global models such as EGM2008 (*Earth Gravitational Model*) or EIGEN (*European Improved Gravity model of the Earth by New techniques*). They have global coverage, generally constructed from data obtained from satellite observations, and often have the definition of "origin" as a limitation. If one (or more) points are available with information of h and H in the area, it is possible to adjust the overall model from N to a permanent station. It can be a useful result for a broad area of study.

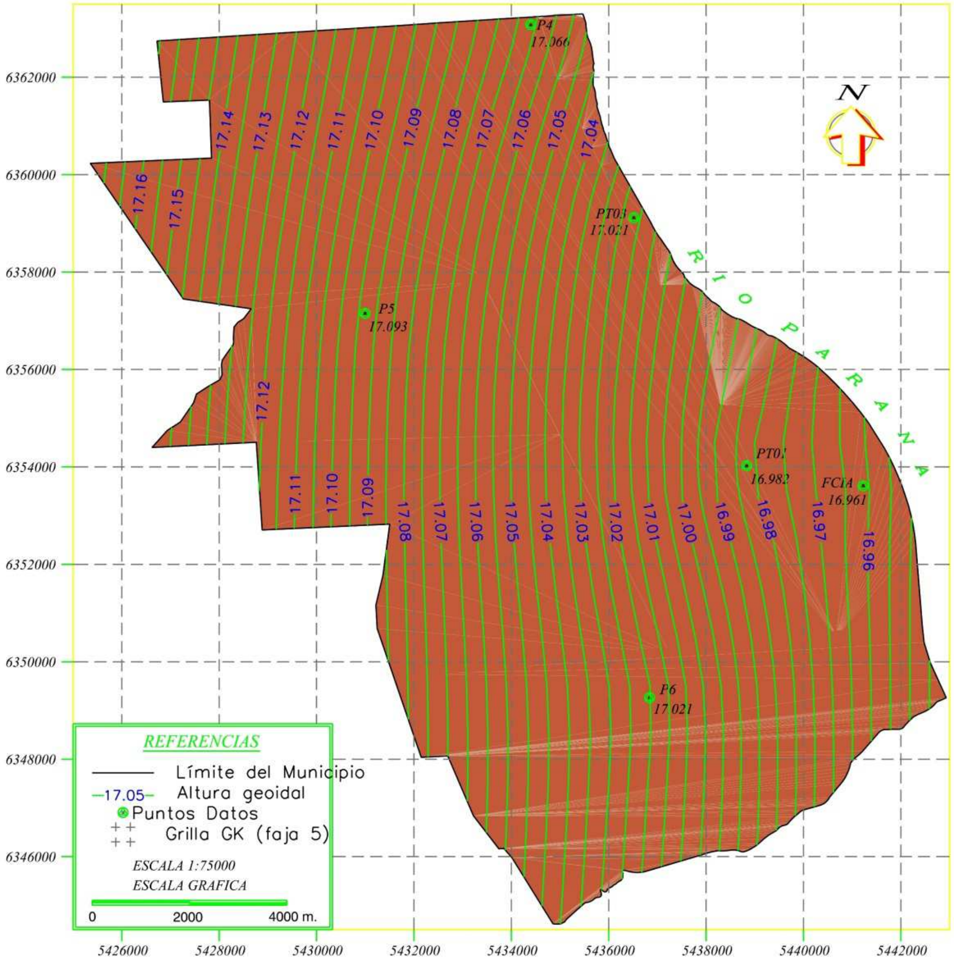


Figure 3. Model of geoid of city Rosario, Argentina, MGR06
Source: Balbarani et al (2006)

In the city of Rosario and surrounding areas, EGM2008 was calibrated with the N from the permanent station called UNRO, the result of this work is represented in Figure 4.

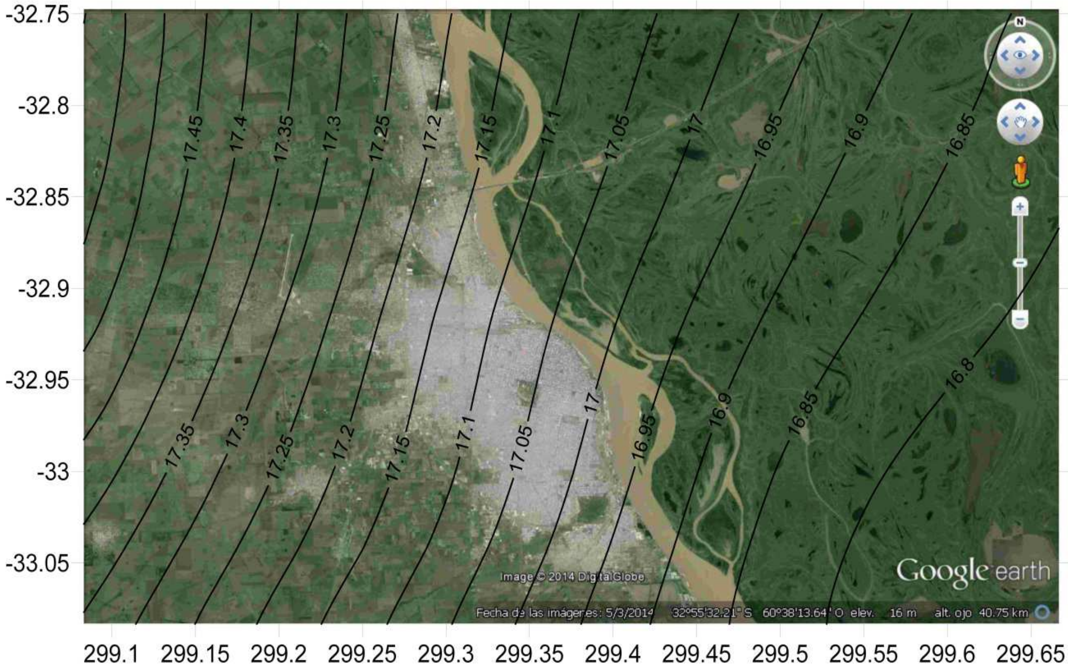


Figure 4. EGM2008 calibrated with the permanent station UNRO

A permanent station consists of a GNSS receiver tracking all visible satellites, continuously for 24 hours/7 days a week, along with a storage and publication of data (usually via the Internet, in real or deferred time).

All the permanent stations form a network; in the case of Argentina it is called RAMSAC (acronym in Spanish *Red Argentina de Monitoreo Satelital Continuo:* http://www.ign.gob.ar/NuestrasActividades/Geodesia/Ramsac (Continuous Satellite Monitoring Argentine Network). Currently RAMSCA is composed of more than 70 stations and it is administered by the National Geographic Institute (IGN).

To make a permanent station useful for georeferencing activities, geodetic coordinates of the station (latitude, longitude and ellipsoidal height h) must be determined and published, to be available for the users. If all permanent stations would have h and H, it would be possible to develop a quite simply a geoid model of regional scope or use the value of N at the station to calibrate a global model for the station's zone. Having H at the same point of the station would be highly relevant to the positioning of 3D land objects and 3D parcels.
Nowadays, very few stations have this double height (H and h). A special recommendation is made to the Geographic Institutes of Latin America to try to determine and publish the H of the permanent stations, as well as g.

3. CASE STUDIES

Following are presented three cases relating to the application of the theory developed. Two correspond with the Argentine city of Rosario and the other one to the city of Quito in Ecuador.

3.1 Complex of buildings “Ciudad Ribera”, Rosario, Argentina

According to the legislation enforced in Argentina, the public domain in navigable courses extends to the shoreline called **towpath**, which is a restriction to private ownership established in Art. 2639 of the Civil Code, and is defined as a 35 meter strip measured from the shore of navigable waterways toward the interior of adjoining properties.

The level is officially established for the city of Rosario at 4.16 meters (13.65 ft). What is unique is that this height is referred from the port of Rosario’s hydrometer (0.0m); which establishes strictly a local surface reference. Figure 5 is an adaptation of the cut represented in the survey map of 2009 which represents the area where building "Ciudad Ribera" was built, close to the banks of the Parana River. In the analysis it is can see that the height is precisely the determinant of the boundary between the private domain and the public domain.

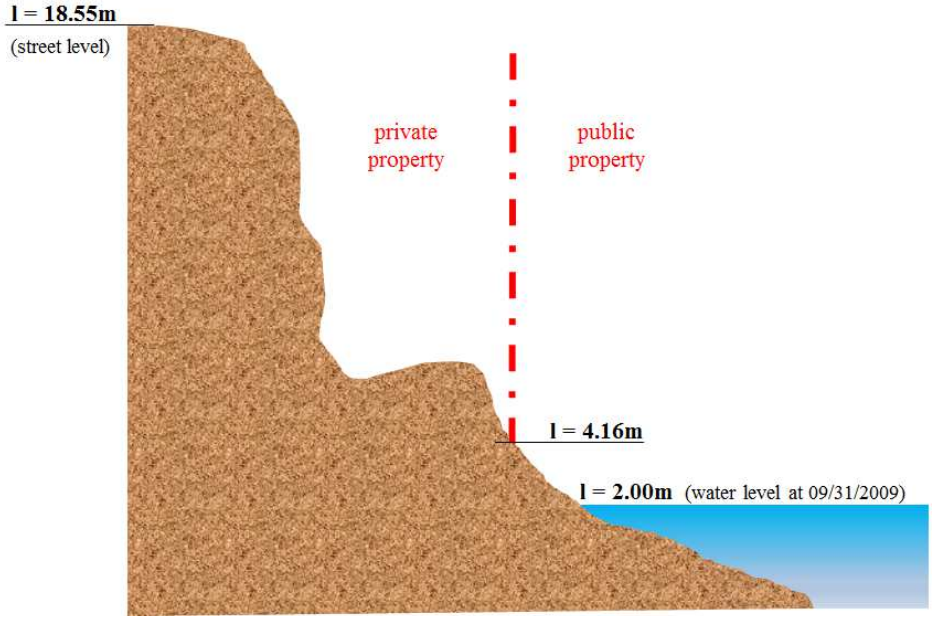


Figure 5. Profile across the site of the building "Ciudad Ribera". Location of public-private boundary and local heights.

In this case, three different reference surfaces come together at the same spatial location: the line that represents the intersection natural terrain with the vertical surface that divides the private domain of the public (Table 1).

Table 1

Local system	4,16m (13.65 ft)
National system (elevation above sea level)	7,75m (25.43 ft)
Global system (ellipsoidal elevation according to local geoid)	24,71 m (81.07 ft)

Taking these references, the natural terrain around the building complex "Ciudad Ribera" has the local, ellipsoidal and orthometric heights described in Table 2.

Table 2

Local system	18,55m (60.86 ft)
National system (elevation above sea level)	22,14m (69.36 ft)
Global system (ellipsoidal elevation according to local geoid)	39,10m (128.28 ft)

3.2 Building "Embarcadero", Rosario, Argentina.

This building was surveyed under Horizontal Property regime (National Law No. 13512). The case was chosen because it evidences a unique situation in legal terms: the basement is for garages (private domain), but part of the ground floor, which has no construction, is subject to an easement for public use regulated by the Municipality of Rosario.

As Figure 6 shows, the Land Surveyor established a local plane as a reference, attributing 0.00 m at the ground level, which is the reference for every single parcel (public or private). Applying the theory developed above, there were determined the relationships between local, orthometric and ellipsoidal (Table 3).

Table 3

Local system	0,00m (00.00 ft)
National system (elevation above sea level)	23,07m (75.45ft)
Global system (ellipsoidal elevation according to local geoid)	40,03 m (131.23ft)

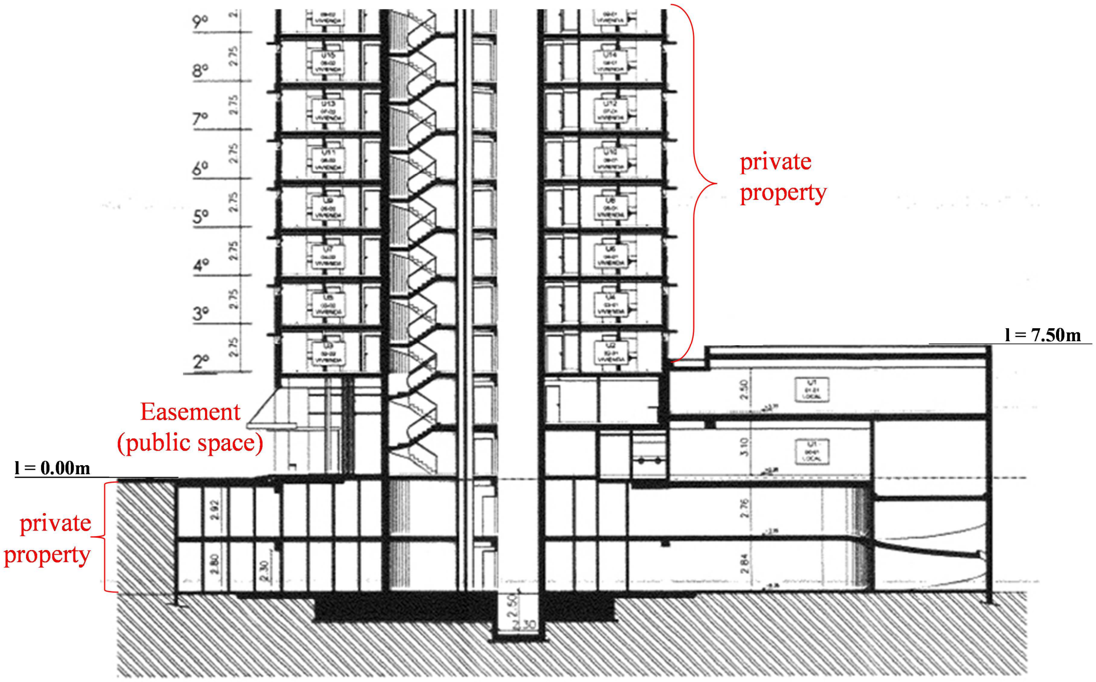


Figure 6. Longitudinal section of the building "Embarcadero"

The height of the base of the building "Embarcadero" was obtained by geometric leveling, starting from the fixed point V1. This point is located about 200 m from the building and it is part of the North Coast Survey Rosario. The height above sea level of point V1 is 23, 51 meters (source: Municipality of Rosario). The ellipsoidal height was obtained using the value of N = 16,96 meters provided by the geoid model MGR06 Rosario.

3.3 Building “Sr. Washington Calahorrano”, Quito, Ecuador

In this case, the strategy to determine the heights of the 3D plots was different. Instead of making field measurements, we chose to take advantage of an existing altimetry map registered at the territorial cadastre office and extrapolate data.

The surveyor, in the same way as in the case of buildings in Rosario, also established a local level as a reference, attributing 0,00 meters in height on the ground floor (Figure 7). Knowing that the geoid undulation in the area 27,50 meters, relations between the local ellipsoidal and orthometric heights were determined (Table 4).

Table 4

Local system	0,00 m (00.00 ft)
National system (elevation above sea level)	2,767.20m (9078 ft)
Global system (ellipsoidal elevation according to local geoid)	2,794.70m (9167 ft)

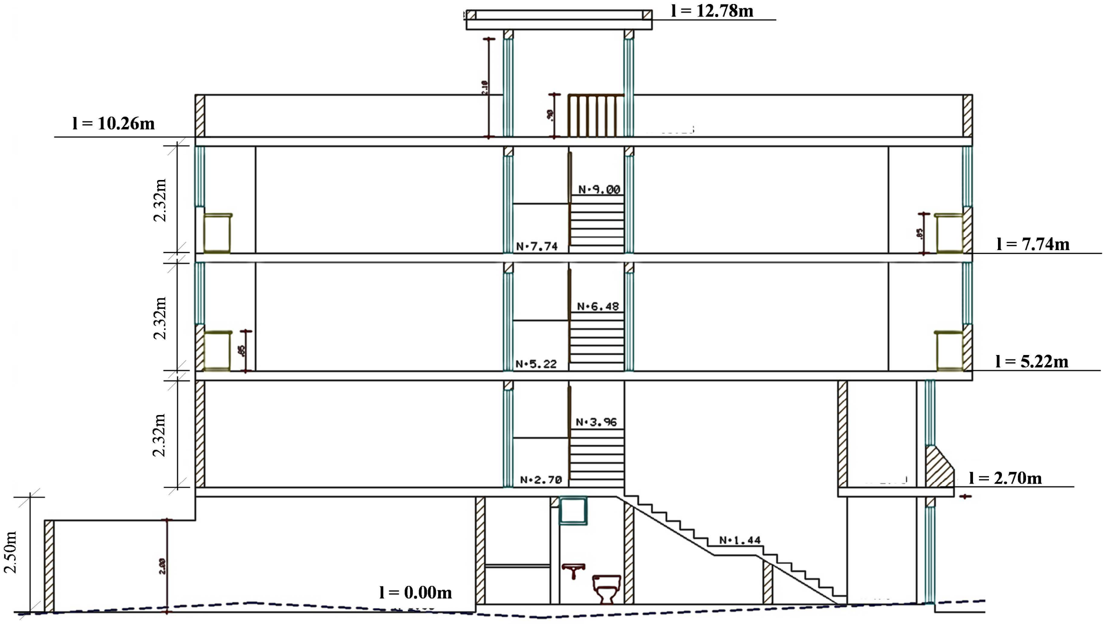


Figure 7 – Longitudinal section of the building “Sr. Washington Calahorrano”

4. CONCLUSIONS AND RECOMMENDATIONS

A 3D cadastre is a register that contains the spatial position of objects and land plots in the space, defined with adequate precision and at a particular time. In terms of positioning, the main problem of a 3D cadastre is the establishment of a vertical reference for the definition of heights.

A plane would be efficient as a vertical reference surface to structure a 3D cadastre of areas whose extensions do not exceed 1 km, but this surface is not global and has limited application. A plane cannot be used efficiently in the majority of Latin American jurisdictions.

An ellipsoid is more appropriate for most cases because the height can be obtained with adequate accuracy at a given time. In this case, the tectonic movements are not a problem since, as its effects are known, it is perfectly possible to correlate the coordinates of an object in space, in two different periods.
Ellipsoidal height definitely solves the essential need to register 3D plots, but it is not enough to meet other needs. In cases where it is necessary to know the displacement of the water the orthometric height must be used, together with the ellipsoidal height, to position the land objects.

It can be concluded that it is not possible to set a single precision for the references of heights, but this varies with the character of cadastral objects. Also, worth a clarification: in this work we are only referring to the spatial positioning tolerances, considering the cadastral object as a block, excluding from the analysis accuracies required in internal measures of territorial object.

Each institution responsible for a 3D cadastre shall provide the tolerances that must be observed. We believe that urban land spatial tolerance for 3D parcels georeferencing can be in the order of 10 cm. A similar tolerance correspond to underground public utility passages, such as sewer, gas, water, or electrical networks. For rural properties, accuracy may be of the order of 50 cm in planimetry but should be greater on altimetry, about 20 cm.

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