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Requirements of 3D cadastres for height systems

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ABSTRACT

Three-dimensional (3D) cadastral systems can only be built if there are suitable height reference systems. However, the earth is neither homogeneous nor flat, and the plumb lines are curved and not parallel. Thus, the definition of height and the implementation of geodetic height systems are complex. 3D cadastres must connect to the existing national height reference. In addition, cadastral systems are designed to persist for centuries. Over such long periods, the earth changes, from plate tectonics, erosion, human intervention, etc. Changes in the technology of measurement equipment can also occur, allowing different definitions. These considerations are important in the design of a 3D cadastre. At minimum, the height system used for the cadastre must be well-defined, to enable adjustments from potential changes in the height system or even the actual point heights.

This study examines existing height systems and the determination of height in the context of cadastral tasks. Accuracy requirements for height in a 3D cadastre are analyzed using typical examples. The selected height system must support these requirements. This study also develops the questions that must be answered and highlights the problems that can emerge in some of the solutions. There is no height reference system that fits all needs, and each solution has advantages and disadvantages. Different systems may be optimal for different countries. It may also be beneficial to allow different geometrical qualities for different parts of a country.

1. Introduction

In discussions regarding three-dimensional (3D) systems, computer scientists and technicians typically assume the existence of suitable height reference systems. van Oosterom et al., for example, talk about 3D objects without a clear identification of the three spatial components (van Oosterom et al., 2005). This approach works for modeling purposes but may lead to problems during implementation. Other assumptions usually not questioned in the literature on 3D cadastres are the following: height is represented by a single number, the direction of the vertical axis is independent of location, the vertical axis can be represented by a straight line, and the method used to determine height is irrelevant. The validity of these assumptions is crucial because a 3D cadastre is used to provide sound legal protection. This cannot be guaranteed, for example, if the results of the height observation depend on the method used. Because the earth is neither homogeneous nor flat, the plumb lines, which are assumed to be representations of the vertical axis, are neither straight nor parallel. This situation causes problems in the definition of height and the implementation of geodetic height systems. Different observation methods refer to different height definitions, producing varying height values with varying accuracy. Thus, none of the typical assumptions are completely valid. While some assumptions may be satisfactory for local applications with limited accuracy demands, they have a much larger effect on applications where height must be determined for large areas, e.g., entire countries.

3D cadastres encounter the problems of other 3D systems, but additionally, cadastral systems are designed to persist for centuries. Over such long periods, the earth changes considerably, and this fact must be incorporated into the system design. Classical two-dimensional (2D) cadastres did not face this problem because of the following reasons:

1. 2D cadastres use an analog representation at scales where the effects of drawing precision and line width exceed the change in reality.
2. 2D cadastres define the boundary line itself in reality and use the cadastral representation as an approximation only.

However, there are also 2D cadastres with fixed coordinates. These types of cadastres also have to address earth's changes.

Neunzert defined the cadastral principles for changing boundaries for the system in Colorado, USA (Neunzert, 2011, p. 5), as follows:

- If nature moves a monument, the property moves with it.
- If a human moves a monument, it is an illegal act.

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However, there may not always be monuments determining the boundary. In these cases, the represented boundary in the parcel documentation, knowledge of the land owners, and other evidence from reality must be adapted to reconstruct the boundaries. The importance of the different information sources may vary with the jurisdiction.

Today, analog representations are not applicable because a modern cadastre utilizes the benefits of computer systems including databases and their data models (Kaufmann & Steudler, 1998). Depending on the level of detail used for the 3D representation, the second approach may not be valid either. Stoter and van Oosterom present examples where the level of detail in the cadastral representation is so high that it cannot be seen as only an approximation (Stoter & van Oosterom, 2006, pp. 56–59). Stoter and van Oosterom also addressed the question of height (Stoter & van Oosterom, 2006, pp. 192–195), but they approached the problem mainly from the modeling perspective. However, geodesists have defined various systems for height definition: geopotential heights, dynamic heights, orthometric heights, normal heights, and ellipsoidal heights (Hofmann-Wellenhof & Moritz, 2005, pp. 157 ff.). Each of them has advantages and disadvantages. In this study, the various aspects of the height problem are investigated from both a geodetic and a cadastral perspective to provide a solid basis for further research. The questions posed are the following:

1. What is state of the art in the definition of height?
2. What are the benefits and disadvantages of the various height systems for 3D cadastres?
3. What other questions must be answered both on an international and a national level?

This paper starts with a discussion of existing height systems, their characteristics, and how the most commonly used height determination systems work. These differences must be considered when selecting a height system for a 3D cadastre. Section 3 then shows the typical methods to obtain heights. Section 4 introduces the difference between absolute and relative heights. Accuracy requirements for height in a 3D cadastre are defined in Section 5 using prototypical examples. For example, a tunnel below the Alps requires less precision than the vertical separation between two apartments in a building. Section 6 connects the discussion to the data model in the ISO (International Organization of Standardization) standards, esp. ISO 19107, Geographic Information – Spatial Schema. Section 7 presents the conclusions and some questions for further research.

2. Definition of height

Height is usually defined as the "*vertical distance from a datum* (Wolf & Brinker, 1989, p. 109)." This leads to several questions:

– What measurement unit shall be used to determine the distance?
– Is distance a geometrical property?
– Which datum shall be used as the measurement start point?
– How is vertical defined?

These questions, which at first seem trivial, can offer some challenges. Meters and gal (0.01 m/s^2) are used as measurement units to determine height; the geoid, the pseudo-geoid, or the ellipsoid can be used as a datum; and the vertical line may be assumed to be straight or bent. These differences result from different approaches in the definition of height, which are discussed in the remainder of the paper.

There are several practical requirements for height systems:

1. Height (or height differences) must be easy to determine. In everyday experience, height seems to be similar to dimensions such as width or diameter. Basically, it should be as simple as possible to determine the height.
2. Heights must be well-defined and path-independent, i.e., the height difference of a closed loop should be zero. Any other value would contradict our logical systems because it would be possible to increase the height of a point by repeatedly computing it.
3. Correctional terms for observations must be small enough to be ignored for small surveys. Correctional terms are typically difficult to compute and require additional information. Both aspects lead to additional computational costs and make the process of height determination more complicated.
4. Heights must be free of hypothesis. Any hypothesis could be falsified by additional observation or experiments. This effect could subsequently lead to contradictions between previously determined heights and new measurements.
5. Heights must be physically meaningful. For example, the idea that water flows naturally from a point with a specific height to another point with the same height contradicts common sense, so it should be avoided, at least locally.
6. Heights must be geometrically determined. Unlike other properties, geometrical properties are easy to determine, and such observations are also inexpensive.

Rod leveling is a simple method to determine height differences. It uses a plumb line to determine the vertical direction but contradicts the second requirement that closed loops should have no height difference, as shown in Fig. 1. All points on any equipotential surface have the same potential energy, but the equipotential surfaces are not parallel. The plumb lines between points A and A′ and points B and B′ are perpendicular to the equipotential surfaces, and because the surfaces are non-parallel, these plumb lines are curved. The lowest equipotential surface shown in Fig. 1 is at sea level and is the geoid (defined as the average sea level). The thick line connecting points A and B represents the surface of the earth. Assume that the height difference between points A and B is determined as a length along the plumb line. The length between points A and A′ is different from the one between points B and B′. Rod leveling would determine the height difference in small steps along the surface, resulting in a value between these extremes. This could not happen if the second requirement holds.

A number of different height systems have been proposed that fulfill the above requirements. The most commonly used systems are the following (Hofmann-Wellenhof & Moritz, 2005, pp. 159 ff):

– geopotential height,
– dynamic height,
– orthometric height,
– normal height, and
– ellipsoidal height.

2.1. Geopotential height

The geopotential height or geopotential number, *C*, of a point is the potential difference of the point's potential energy and the geoid's potential energy. Because it is a potential difference, the geopotential number, *C*, is path-independent. The geopotential number is typically measured either in J/kg (Joule per Kilogram), in m^2/s^2, or in gal m. gal is a measure for acceleration, and its definition is cm/s^2. Although the potential difference does not describe a distance, it is a natural criterion for heights because on a surface with constant potential energy, objects do not start to move if no force is applied and, in particular, water does not flow.