Georeferencing Point Clouds – Meeting the Expectations of the User

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SUMMARY

Point clouds are commonly used both for model creation and as a basis for design, and the users of point clouds and their derived products include groups with limited knowledge about geodata, reference systems, and data quality. There are several combinations of platforms and sensors that are used to produce point clouds, and there are also several methods that can be used for georeferencing point clouds. The choice of georeferencing method will impact the geometry of the final point cloud and all its derived products. Georeferencing a point cloud requires decisions regarding the plumb line direction and the horizontal scale, but there are no standardized ways of expressing these decisions as metadata. Some users of point clouds or their derived products will likely have a preference of whether the point cloud should follow the curvature of the Earth or a flat reference surface, and whether horizontal distances should be as measured or reduced to a map projection. Other users might not consider these factors at all but will still hold assumptions regarding the geometry of the data. A more widespread use of point clouds and higher degrees of automation makes it necessary to be able to describe and manage these differences unambiguously. This paper gives an overview of common georeferencing methods used for terrestrial laser scanning and what type of point cloud they result in. Numerical estimates for the magnitude of the differences between the different types of point clouds are also presented. From the overview of methods and the numerical estimates, it is shown that the most significant geometrical differences can be handled by introducing two metadata parameters describing the shape and the horizontal scale of the point cloud. Future research should expand upon this and include mobile laser scanning as well as photogrammetry, and the consequence analysis should use error propagation theory to show how the georeferencing methods affect data quality over time.

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1. INTRODUCTION

The point cloud is today a very common datatype within the geographic domain. They can be produced by either laser scanning or photogrammetry and they can be captured from either stationary (terrestrial) or mobile platforms. Point clouds can be used either in isolation or in combination with other geodata, and for the latter to be possible, it is necessary to georeference the point cloud. Metadata describing the coordinate reference system (CRS) used for a point cloud are typically limited to a map projection and a vertical datum, or possibly a reference ellipsoid if Earth-centered, Earth-fixed (ECEF) coordinates are used. There are several different georeferencing methods used in practice today, ranging from strict to approximate and with non-negligible differences between them. These differences are not sufficiently described using only a CRS as metadata. Point clouds can be used for many different purposes and the desired characteristics of the point cloud will depend on its intended use. For example, if one wants to use a point cloud to conduct measurements inside a building, the relative accuracy within the point cloud is of much greater importance than the absolute geographic coordinates of the point cloud. On the contrary, if a point cloud is used to create a terrain model that will be used as a basis for designing a road, it is much more important that the point cloud follows the varying scale in the chosen map projection so that it can be seamlessly combined with geodata from other sources. Because the preferred characteristics of a point cloud depends on circumstances, it is not possible to say that a method is correct or incorrect.

Since the users of point clouds and their derived products have vastly different backgrounds and areas of expertise, it cannot be assumed that they all are familiar with the different methods of georeferencing or their consequences. Instead, we must find ways to describe these the different types of point clouds using metadata so that software developers can manage and transform them in order to the meet the needs of their users. How large the discrepancies between the different methods are depends on several factors and will therefore vary on a case-to-case basis. Nonetheless, the differences are systematic, and errors can therefore be avoided given a proper framework. Since point clouds are used as a basis for design, the errors stemming from these differences might propagate and grow larger over time through continued use.

1.1 Aim and contribution

In this article, we describe georeferencing methods that are commonly used for terrestrial laser scanning (TLS), what type of point clouds they lead to, and we propose metadata parameters that can be used to describe these different types. We also present numerical estimates of the errors introduced by incorrectly handling these differences. The point clouds are described by their horizontal scale and their plumb line direction. The horizontal distances can be either as measured or reduced to a map projection, and the plumb line direction can be either parallel for all locations in the point cloud or varying according to the curvature of the Earth.

The aim of this article is to raise awareness of the issue at hand, and the contributions are the overview of common TLS georeferencing methods, the description of their consequences, and the development of metadata and vocabulary to describe the differences between point clouds.

1.2 Background

To georeference a point cloud is to transform the coordinates of the points from the local frame in which they were captured to a CRS. This gives the point cloud a position relative to the physical Earth and it makes it possible to use it in combination with other geodata. The georeferencing process for TLS point clouds can be performed in different ways, but most of them can be described as direct or indirect (Scaioni, 2005; Alba and Scaioni, 2007; Otepka et al., 2013; Fan et al., 2014), or as sensor-driven or data-driven (Schuhmacher and Böhm, 2005; Osada et al., 2017). In direct (sensor-driven) georeferencing methods, the position and orientation of the laser scanning instrument are determined, and this information is then used to "directly" acquire a georeferenced point cloud. Indirect (data-driven) methods use ground control points (GCPs) with known coordinates. These can either be in the form of specialized targets or highly distinguishable features. Since the coordinates of the GCPs are known in both the local point cloud coordinate system and in the CRS, it is possible to derive transformation parameters between the two.

The accuracy of georeferencing is typically determined by the residuals between the coordinates of known points and their corresponding coordinates in the georeferenced point cloud. Any points used for determining the final accuracy should not be used when determining the transformation parameters. Most studies on the topic are concerned with one of two questions: i) making georeferencing more accurate or ii) reducing the amount of work that goes into georeferencing. The second topic includes both making georeferencing less cumbersome, as placing and surveying targets can be time consuming, and simply making georeferencing possible, as there are many locations where GCPs cannot be placed. The general conclusions are that indirect or data-driven georeferencing using GCPs is more accurate, while direct or sensor-driven georeferencing requires less manual work and is more accessible in challenging locations (Schuhmacher and Böhm, 2005; Alba and Scaioni, 2007).

One topic that is not covered in the literature is the question of how different georeferencing methods affect the geometry of the resulting point cloud. There are many different ways to georeference point clouds, and most of them, depending on the intended use of the point cloud, can be considered as "correct". Some methods are strict in a geodetic sense while other methods use approximations. The differences between methods are systematic and not affected by measurement errors, and they are therefore best reasoned about in a theoretical sense.

2. COORDINATE SYSTEMS

The coordinates captured by a laser scanner relate to a local coordinate system l, which is defined by the axes of the non-rotating part of the laser scanner – see Figure 1. The position and orientation of the l system with respect to the Earth depends on the instrument set up, which is generally arbitrary, but it might be aligned with the local geodetic horizon if the instrument is levelled. The Cartesian coordinates (x_i^l, y_i^l, z_i^l) of a scanned point i are computed using measured polar coordinates, i.e. slope distance r and angles H and V determined by the position of the line of sight with respect to the $x^l y^l$ and $x^l z^l$plane, respectively:

$$\begin{bmatrix} x_i^l \\ y_i^l \\ z_i^l \end{bmatrix} = \begin{bmatrix} r_i \cos H_i \ \cos V_i \\ r_i \sin H_i \ \cos V_i \\ r_i \sin V_i \end{bmatrix} \tag{1}$$

If the instrument is levelled, then H and V are called horizontal and vertical angles.

Figure 1. Local coordinate system

The local coordinate system can be considered as Euclidean with the following properties:

- The coordinate axes are mutually perpendicular
- The scale is constant and equal along each axis
- The shortest path between two non-identical points is a straight line
- The sum of angles in a triangle is π radians

The geometry of a measured object is not distorted in a Euclidean system. The coordinates in a CRS are usually expressed as Cartesian coordinates (X, Y, Z), also referred to as ECEF, or as cartographic or projected coordinates (N, E, H), which stand for Northing, Easting and Height above geoid. ECEF coordinates can be considered as Euclidean with the above listed properties while projected coordinates cannot.

3. GEOREFERENCING METHODS

Georeferencing is a transformation from a local coordinate system to a CRS. The georeferenced coordinates are expressed either as ECEF or as projected coordinates. This transformation can be performed in various ways, either mathematically strictly or by using approximations.

The transformation is performed by the Helmert transformation given by:

$$p^b = T^b + SR_a^b p^a \tag{2}$$

where:

- p^a and p^b are vectors containing coordinates in systems a in b, resepctively
- T^b is the translation vector from a to b, i.e. the coordinates of the origin of system a expressed in system b
- S is a diagonal matrix containing the scale factors for the respective axes
- R_a^b is an orthogonal 3×3 matrix that rotates system a so that it becomes parallel with system b. The rotation matrix has three degrees of freedom, which means that each element is a function of the three rotation angles around each coordinate axis.

Generally, nine transformation parameters are required in order to transform the coordinates of a point: three translations, three rotations and three scale factors. In practice, three different scale factors are rarely used. Instead, either one scale factor is used for all three axes or one scale factor is used for the horizontal axes and one for the vertical axis. It is undesirable to rescale vertical coordinates in a point cloud, even though this likely occurs rather frequently in practice. A scale factor applied to all three axes should only be equal to 1, which implies a rigid body transformation without any scaling. If a scale factor is used to scale the horizontal coordinates to fit a map projection, the scale factor for the vertical axis should be equal to 1.

Let us assume that we scanned a larger geographic area using a terrestrial laser scanner. The instrument was set up at several locations and it was levelled. There are the following possibilities of georeferencing the point clouds from the individual instrument set ups.

3.1 Strict methods

1. Strict local to (X, Y, Z) – Figure 2a

This transformation can be performed in one or two steps, depending on how many control points are available. In the first step, all individual point clouds are registered, i.e. transformed to the coordinate system defined by a chosen instrument set up. The registered point cloud is then transformed to the (X, Y, Z) system, denoted by e:

$$p^e = T^e + SR_l^e p^l \tag{3}$$

Assuming a correctly calibrated instrument, the scale factors are equal to 1, which means that S is an identity matrix. The first step (registration) is performed using the same form of Helmert transformation as used for the georeferencing. The local coordinate systems are treated as non-levelled; therefore, six transformation parameters are required. The transformation parameters for georeferencing are determined by scanning at least three non-collinear control points with known (X, Y, Z) coordinates.

This georeferencing approach does not introduce any distortions, so the point cloud is 1:1 representation of the scanned scene. The scale is constant along all axes and the vertical lines (e.g. vertical edges of buildings) are not parallel but will instead follow the curvature of the Earth.

2. Strict local to (N, E, H) – Figure 2b

This method is a continuation of the strict local to (X, Y, Z) method. After transforming the local coordinates to (X, Y, Z), the (X, Y, Z) coordinates are projected to a chosen cartographic projection and to a chosen vertical reference system. The projected coordinates are given in form of horizontal coordinates Northing and Easting (N, E) defined in the cartographic plane. As the cartographic plane is a projection of ellipsoidal surface onto a plane, which cannot be done without distortions, the (N, E) coordinate system is not Euclidean. Since the scale is not constant, the shortest path between two points is generally a curve and the sum of angles in a triangle is not necessarily π radians. All plumb lines become parallel.

3. Strict direct georeferencing – Figure 2a

Direct georeferencing means that the transformation parameters between the instrument coordinate system and CRS are determined by measuring the instrument's position and orientation using other sensors. The position can be determined by either centering the instrument over a control point or by using GNSS or total station. The orientation can be achieved by levelling the instrument (using inclination sensors) and by scanning at least one control point. By levelling, the instrument's z^l axis is aligned with the local plumb line, and by scanning a control point, the azimuth of the x^l and y^l axes can be determined. To obtain a correct orientation of the instrument with respect to the CRS, the deflection of vertical must be taken into account. The deflection of vertical is the angle between the vertical (= normal to the ellipsoid used by the CRS) and the plumb line. This method is described in detail in Osada et al. (2017).

3.2 Approximate methods

In practice, it is common to use approximate georeferencing methods that are based on the following assumptions:

i. The plumb lines in the scanned area are assumed to be vertical lines parallel to each other. If all instruments are levelled and if we assume that the vertical axes of all instrument set-ups are parallel, then only four transformation parameters (three translations and one rotation around the vertical axis) are necessary for the registration. This type of registration is from now on referred to as registration *with plumb line constraint*. This assumption is feasible when scanning smaller geographic areas. The practical advantage of this approximation is that fewer tie points and smaller overlaps between neighboring scans are required for the registration.

ii. The cartographic system is considered to be a Euclidean coordinate system. The advantage of this assumption is that it is not necessary to convert the cartographic coordinates into ECEF.

1. Approximate local to (N, E, H), one step – Figure 2d

In this approach each instrument set up is georeferenced individually, and no registration between neighboring scans is performed. The transformation parameters are determined by scanning control points with known (N, E, H) coordinates. One scale factor for horizontal coordinates (N, E) is estimated and the scale factor for H is equal to 1. If the instrument is levelled, at least two control points are required and at least one of them with known H. In this case, five transformation parameters are estimated: three translations, one scale factor and one rotation around the Z axis. If the instrument is not levelled, then all three rotations must be estimated, which means that there are seven transformation parameters. As illustrated in Figure 2d, the georeferenced point cloud has different horizontal scale for each set up and the directions of the plumb lines are varying within each individual scan but close to constant over the entire point cloud. This type of variation is from now on referred to as semi-constant vertical direction.

2. Approximate local to (N, E, H), two steps – Figure 2c

In this approach, the individual set ups are first registered with plumb line constraint. The scale factor is equal to 1 and only one rotation is considered when registering neighboring set ups. In the second step, the registered cloud is georeferenced using five parameters transformation (one scale for horizontal coordinates, one rotation and three translations). The georeferenced point cloud has a semi-constant horizontal scale, which approximates either the scale of the cartographic projection or the terrain for the given geographic location. The scale is constant across the entire point cloud for any given height but varies slightly between different heights. The vertical direction is varying in the same way as in the previous approach.

3. Approximate direct georeferencing – Figure 2a

This method is similar to the strict direct georeferencing, but the deflection of vertical is neglected. The shape of the georeferenced point cloud is similar to Figure 2a, but the neglected deflection of vertical will cause positional errors in the point cloud (mainly in height). The errors will depend on the distance from the scanner and elevation angle and can reach several centimeters for distances over 100 m (Osada et al., 2017).

4. CONSEQUENCES AND CATEGORIZATION

This section describes and analyzes the point clouds resulting from the different georeferencing methods presented in Section 3. The first subsection describes and visualizes the resulting point clouds, and the second subsection provides numerical estimates for the magnitude of the differences between the point clouds.

4.1 Visualization of point cloud geometries

The different types of point cloud geometries are shown in Figure 2.

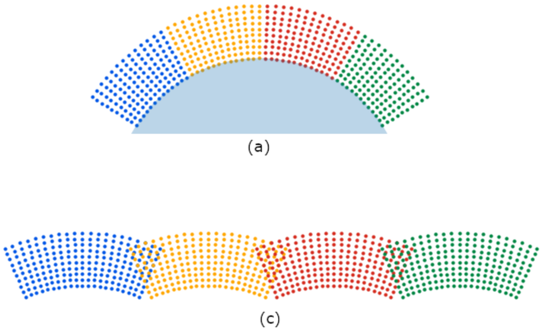

Figure 2. Different types of point cloud geometries. (a) shows how the individual scans were captured in relation to the Earth and (b), (c), and (d) are the results of different georeferencing methods. The differences in scale and the curvature of the Earth are greatly exaggerated.

The scenario shown in Figure 2 is a scene consisting of four separately scanned point clouds. Subplot (a) shows the point clouds as they were captured and what they would look like if they were georeferenced strictly to (X, Y, Z) coordinates. In this case, all geometries are undistorted, and the plumb line directions will vary throughout the scene. Subplot (b) shows the result of a strict transformation from local coordinates to (N, E, H). In this type of point cloud, the horizontal scale is varying, and the plumb line direction is constant. As a result, geometries are distorted but it is possible to seamlessly combine the point cloud with geodata from other sources expressed in the given map projection. In subplot (c), the horizontal scale and the up direction are both semi-constant. The scale is constant within each scan and constant between scans for a given height. However, the scale over the entire point cloud will vary for different heights. This effect is visible when comparing subplots (a) and (c) in Figure 2. Points in the top rows are closer together in (c) than in (a), while points in the bottom rows are farther apart. The plumb line direction within each individual scan will vary according to the curvature of the Earth, but the mean up direction will be the same for the whole scene. This type of point cloud is the result of approximate two-step georeferencing to (N, E, H) coordinates using plumb line constraints. Subplot (d) is identical to (c) in terms of the semi-constant up direction, but in this case, the horizontal scale is varying between the different scans but is constant within each scan. This is the result of approximate one-step georeferencing to (N, E, H).

4.2 Numerical estimates

The first aspect considered is the difference in height due to the curvature of the Earth. This difference is shown in Figure 3.

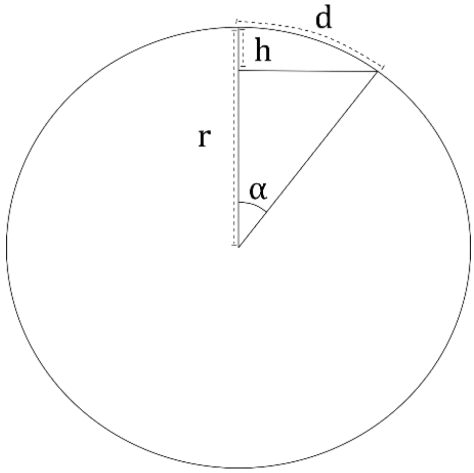

Figure 3. Height difference h due to the curvature of the Earth at distance d. r is the radius of the Earth and α is the angle corresponding to d.

From the quantities shown in Figure 3, we can calculate the height difference h in the following way:

$$h = r \cdot (1 - \cos \alpha) \tag{4}$$

$$\alpha = d \cdot \frac{2\pi}{2\pi \cdot r} = \frac{d}{r} \tag{5}$$

Where r is the radius of the Earth, d is the distance between the origin and the point, and α is the angle corresponding to the distance expressed in radians. Magnitudes of h for different distances d are shown in Table 1.

Table 1. Shift in vertical distance due to the curvature of the Earth as a function of horizontal distance along the surface of the Earth.

Horizontal distance	Vertical distance
100 m	0.8 mm
200 m	3.2 mm
500 m	2 cm
1 km	8 cm
2 km	32 cm
5 km	2 m
10 km	8 m

This effect is most pronounced when comparing subplots (a) in Figure 2 with (b), (c), and (d). Point cloud (a) follows the curvature of the Earth while the other point clouds are flattened, and the difference in height depends on the total extents of the point cloud. The effect is also present internally in point clouds (c) and (d), where each individual scan follows the curvature of the

Earth while the combined point clouds are flattened. In the latter case, the magnitude of the height difference will in most circumstances be limited to well under 1 millimeter, since the usual range of terrestrial laser scanning is below 100 m

In order to analyze the varying up direction, let us consider a spherical Earth with a radius of 6371 kilometers. On this Earth, one degree along a great circle corresponds to roughly 111 kilometers on the surface of the Earth. One arc minute and one arc second correspond to 1853 meters and 31 meters, respectively. Therefore, the difference between a constant and a varying up direction will be one arc second if the extents of the point cloud is 31 m, and so on.

Another aspect to consider is the difference in scale between the terrain and the map projection. This difference will depend on both the distance to the central meridian, assuming a transverse Mercator projection, and the height above the reference ellipsoid. The difference in scale at the central meridian of a Universal Transverse Mercator (UTM) zone at the height of the reference ellipsoid is 400 parts per million (ppm), which is equivalent to 4 centimeters per 100 meters. The difference in scale due to height above the reference ellipsoid increases with roughly 16 ppm per 100 meters of height (Uggla and Horemuz, 2018).

The change in scale between different heights that is present in Figure 2c also depends on the curvature of the Earth and the difference in height above the ellipsoid, and it will therefore also be limited to a maximum of 16 ppm per 100 meters of height. However, in practice, this number will likely be smaller, as the horizontal shift will be spread across the entire height of the point cloud, where lower points will move farther apart and higher points will move closer together. The maximum horizontal shift of points due to this effect for a point cloud that is 100 meters wide and where the height difference between the highest and lowest points is 100 meters is 1.6 millimeters. Considering that the height variation in point clouds usually is a lot less than 100 meters, this effect will be very small in most practical scenarios.

5. PROPOSED METADATA

As shown by the numerical estimates, there are many common situations where the conceptual differences between the different methods for georeferencing will be negligible. For a point cloud from a single scan, the differences in terms of plumb line direction will be limited to a few arc seconds and the difference in height will be less than a millimeter. On the other hand, for a point cloud that is created by combining data from several different instrument positions and that spans a larger distance, for example a laser scanned tunnel, the differences between methods can be significant.

The one aspect that will always be important for point clouds created from single and multiple scans alike is the difference in scale between the terrain and the map projection. These differences can be large in relatively normal scenarios involving common map projections and elevations. It is not possible to categorically say that one way to handle the scale is correct, as this will depend on the situation and expectations of the user. In certain cases, seamless combination with other geodata is more important than maintaining the dimensions of geometries and vice versa. It is therefore of great importance that the scale of the horizontal coordinates can be stated in the point cloud's metadata. There is as of today no standardized way to include this information in a point cloud, and most point clouds would likely include a map projection and vertical datum as their georeferencing metadata regardless of whether they were georeferenced using a rigid body or a strict transformation.

A second aspect that might be significant in certain cases is the difference in height due to the curvature of the Earth. The difference between (a) and (b), (c), and (d) in Figure 2 becomes quite severe over longer distances. On the other hand, the internal inconsistencies regarding both height and horizontal scale for point clouds (c) and (d) will be negligible in most realistic scenarios.

Considering the above, the most important aspects are whether the point cloud follows the curvature of the Earth or if it is flattened and whether the horizontal scale corresponds to the terrain or the map projection. According to these two attributes, the point clouds in Figure 2 would be categorized as shown in Table 2.

Table 2. Categorization of point clouds according to scale and shape. Scale either corresponds to the terrain or the map projection, and the shape is either curved or flat.

Scale / shape	**Curved**	**Flat**
Terrain	(a)	(c)
Map projection		(b) and (d)

The differences shown in Table 2 can be described using two metadata attributes, which both can take on one of two values. There would be no ambiguity in these parameters, and they would be entirely machine-readable.

6. CONCLUSIONS AND FUTURE RESEARCH

The aim is to meet the expectations of the users of 3D data, whether those are that the data resembles reality as closely as possible, that all vertical lines are parallel, or that the data can be seamlessly combined with other geodata. By adopting the metadata parameters suggested in this article, it will be possible for both humans and software to better understand the data they are working with and whether any transformations are necessary for the data to conform to their preferences. The scope of this article is limited to TLS, but for the future, it should be expanded to also include point clouds created by mobile laser scanning as well as photogrammetry. In addition, the geometric discrepancies should not only be analyzed considering their initial magnitudes, but rather be considered in a longer perspective using error propagation.

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BIOGRAPHICAL NOTES

Gustaf Uggla is since 2017 a PhD student at the Division of Geodesy and Satellite Positioning, KTH Royal Institute of Technology. His research is focused on the integration of geodesy and building information modelling (BIM) and has developed to encompass two distinct areas – georeferencing geometric data from Euclidean to geodetic coordinate systems and interpreting semantic information in point clouds using machine learning.

Milan Horemuz has been working at KTH in Stockholm since 1996 with research and education in the field of applied geodesy. His current position is associate professor in geodesy, and he has also an administrative function, director of Master program in Transport and Geoinformation Technology. His research interest is in area of geodetic surveying, satellite positioning, and laser scanning.

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