Error budget of laser scanners: Applications in geomorphic surface change quantification

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One of the principles in Geodesy is that every measurement is attributed with errors. These can be of different nature, and are typically grouped into gross, systematic, and random. While gross errors can be avoided by making measurements carefully and may be detected by checking for outliers in analyses; and systematic errors may be removed using models, random errors are inherent properties of any measured data. In the following, we address random errors and uncertainties as equal in accordance with the GUM 1995 (JCGM 100:2008).

Geodetic measurements and their associated uncertainties are often most easily described in their respective sensor coordinate system. For an airborne laser scanning system, this system is formed by the range measurement, the scan angle and a timestamp. In combination with the calibration parameters (i.e. lever arm and misalignment), the trajectory and the attitude of the platform (roll, pitch, yaw), these measurements can be converted to Cartesian coordinates. However, all of the values needed for the transformation may carry their own uncertainties, resulting in non-homogenous per-point uncertainties on the ground.

Similar considerations can be made for many other systems. In our application, we focus on terrestrial laser scanning. Here, a different set of three measurements are taken to form a single 3D point: a range and two angles. Typically, these are transformed to cartesian coordinates, but their random error magnitudes are much more easily understood in the original polar system. The laser rangefinder typically has a precision of a few millimeters, and the uncertainty associated with the measurement is attributed to both the beam divergence of the laser and the field of view of the receiver optics, which can be combined to find the Effective Instantaneous Field of View (Lichti and Jamtsho, 2006). Since not a single point is illuminated, the ranging uncertainty is further dependent on the incidence angle between the laser beam and the scanned surface, as well as the within-footprint roughness and the intensity of the received signal.

Acknowledging these contributions to individual per-point errors and modelling the main influences allows the propagation of this error to higher-level products. In some analyses, additional error sources must be included, such as the (spatially variable) coregistration error when working with multiple datasets.

In the example of geomorphic surface change quantification, geometric distances can be calculated by using the “Multiscale Model-to-Model Cloud Comparison” (M3C2) by Lague et al. (2013). This method aggregates points from two epochs by projecting them onto the normal vector of the reference epoch. The spread of the points in this projection, i.e. the standard deviation of the projected points along the axis, is hereby used as a measure of geometric accuracy and propagated into the distance value. A statistical test may then be used to separate quantifiable change from such that cannot be distinguished from measurement noise. Lague et al. motivate this by arguing that for planar surfaces, the within-plane-roughness is equivalent to the measurement (ranging) noise.

However, in reality, we often observe morphologic objects and surfaces that are not planar in the scale of the aggregation neighbourhood. In our example, we observe a rock glacier in the Austrian Alps, the Äußeres Hochebenkar, located in the upper Ötztal valley, Tyrol. This rock glacier is covered with boulders containing lots of sharp edges and corners. Our dataset consists of multi-temporal TLS scans from 2015 to 2019, with multiple additional acquisitions in the summer months of 2018 and 2019 (Pfeiffer et al., 2019).

Using the approach of error propagation from the single sensor measurement, including terms of roughness, intensity, incidence angle as well as between-epoch terms of coregistration, we propagate the uncertainties to the final distance metric and carry out a significance (t-)test. With this, we hope to achieve a lower level of detection, referring to the minimum change that can be reliably quantified, than with current methods. This is especially important when working at a high temporal resolution, as the observed change magnitudes between consecutive timestamps decreases while the noise level stays approximately the same.

Change quantification is commonly carried out in one direction per location, which is, in the case of M3C2, determined using the normal vector at a neighbourhood size that is most planar and therefore results in the "best" normal vector estimation. However, the choice of the direction in which change should be looked for is closely linked to the type of change that is to be quantified. In the example of the rock glacier, multiple superimposed processes result in the morphologic change that is observed. Main contributions are (a) a creep movement of the rock-ice mass downhill, including areas of pile-up and stretching when movement speeds differ by location, and (b) falling of individual surface boulders, which again lead to a change in surface morphology. To identify and quantify the influence of the creep movement, the direction of change that is being analysed should be normal to the general rock glacier surface, and therefore should use a rather large (i.e., a few meters) search radius. For the movement of individual boulders, especially pre-failure, i.e. small movements that may indicate a boulder in a metastable position, smaller neighbourhoods resulting in change directions normal to the individual rock surfaces should be chosen (Zahs et al., 2019).

To verify our method, we introduce a lab experiment, where a surface is scanned multiple times while being rotated. For each of the rotation steps, the displacement is calculated using tachymetric measurements. Close to the axis of rotation, noise cannot be be distinguished from real change, but the further away from the axis (where the resulting displacement is bigger), the observed change values become larger than their associated uncertainties. Since the real displacement can be easily calculated, we can verify whether the observed change in a specific area corresponds to real change or simply displays noise.

The example of change quantification is only a small application where a better handling of the uncertainties associated with both measurement and method may give increased insights on the results. Other applications include primitive-fitting, e.g. for stem curve modelling or roof type extraction, but also many other TLS-based analyses where data from multiple scan positions, and therefore with different per-point uncertainties, is combined.

Further extensions to the proposed method allow the use of data acquired from other sensors and/or platforms, and, therefore, data fusion techniques that are aware of the individual sensor's strengths and weaknesses. Especially when working with historic data to extend timelines further back, including the error budget makes sure that the more recent observations are used to their full potential, and give a measure on the reliability of the analyses.

References:

JCGM, 2008. Evaluation of measurement data — Guide to the expression of uncertainty in measurement (GUM 1995 with minor corrections).

Lague, D., Brodu, N., Leroux, J., 2013. Accurate 3D comparison of complex topography with terrestrial laser scanner: Application to the Rangitikei canyon (N-Z). ISPRS Journal of Photogrammetry and Remote Sensing 82, 10–26. https://doi.org/10.1016/j.isprsjprs.2013.04.009

Lichti, D.D., Jamtsho, S., 2006. Angular resolution of terrestrial laser scanners. The Photogrammetric Record 21, 141–160. https://doi.org/10.1111/j.1477-9730.2006.00367.x

Pfeiffer, J., Höfle, B., Hämmerle, M., Zahs, V., Rutzinger, M., Scaioni, M., Lindenbergh, R., Oude Elberink, S., Pirotti, F., Bremer, M., Wujanz, D., Zieher, T., 2019. Terrestrial laser scanning data of the Äußeres Hochebenkar rock glacier close to Obergurgl, Austria acquired during the Innsbruck Summer School of Alpine Research. Institute of Geography, University of Innsbruck.

Zahs, V., Hämmerle, M., Anders, K., Hecht, S., Sailer, R., Rutzinger, M., Williams, J.G., Höfle, B., 2019. Multi-temporal 3D point cloud-based quantification and analysis of geomorphological activity at an alpine rock glacier using airborne and terrestrial LiDAR. Permafrost and Periglacial Processes 30, 222–238. https://doi.org/10.1002/ppp.2004