ESTIMATION OF PLANIMETRIC ACCURACY OF LASER SCANNING DATA. PROPOSAL OF A METHOD EXPLOITING RAMPS

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ABSTRACT

A method is described for the estimation of planimetric precision of laser scanning data. Due to the nearly random distribution of the points hit by the laser, it is difficult to use the very standard technique of measuring the same points with the instrument under investigation and with another one, whose performances are well known and better than those expected from the former. But when the terrain is not flat, it could be said that the planimetric errors affect altimetric precision of the points measured by the laser scanner; we will show exactly what this means. We will also show that this behaviour can be exploited to estimate planimetric precision, provided that the shape, position and attitude of some ramps is known. The paper first of all focuses on the method's description, then it shows some initial results obtained from Pavia's test area.

1 INTRODUCTION

Laser scanning is rather a new technique which is already widely used. Nevertheless, it hasn't yet been completely investigated for some aspects, such as the accuracy of the sparse (X,Y,Z) data. Altimetric accuracy can be easily estimated on flat areas such as car parks, sport fields, squares and road crossings. Planimetric accuracy, instead, cannot be easily assessed by usual methods, based on the comparison of measurements given by different techniques. Indeed laser sensor scans the world below blindly and the points measured by it do not necessarily coincide with features usually exploited by surveyors such as building corners or edges. Therefore it is almost impossible to measure the same points with the laser and with another instrument, such as GPS.

One solution is represented by interpolation. Laser data could be interpolated to obtain grids and these could be analysed to find building edges and to determine their position. These positions could finally be checked by means of direct measurements. But unfortunately the gridding process and the following edge extraction introduce into the data some errors which are not easily distinguishable from the errors originally affecting the laser data. Therefore, even if gridding and grid analysis are well known and powerful methods, we tried to develop another way of assessing planimetric precision.

The method suggested by us does not require gridded data and it is based, instead, on sparse points. It exploits planar man-made surfaces such as court ramps and river banks. Let's consider first of all a simplified ramp and let's suppose that a laser pulse has struck a point whose true coordinates are (X_0, Y_0, Z_0). Due to the measurements errors, the sensor will return, for the hit point, the position (X, Y, Z).

The relationship between the real, unknown, position and the measured one involves random errors (and systematic ones, if any)

$$(X, Y, Z) = (X_0, Y_0, Z_0) + (e_X, e_Y, e_Z) \tag{1}$$

Once we have measured the ramp with a high-precision method, such as GPS or a mixture of it with other land surveying methods, it is possible to estimate the parameters *a*, *b* and *c* of the plane with a least squares approach; then, it is possible to compare the measured height, *Z*, and the height of the ramp at the same location, given by $aX + bY + c$.

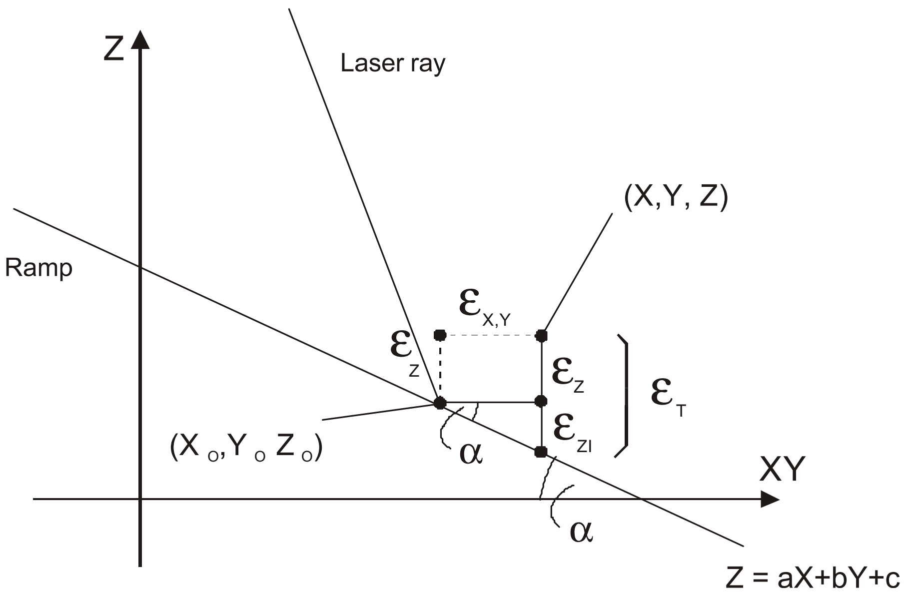

Figure 1 – Heuristic explanation of the origin of the altimetric error induced by planimetric error

As the drawing suggests, the total estimated error, ε_T, equals the sum of the pure altimetric error ε_Z with the induced error, ε_{ZI}, that is, the projection of the planimetric error, ε_{XY}, onto the vertical plane

$$\begin{aligned} \varepsilon_T &= Z - (aX + bY + c) \\ &= \varepsilon_Z + \varepsilon_{XY} \tan \alpha \end{aligned} \tag{2}$$

where α indicates the inclination of the ramp. The order of magnitude of the errors of laser scanners can be assumed to be 30-40 cm for *X* and *Y*, and 15-20 cm for *Z*. Since the slope $p = \tan\alpha$ of a court's ramp can easily reach the value of 20% or more, it can be argued that the induced altimetric error easily assumes values around 6-8 cm. Therefore, this component of the total error is clearly recognizable and significant, provided that the ramp has been surveyed with high precision methods, whose uncertainty is not greater than 1-2 cm. So if the pure altimetric error has been previously estimated and precisely known ramps are used to estimate the total altimetric error, the component of the latter induced by planimetric error can be estimated by subtraction; the pure planimetric error can be finally quantified.

Our method is based on three steps. First: estimation of the pure altimetric accuracy of the laser scanner by means of flat surfaces. Second: very accurate measurement of the equation of some court ramps by means of GPS and land surveying measurements. Third: estimation of the total height error and then of the laser planimetric error as the difference between the former and the pure laser altimetric error. Due to the high density of the laser data we have, there some tens or even some hundreds of laser points available for each test site, and this greatly increases the reliability of our estimations. It is remarkable that, using some ramps with different orientations, it could be also possible, in principle, to discriminate different values for ε_X and ε_Y. Finally our approach, besides allowing the estimation of the planimetric random error, easily allows us also to discover any systematic error, as we will show in a further section of the paper.

This paper will give a description of the test site (Section 2) that has been made in Pavia, Northern Italy, in the frame of a national research project. We will also describe some of the check-areas we have measured inside the site; by *check-areas*, we mean small parts of the territory such as tennis courts, court ramps or underground parking ramps, which we have measured with high precision methods. Then we will expose, in some detail, the basic formulas (Section 3) of our approach, explaining how we propose to estimate the unknowns. Finally, we will give the initial but interesting results for one flat check-area (section 4). Some conclusions and a quick sketch of our future activities will conclude the paper.

2 THE TEST AREA AND THE CHECK-AREAS

In the frame of a national research project, chaired by prof. Galetto of the University of Pavia, a test area has been made in Pavia. First of all, we created a GPS, high-precision network, consisting of twelve vertices; it is connected with the geodetic Italian network called IGM95. We conducted spirit levelling measurements so that now we know, for each point of the network, the ellipsoidal height, as well as the orthometric height. Thus we could characterize geoid undulations in a very detailed way. Our test site also has a good mapping support, indeed we have a 1:500 raster map of downtown, a 1:2000 vector map of all the town territory and a 1:10000 raster map covering all the region. Finally, our town has several good photogrammetric coverages.

Our test site has been surveyed with laser scanners twice. The first time was in mid November 1999 and we used the Toposys sensor, installed on a plane of the Italian Company CGR (Compagnia Generale Ripreseaeree), whose headquarters are in Parma. It is remarkable that, thanks to the big and powerful plane used, photogrammetric images were acquired, together with laser data. The Toposys flight had three stages: one with a height over the terrain of 850 metres and the last-pulse mode; another with the same height and the first pulse mode; a third one, much smaller, with the last pulse and only 400 metres above the ground. The German company delivered the raw-data, that is sparse points, subdivided for each acquired stripe, and gridded data, with a step of one metre. They all are in the UTM(ED50) format; heights are above the sea level. In this paper we will only take into account raw-data.

Other laser data were acquired at the beginning of December, 1999, with an Optech 1210 sensor operated by an Italian Company called Aquater, whose headquarters are in San Lorenzo in Campo, PS. The Optech instrument is highly configurable and we decided to operate with three different settings: there is a part on the town, with an expected homogeneous density of two points per square metre; there is another part, on the countryside, with a lower, homogeneous density; the third dataset is related to the surveying of suspended cables and it is made of sparse, high density, sections. It is remarkable that the Optech instrument we used is able to acquire the position and intensity of the first pulse, as well as of the last pulse, at the same time. Aquater delivered only raw-data in the WGS-84 datum, without any altimetric or geodetic conversion, or interpolation. They put together data coming from different stripes.

2.1 Characteristics of the check-areas

We have already measured two check-areas: one tennis court and the ramp of a underground parking. About the first, we have measured with GPS ten points evenly distributed. The convex polygon enclosing them has a surface of 259 square meters. The ten check points have the following main characteristics

$$\begin{aligned} m_Z &= 100.869 \quad \text{m} \\ s_Z &= 0.0098 \quad \text{m} \end{aligned} \tag{3}$$

Please note that we have used ellipsoidal heights, in order to manipulate data as less as possible. The second check-area is, as already said, a ramp; we have measured nine points on it, and some others nearby. Its main features have been estimated by a least squares adjustment. The following table summarizes the results (see the next section for a full clarification of the notation)

Geometrical parameters		Least squares adjustment results	
Width	3.96 m	p	0.20798 20.798 %
Length	12.71 m	a	0.21434131 rad
Difference in height	2.64 m	c	-1039298.87 m
Surface	50.33 m^2	s_0	0.013 m

Table 1: Main features of the ramp chosen as check-area

3 BASIC FORMULAS OF OUR ESTIMATION TECHNIQUE

This is the core of our paper, where we describe the method we are using and tuning. Let's define, first of all, what we mean by ramp. A ramp is a planar object whose projection on the X-Y plane is a rectangle. Besides, its height changes along the longitudinal axis, but it doesn't change along the transverse axis. Let's now define the equation of a ramp. Provided that the object coordinate system is *(X,Y,Z)*, we will associate an intrinsic coordinate system, called, (X',Y',Z'), to each ramp. Its origin coincides with the mid point of the lower edge; the *Z'* axis is parallel to the object *Z* axis. The *Y'* axis is parallel to the longitudinal ramp axis and it grows along the direction that makes the ramp's height grow. In such a system, the equation of the plane containing the ramp is

$$Z' = pY' \tag{4}$$

where p is the slope. To express the same equation in respect to the object coordinate system, we have to take into account an offset, (X_0, Y_0, Z_0), which represents the position of the origin of the intrinsic system with respect to the object system, and a planar rotation angle α. We have chosen to use the clockwise angle formed by the *Y'* axis with respect to the *Y* axis, so that the angle represents the *azimuth* of the longitudinal axis of the ramp. Therefore the equation of the plane containing the ramp is

$$\begin{aligned} Z &= p\sin\alpha\,(X - X_0) + p\cos\alpha\,(Y - Y_0) + Z_0 \\ &= X\,p\sin\alpha + Y\,p\cos\alpha + Z_0 - (X_0 p\sin\alpha + Y_0 p\cos\alpha) \end{aligned} \tag{5}$$

It is also possible to give a parametric description of the ramp in the following way

$$\begin{aligned} X &= X_0 + t\cos\alpha + u\sin\alpha \\ Y &= Y_0 - t\sin\alpha + u\cos\alpha \\ Z &= Z_0 + u\,p \end{aligned} \tag{6}$$

where u and t span the width and the length of the ramp, respectively. Now, let's come to the problem of the estimation of the planimetric precision. Let's form the difference between the height measured by the scanner, *Z*, and the height of the ramp in the position *(X,Y)* supplied by the scanner

$$\Delta = Z - (X\,p\sin\alpha + Y\,p\cos\alpha + c) \tag{7}$$

where we have synthesized all the non-essential parameters into c. This random variable can be investigated experimentally and its mean and variance estimated: we have as many extractions as the number of the laser points which hit the ramp. We will assume at the moment that ramp parameters, p and α are constant, while they should be more properly treated as random variables themselves. Our assumption is justified because those parameters will be estimated with GPS, with a much higher precision than laser points. In any case the formulas we are giving can be easily generalized to consider the randomness contained in those parameters. Instead, the randomness contained in the laser-measured coordinates will be taken into account, assuming that *X,Y*, and *Z* are random variables having respectively mean values (X_0, Y_0, Z_0) and variances $(\sigma_X^2, \sigma_Y^2, \sigma_Z^2)$. It's easy to calculate mean and variance of the Δ variable

$$\begin{aligned} \mu_\Delta &= Z_0 - (X_0\,p\sin\alpha + Y_0\,p\cos\alpha + c) = 0 \\ \sigma_\Delta^2 &= \sigma_Z^2 + \sigma_X^2\,p^2\sin^2\alpha + \sigma_Y^2\,p^2\cos^2\alpha \end{aligned} \tag{8}$$

where the first equation simply demonstrates that our estimation is correct. About the second one, let's now assume that the variances of the two planimetric components coincides; let's indicate their common value with σ^2_{XY}. Now we can write the final expression for the variance

$$\begin{aligned} \sigma^2_\Delta &= \sigma^2_Z + \sigma^2_{XY} p^2 \\ \sigma^2_{XY} &= \frac{\sigma^2_\Delta - \sigma^2_Z}{p^2} \end{aligned} \tag{9}$$

Therefore, the dispersion of the Δ variable is the sum of two components: the pure height error committed by the laser sensor, σ^2_Z, and the induced error, $\sigma^2_{XY} p^2$, which is a function of the planimetric error and of the slope of the ramp. Indeed the first of the (9) formally demonstrate what can be intuitively thought: that, on flat areas, planimetric error has no effect.

Now if σ^2_Z has already been estimated on some flat areas; if one ramp is very precisely known; if this ramp has been scanned by a laser sensor, then the total height error can be easily estimated simply forming the differences indicated in (7). Therefore the planimetric error can be calculated by means of the second of (9).

All what we have said could be repeated and reformulated for a general surface: we could speak of *local* slope, rather than, simply, of surface's slope. But planar surfaces make everything easier and, provided that our towns offer many pure ramps, we will use them, exclusively. Besides, equations (9) shows why it is necessary to look for the steepest available ramps: because the induced altimetric error is proportional to the slope.

Our formulas allow also to detect systematic errors, due for instance to non perfect sensor orientation. Indeed let's suppose that the Z measurements are affected by a bias Δ_Z. This implies that the first of (8) become

$$\begin{aligned} \mu_\Delta &= Z_0 + \Delta_Z - (X_0 p \sin\alpha + Y_0 p \cos\alpha + c) = \\ &= \Delta_Z \neq 0 \end{aligned} \tag{10}$$

Let's suppose again that one planimetric component, X, is affected by a bias Δ_X. We can argue

$$\begin{aligned} \mu_\Delta &= Z_0 - ((X_0 + \Delta_X) p \sin\alpha + Y_0 p \cos\alpha + c) = \\ &= -\Delta_X p \sin\alpha \neq 0 \end{aligned} \tag{11}$$

So if the estimated mean of the Δ random variable is significantly different from zero, we must think there are systematic errors. But since we can always suppose that systematic height errors have been discovered and corrected during the first step of our procedure, we come to the conclusion that (10) will never happen, and relations (11) can be used to detect planimetric systematic errors.

4 ESTIMATION OF THE ALTIMETRIC PRECISION

This section illustrates some first results on altimetric precision which we obtained on a flat check-area. We think they are interesting even if they don't constitute a full and complete application of our proposed methodology. The estimation has been worked out exploiting a tennis court whose ellipsoidal height is now known very precisely. We selected the raw-data coming from both sensors which are inside the court, and then we made a comparison of the height given by the lasers and of the height directly measured on the ground.

It is remarkable that we have in Pavia a permanent GPS station, which is part of our geodetic network and that both the companies used data produced by our station to reference their products. Therefore the products delivered by both companies are, from this point of view, perfectly homogeneous between each other and in respect with the local GPS network, that we used to make the control measurements.

4.1 Results for the Optech sensor

The Optech sensor is able to measure the first pulse, as well as the last, for each emitted ray. So we verified, first of all, the differences between the coordinates of the first pulse and the coordinates of the last pulse. Provided that they refers to a flat surface, they should coincide. Please notice that there are 357 points inside the court, so our estimations are good and reliable.

	ΔX	ΔY	ΔZ
m	-0.009	-0.021	-0.075
s	0.008	0.020	0.050

Table 2: Differences between first pulse and last pulse (*F-L*), in metres.

Then we computed the differences between the measured height values and the true value, determined by GPS. The following table summarizes results for the first and last pulse.

	ΔZ_f	ΔZ_l
m	-0.246	-0.170
s	0.152	0.142

Table 3: Mean value and dispersion of the height errors, for the first pulse and last pulse, respectively (metres).

It is remarkable that both tables shows that the first pulse is lower than the last. Besides, there is certainly a small systematic error and, to finish, the random error has the correct order of magnitude.

4.2 Results for the Toposys sensor

The tennis court check-area is particularly interesting for the Toposys data we have, because four stripes lie on it, two in the first pulse mode and two in the last pulse mode. Therefore it is possible to verify the agreement between them. For each stripe, there are approximately 1200 points inside the court. The following table shows the main results.

	ΔZ *(31218)*	ΔZ *(31219)*	ΔZ *(31306)*	ΔZ *(31307)*
m	-0.275	-0.270	-0.228	-0.283
s	0.050	0.050	0.052	0.050

Table 4: Analysis of the errors for two last pulse stripes and for two first pulse stripes, respectively (metres).

We deleted five points from the first stripe, because they have residuals around 25 metres. Apart from this problem, there aren't differences between the stripes. Also in this case there is a significant systematic error: it has the same order of magnitude and the same sign of the error of the other instrument. The dispersion, on the other hand, is smaller than we expected.

5 CONCLUSIONS AND ACKNOWLEDGMENTS

Even if the prevalence of systematic errors on the random ones will require a specific tuning of the our proposed methodology, we think it is interesting and effective, so we'll go on, fully applying it to a bigger number of check-areas, which we are already measuring.

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6 REFERENCES

Haala, N., 1999. Combining multiple data sources for urban data acquisition. Proc. of the Photogrammetric Week 1999, Stuttgart, Germany.

Jiang X. and Bunke H., 1994. Fast segmentation of range images into planar regions by scan line grouping, Machine Vision and Applications, No. 7, pp. 115-122.

Maas H.-G., Vosselman G., 1999. Two algorithms for extracting models from raw laser altimetry data, ISPRS J. Photogramm. Remote Sensing, Vol. 54, No. 2-3, pp. 153-163.

Ackermann F. (1996) – Airborne laser scanning for elevation models – GIM, Geomatics Info Magazine, Vol. 10, n. 10, 1996, pp. 24-25.

Casella V., Galetto R. (1998) – Tecniche innovative per il rilevamento terrestre, aereo e da satellite (Innovative techniques for terrestrial, airborne and satellite surveying) – Proceedings of the II ASITA Conference, Bolzano, Italy, November 24-27, 1998, pp. 33-53.

Kraus K., Pfeifer N. (1998) – Determination of terrain models in wooded areas with airborne laser scanner data – ISPRS Journal of Photogrammetry & Remote Sensing, Vol 53. n. 4, August 1998, pp. 193-203.