

LIDAR FILTERING: TESTING OF AN AUTOMATIC PROCEDURE DEVELOPED IN THE FREE OPEN SOURCE GIS GRASS

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ABSTRACT:

The goal of this study was to analyze the filtering performance of LiDAR data of an algorithm implemented by our group of research. The algorithm is completely automatic and needs only the raw data classified as first and last pulses. It was implemented in the open source software GRASS and it is composed of three functions that have to be launched in sequence: *v.lidar.edgedetection*, *v.lidar.growing* and *v.lidar.correction*. Starting from the classified points, the algorithm can performed a grid DTM/DSM. The check of the algorithm quality was carried out with a dataset that represents a real case, being already used to create a DTM/DSM along some urbanized areas of Sardinia Region Coast, in Italy. The first control regarded the filtering performance of the implemented algorithm. It was performed by comparing our results with those one obtained by TopScan, a German company which executed the same processing on behalf of Sardinia Region, using a preliminary automatic algorithm followed by a manual correction. Sardinia's products were checked by visual comparison with high resolution orthophotos (12.5 cm) and with terrain survey measurements. We assumed Sardinia's classification as a reference. Another control was then carried out to check the gridded products (DTM and DSM) with GPS measurements. Lastly, we checked the computational performances in terms of time when the adopted resolution of the grid DTM/DSM varies.

1. INTRODUCTION

Nowadays LiDAR technology is widely used to perform DTM and DSM. The high acquisition frequency (larger than any other method), the good accuracy and the short time necessary to acquire the data make LiDAR technology a method of fundamental importance (Baltsavias, 1999).

A still open issue concerns the filtering of raw data. In fact LiDAR data are generally filed as first and last (in some cases also multiple) pulses, without information about the objects which caused the reflection of the signal. This means that it is not possible to distinguish between points lying on the terrain or on a generic object on the ground. Therefore, the creation of the DTM becomes impossible by using only the raw data without a preliminary filtering process (Sithole, 2005).

A DTM is usually the main goal of a LiDAR survey (while a DSM can be obtained with a simple interpolation of the first pulses) and thus the development of automatic and quick filtering algorithms becomes an issue of essential interest.

A filtering algorithm should be able to process several millions points and classify them as belonging or not to the ground (Sithole and Vosselmann, 2004). Many filtering algorithms were developed in these last years but often they are included in proprietary and not freeware software and many users have not the possibility to use them.

Our group of research implemented a filtering procedure in the free open source GIS software GRASS (Geographic Resources Analysis Support System) (Neteler and Mitasova, 2002), which is one of the OSGeo (Open Source Geospatial) projects. The algorithm is free downloadable and it is composed of three functions that have to be launched in sequence: *v.lidar.edgedetection*, *v.lidar.growing* and *v.lidar.correction*

(the terminology refers to the versions 6.X). The whole classification process is fully automatic and needs only the raw data classified as first and last pulses (Antolin and Brovelli, 2007, Brovelli et al., 2004).

The first function *v.lidar.edgedetection* recognizes the edges of the objects. It starts with an interpolation of the sparse data on a regular grid by using bilinear splines, so that a continuous surface is created. The new surface (especially the magnitude of the gradient and its slope) is compared with the sparse data in order to identify the edges and classify each point in two main categories: *ground* and *object*.

The second function *v.lidar.growing* fills in the edge lines previously founded. The method is based on the hypothesis that the inner part of an object has a height value larger than that close to its edge.

At the end of the computation each point is classified as single pulse terrain, double pulse terrain, single pulse object and double pulse object.

Obviously, the previous hypothesis can be unverified. This means that classification errors could appear in particular situations. For this reason it is opportune to use also *v.lidar.correction*, which executes a final correction of the previous misclassification errors. This function is based on a preliminary large step interpolation of the points classified as ground and a following analysis of the residuals between the new surface and the sparse points.

Though the complete algorithm is composed of three different functions, it is possible to launch them together (e.g. with a simple LINUX script). In any case we preferred to split the

procedure in a way that it is possible to control the results of each single step.

The algorithm is highly customizable, as it is based on a great number of parameters, even if, in its usage with datasets morphologically different, it has shown that a specific set of parameters can be suggested as optimal.

Starting from the points classified as single pulse terrain the DTM can be computed. The used command in this case (always performed by us and called *v.surf.bspline*, still free available in GRASS) interpolates the point data on a regular grid using bilinear or bicubic splines with Tychonov regularising parameter (Brovelli and Cannata, 2004).

What we want to show in this paper is not the detailed functioning of the algorithm, but the quality of the products that can be obtained with it.

The control was performed comparing our results (that from here we will call GRASS results) with the results obtained by TopScan, a German company which performed the same process on behalf of Sardinia Region by using a preliminary automatic algorithm followed by a manual control (hereafter those products are named Sardinia's products).

Sardinia's products were checked by visual comparison with high resolution orthophotos (12.5 cm) and terrain measurements. For these reasons, we can assume Sardinia's products as a good reference.

The control regarded the classification of the raw data (filtering analysis), the DSM and the DTM. This kind of control can be considered as a relative control, because the initial data are the same for both two products, despite the two procedures are completely different and independent.

To check the absolute precision of GRASS products a comparison with a new set of points measured with a GPS (RTK survey) was performed. In this case the data are completely independent and the larger accuracy of the GPS data (± 0.03 m) than LiDAR ($\pm 0.2-0.3$ m) ensures a good dataset as reference.

The last control was to test the performances of the algorithm to verify the applicability on real cases. The computational cost depends on the number of the splines used to interpolate the raw data. A larger number of splines implicates a better resolution (but not always a better solution) but it increases the computational time. Thus a compromise between quality and time becomes necessary.

In the following paragraphs the controls are presented, starting from the filtering and grid products, up to the algorithm performances.

2. CLASSIFICATION CONTROL

2.1 Dataset description

The original dataset is composed of $286 \cdot 10^6$ points acquired with an Optech ALTM 3100. It covers an area of 59.3 km^2 along the East Coast of Sardinia Region, in the urbanized areas from Porto Rotondo to San Teodoro. It is composed of 63 strips acquired in three days, with a sidelap always larger than 50%. The altitude above the ground is 1000 m and the scan rate is 70

kHz. The areas were mapped with a mean laser spot density of higher than 1 points/m^2 roughly.

The dataset was filed as first and last pulses in ASCII text files, reporting the cartographic coordinates (UTM WGS84) and the intensity. From the ellipsoidal height the orthometric height was calculated according with Italian quasi-geoid.

The whole dataset was divided in 28 areas, which corresponds to the municipalities along the considered part of Sardinia's coast.

2.2 Reference data description

The raw data were acquired and processed by TopScan/HANSAER associated with the Italian company Aerosistemi S.r.l. and the German company Hansa Luftbild Sensorik und Photogrammetric GmbH. These companies performed the entire process on behalf of Sardinia Region.

Firstly TopScan performed a classification of the raw data in three categories: *ground*, *vegetation* and *buildings* points. The used method is based on a preliminary automatic algorithm implemented by TopScan itself. This algorithm is able to divide the ground points from the object points. Then the object points were divided in buildings and vegetation points. Lastly a manual correction was performed to correct residual errors due to misclassifications.

With the points classified as terrain a grid DTM was performed by using an interpolation. The DSM instead does not require any preliminary filtering operation and can be obtained with an interpolation of the data classified as first pulse. TopScan's interpolation method was the linear prediction with bell curve as base function (Kraus and Pfeifer, 2001).

Both DTM and DSM have a resolution of 2 m and were checked by visual comparison with high-resolution orthophotos and a spatial DB. The height accuracy instead was checked with survey measurements (GPS and Total Station).

All these qualities make Sardinia's products a good reference to analyze the classification and the DTM/DSM that our method is able to provide.

2.3 Test of GRASS classification method

To test the results of GRASS filtering algorithm a comparison with the Sardinia's classification was performed.

The main problem was to compare sparse points considering their classification. In fact a simple count of the points which belong to some determined categories is not sufficient to compare the classification (e.g. two methods can classify exactly the same number of points but these have a different location). That implicates that is necessary to compare each single point by using its spatial coordinates.

The vast number of points (over $280 \cdot 10^6$) implicates more than 10^{17} combinations, and it makes impracticable the control itself. Even if we searched a method to decrease the number of operation, it could not make the control workable.

For this reason a reduction of the data and a method able to speed up the control becomes inevitable.

The method used to compare the vector points was based on their rasterization on a regular grid with square cells. The resolution was fixed equal to 0.5 m, so that into each cell only a

point data was included. In some rare cases in a single cell the presence of several data was noticed (up to 3 or 4 points) and so also an ambiguity. To solve this problem we used an algorithm which evaluated the mean height. Another possible solution could be the reduction of the cell size, but we preferred to avoid this choice that implicates a larger number of cells.

The results of the rasterization process are 2 maps which correspond to Sardinia and GRASS classification. The advantage is the possibility to subtract the map (that is easy because the procedure is based on raster algebra operations) in order to obtain a raster map of the height differences. Where the both maps contained a float value the difference could be calculated, instead where one or both maps presented a "nodata" value also the difference map contained this one.

This means that the statistics on the difference map are identical to the statistic carried out on the original correspondent vector points (exception made for the very few cells with an ambiguity).

Starting from the original dataset a representative set was extracted considering the spatial distribution of the points and the morphology of the area. It is composed of 5 areas with a number of points variable from $1.5 \cdot 10^6$ to $8 \cdot 10^6$. The morphology of the areas is also variable enough and includes urban, rural and wooded areas.

Before filtering an outlier rejection was performed. The function used is *v.outliers*, which performs an interpolation of the data on a regular grid and then calculates the differences between the new surface and the spread points. The residuals are compared with a fixed threshold: data corresponding to residual exceeding the threshold are considered as outliers.

The filtering method developed in GRASS needs some input parameters. This makes the algorithm highly customizable and capable to elaborate dataset morphologically different. In any case, a default parameter set is suggested as optimal being the choice of the parameter often complicated.

The three functions that compose the algorithm were launched in sequence with the default set of parameters to perform a classification in 5 representative test areas, obtaining a subdivision of the points in *terrain* and *object*. Sardinia's classification instead is based on *terrain*, *vegetation* and *building* points and considering that the points suitable for the realization of the DTM are the terrain points only, we compared the points classified as terrain by us and by TopScan.

The statistics of the difference related to the points classified as *terrain* by both procedures are shown in table 1.

| AREA | A | B | C | D | E |
|---------|---------|---------|---------|--------|---------|
| F | 2856668 | 2250790 | 4005581 | 728888 | 1550308 |
| L | 2861842 | 2253878 | 4008225 | 729011 | 1550749 |
| TS | 1885229 | 1655103 | 3289329 | 568432 | 1214066 |
| GR | 2184190 | 1830501 | 3664729 | 636919 | 1408589 |
| C | 1676170 | 1577317 | 3233053 | 525629 | 1159922 |
| | | | | | |
| % TS/GR | 86,31 | 90,42 | 89,76 | 89,25 | 86,19 |
| % C/T | 88,91 | 95,30 | 98,29 | 92,47 | 95,54 |

Table 1. Difference between the classifications
Legend: F, L = first and last pulses; TS, GR = TopScan and GRASS terrain points, C = corresponding points

As it is possible to see the number of points classified as terrain by GRASS is always larger than TopScan, but the points in common between the two methods are approximately equal to TopScan's terrain points. This means that GRASS finds the same points of TopScan but in addition finds others points. A following control demonstrated that the excess GRASS terrain points are generally located under the vegetation but on the ground (see. figure 1), and for this reason they were removed by the manual control of TopScan. That means that the considered points are not a classification error.

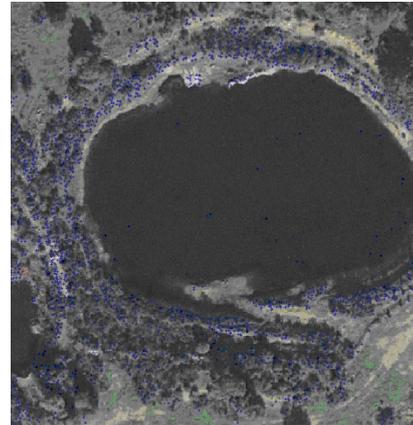


Figure 1. Mismatch between GRASS and TopScan terrain points classification.

In area B a building vector mask was manually performed starting from the orthophotos (177 buildings). Then the mask was rasterized with a resolution of 0.2 m. The basic idea was to use the mask to control the number of points classified as terrain that belong to the mask: these points are a classification error. The number of points classified as terrain but that lie in building mask is shown in the following table (Table 2).

| GRASS | | TopScan / Sardinia | |
|-------------|------------|--------------------|------------|
| mask points | percentage | mask points | percentage |
| 9819 | 0.53% | 5588 | 0.34% |

Table 2. Points classified as terrain that lie into buildings

A followed analysis demonstrated that the points classified as terrain that lie in the mask are often close to the edges of the buildings. Figure 2 depicts a generic situation where it is possible to observe an error along the North edge of the roofs. For this reason we considered this points still belonging to the terrain, because they are due to errors committed during the manual realization of the mask. In fact the orthophotos present a perspective deformation due to the distance of the considered buildings from the nadir point and the objects that have a relief displacements are so distorted.



Figure 2. GRASS and TopScan terrain points in the buildings mask. The error is close to the building edge and so it is probably due to the mask itself.

3. DTM/DSM RELATIVE CONTROL

3.1 Creation of gridded products with GRASS

Starting from the points classified as terrain by GRASS it is possible to compute the DTM. The used procedure (another GRASS algorithm performed by us and called *v.surf.bspline*, still free available in GRASS) executes the interpolation of sparse points on a regular grid using bilinear or bicubic splines. The DSM instead can be performed with a simple interpolation of the first pulses, without a preliminary filtering procedure.

Splines interpolation requires as input the spatial resolution, which corresponds to the splines number that will be used. A large number of splines implicates an increment of the number of unknowns and problems related to the irregular behaviour in correspondence of zones with a lack of data. Another problem related to use a high resolution is the possibility to have a number of unknowns larger than the number of equation: the spline coefficients cannot be estimated. A low resolution instead implicates a surface that does not follow the data trend where the points have a high variability.

The density of the raw data is 1 point/m², so we choose a spatial resolution of the splines equal to 4 m to avoid problems related to the lack of data and the increment of the computational cost. In 2 areas (with a surface of 3.01 and 6.58 km² respectively) a DTM and a DSM were performed with a resolution of 2 m.

3.2 Relative control

A grid model can be intended as a raster. This means that it is possible to operate with grid model using algebra raster procedures. The basic idea is to compare Sardinia and GRASS gridded products with a raster difference and obtaining a new raster map. The results related to the DTMs map difference are shown in table 3.

| Area | S (km ²) | mean (m) | std (m) | min (m) | max (m) |
|------|----------------------|----------|---------|---------|---------|
| B | 3,011 | -0,11 | 0,35 | -4,79 | 3,02 |
| C | 6,58 | -0,08 | 0,27 | -3,88 | 1,69 |

Table 3. Differences between Sardinia and GRASS DTMs

The average of the difference is about -0.1 m and the standard deviation results lower than 0.4 m. The spatial resolution of the

DTM makes the error irrelevant and probably caused by the presence of particular situations (as indicated also by the minimum and maximum values).

A more detailed control about the error size indicated that the major part of the errors (over 95%) has a value lower than 1 m. This analysis was performed by using some thresholds value (0.5, 1, 2, 3 m) and verifying the number of elements which belong to the fixed threshold. Results are shown in table 4, where it is possible to observe that the points with an error larger than 3 m are an irrelevant percentage.

| Area | • < 0,5 | 0,5 ≤ • < 1 | 1 ≤ • < 2 | 2 ≤ • < 3 | • ≥ 3 |
|------|---------|-------------|-----------|-----------|-------|
| B | 90,73% | 6,82% | 2,03% | 0,35% | 0,07% |
| C | 93,81% | 4,80% | 1,22% | 0,16% | 0,01% |

Table 4. Distribution of the DTM error (threshold values in meters)

In any case, another control was performed to discover the causes of the difference where there are significant discrepancies. The map of the difference was superimposed on a high quality orthophoto (resolution 0.125 m) and then a legend about the difference was associated. This process allowed us to find the zones where the discrepancies assumed the largest values.

This control demonstrated that the larger differences are located close to particular elements like big rocks, wharfs, foundations, pools et cetera.

The reflection given by a big rock is similar to the reflection of a building. Thus, a big rock can be interpreted by GRASS as a building and so removed. Sardinia's classification instead includes also this kind of elements, and during the manual correction it is possible to distinguish a rock with respect to a building. In figure 3 the differences between Sardinia and GRASS DTMs are shown, and they assume a positive value where there is a rock, which confirms the previous hypothesis. In any case, in our opinion, only with a manual control it is possible to take account of these anomalous situations.

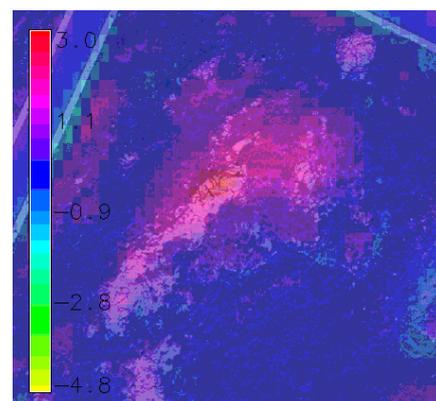


Figure 3. Typical element which causes misclassification

Another interesting case is the presence of wharfs (figure 4). The automatic algorithm classifies a wharf like a logical continuation of the terrain because these elements have a height almost equal to the terrain. It is possible to observe that others objects (e.g. motorboats) and the undep water have the same problems.



Figure 4. Problems with wharfs or undep water: many points are classified as terrain

The control of the GRASS DSM was performed with a comparison with Sardinia DSM. The areas in which the control was performed are always the same already used in the previous analysis.

To create a DSM with GRASS it is sufficient to interpolate the points classified as first pulses. In this case we used bicubic splines with resolution of 4 m and we choose a resolution of the DSM always equal to 2 m.

The differences were calculated with the procedure already used for the DTM and are shown in table 5.

| area | mean | σ | $\bullet < 1$ | $1 \leq \bullet < 2$ | $2 \leq \bullet < 3$ | $\bullet \geq 3$ |
|------|------|----------|---------------|----------------------|----------------------|------------------|
| B | 0,03 | 0,84 | 87,70% | 8,17% | 2,66% | 1,47% |
| C | 0,04 | 0,52 | 94,91% | 3,63% | 0,96% | 0,50% |

Table 5. Distribution of the DSM error (units in m)

The mean of the difference is almost zero but the standard deviation has a larger value than in the DTM analysis. Anyway the error is at least at 87 % lesser than 1 m and is due mainly to the usage of two different interpolation methods.

4. DTM/DSM ABSOLUTE CONTROL

4.1 Dataset and procedure

The controls previously shown were performed with the raw LiDAR data, starting from the filtering up to the interpolation on a regular grid. They were based on the comparison with another DTM/DSM. This analysis demonstrated a good correspondence between GRASS and Sardinia results, but it is not sufficient to check the absolute precision of the implemented algorithm.

The goal of this paragraph is to show the results related to the difference between gridded GRASS products and 218 points measured with a GPS. The precision of the RTK GPS survey

was ± 0.03 m, while raw LiDAR data have a precision larger than ± 0.15 m. This implicates that GPS coordinates become useful to test the absolute accuracy of GRASS DTM and DSM. The procedure to check GPS and GRASS data was based on raster differences. Also in this case a GPS raster file was created. After an analysis on the distances between each GPS point we choose a resolution of the GPS raster map equal to 0.5 m, which avoided overlapping between the GPS raster points. The map is composed of only 218 full cells, and the remaining part is completely empty.

The next step was to calculate the differences between the GPS maps and the DTMs. The control was performed in 3 areas (2 areas have been already used during the relative control, in addition we choose another area). To complete the tests also the original Sardinia's DTM was used in this comparison. The results are shown in table 6.

| | num | mean (m) | σ (m) | max (m) | min (m) |
|--------------|-----|----------|--------------|---------|---------|
| GPS-GRASS | | | | | |
| area 16 | 88 | 0,21 | 0,17 | 0,47 | -0,48 |
| area 15 | 72 | -0,01 | 0,14 | 0,26 | -0,45 |
| area 14 | 58 | 0,36 | 0,16 | 0,73 | -0,19 |
| GPS-Sardinia | | | | | |
| area 16 | 88 | 0,24 | 0,08 | 0,50 | 0,11 |
| area 15 | 72 | 0,21 | 0,07 | 0,39 | 0,08 |
| area 14 | 58 | 0,27 | 0,14 | 0,57 | -0,38 |

Table 6. Difference between GPS measures and grid products

The results using GRASS and Sardinia DTMs are close enough but Sardinia DTM always presents a lower discrepancy. In any case, considering the spatial resolution of 2 meter and the complicated morphology of the chosen areas both results can be accepted (we remember that Sardinia's procedure is semi-automatic).

The last control regards the DSM precision. Also in this case the control was based on the differences, but the points were measured with a Total Station to obtain information also about the point that lie on roofs (figure 5).

The main occurred problem was the position of the point used to perform the control, because they are generally located next to the building edge, where the DSM has a significant variation. The roofs in the areas have typically pitched faces, and it is obvious to forecast larger discrepancies than in the DTM control, because an optimal and representative control must be carried out in flat areas, where the spatial resolution of 2 m becomes irrelevant.



Figure 5. Typical case of points on a buildings (black spots)

Firstly the control points were rasterized with a resolution of 0.2 m and then the differences were calculated. The mean was 1.45 m and the standard deviation 2.87 m, the maximum difference was larger than 7 m. These results are due to the position of the points and, as previously said, they generally lie close to the edge of the buildings and so the differences can be calculated by using the cells which have the height of the terrain or a intermediate value between the terrain and building heights. To avoid this problem the difference were manually calculated in order to chose the exactly cells. The new results indicated a mean of 0.22 m and standard deviation of 0.73 m, that are acceptable values.

5. ALGORITHM PERFORMANCE

As previously described, the algorithm is composed of three sub-functions but the computational cost is primary due to the first one: the edge detection phase. The necessary time to complete this step depends on the fixed splines resolution. To halve the splines step means to increment the number of splines by four times (and obviously also the number of unknowns). Therefore it is obvious that the choice of an appropriate number of splines depends on the density of the raw data and on the accuracy of the final products. While we can suggest a default set of parameters that we consider adequate for many situations, the choice of the spline resolution must be made always considering what the users wants to obtain. The unique general rule we suggest is to use a spline step larger than the mean density of the original spread data.

The last function that composes the algorithm still requires the splines step as input parameter, but in this case we suggest to use the default parameter (60 m), because the interpolated surface in this case must be smooth. In fact only a control with a smooth surface is necessary in order to detect misclassification errors.

The performances of the algorithm were evaluated with the analysis of the results as a function of the splines resolution. The test was performed in an area of 6.58 km², with a splines step variable from 4 to 32, passing through the multiple of 2. The used computer has a processor Core Duo T5500 and 2 GB. The necessary time during any test was appointed and the results are shown in figure 6.

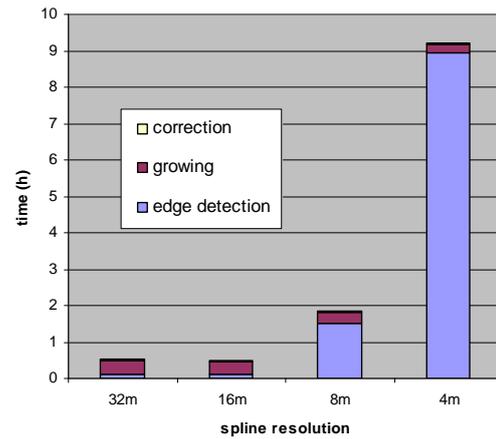


Figure 6. Time as a function of the spline resolution

The main part of the computational cost is given by the edge detection step. In fact it depends on the spline resolution. The necessary time has a value of some hours when the resolution is very high; instead when a low resolution is fixed it is necessary to wait only for few minutes. The other two commands have a computational time constant during the different elaborations. The accuracy of the new DTMs can be again estimated using a comparison with the Sardinia's DTM and the points measured with the GPS (see table 7). It is obvious that a large step generates a not so much accurate DTM (e.g. when the resolution is 32 m the mean error is 0.59 m and the root mean square error is 1.2 m). In any case, when a low resolution DTM is required, it is possible to compute it in few minutes (less than 30) because the error committed is always smaller than 1.5 m. On the opposite, when we need a better accuracy (e.g. mean error less than 0.35 m and root mean square less than 0.39 m in our case), more detailed splines are required and so more computing time (several hours).

| splines step (m) | Sardinia minus GRASS DTM (m) | | | |
|------------------|------------------------------|------|------|-------|
| | mean | std | max | min |
| 4 | -0,11 | 0,35 | 3,02 | -4,79 |
| 8 | -0,05 | 0,31 | 4,43 | -3,62 |
| 16 | 0,04 | 0,38 | 5,47 | -3,62 |
| 32 | -0,05 | 0,49 | 5,55 | -3,47 |
| | GPS minus GRASS DTM (m) | | | |
| | mean | std | max | min |
| 4 | 0,36 | 0,16 | 0,73 | -0,19 |
| 8 | 0,56 | 0,43 | 1,74 | -0,41 |
| 16 | 0,66 | 0,5 | 1,96 | -0,06 |
| 32 | 0,91 | 0,68 | 2,53 | 0,03 |

Table 7. Results as a function of the splines resolution

6. CONCLUSIONS

An algorithm to filter LiDAR raw data and several controls about the obtainable results were presented. The algorithm is completely free and already available on Internet (<http://grass.itc.it>). The possibility of having such a kind of algorithm completely integrated within a GIS (GRASS), its filtering performances (here presented) also in fully automatic

processing, make our method interesting in many applications. In any case, being the product an open source, the interested users can also improve its functionalities by changing parts of the code or implementing new modules.

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REFERENCES

Antolin Sanchez R., Brovelli M.A., 2007, LiDAR data filtering with GRASS GIS for the determination of digital terrain models, *Atti del Convegno: I Journada de SIG libre, SITGE; Girona (Spain)*.

Baltsavias, E.P. (1999). Airborne laser scanning: basic relations and formulas. *ISPRS Journal of Photogrammetry & Remote Sensing* 54, pp. 199-214.

Brovelli M. A., Cannata M. and Longoni U. M., 2004, LIDAR data filtering and DTM interpolation within GRASS, *Transactions in GIS*, vol. 8, iss. 2, pp. 155-174.

Brovelli M. A., Cannata M., 2004, Digital terrain model reconstruction in urban areas from airborne laser scanning data: The method and an example for Pavia (Northern Italy), *Computers & Geosciences*, vol. 30, pp. 325-331.

GRASS website: <http://grass.itc.it/>

Kraus K., Pfeifer N., 2001, Advanced DTM generation from LIDAR data, *IASPRS*, Vol. XXXIV – 3/W4, Annapolis, MD.

Neteler M., Mitasova H., 2002, *Open Source GIS: A GRASS GIS Approach*, ISBN: 1-4020-7088-8, Kluwer Academic Publishers, Boston, Dordrecht, Book Series: The Kluwer international series in Engineering and Computer Science: Volume 689.

OSGeo website: <http://www.osgeo.org/>

Sithole, G., Vosselmann, G., 2004: Experimental comparison of filter algorithms for bare-Earth extraction from airborne laser scanning point clouds. *ISPRS JPRS*. Volume 59, Issues 1-2.

Sithole, G., 2005: "Segmentation and Classification of Airborne Laser Scanner Data. Ph.D. Thesis. Publications on Geodesy, 59. Publications of Netherland Geodetic Commission. ISBN 90 6132 292 8, 184 pages.

