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DIGITAL ELEVATION MODELS DERIVED BY ALS DATA: SORRENTINA PENINSULA TEST AREAS

Luca Pizzimenti[1], Alessandro Tadini[2,3], Roberto Gianardi[4], Claudia Spinetti[5], Marina Bisson[3], Carlo Alberto Brunori[1]

[1]**INGV** (Istituto Nazionale di Geofisica e Vulcanologia, Sezione Sismologia e Tettonofisica)
[2]**Università di Firenze** (Dipartimento di Scienze della Terra)
[3]**INGV** (Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa)
[4]**Università di Pisa** (Dipartimento di Scienze della Terra)
[5]**INGV** (Istituto Nazionale di Geofisica e Vulcanologia, Centro Nazionale Terremoti)

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Introduction

The digital representation of the Earth surface is essential in any disciplines of the Geosciences. An accurate mapping of the Earth's surface at different scales is considered a prerequisite for modeling natural phenomena as water flow, mass movement, structural and tectonic deformations. For instance, in the geomorphological context, the availability of accurate digital topography improves the knowledge of structural elements and tectonic alignments [e.g. Azzaro et al., 2012], allows to better define the source areas of landslides [e.g. Bisson et al., 2013] and to reconstruct a detailed drainage network [e.g. Ozdemir and Bird 2009]. In the volcanological context, the topography becomes fundamental in order to map the invasion areas of lava flows [e.g. Felpeto et al., 2001; Tarquini and Favalli 2010], pyroclastic flows [e.g. Esposti Ongaro et al., 2008] and volcanoclastic debris flows and lahar [e.g. Muñoz-Salinas et al., 2009]. Also, in the hydrogeological studies, an accurate topography allows to reconstruct the surface of glaciers [e.g. Arnold et al., 2006], the relative changes in thickness during the time, and to identify areas invaded by possible flood or overflows of rivers [e.g. Khuat Duy et al., 2010].

Terrain models reproduce the variation of terrain elevation through a continuous surface by interpolating a large amount of 3D points georeferenced into a specific cartographic system [Li et al., 2004]. In detail, Earth digital models can be classified in three typologies: the Digital Elevation Model (DEM), the Digital Terrain Model (DTM), and the Digital Surface Models (DSM). The DEM derives from the processing of bare soil elevation (ground). The DTM includes the ground elevations and natural features such as the levee of rivers, the boundary of the lakes, the edge of a crater, and many others. The DSM is the restitution of the landscape based on heights of bare soil, vegetation and anthropic features.

The elevation data of the terrain can be acquired by using the traditional method based on digitalization of raster cartography combined with GPS survey or more recently through remote sensing techniques such as the Light Detection and Ranging (LiDAR) technology. The models can be stored in two digital formats: TIN (Triangulated Irregular Network) and Raster. The first is a vector model represented by a network of triangles where each point has an elevation, the second is a numeric matrix where the elevation is stored in each cell. The resolution of the spatial model is defined by the density of input points in case of TIN format and by the cell size in case of Raster format.

In this technical report the high-resolution DEMs of two municipalities of the Sorrentina Peninsula (Naples and Salerno provinces, Southern Italy) obtained after processing Airborne LiDAR data, are presented. The two above-mentioned municipalities represent two test areas corresponding to the Amalfi/Conca dei Marini and Castellammare di Stabia municipalities respectively. The availability of high-resolution DEMs represents one of the key elements for morphometric analyses useful for landslide hazard investigation [Bisson et al., 2013]. The hazard investigation in Peninsula Sorrentina is the aim of the LCC project [Spinetti et al., 2016].

1. LiDAR technology

The Light Detection and Ranging (LiDAR) is a remote sensing technique that allows to acquire great amounts of a surface X, Y, Z points ("points cloud") by scanning the surface with a laser instrument. If the laser is mounted on an aircraft or helicopter the technique is called Airborne Laser Scanning (ALS); if the laser is fixed on the ground the technique is called instead Terrestrial Laser Scanning (TLS).

In this report, we deal with the ALS technique. This technique allows to investigate a study area flying with an aircraft or helicopter equipped with an active sensor (laser), a GNSS receiver (Global Navigation Satellite System) and an Inertial Navigation System (INS). During the flight the LiDAR sensor emits a focused beams of laser (pulse). The pulse repetition frequency (PRF), defined as the number of pulses emitted per second, can reach more than 10^5 pulses/points per second. The beam hits the target on the surface (ground, vegetation, anthropic structures, etc.) and the return signal is recorded by the instrumental system. This system i) measures the two-way travel time of light from the sensor to the target, ii) defines the position and attitude of the aircraft through the GNSS and INS system (since the value of the speed of light is known) and therefore iii) is able to acquire the geometric position (X, Y, Z) of each scanned target/point of the Earth surface.

During an ALS scanning, a series of elements must be recorded to allow a correct data acquisition: i) the flight path (ground track and flight height); ii) the scan angle; iii) the footprint diameter (area illuminated by each beam), that is the diameter of the pulse intercepted by a plane positioned perpendicularly to the pulse axis at a distance from the instrument equal to a nominal flight height [Gatziolis and Andersen, 2008]; iv) swath width; v) the overlapping zones between adjacent swaths in order to achieve a more uniform distribution of points over the ground; vi) the Pitch, Roll and Yaw parameters (used to define the correct position of aircraft) recorder by the IMU (Inertial Measurement Unit); vii) across-track resolution (across-track spacing of the laser pulses); viii) along-track resolution (see Figure 1).

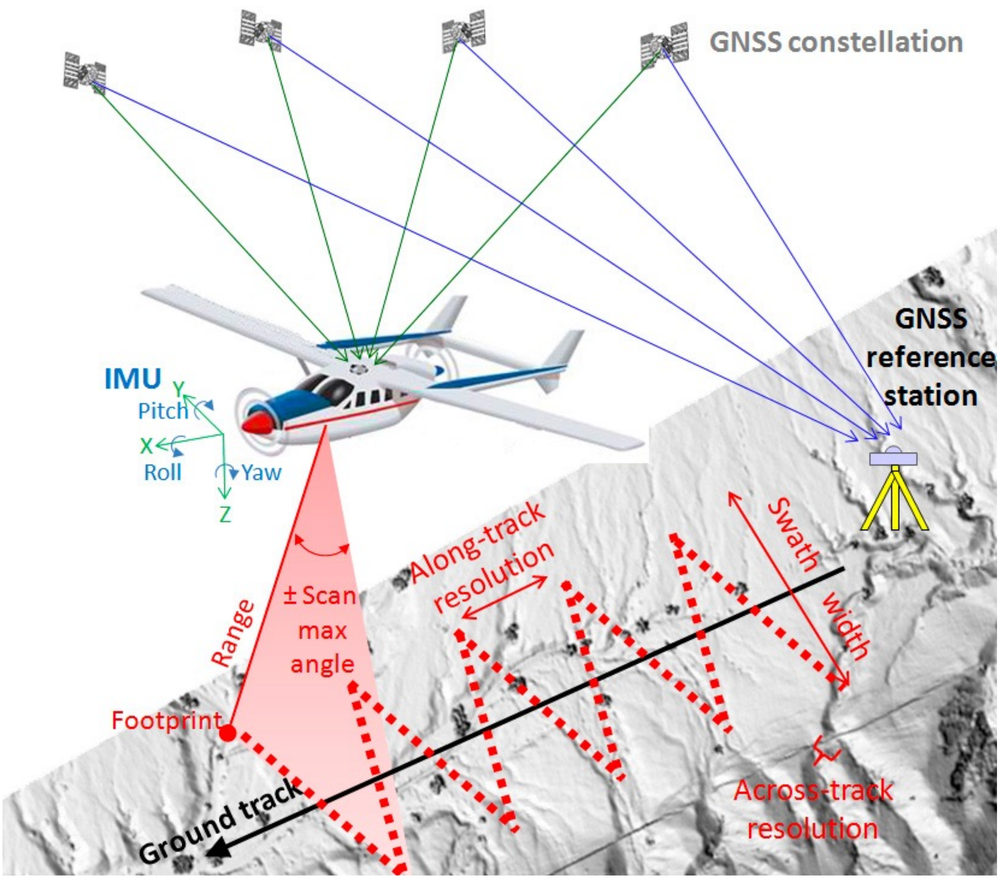

Figure 1. Schematic diagram illustrating the basic operational principles and main system components of ALS technology. Ground track is the projected flight direction. Integrated navigation system (INS) processes and combines observations of IMU (Inertial Measurement Unit) and GNSS (Global Navigation Satellite System). Airborne LASER scanning is performed along two dimensions: the first dimension is along the airplane flight direction and is achieved by the forward motion of the aircraft. The second dimension, generally perpendicular to the flight direction, depends on a scanning mechanism and the aircraft motion, defining the laser pulses distribution over the ground. Independent of the scan mechanism employed, the system scanning angle and flying height determines the swath width. The scanning frequency and PRF determine the across-track spacing of the laser pulses (Across-track resolution). The aircraft ground speed and scan frequency determine along-track resolution [Fernandez–Diaz et al., 2014].

In details, the ALS is classified as single pulse system if it detects the return signal from a pulse before emitting a second pulse; whereas it is defined multi-pulse system if it fires a second or third pulse before receiving the returns from the first pulse. In addition, for each single pulse the system can record more return echoes (Figure 2). The intensity of these echoes is defined as signal Amplitude. Each typology of the target hit by the pulse responds with one or more echoes characterized by different amplitude that allow to distinguish ground from vegetation or anthropic features.

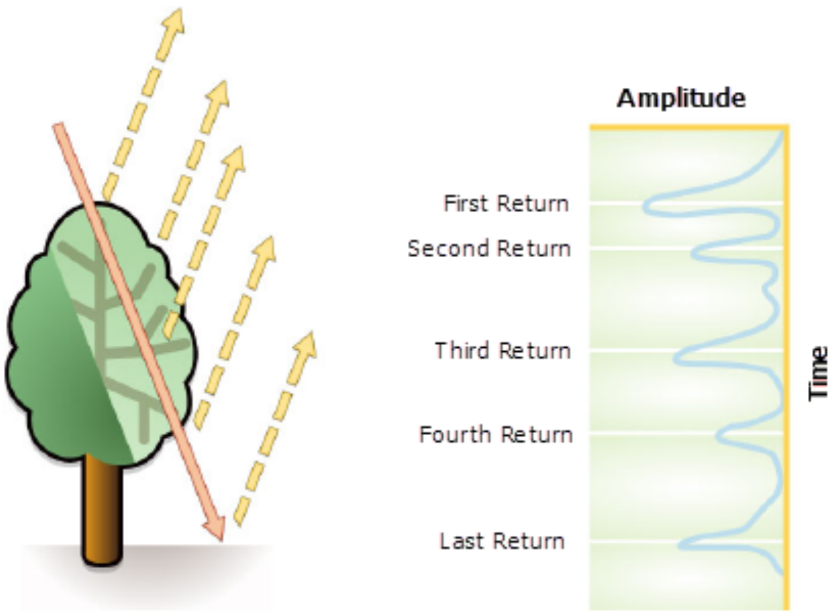

Figure 2. The return echoes.

Most of LiDAR sensors operate in the near-infrared wavelength region of the electromagnetic spectrum, in particular with the wavelength corresponding to 1064 nm.

In this work, the elaborations of LiDAR data acquired by BLOM CGR *S.p.A.* with different specific sensors are described. In details, ALTM Gemini is used for the Conca dei Marini and Amalfi municipality, whereas RIEGL LMS-Q680i sensor was used for Castellammare di Stabia area (see Table 1). The ALTM 3100EA and ALTM Pegasus sensors are used to acquired data by BLOM CGR *S.p.A.* in the other municipalities of the Sorrentina Peninsula.

Sensor	*Frequency*	*Scan Angle*	*Flight height*	*Vertical accuracy*	*Horizontal accuracy*	*Echoes number*
ALTM Gemini	0 - 70 Hz	0 – 50 °	150 – 4000 m	5 - 30 cm; 1 σ	1/5500 x flight height; 1 σ	Up to 4
ALTM 3100EA	0 -70 Hz	0 – 25°	80 – 3500 m	<15 cm at 1.2 km - 1 σ; <25 cm at 2.0 km - 1 σ; <35 cm at 3.0 km - 1 σ;	1/2000 x flight height; 1 σ	Up to 4
ALTM Pegasus	0-140 Hz	0 – 75°	300-2500 m	5-15 cm, 1 σ	1/5500 x flight height; 1 σ	Up to 4
RIEGL LMS-Q680i	80-400 Hz	± 30 °	800-5000 m	2 cm	2 cm	Up to 3

Table 1. LiDAR sensors characteristics.

The main performance characteristic of Airborne LiDAR sensor is the high degree of accuracy (vertical and horizontal) of acquired data that permits to create Digital Elevation Models with very high resolution. Typically, the airborne LiDAR-derived elevation points have absolute accuracies ranging from 15 to 30 cm and to 10 - 20 cm in X and Y, respectively, depending on flight acquisition elevations [Carter et al., 2012].

This characteristic depends on several factors among which we report the most important: i) the instrumental accuracy of the sensor used during the acquisition; ii) the GPS system used and the relative data processing; iii) a suitable GPS coverage; iv) the atmospheric conditions (humidity content, presence of cloud, etc.).

Moreover, we introduce a short discussion on the positive and negative aspects offered by the Airborne LiDAR technology. As regards the advantages we can summarize as follows:

a) Rapid acquisition of a large number of data on over large areas at very high resolution.
b) Acquisition of terrain elevation data in not easily accessible areas, such as zones with very dense vegetation.
c) Easy integration of acquired data with other data in a GIS environment.
d) The data acquisition can occurs during day or night under clear weather conditions.

As what concerns the disadvantages, LiDAR technology does not always is the best solution for the acquisition of 3D data. For example:

a) LiDAR surveys are cost effective for large areas because of system mobilization, acquisition and post – acquisition operations. LiDAR survey is infact expensive for the mobilization of all the system and for the associated aerial photography survey. On the contrary, the cost is reduced if the investigation concerns large areas.
b) Very steep slopes can influence the accuracy data: the relationship between slope and vertical accuracy is known to be influenced by the amount of horizontal error in the LiDAR system, due to the built–in horizontal error of the survey system, resulting from the aircrafts' GPS, INS and IMU systems. [Tinkham et al., 2012; Bater & Coops, 2009].
c) In case of very dense vegetation the acquisitions of the ground points becomes difficult. Infact, in mountain forests the beam does not always reach the ground and, consequently, the dense undergrowth may be confused with bare soil. However, by increasing the pulse density (i.e., the number of pulses emitted from the LiDAR sensor per unit space) ther is a greater likelihood that more pulses will pass through openings in vegetated canopies and reach the ground. [Hodgson et al., 2005].

2. Amalfi and Conca dei Marini

The Amalfi and Conca dei Marini municipalities are located in the southern part of Sorrentina Peninsula (Figure 3). They cover a surface of about 7.4 km^2 with a population of almost 6000 inhabitants [ISTAT, 2011].

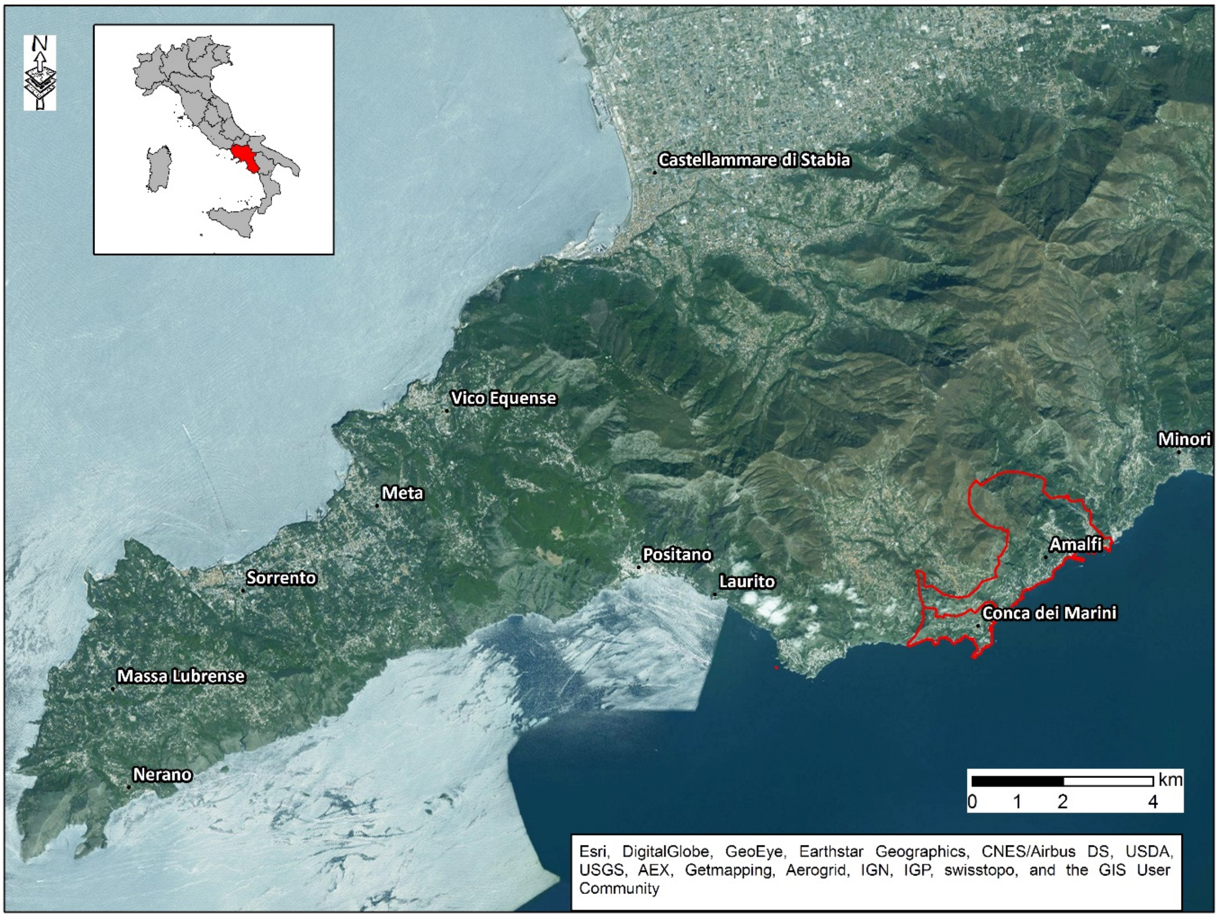

Figure 3. Amalfi and Conca dei Marini municipalities (in red) and the Sorrentina Peninsula between the Gulf of Napoli and Gulf of Salerno.

2.1 Data Source

The Amalfi and Conca dei Marini Raw data have been provided by Ministero dell'Ambiente e della Tutela del Territorio e del Mare (MATTM) with Licence Creative Commons 3.0 Italy (CC BY-SA-3.0IT).

The study area is covered by four strips oriented in NE-SW direction acquired by the airborne flight on 12th of February 2008. In figure 4 raw data strip files are showed.

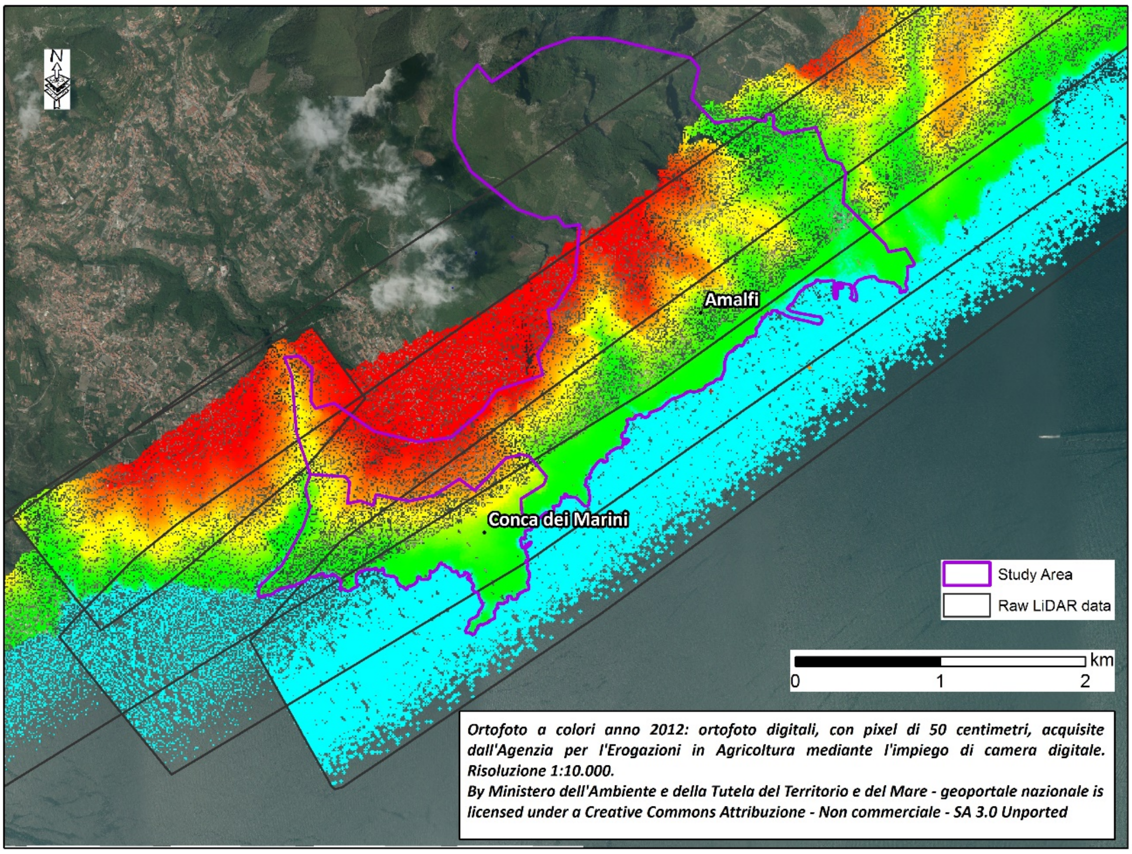

Figure 4. LiDAR strips Raw data.

The files containing the clouds of points of the LiDAR strips stored in the .LAS format that is a public file format for the interchange of 3D point cloud data. This format supports the exchange of any 3-dimensional x, y, z tuplet. This binary file format is an alternative to proprietary systems or a generic ASCII file interchange system used by many companies (asprs - *https://www.asprs.org/*).

From the LAS files we extract for each acquired point the X and Y geographic coordinates, Z elevation, the number of laser pulse returns to the sensor and the relative intensity. The acquired Z value is the elevation referred to the WGS 84 ellipsoid that will be converted into orthometric height referred to geoid EGM2008 (Earth gravitational Model 2008). Raw data were originally acquired in geographic coordinate system lat/long WGS84 and then converted in projected coordinate system WGS84 UTM Zone 33.

2.2 Data elaboration and procedures

A digital terrain model is a mathematical (or digital) model of the terrain surface. It is obtained by using one or more mathematical functions named interpolation functions that work on a set of measured data points to reproduce the topography.

The procedures used to elaborate LiDAR data and to create the best representation of bare soil are based on LAStools commercial software suite (Figure 5), (Martin Isenburg, LAStools - efficient tools for LiDAR processing. version 160429) a collection of highly efficient scripts that permit to classify, organize in tiles, convert, filter, raster, triangulate, etc. LiDAR data.

In this work we process LiDAR data by means a customized and highly automated procedure running the opportune sequence of *LAStools* scripts (*lastile*, *lasground new*, *lasheight* and *lasclassify*).

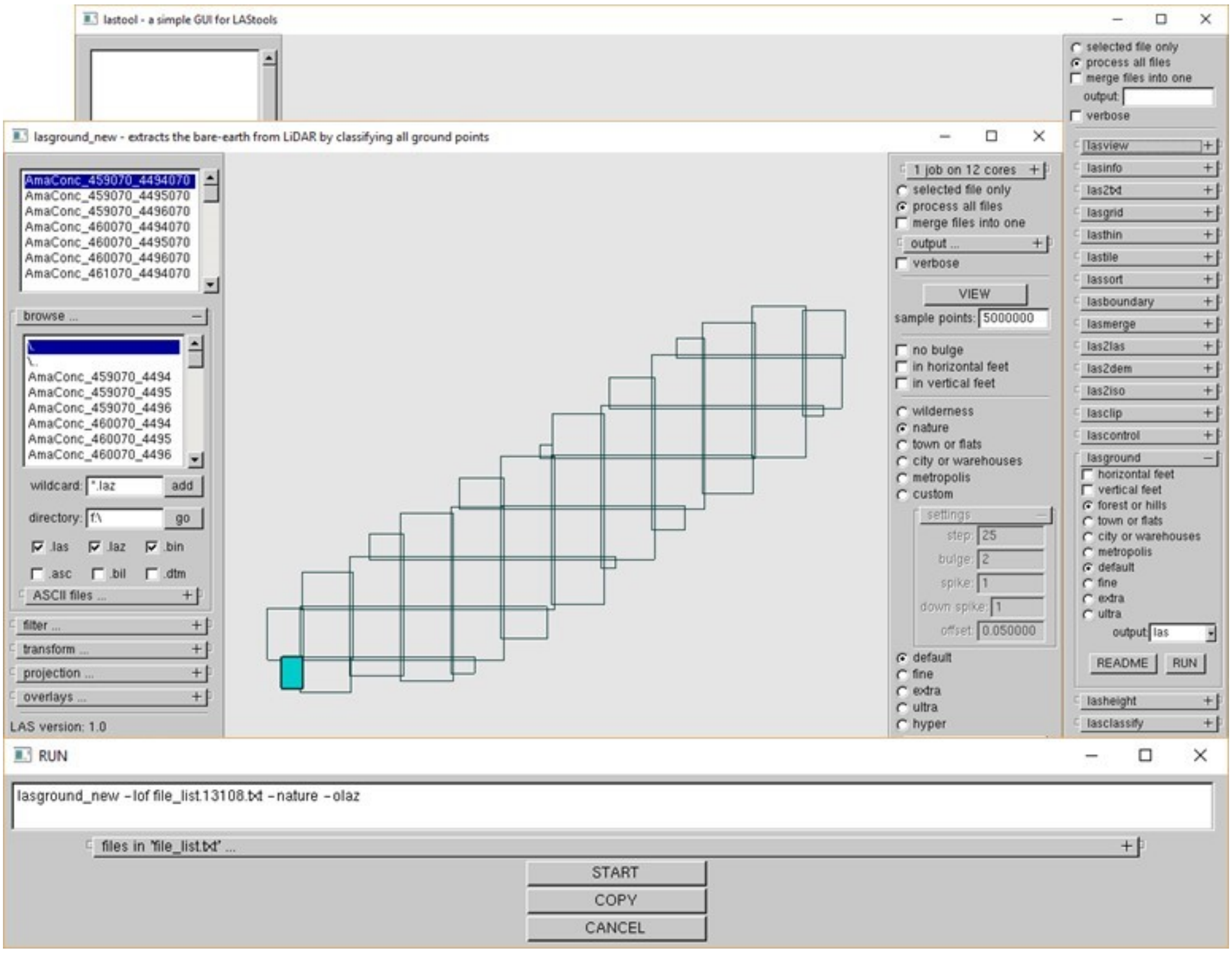

Figure 5. LAStools commercial software suite (rapidlasso GmbH - https://rapidlasso.com/).

The workflow in figure 6 shows the sequence of the used tool.

Figure 6. Workflow of LiDAR data processing.

The first step consists of organizing raw strips into 1 km squared overlapping tiles (30 meters of overlap) (Figure 7). In the second step the bare soil points are extracted by classifying LiDAR acquisitions into ground point (class = 2) and non-ground points (class = 1). In the third step the script computes the relative height of each non-ground points (class = 1) with respect to the height of nearest points of class = 2 (bare soil) (Figure 8). In the fourth step, all these points are classified as buildings and vegetation. In the last step, the overlapping portions between tiles are removed.

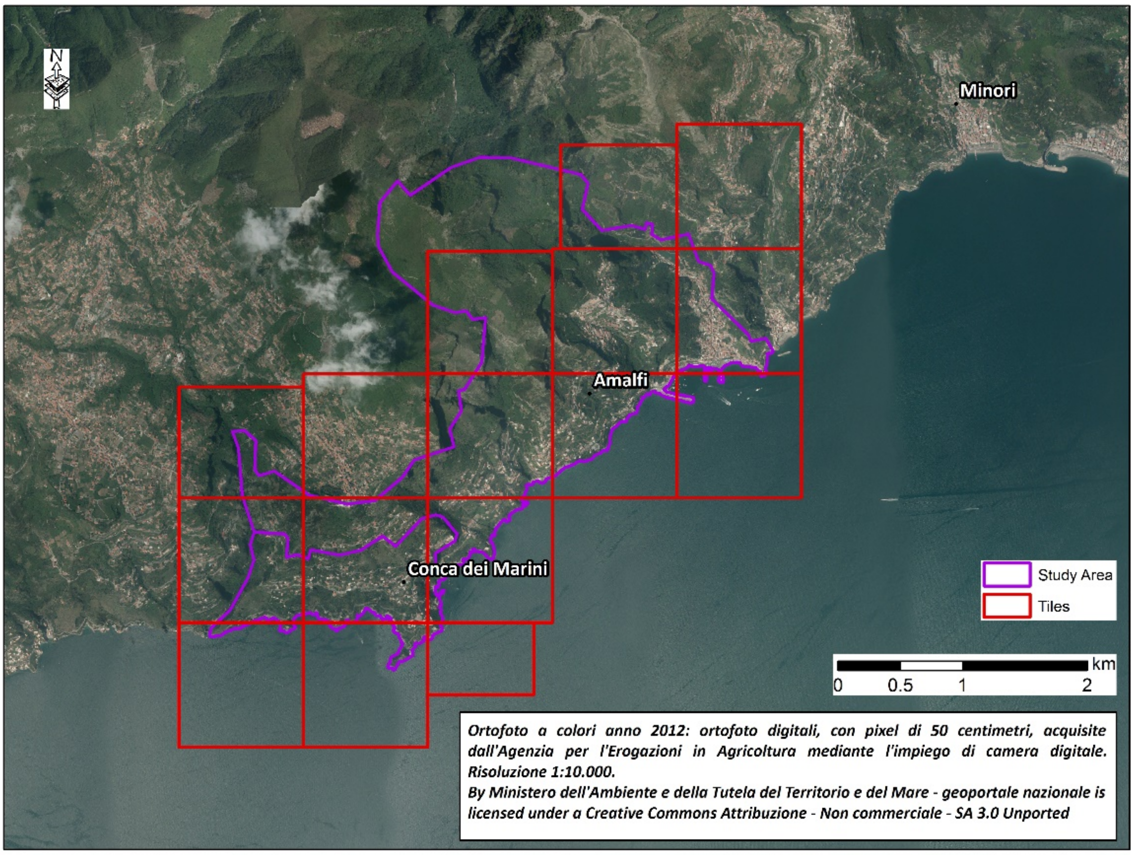

Figure 7. Amalfi and Conca dei Marini areas covered by LiDAR data in 1km × 1km tiles format.

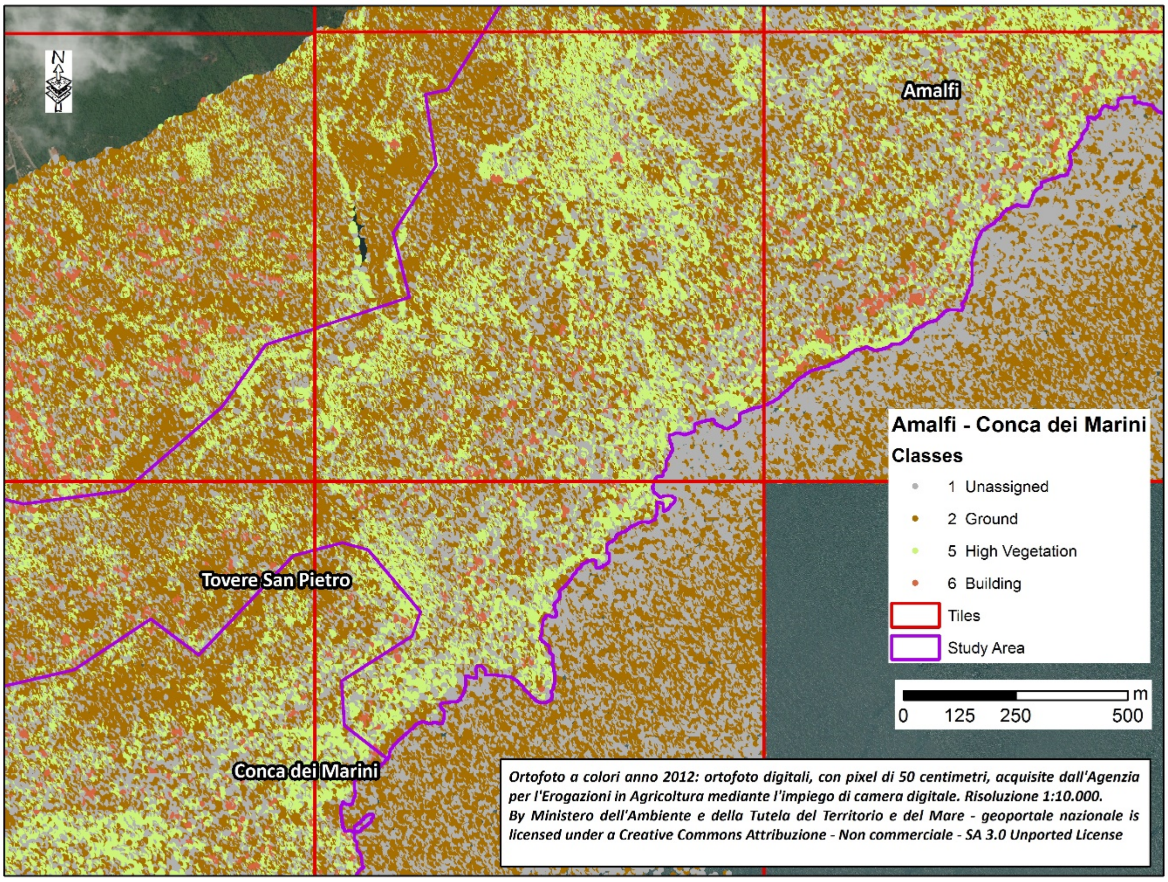

Figure 8. Points cloud classification with classes description.

At this point of the work, the LAS Dataset (LASD) is created. In this way is possible visualize and analyze directly LAS files in their native format and calculate detailed statistics for original and derived information such as extension of areas covered by LiDAR acquisition, number of returns for each point, point number for each class, etc. (Figure 9).

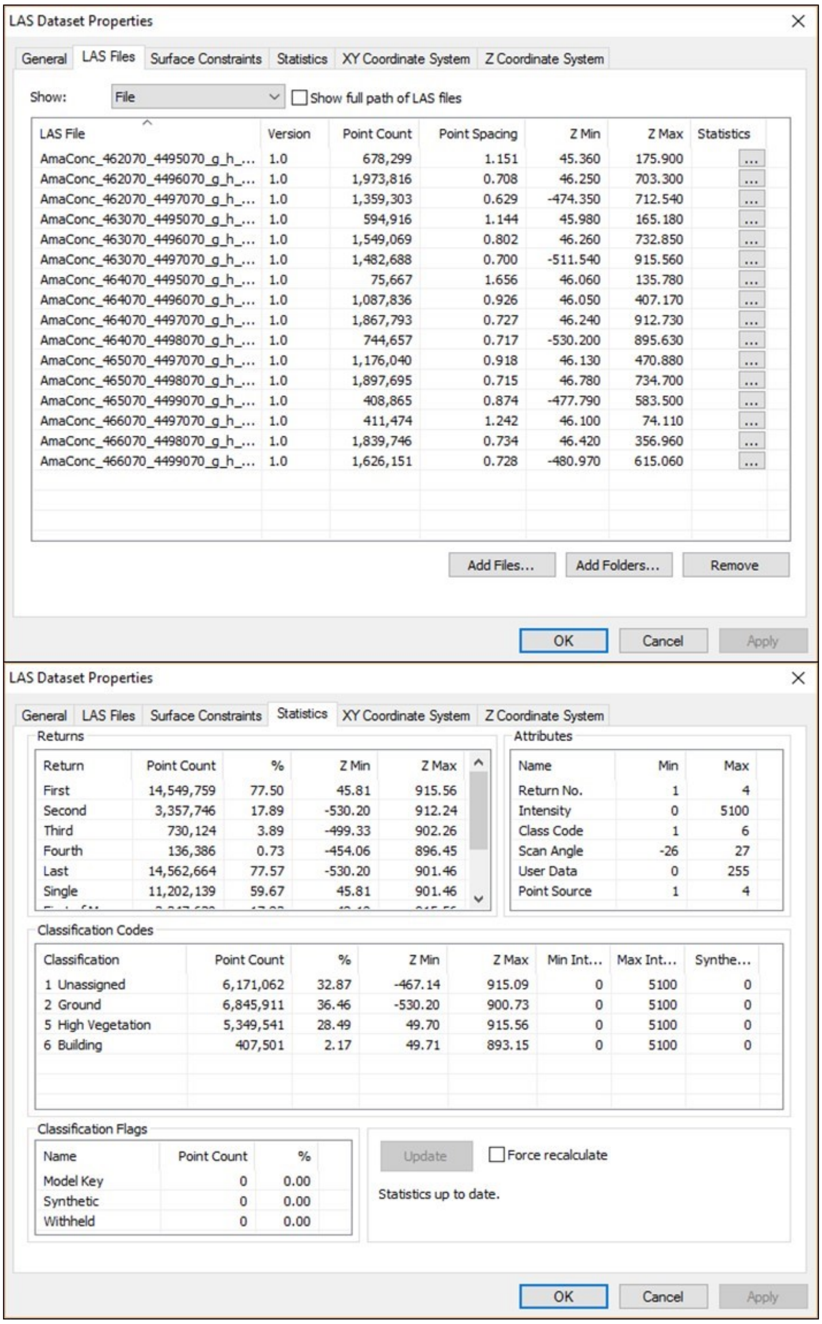

Figure 9. LAS statistical properties.

The following elaborations were performed in ArcGIS environment using the LAS dataset toolbar. This toolbar allows the display LiDAR points as a TIN or points cloud and it provides others facilities useful for the classification quality control before the production of the digital terrain model (DTM). For instance, using LAS dataset tools we can produce elevation profiles that allow the visualization, analysis and editing of LiDAR points, in order to correct the misclassified ones. The misclassification can occur in several environment such as in densely urbanized areas or particular morphological context characterized by steep slopes. In the Amalfi urban center case, the profile is shown in Fig. 10 highlighting the wrong classification of building (red points).

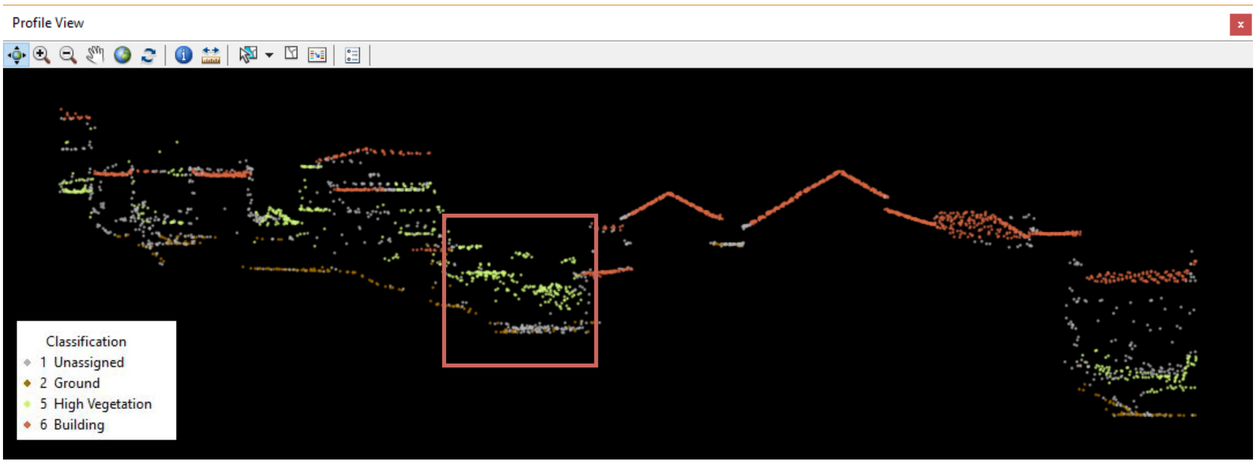

Figure 10. LiDAR points classification in densely urbanized area of Amalfi. The red box highlights a sector visible with greater detail in the next figure (figure 11).

These issues have been solved with a manual intervention reclassifying those points and removing the spikes that altered the results (Figure 11).

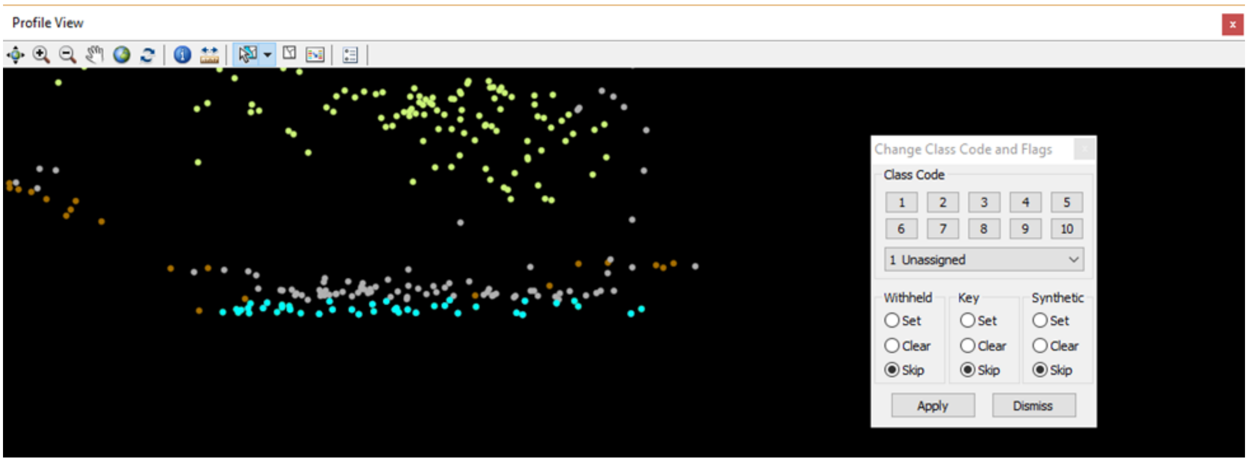

Figure 11. Example of class editing. In light blue color highlighted points for the editing.

In order to choose cell size for the DEM construction, by means the Point File Information tool it is possible to generate statistical information about all tile that in our case indicates a value of 2 meters (Figure 12).

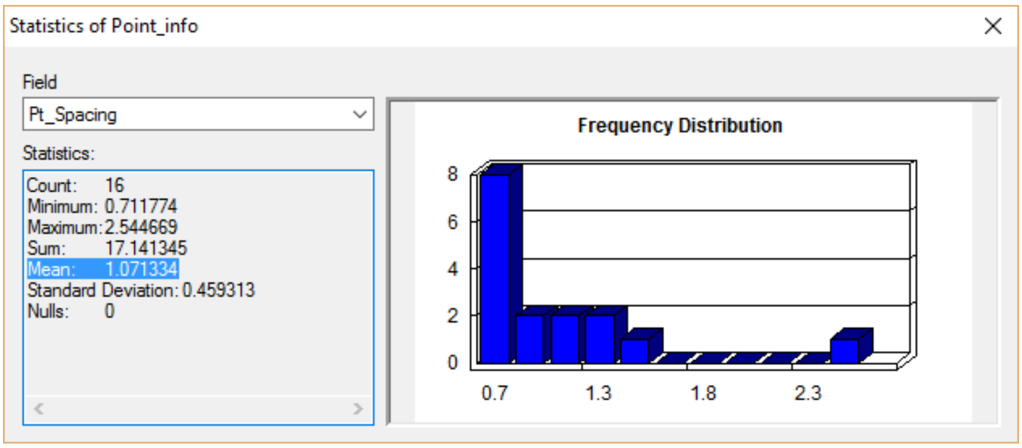

Figure 12. Frequency distribution of points cloud to define the average point spacing.

In order to interpolate the points cloud, we have chosen the Inverse Distance Weighting (IDW) algorithm obtaining an elevation matrix with spatial resolution of 2 meters. The IDW algorithm interpolates a set of weighting points to reproduce a surface variation. IDW determines cell values using a mathematical function of points weighted according to the distance between the input point and the output cells. The greater the distance from the input point and the output cell, the less influence the input point. In this work, the function used is the polynomial equation with an exponent set up p = 2 (Figure 13).

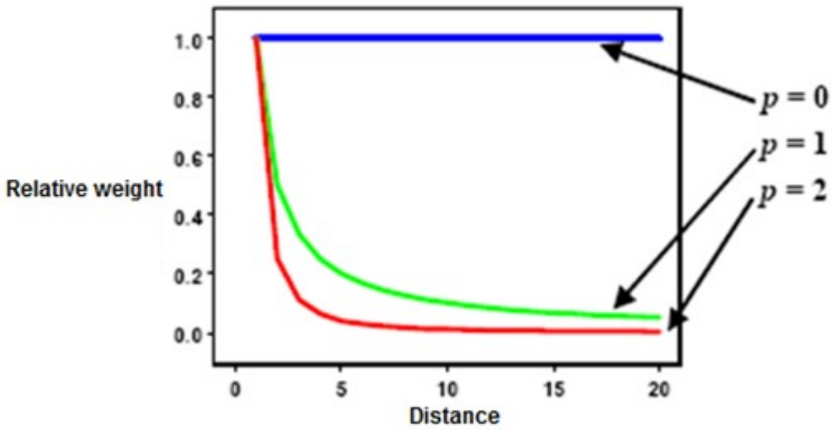

Figure 13. Behavior of weight with distance illustration.

The digital terrain model obtained shows in each cell an elevation in WGS84 ellipsoid coordinates. So, it is necessary to convert the heights into geoid heights, summing or subtracting the geoid undulation values (N), defined as the difference between the ellipsoid and the geoid elevation in a specific earth surface point (p) using the relations:

$$h = N + H \tag{1}$$

$$H = -N + h \tag{2}$$

Where: N is the geoid ondulation; *H* is the orthometric height of the point (p); *h* is the ellipsoid height of the point (p).

This operation was carried out using EGM 2008, Global 2.5 Minute Geoid Undulations released by U.S. National Geospatial – Intelligence Agency (NGA).

2.3 Resulting Maps

Finally, the result of previous processes is represented in Figure 14.

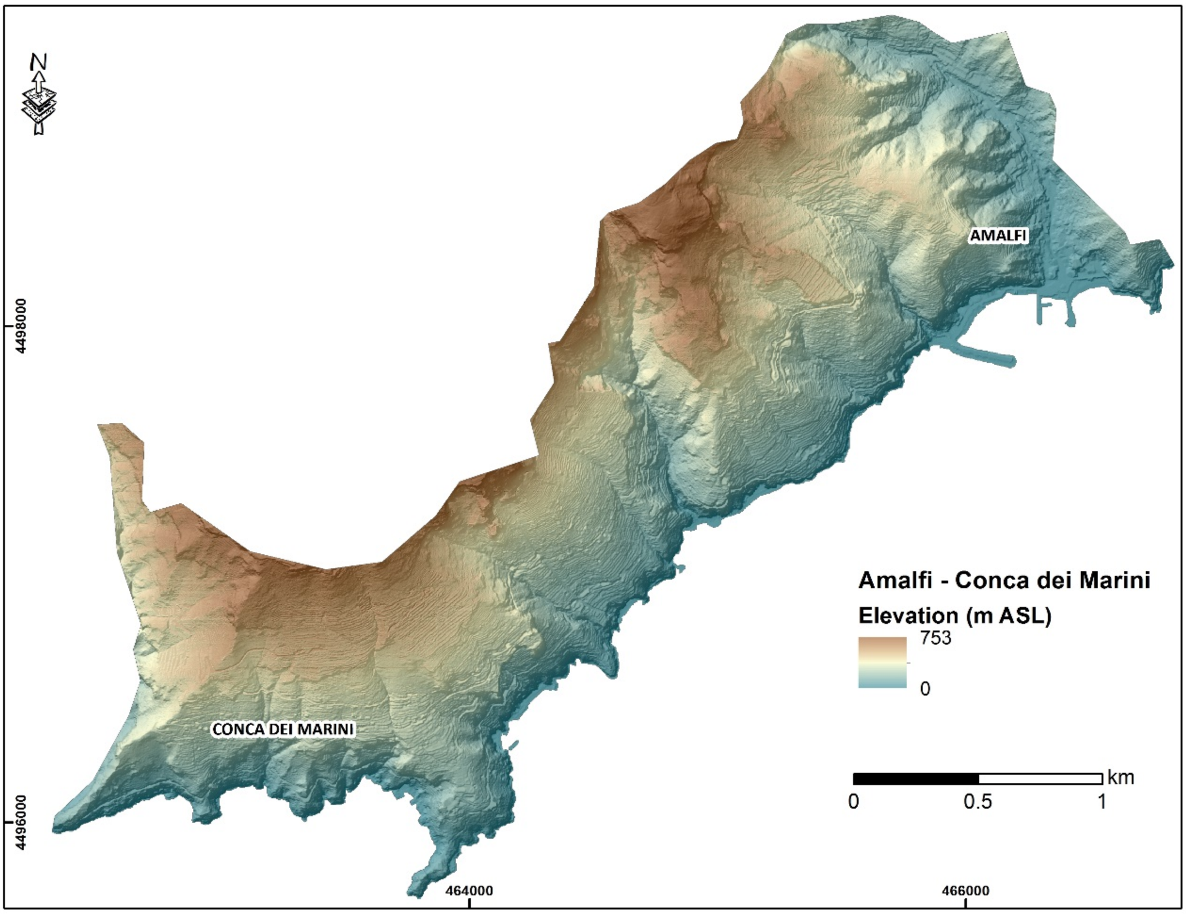

Figure 14. Amalfi and Conca dei Marini Digital Elevation Model result.

The resulting DEM (Figure 14) is composed of a total of almost 1.3 million cells with 2×2m cell size with a minimum value of -1 m and a maximum value of 752.9 m. 13906 are the cells with height values lower than 0 m. These cells are located along the coastline and some of these are close to the transition between sea cliffs and sea level. Moreover, the unavailability of an accurate coastline affected the determination of the true transition between the terrestrial domain and the sea domain.

3. Castellammare di Stabia

The Castellammare di Stabia municipality is located in the northern part of Sorrentina Peninsula (Figure 15). It covers a surface of about 18 km^2 with a population of almost 66000 inhabitants [ISTAT, 2011].

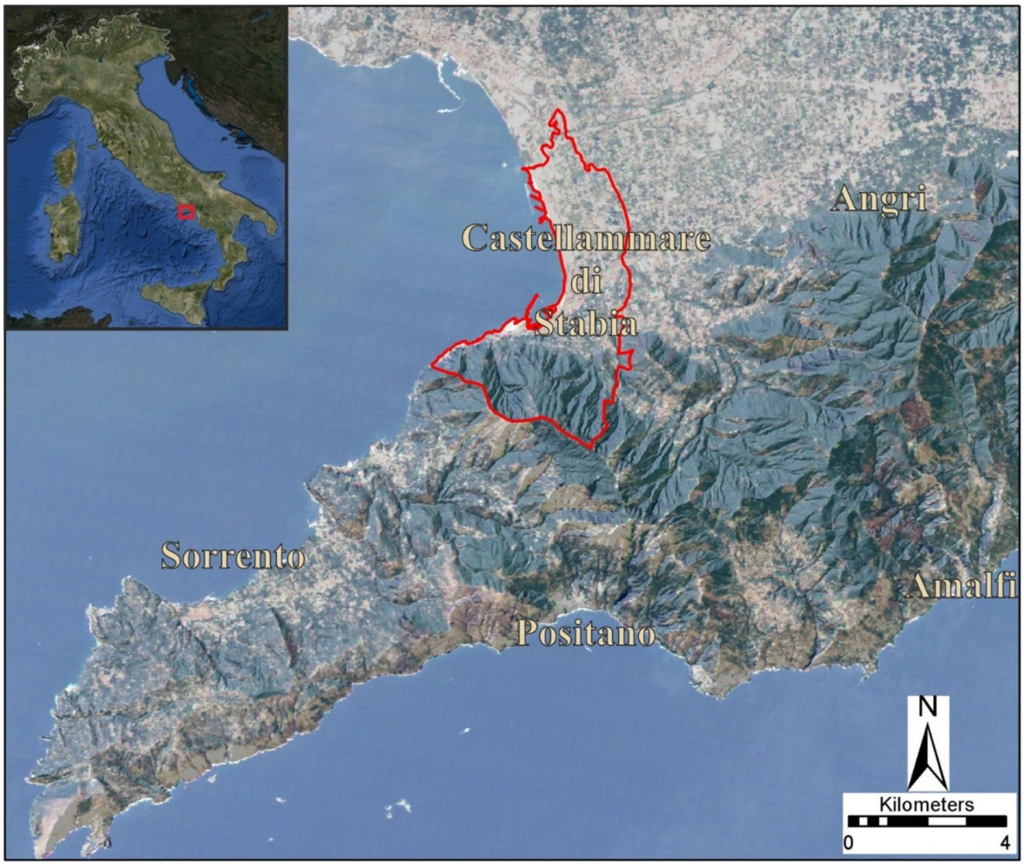

Figure 15. Castellammare di Stabia municipality (in red) and the Sorrentina Peninsula beetween the Provincia di Napoli and Provincia di Salerno (landsat image from Fornaciai et al., [2008]).

3.1 Data Source

The 3D LiDAR data used to create topography of Castellammare di Stabia municipality have been provided by the "Ufficio Sistema Informativo Territoriale (SIT)" of the "Provincia di Napoli" Project of Digital Mapping of the entire Provincia di Napoli (Project "Centro Satellitare Cave della Provincia di Napoli – Ce.CO.SCA"). This Project was aimed to acquire and elaborate 3D points in the entire Provincia for producing a very high Digital Surface Model (DSM) and a Digital Terrain Model (DTM) geocoded to WGS84 UTM ZONE 33 reference coordinate system. The 3D points were acquired through two airborne fields dated 2009 and 2012 performed with a RIEGL LMS-Q680i sensor. This sensor permits to make 2.66 $x10^5$ measurements per second on the ground with an instrumental horizontal and vertical accuracy ranging up 20 mm. Both DSM than DTM were provided in 5451 ASCII files (3615 from 2009 and 1836 from 2012) stored as matrices of 500 rows x 500 columns with a cell size of 1 meter.

In details, Castellammare di Stabia municipality was covered by a total of 110 ASCII files: 52 coming from the 2009 flight and 58 from the 2012 flight. Figure 16 shows the reference frame that organizes the source data of Castellamare di Stabia in 110 tiles.

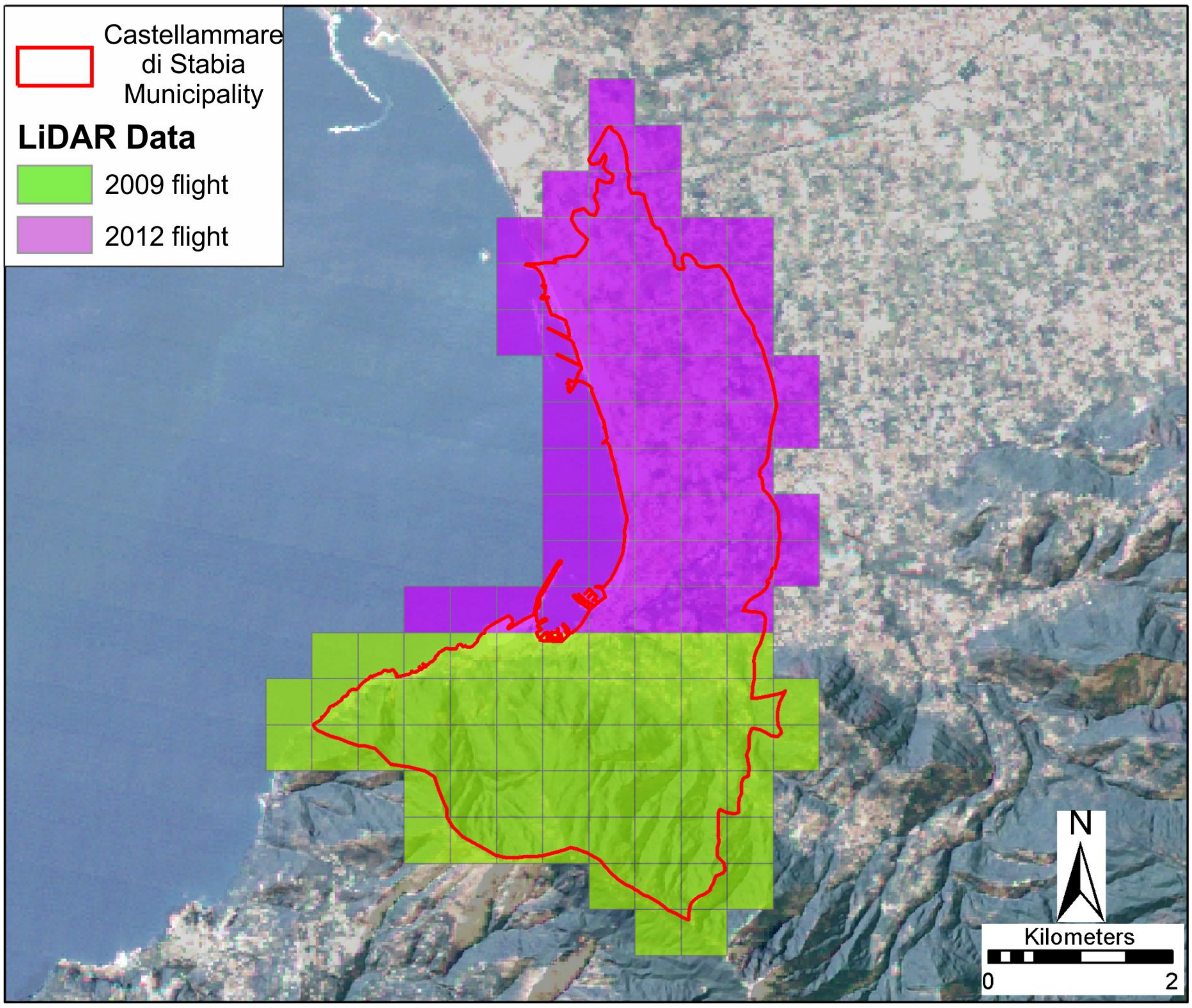

Figure 16. Castellammare di Stabia municipality with the LiDAR reference frame highlighting different date of data acquisition (Landsat image from Fornaciai et al., [2008]).

3.2 Data elaboration and procedures

During the elaborations of the source data, several issues have been encountered, including: i) incorrect digit of several ASCII files corner coordinates (which were lacking the decimal digits); ii) lack of data in some inland parts of the municipality; iii) imprecise delineation of the coastline. All the elaborations have been performed working in GIS environment, and in detail using the tools available on ESRI ArcGIS® 10 platform (Figure 17).

Regarding point i) we have verified that some ASCII files did not overlap perfectly with the grid corners of the related reference frame, while others matched perfectly. The former ones were recognized to be lacking (in the ASCII) the decimal part of the coordinates of the lower left corner, 0.17 for the X and 0.46 for the Y. Due to the high amount of ASCII files, we took advantage of a specific tool “Model Builder”. This tool allows to develop routines for the iteration of high amount of data. In our case ASCII files which were missing the decimal part of the lower left X and Y coordinates are used as input data for routine “Model Builder”.

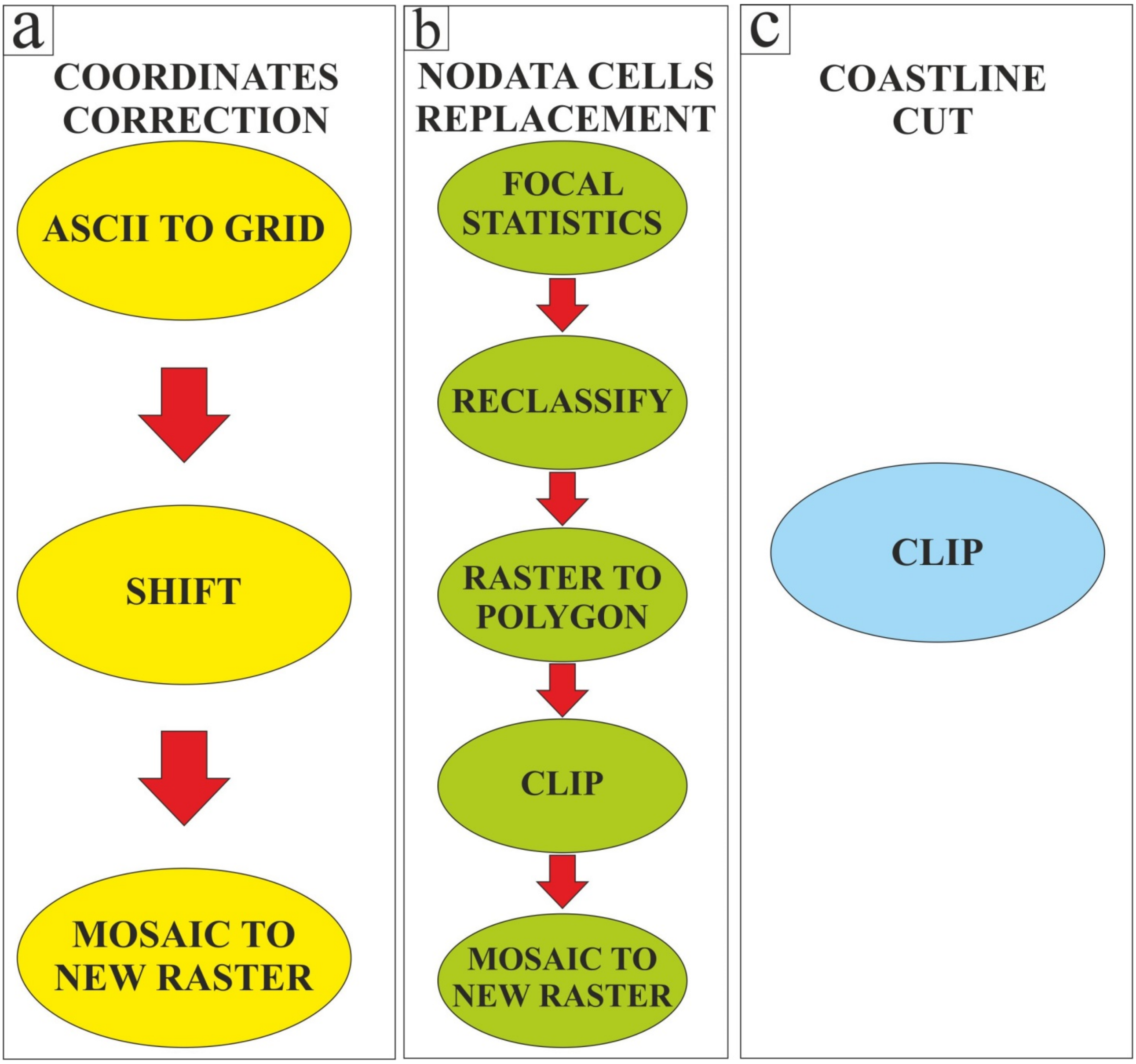

Figure 17. Workflow for different tools usage through data elaboration as described in the text.

Through the "Model Builder" routine, a sequence of logical elaborations was implemented. Firstly, the conversion of all the ASCII into Raster GRID format, then the shift of 0.17 m towards W and of 0.46 m towards N, subsequently a conversion into ASCII again (this latter step was performed in order to keep track of a correct version of the original raw data) and finally the merging of all grids (corrected and remaining) into a global DEM using the tool "Mosaic to New Raster" (Figure 17a).

Regarding point ii), the problem of the sparse lacking of data (individuated in the ASCII and in the related GRID as "NoData" cells) was solved by filling such cells with values resulted from the mean of the values of the adjacent cells. This step was performed with the "Focal statistics" tool. This tool performs a neighborhood operation that computes an output raster where the value for each output cell is a function of the values of all the input cells that are in a specified neighborhood around that location. The final output result of such operation is a new raster which can be qualitatively defined as "blurry" with respect to the original one. For our purposes, we performed a focal statistics using a 3x3 neighborhood filter. Successively, the "NoData" parts of the original raster were filled with the following procedure: a) reclassifying the original raster (using the "Reclassify" tool), giving the values 0 and 1 to cells with "NoData" and to cells with any value, respectively; b) creating a polygonal shapefile using only inland cells with the value 0 (using the tool "Raster to Polygon"); c) this new shapefile is used to clip the raster derived from "Focal statistics" and to mosaic the resulting clipped parts with original raster, using the “Clip” and “Mosaic to New Raster” tools respectively. In this way, we obtained a final raster where most of its parts derive from original LiDAR data, while the former “NoData” cells have been replaced with cells created with the “Focal Statistics” tool. All the steps and relative tools for point ii) are summarized in Figure 17b.

Regarding point iii) the original source data comprised seaward part without any clear delineation of the coastline. In order to provide a correct representation of the coastline, the polygonal shapefile of the municipality boundary, updated to census dated 2011, was downloaded by ISTAT website (http://www.istat.it/it/archivio/124086) and slightly modified manually to reproduce the coastline more consistent with DEM Lidar data. The final product is a DEM cut according to the revised Castellammare di Stabia municipality boundary by using the “Clip” tool (Figure 17c).

3.3 Resulting Maps

The resulting DEM (Figure 18a) is composed of a total of more than 17 million cells with a minimum value of -0.5 m and a maximum value of 1198.4 m, respectively.

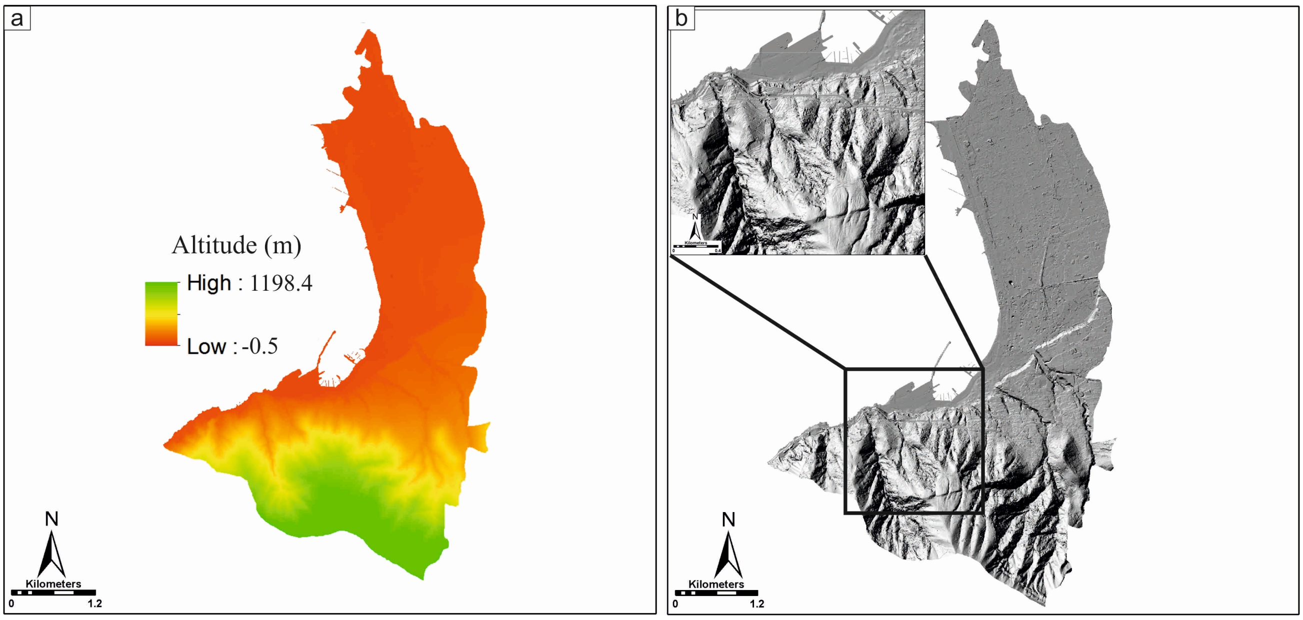

Figure 18. a) DEM of the Castellammare di Stabia municipality; b) the shaded relief image of the Castellammare di Stabia municipality (the inset shows an enlarged area where the high quality of the surface can be easily appreciated).

Areas with height values lower than 0 m are referred to some cells along the coastline (few cm’s below 0) that are probably related to inaccuracy of the LiDAR sensor. From the point of view of the general distribution of plain-like versus mountain-like areas, we have chosen a threshold value of 145 m to discriminate between this two end-members (we have chosen this value because it represents a marked break-in-slope in this particular case). Most of the Castellammare di Stabia municipality has an elevation <145 m (10.7 km^2, 60.3% of the total) while the remaining part (7.02 km^2; 39.7% of the total) has an elevation >145 m.

Finally, with the aim to facilitate future identification of main geomorphologic features of the municipality area, the shaded relief was derived from DEM setting the illumination parameters (azimuth = 315° from N and dip direction = 45°; Figure 18b). The quality of the data can be appreciated from the inset in Figure 18b, where the enlargement shows the level of details of an area with a high density of morphological features (valley axes, drainage pattern, etc.) that can be easily identified and traced.

4. Concluding Remarks

This technical report summarizes all the steps performed in order to obtain high-resolution DEMs (derived from ALS LiDAR data) on two test areas of the Sorrentina Peninsula (Southern Italy) corresponding to the municipalities of Amalfi/Conca dei Marini and Castellammare di Stabia.

The topography of Amalfi/Conca dei Marini municipalities has been represented by means of a 2 m resolution DEM produced by:

- elaboration of the LiDAR raw data processing to classify 3D points;
- interpolation of the 3D point using the IDW algorithm for generating the bare soil surface;
- Conversion ellipsoidic to orthometric height by means of the Earth Gravity model EGM2008.

The topography of Castellammare di Stabia area has been represented through a 1 m resolution DEM through the following processing steps:

- Elaborations for solving intrinsic problems of source data (ascii raster);
- Statistical analysis and filtering procedure for filling lacks of few data;
- Mosaicking of the elevation matrices in Grid Esri format;
- Restitution of the final DEM and a shaded relief image.

In conclusion, high resolution topography data in Amalfi/Conca dei Marini and Castellammare di Stabia (2 m and 1 m, respectively) are the base topography of the LCC project [Spinetti et., 2016] and will be available for future studies aimed to hazard analysis.

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