

TERRA: Terrain Extraction from elevation Rasters 6 through Repetitive Anisotropic filtering 7 8 9

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19 ABSTRACT

20 Over the past decades, several filters have been developed to derive a Digital Terrain Model (DTM) from a Digital Surface 21 Model (DSM), by means of filtering out aboveground objects such as vegetation. In this filtering process, however, one 22 of the major challenges remains to precisely distinguish sharp terrain features, e.g. ridges, agricultural terraces or other 23 anthropogenic geomorphology such as open-pit mines, riverbanks or road ramps. Hence, loss of elevation data around 24 terrain edges (and consequent smoothing) is very common with existing algorithms. In terraced landscapes, the 25 preservation of precise geomorphology is of key importance in digital terrain analyses, such as hydrologic and erosion 26 modelling, or automatic feature recognition and inventorying. In this work, we propose a new filtering method called 27 TERRA (Terrain Extraction from elevation Rasters through Repetitive Anisotropic filtering). The novelty of the algorithm 28 lies within its usage of terrain aspect to guide the anisotropic filtering direction, therefore maximising the preservation of 29 terrain edges. We derived six DTMs from DSMs using UAV Structure from Motion (SfM) photogrammetry, laser 30 altimetry and satellite sources (grid resolutions ranging from 0.1-1.0 m). The results indicated a close agreement of DTMs 31 filtered using the TERRA algorithm and reference DTMs, while terrace risers were well preserved even under thick 32 canopies of vines and trees. Compared to existing filtering approaches, TERRA performed well in minimising Type I 33 errors (false ground removal), while Type II errors occurred locally where vegetation was covering the terrace edges. 34 Given the promising filtering performance, and supported by the minimal requirements of parameterisation and 35 computation, the TERRA algorithm could be a useful tool in DTM preparation for digital terrain analysis of agricultural 36 terraces and similar hillslopes characterised by a complex mosaic of sharp terrain and non-terrain features.

37 *Keywords:* Digital Terrain Model (DTM) extraction; terraces; anisotropic filtering; vegetation removal; edge preservation

38 Graphical abstract



39 40

41 **1. INTRODUCTION**

Topographic data are widely used as powerful supportive information in various fields of research and in civil applications, such as environmental management or landscape planning. With modern advances in remote sensing techniques, such data are increasingly accessible with improving level of detail (Passalacqua et al., 2015; Tarolli, 2014), often organised as regular-grid Digital Elevation Models (DEMs). Remotely sensed elevation data, however, typically contains both bare-earth and aboveground information such as vegetation cover (Digital Surface Model, DSM). Many

- 47 applications require either purely ground information (Digital Terrain Model, DTM), e.g. in hydrology, or the height 48 difference of a DTM and DSM, e.g. as a Canopy Height Model (CHM). Therefore, differentiation between ground and 49 non-ground elevation data is of wide interest. A range of systematic filtering methods have thus emerged, which however have a common issue with the preservation of sharp terrain features (Liu, 2008; Meng et al., 2010). This limits reliable 50 51 digital terrain analysis in landscapes characterised by terrain ridges, or sharp anthropogenic features such as open-pit 52 mines, riverbanks, urban ramps or agricultural terraces. Terraced landscapes represent one of the most widespread 53 examples of complex anthropogenic geomorphology (Tarolli et al., 2014; Wei et al., 2016), of which the culture-historical 54 and economic values are widely recognised, e.g. by the United Nations Educational, Scientific and Cultural Organization 55 (UNESCO) and the Food and Agriculture Organization (FAO) (Dela-Cruz and Koohafkan, 2009). Precise information 56 on terrain morphology is of key importance in several types of terrace terrain analysis, e.g. (semi-)automatic terrace 57 recognition and inventories (Bailly and Levavasseur, 2012; Sofia et al., 2016, 2014), high-precision soil erosion simulations (Pijl et al., 2019a; Tarolli et al., 2015) or digital designs of terrace drainage systems (Pijl et al., 2019b). 58
- 59 Various approaches exist for identifying terrain from regular-grid DSM, that are typically based on geometrical 60 characteristics such as slope (Roggero, 2001; Sithole, 2001; Vosselman, 2000), mathematical morphology (Chen et al., 61 2007; Zhang et al., 2003), or alternatively on linear prediction or interpolation-based methods (Kraus and Pfeifer, 1998). 62 In order to provide a systematic comparison of ground-filtering algorithms, the ISPRS Working Group III/3 evaluated the performance of eight established methods (Sithole and Vosselman, 2004). These algorithms (developed by Axelsson, 63 64 1999; Brovelli et al., 2002; Elmqvist et al., 2001; Pfeifer et al., 1998; Roggero, 2001; Sithole, 2001; Sohn and Dowman, 65 2002; Wack and Wimmer, 2002) represented the different filtering approaches and were tested for different landscape 66 types and elements. Three terrain types were found to be particularly challenging: steep slopes, vegetated slopes, and 67 discontinuous terrain features. Interestingly, all three characteristics are typical descriptors of terraced landscapes, making 68 it one of the most challenging environments for automatic DTM-from-DSM generation. Under these circumstances, 69 typically, ground features are falsely removed as aboveground features (Type I error). In particular, sharp ridges were 70 shown to be very poorly preserved, with 7 of 8 algorithms removing these elements in >50 % of all cases, and 1 algorithm 71 in 10-50 % of cases (Sithole and Vosselman, 2004).
- 72 The difficulties of filtering discontinuous terrain are pointed out by Meng et al. (2010) as well, who relate it to the 73 conventional assumptions about (non-)terrain geometry that underlie the algorithms. Sharp geomorphological features 74 share 3 out of 4 typical properties of non-ground features, i.e. steep slopes, large elevation differences, and local 75 heterogeneity of elevations. The edge-preservation challenge is widely reported in diverse filtering approaches, e.g. multi-76 directional ground filtering (Meng et al., 2009), one-dimensional and bi-directional labelling (Shan and Aparajithan, 77 2005), or Simple Morphological Filter aided by novel image-processing techniques (Pingel et al., 2013). The two-step 78 adaptive extraction method by Yang et al. (2016), specifically designed to preserve terrain breaklines, also produces Type 79 I errors (false ground-point removal) around terrace edges, underlining the persisting challenges of this terrain type. An 80 increasingly common approach is segmentation-based filtering based on supervised training (Grilli et al., 2017). Famous 81 examples include graph-cut methods (He et al., 2018; Ural and Shan, 2016) or the CANUPO algorithm (Brodu and Lague, 82 2012), which group data points based on multi-scale homogeneity in geometric characteristics. Despite their powerful 83 potential in many applications, such approaches rely on active supervised learning and are known to be computationally 84 very heavy, both limiting their adoption and suitability for large-scale analyses (Grilli et al., 2017; Lermé and Malgouyres, 85 2017). Also non-geomorphologic filters reportedly have limited applicability in these terraced landscapes, e.g. NDVI-

- based segmentation in vineyard terraces that is typically hampered by grass cover (Burgos et al., 2015; Santesteban et al.,
 2013).
- Interesting opportunities, however, lie in the regular geometry of hillslope terrain, particularly in engineered terraces. Anisotropic filtering holds potential for terrain edge-preservation in the filtering process (Passalacqua et al., 2015). Given that slope aspect is often not entirely mono-directional across hillslopes, its local anisotropy could dictate the filtering direction. While anisotropy or non-linear filters has been successfully applied for edge-preserving terrain smoothing from noise (Passalacqua et al., 2015; Perona and Malik, 1990), a filter driven from terrain slope anisotropy has not been developed before, to the best of our knowledge. If one can assume that ground elevation changes are locally homogeneous in sign (i.e. consistently up- or downhill), a simple iterative erosive operation could progressively remove objects with
- 95 opposite elevation change.
- 96 This paper proposes a novel DTM-from-DSM filtering algorithm called TERRA (Terrain Extraction from elevation 97 Rasters through Repetitive Anisotropic filtering). The filter has a primary focus on the preservation of sharp terrain 98 features on complex vegetated hillslopes, by acting as an anisotropic erosive terrain "scrapper" whilst maintaining larger 99 perpendicular objects such as contour terraces. The regular-grid approach of the TERRA algorithm favours its timeefficiency (Grilli et al., 2017; Shan and Aparajithan, 2005; Wack and Wimmer, 2002) and allows generic applicability, 100 101 i.e. it could be applied independently of data source and surveying platform. Thus, the algorithm could be a powerful tool 102 in DTM creation e.g. in support of high-resolution analysis on field scale (e.g. LiDAR- or photogrammetry-based) or 103 large-scale geomorphologic inventories (e.g. satellite-based). Filtering performance is evaluated in terms of non-ground 104 removal and ground preservation compared to ground-truth elevation data, as tested on six different topographic datasets 105 of challenging vegetated terrace landscapes.
- Section 2 of this article elaborates on the technical details of the TERRA algorithm (2.1), the background of the several test sites (2.2), the diverse origin of topographic data (2.3), the parameterisation of the algorithm (2.4), and the experimental design for performance assessment of TERRA (2.5). Filtering results by TERRA and its performance are then presented in Section 3, while Section 4 furthermore touches on its limitations and further potential.

110 2. MATERIALS AND METHODS

111 **2.1 TERRA:** a new digital elevation model filtering algorithm

112 The TERRA algorithm virtually acts as a "scrapper" removing topsoil elements in the slope direction at each DSM grid 113 node. It works as a smoothing operation but locally directed along the slope while only considering downhill neighbouring 114 values. Firstly, it computes the slope direction (aspect) at coarser spatial resolution as a multiplication of aggregation 115 factor η and grid resolution r, thus avoiding slope noising resulting from vegetation and preventing interruption by non-116 terrain features. This slope direction is secondly resampled at each initial DSM grid node (Figure 1, note that the 117 aggregation window for determining slope direction is kept relatively small in this figure for visual understanding). TERRA then operates as an iterative focal anisotropic filter. For each grid node (i,j) of the DSM at a given iteration m, 118 119 anisotropy results from null weights given by kernel function K to downstream nodes within the focal window, i.e. in

120 front of the semi-circular sector of the slope aspect at (i,j) node (Figure 1).





122 Figure 1 – Schematic top-view of the TERRA filtering algorithm, showing the determination of hillslope aspect (coarser resolution

123 with η cells) and subsequent attribution of null weights to all downstream grid nodes within kernel K (finer resolution with λ cells).

124 At each iteration *m* over the grid, elevation value Z_m on grid node (i,j) is computed as:

125
$$Z_m(i,j) = \operatorname{argmin}(Z_{m-1}(i,j), K_{i,j}(\lambda,\eta))$$
(Eq.1)

With $K_{i,i}(\lambda,\eta)$ as the chosen kernel averaging function (e.g. median). The processes is repeated from m equal to 1 up to M, 126 127 the total number of iterations. The three algorithm parameters η , M and λ can be linked to physical properties of the 128 studied surface. Let us consider the terrain features of interest are of maximum size c^{*r} and topsoil elements to remove 129 are of maximum length b^{*r} along slope direction (illustrated in Figure 2, corresponding to the study case in Figure 3, 130 bottom-right). According to the Nyquist-Shannon theorem of sampling, the η parameter should be chosen in order to preserve terrain contour curvature at least two times coarser than c ($\eta \ge 2c$). The M parameter should be initiated with 131 132 the value of b, given that the iterative filtering will "scrap" a given non-terrain object cell by cell, with a maximum number 133 of b (this iterative filtering is illustrated in Figure 2). The latter λ parameter is less sensitive and controls the desired level 134 of smoothing on terrain data related to the used kernel averaging function. The TERRA algorithm is freely available as R 135 script under GNU GPL licence at: https://www.umr-lisah.fr/?q=fr/scriptsr/terra-script-r (see Supplementary Material A).



Figure 2 – Schematic side-view transect elevation profile of a DSM and several DTMs filtered with given iterations m, illustrating also the physical meaning of b*r (maximum downslope length of non-terrain object) and c*r (dimension of typical terrain features, here a terrace bank). The determination of slope direction at η -scale (i.e. right-to-left direction) is not affected by local interruptions such as the building or vegetation, considering that $\eta \ge 2c$.

141 **2.2 Test sites**

142 A total of four test sites across three Mediterranean countries were used for testing the TERRA algorithm (Figure 3). 143 These locations provided six distinct application scenarios due to multiple topographic data sources in some of the sites 144 (Table 1). A common characteristic of all sites is the presence of agricultural terraces that are to some extent covered by 145 vegetation. In Italy, two terraced vineyards are selected that are characterised by dry-stone walls (vertical) and earth banks 146 (typically inclined to about 45°), respectively located in the Verona province (45°31'36.80"N; 10°54'54.32"E) and Treviso 147 province (45°56'43.26"N; 12°10'4.49"E). The Roujan site is part of an observatory in Mediterranean France (43°28'56.01"N; 3°20'55.69"E) that has been monitored since 1992 (ORE OMERE: http://www.obs-omere.org/; Molénat 148 149 et al., 2018), containing wider vineyard terraces with intermittent dry-stone walls that are partly covered in natural shrubs. The Cap Bon test site in Tunisia (36°52'55.68"N; 10°54'45.25"E) is located on the steep slopes of a hill where a mixed 150 151 soil conservation system was settled. This soil conservation system consists in small shrubs associated to contour lines 152 benches. This test site is located just near to Kamech, the second site of the OMERE observatory mentioned above.



Figure 3 – Location of the four test sites of this study: Roujan, France (top-left); Kamech, Tunisia (bottom-left); Treviso, Italy (top right); and Verona, Italy (bottom-right). For each site, orthomosaics are displayed with geographical extent in the WGS 84-UTM 32
 coordinate system (EPSG: 32632).

157 **2.3 Topographic data sources**

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158 The various sites offer an interesting set of test cases, given their diversity in topographic data source. In Treviso (TRE) 159 and Verona sites (VER-O and VER-D), very high-resolution elevation data (0.1 m) was obtained using Unmanned Aerial 160 Vehicles (UAVs) and photogrammetric processing. An independent source of ground elevation data was provided through 161 accurate field-measurements of DGPS reference points. In Roujan, high-resolution surface topography data (1 m) was 162 obtained from Pleiades optical satellite imagery (ROU-P) and LiDAR laser altimetry (ROU-L), with the latter also 163 providing a reference terrain model without vegetation. The Kamech dataset (KAM), high-resolution elevation data (0.3 164 m) was obtained by photogrammetric processing of digital aerial imagery acquired by the Tunisian office of topography 165 and cadastre.

166 UAV-SfM photogrammetry

167 In Treviso and Verona, UAV surveys were carried out during October 2017 (TRE and VER-O datasets) using a DJI

Phantom 4 Pro (20 MP optical camera with 8.8 mm focal length). In the latter site, a repeated UAV survey was carried 168

169 out during December 2017 (VER-D dataset), when no leaves were present on the grape vines, using a DJI Mavic Pro

170 (12.3 MP optical camera with 4.7 mm focal length). Nadir images were taken from a 50-m altitude with >75 % front- and 171 side-overlap, and oblique images were sparsely captured to better cover hidden parts (e.g. terrace fronts or vegetation

172 blind spots), with a total number of 316, 146 and 254 images for TRE, VER-O and VER-D, respectively. Reference

terrain elevation points were measured using a TopCon HyperV DGPS device for calibration of the photogrammetric 173

- 174 analysis (resp. 18, 19 and 17 ground control points) and as an independent validation dataset for the vegetation filtering
- 175 process (dense transects of 60 and 200 points for the two locations, resp.).

176 UAV imagery was processed using Structure-from-Motion (SfM) photogrammetry software Agisoft Photoscan, in order 177 to derive a 3D model from the overlapping 2D images and additional ground control points. The resulting dense point 178 clouds had a point density of 694, 1545 and 2023 pt/m² and a recommended DEM resolution of 0.03, 0.02 and 0.02 m/pix, 179 which was harmonised to 0.1 m for the TRE, VER-O and VER-D datasets. In addition to the DSMs, reference DTMs 180 were derived by manual point cloud filtering (further elaborated in Section 2.5), with vertical errors to DGPS points of 181 0.09 ± 0.06 m, 0.02 ± 0.06 m and 0.02 ± 0.10 m, respectively for the three datasets.

Table 1 – Study sites and their main characteristics, used in this study for testing the filtering algorithm.

DATASET ACRONYM	LOCATION	TERRACE TYPE	VEGETATION TYPE	DATA SOURCE	REFERENCE DTM	RESOLUTION (m)
TRE	Treviso (IT)	earth banks, relatively steep	vineyards (rows)	UAV SfM	manual filtering + DGPS	0.1
VER-O	Verona (IT)	earth banks & dry- stone walls	vineyards (pergola cultivation), leaves-on	UAV SfM	manual filtering (VER-D) + DGPS	0.1
VER-D	"		vineyards (pergola cultivation), no leaves	UAV SfM	manual filtering + DGPS	0.1
ROU-L	Roujan (FR)	dry-stone walls, partly vegetated	vineyards (rows), lines of trees and bushes	LiDAR	LiDAR DTM	1.0
ROU-P	"	"	u	Pleiades (stereoscopic)	LiDAR DTM (ROU-L)	1.0
KAM	Kamech (TN)	contour bunds	sparse trees and low bush	aircraft SfM	manual filtering	0.3

185 Multi-echo LiDAR

- 186 In Roujan, Aerial Laser Scanning (ALS) was carried out during June 2002. A helicopter mounted with a Falcon II Toposys
- 187 LiDAR system covered the area from a 900-m altitude, with a 83 MHz laser pulse emission rate and a 10 pt/m² 3D points

spatial sampling rate. Multi-echo information was used to create a 1-m DSM (from first pulse points) and DTM (from

- 189 last pulse points, followed by a multi-step filtering process). For more details about this particular ALS survey and data
- 190 processing, the authors refer to Bailly et al. (2008). DGPS validation points taken in the field showed a vertical error
- standard deviation of the 1-m DTM of 0.06 m in flat areas and 0.15 m on the steepest slopes.

192 Pleiades satellite

- 193 In Roujan, Pleiades satellite imagery was recorded during the leaves-off period of January 2013 (ROU-P). A stereo pair
- of images was taken with a high incident angle of 30° (base-to-height ratio of about 1/1.6). A 1-m DSM was constructed
- using *MICMAC* software (Pierrot-Deseilligny et al., 2011; Pierrot-Deseilligny and Paparoditis, 2006). For more technical
- details on the photogrammetric analysis of this particular dataset, the authors refer to Sofia et al. (2016). Validation with
- 197 ground-measured DGPS points showed a vertical error standard deviation of 0.51 m.

198 *Airborne SfM photogrammetry*

For Kamech (KAM), aerial imagery was available from airborne survey performed by the Tunisian office of topography and cadastre during June 2010. The whole set of images was acquired with a *Vexcel UltraCamXp* at an average altitude of 5200 m. From this set, four images covering the area of interest were extracted. Each image has 11310*17310 pixels with an average ground sampling distance of 0.3 m. Four GCPs picked on Google Earth imagery were used to obtain an absolute geographic reference (estimated vertical accuracy <10 m). SfM photogrammetric processing was carried out using *Agisoft Photoscan* software and a DEM at 0.3 m resolution was exported. For this test site, no validation data is available.

206 2.4 Parameterisation

207 The TERRA algorithm was tested for the six test datasets with the parameters given in Table 2. Aspect aggregation factor 208 η and number of iterations M were determined from the physical dimensions of area-specific objects. Both parameters should be at least the downslope length of non-terrain objects: for η to correctly determine terrain aspect, and for M to 209 210 allow enough "scrapping" iterations to remove the object (as described in Section 2.1). Parameter values could be 211 translated into metric equivalents by considering raster resolutions (see Table 1), e.g. if the pergola canopy found in VER-212 D has a maximum downhill length of 8 m, the η and M parameters could be set to 100 (10 m equivalent * 0.1 m resolution). Finally, kernel size (λ) was set to 7 for all datasets, based on an arbitrary assumption of allowed semi-circular (downhill) 213 214 smoothing. Initial tests suggested limited sensitivity of the produced results by varying kernel sizes, although no elaborate 215 sensitivity analysis was carried out for this parameter in the presented study. 216

Table 2 – TERRA	parameter values	used in this study.
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DATASET	ASPECT AGGREGATION FACTOR (η)	TOTAL NUMBER ITERATIONS (M)	KERNEL SIZE (λ)
TRE	30 (equiv. 3 m)	30 (equiv. 3 m)	7
VER-O	100 (equiv. 10 m)	100 (equiv. 10 m)	7
VER-D	100 (equiv. 10 m)	100 (equiv. 10 m)	7
ROU-L	30 (equiv. 30 m)	30 (equiv. 30 m)	7
ROU-P	30 (equiv. 30 m)	30 (equiv. 30 m)	7
KAM	30 (equiv. 9 m)	30 (equiv. 9 m)	7

218 **2.5 Reference DTMs and filtering performance assessment**

219 Reference DTMs were available from different sources varying among datasets (Table 1). For the SfM-photogrammetric datasets (i.e. TRE, VER-O, VER-D, KAM), a reference terrain model was obtained by manual filtering based on the 220 221 original point cloud, which is an established approach for relatively small datasets (Meng et al., 2010; Sithole and 222 Vosselman, 2004). The manual filtering was done using *CloudCompare v2.9.1* software, based on the vertical distance 223 of any point to surrounding points while paying close attention to the preservation of complex landscape features 224 (examples in Figure 4). An exceptional case was the VER-O dataset, in which ground points were insufficient to provide 225 a complete reference DTM, hence the VER-D reference DTM was used (thus implying an uncertainty due to shifts). For 226 the LiDAR-based dataset ROU-L, a reference DTM was readily available. The same reference DTM was also used for 227 comparison with the filtered ROU-P DTM, after a vertical shift was performed corresponding to the average distance of 228 their DSMs (3.64 m, which relatively homogeneous throughout the study site, with a standard deviation of 0.27 m). Such comparison can further be justified as no changes in terrace morphology were detected between the timing of the ROU-229 230 L (2002) and ROU-P (2013) datasets (Sofia et al., 2016), and erosion rates in Roujan are relatively low with a reported 231 0.695 mm/year (Paroissien et al., 2010).

232 The filtering performance of TERRA was done in several steps. Firstly, the filtered DTMs were compared to dense DGPS 233 transect available from the field surveys of TRE and VER-O, based on Root Mean Square Error (RSME) values (Section 3.1). Secondly, the filtered DTMs were compared to the original DSMs, based on a visual interpretation of the difference 234 235 maps (Section 3.2). Lastly, the filtered DTMs were compared to the reference DTMs based on difference maps and 236 transect elevation profiles (Section 3.3). The maps were classified according to Type I and II errors in order to allow a 237 quantitative comparison with literature. For this particular purpose, a threshold was introduced to distinguish between 238 appropriate filtering and terrain underestimation (i.e. false ground removal or Type I error) or overestimation (i.e. false 239 non-ground preservation or Type II error). This threshold was set variable for the different datasets, as twice the raster 240 resolution in case of SfM-derived datasets as empirically estimated in many previous studies (e.g. Lane et al., 2000), thus 241 0.2 m for TRE, VER-O, VER-D; and 0.6 m for KAM), and as 0.3 m for the ROU-L and ROU-P datasets, corresponding 242 for the former to the 95% confidence band for random altimetric errors in LiDAR measurements.



Figure 4 – Snapshot of manual aboveground filtering (red) in preparation of reference DTMs for the VER-O, VER-D and TRE datasets. Various vineyard cultivation types can be distinguished, e.g. the typical pergola in Verona (second row), with a reduction of canopy cover between the UAV flights of October and December, 2017.

247 **3. RESULTS**

248 **3.1 Comparison of filtered DTMs and DGPS**

249 Figure 5 illustrates the generally strong agreement between field-measured DGPS points (black circles) and the filtered 250 DTM elevation profile across these points (blue lines) alongside with the original DSM elevations (red lines). RMSE 251 values between the measured points and filtered DTM are respectively 0.121 m and 0.256 m for the TRE and VER-O 252 datasets. In the former, additional comparison of the reference DTM with the DGPS points reveals a RMSE of 0.110 m, 253 indicating that almost the entire error of the filtered DTM can instead be explained by a photogrammetric error 254 (considering also that vegetation is not abundant, see Figure 5). The remaining errors are limited (roughly 0.011 m) and 255 indicate promising filtering performance. This is underlined by the case of VER-O, where thick vegetation coverage is 256 present, and the RMSE of the DSM and DGPS was originally 1.744 m. The remaining error can be attributed to situations 257 where terrace edges are covered in overhanging vegetation, e.g. around VER-O transect lengths 90 m and 170 m in Figure 258 5. A further comparison of filtered and reference DTMs is given Section 3.3, following a comparison with the original 259 DSMs in Section 3.2.



Figure 4 – DGPS transect elevation values (black circles) and corresponding extracts of DSM (red lines) and filtered DTM (blue
 lines; DTM_filt) in TRE and VER-O datasets.

263 **3.2 Comparison of filtered DTMs and original DSMs**

264 DTMs derived from the original DSMs by the TERRA algorithm are shown in Figure 6 (left and centre columns). The difference maps show clear patterns of aboveground features (right column, reddish colours), such as vine rows (TRE, 265 VER-O, VER-D), the building (VER-O, VER-D), and trees and bushes (VER-D, ROU-L, ROU-P, KAM). Even in VER-266 267 O, originally significantly covered in pergola type vines, a DTM is derived that is visually very close to VER-D (while the latter has much more ground information). Terrace edges are still evident in VER-O, although additional sharp micro 268 269 'ridges' are detectable where the canopy ends on the banks of some terraces (e.g. eastern segment of VER-O, filtered DTM). Some remainders of vegetation can be detected under terrace edges (e.g. middle segments of VER-O and VER-270 271 D), which is further explored in the following section. Instead, vegetation located slightly further from ridges are removed 272 well (e.g. visible just north and south of the house in VER-O and VER-D).

273 **3.3 Comparison of filtered and reference DTMs**

Difference maps and transect profiles show that there is generally a good agreement between filtered and reference DTMs across the study sites (Figure 7). Sharp terrain edges such as terrace fronts are well preserved throughout the study areas, even in the case of near-vertical stone walls of VER-O and VER-D (Figure 7, e.g. between transect length 90–100 m). Some deviations exist, which are predominantly negative and result from remaining vegetation in the filtered DTM (cyan colours). Two recurring situations of such errors can be recognised:

- (i) Dense vegetation is present at the foot of a terrace wall, with elevation values similar to the upslope terrace
 elevation. In this case, a continuous surface is produced, consisting of terrace terrain elevations and remainders of
 canopy elevations. Some examples can be found throughout the difference map of VER-D (Figure 7, dashed circles),
 and related transect at lengths 17 m and 35 m (see dashed arrows).
- (ii) Dense vegetation is located on top the terrace and 'overshadowing' the terrace edge. In this case, terrace fronts are
 estimated to be located at the vegetation edge, which is often too wide compared to the actual bench width. Examples
 are visible in the transect profiles of VER-O (around 40 m, see dashed arrow), ROU-L and ROU-P (around 25 m and
 30 m, see dashed arrows), and throughout the respective difference maps (see dashed circles).



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Figure 6 – Digital elevation models for each dataset: the original DSM (left), the DTM filtered using the TERRA algorithm (centre), and the difference map (right); all displayed in coordinate system WGS 84-UTM 32 (EPSG:32632)

A quantification of the spatial distribution of Type I and II errors is provided in Table 3. In general, the TERRA algorithm 290 291 performs very well in avoiding Type I errors (i.e. ground is preserved), and is more prone to Type II errors (i.e. non-292 ground is falsely preserved). On average, Type I errors are relatively sparse with 5.1%, which indicates an improved 293 performance compared to the 8 filtering approaches evaluated by Sithole and Vosselman (2004), of which 7 show Type 294 I errors in more than 50% of cases. Type II errors here are generally more frequent with an average of 19.9%, but 295 performance according to Sithole and Vosselman (2004) would be classified as Fair (10-50%) or Good (<10%) for the 296 individual datasets (Table 3, third column), which is comparable with the 8 considered filters under vegetated slopes. 297 Two datasets show notably high errors: (i) ROU-P in Type I errors occurring on the horizontal terrace banks (Figure 7, 298 ROU-P, purple colours), which can be related to general quality of the dataset combined with the usage of an external 299 reference DTM (from ROU-L); (ii) ROU-L in Type II errors, which are mostly related to a large flat vineyard canopy covering the eastern segment of the study site (Figure 7, ROU-L, cyan colours). Additionally, Type II errors are indeed 300 301 relatively high in the zones where terrace edges are covered in vegetation (situation -ii- in the previous paragraph), i.e. 302 VER-O (41.2%), ROU-L (18.1%) and ROU-P (50.9%, combined with the effect of the flat vineyard).



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Figure 7 – Distance comparison of terrain elevations: difference maps of reference and filtered DTMs considering a specific threshold for Type I and II errors (resp. purple and cyan colours), and transect elevation values extracted along the black solid arrows depicted on the maps in downhill direction (DSM as red lines; reference DTM as black; filtered DTM as blue); all displayed in coordinate system WGS 84-UTM 32 (EPSG: 32632).

Furthermore, the derived DTMs have mean elevations relatively close to the reference DTMs (Table 3), i.e. <10 cm for high-resolution datasets TRE, VER-D and KAM, and <70 cm for the LiDAR-based and Pleiades-based datasets ROU-L and ROU-P. The mean distance between the filtered and reference DTMs of VER-O is slightly higher, which is biased by the different origin of the reference (i.e. deriving from the VER-D survey). Pearson's correlation coefficients of

- reference and filtered DTMs range between 0.995 and 0.999 for all datasets, emphasising the expected overall agreement of derived elevation values with the reference on steep slope test sites. Only in the case of KAM the reference DTM is generally higher than the filtered DTM (Table 3), which is related to the slight "scrapping" of the top of the contour bunds (Figure 7, dashed circles and arrows).
- Table 3 Statistics on terrain elevations: mean and standard deviation of the reference DTMs, filtered DTMs, and difference maps;
- 317
- the Pearson correlation coefficient of reference and filtered DTMs; and the Root Mean Square Error (RMSE) of ground-measured DGPS values vs. their extracts from the filtered DTMs.
- 318

DATASET	TYPE I errors	TYPE II errors	REFERENCE DTM <i>mean</i> ± <i>std</i> . (m)	FILTERED DTM mean ± std. (m)	REFERENCE DTM – FILTERED DTM mean ± std. (m)	CORRELATION COEFFICIENT (reference and filtered)
TRE	1.5%	6.1%	309.21 ± 5.88	309.30 ± 5.83	-0.09 ± 0.59	0.996
VER-O	0.8%	41.2%	229.66 ± 3.73	229.86 ± 3.83	-0.20 ± 0.35	0.995
VER-D	0.8%	3.0%	229.65 ± 3.72	229.65 ± 3.72	0.00 ± 0.11	0.999
ROU-L	3.5%	50.9%	94.2 ± 14.10	94.7 ± 14.20	$\textbf{-0.51} \pm 0.81$	0.998
ROU-P	23.3%	18.1%	90.6 ± 14.10	91.2 ± 14.20	-0.63 ± 1.07	0.997
KAM	0.9%	0.0%	182.68 ± 6.14	182.68 ± 6.15	0.07 ± 0.11	0.999
average:	5.1 %	19.9 %	-	-	-	-

319 4. DISCUSSION

320 **4.1 Performance and novelty of TERRA algorithm**

This study presented TERRA, a novel filtering algorithm for deriving a DTM from a DSM. Its development was motivated by the general difficulties that existing filters commonly have with the preservation of sharp terrain features, due to their similarities with non-ground features (Meng et al., 2010, 2009; Pingel et al., 2013; Shan and Aparajithan, 2005). To the best knowledge of the authors, TERRA is the first filter to make use of anisotropy in terrain aspect to guide the filtering direction, and as such, minimise the loss of valuable terrain information (Type I errors).

326 The studied topographic datasets represent a typical challenge for existing methods, i.e. steep, vegetated and discontinuous 327 slopes (Sithole and Vosselman, 2004), which are all common features of the agricultural terraces considered here. Results 328 show that the TERRA algorithm is able to derive a DTM from a given DSM with terrain elevations very close to the 329 reference (r>0.995), with minimal parameterisation requirements that can easily be estimated a priori from the 330 dimensions of known physical objects. The largest deviations from the reference terrain is found where dense vegetation 331 is present around terrace walls, resulting in false preservation of above-ground remainders (Type II errors on 19.9% of 332 surface). However, the TERRA algorithm performs particularly well in preserving terrain features such as terrace edges 333 under diverse conditions of canopy type and the origin of topographic data (Type I errors on 5.1% of surface). The 334 performance is further characterised by relatively fast computations, thanks to the regular-grid data structure, e.g. when 335 compared to 3D point cloud-based filters (Grilli et al., 2017; Lermé and Malgouyres, 2017).

336 4.2 Limitations of methodology

Limitations to the presented methodologic set-up affect the results due to various reasons, including the algorithm structure and the data origin and comparison. Tests of the TERRA algorithm in various conditions give a good initial confidence of wider application and further testing of the method. The major source of errors in this study is the presence of vegetation around the terrace front, covering the edge either from above or from the side (Section 3.3). Additionally, certain specific topographic conditions could hypothetically to be more difficult in terms of vegetation filtering and terrain preservation:

- (i) The presence of contour-structures with risers such as contour bunds or stone walls, that are actually considered
 part of the terrain but are likely to be "scrapped" (as suggested by the results from the KAM dataset here);
- 345 (ii) Highly sinuous hillslopes with strong contour curvature, e.g. in a strongly concave or convex hill segment, will 346 impede the determination of hillside aspect, while the aspect aggregation factor η has a lower limit dictated by the 347 dimensions of non-terrain objects.

348 Uncertainties in the presented material also result from topographic data sources. Examples include photogrammetric errors or the inherent noise related to satellite stereography, creating artefacts in the DSM. On the one hand, the TERRA 349 350 filter can cope with this issue, or even improve it by filtering it out. On the other hand, final results will be affected 351 negatively when artefacts are in the dimensional order of magnitude of features of interest (e.g. terrace wall height). Other 352 data-related uncertainties derive from the set-up of this study, where reference DTMs of VER-D and ROU-L were used 353 for VER-O and ROU-P as well (in order to provide a more precise or complete reference). In this case, comparisons 354 between produced and reference DTMs have a systematic error due to different data origins (two distinct photogrammetric analyses for VER-datasets, or laser altimetry vs. satellite stereography for ROU-datasets). 355

356 4.3 Potential applications

- 357 With the development of a robust, reliable and rapid tool for DTM generation from the DSM, studies related to feature 358 detection and inventories can be facilitated. Particularly considering that (semi-)automatic feature extraction is typically sensitive for sharp terrain features and curvature (Bailly and Levavasseur, 2012; Sofia et al., 2016, 2014; Tarolli et al., 359 360 2014), the preservative performance TERRA algorithm is very suitable for this analysis, and carries strong potential for 361 large-scale application. Apart from the focus on terraced landscapes, the algorithm might also perform well in landscapes 362 with similar features, such as open-pit mines, riparian zones in anthropogenic lowlands (polders), or urban ramps (Sithole and Vosselman, 2004), provided that a sloping surface is present. Similarly, in such applications, it may become a 363 364 powerful DTM preparation tool to aid feature extraction analyses, such as in the mapping of drainage networks (Bailly et 365 al., 2008), landslide crowns (Tarolli et al., 2012), open-pit mines (Xiang et al., 2018), or for the geomorphometric 366 characterisation of anthropogenic features (Tarolli et al., 2019). Finally, due to its ability to erase small obstacles along slopes, the proposed filter may also be beneficial for pre-processing noisy DEMs before hydrological analyses based on 367 368 flow direction computing. Further research is needed and encouraged to explore the potential of the TERRA algorithm, 369 and to test it as a pre-processing link in a longer chain of topographic analyses.
- 370

371 **5. CONCLUSIONS**

The proposed TERRA filtering algorithm is shown to have a convincing performance in first tests. Filtered DTMs produced from DSMs are relatively close to the reference DTMs in the six datasets, under various conditions of topography, presence of aboveground features, and data source and resolution. Sharp terrain features such as terrace edges are very well preserved (low Type I errors), which distinguishes the TERRA algorithm from most existing filters. Minor Type II errors occur where terrace edges are covered by vegetation on top of the terrace, or form a continuous surface with downslope vegetation located at the foot of the terrace wall.

378 Presented results create confidence for further application of the algorithm, based on its filtering skill and supported by 379 minimal parameterisation requirements and computational efficiency due to the raster-based approach (as compared to a 380 3D-cloud-based approach). Further applications and analyses are encouraged for DTM creation and testing purposes. The 381 algorithm may also play a key role in (semi-)automatic mapping of terrace structures, allowing a rapid DTM preparation 382 step while maintaining typical terrain features (e.g. sharp edges) often critical for such analyses. Testing for DSM filtering in other environments such as anthropogenic landscapes with sloping terrain (e.g. hydraulic engineered lowlands, open-383 384 pit mines) is also encouraged in future exploration. The TERRA algorithm is freely available as R script under GNU GPL licence at: https://www.umr-lisah.fr/?q=fr/scriptsr/terra-script-r (see Supplementary Material A). 385

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SUPPLEMENTARY MATERIAL A: R script TERRA

available at https://www.umr-lisah.fr/?g=fr/scriptsr/terra-script-r # This file is the R code of the TERRA algorithm # see https://doi.org/10.1016/j.jag.2019.101977 # "TERRA: Terrain extraction from elevation rasters through repetitive # # anisotropic filtering# # Copyright(c) 2019, AgroParisTech # == GNU General Public License Usage == # TERRA.R is a free tool: you can redistribute it and/or modify # it under the terms of the GNU General Public License as published by # the Free Software Foundation, either version 3 of the License, or # (at your option) any later version. TERRA.R is distributed in the hope that it will be useful, # # but WITHOUT ANY WARRANTY; without even the implied warranty of # MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the # GNU General Public License for more details. # See <http://www.gnu.org/licenses/> # == Other Usage == # Other Usage means a use of TERRA algorithm that is inconsistent with the GPL # license, and requires a written agreement between You and AgroParisTech. # Licensees for Other Usage of TERRA.R may use this file in accordance # with the terms contained in the written agreement between You and AgroParisTech. ***** # @author Jean-Stéphane BAILLY <bailly@agroparistech.fr> # Require to call first the "raster" R package # Input and parameters # Input : # - dsm : dsm name to be filtered in raster R format # Parameters : # - lambda : Kernel size # - eta : spatial aggregation factor # - M : number of iteration ****** # Output : # - filtered dtm in raster R format # Note that the Kernel statistic used here is the mean but it can be changed manually by any other statistics (min, median, etc) # # Execution example including TERRA compilation : # source('TERRA.R')

[#] mnt<-TERRA(dsm=mns,lambda=7,eta=10, M=5)</pre>

```
TERRA<-function(dsm=mns,lambda=7,eta=10, M=5)</pre>
{
#structural element inner aspect
K<-matrix(0,lambda,lambda)</pre>
X<-col(K)-(((lambda-1)/2))-1
Y<-(nrow(K)-row(K))-((lambda-1)/2)</pre>
azi<-atan(Y/X)</pre>
azi[X<0]<-azi[X<0]+pi</pre>
azi[X>=0 & Y<0]<-azi[X>=0 & Y<0]+2*pi
azi<-2*pi-azi
azi[azi==(2*pi)]<-0</pre>
azi<-azi+(pi/2)</pre>
azi[azi>=(2*pi) & !is.nan(azi)]<-azi[azi>=(2*pi) & !is.nan(azi)]-(2*pi)
DSM<-dsm
for(i in 1:M)
{
#low frequency slope calculation
AGG<-aggregate(DSM, fact=eta, expand=TRUE)
ASP<-terrain(AGG, opt='aspect', unit='radians')</pre>
asp<-resample(ASP, DSM, method="ngb")</pre>
MNS<-as.matrix(DSM)</pre>
ASP<-as.matrix(asp)
MNT<-MNS
for (i in (1+(lambda-1)/2):(nrow(MNS)-(lambda-1)/2)) # i: row.index
{
       for (j in (1+(lambda-1)/2):(ncol(MNS)-(lambda-1)/2))  # j: col.index
       {
              if(!is.na(ASP[i,j]))
              {
                      shift<-ASP[i,j]</pre>
                      s1<-azi>=(shift-pi/2) | azi>=(shift+3*pi/2) | azi<=(shift-3*pi/2)</pre>
                      s2<-azi<=(shift+pi/2) | azi>=(shift+3*pi/2) | azi<=(shift-3*pi/2)
                     W<-(s1 & s2)
                      W[((lambda-1)/2)+1,((lambda-1)/2)+1]<-TRUE
                     W<-!(W)
                      cand<-mean((W*MNS[(i-((lambda-1)/2)):(i+((lambda-1)/2)),(j-((lambda-</pre>
1)/2)):(j+((lambda-1)/2))])[W==T], na.rm=T)
                      if(!is.na(cand)){ if(cand<MNT[i,j]) {MNT[i,j]<-cand}}</pre>
              }
       }
}
values(DSM)<-MNT
}
mnt<-dsm
values(mnt)<-MNT</pre>
invisible(return(mnt))
}
```