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Resolution and Precision of Fast Long-Range Terrestrial Photogrammetric Surveying Aimed at Detecting Slope Changes

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1 **Resolution and precision of fast, long range terrestrial photogrammetric surveying**
2 **aimed at detecting slope changes**

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12

13 **Abstract**

14 Structure-from-Motion (SfM) is currently used for geological-geomorphological purposes
15 under the condition that the modeling is based either on several ground control points (GCPs)
16 well distributed in the scene or on Direct Georeferencing (DG). In emergency conditions and
17 in presence of active morphodynamic processes, it could be unfeasible to use GCPs or DG. A
18 study aimed at evaluating the quality of the results achievable by means of completely free
19 SfM modeling of images taken from a distance of some hundred meters is shown here. It is
20 based on an experiment with an artificial target and some surveys of a bedrock scarp, where
21 resolution and precision are evaluated as empirical functions of distance and focal length,
22 taking into account the issues related to the scale factor. The problems related to the
23 recognition of localized surface changes by means of multitemporal surveys are also studied.
24 The main result is that the free approach can really be used in geomorphological and
25 seismotectonical surveying carried out in emergency conditions.

26 **Subject Headings:** Structure-from-Motion; Spatial Resolution; Precision; Change Detection;
27 Slope Stability; Central Apennines.

28 **1. Introduction**

29 Structure-from-Motion (SfM) is increasingly used in geological and geomorphological
30 surveying because it allows a fast and inexpensive generation of accurate photorealistic point
31 clouds and digital models with the currently available computation resources (see e.g. Brunier
32 et al. 2016; Smith et al. 2016). In case of good light conditions and absence of disturbances
33 like vegetal cover, SfM is often used instead of the expensive Terrestrial Laser Scanning
34 (TLS) because of similar performance (Nouwakpo et al. 2016; Teza et al. 2016; Pesci et al.
35 2018).

36 A fundamental step of the photogrammetric modeling is the bundle adjustment (BA),
37 which consists in a simultaneous refinement of the 3D coordinates that describe the scene
38 geometry, the camera positions, orientations and optical characteristics (Murtiyoso et al.
39 2018). The standard approach is based on block BA (Triggs et al. 2000), where the
40 coordinates of several Ground Control Points (GCPs) measured by means of GNSS and/or
41 total station, and also recognized in some input images, are incorporated into the BA
42 procedure. The achievable precision is directly related to the number of GCPs and their
43 distribution. In particular, a uniform and dense GCP spatial distribution is required in those
44 cases where highly accurate products are needed (Caroti et al. 2015; Tonkin and Midgley
45 2016; Al-Halbouni et al. 2017). A direct access to the surveyed surface is required, but it
46 could be difficult or hazardous in unstable slope areas. Moreover, multipath effects and/or
47 limited satellite visibility can affect the GNSS-based measurement of GCPs in the case of a
48 vertical rock cliff (Jaud et al. 2016). Finally, the time-intensive nature of GCP collection
49 requires a balance between GCP quantity and survey quality. For example, several working
50 hours are necessary to acquire 20-30 GCPs by means of GNSS measurements on a ~2 ha
51 surface.

52 Sometimes, not enough reliable GCPs can be measured. In these cases, the direct
53 georeferencing (DG) can be used (Turner et al. 2014). Such an approach is particularly

54 suitable for aerial SfM because an Unmanned Aerial System (UAS) is typically equipped with
55 a GNSS receiver. In this case, the camera positions (positions and orientations if an Inertial
56 Measurement Unit, IMU, is also available), defined with respect to a suitable reference
57 system, are used in order to provide a georeferenced point cloud. The DG workflow seems to
58 lead to higher errors compared to GCP-based modeling. Nevertheless, an adequate DG
59 workflow can produce topographic data with sufficient quality for some applications even if
60 low cost UAS and SfM-photogrammetry package are used (Carbonneau and Dietrich 2017).
61 Finally, the cost of instruments necessary for a DG-based survey is an order of magnitude
62 lower than the one necessary for a GCP-based survey (~2,000 \$ instead of ~15,000-20,000 \$).

63 The fact that a high precision geodetic survey should be based on GCPs or at least on
64 DG is a shared and well-founded opinion. On the contrary, point clouds and digital models
65 obtained by means of a completely free SfM modeling are considered to be suitable for
66 representation purposes but unsuitable for quantitative analyses because of deformations with
67 respect to the true shape, incorrect scale factor (SF) and lack of georeferencing. Since in some
68 cases the surveying in emergency conditions could be incompatible with GCPs or also DG, it
69 is important to understand what can be achieved in these cases. For this reason, the issues
70 related to a completely free SfM surveying and modeling of a rock cliff are faced in this
71 paper. In particular, the answers to these important questions are proposed: Can a completely
72 free SfM modeling be used be used in geomorphological and seismotectonic surveying, at
73 least in emergency conditions? What is a possible solution of the SF problem? What are
74 reasonable estimates of resolution and precision? What conditions should the observed rock
75 cliff satisfy in order to have meaningful results from multitemporal observations?

76

77 **2. Preliminary experiment with an artificial target**

78 This experiment was carried out in order to evaluate the resolution, i.e. the size of the smallest
79 feature that can be detected and measured, of SfM modeling as a function of the acquisition
80 distance and technical specification of the used camera.

81 The artificial target is a white rectangular planar wood panel whose base and height are
82 1 m and 0.3 m respectively (Fig. 1a). Some 0.2 m high vertical black rectangular elements are
83 placed on the panel. On the left side there are ten elements whose widths range from 1 mm to
84 10 mm, and on the right side there are ten elements between 11 mm and 20 mm. The color
85 contrast between black vertical elements and white background facilitates their recognition.
86 The target was placed on a masonry wall in order to integrate it within a more extended
87 environment.

88 [Figure 1]

89 The images were taken by means of a Nikon D3300 camera, equipped by a lens which
90 allows the choice of a focal length in the range 55-300 mm, whose main technical
91 specification are summarized in Table 1. The experiment layout is shown in Fig. 1b. The
92 camera was placed along five lines parallel to the masonry wall at distances of 10 m, 20 m, 30
93 m, 40 m and 50 m. Seven evenly spaced points were considered for each line and three
94 images were taken from each point by using three different focal lengths f , i.e. 55 mm, 102
95 mm and 210 mm. The image acquisition was carried out by moving parallel to the target as in
96 the case of terrestrial surveying of a slope. The camera's optical axis was always aimed at the
97 target in order to ensure that it was in the center of each image. In this way, the survey was
98 very like to the observation of a natural surface. The price to pay was a changing acquisition
99 distance along each line (10-11.9 m, 20-23.8 m, 30-35.7 m, 40-47.5 m, 50-59.4 m, with mean
100 distances of 10.8 m, 21.6 m 32.4 m, 43.2 m and 53.9 m respectively).

101 For each line and each f , a dense point cloud was generated from the corresponding
102 seven images by using PhotoScan (now called Metashape, Agisoft 2020). The image
103 alignment was carried out with the full size images, without subsampling, by choosing the

104 option “High accuracy” in PhotoScan. Similarly, the choice “Ultra High” for quality led to a
105 dense point cloud generation based on full size images. Moreover, in order to reduce noise
106 and keep the small details at the same time, the chosen option for depth filtering was
107 “Moderate”. A total of 15 point clouds were obtained. Each point cloud was inspected by
108 using PolyWorks (Innovmetric 2020) in order to recognize and evaluate the black vertical
109 elements. These elements were automatically selected because they are dark color features on
110 a light background. Since the i -th element has the width of i mm and the difference between
111 the i -th and the $(i+1)$ -th element is 1 mm, if the element i can be seen but its width cannot be
112 measured and the element $i+1$ is visible and its width can be measured, an estimate of the
113 point cloud resolution, i.e. the size of the smallest object that can be discerned, is $i+0.5$ mm.

114 The results are shown in Fig. 2, where the resolution vs. acquisition distance d is shown
115 together with the Ground Sampling Distance (GSD), i.e. the distance between the centers of
116 two adjacent pixels measured on the observed surface, namely the image resolution, vs. d . It
117 is $GSD = pd / f$, where p is the size of the single pixel of the sensor. In order to show the
118 ratio between resolution and GSD by means of only a sequence of points and better evaluate
119 the ratio between the point cloud resolution and the GSD, the case $f_0 = 55$ mm is used as a
120 reference; the results for $f_1 = 102$ mm and $f_2 = 210$ mm are taken into account by means of
121 the normalized distance $d_{Ni} = d f_0 / f_i$.

122 The average ratio between resolution and GSD is ~ 2.5 . This is the main result of the
123 preliminary experiment. It is important to point out that a resolution equal to the GSD is not
124 expected and is not possible. Even if a high quality lens is used, two images related to a same
125 area but taken from two different positions cannot have a perfect pixel-by-pixel match. This is
126 like the case of a TLS, whose resolution is not equal to the sampling step (Lichti and Jamtsho
127 2006; Pesci et al. 2011). Another similarity is the fact that the probability of reacquisition of a
128 same point in two scans carried out with the same parameters is very low. The data provided

129 by a TLS instruments have an area nature, not a punctual one, i.e. a point in the same area, not
130 the same point, is acquired in a second scan.

131 [Figure 2]

132 [Table 1]

133 It is important to note that: (1) the target is composed of dark elements with clear
134 boundaries on a white planar background in order to allow a quick and easy recognition of
135 these elements on the point clouds; (2) the distribution of the element widths is discrete; (3)
136 the range of acquisition distances is no more than 10-50 m. For all these reasons, the fact that
137 the point cloud resolution is ~ 2.5 times the GSD, is not a general result but is rather a limit
138 value for the resolution that can be reached under optimal conditions in which disturbances
139 due to complex morphologies and light problems are almost absent. Since the GSD linearly
140 increases with the distance, it is reasonable to assume that this result can be extrapolated to
141 distances greater than 50 m under the condition that a flat surface is observed with optimal
142 lighting. For a general surface, the result is a lower limit of the resolution. For this reason, it is
143 called resolution limit (RL). Possible changes and differences between models that are lower
144 than such a limit cannot be accepted, but should be considered to be negligible instead. It is
145 important to note that the GSD, even if it is not the resolution of the final 3D object (point
146 cloud or model), constrains this parameter. The Modulation Transfer Function (MTF) of an
147 imaging system is a measurement of its ability to transfer contrast at a particular resolution
148 from the observed object to the image. Although a true MTF estimation was not carried out,
149 the experiment provided some information about it. The RL roughly corresponds to the spatial
150 frequency at which the MTF is 50%. Moreover, the result $RL \sim 2.5 GSD$ means that the
151 spatial frequency limit is $\sim 0.8 f_N$, where $f_N = 1/(2GSD)$ is the Nyquist frequency, i.e. half
152 the sampling frequency.

153

154 **3. Geological setting**

155 Mountain slopes in an active tectonic setting are exposed to different processes responsible
156 for their long-term morphology. Aside from active faulting and other form of coseismic
157 displacement during an earthquake, active faults exhibit also afterslip and, in some cases,
158 aseismic creep in the interseismic periods. Moderate-to-strong earthquakes perturb the
159 dynamic equilibrium of a mountain slope also through shaking-induced triggering of mass
160 movement. Gravitational processes are also well documented in tectonically active regions
161 (Baroň et al. 2016). Often, effects of reactivation of tectonic faults act on mountain
162 morphology. Besides tectonics, there are several exogenic processes contributing to mountain
163 morphologies, such as weathering, mass wasting, erosion and deposition. These processes are
164 mainly related to gravity and lateral topographic gradients. Therefore, the detection of
165 morphological changes and related rates is important to determine areas prone to deformation.
166 Ultimately the goal is to properly model the observed variations to their causative factors.

167 [Figure 3]

168 The central Apennines are a mountain chain composed of individual NW-SE oriented
169 slopes separated by karstic plateaus, glacio-fluvial valleys and fluvio-lacustrine basins. The
170 generally NW-SE oriented bedrock scarps (BSs) positioned at various heights along the
171 individual mountain slopes are important geomorphic features of this area. These structures
172 are often thought to be a direct surface exposure of the region seismogenic faults and their
173 heights are directly associated with earthquake surface faulting. Generally, the other processes
174 known to affect mountainous morphology are neglected in the studies about central
175 Apennines. It was recently shown that the exposure of these BSs occurs at fast rates and
176 without earthquake slip due to not yet very well understood mechanisms, probably driving BS
177 exposure in interseismic times (Kastelic et al. 2017). Moreover, during earthquakes, gravity
178 and earthquake shaking-induced movement on pre-existing discontinuities significantly
179 influence the coseismic surface deformation (Di Naccio et al. 2019). These evidences suggest

180 that a more specific study of terrain movements have to be considered to better quantify the
181 non-tectonic contribution, which should be quantified and eventually subtracted from the
182 estimates of tectonic deformation. This issue has important implications in different aspects,
183 for example in seismic hazard studies where only the long-term seismogenic component of
184 the overall deformation is needed, thus all other components of the total deformation pattern
185 need to be removed.

186 Campo Felice (Fig. 3) is a BS in the central Apennines characterised by a significant
187 lowering rate without seismogenic component (Kastelic et al. 2017). The surveys were aimed
188 at studying a large portion of this BS and its underlying mountain slope, where change rates
189 in the range between ~ 1 cm/a and ~ 10 cm/a are typically expected. Therefore, the surveying
190 method should be able to detect these changes. A possible solution is the ground-based
191 interferometric Synthetic Aperture Radar (SAR), which allows the real-time detection of
192 millimetric changes with pixel resolution of half meter (Ferrigno et al. 2017), but this is an
193 expensive technique. SfM seems the most appropriate choice due to its performance and low
194 cost and the need to develop time series of point displacements and models of differential
195 movements on the BS.

196

197 **4. Surveys and Results**

198 *4.1 Surveys*

199 The rock cliff chosen for in situ SfM experiment was also surveyed by means of TLS
200 technology in order to obtain a reference metric point cloud with the correct verticality. An
201 Optech ILRIS-3D ER instrument was used from ~ 250 m mean distance (Fig. 4). An
202 inspection of the point cloud led to basic information as slope inclinations and distances
203 between some areas of the cliff. TLS is an expensive technique, but this measurement was
204 carried out once and for all.

205 [Figure 4]

206 The SfM surveys were performed in April 2018 by using a Nikon D3300 camera. The
207 images were acquired with three f values: 55 mm, 110 mm and 220 mm. Each f was set by
208 acting on the camera lens ring (among the values written on the ring, there are 55 mm, 102
209 mm, 110 mm, 210 mm and 220 mm). Since possible changes in f can have a significant
210 impact the model fidelity, for each image the Exif data were read in order to check the actual
211 f . For each f , two sets of 30-44 images, depending on f , were acquired from the paved road
212 that runs roughly parallel to the BS at ~ 250 m distance from the road to this BS. Details on
213 data acquisition and processing are summarized in Table 2. The photographer walked for
214 ~ 300 m along the road acquiring an image every 10 m to have a good spatial coverage and
215 image overlap and repeated the procedure as she turned back. The camera was always aimed
216 with parallel optical axes. The surveys were repeated in March 2019 to provide multitemporal
217 data.

218 [Table 2]

219

220 ***4.2 Photogrammetric modeling and resolution evaluation***

221 The photogrammetric modeling was carried out by using PhotoScan with a free-network BA
222 approach. Before the dense point cloud generation, the image alignment was checked and,
223 where necessary, corrected. The options for image alignment (“High accuracy”) and dense
224 point cloud generation (“Ultra High quality” and “Moderate depth filtering”) were the same as
225 those for the above described experiment (see Table 2 for more information).

226 Figure 5 shows the 55 mm point cloud together with the boundaries for the three f . The
227 longer the focal length, the smaller the modelled area. The area of interest is the area where
228 there is the transition between rock and debris, i.e. the BS contact with alluvium/colluvium
229 (Section 3). It corresponds to the area covered by the 220 mm point cloud.

230 [Figure 5]

231 In order to obtain metric objects, the point clouds were scaled by means of the polylines
232 method (Pesci et al. 2016). It is based on the choice of some common homologous points (e.g.
233 morphological details) recognized in all point clouds and on the calculation, in each point
234 cloud, of the length of the closed polyline connecting these points. The recognition of
235 homologous point is quite simple because the SfM-based point clouds are photorealistic. Let
236 L_i be the polyline length related to the point cloud i . In order to express the point cloud j in
237 the same scale of the point cloud i , the scale factor $SF_{ji} = L_i / L_j$ must be used. Therefore, it is
238 $S_{ji} = S_j SF_{ij}$, where S_{ji} indicates an object initially defined in the scale j changed to the scale
239 i . If i is metric, also j becomes metric. The SfM point clouds were made metric by extracting
240 from the TLS point cloud the polyline that correspond to the SfM ones. This final task was
241 not as easy as the previous ones because the radiometric information of the TLS point cloud is
242 the intensity in the near infrared band and the recognition of homologous points is not trivial.
243 In order to have meaningful results, the polyline should roughly coincide with the boundaries
244 of the area of interest. The problems related to the choice of the closed polylines used to
245 evaluate the scale factor are discussed in detail in the Online Supplementary Material.

246 The metric point clouds can be registered onto the same reference frame by means of
247 rigid body transformations in order to allow their comparison. Like the above described
248 approach to data scaling, the SfM point clouds were registered between them. A 110 mm
249 point cloud was aligned to the TLS one after this, and the resulting rigid body transformation
250 was applied to all SfM point clouds to allow the data comparison. Data scaling, registration
251 and comparison were carried out by using PolyWorks. In particular, the comparison between
252 two point clouds was carried out by generating a 2.5D model from the reference one and
253 measuring the distance between each element of the second point cloud and this model. The
254 statistical data analysis was carried out with Origin package by OriginLab.

255 A test of repeatability was carried out. The maps of differences between each pair of
256 point clouds related to the same f are shown in Fig. 6: 55 mm (Fig. 6a), 110 mm (Fig. 6b) and
257 220 mm (Fig. 6c). In order to facilitate the result interpretation, areas affected by vegetation
258 coverage were excluded from the analysis. The results are summarized in Table 3.

259 [Figure 6]

260 [Table 3]

261 The statistical analysis of the differences between each pair of point clouds related to
262 the same f shows that, with the exception of the 55 mm case, the distribution has smaller
263 standard deviation (SD) as f increases, as expected (Fig. 7a). Even if it is quasi-symmetric and
264 almost zero-centered, this distribution typically is not normal since it has high kurtosis and,
265 therefore, the probability mass is concentrated around the mean but there are occasional
266 values far from the mean. In the 55 mm case, the values are not distributed around zero but
267 seem to come from the sum of two symmetric distributions. This result can be related to the
268 fact that the area taken in a single 55 mm image is relatively wide and, because of the slope
269 angle of the cliff, different zones could be observed under very different conditions. The local
270 distance and incidence angle can change, leading to different size and shape of the surface
271 corresponding to a single pixel and making the registration harder. The corresponding map of
272 differences (Fig. 6a) shows a pattern that seems to indicate an imperfect alignment, even if the
273 values are small in consideration of the acquisition distance. A higher f lead to a lower field of
274 view and, therefore, to a lower within-image variability of distance and incidence angle. The
275 experiment with an artificial target described in Section 2 shows that the RL is about 2-3
276 times the GSD. If the comparison between two point clouds provides differences smaller than
277 this limit, these differences are considered to be negligible and therefore rejected. For 250 m
278 acquisition distance, the estimated RLs are 70 mm, 40 mm and 35 mm for 55 mm, 110 mm
279 and 220 mm focal length respectively, whereas three times the standard deviations of the

280 differences are 60 mm, 35 mm and 25 mm respectively. Therefore, the detected differences
281 are negligible and the repeatability of the results is confirmed.

282 [Figure 7]

283 The comparisons between point clouds obtained by means of different f is shown in Fig.
284 6: 55 mm vs. 110 mm (Fig. 6d); 55 mm vs. 220 mm (Fig. 6e) and 110 mm vs. 220 mm (Fig.
285 6f), and are summarized in Table 3. Like the case of repeatability test (Fig. 6a-c). there are
286 systematic effects in case of comparisons with respect to the 55 mm point cloud. No
287 systematic effects are observed for other point clouds and no patterns appear. Moreover, it
288 should be noted that similar results are obtained whatever the point cloud for a given f is used.

289 A statistical analysis of differences between the point clouds obtained with different f
290 showed a poor agreement between the 55 mm data and the ones related to higher f (Fig. 7b).
291 The SfM models obtained through images with higher f offer a level of precision that can be
292 though reliable and statistically representative of the process responsible for the possible
293 differences detected. These results, like the ones shown in Fig. 7a, show that significantly
294 better results are obtained for 110 mm and 220 mm with respect to 55 mm.

295

296 ***4.3 Analysis of multitemporal data***

297 Scaling and registration of the 2019 point clouds were carried out with respect to a 2018 point
298 cloud obtained from 110 mm images. Preliminary results on detection of changes occurred in
299 the time span 2018-2019 for a f of 110 mm are shown in Fig. 8. At the acquisition distance
300 (~250 m), no real movements along the contact between the rock and the deposit were
301 observed. Faint traces of these movements can be seen, but they are below the RL, i.e. 30-40
302 mm at such a distance (Fig 8.d). On the contrary, significant differences were detected about
303 the deposit accumulation on the wedges. Differences due to the vegetation cover also appear.

304 These results testify that the proposed simplified approach without GCPs and DG,
305 although conceived for observations in emergency conditions, can recognize and quantify the

306 natural processes that affect a mountain slope if they involve a limited area of this slope.
307 Everything suggests that the time passed between the two multitemporal observations is too
308 short to allow the quantification of movements along the contact between rock and deposits.
309 In particular, Kastelic et al. (2017) estimated the lowering of the detrital part besides the BS
310 by means of direct in situ measurements, providing values of the order of 10 mm/a. Therefore,
311 a time span of about four year is needed to observe surface variations.

312 [Figure 8]

313

314 **5. Discussion**

315 The discussion focuses on the results that can be obtained by means of SfM without GCPs
316 and DG in the case of a rock cliff observed from 250 m, mainly in terms of spatial resolution
317 and minimum detectable magnitude of changes.

318 Some software manufacturers (e.g. Agisoft) claim that the typical resolution of a
319 photogrammetric model is 2-3 times the GSD of the taken images. Obviously, any statement
320 by a manufacturer must be verified under operating conditions. On the one hand, the assertion
321 about the resolution seems to be confirmed by the results of the preliminary experiment. The
322 value found in the experiment was ~ 2.5 times the GSD. On the other hand, it should be noted
323 that these results were obtained in 2D conditions, with a smooth surface and a high color
324 contrast between recognized elements and background. Therefore, this result is not general
325 and cannot be directly extrapolated to rough surfaces and/or cases where there is not enough
326 color contrast because of the color of the objects or the light conditions. In these cases, this is
327 simply a lower limit of the resolution. In particular, some experimentations on 3D natural
328 surfaces are required.

329 Several authors compared the SfM and TLS performance in terms of resolution and
330 accuracy, both for architectural/cultural heritage documentation (see e.g. Teza et al. 2016) and
331 geological/geomorphological survey (Nouwakpo et al. 2016). In particular, the last paper

332 showed that TLS and SfM have similar performance at least if the vegetal cover is negligible
333 and several GCPs are used. Performance of SfM was evaluated e.g. by Caroti et al. (2015),
334 which found that, in the observation of a façade, the root mean square error (RSME) ranges
335 from 3 to 5 times the GSD in the case of free-net BA and ranges from 2 to 4 times the GSD if
336 6-12 GCPs evenly distributed on such a façade are used to constrain the BA.

337 This article deals with the observation of a rock cliff whose extension is some
338 tens/hundreds m² where targets for total station or GNSS receivers cannot be placed. If a high
339 extension surface is observed, the use of a suitable number of GCPs is strongly recommended
340 because a free-network BA in this case could provide not more than preliminary values. A
341 possible solution of the issues related to difficult or impossible access to a slope is the use of a
342 reflectorless total station to accurately locate some features that can be recognized on the
343 observed scenario (e.g. corners of natural or artificial objects). In this case, for mid acquisition
344 distances the error is not significantly higher than the one of a GNSS survey carried out with
345 receivers mounted on topographical tripods (Beshr and Elnaga 2011). However, such an
346 instrument should be available for each survey, which is a problem for users whose available
347 economic resources are limited or fast measurements and results are needed. The
348 measurement campaigns were deliberately carried out without camera pre-calibration in order
349 to show the quality of the results obtainable in emergency conditions and without any
350 preparation. However, it should be noted that a camera pre-calibration is generally
351 recommended.

352 The data acquisition was carried out with different focal lengths and, therefore, different
353 GSDs. The results obtained in the 55 mm case (GSD of 18 mm at 250 m), are not adequate.
354 The repeatability is not good; the distribution of the differences between two point clouds
355 obtained in similar conditions is bimodal and not centered in zero. The pattern of differences
356 shows that the bimodality of the distribution is mainly due to issues in data registration. In
357 other words, the quality of the modeling aimed at aligning the point clouds is conditioned

358 from an unsuitable choice of the focal length, also taking into account the image field of view
359 and the slope angle of the cliff. All these issues do not appear if f is 110 mm or 220 mm,
360 where the GSD is 9 mm and 4.5 mm respectively. Therefore, the results suggest the choice of
361 the lens on the basis of the magnitude of the changes that should be detected. Finally, it
362 should be noted that, in case of observation of a subvertical cliff with 55 mm f , the
363 registration is easy and accurate (Pesci et al. 2019).

364 If the aim is the detection of possible changes occurred between two multitemporal
365 surveys and the SD of each model is σ , the SD of the difference is $\sqrt{2}\sigma$. The results show that
366 changes higher than 30-40 mm for a distance of ~ 250 m can be observed.

367 The used camera is a prosumer device, i.e. a mid-cost camera. Its crop factor (CF) is 1.5
368 (Table 1). It is commonly defined as $CF = diag_{35} / diag_S$, where $diag_{35}$ is the diagonal length
369 of a standard 35 mm photographic film, where $diag_{35} = 43.3$ mm for a 3:2 aspect ratio (36
370 mm x 24 mm sensor size) and $diag_S$ is the diagonal length of the specific sensor (in mm). A
371 professional full frame camera is characterized by $CF = 1$. A high CF leads to an excessive
372 squeezing of the pixel data on a small size sensor and, therefore, a low Signal-to-Noise Ratio
373 (SNR) and a low field of view, depending on focal length. If the CF increases, the other
374 factors and parameters being equal, the actual resolution of an image is worsened. This fact
375 should be taken into account if a camera mounted on a low cost UAS is used because the CF
376 could reach 4 or also 5.

377 A criticism can be made about the fact that the obtained results have area nature and, in
378 particular, do not have point nature. This is not a problem because the comparison between
379 point clouds for geological/geomorphological purposes is always based on comparisons
380 between areas and is never based on a direct comparison between points. For example, the
381 calculation of the displacement field from multitemporal point clouds by means of the
382 piecewise alignment method (Teza et al. 2007) and the correlation between digital

383 orthoimages generated from SfM-based point clouds (Travelletti et al. 2013) have area nature.
384 If the aim is to evaluate volumetric changes, the calculation is, a fortiori, based on comparison
385 between corresponding areas or between an area and a reference plane. In all cases, a single
386 point is never considered.

387 Another criticism can be made with regard to the use of TLS data for the SF
388 computation. This seems to contradict the claimed low cost of the procedure. However, the
389 TLS-based point cloud, or a SfM-based point cloud generated by using several GCPs, is
390 required once and for all and no further expensive surveys are required.

391 The polyline-based procedure aimed at providing the SF could also be used in those
392 cases where no reliable reference models are available. For example, Google Earth (GE)
393 imagery could be used to estimate the SF. However, the GE images are not orthorectified and,
394 moreover, no public information about the data lineage and the procedures of data processing
395 is available. No more than a first, rough estimate of the SF can therefore be obtained.
396 Moreover, such a preliminary SF could be obtained under the condition that GE images
397 having a relatively high resolution are available and that the rock cliff is not sub-vertical. In a
398 metropolitan area the positional accuracy, expressed in terms of RSME, is typically in the
399 range 0.7-1 m, which is sufficient for deriving ground truth samples, measurements, as well as
400 large-scale maps (Pulighe et al. 2017), but in a rural area the RMSE can reach 5 m (Paredes-
401 Hernandez et al. 2013). Therefore, in large part of the mountain areas the GE image resolution
402 does not allow a preliminary SF estimation. A quasi-accurate SF could be obtained if 30 cm
403 resolution digital orthoimages obtained from WorldView-3 satellite data (Vajsová et al. 2015)
404 or 50 cm resolution orthoimages from Pléiades 1A/1B (Agrafiotis and Georgopoulos 2015)
405 are used instead. This because orthorectified data having well defined precision and resolution
406 are used and elevation data are embedded in a GeoTIFF file, allowing better recognition of
407 homologous points.

408 In order to exclude possible systematic errors or distortions due to photogrammetric
409 modeling, a final check was carried out by comparing the SfM point clouds and a reference
410 TLS survey (Fig. 9). The difference maps show the absence of systematic errors for f of 110
411 mm and 220 mm. In the 55 mm case the differences range in the interval ± 0.06 m and
412 describe a pattern distributed along the diagonal of the surface.

413 [Figure 9]

414 In active tectonic studies it is important to properly quantify the seismogenic
415 deformation, discarding any other process that could contribute to the short- and long-term
416 landscape shaping. For this scope a cost- and time-effective method able to guarantee good
417 resolution power is suitable for the surveying of surface deformations along BSs and
418 mountain slopes both in coseismic and interseismic conditions. The proposed SfM models
419 offer a chance to construct a database of BSs (and mountain-slopes) evolution through time,
420 thus allowing to quantify and compare the spatially variable exposure rates. An analysis of
421 multitemporal data collected in 2018 and 2019 confirms the results about precision and
422 accuracy that can be reached with the proposed approach. Changes higher than the RL (30-40
423 mm at ~ 250 m distance) can be easily detected, whereas no more than faint traces of possible
424 incipient changes can be detected along the contact between the rock and the deposit, where
425 the velocity is ~ 10 mm/a. Therefore, the proposed approach can be used in emergency cases
426 (earthquakes, landslides, volcanic eruptions) when easy-to-manage instrumentation and
427 reliable results are equally needed.

428 Since a true georeferencing is not carried out, the completely free approach can be used
429 only if the unstable area is a portion of the observed scene. In this case, the multi-temporal
430 models can be co-registered on the basis of the stable parts of the rock cliff, provided that they
431 surround the unstable areas. Even if this condition is often satisfied, this fact leads to an
432 objective limitation of the proposed approach.

433 The time necessary to carry out the SfM survey was about 0.5 h and the polyline-based
434 point cloud scaling required about 1 h. The computation times summarized in Table 2 show
435 that the complete data processing (point cloud generation and scaling) of 220 mm data
436 required about 5 h in the case of a notebook equipped with an Intel Core i7, 2.40 GHz CPU
437 and 16 Gb RAM. Therefore, the procedure can be really used in emergency conditions.

438

439 **6. Conclusions**

440 The feasibility of terrestrial SfM surveys without GCPs and DG aimed at evaluating slope
441 movements from distances of hundreds of meters was investigated by means of an experiment
442 with an artificial target and in situ multitemporal surveys in Central Apennine area, Italy.
443 Three different focal lengths (55, 110 and 220 mm) were considered and the point clouds
444 were scaled on the basis of TLS data.

445 The results shown that there is a resolution limit, which is ~ 2.5 times the GSD. In
446 particular, for ~ 250 m acquisition distance, the data obtained with focal lengths of 110 mm
447 and 220 mm are widely comparable to each other and allow the observation of deformation
448 patterns of at least 30-40 mm under the condition that there are localized unstable areas in a
449 relatively stable cliff. The results prove the effectiveness of the used approach in surveying of
450 mountain slopes in emergency conditions where the standard technique (modeling based on
451 GCPs or at least DG) cannot be used.

452

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457 realization.

458 The authors wish to dedicate this article to the memory of Enzo Boschi (1942-2018).

459

460 **Notation**

461 *The following symbols and acronyms are used in this paper:*

462 BA: bundle adjustment;

463 BS: bedrock scarp;

464 CF: crop factor;

465 f : focal length;

466 f_N : Nyquist frequency;

467 GCP: Ground Control Point;

468 GNSS: Global Navigation Satellite System;

469 GSD: Ground Sampling Distance;

470 MTF: Modulation Transfer Function;

471 p : pixel size;

472 RL: resolution limit;

473 σ : standard deviation;

474 SF: scale factor;

475 SfM: structure-from-motion;

476 TLS: terrestrial laser scanning;

477

478 **Online Supplemental Material**

479 Quality of the scale factor as a function of polyline size.

480

481 **Data Availability Statement**

482 Some or all data, models, or code that support the findings of this study are available from the

483 corresponding author upon reasonable request.

484

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594

Figure captions

595

596

597 **Fig. 1.** Experiment with an artificial target: (a) target; (b) a point cloud; (c) a particular of the
598 point cloud; (d) selection of the dark points; (e) layout.

599

600 **Fig. 2.** Results of preliminary experiment with an artificial target: ground sampling distance
601 (GSD), i.e. pixel size, and point cloud resolution vs. acquisition distance for a focal length (f)
602 of (a) 55 mm; (b) 102 mm; (c) 210 mm; (d) ratio between resolution and GSD vs. acquisition
603 distance; (e) GSD and point cloud resolution vs. distance normalized for $f = 55$ mm.

604

605 **Fig. 3.** Campo Felice bedrock scarp: (a) general tectonic setting of the central Apennines. The
606 lines stand for active faults mapped on the basis of geomorphic characteristics (Schlagenhauf
607 2009) and the star marks the position of the bedrock scarp; (b) image of the surveyed
608 mountain slope with the exposed bedrock scarp; (c) geologic and morphologic characteristics
609 of the mountain slope.

610

611 **Fig. 4.** TLS-based survey: (a) vertical point cloud cross section and slope inclination; (b)
612 frontal perspective view of the central part of the surveyed slope. A distance between two
613 points of the cloud provide an immediate scale for the surveyed area.

614

615 **Fig. 5.** SfM-based survey: (a) point cloud obtained from images with 55 mm f , where the lines
616 indicate the boundaries of the areas modelled for the used f values; (b), (c), (d) sample images
617 taken with f of 220 mm, 110 mm e 55 mm respectively; (e) camera positions and orientations
618 with respect to the observed cliff in the case of 55 mm f .

619

620 **Fig. 6.** Maps of differences between the pairs of point clouds related to focal length of 55 mm
621 (a), 110 mm (b) and 200 mm (c). Maps of differences between point clouds related to
622 different focal lengths: (d) 55 mm vs. 110 mm; (e) 55 mm vs. 220 mm; (f) 110 mm vs. 220
623 mm.

624

625 **Fig. 7.** Distributions of differences between pairs of point clouds. Pairs related to the same
626 focal length: (a) 55 mm, (b) 110 mm and (c) 220 mm; pairs related to different focal lengths:
627 (d) 55 mm vs. 110 mm; (e) 55 mm vs. 220 mm; (f) 110 mm vs. 220 mm. For each distribution
628 of observational data, the corresponding normal distribution with the same parameters is also
629 shown.

630

631 **Fig. 8.** Multitemporal data comparison for a focal length of 110 mm: (a) 2019 point cloud, on
632 which the boundary of 2018 point cloud is shown; (b) 2018 point cloud; (c) 2018-2019
633 differences in the range ± 0.1 m; (d) 2018-2019 differences in the range outside the resolution
634 limit (0.04 m); (e) 2018-2019 differences inside the range ± 0.04 m.

635

636 **Fig. 9.** SfM and TLS point clouds comparison: difference maps for focal length of (a) 55 mm,
637 (b) 110 mm and (c) 220 mm; (d) TLS and 55 mm SfM point clouds.

638

Table 1. Camera technical specifications.

Feature/parameter	Unit	Value
Camera	-	Nikon D3300
Focal length	mm	55-300
Crop factor	-	1.5
Equivalent focal length 35 mm	mm	83-450
Sensor number of pixels	-	6000 x 4000
Sensor size	mm x mm	23.5 x 15.6
Pixel size	mm	0.0039
Aperture (f-stop)	-	<i>f</i> /8
Sensibility	ISO	400

Table 2. Some details about the PhotoScan data processing

Survey			Number of tie points	Number of points (10 ⁶)	Computation time (h)		
<i>f</i> (mm)	#	Images taken			Camera alignment	Dense point cloud generation	Total
55	1	30	1071	21.140	0.08	0.82	0.90
55	2	30	1133	21.250	0.08	0.82	0.90
110	1	42	1906	39.950	0.12	3.33	3.50
110	2	42	1880	40.570	0.12	3.33	3.50
220	1	44	2656	50.960	0.15	3.65	3.80
220	2	44	2750	47.410	0.15	3.65	3.80

Note: The computation times are referred to a notebook equipped by an Intel Core i7, 2.40 GHz CPU and 16 Gb RAM

Table 3. Main statistical parameters of data comparisons

Point cloud (<i>f</i> , mm)	U/B ¹	Mean (m)	Median (m)	SD (σ , m)	skewness	kurtosis
55	B	0.006	-0.005	0.018	-0.26 ^a	35 ^a
110	U	-0.001	-0.002	0.012	0.34	20
220	U	-0.001	-0.001	0.007	0.30	41
55-110	B	0.002	0.003	0.031	-0.96 ^a	18 ^a
55-220	B	0.023	0.025	0.034	0.24 ^a	5.6 ^a
110-220	U	0.001	0.002	0.016	-1.0	4.1

Note: U: unimodal distribution; B: bimodal distribution.

^a Since the distribution is bimodal, the values of skewness and kurtosis are not significant.















