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1 **Three-dimensional (3D) reconstructions of the coastal cliff face in**
2 **Normandy (France) based on oblique Pléiades imagery: assessment of**
3 **Ames Stereo Pipeline® (ASP®) and MicMac® processing chains**

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14 **Three-dimensional (3D) reconstructions of the coastal cliff face in**
15 **Normandy (France) based on oblique Pléiades imagery: assessment of**
16 **Ames Stereo Pipeline[®] (ASP[®]) and MicMac[®] processing chains**

17 Images from agile (viewing angle over 40°) and very high spatial resolution
18 satellites (inferior to 1 m) can be useful for monitoring cliff faces, which is the
19 best proxy to better understand coastal cliff dynamics. However, these images
20 with a specific configuration are rarely used, partly because it is cumbersome to
21 process them. Based on Pléiades images of the coastal cliff face along the coast
22 of Normandy, with a high angle of incidence (up to 40°) and taken on multiple
23 dates, the paper aims to identify i) the best open-source processing chain to
24 reconstitute three-dimensional (3D) cliff faces by stereo restitution ii) the reasons
25 behind its best performance and iii) the key parameters to change depending on
26 the image datasets or processing chains so as to facilitate transposition. The
27 Ames Stereo Pipeline[®] (ASP[®]) and MicMac[®] software programmes were tested
28 using different parameters (matching algorithm, size of correlation window, etc.)
29 for the 3D reconstructions. MicMac[®] provides the best performance using
30 GeomImage (1-2 pixel matching) with a size of correlation window of 3 × 3 or
31 7 × 7 associated with a regularization parameter of 0.10. With these parameters,
32 the point clouds of the cliff face have an average point density of 1.70 point m², a
33 mean distance from Unmanned Aerial Vehicle (UAV) ground truth data of
34 0.04 m and a standard deviation of 1.72 m. With these characteristics, the
35 threshold of rockfall detection using a multi-source comparison is assessed at 100
36 m³, which involves that the large majority of rockfalls (69%) around the study
37 area could be detected by a diachronic approach. Considering the daily Pléiades
38 revisiting time, this method offers a great opportunity to monitor erosion and to
39 better understand coastal cliff dynamics.

40 Keywords: Pléiades satellites, oblique images, 3D restitution, cliff face, coastal
41 erosion.

42 **Introduction**

43 Starting in the 2000s, the new generations of very high spatial resolution (less than 1 m
44 in panchromatic mode) and agile satellites with short revisit time (QuickBird,
45 WorldView, GeoEye, Pléiades, until around 40°) offer a greater scientific potential to
46 combine large scale, high-resolution studies (Poli et al. 2015; Collin et al. 2018), and to
47 do three-dimensional (3D) topographic reconstructions from pairs or triplets of images
48 from different viewing angles. Some topics in geosciences have explored the potential
49 of these new datasets. Elevation changes in glacier topography can be studied thanks to

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50 Pléiades stereo imagery (Berthier et al. 2014), height changes due to earthquakes can be
51 determined by stereo and tri-stereo reconstructions with a precision of a few decimetres
52 (Zhou et al. 2015), lava flow volume can be estimated with Digital Elevation Model
53 (DEM) of Difference (DoD) computed from Pléiades triplet images (Bagnardi,
54 González, and Hooper 2016).

55 To observe all the changes of the coastal cliff, the entire cliff face (from the foot
56 of the cliff to its top) should be observed. This means that the best point of view is
57 horizontal. However, cliff face surveys are quite rare given that few datasets use this
58 point of view. Until recently, most datasets had a vertical point of view (aerial
59 photographs, aerial Light Detection And Ranging (LiDAR), satellite imagery, etc.), and
60 therefore the most common proxy to determine the evolution of the cliff was the cliff
61 top (e.g. Costa 1997; Zviely and Klein 2004; Foyle and Naber 2012). The arrival of
62 agile (i.e. satellites able to observe the field from a high angle of incidence) and very
63 high spatial resolution satellites, Terrestrial Laser Scanners (TLS), terrestrial
64 photogrammetry, mobile laser scanners set up on a boat have made it easier to observe
65 the cliff face and therefore to record its changes (e.g. Letortu et al. 2020; Gulyaev and
66 Buckeridge 2004; Letortu et al. 2018; Michoud et al. 2014, respectively). Whereas i)
67 coastal cliffs likely exist on roughly 52% of the global shoreline (Young and Carilli
68 2019) ii) many people, houses, companies, infrastructure are/could be threatened by the
69 risk of coastal erosion iii) there are high societal and political demands for reliable,
70 homogeneous, perennial and low-cost data on long stretches of coastline in order to
71 better understand erosion and protect inhabitants iv) various agile and very high spatial
72 resolution satellites are available (e.g. QuickBird, GeoEye, WorldView and Pléiades),
73 this research topic is still in its early stages with a unique paper (Letortu et al. 2020).

74 Pléiades-HR (High-Resolution Optical Imaging Constellation) is a two-
75 spacecraft constellation of CNES (the French Space Agency). The Pléiades 1A and 1B
76 satellites were launched (16 December 2011, 02 December 2012, respectively) by the
77 Soyuz launcher from the French Guiana Space in Kourou. The Pléiades satellites have
78 six main qualities that are useful for coastal cliff studies (ASTRIUM 2012):

- 79 (1) The very high spatial resolution of their images (e.g. a ground sampling distance
80 of 0.70 m at the nadir for panchromatic images);
- 81 (2) A high level of agility, with a theoretical viewing angle up to 47°;
- 82 (3) The daily revisit frequency;
- 83 (4) A swath width of 20 km at the nadir, in line with the coastal management scale,
84 i.e. the hydro-sedimentary cell (from hundreds of metres to hundreds of
85 kilometres);
- 86 (5) A mission lifetime of ten years and a continuity of measurements between the
87 next versions of the satellites (Pléiades Neo constellation);
- 88 (6) Free access to the images under certain conditions for research institutes.

89 The EROFALITT (erosion of coastal cliffs) project was funded by CNES (2016-
90 2020) in order to explore the potential of Pléiades images to monitor the evolution of
91 coastal cliffs by observing the cliff face proxy. With Pléiades images with a high angle
92 incidence, 3D reconstitutions of cliff faces along the coast of Normandy (NW France)
93 were performed. This project was challenging because:

- 94 • It is located in Varengeville-sur-Mer (Seine-Maritime), where disturbed weather
95 and the NNE orientation of the cliff face can alter the image quality (due to
96 clouds and shadows, respectively);

- 97 • It has uncommon image acquisition modalities: because of the NNE orientation
98 of the cliff face, it was shown that the standard stereo or tri-stereo acquisition
99 was unsuitable. Another acquisition modality was proposed: a multi-date survey
100 over several consecutive days. As the orbital pass position of the Pléiades
101 satellites changes daily, a mono-acquisition up to an incidence angle of 40°
102 (across-track) acquired on successive days (around 13:20 in local time,
103 Universal Time Coordinated (UTC) + 2) can be used to observe the cliff face at
104 various viewing angles to reconstruct it in 3D via stereo restitution. To assess
105 the impact of the angle of incidence, two sets of images were simultaneously
106 requested each day: one with a pitch imaging angle of 40° and a second one with
107 a pitch imaging angle between 0° and 10° (more details in Letortu et al. 2020);
108 • There is a limited choice of image processing software programmes as this is an
109 unusual image dataset.

110 The objectives of this paper are to answer two main questions:

- 111 • What is the best processing chain to obtain a 3D reconstitution of the cliff face
112 between Ames Stereo Pipeline[®] (ASP[®]) and MicMac[®] from our image dataset?
113 Why?
114 • What are the key parameters that depend on the images or the processing chain
115 per software in order to facilitate any transposition of our method to other sites
116 or images (no need to test all the parameters, but only a few)?

117 A high angle of incidence and multi-date images acquired by a push broom
118 sensor limit the number of software programmes that can be used to process images
119 (e.g. ASP[®], ERDAS IMAGINE[®], Satellite Stereo Pipeline[®] (S2P[®]), MicMac[®], Agisoft

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120 Metashape[®]). Previously, we used ERDAS IMAGINE[®] (Letortu et al. 2020); however
121 open-source software and well-documented processing were important criteria in our
122 choice of which software to test. Our goal is to understand why one software package or
123 processing parameter works better than another, therefore we must avoid the ‘black
124 box’ effect. Consistent with these requirements, we selected the ASP[®]
125 (<https://ti.arc.nasa.gov/tech/asr/groups/intelligent-robotics/ngt/stereo/>; Shean et al.
126 2016) and MicMac[®] (<https://micmac.ensg.eu/>; Rupnik, Daakir, and Pierrot Deseilligny
127 2017) software programmes and the test will focus on the parameters used in stereo
128 matching algorithms. The tests are based on the best images in our set acquired in June
129 and July 2017 with pitch imaging angles of 40° and between 0° and 10° (Letortu et al.
130 2020).

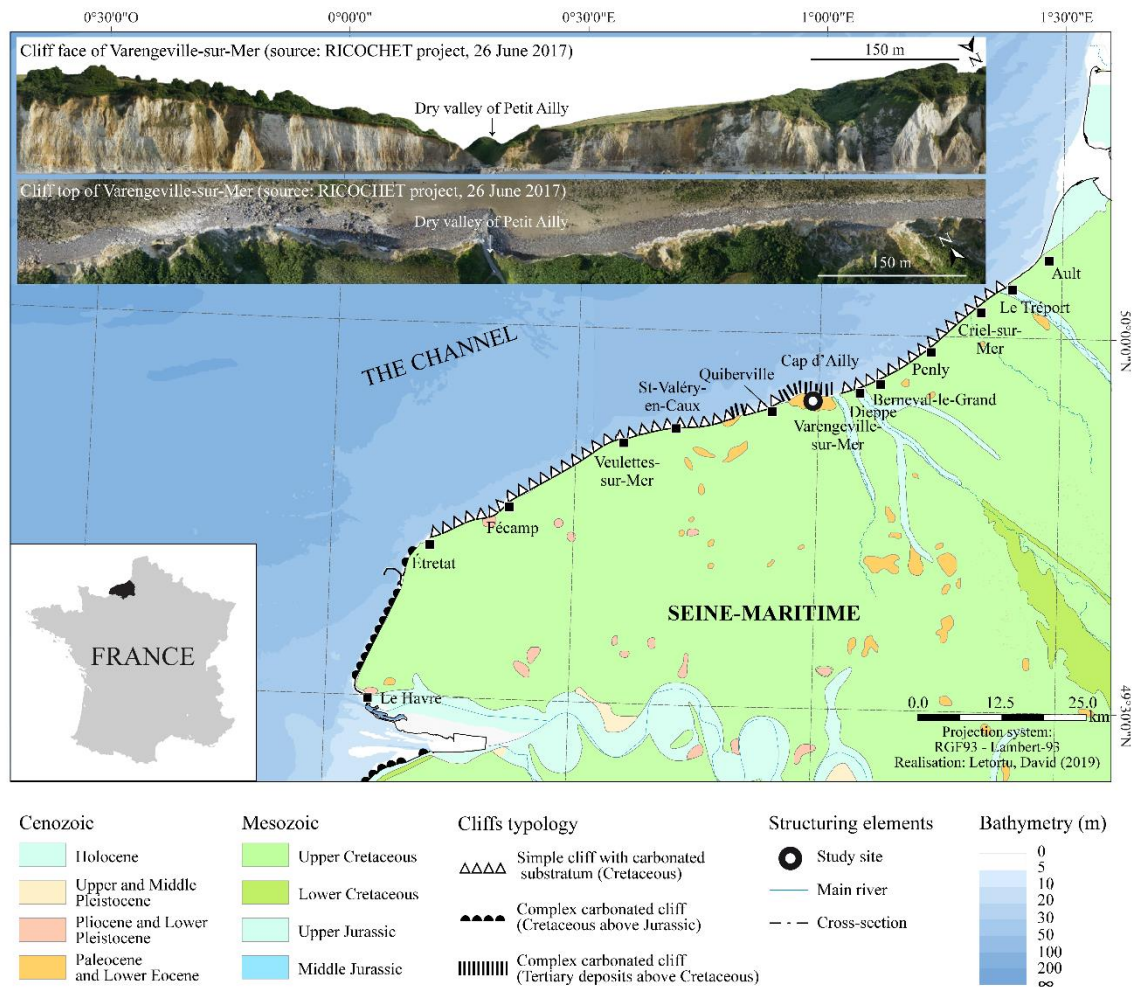
131 First, the material and methods including the study area will be described, then
132 the results of our software and processing chain comparison will be presented and
133 discussed.

134 **Materials and methods**

135 *Study site*

136 Located in Normandy (Seine-Maritime, NW France) along the English Channel,
137 Varengeville-sur-Mer (1°00'27.34"E; 49°54'59.77"N) is characterized by sub-vertical
138 coastal cliffs (70° to 90°) carved in Upper Cretaceous chalk with flints (part of the Paris
139 Basin; Pomerol et al. 1987; Mortimore et al. 2004). The study area stretches over 600
140 m, extending 300 m on both sides of the dry valley, called Petit Ailly (Figure 1). These
141 cliffs are mainly white in colour (chalk), but are darkened (brown colour) by a bed
142 comprised of clay and sand sediment from the Tertiary Period (Palaeogene). These
143 cliffs are very prone to erosion (0.36 m year⁻¹ between 2010 and 2017 (Letortu et al.

144 2019) whereas the average county retreat rate is 0.15 m year⁻¹ (between Cap d'Antifer
 145 and Le Tréport, during the 1966-2008 period (Letortu et al. 2014)), with many rockfalls
 146 of several cubic metres to hundreds of thousands of cubic metres (Letortu et al. 2015).
 147 A fatality occurred in August 2015 in Varengeville-sur-Mer due to falling rocks.



148
 149 Figure 1. Presentation of the study area of Varengeville-sur-Mer (Seine-Maritime,
 150 Normandy, France).

151
 152 Climatically, the study area belongs to the western part of Europe, which is
 153 particularly exposed to the influences of low oceanic pressures, and thus, to the types of
 154 disturbed weather that dominate approximately 2/3 of the year (Pédelaborde 1958;
 155 Trzpit 1970).

156 The average tidal range is 8 m (macrotidal environment). At low tide, the
157 foreshore is characterized by a wide shore platform slightly inclined to the sea covered
158 by sand and with a gravel barrier near the contact with the cliff foot. The average
159 altitude of the Varengeville-sur-Mer cliffs is approximately 30 m and the coastline is
160 relatively jagged due to rockfall scars that exploit pre-existing fracturing. The cliff face
161 is oriented toward the NNE (Figure 1).

162 This site, found on both sides of the dry valley of Petit Ailly, was chosen
163 because the cliff dynamics are frequently monitored (e.g. Costa et al. 2019; Letortu et
164 al. 2019). Since 2010, it is surveyed by terrestrial laser scanners (3 to 4 times a year),
165 Unmanned Aerial Vehicle (UAV) (up to once a year), and aerial topo-bathymetric
166 LiDAR (every 3 years). Since 2014, it belongs to the French Observation National
167 Service DYNALIT (coastal dynamics), which encompasses various coastal sites of
168 scientific interest to better understand the coastal dynamics.

169 The acquisition of oblique and multi-date images from satellites in this study
170 area is challenging for four reasons:

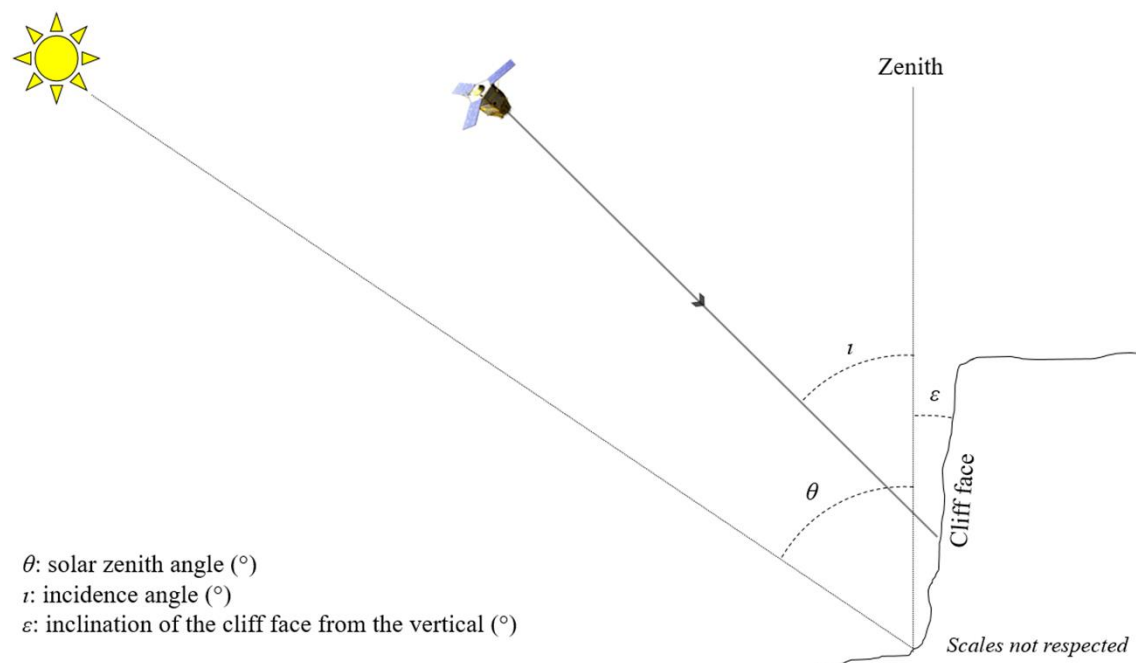
- 171 (1) cloudy and rainy weather is frequent because it is located in mid-latitudes where
172 disturbed weather dominates, and therefore it can be rare to have good
173 conditions for image acquisition;
- 174 (2) while the Pléiades satellites have a meridian orbit, the NNE orientation of the
175 cliff face makes it difficult to acquire the image;
- 176 (3) the cliff face is sub-vertical (70° to 90°) and, due to its orientation, it is in the
177 shadow cast by the cliff at the time the satellite passes over, even during summer
178 (Figures 2 and 3);
- 179 (4) a high tidal range may hide the cliff foot whereas the whole cliff face is needed.

180 **Data**

181 Images were acquired in autumn 2016 (four stereoscopic pairs), in summer 2017 (five
182 stereoscopic pairs) and in winter 2017/2018 (five stereoscopic pairs), covering the 20 km-
183 long cliff line from Quiberville to Berneval-le-Grand (Figure 1). Out of these 28 images,
184 the most relevant stereoscopic pairs for the 3D reconstitution are from June to July 2017
185 as the weather was sunny and there were few shadows on the cliff face (Letortu et al.
186 2020).

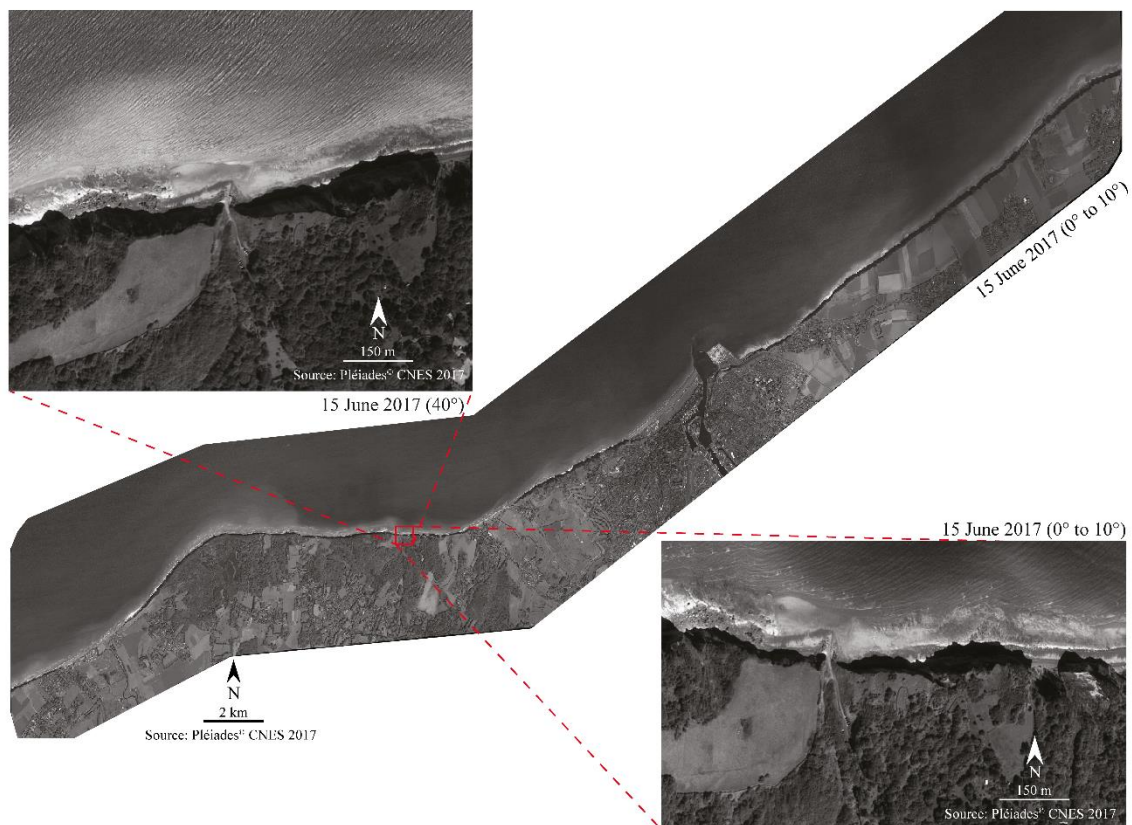
187 We decided to focus on six relevant images (10 June 2017, 15 June 2017, 06
188 July 2017 with incidence angles of 0° to 10° and 40°) and therefore we reduced the
189 study area to only around the dry valley of Petit Ailly at Varengeville-sur-Mer (600 m
190 long), where validation data are available. Over this spatially limited area, a large
191 number of tests on the image processing workflow can be considered in terms of
192 computing resources and computing time (Figures 2 and 3).

Image date	Local time of satellite pass (UTC+2)	Solar zenith angle (°)	Image incidence angle (°)
10 June 2017 and 15 June 2017	13:20 and 13:31	62.1 and 62.9	40
10 June 2017 and 15 June 2017	13:21 and 13:33	62.2 and 62.7	0 to 10
10 June 2017	13:21 and 13:20	62.2 and 62.1	0 to 10 and 40
15 June 2017	13:33 and 13:31	62.7 and 62.9	0 to 10 and 40
15 June 2017 and 06 July 2017	13:31 and 13:20	62.9 and 61.5	40
15 June 2017 and 06 July 2017	13:33 and 13:21	62.1 and 61.5	0 to 10



193

194 Figure 2. Date, local time of satellite pass, solar zenith angle, and incidence angle of the
 195 images selected for the tests.



196

197 Figure 3. Complete spatial extent of the Pléiades panchromatic image (wavelengths
198 between 470 and 830 nm of the visible spectrum) acquired on 15 June 2017 (0° to 10°)
199 and cropped images around the study area in Varengeville-sur-Mer with incidence
200 angles of 0° to 10° and 40°.

201

202 Ground truth data in this paper are from the UAV 3D reconstruction. This
203 survey was ordered for the RICOCHET (multi-risk assessment on coastal territory in a
204 global change context) project and performed by Azur Drones company on 26 June
205 2017. With a Sony A7R – 36 Mp sensor mounted on an octocopter Mikrokopter, image
206 acquisition were oblique with manual framing. The 3D reconstruction was based on
207 1740 photographs (spatial extent of about 400 m on both sides of the dry valley of Petit
208 Ailly) and 11 targets located to the ground and measured by Differential Global
209 Positioning System (DGPS). It was projected in an absolute coordinate system, in
210 Lambert-93 and associated Réseau Géodésique Français 1993 (RGF93) and

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211 Nivellement Général de la France-Institut Géographique National69 (NGF-IGN69),
212 which is the official reference system in France (European Petroleum Survey Group
213 (EPSG) registry: 2154). The 3D reconstruction error was of 2.11 cm, with a sampling
214 distance of 3 cm.

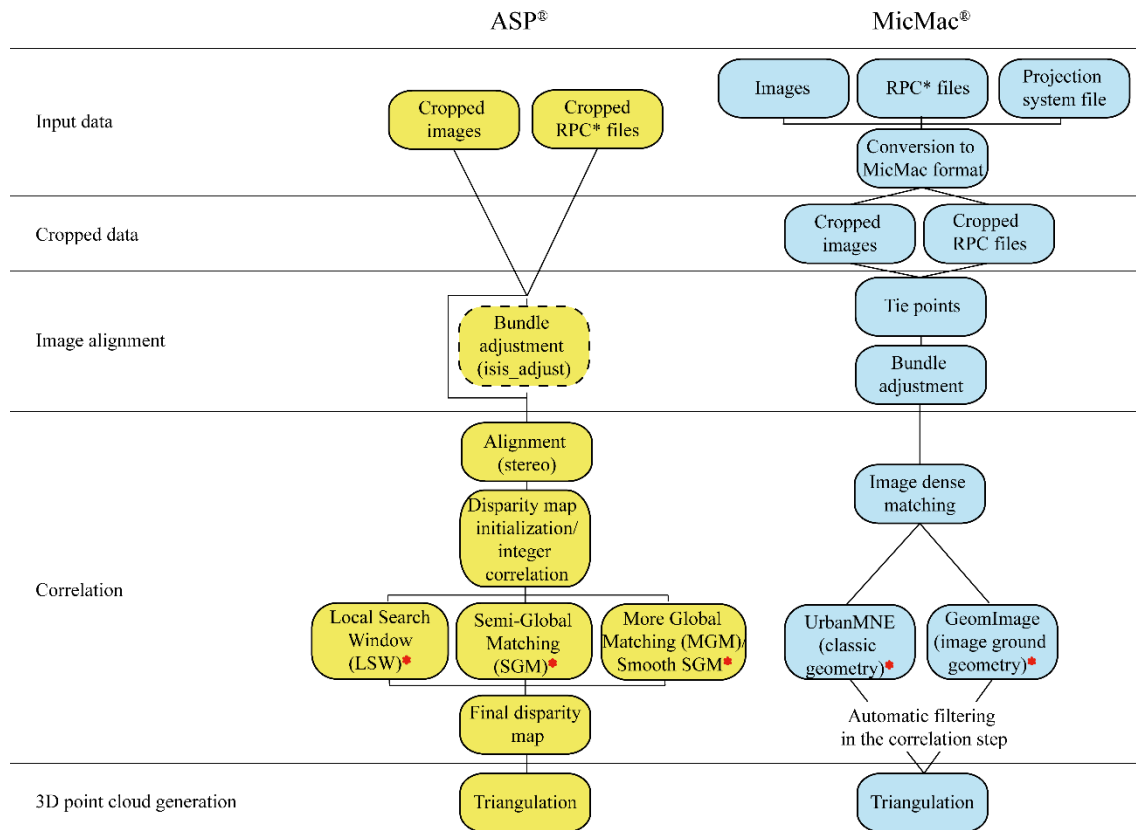
215 TLS ground truth data are also used in this paper. The raw TLS point cloud was
216 obtained from a RIEGL VZ-400 (laser pulse in the near-infrared (1550 nm)) on 25
217 September 2015, which provides scan data acquisition with theoretical 0.005 m
218 accuracy and 0.003 m precision at a range of 100 m (RIEGL Laser Measurement
219 Systems 2014). In Varengeville-sur-Mer, two scanner stations (located at about 75 m
220 from the cliff face) provided each a dense 3D point cloud (more than 22.5 million
221 points). Twenty-one reflective targets (10 cm high cylinders) with different distances
222 from the scanner were used to georeference the point cloud because they were measured
223 by a total station (Trimble M3). The point cloud (spatial extent of about 150 m on both
224 sides of the dry valley of Petit Ailly) was thus projected in Lambert-93 and associated
225 RGF93 and NGF-IGN69. The TLS data processing encompassed three steps : i)
226 georeferencing and point cloud assembly (RiscanPRO®) ii) manual point cloud filtering
227 including areas without overlap with previous TLS data, noise and vegetation
228 (Fledermaus®) and iii) Delaunay two-and-a-half-dimensional (2.5D) meshing (best fit
229 plane, Cloudcompare®) (more details in Letortu et al. 2018). The 2.5D mesh was used
230 for dataset comparison.

231 Both methods proved to be relevant in coastal cliff erosion studies thanks to
232 their high resolution and their centimetre precision (Letortu et al. 2018).

233 ***Methods***

234 *Software packages*

235 The image processing workflow of each software mainly follows the traditional stereo
 236 restitution steps for 3D reconstructions (Figure 4): input data, cropped data, image
 237 alignment, correlation and 3D point cloud generation (NASA 2019; Rupnik et al. 2020).



-- Step not compulsory; *Rational Polynomial Coefficient; *Matching algorithm parameters to test

238
 239 Figure 4. Image processing workflow of ASP® and MicMac® to obtain a 3D point cloud
 240 (NASA 2019; Rupnik et al. 2020).

241

242 Since the images are taken from different viewpoints, the apparent motion of the
 243 scene between the views is computed (called “disparity” in the case of stereo-rectified
 244 image pairs) (Hartley and Zisserman 2003). Stereo matching in the correlation step is
 245 the core of the image processing workflow (Figure 4). It involves identifying pixel
 246 correspondences between the left and right epipolar images. Our tests focused on this
 247 correlation step, which is different between ASP® and MicMac®.

- 248 In ASP[®], three matching algorithms are possible (Figures 4 and 5):
- 249 • Local Search Window (LSW), which is the default ASP[®] correlation algorithm.
- 250 A disparity value is computed by correlation for each valid pixel identified in the
- 251 input image. As the search window size is a key parameter of the correlation step
- 252 and in order to be efficient in larger search ranges, a Gaussian pyramid approach
- 253 is applied, that is to say disparities are first estimated using sub-sampled images,
- 254 and are gradually refined at higher resolution.
- 255 • Semi-Global Matching (SGM), introduced in Hirschmuller (2008). The
- 256 “classical” SGM algorithm has undergone two important changes in ASP[®] in
- 257 order to include unrectified, larger images (NASA 2019): i) two-dimensional
- 258 (2D) disparity search is performed, similarly to what is done in the Neighbor-
- 259 Guided Semi-Global Matching algorithm (Xiang et al. 2016) and ii) ASP[®] uses a
- 260 multi-resolution hierarchical search combined with a compressed memory
- 261 scheme similar to what is used in the SGM algorithm (Rothermel et al. 2012).
- 262 This SGM algorithm is based on multi-directional dynamic approaches. Even if it
- 263 can be time-consuming because of significant memory requirements, SGM
- 264 algorithm appears to be more effective in images with less texture and can
- 265 discern finer resolution features than LSW since it tends to use much smaller
- 266 matching kernels. However, SGM is prone to generate artefacts at tile boundaries
- 267 and to produce inaccurate results in textureless regions. The ASP developers
- 268 recommend using it cautiously in order to minimize these drawbacks (NASA
- 269 2019).
- 270 • More Global Matching/Smooth Semi-Global Matching (MGM/SSGM):
- 271 introduced in Facciolo, Franchis, and Meinhardt (2015), the MGM algorithm

272 (also called SSGM algorithm) reduces the amount of high-frequency artefacts in
273 textureless regions in the output image but at the expense of a longer computing
274 time. A hybrid SGM/MGM mode is also proposed in ASP[®] where MGM only is
275 used for the final resolution level which obtains results somewhere between the
276 pure SGM and MGM options (NASA 2019).

277 In ASP[®], the cost-mode variable (Figure 5) allows the user to choose the cost
278 function used during the correlation step:

- 279 • Normalized Correlation Coefficient (NCC) (cost mode 2): the traditional area-
280 based matching cost is the square difference of the pixel intensities. NCC often
281 accomplishes the matching cost aggregation. This is a window-based matching
282 technique that accounts for compensating gain changes. The disparity is then
283 determined by a local winner-take-all operation in a small search window and
284 checking with a simple threshold. The last step is characterized by sub-pixel
285 interpolation and other post processing (Hu et al. 2016).
- 286 • Census Transform (cost mode 3): it associates a binary string to each pixel that
287 encodes whether or not the pixel has a smaller intensity than each of its
288 neighbours. Not only does it store the intensity ordering but also the spatial
289 structure of the local neighbourhood (Hirschmuller and Scharstein 2008). It
290 performs well for outdoor environments with uncontrolled lighting. ASP[®] allows
291 the application of census transform only with the SGM correlator (NASA, 2019).
- 292 • Ternary Census Transform (cost mode 4): A modification of the census
293 transform, which is more stable on low contrast terrain. The difference of the two
294 census transform matching costs lies in the encoding of the results. For any given

295 rectangular window, a pixel will be encoded into a bit string in the Census
296 Transform and into two bits in the Ternary Census Transform (Hu et al. 2016).

297

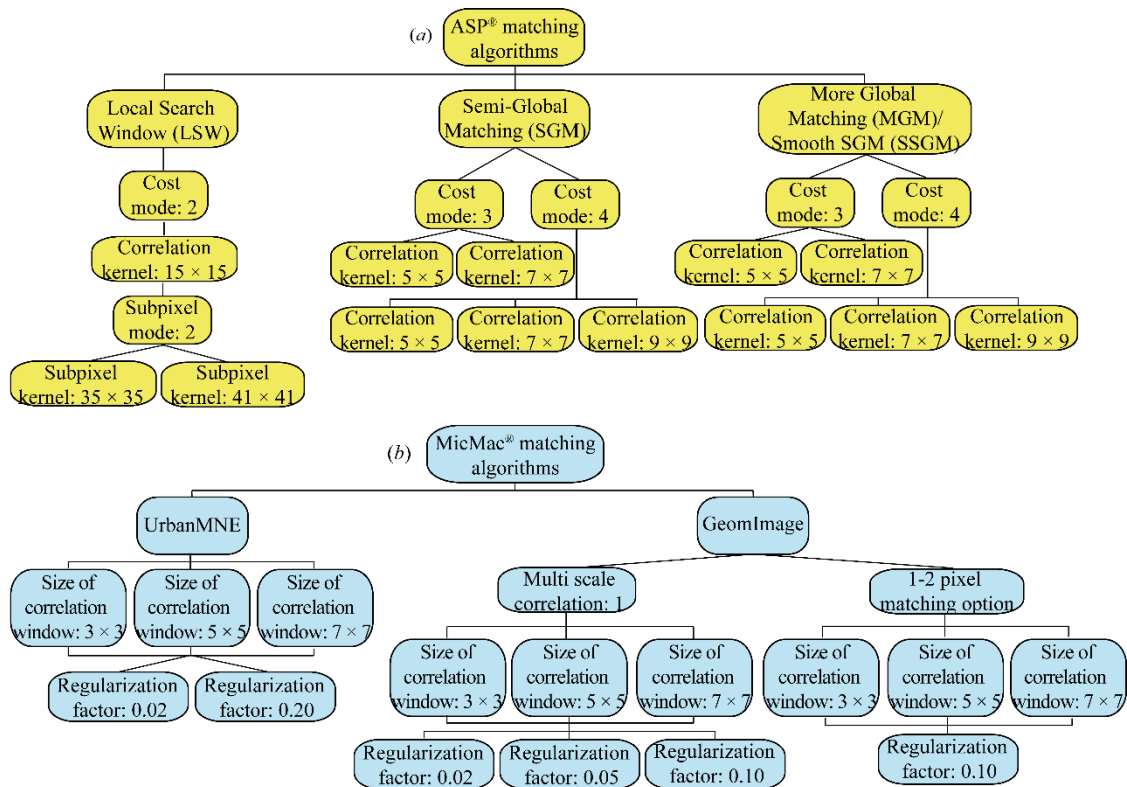
298 In MicMac[®], the Malt tool proposes two semi-global matching algorithms,
299 where the choice of the cost function is included in the step performed to choose a
300 matching algorithm (Rupnik et al. 2020) (Figures 4 and 5):

- 301 • UrbanMNE is for a matching adapted to the urban digital elevation model. It
302 handles matching in ground geometry, adapted to a scene that can be described
303 by a single function $Z = f(X,Y)$ (where X, Y, Z are Euclidean coordinates).
304 Having the output geometry equal to the input geometry, UrbanMNE is
305 perfectly adequate for modelling quasi-planar objects.

- 306 • GeomImage is for matching in ground image geometry (Rupnik, Pierrot-
307 Deseilligny, and Delorme 2018). In this case, matching is performed by using the
308 ‘ground image geometry’, which is more flexible and better suited for the
309 modelling of fully 3D objects. With this mode, the geometry of the modelling is
310 adapted to a selected point of view, consistent with the acquisition. In addition,
311 Malt GeomImage handles a ‘One-Two-Pixel multi-view image matching’ (1-2
312 pixel matching) method, which is a new matching cost function that produces
313 surfaces with enhanced resolution compared to the window-based semi-global
314 matching technique, where the data term is replaced by a multi-view single pixel
315 similarity measure, and a two-pixel window (Rupnik and Deseilligny 2019;
316 Rupnik et al. 2020).

317 Because of different processing workflows, it could be difficult to standardize
318 the processing parameters within the software itself and between software packages. We

319 tried to optimize the consistency of the comparison (Figure 5). As the area of interest
 320 corresponds to steep slopes, we used small correlation windows (5×5 pixels, 7×7
 321 pixels, 9×9 pixels), but the small size of the windows may introduce more false
 322 matches or noise (NASA 2019). For LSW, a larger correlation kernel is used (15×15)
 323 due to its difficulty to find tie points on the cliff face. The regularization factor adds a
 324 constraint on the a priori position of the reconstructed points. The higher the factor, the
 325 more regular the result.



326
 327 Figure 5. Parameters for the matching algorithms tested in (a) ASP® and (b) MicMac®.
 328

329 While running MicMac® as ASP®, no Ground Control Points (GCPs) were
 330 provided. The Rational Polynomial Coefficients (RPCs) provide an approximate
 331 localization model used for geometric processing and orthorectification (ASTRIUM
 332 2012). Bundle adjustment without GCPs ensure good results and do not introduce

333 undesirable deformations (Rupnik et al. 2016). Because of frequent georeferenced point
334 clouds (coming from UAV or TLS) as ground truth data, the roughly georeferenced
335 satellite point clouds are then realigned by Iterative Closest Point (ICP) co-registration
336 algorithm (CloudCompare®).

337 Quality Assessment

338 A relative precision criterion is compulsory in order be able to assess the 3D
339 reconstruction quality and therefore the relevance of our data to make single-source or
340 multi-source comparisons (TLS data or UAV data). Thus, 3D reconstructions from the
341 Pléiades images were filtered (artefact removal), georeferenced and compared to ground
342 truth data at Varengeville-sur-Mer, acquired on 26 June 2017 using UAV. These
343 synchronous surveys (UAV and satellites) allow to limit errors due to erosion events.
344 The UAV and Pléiades point clouds were cut in order to have the same spatial extent
345 (53700 m²) and the UAV point cloud was subsampled at 5 cm. A semi-automatic co-
346 registration (ICP in CloudCompare®) using a rigid-body transform was performed to
347 georeference the Pléiades point clouds by fitting on the UAV mesh (considered as the
348 reference). This co-registration is efficiently constrained vertically (shore platform,
349 plateau) and alongshore. Thus, the precision error of the Pléiades 3D reconstructions is
350 assessed in comparison with Root Mean Square Error (RMSE in m) of the co-
351 registration. Precision error is assessed in the cross-shore direction (which is the
352 direction of erosion on the cliff face), based on the relative distance (normal of the cliff
353 face) after fitting.

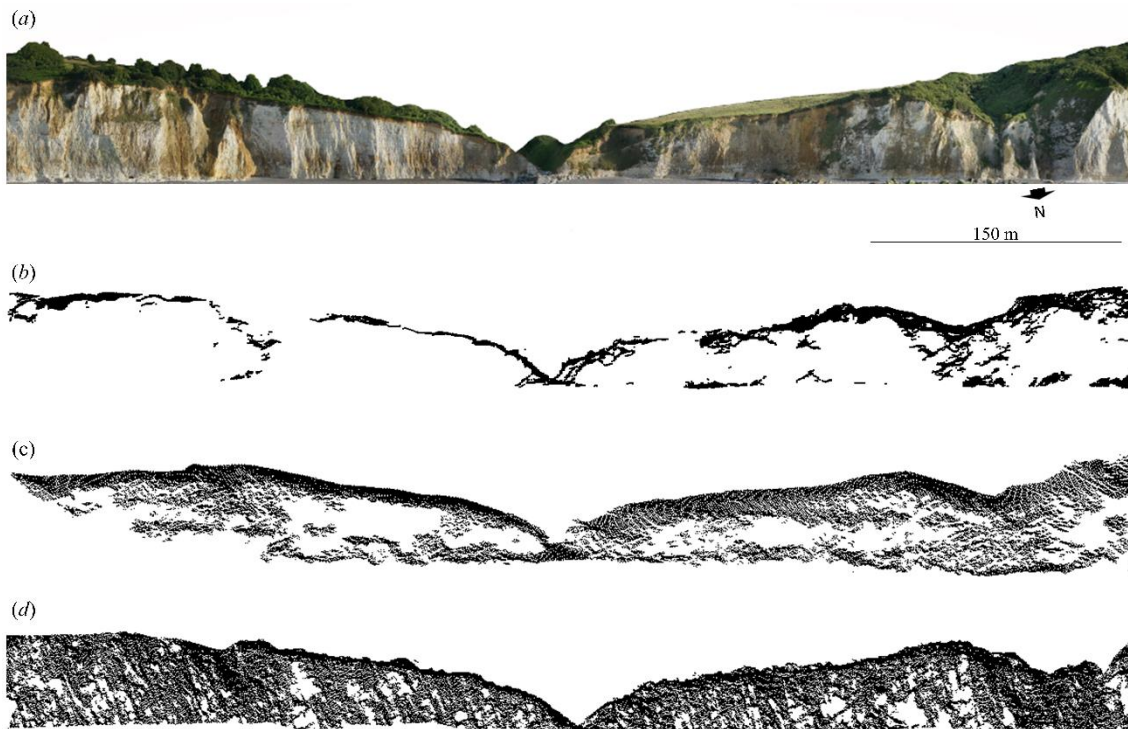
354 The georeferencing error (absolute error) is of lesser importance because we
355 have frequent perfectly georeferenced and very high resolution surveys (TLS or UAV)
356 that allow to align the point clouds coming from the Pléiades images.

357 **Results**

358 *Criteria for 3D reconstruction ranking*

359 Based on 146 tests performed with ASP® and MicMac® on different pairs of images, we
360 sorted our results based on the:

- 361 • Relative precision in comparison with UAV data (mean distance which allows to
362 calculate the distance relative to the mesh of the UAV data, and standard
363 deviation to assess point dispersion);
- 364 • Point density of the clouds;
- 365 • Quality assessment of the reconstructions (not satisfactory, few satisfactory,
366 satisfactory) taking into account the homogeneity of the reconstructed point
367 distribution over the cliff face, artefacts and noise (Figure 6). Satisfactory
368 reconstructions provide visibility of structural discontinuities from the cliff foot
369 to the cliff top in order to observe rockfalls irrespective of their locations over
370 the cliff face.



371

372 Figure 6. Cliff face reconstructed from UAV data (RICOCHET project, 26 June 2017)
373 (a) and quality ranking of the 3D reconstructions from Pléiades images at Varengeville-
374 sur-Mer: (b) not satisfactory result (10 June 2017 and 15 June 2017 at 40°, MicMac®,
375 UrbanMNE, size of correlation window: 5 × 5, regularization factor: 0.20), (c) few
376 satisfactory result (10 June 2017 and 15 June 2017 at 40°, ASP®, Local Search
377 Window, cost mode: 2, correlation kernel: 15 × 15, subpixel kernel: 41 × 41), (d)
378 satisfactory result (10 June 2017 and 15 June 2017 at 40°, MicMac®, GeomImage, multi
379 scale correlation: 1, size of correlation window: 3 × 3, regularization factor: 0.05).

380

381 Unsurprisingly, and regardless of the software used, satisfactory reconstructions
382 (48/146) have a minimum of one image with an incidence angle of 40°. When the 3D
383 reconstruction uses two images with angles of 0° to 10°, the cliff face reconstruction is,
384 at best, assessed as ‘few satisfactory’, i.e. with noise, artefacts or holes (Table 1) due to
385 the acquisition geometry which is not adapted to the sub-vertical cliff face (Jaud et al.
386 2019; Letortu et al. 2020). There are more satisfactory reconstructions of the cliff face
387 when the stereo restitution uses two images with an angle of 40°.

388 Among the 146 tests, the best 3D reconstruction per image pair was selected
389 based on the three parameters described below. The objective was to select a
390 satisfactory 3D reconstruction, with the best compromise between low mean distance
391 and standard deviation values, and a high point density value (Table 1). The best
392 reconstructions were selected and there are ten (Table 2). Taking only the mean error
393 and standard deviation values into account, the reconstructions from the 0° to 10°
394 datasets may seem more precise than the 40° stereo pairs, but in reality, this is weighted
395 by the fact that most of the points reconstructed at 0° to 10° are located on the top of the
396 cliff and less on the cliff face.

397 Table 1. Extract of the original table of the 146 tests with the selection of the best 3D
398 reconstruction per pair (e.g. 10 June 2017 and 15 June 2017 at 40° using MicMac®).

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Software	Date of image pair	Angle of Incidence (°)	Matching algorithm	Specifications of each software ASP®: cost mode / correlation kernel (subpixel kernel) MicMac®: size of correlation window / regularization parameter	Point density (number of points m ⁻²)	Mean distance (m)	Standard deviation (m)	Quality assessment of 3D reconstruction (the best one per pair in bold)
MicMac®	10 June 2017 and 15 June 2017	40	UrbanMNE	3 × 3 / 0.02	0.44	-0.17	4.54	not satisfactory
		40	UrbanMNE	3 × 3 / 0.20	0.44	0.22	2.92	not satisfactory
		40	UrbanMNE	5 × 5 / 0.02	0.53	0.07	2.99	not satisfactory
		40	UrbanMNE	5 × 5 / 0.20	0.47	0.29	3.74	not satisfactory
		40	UrbanMNE	7 × 7 / 0.02	0.52	0.08	3.17	not satisfactory
		40	UrbanMNE	7 × 7 / 0.20	0.47	0.20	3.13	not satisfactory
		40	GeomImage (CorsMS: 1)	3 × 3 / 0.02	1.64	-0.07	2.60	satisfactory
		40	GeomImage (CorsMS: 1)	3 × 3 / 0.05	1.71	0.00	2.37	satisfactory
		40	GeomImage (CorsMS: 1)	3 × 3 / 0.10	1.72	0.15	2.12	satisfactory
		40	GeomImage (CorsMS: 1)	5 × 5 / 0.02	1.83	0.13	2.20	satisfactory
		40	GeomImage (CorsMS: 1)	5 × 5 / 0.05	1.84	0.16	2.30	satisfactory
		40	GeomImage (CorsMS: 1)	5 × 5 / 0.10	1.82	0.19	2.28	satisfactory
		40	GeomImage (CorsMS: 1)	7 × 7 / 0.02	1.76	0.08	2.12	satisfactory
		40	GeomImage (CorsMS: 1)	7 × 7 / 0.05	1.81	-0.09	2.06	satisfactory
		40	GeomImage (CorsMS: 1)	7 × 7 / 0.10	1.79	-0.09	2.03	satisfactory
		40	GeomImage (one-two pixel matching)	3 × 3 / 0.10	1.70	-0.05	1.83	satisfactory
		40	GeomImage (one-two pixel matching)	5 × 5 / 0.10	1.75	-0.08	1.92	satisfactory
		40	GeomImage (one-two pixel matching)	7 × 7 / 0.10	1.67	0.14	2.46	satisfactory

400 **Table 2. The best cliff face 3D reconstructions per image pair based on 146 tests**

Software	Date of image pair	Angle of Incidence (°)	Matching algorithm	Specifications of each software			Mean distance (m)	Standard deviation (m)	Quality assessment of 3D reconstruction
				ASP®: cost mode / correlation kernel	Point density (number of points m ⁻²)	Standard deviation (m)			
ASP®	10 June 2017 and 15 June 2017	40	MGM/SSGM	3 / 7 × 7	0.93	0.01	2.97	satisfactory	
	10 June 2017 and 15 June 2017	0 to 10	MGM/SSGM	4 / 7 × 7	0.89	0.06	2.94	few satisfactory	
	10 June 2017	0 to 10 / 40	MGM/SSGM	4 / 7 × 7	0.49	-0.30	2.50	satisfactory	
	15 June 2017 and 06 July 2017	40	MGM/SSGM	3 / 7 × 7	0.95	0.13	1.91	satisfactory	
	15 June 2017 and 06 July 2017	0 to 10	MGM/SSGM	3 / 5 × 5	0.50	0.07	1.68	few satisfactory	
MicMac®	10 June 2017 and 15 June 2017	40	GeomImage (1-2 pixel matching)	3 × 3 / 0.1	1.70	-0.05	1.83	satisfactory	
	10 June 2017 and 15 June 2017	0 to 10	GeomImage (1-2 pixel matching)	3 × 3 / 0.1	1.46	0.06	1.21	few satisfactory	
	10 June 2017	0 to 10 / 40	GeomImage (1-2 pixel matching)	7 × 7 / 0.1	1.61	0.07	1.96	satisfactory	
	15 June 2017 and 06 July 2017	40	GeomImage (1-2 pixel matching)	3 × 3 / 0.1	1.79	0.11	1.38	satisfactory	
	15 June 2017 and 06 July 2017	0 to 10	GeomImage (CorsMS: 1)	3 × 3 / 0.2	1.28	-0.06	1.72	few satisfactory	

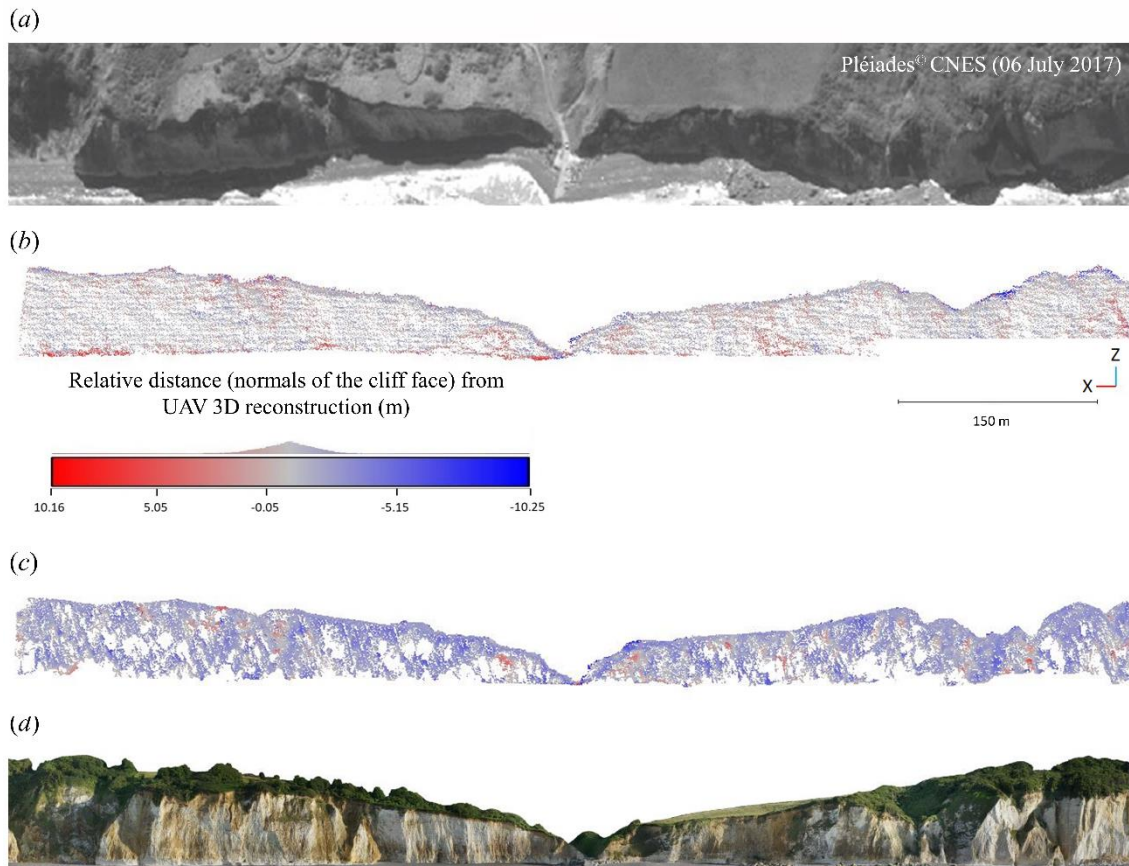
401

402 ***Identification of the best image processing chain for the 3D cliff face***
 403 ***reconstruction***

404 The comparison is made on the satisfactory results obtained with ASP® and with
 405 MicMac® (Table 2). The precision of the cliff face reconstruction is slightly better with
 406 MicMac® than with ASP® (average relative distance of 0.04 m and -0.05 m,
 407 respectively) along with the standard deviation, which is lower with MicMac® than with
 408 ASP® (average standard deviation of 1.72 m and 2.46 m, respectively). Furthermore,
 409 point clouds with MicMac® present a higher density (1.57 point m⁻² on average) than
 410 with ASP® (0.75 point m⁻² on average). With a better average precision associated with
 411 a lower error dispersion on the cliff face and a higher point density, the 3D
 412 reconstruction with MicMac® provides the most reliable dataset.

413 The relative differences in the 3D restitution from the image sets at 40° are distributed
 414 randomly over the entire cliff face (Figure 7). These are mainly artefacts or noise that

415 have not been removed during manual filtering.

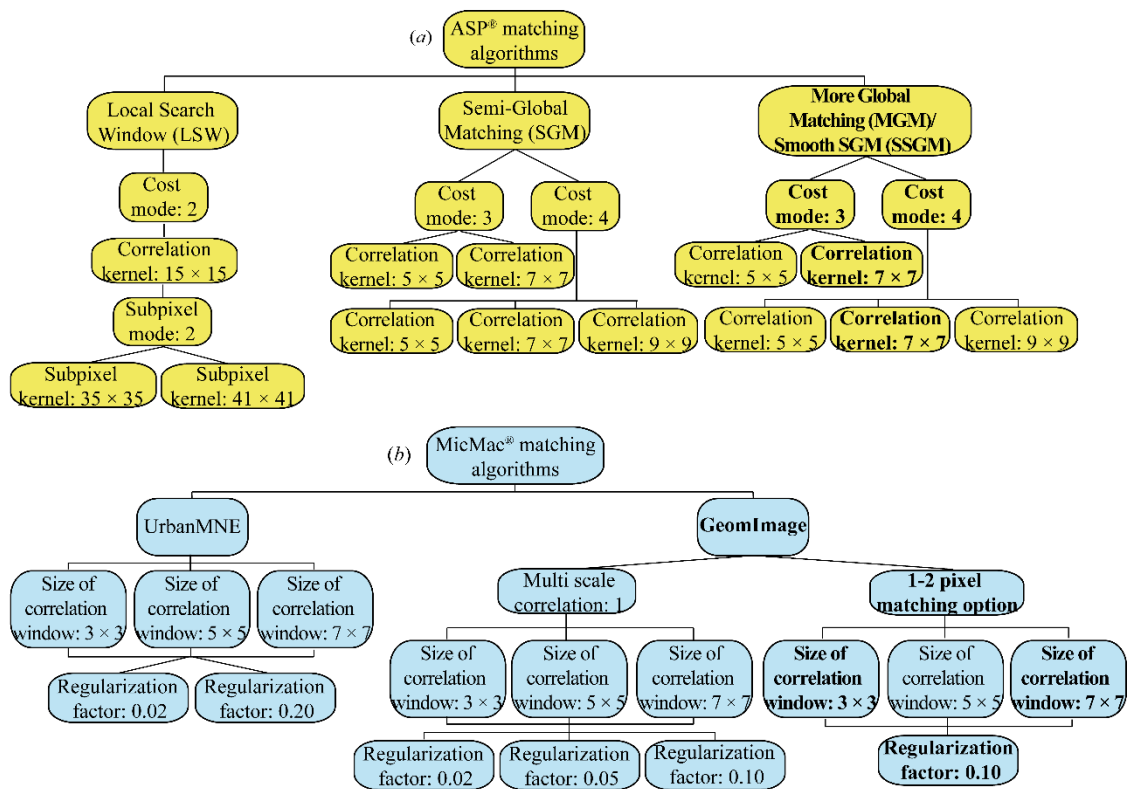


416
 417 Figure 7. Relative distance of the cliff face normals (in m) at Varengeville-sur-Mer
 418 between the 3D reconstructions (stereoscopic pair on 15 June 2017 and (a) 06 July 2017
 419 at 40°) with (b) ASP® (More Global Matching, cost mode: 3, correlation kernel: 7 × 7)
 420 and (c) MicMac® (GeomImage, size of correlation window: 3 × 3, regularization
 421 parameter: 0.10) compared with (d) UAV 3D reconstruction (26 June 2017).

422

423 Per software programme, the best processing chain is (Table 2, Figure 8):

- 424 • In ASP®: MGM/SSGM matching algorithm, with a cost mode 3 or 4 and a
 425 correlation kernel of 7 × 7.
- 426 • In MicMac®: GeomImage (1-2 pixel matching) matching algorithm with a
 427 correlation window size of 3 × 3 or 7 × 7, associated with a regularization
 428 parameter of 0.10.



429

430 Figure 8. Best parameters (in bold) for satisfactory 3D reconstructions of the cliff face
 431 at Varengeville-sur-Mer with (a) ASP® and (b) MicMac®.

432

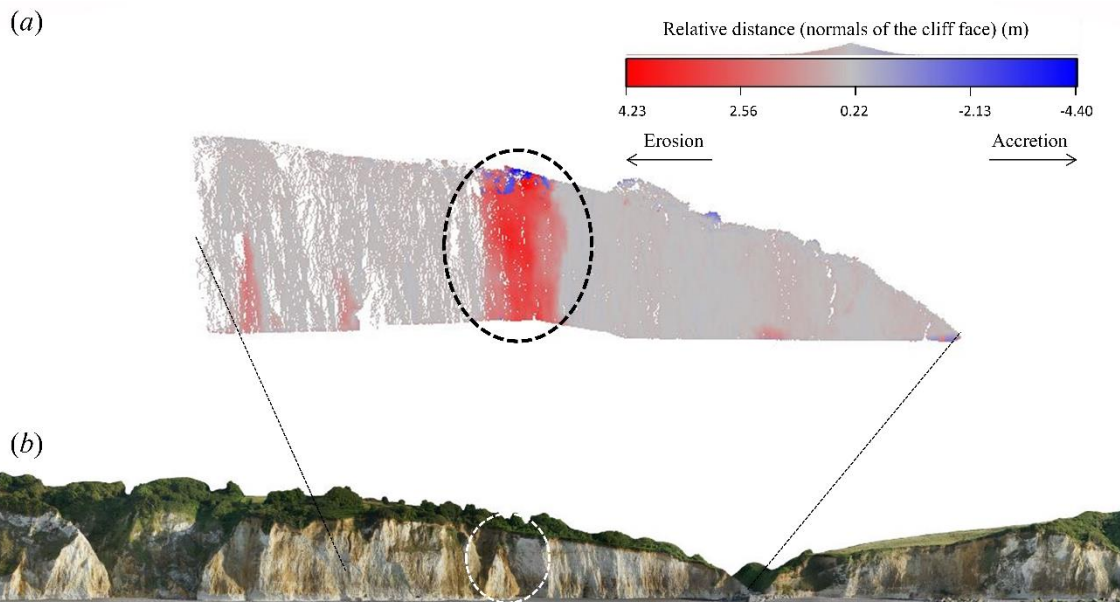
433 In MicMac®, GeomImage matching algorithm has better results than
 434 UrbanMNE one due to the topography of the cliff face and the acquisition geometry. As
 435 illustrated in Figure 8, the SGM methods provide better results as they are solved with
 436 multi-directional dynamic programming techniques, and thereby do not impose any
 437 constraints on the regularity term. The optimization is thus resolved along independent
 438 lines of pixels. These approaches provide robust reconstructions within a reasonable
 439 processing time (around 30 min for images of 1 million pixels). The reconstructed
 440 surfaces are morphologically preserved because the template windows chosen are small
 441 (3×3 , 7×7) in the optimization process. In the SGM approach, occlusions are
 442 typically predicted by performing a symmetric consistency check in a stereo pair.

443 **Discussion**

444 *Potential of this approach for diachronic monitoring*

445 The presented dataset is rather original and challenging given its unusual
446 configuration (high imaging angle, multiple dates) and the fact that the images present
447 shadows over the area of interest. Thus, this study highlights the flexibility of the tested
448 processing chains.

449 At this stage, a first quantification of the eroded volume can be estimated by
450 using a ‘satisfactory’ cliff face reconstruction and an older dataset collected in 2015
451 using TLS. A difference was calculated between the point cloud of the stereoscopic pair
452 on 10 June 2017 and 15 June 2017 at 40° and the TLS mesh collected on 25 September
453 2015. On the eastern part of the cliff face, where there is an erosion area, the Pléiades-
454 TLS comparison calculates an eroded volume of 796.5 m³ for a surface area spanning
455 4752.5 m². This calculation is then compared with the result of the differences between
456 the TLS mesh (25 September 2015) and the UAV point cloud (26 June 2017) which
457 leads to an eroded volume of 1134.4 m³ (over the same surface, knowing that the
458 surface affected by the rockfall is of 543 m²) (Figure 9). The difference in the two
459 volumetric estimations demonstrates that it is possible to quantify erosion by using
460 Pléiades satellite photogrammetry within a margin of error of approximately 0.071 m³
461 m⁻².



462

463 Figure 9. (a) Relative distance (m) of the cliff face between the TLS mesh (25
464 September 2015) and (b) the UAV data (26 June 2017) with detected erosion at
465 Varengeville-sur-Mer.

466

467 For highly erosive areas, high angle of incidence images from the Pléiades
468 satellites provide a new approach for a first order quantification of erosion on large
469 portions of cliff lines (in line with the hydro-sedimentary cell), with high repeatability,
470 satisfactory resolution and precision, and at low cost. This method therefore provides
471 major opportunities for improving the knowledge about coastal cliff dynamics thanks to
472 the rockfall detection threshold assessed at 100 m^3 , which corresponds to 69% of
473 rockfalls censused around the study area (Letortu et al. 2015). The creation of a
474 considerable rockfall database on large stretches of coasts is thus possible, which could
475 help to better understand rockfall triggers and, ultimately, to protect people (Naylor,
476 Stephenson, and Trenhaile 2010).

477 **Contribution of tri-stereo reconstruction**

478 MicMac® gives the best results in stereoscopic reconstruction and, unlike ASP®,
 479 it can also be used to perform tri-stereoscopic reconstructions. Eighteen tri-stereo tests
 480 were carried out with MicMac® from images with an incidence angle of 40° (10 June
 481 2017, 15 June 2017 and 18 June 2017, Table 3), they are mostly satisfactory (11/18).
 482 Compared with stereoscopic pairs, the point density is slightly higher with a
 483 stereoscopic triplet (1.82 point m⁻² versus 1.70 point m⁻²), the mean distance is lower
 484 (0.01 m versus 0.04 m) but has a higher data dispersion (standard deviation of 2.14 m
 485 versus 1.72 m) due to the presence of a higher number of artefacts.

486 Table 3. 3D reconstruction tests based on tri-stereo matching in MicMac® (triplet
 487 images: 10 June 2017-15 June 2017-18 June 2017).

Date of image triplet at 40°	Tri-stereo matching algorithm	Size of correlation window / regularization parameter	Point density (number of points m ⁻²)	Mean distance (m)	Standard deviation (m)	Quality assessment of 3D reconstruction (the best one in bold)
10 June 2017, 15 June 2017 and 18 June 2017	UrbanMNE	3 × 3 / 0.02	0.48	0.38	4.18	not satisfactory
	UrbanMNE	3 × 3 / 0.20	0.38	0.15	2.82	not satisfactory
	UrbanMNE	5 × 5 / 0.02	0.45	0.42	3.11	not satisfactory
	UrbanMNE	5 × 5 / 0.20	0.35	0.78	3.99	not satisfactory
	UrbanMNE	7 × 7 / 0.02	0.47	0.20	2.71	not satisfactory
	UrbanMNE	7 × 7 / 0.20	0.39	0.25	2.94	not satisfactory
	GeomImage (CorsMS: 1)	3 × 3 / 0.02	2.31	0.31	3.21	satisfactory
	GeomImage (CorsMS: 1)	3 × 3 / 0.05	1.98	0.05	2.45	satisfactory
	GeomImage (CorsMS: 1)	3 × 3 / 0.10	1.72	0.06	1.54	satisfactory
	GeomImage (CorsMS: 1)	5 × 5 / 0.02	1.71	0.08	1.51	satisfactory
	GeomImage (CorsMS: 1)	5 × 5 / 0.05	1.70	0.07	1.50	satisfactory
	GeomImage (CorsMS: 1)	5 × 5 / 0.10	1.98	0.06	2.75	satisfactory
	GeomImage (CorsMS: 1)	7 × 7 / 0.02	1.66	0.09	1.54	satisfactory
	GeomImage (CorsMS: 1)	7 × 7 / 0.05	1.63	0.10	1.52	satisfactory
	GeomImage (CorsMS: 1)	7 × 7 / 0.10	1.58	0.13	1.57	satisfactory
	GeomImage (1-2 pixel matching)	3 × 3 / 0.10	1.97	0.35	3.31	satisfactory
	GeomImage (1-2 pixel matching)	5 × 5 / 0.10	1.72	0.05	1.74	satisfactory
	488 GeomImage (1-2 pixel matching)	7 × 7 / 0.10	1.89	0.33	3.06	few satisfactory

489 **Conclusions**

490 As previously mentioned (Jaud et al. 2019; Letortu et al. 2020), a stereo restitution of
 491 the cliff face based on images with an angle of incidence of 0° to 10° appears not
 492 adapted to the sub-vertical slope (70° to 90°) whereas images with an angle of incidence

493 of 40° allow satisfactory results to be achieved. Between ASP[®] and MicMac[®], the best
494 open-source stereo restitution software to use high angle incidence and multi-date
495 images is MicMac[®] and the best performance is obtained using GeomImage (1-2 pixel
496 matching) with a size of correlation window of 3 × 3 or 7 × 7 associated with a
497 regularization parameter of 0.10. With these parameters, 3D cliff face reconstructions
498 have an average point density of 1.70 point m⁻², a mean distance from UAV ground
499 truth data of 0.04 m and a standard deviation of 1.72 m. The ASP[®] software with the
500 MGM/SSGM stereo matching algorithm is the second-best option, with cost mode 3 or
501 4 and a correlation kernel of 7 × 7. These parameters provide point clouds with an
502 average point density of 0.79 point m⁻², a mean distance of -0.06 m and a standard
503 deviation of 2.46 m. These point cloud characteristics used in a diachronic approach can
504 detect rockfalls above 100 m³, which includes the large majority of rockfalls (69%)
505 around the study area (Letortu et al. 2015). Pléiades oblique images appear to be a great
506 opportunity for monitoring cliff faces, for quantifying erosion over large spans of
507 coastline and for creating a rockfall database which could help to better understand
508 rockfall triggers (in order to people prevention/protection).

509 Future projects aim at developing new approaches to optimize the detection and
510 quantification of cliff face erosion using Pléiades images (including the Pléiades Neo
511 constellation that will be launched in 2021 and 2022, with a spatial resolution of
512 panchromatic images of 0.30 m at the nadir). To achieve this goal, images should have
513 an angle of incidence from 20° to 30° (the best imaging angles for cliff face survey
514 (Jaud et al. 2019) when cliffs have a sub-vertical slope (70° to 90°) as in Varengeville-
515 sur-Mer) and should be acquired in a favourable environment (few cloud cover and cliff
516 face orientation parallel to the Pléiades orbit). About the method, instead of relying on a
517 3D reconstruction of the entire cliff face by stereo- and tri-stereo restitution, new

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518 methods will be based on a prior change detection on the cliff face in order to identify
519 erosion areas. A diachronic 3D reconstruction of these areas should improve the
520 quantification of the cliff erosion.

521 **Author Contributions**

522 Pauline Letortu and Marion Jaud conceived and designed the data acquisition and data
523 analysis methods. Roza Taouki processed the images. Roza Taouki, Marion Jaud and
524 Pauline Letortu contributed to the data analysis. Pauline Letortu, Roza Taouki and
525 Marion Jaud wrote and illustrated the paper. Stéphane Costa and Olivier Maquaire
526 organized the UAV survey, used as ground truth data. Pauline Letortu, Marion Jaud and
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