

1 **Unmanned Aerial Vehicle (UAV) based mapping**  
2 **in engineering geological surveys: considerations for optimum results**  
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14 **Abstract**

15 UAVs have been used in engineering for at least two decades, mainly focusing on structural  
16 health monitoring, geological surveys and site inspections, especially at cases where a rapid  
17 assessment is required, for example after a natural disaster. While there is a wide range of  
18 recognition algorithms for the automatic identification of structural damage, structural  
19 geological features etc. from the acquired images, the parameters affecting the resolution of  
20 these images are often overlooked. As a result, the UAV technology is not used at its full  
21 potential and at times, it is even regarded as leading to poor outcomes. This paper discusses the  
22 main parameters affecting the resolution of the images acquired by a UAV. We present a case  
23 study of the structural geological mapping of a coastal area carried out using two types of UAVs:  
24 a fixed wing and a hexacopter. A comparison between the structural geological maps based on  
25 the orthophotos and one produced using conventional techniques shows that the level of detail  
26 is the same and the time spent is at least 5 times less when using a UAV. The fixed wing is faster  
27 and therefore, can cover large areas while the copter gives better resolution images as it can fly  
28 at lower heights. The latter is cost and time effective only if it is used for surveys limited to small  
29 areas. The characterization of some structural geological features has not been possible based  
30 solely on the orthophotos. We show that in order to achieve the desired accuracy, a ground  
31 sample distance of at least half that value is required. We discuss technical aspects, such as the  
32 effect of topography and UAV orientation on the overlap value, the camera calibration, number  
33 of control points and lighting conditions, that should be taken into account prior to flying a UAV  
34 and provide recommendations on how to obtain optimum results, i.e. orthophotos that suit the  
35 needs of the project.

36 **Keywords:** UAV, fixed wing, VTOL, mapping, image resolution, engineering geological survey

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## 37 **1. INTRODUCTION**

38 Unmanned Aerial Vehicles (UAVs) allow for the effective monitoring of large areas of land and  
39 existing infrastructure within a very short time compared to conventional techniques, a  
40 favourable characteristic, especially at cases where urgent intervention is required, e.g. when a  
41 natural disaster occurs, e.g. a rock slide (Greenwood et al., 2016; Tannant et al., 2017); 2016  
42 Kaikura earthquake, New Zealand (Erickson, 2017), or when inspection is necessary but the  
43 site cannot be accessed due to Health and Safety concerns, e.g. 2011 Fukushima earthquake,  
44 Japan (Ackerman, 2011). The main principle is that a UAV takes aerial images, incorporated  
45 with spatial data based on GNSS and/or Inertial Measurement Unit (IMU), over an area to finally  
46 produce a high resolution 3D point cloud that can be used for a wide range of geological,  
47 civil/mining engineering applications and projects. The images are all processed to form a  
48 single image (mosaic) representing the area of interest. This image is geometrically corrected  
49 (orthomosaic) and georeferenced and can be used to extract information such as distances and  
50 locations, in the same way as a map.

51 UAVs have significantly developed during the last decades. They operate remotely in the form  
52 of small platforms carrying cameras and, for the majority of applications, are available as small  
53 or micro aircrafts or Vertical take-off and landing (VTOL) copters with four (quadcopters), six  
54 (hexacopters) or more propellers (Hackney and Clayton, 2015; Jordan, 2015). Currently, most  
55 of them are equipped with GNSS receivers and/or other sensors (e.g., Inertial System sensors,  
56 etc.). Telemetry facilities are frequently deployed for data transmission and/or management in  
57 almost real time when an immediate reaction is necessary (Jordan, 2015). The leading  
58 application of UAVs is undoubtedly 3-dimensional (3D) mapping, visualisation and modeling,  
59 thus contributing to applications such as topographic surveys, photogrammetric solutions,  
60 progress monitoring, disaster analysis, archaeological mapping, agriculture and forestry (e.g.,  
61 Remondino et al, 2011; Niethammer et al., 2012; Draeyer and Strecha, 2014; Cryderman et al.,  
62 2015). A detailed discussion on the evolution of UAVs and the state of the art of this technology  
63 is given in a review work by Watts et al. (2012) and Colomina and Molina (2014). The latter  
64 conclude that the majority of commercial applications is supported by UAVs, the market of  
65 which is progressively developed: the UAV production, the civil/ commercial applications and  
66 the research on UAVs have increased by 68%, 78% and 55%, respectively, between 2005 and  
67 2013 (Colomina and Molina, 2014; Table 1, p. 80).

68 With the ever increasing use of UAVs there have been a number of studies focusing on the  
69 efficiency of UAVs in geotechnical, geological and other engineering applications. Siebert and

70 Teizer (2014) used a UAV technology for the estimation of position errors and volume  
71 uncertainty estimation in construction and other civil engineering projects (e.g., roadworks,  
72 excavation, mining works, etc.). Error in heights was determined at the level of about 4 cm when  
73 the flight level was at 30 m and the difference in a volume of 440 m<sup>3</sup> was found to be  
74 approximately 9% as compared to the figure obtained by conventional surveying using GPS.  
75 Similar results and techniques are also reported in Draeyer and Strecha (2014) for the  
76 determination of stockpile volumes and in Raeva et al (2016) for the case of mining in quarries.  
77 Engineering geology mapping surveys include detailed mapping of the outcrop, annotation of  
78 all features, names, dips and strikes that allow for the characterization of the site. UAVs can  
79 produce a very detailed image of the outcrop (e.g. Peng et al., 2017; Martínez-Martínez et al.,  
80 2017) but, in most cases, there is the need for someone to go on site for reconnaissance  
81 (Cawood et al., 2017). New developments on algorithms and image processing techniques  
82 permitted the automatic identification of types of rocks, faults, dip and strike measurements so  
83 manual work can significantly be reduced, e.g. Michlethwaite et al. (2012); Stumpf et al. (2013);  
84 Vasuki et al. (2014); Bemis et al. (2014).

85 Based on the reviewed literature, there are no easily accessible guidelines available regarding  
86 the choice of some of the parameters that greatly affect the quality of photos and consequently  
87 the orthomosaic obtained from a UAV e.g. overlap between photos, flight height, light  
88 conditions, specifications of the lens and camera, and weather conditions. As a result, if the user  
89 is not experienced or does not have a basic knowledge on surveying and photogrammetry  
90 (quite common considering the wide range of UAV user backgrounds), a poor quality  
91 orthomosaic is produced on which an automated image algorithm can do little. This frequently  
92 leads to the misconception that a poor outcome is always due to limitations of the UAV  
93 technology. This paper focuses on the use of UAVs for engineering mapping surveys and makes  
94 recommendations on the parameters that should be considered prior to flying a UAV in order  
95 to achieve optimum resolution of the obtained images. A case study on the mapping of  
96 structural geological features at an outcrop along the coast of South Ayrshire (Scotland) is also  
97 presented.

98

## 99 **2. PRINCIPLES OF PHOTOGRAMMETRY AND CHOICE OF FLIGHT PARAMETERS**

100 There are a number of technical parameters that need to be considered prior to flying a UAV:  
101 the required resolution of the orthophotos, the flight height, the overlap between the photos,  
102 the lens and camera characteristics. These parameters are important because they, not only

103 affect the resolution of the obtained images, but also the time spent on site and the post-  
104 processing time and effort for the production of the point cloud and the orthomosaic. In  
105 addition, the resolution of the final orthomosaic significantly affects the amount of information  
106 that can be extracted and any results obtained from the use of automatic feature detection  
107 algorithms.

108 For engineering geological mapping surveys, a spatial resolution of less than 10cm is generally  
109 good. This translates to a requirement of maximum 10cm/pixel, i.e. the Ground Sample  
110 Distance (GSD, the distance on the ground between the centres of two adjacent pixels) should  
111 be 10cm/pixel or less. For a certain GSD, the flight height depends on the focal length  $F_L$ , the  
112 sensor width  $S_w$  and the number of pixels per photo width  $P_N$  (He et al., 2012)

$$113 \quad F_H = GSD * F_L * \frac{P_N}{S_w} \quad (1)$$

114 where

115  $F_H$  is the flight height (m)

116  $GSD$  is the ground sample distance (m)

117  $F_L$  is the focal length (mm)

118  $P_N$  is the number of pixels per image width

119  $S_w$  is the sensor width (mm)

120 From eq. 1 it is evident that keeping the flight height, number of pixels per image width and  
121 sensor width the same and increasing the focal length, results in a better GSD, i.e. spatial  
122 resolution. For example, for a flight height of 75m, a sensor width of 35.9mm and 7360 number  
123 of pixels per image width, a lens with 15mm focal length gives a GSD of 2.4cm/pixel. This value  
124 becomes equal to 1.5cm/pixel and 1cm/pixel for a lens with focal length of 25mm and 35mm,  
125 respectively.

126 However, the GSD and the camera used are not the only parameters that should be considered  
127 before choosing the flight height. Other factors to be accounted for are the flight time and the  
128 number of images required to cover a specific area. Both depend on the overlap percentage, i.e.  
129 the percentage of the same area on the ground covered by adjacent images as shown in Figure  
130 1b. In general, an overlap value of more than 60% for the forward overlap and at least 20% for  
131 the side overlap is considered adequate in photogrammetry in order for an orthomosaic to be  
132 created. In practice, for UAVs, a higher overlap value, e.g. 80%-85%, would minimize the  
133 possibility of gaps in the orthomosaic and is recommended (Campbell and Wynne, 2011).  
134 However, it might not always be achievable due to camera triggering limitations and the flight

135 parameters. For example, in the absence of wind, a UAV that flies at 23.5 m/s equipped with a  
 136 camera that has a triggering limitation of 1 Hz will need a flight height at which 23.5 m  
 137 represents 20% of the along track image footprint to achieve an 80% forward overlap. For a  
 138 sensor size of 24mm and a focal length of 35mm, it needs 175 m above ground level to achieve  
 139 an along track image footprint that lets the camera capture 80% forward overlap. This flight  
 140 height might not allow for the desired image resolution. Furthermore, there might be additional  
 141 limitations, e.g. the maximum flight height in the UK is 500ft (approximately 152 m) (Civil  
 142 Aviation Authority, 2016) which means that a flight height of 175m is not permitted.

143 From trigonometry, the Ground distance  $G_{Dx}$  (footprint perpendicular to the flight line) is  
 144 related to the flight height  $F_H$ , the focal length  $F_L$  and the sensor width  $S_w$  as (see Figure 1a for  
 145 reference)

$$146 \quad G_{Dx} = (F_H / F_L) * S_w \quad (2)$$

147 Similarly the Ground distance  $G_{Dy}$  (footprint along the flight line) is given by

$$148 \quad G_{Dy} = (F_H / F_L) * S_L \quad (3)$$

149 where  $S_L$  is the sensor size in the direction perpendicular to the flight line.

150 The flight line spacing  $F_{LS}$  (Figure 1b) is given by

$$151 \quad F_{LS} = G_{Dx} * (1 - \text{side overlap}) \quad (4)$$

152 while the number of flight lines  $N_{FL}$  is equal to

$$153 \quad N_{FL} = W / F_{LS} \quad (5)$$

154 where  $W$  is the width of the surveyed area.

155 The distance between the images  $D_i$  is given by

$$156 \quad D_i = G_{Dy} * (1 - \text{forward overlap}) \quad (6)$$

157 The number of images per flight line of length  $L$  is

$$158 \quad N_i = (L + G_{Dy} / 2) / D_i \quad (7)$$

159 and the total number of images per flight is equal to

$$160 \quad N_{Ti} = N_{FL} * N_i \quad (8)$$

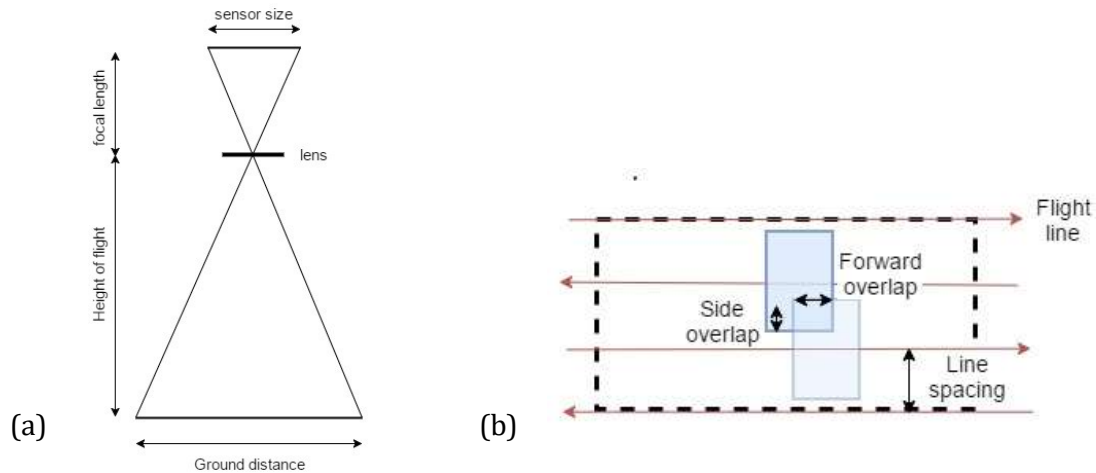


Figure 1 (a) Schematic diagram (not in scale) showing the relationship between the flight height, the focal length, the sensor size and the ground distance. (b) Schematic representation of the flight lines (red solid arrow lines) above the area of interest (dashed line) the forward and side overlap and the flight line spacing. The blue rectangles represent the footprint of images on the ground. Figure not in scale.

162 For example, the Sony A7R camera has a sensor size 39.5mm x 24mm. If the area to be surveyed  
 163 is 200m x 100m, using a lens with a focal length of 15mm and a flight height of 75m would result  
 164 in a ground distance (footprint) for each photo of 197.5m x 120m (equations (2) and (3)  
 165 respectively). The spacing between the flight lines for an overlap of 80% (0.8) is 39.5m (eq.4)  
 166 and the number of flight lines required for an area of width 100m is 3 (rounded up from eq.5).  
 167 The distance between the images is 24m (eq.6) and the number of images per flight line (length  
 168 equal to 200m) is 11 (rounded up from eq.7). This brings the total number of acquired images  
 169 for this area to 33 (eq.8).

170 For the Sony A7R camera (mounted on Trimble UX5 HP fixed wing) Figure 2 summarises how  
 171 the GSD, the flight time and the number of acquired images change with the flight height and  
 172 the focal length (lens) for an area of 1km x 1km. Numbers in Figure 2a and c have been  
 173 calculated using eq.(1) –(8) while Figure 2b numbers were calculated using the Trimble Flight  
 174 Calculator (<http://uas.trimble.com/calculator>).

175 From Figure 2 it is evident that the focal length of the camera plays a significant role on the  
 176 flight height as it can result in the same or even better resolution at twice the flight height to  
 177 the one achieved by a lens with a smaller focal length (Figure 2a). Choosing a higher flight height  
 178 reduces the flight time (Figure 2b) and the post-processing time since the number of acquired  
 179 images covering the same area is significantly smaller.

180 When the camera and focal length (lens) do not change, the impact of the flight height on the  
 181 image resolution, the flight time and number of images is more prominent. Figure 3(a) and (b)  
 182 show the effect of the flight height on the change of the GSD, the number of images acquired and

183 the flight time (calculated using the Trimble Flight Calculator) for a survey area of 1km<sup>2</sup> and  
 184 0.01km<sup>2</sup>, respectively. The results refer to an Olympus E-PL7 camera with a 14mm lens,  
 185 mounted on Trimble ZX5 (hexacopter). This allowed for a wider range of flight height values  
 186 compared to those for the fixed wing.

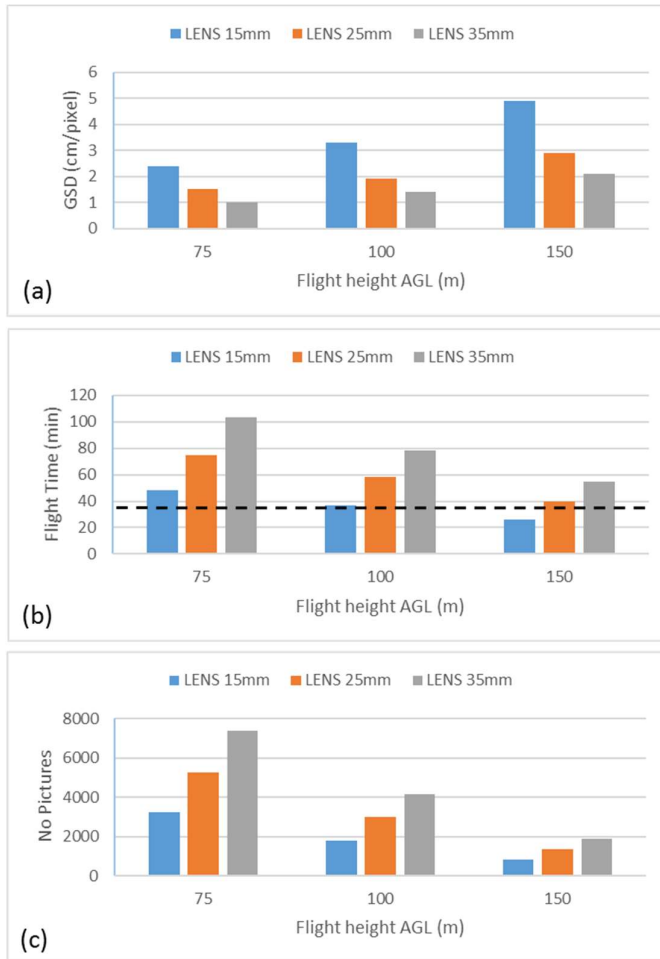


Figure 2 Change of (a) the GSD, (b) the flight time and (c) the number of acquired images with the flight height and the focal length (lens) for a survey area of 1km x 1km as obtained for the Sony A7R camera mounted on Trimble UX5 HP (fixed wing). The dashed horizontal line in (b) denotes the threshold of 35 mins which is the maximum time per flight for the UX5 HP.

187 As can be seen from Figure 3a, the resolution of the images (GSD value) could be better than  
 188 0.1cm/pixel, however, this would require 326 flights (or at least 4.5 days for a maximum time  
 189 of 20 minutes per flight for the ZX5). Even if the flight time was acceptable, the total number of  
 190 acquired images (~1,550,000) would have made the post-processing impossible. A relatively  
 191 manageable number of images, i.e. less than 8,000, for a commonly used computer, would  
 192 translate to a flight height of 75m or less for a 1km<sup>2</sup> survey area. But the required flight time is  
 193 still quite high at 435 min (more than 7 hours) resulting in the need of 22 flights. Even at a flight  
 194 height of 150m, the required number of flights to cover the 1km<sup>2</sup> area would be 10.

195 These numbers reduce by at least 2 orders of magnitude if the area to be surveyed is smaller as  
 196 shown in Figure 3(b). While the value of the GSD does not change for the same flight height  
 197 between Figure 3(a) and Figure 3(b), the differences in the required flight times and number of  
 198 acquired images are significant. An area of 0.1km x 0.1km can be surveyed with a single flight  
 199 (16 minutes) at 25m flight height, resulting in a GSD value smaller than 1cm/pixel.

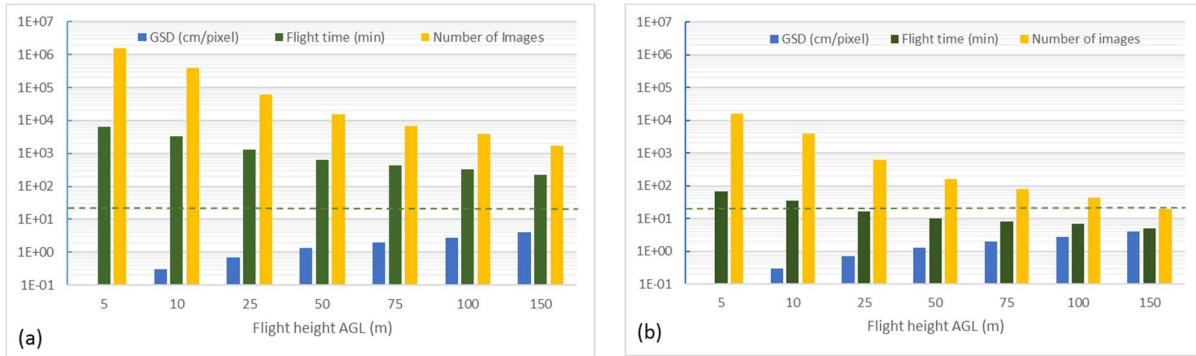


Figure 3 Change of the GSD (blue), the flight time (green) and the number of acquired images (yellow) with the flight height for an area of (a) 1km x 1km and (b) 0.1km x 0.1km. The focal length (lens) is 14mm and the camera used is the Olympus E-PL7 mounted on Trimble ZX5 (hexacopter). The dashed horizontal line denotes the threshold of 20 mins which is the maximum time per flight for the ZX5. Note that the y-axis for both plots is in logarithmic scale.

200 The choice in the range of values used for the flight height in Figure 2 and 3 was dictated by  
 201 aviation regulations. In the UK, the maximum flight height above ground level (AGL) and the  
 202 maximum horizontal distance from the person in charge are defined by the Civil Aviation  
 203 Authority (CAA) as 122 m (400ft) and 500m (Visual Line Of Sight, VLOS ) and 152m (500ft) and  
 204 750m (Extended VLOS, EVLOS), respectively. In other European countries the flight height is  
 205 150m, in the US it is 400ft (122m). There are also limitations due to the UAV technology itself.  
 206 For example, for the fixed wing and the hexacopter used in this study, the minimum flight height  
 207 is 75m and 20m (for an autonomous flight), respectively.

### 208 3. CASE STUDY: STRUCTURAL GEOLOGICAL MAPPING OF A SEDIMENTARY OUTCROP IN 209 SOUTH AYRSHIRE (SCOTLAND)

210 We tested the UAV technology on a project demanding high resolution: the structural geological  
 211 mapping of a fault zone outcrop in Scotland’s south-west coast. The field area is located on  
 212 Whitehouse Shore, a rocky beach a few miles south of the town of Girvan, South Ayrshire. The  
 213 outcrop has well exposed sedimentary and structural geological features (Figure 4) and is  
 214 located within an Ordovician inlier in the Midland Valley Terrane (McCay, 2014). The area has  
 215 been mapped in detail as part of previous projects (Lawson and Weedon, 1992; McCay, 2014)  
 216 and therefore, constituted a favourable site that allowed for comparisons between the  
 217 previously generated maps from conventional geological mapping surveys and maps generated  
 218 as part of this case study based solely on orthomosaics.



Figure 4 The outcrop along Whitehouse Shore, South Ayrshire, Scotland. Inset left: the UX5 HP. Inset right: the ZX5 hexacopter.

219 The UX5 HP (fixed wing) and ZX5 (hexacopter) of TRIMBLE were used for the data collection  
 220 for this case study (Figure 4inset). Their main technical characteristics are provided in Table 1.

221  
 222

**Table 1.** Main technical characteristics of TRIMBLE UX5 HP and ZX5

	<b>UX5 HP</b>	<b>ZX5</b>
Type	Fixed Wing	Rotary Wing
Dimensions	100 x 65 x 10.5 cm	85 x 49 cm
Camera	Sony A7R, 36 MP	Olympus E-PL7, 16 MP
Image dimensions	7360 x 4912 pixels	4608 x 3456 pixels
Focal length	15 mm	14 mm
Sensor size	39.5mm x 24mm	17.3mm x 13mm

223  
 224  
 225  
 226  
 227

For the field measurements, two flights were planned using the UX5 HP and the ZX5 copter.

Table 2 summarises the parameters considered for the flight plan.

228 **Table 2.** Flight plan parameters for the Whitehouse Shore outcrop survey.  
 229

	<b>UX5 HP</b>	<b>ZX5</b>
Flight height $F_H$ (m)	79	30
Area length, L (m)	120*	56*
Area width, W (m)	55*	64*
Forward overlap (%)	87	89
Side overlap (%)	87	89

230 \*These are nominal dimensions as the actual shape of the areas surveyed with the UX5 HP and ZX5 was not rectangular.  
 231

232 The field measurements at Whitehouse Shore lasted about four hours including necessary work  
 233 prior to the flights on the establishment of five control points along the beach. The take off of  
 234 the UX5 HP took place at a location approximately 500m away from the beach. The flight lasted  
 235 8 minutes. The flight with the ZX5 lasted approximately 14 minutes. The take off and landing  
 236 took place directly on the beach area. Figure 5(a) and (b) show the final orthomosaics obtained  
 237 from the UX5 HP and ZX5, respectively.

238 Using the orthomosaics and software ‘Trimble Business Centre, TBC’, two structural geological  
 239 maps were produced and presented in [Figure 7Figure-6](#) and [Figure 6Figure-7](#). These maps  
 240 contain the main geological formations of the area under consideration, such as thrust faults,  
 241 strike-slip faults, fractures, joints and other geological structures. Several thrust faults (shown  
 242 as red dashed lines in [Figure 7Figure-6](#) and [Figure 6Figure-7](#), respectively) have been  
 243 recognised over the field site. Another significant geological feature of the field site, clearly  
 244 observed and delineated, is the middle or main strike-slip fault also shown in the maps. It is  
 245 represented by a thick red line labelled ‘Main Fault Gully’. Also, a splay is illustrated close to  
 246 the main strike-slip fault showing almost the same direction. The main-strike slip fault contains  
 247 an extensive uncemented brecciated zone which is composed by pebbles and sand (blue area  
 248 in [Figure 7Figure-6](#) and [Figure 6Figure-7](#)). This zone is also present near the splay fault and is  
 249 labelled ‘covered zone’. The covered zone is surrounded by two rocks; red mudstone and green  
 250 mudstone (shown as grey and green area, respectively, in [Figure 7Figure-6](#) and [Figure 6Figure](#)  
 251 [7](#)). Sandstone bands are observed along the red mudstone. Furthermore, a series of joints and  
 252 shear fractures are clearly detected mainly around the strike-slip fault. Shear fractures are  
 253 primarily characterised over the study area by their small scale offsets of the sandstone bands  
 254 and thrust faults, as it is also reported in McCay (2014). Shear fractures are quite different from  
 255 the strike-slip faults not only concerning their smaller offset but also due to their simple  
 256 composition. Two typical cases of shear fractures labelled as ‘Fracture with Green Halo’ and

257 'Carbonate Vein' were observed. The colour and resolution of the images did not allow for the  
258 characterization of other visible fractures and joints (labelled as 'Unidentified Fractures').  
259

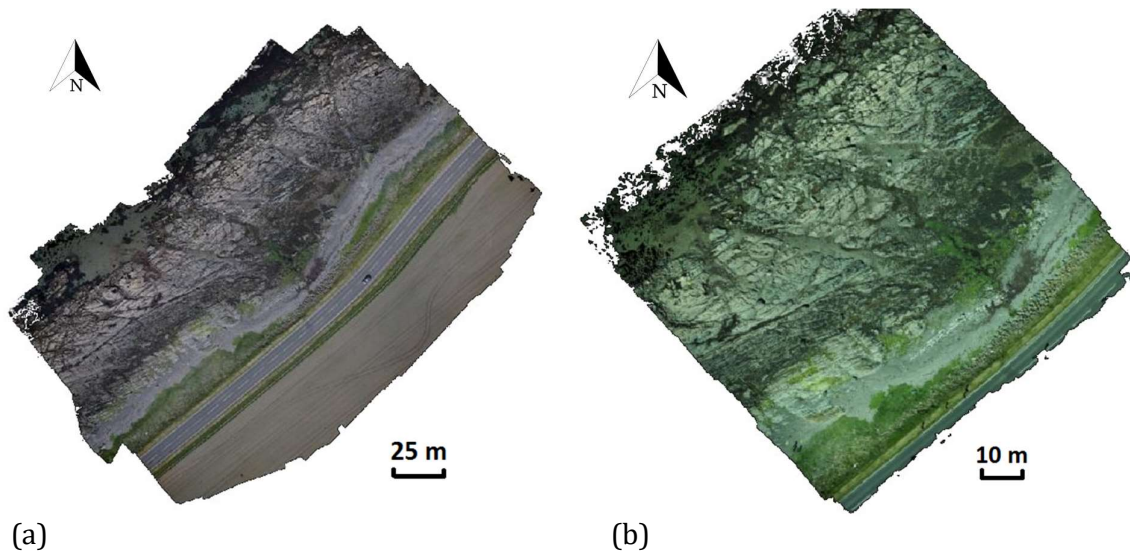


Figure 5 Orthorectified photos from the surveyed area (a) by the UX5 HP and (b) by the ZX5.

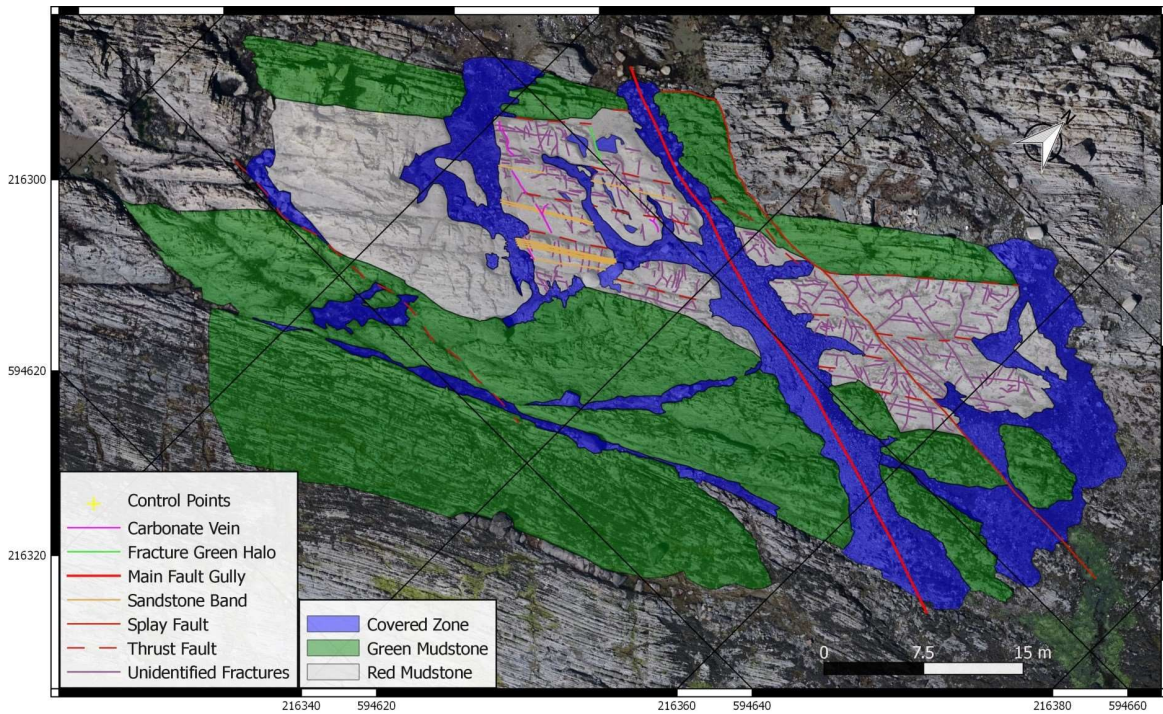


Figure 76 Detailed georeferenced map of the surveyed area using the UX5 HP showing the distribution and locations of the geological structural features. The map is overlaid on the orthomosaic from the images obtained by the UX5 HP.

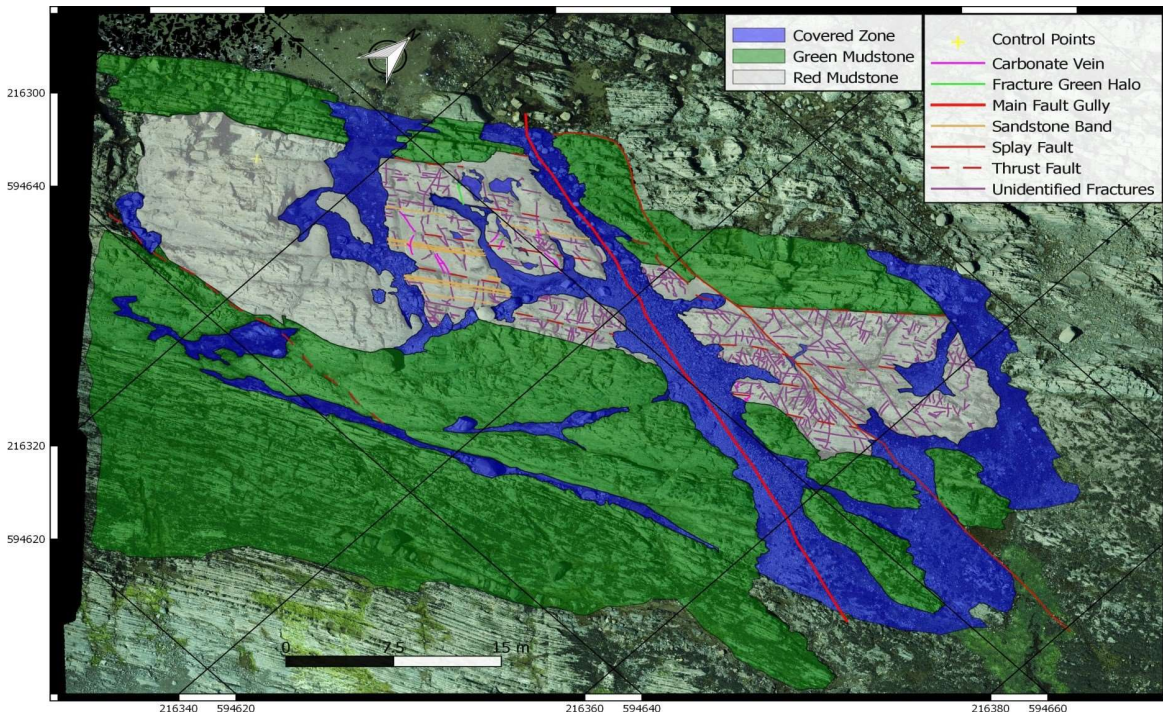


Figure 67 Detailed georeferenced map of the surveyed area using the ZX5 showing the distribution and locations of the geological structural features. The map is overlaid on the orthomosaic from the images obtained by the ZX5.

260 Due to the lower flight height and lower speed (3m/sec as opposed to 23.5m/sec for the UX5  
 261 HP) the map produced using the ZX5 orthomosaic is more detailed compared to the map from  
 262 the UX5 HP. According to the theoretical GSD value for the ZX5, i.e. 0.8cm/pixel, we should have

263 been able to distinguish objects that (1) have a length or width of at least 8mm or more, and (2)  
 264 are 8mm apart or more. On the SW part of the surveyed area shown in [Figure 6](#)~~Figure 7~~ the  
 265 geological formation of green mudstone covers a larger area than that of [Figure 7](#)~~Figure 6~~ due  
 266 to the high resolution of ZX5 that made possible to identify the limit of the green mudstone in  
 267 the orthomosaic. This was not possible to achieve in the orthomosaic of UX5 HP where the limits  
 268 of the formation were not distinct. In addition, in the area covered by red mudstone (NE area),  
 269 more fractures are detected in the map based on the ZX5 orthomosaic ([Figure 6](#)~~Figure 7~~)  
 270 compared to those in the map based on the UX5 HP orthomosaic ([Figure 7](#)~~Figure 6~~) despite the  
 271 fact that for the vast majority of them, their nature remains unidentified on both maps.  
 272 In an attempt to determine some of the main geometrical characteristics, i.e. width and length,  
 273 of the structural geological features that were identified in the orthomosaics, we selected a well-  
 274 defined joint (Figure 8a). Its length and width were measured in the field and found equal to  
 275 0.936 m and 0.034 m, respectively. The length was measured using a measuring tape. The error  
 276 of these measurements was within 1mm. The determination of both the width and the length  
 277 of the joint using exclusively the orthomosaic was not straight forward. Although, the GSD value

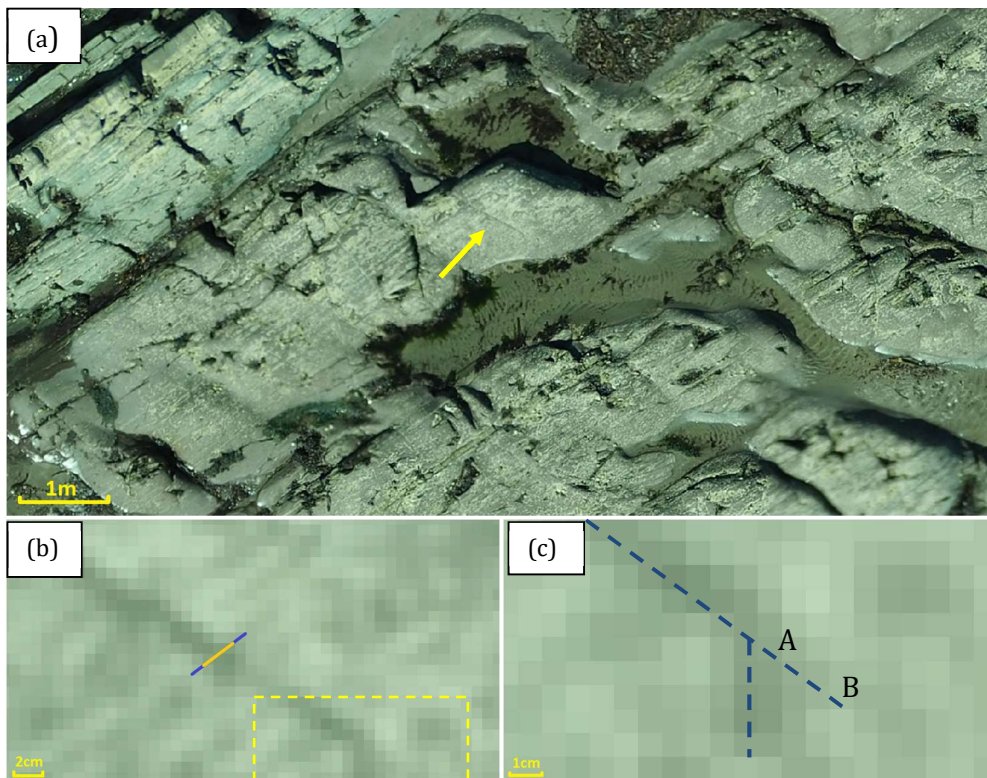


Figure 8 Determination of geometrical characteristics, i.e. length and width, of a joint. (a) zoomed area of the orthomosaic of Figure 5b. The yellow arrow points at the selected joint. (b) Zoom at the right end of the selected joint in (a). The width of the joint could be determined as the length of the yellow line or the length of the yellow and blue lines. (c) Zoomed area included in the rectangle (yellow dashed line in (b)). There is an ambiguity as to where the joint and the splay joint end.

278 is very small (0.8cm/pixel for the ZX5), this does not mean that the accuracy that can be  
279 achieved is the same. As shown in Figure 8c the width of the joint could be defined as the length  
280 of the yellow line (0.023 m) or the length of both the blue and yellow lines (0.047 m). The  
281 discrepancy is approximately twice the pixel length. For the joint length, the uncertainty is  
282 higher: the end of the joint could be defined at any location along the line defined between A  
283 and B in Figure 8c. The uncertainty here is approximately 24 mm (i.e. three pixels). The  
284 ambiguity in recognizing the edges of faults, fractures and joints is extensively discussed in  
285 studies focused on the development of automated recognition algorithms such as that by Kovesi  
286 (1999).

287

#### 288 4. DISCUSSION

289 This study focused on the optimum use of UAVs for engineering geology projects and presented  
290 a structural geological mapping survey as a case study.

291

##### 292 4.1 Comparison with conventional geological mapping surveys

293 There are two main advantages for the use of a UAV in engineering geological mapping surveys.  
294 First, it requires significantly less time and effort to map an area of the same or even much  
295 bigger size compared to commonly used mapping techniques. In this study, we focused on an  
296 outcrop along the Whitehouse shore that had been mapped before by McCay (2014) using  
297 conventional mapping techniques (Figure 9). The smallest area that was surveyed in our study  
298 was that obtained by the ZX5. This area is approximately 3 times bigger than the area presented  
299 in Figure 9. Yet, it took about a fifth of the time (including the time in the field and the post-  
300 processing time) to produce a structural geological map of the same dimensions and of the same  
301 level of detail as that in Figure 9 (personal communication with Alistair McCay on 12/9/2016).

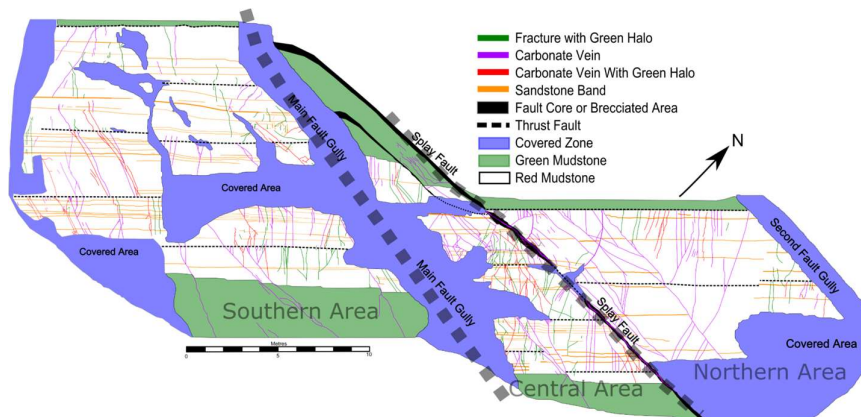


Figure 9 Detailed geological map of the Whitehouse Shore produced based on conventional geological mapping survey techniques (after McCay, 2014)

302 The second merit of using a UAV for structural geological mapping is that the produced  
303 orthomosaic is georeferenced. Where it lacks is the identification and characterization of some  
304 structural geological features. Although in our study it was possible to identify the feature type  
305 for most of them, there were some for which visual inspection was necessary and no safe  
306 conclusions could be made based only on the image. It should be noted that the amount of  
307 information that can be extracted from an image also depends on the camera calibration (as  
308 discussed in the following paragraph) and the experience of the observer. A more experienced  
309 geologist or engineer would be more likely able to identify more feature types on an image  
310 compared to those identified by a less experienced person. This number would differ again if  
311 using an automated recognition algorithm.

312

#### 313 **4.2 Technical considerations**

314 We show that for favourable weather conditions such as those prevailed in our study, the  
315 achieved resolution of the orthomosaic depends on the flight height and the sensor size and  
316 lens. The flight height is restricted by the type of the UAV, i.e. copter or fixed wing, the aviation  
317 regulations and the application itself. As shown in Figure 2a the flight height can be increased  
318 if using a lens with a bigger focal length or as derived from eq. 1, a bigger sensor size. The last  
319 two imply a high resolution camera which, on one hand, might conform with the resolution  
320 requirements of a project but on the other, results in increased cost and payload requirements.

321 For a flight height of more than 80m, a sensor size of 7360 pixels and a 15 mm lens can achieve  
322 a GSD better than 8mm/pixel, a value that is adequate for most engineering projects. If a lower  
323 height is adopted, for example when using a copter, another factor to be considered is the  
324 number of images acquired as it significantly affects the post-processing time. The latter  
325 depends on the processing software used and the camera. UASmaster (Trimble Business  
326 Centre), the software used for the processing of images in this study, can process 100 images  
327 within 1-2 hours. For 1000 images it takes 6 - 8 hours (this includes tasks such as tie point  
328 extraction, Ground Control Point (GCP) measurement and camera calibration/exterior  
329 orientation-EO) plus 1-2 hours for deliverable creation. For 8000 images the processing time  
330 consists of 24-36 hours each for point extraction and GCP measurement/EO and 4-6 hours for  
331 deliverable creation. These times refer to an Intel Xeon dual processor @ 2.6 GHz and 48Gb  
332 RAM and indicate an almost perfect linear relationship between the number of images and the  
333 processing time. It should be noted here that for the same processor and number of images, the

334 camera also affects the processing time. For example, a 56MP camera will result in a  
335 significantly different, i.e. three times higher, number of pixels per image compared to a 16MP  
336 camera.

337 The number of ground control points (GCP) can significantly affect the accuracy of the  
338 orthomosaic (Tonkin and Mingley, 2016). The number of GCPs required depends on the  
339 topography and the method used to establish a GNSS position. For example, post-processing  
340 kinematic (PPK) and Real-time kinematic (RTK) only require one GCP. This is the minimum  
341 GCP number recommended to allow for the control of the height component of the GNSS  
342 measurements. The minimum number in all other cases is at least four or five per flight and  
343 their geometrical distribution should be suitable for the site topography (Tonkin and Mingley,  
344 2016).

345 GCPs are also used for the calibration of the camera. The calibration of the camera models the  
346 lens distortion. In most cases it is also important to calibrate for white balance. The latter does  
347 not affect the accuracy of the produced orthomosaic but it affects the true colours of the  
348 acquired images, which might be significant for projects related to geological mapping. The  
349 calibration of a camera for photogrammetric purposes has been extensively discussed in the  
350 international literature, e.g. Zhang, 2000; Wang et al., 2008; Balletti et al. 2014.

### 351 **4.3 User errors**

352 As with every other technology, UAVs require sensible use. In many cases, the result of a UAV  
353 survey reflects user errors. One of the parameters that are controlled by the user and affect the  
354 quality of the orthomosaic is the forward and side overlap. The recommended value for the  
355 forward and side overlap is at least 80% for mapping surveys that require high accuracy  
356 (Gatewing, 2013). This might not be always achievable if the shutter speed of the camera is too  
357 slow for the chosen flight height and UAV speed. Also it can be compromised by not anticipating  
358 the effects of topography and the UAV orientation overlap. An example of the effect of  
359 topography on the overlap value is shown in Figure 10. Figure 10a shows the orthomosaic of a  
360 hill area. The black spots visible at the top left of the image are areas that lacked sufficient tie  
361 points (i.e. common points among the images) for the images to be tied together. That particular  
362 area of the orthomosaic should depict a hill. Figure 10b shows the point cloud focusing on that  
363 hill. It is rotated so that the noise in the point cloud corresponding to the black spots in the  
364 orthomosaic (Figure 10a) is apparent. In this case the overlap that was chosen by the user was  
365 85% and the flight height 91m AGL. However, the topography was not flat (presence of a hill)

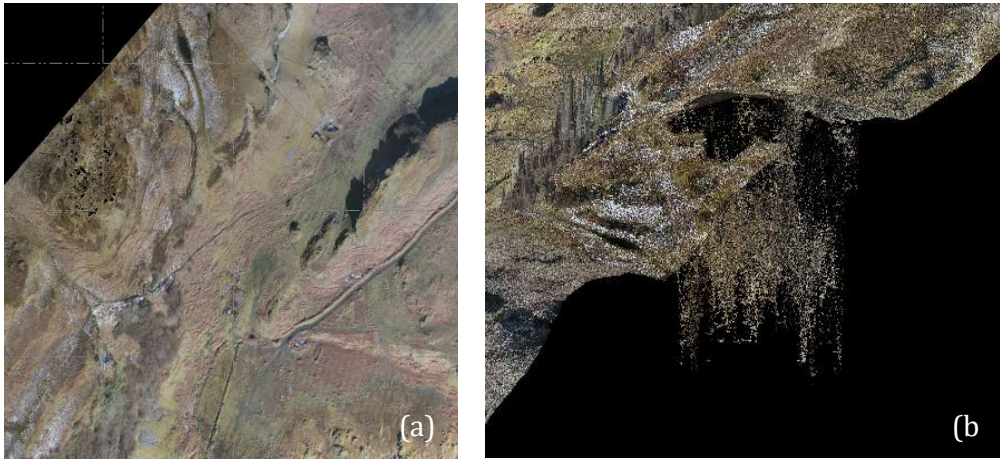


Figure 10 Effect of poor overlap on the orthomosaic. (a) orthomosaic of a hill area. The black spots at the top left are due to poor overlap. As a result the top of the hill is missing. (b) Point cloud of the area where the black spots in (a) appear. The result is noise. Images courtesy of Survey Solutions Scotland Ltd.

366 and the take off point was not at the top of the hill but approximately at mid height. As a result,  
 367 the effective overlap value for the area close to the top of the hill was much smaller (see Figure  
 368 11a) than 85%.

369 The effect of the UAV orientation and how it compromises the overlap value is shown in Figure  
 370 11b. The pitch, roll and yaw values are known and provided by the inertial system. They help  
 371 orientate the images correctly, however, that requires a high standards IMU. Even then, if the  
 372 image isn't taken in the right orientation, e.g. due to excessive yaw because of unfavourable  
 373 wind direction, no amount of re-orientation will make the photos overlap.

374 The wind direction is not the only meteorological factor affecting the quality of a UAV survey. A  
 375 UAV flight should take place in good light conditions. Although the AutoISO can compensate for  
 376 unfavourable light conditions, this function might be limited in some cameras. A detailed  
 377 discussion on poor light conditions during a UAV flight and the resulted artefacts on the  
 378 acquired images is presented in Whitehead and Hugenholtz (2014).

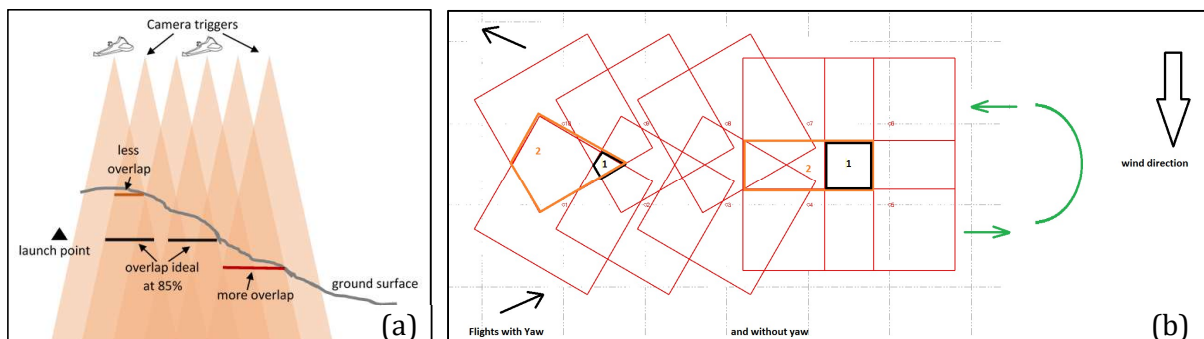


Figure 11 Overlap compromise with (a) topography. and (b) with yaw. In (a) the overlap value is the one specified by the user at the elevation of the launch point. At higher elevations, the effective overlap is less, at lower elevations the effective overlap is more. The change might be significant if the changes in the topography of the surveyed area are major. In (b) the size of the area that is overlapped for two cases, numbered 1 and 2, is shown for the same nominal overlap value for a flight with yaw (b-left) and without (b-right). Figures not in scale.

379 Another very common misconception is that the accuracy of measurements based on the  
380 images acquired by a UAV survey is equal to the value of the GSD. Our case study has shown  
381 that this is not true. The GSD value should be at least half the accuracy required by the project  
382 in order to minimize the ambiguity introduced by the pixel colourings as shown in Figure 8.

383 A UAV is a tool and as such it should be used for the right application. For mapping/monitoring  
384 of small areas, i.e. less than 10,000m<sup>2</sup>, a VTOL (vertical take-off and landing) is more  
385 appropriate, while a fixed wing is more suitable for covering larger areas. Figure 12 shows how  
386 the survey of a small area, as the one along the Whitehouse shore presented in this paper, is  
387 affecting the shape of the flight lines for a fixed wing aircraft. For the fixed wing aircraft (UX5  
388 HP) the flight lines are not strictly straight above the area under survey as would have been in  
389 an optimum case (Figure 12a). Instead, they are curved along at least half the length of the area  
390 of interest due to the turning circle required by the UX5 HP. This results in images that have a  
391 compromised overlap as shown in Figure 11b. On the contrary, Figure 12b shows the flight lines  
392 for the ZX5 hexacopter (VTOL) over the same area. In this case, all flight lines are straight and  
393 parallel.

394

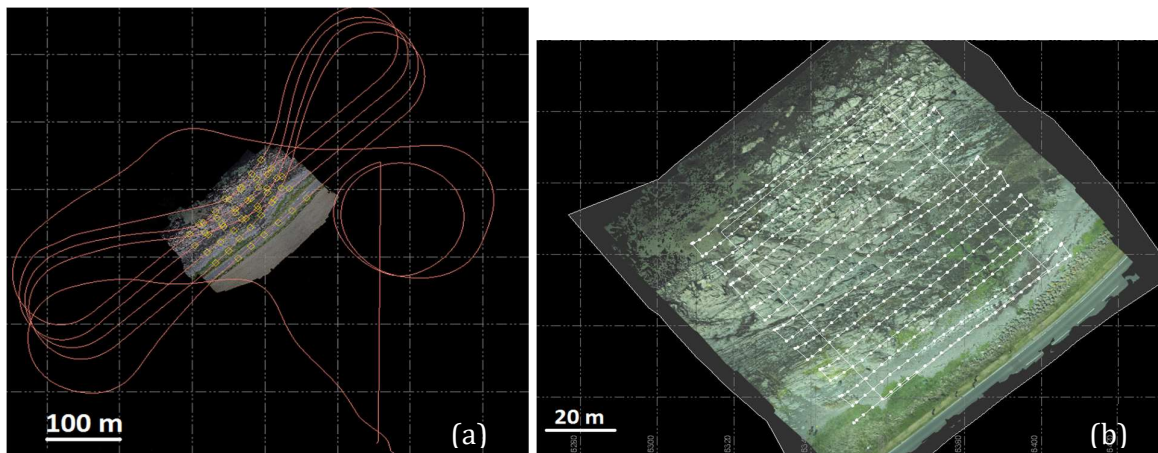


Figure 12 UAV survey at Whitehouse shore. Flight lines for (a) the UX5 HP (red lines) and (b) the ZX5 (white lines). The yellow boxes in (a) and the white dots in (b) indicate the locations where the camera was triggered.

395

## 396 5. CONCLUSIONS

397 UAVs are a promising technology with great potential as a tool in engineering geology projects.  
398 As every tool, it requires sensible use and more importantly, a good understanding of the  
399 surveying principles involved. This technology has already become the Holy Grail in mapping  
400 surveys, in many cases totally replacing terrestrial surveying equipment: its ability to cover  
401 large areas in very little time is a highly desirable characteristic in an era where quick and

402 effective intervention has become the norm. As shown from this study, this comes with a cost;  
403 high resolution images require more expensive sensors or lower flight heights and computers  
404 with high processing capacity to allow for processing of large numbers of images. An  
405 engineering approach, such as a compromise between the flight height and the detail that can  
406 be derived from the orthomosaics, is required almost at all times, if, for example, cost and time  
407 are the driving parameters. Due to the wide availability of UAVs and their ease of use, the  
408 number of operators with limited surveying and photogrammetric knowledge is constantly  
409 increasing. This study offers comprehensive guidance on the consideration of the main  
410 technical parameters in order to utilize UAVs to their maximum potential.

411

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415

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418

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