Brief Communication: Landslide motion from cross correlation of UAV-derived morphological attributes

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Replies to the referees

We would like to thank the two anonymous referees for their valuable comments and their constructive arguments that have helped improve the manuscript. Replies to the comments received have been addressed separately for each referee below. The line and page numbering used by the referees, which refer to the discussion paper, were also followed here.

Replies to the comments of Referee 1 (R1)

R1 presented a valid argument about the fusion between DEM differencing and image correlation with *openness*. The word "fusion" was erroneously chosen as it misinterpreted the methodological workflow. There is no fusion between the two techniques, a) DEM differencing and b) image correlation. DEM differencing was applied to illustrate the subsequent elevation changes. For instance, the DEM differences indicated the dramatic changes occurred between February and May 2016 (Figure 3f). These elevation changes could explain the NCC function decorrelation (voids in the displacement map, Figure 3c). Additionally, the DEM differences illustrated vegetation growth at the foot of the slope (Figure 3f). Due to vegetation variations, noise was generated (Figure 3c). As was also observed by Referee 2 (R2), elevation differences and displacement maps can be jointly used to interpret landslide deformation. The systematic downward horizontal movement of the eastern lobe is shown in Figures 3a, b, c and Figure 4a. This movement formed ground accumulation, generating positive elevation differences (seen in Figures d, e and f). Figure 4c also illustrates the surface change produced by the horizontal movement along Profile AB. Hence, DEM differencing could support the explanation of errors derived from the image correlation function. It can also illustrate the two types of movement, as observed by R2. Specifically, the first type is the horizontal motion of surface structures (mostly observed over the eastern lobe) and the second type is the vertical change generated by slope failures (as occurred over the western lobe and at the back scarp), in Figures 3e and 3f respectively. To make these points clear, the sentence in the Conclusions (page 7 lines 10-12) "*The analysis has illustrated that the fusion of openness morphological attribute along with DEM differencing can support the comprehensive interpretation of landslide behaviour, providing a holistic overview of 3D surface deformation patterns."* was changed to: *"The analysis has illustrated that openness implemented with image cross-correlation functions can be used in conjunction with DEM differencing to support the comprehensive interpretation of landslide behaviour, providing a holistic overview of horizontal and vertical deformation patterns."*

Additionally, R1 commented that DEM differences are hardly mentioned throughout the paper. Numerical results of elevation differences were added in line 20 of page 5 to address this comment. Specifically:

"Part of the western lobe collapsed, creating a dramatic change of -0.70 m maximum ground loss and a +0.50 m maximum ground accumulation within 11 months (Figure 3e). The surface ruptured at the upper part of the slope, yielding a maximum ground subsidence of approximately -1.70 m and a maximum elevation increase of approximately +1.05 m, as seen in Figure 3f. In addition, Figure 3f depicts the grass growth…"

Other corrections were added in line 21 of page 5 as below:

"Also, over the regions with extreme deformations (e.g. back scarp in Figure f), decorrelation created voids on the displacement map (Figure 3c)."

To demonstrate that DEM differencing supported the landslide interpretation, as also observed by R2, the following sentence was added in line 33, page 6:

"The episodic surface ruptures generated vertical ground loss and accumulation, as seen in Figures 3e and f. The horizontal downward motion of the front part of the eastern lobe was illustrated as positive elevation change. This motion was also identified with the image cross-correlation analysis (Figure 3)."

It was suggested that the first paragraph of the Results section be transferred to the Methodology section as it does not represent pure results of the workflow. However, this paragraph constitutes the results of the experiment using synthetic datasets, an essential step to tune the NCC parameters (as correctly characterised by R1, the "calibration" step). To address this comment the following sentence was therefore added to the beginning of the Results section: *"Before presenting the horizontal and vertical displacements over the Hollin Hill landslide, the results of the synthetic experiment are firstly described. All four…"*

Additional changes were made (line 6, page 5):

"*Some scattered points fell within the ±0.10 m 3D sensitivity level shown in grey, especially for the March-June 2015 and June-September 2015 epoch pairs.*"

Legends were added to Figure 3 and 4 to aid interpretation (see pages 6 and 7 in the current document).

<u>Replies to the comments of Referee 2 (R2):</u>

In addressing the first comment of R2, the phrases "*3D motion*", "*3D*" and "*3D surface changes*" were removed from the manuscript and replaced by the phrase "*horizontal motions and elevation differences*". To avoid misunderstanding, the word "*3D*" was also removed from the title. This also addresses the specific comment 10 (page 4) regarding the phrase "*3D surface deformation*". To clarify, there was no combination of 3D vectors in the presented work, but a cross-correlation analysis and DEM differencing which produced horizontal 2D motion and elevation changes, respectively.

The second comment concurs with one of the comments of R1, both suggesting that the limitations should be summarised in the Conclusions section, even though they were already mentioned in the Discussion section. This was addressed in line 12, page 7, as follows:

"Major limitations include the reliance on a priori knowledge of the landslide type and displacement magnitude to tune the image cross-correlation function parameters, use of field data for cross validation, manual surface feature identification and manual cleaning or threshold definition to remove erroneous displacement vectors. These limitations affect the performance of the resulting horizontal motions and elevation changes."

Answers to specific comments are shown below.

- Comments 1-3, page 1:
    - The word "effective", in line 13, was deleted.
    - The word "characteristic" is added in lines 16-17.
    - The phrase "unmanned aerial vehicles" was added in line 21.
- Comments 4 and 5, page 2:
    - The word "combined" was substituted with the word "implemented".

- In order to add the size of the targets, lines 29 and 1 were changed to:

  "Circular targets of 0.40 m diameter (equal to 8-10 pixels), with centres easily recognisable in the imagery, were established. Between 11 and 20 targets were surveyed for each of the different campaigns using rapid static Global Navigation Satellite System (GNSS)."

- Comments 6 and 7, page 3:
  - To improve clarify as to how the sensitivity level was derived the following changes were made in lines 10-11: "*Peppa et al. (2016) described an approach to derive the vertical sensitivity with the use of DEM standard deviations. An approximate ±0.10 m sensitivity level, corresponding to the lowest detectable change, was estimated by applying error propagation (with a 95% confidence level) to the 3D RMSE values, calculated at check points. Both approaches resulted in a sensitivity level of the same order of magnitude."*
  - The phrase "3x3 pixel window" was added in line 20.

- Comments 8, 9, 11 and 12, page 4:
  - COSI-Corr provides displacements in Easting and Northing separately, which can be combined to generate a 2D motion map. To clarify this, the following sentence was added in line 4: *"The computed displacements in Easting and Northing were combined to provide 2D motion maps across successive epochs."* Figure 3 also presents the 2D displacement of this combination. Indeed the displacement magnitude is significantly greater in Northing than Easting.
  - To describe how the 27 sample points were identified, the following sentence was added: *"These points were identified on visually identifiable characteristic surface breaks and evenly distributed across the site with displacement magnitudes from cm- to m-level."*
  - In line 18 the phrase "characteristic surface structures were manually located" means that 2D coordinates from particular positions located on December 14 openness were extracted and used as input to the CIAS tool. To clarify this, the following changes were made: "*Thus, characteristic surface structures were manually located over the December 2014 openness image and the derived 2D coordinates were used as input to the CIAS tool. The planimetric vectors of these locations, between December 2014 and May 2016, were automatically derived with the same tool."*
  - To be more specific for the threshold parameters, the following sentences were added in line 20: "*For instance, the sensitivity level could serve as a threshold to remove vectors of lengths lower than ±0.10 m. Based on previous knowledge of the Hollin Hill landslide (Uhlemann et al., 2017), a specific azimuth range could be used as an additional threshold to exclude vectors showing, for example, backward motion due to rotational failures."* This sentence also partly addresses the comment of R1 regarding the knowledge of presence of local rotational failures (paragraph C2). To clarify further, the following text was added to the Discussion on page 6:

    "Even though threshold definition can automatically remove spurious vectors, it is not a straightforward process as it relies on a priori knowledge of the landslide. Where such information is unavailable, additional field data may be used. This demonstrates that image cross-correlation performance is strongly related to the landslide movement type. For mixed types, such as the Hollin Hill landslide (a combination of rotational failures with earth flow, as shown in Uhlemann et al. (2017)), the successful application of image cross-correlation is not entirely guaranteed."

- Comment 13, page 5 line 27:
  - One sentence was added in line 28 to show how the threshold of 63º was derived. "*This threshold was derived with the aid of visual inspection along profiles at multiple locations over active parts of the landslide."*

- Comment 14, page 10 line 3: the full name of SNR was added.
- Comment 15, Figure 2:

- The number of samples was added in line 6 of page 5: "*33 and 38 sample points across all epoch pairs with displacement magnitude larger than ±0.10 m were observed manually on orthomosaics and automatically derived with COSI-Corr respectively.*"
- The gray zone was also added as a legend in Figure 2.

- Comment 16, Figure 4:
  - Arrows were included in the legend. Their colour was changed from black to blue to improve their contrast.
  - The dark red region, which represents the 0º-63º class of both epochs openness overlap, was included in the legend.

All changes to Figures 2, 3 and 4 are shown below.

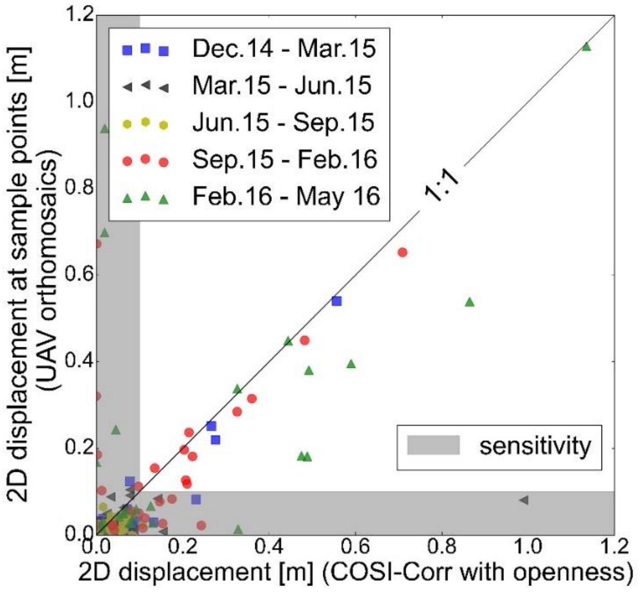

Figure 2: Scatterplot of estimated surface displacements determined by COSI-Corr with *openness* plotted against manual observation per epoch pair.

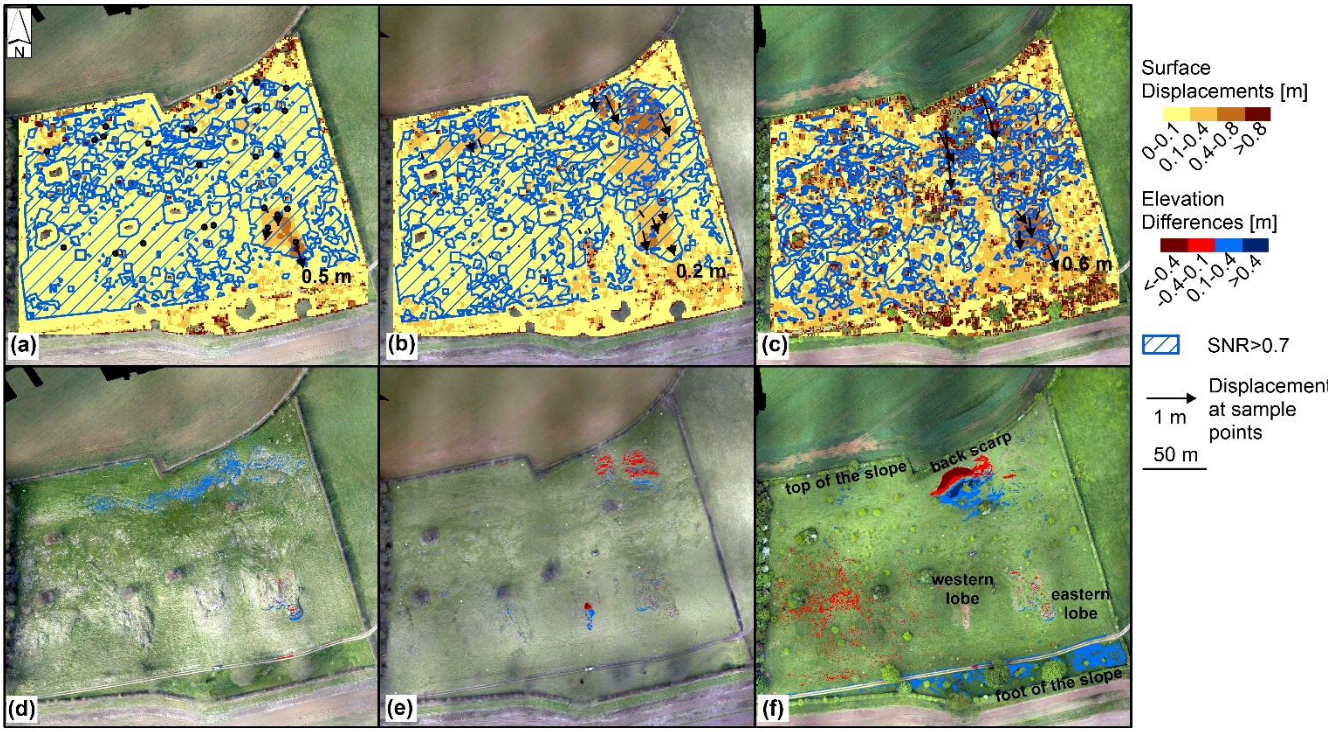

Figure 3: Maps of surface displacements and elevation differences of (a and d) December 2014 -March 2015, (b and e) March 2015-February 2016 and (c and f) February 2016-May 2016, respectively. Manually derived planimetric vectors at sample points are also superimposed.

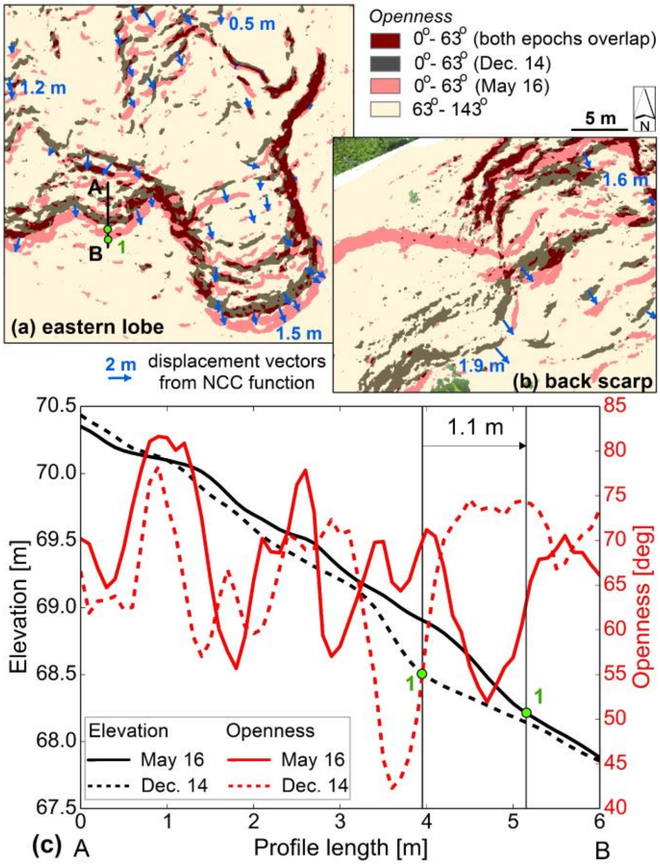

Figure 4: Detailed view of December 2014 and May 2016 openness maps over (a) eastern lobe and (b) back scarp with elevation and *openness* plotted along (c) Profile AB.