Williams, J. G., Rosser, N. J., Hardy, R. J., Brain, M. J., and Afana, A. A.: Optimising 4D Approaches to Surface Change Detection: Improving Understanding of Rockfall Magnitude-Frequency, Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2017-43, in review, 2017.

Response to Reviewer 2.

We thank Reviewer 2 for the constructive and positive review of our manuscript. Below we reproduce the reviewer comments (*italics*) followed by our responses, illustrated with the amendments that we intend to make to the manuscript as a result (in quotation marks " … ").

- *INTRODUCTION: I miss here a clear statement of the objectives of the paper. I know that at the end of the section (i.e. lines 28-30) there is a description about what is done in this work however it sounds to me more introductory to a methodological section than presenting the main goals of the paper. I recommend to include a paragraph with a clear statement of the objectives. The classical reader will expect this at the end of an introduction.*

To clarify the aim of our paper, we will add the following statement at the end of the Introduction:

<u>P3 L29:</u> "This paper presents a technique for change detection from near-continuously collected 3D point cloud data. The dataset includes ~ 10^3 individual point clouds, with each comprising > 10^6 points. Using this method, we demonstrate the influence of survey frequency on firstly the magnitude frequency of rockfall, and secondly on the uncertainty associated with measuring volumetric change through time."

- *The methods section is clear but I think it could be improved using a workflow chart summarizing the different steps in one.*

A workflow diagram will be added, as below. Figure numbers will be amended accordingly.

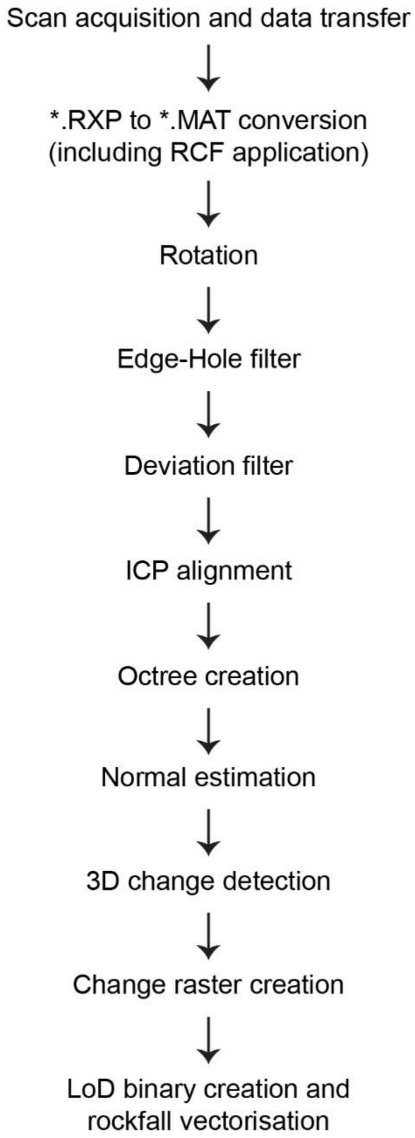


Figure 3: Flow diagram representing the stages of rockfall inventory compilation. All stages following ASCII to MAT conversion were written in MATLAB, with ICP alignment and rockfall vectorisation using the built-in functions *pcregrigid* and *bwboundaries*. Point clouds are initially rotated to become approximately planar across the *x*-*z* plane, enabling the removal of points outside a tight bounding cuboid and rasterising of the point clouds of change. This rotation also enables an efficient solution to subsequent normal direction ambiguity, where the *y* component of each normal vector should always point out of the surface.

- *Fig.1: can be improved. England is floating in the same scale-map? Please use a box to delimitate England in a location box. The rest of the map needs a legend. Provide a legend indicating the meaning of symbols presented (green dots, red lines, etc.). The caption is huge and some information is not necessary, e.g. "powered by solar panels"*

A revised version of original Figure 1 is provided below, which includes delimiting the inset map of the UK, addition of a legend, and the removal of superfluous detail, as suggested by the reviewer. A shortened caption is also provided.

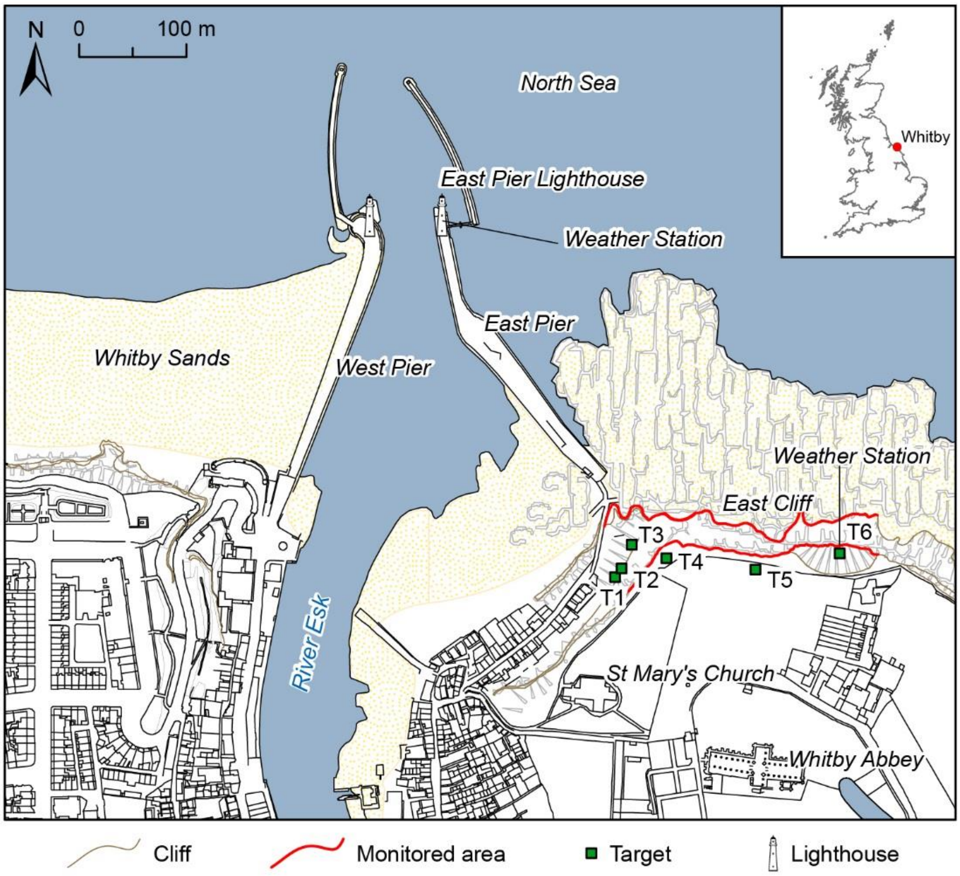


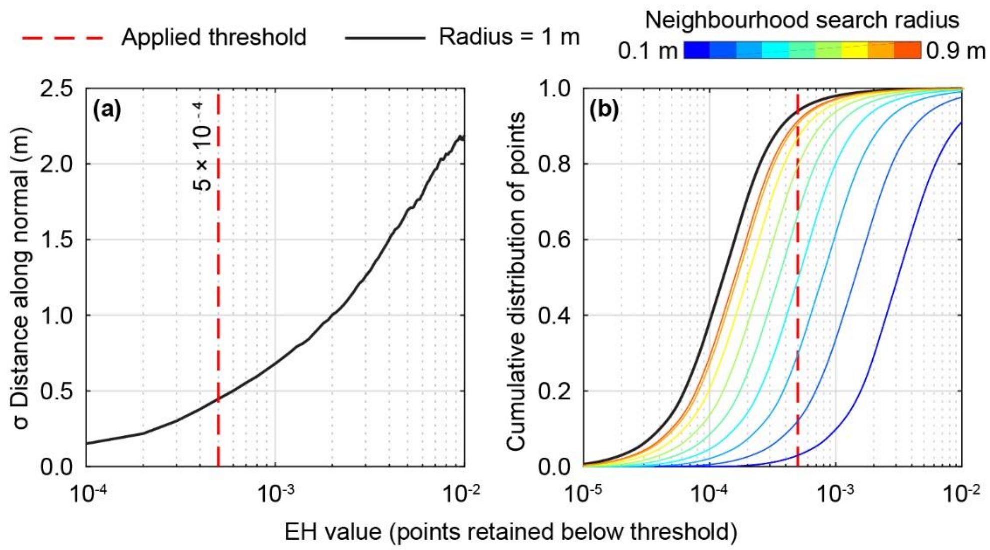
Figure 1: Map of Whitby with the area scanned delineated with red lines. A Riegl VZ-1000 scanner is installed within East Pier Lighthouse. The targets installed for the SiteMonitor4D Range Correction Factor estimation are illustrated (T1 – T6) in addition to the weather stations. Whitby Abbey lies 180 m from the cliff top. Map produced using shapefiles from Ordnance Survey © Crown Copyright and Database Right 2016. Ordnance Survey (Digimap Licence).

- *Fig. 2b I recommend saying "hillshade of the cliff showing the area covered by the TLS" in the caption.*

We will modify the caption to Figure 2(b) as follows: "(b) Slope model of the cliff showing the area covered by the TLS (light grey) draped over a 3D model of the cliff, surveyed from multiple positions along the foreshore (dark grey). The total area measured is 8 561 m^2, or 89% of the cliff face area (9 592 m^2). The cliff is ~ 210 m across and ~ 60 m high."

- *Fig. 3 Caption: please use the superscript instead 10-4. Please indicate in the graph that colors in the figure 3b represent different search radius.*

This error appears to have arisen during conversion to a *.PDF. The superscript has been added in light of this comment. The figure has been amended to more clearly explain the variation in colours:



- *Page 12, L20: the acronyms LoD and DoD show up before the complete term is presented (the term is presented in section 3.5, page 13 which later, please check the use of acronyms along the text)*

This has also been identified by Reviewer 1. The following amendments have been made:

<u>P6 L28:</u> "… thereby lowering the Level of Detection (LoD) that could be applied …"

<u>P5 L5:</u> "… central position of the neighbourhood points (CoG) calculated …"

- *Finally, I would recommend a deeper discussion about the effect of using a spatially homogeneous LoD for change estimation in such a heterogeneous surface (including different layers-lithology with different slopes, small local faults, etc.). Section 3.5: do you assume a homogeneous LoD? This argument deserves a deep discussion.*

We agree that this requires a more full discussion. We add the following at the point in the manuscript when the Level of Detection (the LoD) is presented in the review of other approaches to change detection (Section 3.5), at <u>P13 L9:</u> "The delineation of areas of geomorphic change, here rockfall, involves masking regions of change that exceed a hard threshold at the level of detection (LoD), that is either estimated locally (e.g. Wheaton et al., 2010; Lague et al., 2013) or is estimated across the entire point cloud (e.g. Abellán et al., 2009). Methods that estimate spatially-variable LoDs have enhanced the ability to identify volumetric loss as compared to the application of a single LoD, with the latter set to exceed a significant portion of the modelled uncertainty across the area of interest. Across a rock slope, the likelihood of generating similar point distributions between surveys, which determines the accuracy of change detection, is primarily influenced by the target geometry relative to instrument position and surface reflectance characteristics. These properties may vary with lithology, the surface complexity and moisture, and survey geometry (Clark and Robson, 2004; Bae et al., 2005; Litchi et al., 2007; Kaasalainen et al., 2008; 2010; Pesci et al., 2008; 2011; Soudarissanane et al., 2011; 2016). These factors raise the potential for real change to be masked when using a single LoD but, equally, the application of a single LoD becomes increasingly computationally efficient when dealing with a large number of surveys. The benefits of using a single LoD are primarily in the consistency in measurement across the area of interest. For example, if the purpose of monitoring is to generate a rockfall inventory where the relative magnitude of events is important, a single LoD ensures consistency in the minimum detectable rockfall across the area of interest and minimises the potential for recording erroneous events, which we demonstrate here will accumulate with an increasing number of surveys. A single LoD was therefore identified between scan pairs in which no rockfall occurred as two standard deviations of the 3D change, after Abellán et al. (2009). This was of comparable magnitude to the LoD recorded for every scan pair in the dataset; hence, the maximum-recorded LoD was applied to all scan pairs in the dataset. Similar to Kromer et al. (2017), these change estimates are assumed to include the registration error, which is reduced here through range correction using fine-scanned targets and through ICP. For sites whose geometry creates a highly variable point spacing within a single survey, a spatially variable LoD is appropriate even for the purpose of compiling an inventory of geomorphic events, so long as a record of the LoD across the surface is kept. Open-pit highwalls, for example, typically comprise a series of benches to prevent rockfall from travelling further downslope. This design generates considerable variation in instrument-object distances across the slope and a spatially-variable LoD. More broadly, spatially variable LoDs can be considered better suited to measuring total erosion budgets across a single surface than the relative contribution of individual events of varying sizes."

- *Section 4: the first sentences of the first paragraph sounds again like methods. The real results section starts in line 16.*

The sentences (P15 L11-16) will be removed from Section 4 and will be inserted into section 3.5: "The pairwise change detection method described above was applied to a near-continuous monitoring dataset collected at East Cliff, Whitby. In total, 8 987 point clouds were collected and processed to generate an inventory of 3D rockfall geometries. The LoD was derived for every sequential scan to ensure that no increase in registration or epistemic errors developed through the monitoring period. This value lay consistently between 0.01 – 0.03 m. The maximum LoD, 0.03 m, was therefore applied to each point cloud to prevent recording erroneous pixels in the resulting rockfall inventory. Combined with a cell size of 0.15 m, this provided a minimum detectable rockfall across the survey area of 6.75×10^{-4} m^3. More than 180 000 detachments were detected using the highest frequency of scans (~ hourly) over the 10-month monitoring period. The spatial and temporal distributions of rockfall observed are shown in Fig. 9.

In order to assess the influence of more frequent monitoring on the resultant volume frequency distribution, two inventories were compared. These were analysed over the same monitoring duration, using scans separated by different intervals (T_{Int}) T_{Int} < 1 h (hours) and T_{Int} = 30 d (days)."

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