

Interactive comment on “Estimating velocity from noisy GPS data for investigating the temporal variability of slope movements” by V. Wirz et al.

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Interactive comment on “ Estimating velocity from noisy GPS data for investigating the temporal variability of slope movements“ by V. Wirz, S. Gruber, S. Gubler, and R. S. Purves

Dear Mr. Berthling,

Firstly, as authors we would like to thank you for your constructive comments and suggestions. We have set out to respond fully to both the content and spirit of each comment in full, and hope that the edited manuscript reflects these changes. Below, we describe in detail how we have responded to each individual comment.

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Author’s responds to comments of Referee 1 (I. Berthling)

1. Page 1158, line 25: delete “for example“

AC: Done

2. Page 1156, L14: Reference inserted as suggested (Berthling et al. 2000, Norwegian Journal of Geography, Vol. 54, 182–185, Continuous measurements of solifluction using carrier-phase differential GPS)

3. Page 1158, line 27: GPS signals penetrate snow well, so this may not be necessary.

AC: Indeed, GPS signals can penetrate snow. However, the penetration depth depends on the amount of liquid water. In spring when the snow cover becomes saturated, it is possible that the signal can no longer reach the snow covered GPS antenna. In addition, the signal distortion due to snow (even dry snow) is too strong to be able to use differential precise point positioning and yield sub-cm accuracy. Therefore, our GPS antenna was mounted above ground. To make this clearer we changed the manuscript so that it now reads (page 1158, line 26): “For continuous monitoring, GPS antennae must be positioned above the expected snow depth to prevent signal loss even during wet snow conditions (Schleppe and Lachapelle, 2008).”

Schleppe, J., and Lachapelle, G.. GPS Tracking performance of a HSGPS receiver under avalanche deposited snow. GPS Solutions, 12,13-21, DOI 10.1007/s10291-007-0060-1, 2008.

4. Page 1161, line 23: delete “be“

AC: Done

5. Page 1169, line 8 and 14: delete the comma

AC: Done

6. Page 1169, line 11: Your synthetic velocity examples are well chosen, and Table 2

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is a nice summary of the applicability of the different methods for velocity calculation under different temporal velocity regimes. Here you could underline and maybe provide examples on how these different methods should be applied to (and are illustrations of) real cases where a priori knowledge would imply temporal velocity regimes of a certain kind. For instance, for measurements of gelifluction a sharp acceleration upon thaw would be expected, and knowledge of timing of acceleration may be vital - then maybe SNRT would not be so useful etc.

AC: In order to address this comment we added an additional column in Table 2 (see below). In this column we discuss cases for which different approaches to monitoring velocity (such as the example given above) are more or less suited. Key in applying our method, or indeed any approach to monitoring velocity, is understanding the influence of the measurement method on the data extracted, a point we now also reiterate in the conclusions (see also response to comment 3 from the second reviewer).

7. Page 1171, line 20: word missing

AC: Done; we added "the snowmelt period".

8. Page 1171, line 25: There is a rather sharp drop in elevation as well, and thaw consolidation could also be a likely candidate, if there is substantial amount of fines in the active layer - which may or may not be the case of course. Thaw consolidation would also potentially explain shift in direction of movement as uniform settlement hardly can be expected (see also Berthling, I., Eiken, T., Madsen, H., and Sollid, J. L., 2001a, Downslope displacement rates of ploughing boulders in a mid-alpine environment: Finse, southern Norway: *Geografiska Annaler Series a-Physical Geography*, v. 83A, no. 3, p. 103-116. Berthling, I., Eiken, T., and Sollid, J. L., 2001b, Frost heave and thaw consolidation of ploughing boulders in a mid-alpine environment, Finse, southern Norway: *Permafrost and Periglacial Processes*, v. 12, no. 2, p. 165-177.)

AC: Indeed about 1.5 m of the vertical displacement at pos55 is potentially related to thaw consolidation or erosion of the surface (see also response to comment 5 from the

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second reviewer). To make this point more clearly we modified the manuscript so that it now reads (page 1171, line24): "At pos55 not only a strong acceleration both in the horizontal and vertical direction, but also a clear change in the direction of movement occurred in May 2012. The vertical change is about 1.1 m higher than can be explained by the slope around the boulder (34°). We assume that during this time a second process besides rock-glacier creep was involved, potentially triggered by an increase in pore-water pressure or thawing of the ground: A rotational slide affecting the tongue of the rock glacier (e.g., Roer et al., 2008; Arenson, 2003) might have caused a sharp acceleration of the surface movement and a rotation of boulders. In addition, thaw consolidation might have further increased the amount of surface lowering and the rotation of the boulder (Berthling et al., 2001), however, assessing the magnitude of its contribution is difficult (Brommer et al., 2012)."

Arenson, L. Unstable alpine permafrost: a potentially important natural hazard - variations of geotechnical behaviour with time and temperature, Phd-thesis, Institut for geotechnical engeneering, ETH Zuerich, 2003.

Berthling, I., Eiken, T., Madsen, H., and Sollid, J., Downslope displacement rates of ploughing boulders in a mid-alpine environment: Finse, southern Norway: *Geografiska Annaler Series a-Physical Geography*, 83A, no. 3, 103-116, 2001.

Brommer, C., Fitze, P. and Schneider, H., Thaw-Consolidation Effects on the Stability of Alpine Talus Slopes in Permafrost, *Permafrost and Periglacial Processes*, 23, 1099-1530, DOI: 10.1002/ppp.1751, 2012.

Roer, I., Haeberli, W., Avian, M., Kaufmann, V., Delaloye, R., Lambiel, C., and Kääh, A.: Observations and considerations on destabilizing active rock glaciers in the European Alps, in: *Proceedings of the 9th International Conference on Permafrost*, Fairbanks, Alaska, vol. 2, 1505–1510, 2008.

9. Fig. 2: since the time scale here is not aligned with the time scale of the inclination sensor below, it is difficult to see the relationship (if any) between elevation change and

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inclination change. The question is the chicken and egg: does the rock start to rotate backwards and the elevation of the GPS change accordingly, or does the rotation start because of elevation change (thaw consolidation or something else)? I guess it would be possible to calculate the amount of elevation change from rotation as well as from translation (downslope), to be able to address this question.

AC: Firstly, we apologise for the unaligned timescales, which we have now corrected for both Fig. 2 and Fig. 6. Now, all sub-figures have the same timescale for better readability and comparison between the sub-figures.

As suggested, the data and method do allow us to calculate the amount of elevation change from rotation as well as from translation: The total vertical displacement at pos55 over the entire data period (333 days) at the antenna was 4.83 m. About 0.24 m of this was caused by the rotation of the station. Of the remaining 4.58 m, 3.1 m are due to the horizontal displacement (slope angle of 34°). Hence, about 1.5 m is caused by subsidence (or rotation) of the slope. However, because the main movement of the station occurs in the horizontal direction, in this paper, we concentrate on the horizontal velocity and do not show the vertical velocity estimations. Therefore, we have also not presented the vertical displacement of the mast foot (corrected for the mast-tilt) in the manuscript, though we agree that this data is also of obvious interest.

10. Fig. 6: Comment 1: a, b and d (why d?) not displayed in figure. Self evident, but since it is in the caption it should be in the fig as well. Or drop it.

AC: We removed a, b, and d in the caption as suggested.

Comment 2: grey: does this refer to the line in 'Total rotation'? There is not much else in grey, except for the circles.

AC: In all sub-figures in Fig. 6 the standard deviation of the distances and rotation is shown as grey area ($\pm\sigma$). Except for total rotation, standard deviations are, however, very small and, hence, almost invisible for horizontal displacement at the antenna and

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the foot.

Comment 3: as mentioned above it would be nice also to have the vertical distance of the GPS foot

AC: See author comment above (to point 9).

Changed Tables and figures:

Fig.2: GPS-positions (E, N, h) and inclinometer measurements (inclination θ and its azimuth az) of positions pos55 and pos27 and their error-range (\pm the standard deviation σ , in grey). The temporal resolution is one day. For better readability, the positions (E, N, h) are given relative to the position at the start of the measurements. Note, that vertical axes differ for pos55 and pos27. The vertical black lines indicate differing measurement devices (exchange of measurement device).

Fig.6: Total displacement at pos55 and pos27 of the GPS position at the antenna, the inclinometer-measurements and the position of the GPS foot (corrected for mast tilt). Data-points with an error (in the original data) that is higher than the 95 % quantile are marked with grey circles. The uncertainty (σ) of the cumulative distance (grey) is estimated using 2000 MCS (Sect. 4.1.2). Note that both axis differ for pos55 and pos27.

Table 2: Summary of the sensitivity tests for the different methods and noise-levels. Methods have been applied to estimate the velocities for synthetic time-series with three different movement patterns (A, B, C) and noise-levels (a, b, c; see Sect. 5.1). For SNRT it is distinguished between the different thresholds ($t = 5, 20, 50$).

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., 2, 1153, 2014.

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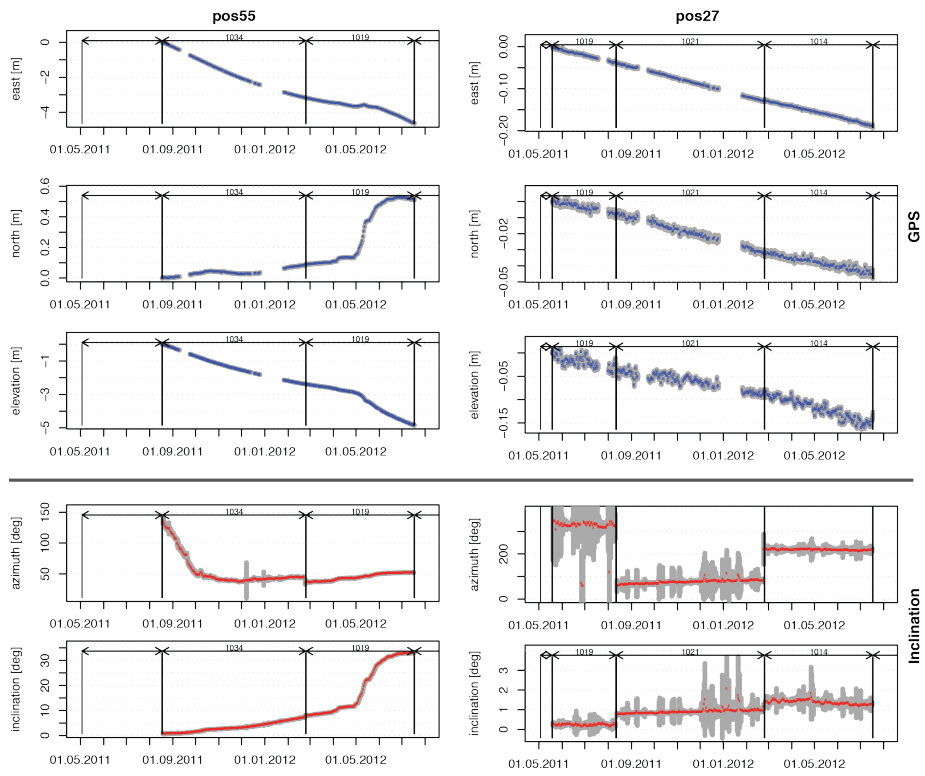


Fig. 1. (Fig 2 in manuscript) see caption of Fig 2

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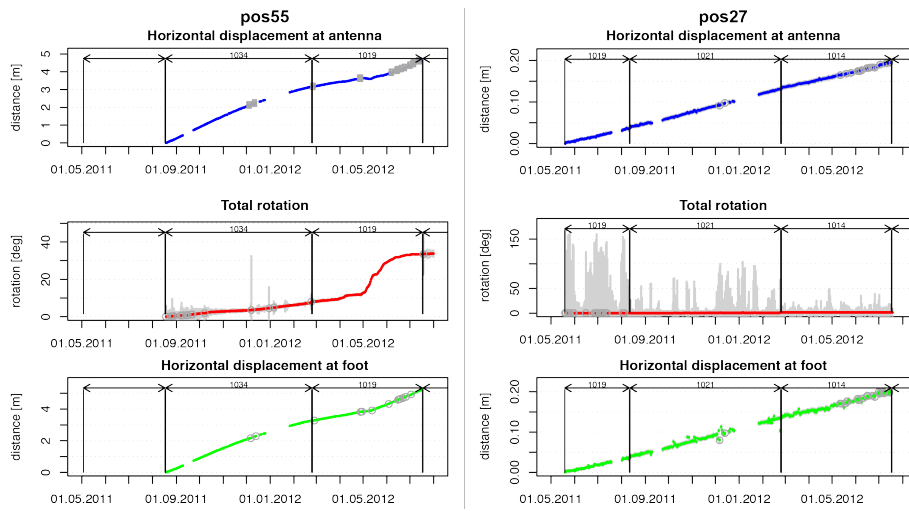


Fig. 2. (Fig 6 in manuscript) see caption of Fig 6

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Name	Noise level			Evaluation	Suitable application (using GPS data with an accuracy on the order of mm to few cm)
	low	medium	high		
<i>simple</i>				+ suitable for time series with low noise-level – not suitable for medium to high noise-levels	Displacement per time larger than about ten times the standard deviation of the error of GPS solutions and smooth transitions between periods of slow and fast movement. Examples are: - Fast moving glaciers - Ice islands or ice bergs
<i>SNRT</i>				returns discrete reliable velocity estimations representative for given periods+ suitable for various noise-levels and variable SNR – for high noise-levels timing of acceleration not correct due to large smoothing-windows	Reliable velocity estimations even for velocities much smaller than ten times the standard deviation of the error of GPS solutions and where the SNR potentially changes over time. Examples are: - Deep-seated landslides (>1mm/d, potentially with sudden acceleration) - Rock glacier movements, potentially with sudden acceleration in spring - Gelfluction, with sharp acceleration during snowmelt - Slow-moving glaciers, such as seracs on hanging glaciers
<i>Spline</i>				+ suitable for time-series with smooth accelerations (sinusoidal movement-pattern) – not suitable for time-series with variable SNR	Velocity estimation of movements with smooth acceleration (sinusoidal velocity-regime), e.g.: - Rock glaciers with sinusoidal movement-regime - Deep-seated landslides in seasonal frost
<i>Lokern</i>				+ suitable for time-series with variable SNR and low to medium noise-level – for a high noise-level and variable SNR the temporal variability is overestimated	Detection of the timing of acceleration, for various movement regimes, even for high noise levels and variable SNR, e.g.: - Glaciers with medium velocity and sudden acceleration or deceleration - Very fast rock glaciers or landslides

Fig. 3. (Table 2 in manuscript) see caption of Table 2