Letter of response to comment on nhess-2021-18

Dear Sigrid Roessner,

We thank you for your valuable comments on our manuscript and appreciate the time and the efforts you have invested. Your feedback has helped us to see and clarify ambiguous areas to further improve our work.

Based on your suggestions we have restructured the entire manuscript, especially introduction, study site description, discussion and conclusion. In addition, we have specified many conceptual and methodological concerns according to your more specific remarks. We have also rephrased several ambiguous paragraphs.

Please find below the following colour coding for the review and your comments in black; our responses to the review are in blue and the changes made to the manuscript are in green (following RC2), orange (following RC1) and in blue by the authors. Reference to line numbers are based on the original preprint.

General comments

The paper represents an interesting contribution to process oriented remote sensing based monitoring of complex landslides with the aim of making a conceptual contribution to early warning. The paper is well written in language and structure and the figures are of good quality. Despite the overall good scientific relevance and presentation quality, in the current form the paper lacks a coherent scientific goal justifying the used approach. This problem already becomes apparent in L40 where the authors state that the study presents a new concept to systematically evaluate remote sensing techniques to optimize lead time for landslide early warning'. Although the presented work is very interesting, it does not fit the stated goal for the following reasons:

- Concept of lead time and need for best possible reduction is not new.
  While we agree that the concept itself may not be knew, we find that using multispectral remote sensing products to assess and increase lead time to ensure the timely prediction of landslide early warning systems represents an important research gap that so far has rarely been addressed. We evaluate the capabilities of remote sensing to identify hot–spots and detect process behaviour changes based on the local conditions. Thus, the landslide process is the precondition. We want to estimate, based on the assumption that the particular sensor is able to deliver the necessary information, the time demand of each sensor for time to warning.
  We have now replaced the phrase optimising lead time with a more precise description of what we have done. Please see revision of the conclusion further below.

L10–11: We introduce a novel conceptual approach ~~for comprehensive~~ to structure and quantitatively assess lead time ~~assessment and optimisation~~ for LEWS.

[…]

L39–41: This study presents a new concept to systematically evaluate remote sensing techniques to ~~optimise~~ estimate and increase lead time for landslide early warnings in these catchments. We do not start from the perspective of available data; instead, we define necessary time constraints to successfully employ remote–sensing data ~~for~~ to provid~~eing~~ early warnings.

[…]

L34: Lead time as defined in the context of LEWS is the interval between the issue of a warning (i.e. dissemination) and the forecasted landslide onset (Pecoraro et al. 2019) and thus crucially depends on time requirements in phases

(1)–(3). The success of an EWS therefore requires measurable pre–failure motion (or slow slope displacement) to allow for sufficient lead time for decisions on reactions and counter measures (Grasso, 2014; Hungr et al., 2014).

- Remote sensing techniques themselves are not the bottleneck for shortening the lead time.
  The goal of our concept is not to refine remote sensing as a technique itself but to provide a tool for choosing the appropriate sensors based on time required for the time to warning phase. We thereby increase lead time.
  We do not agree with your objection to the word "bottleneck" especially given your comment below which says "In remote sensing based approaches lead time mostly depends on the available imaging constellation and data distribution to the end user."

L39–61: This study presents a new concept to systematically evaluate remote sensing techniques to ~~optimise~~ estimate and increase lead time for landslide early warnings in these catchments. We do not start from the perspective of available data; instead, we define necessary time constraints to successfully employ remote–sensing data ~~for~~ to provid~~eing~~ early warnings. This approach reduces ~~the~~ to a small number the ~~of~~ suitable remote sensing products ~~to a small number~~ with high temporal and spatial resolution. With these constraints, we investigated the application of data from satellites and ~~unmanned aerial systems (~~UAS~~)~~ to allow the assessment of the data, after a spaceborne area–wide but low–resolution acquisition, into a downscaled detailed image recording. In so doing, we analysed the capability of these different passive remote sensing systems focusing on spatiotemporal capabilities for ground motion detection and landslide evolution to provide early warnings.

[…]

L94–102: In recent years, data provision for users has increased and today data hubs provide easy accessibility to rapid, pre–processed imagery. ~~Knowledge of the most useful remote sensing data options is vital for complex, time–critical analyses such as ground motion monitoring and landslide early warning.~~ Nonetheless, technological advances can be misleading as they promise high spatiotemporal data availability, which frequently does not reflect reality (Sudmanns et al., 2019). One key problem is the realistic net temporal data resolution which is often significantly reduced due to technical issues, such as image errors and non–existent data (i.e. data availability, completeness, reliability). Other problems include data quality and accuracy in terms of geometric, radiometric and spectral factors (Batini et al., 2017; Barsi et al., 2018). Knowledge of the most useful remote sensing data options is vital for complex, time–critical analyses such as ground motion monitoring and landslide early warning. Timely information extraction and interpretation are critical for landslide early warnings yet few studies have so far explicitly focused on time criticality and the influence of the net temporal resolution of remote sensing data.

- In remote sensing based approaches lead time mostly depends on the available imaging constellation and data distribution to the end user and in case of optical data on the atmospheric conditions (clouds). Both factors are only to a very limited extent in control of the authors - only in case of the UAV data acquisitions.
  Thank you for your comment. We agree that the limitation of meteorological conditions including effects such as cloud shadow and snow are important constraints as we described in L45–55 and L158. We took this into consideration when estimating

the number of available PlanetScope images (Sect. 4.2.) and discussed atmospheric affected images with regard to displacement derivation results in L477–481.
You are right that for UAS campaigns, most of the control is on the user side and only to a very limited part for other satellites. Today, some data providers promise new images daily, sometime even more frequently (e.g. PlanetScope).
But this is the point we want to highlight with our study. In a real world situation, we wish to determine which satellites can provide useful timely information in terms of an effective repetition rate and real availability in the data hub (provider). In addition, the natural conditions such as atmospheric and site specific constraints can reduce the net image number. For this reason, we assess the capabilities of optical remote sensors in a spatiotemporal context for given circumstances to detect hot spots and identify possible changes in slope processes.

L52–55: Previously, high spatial resolution satellite data was obtained at the expense of a reduction in the revisit rates (Aubrecht et al., 2017). Consequently, the return period between two images increased, limiting ground displacement assessment and the range of observable motion rates. The number of useful images was further reduced due to natural factors such as snow cover, cloud cover and cloud shadows.

[…]

L86–91: In general, sensor choice depends on the landslide motion rate with radar at the lower and optical instruments at the upper motion range (Crosetto et al., 2016; Moretto et al., 2017; Lacroix et al., 2019). However, ~~A~~a flexible, cost–effective alternative to spaceborne optical data are airborne optical images taken by UASs ~~(unmanned aerial systems)~~. Freely selectable flight routes and acquisition dates ~~prevent~~ enable avoiding shadows from clouds and topographic obstacles~~, and~~ as well as ~~allow avoiding~~ unfavourable weather conditions and summer time snow cover, all of which frequently impair satellite images (Giordan et al., 2018; Lucieer et al., 2014).

L96–102: […] technological advances can be misleading as they promise high spatiotemporal data availability, which frequently does not reflect reality (Sudmanns et al., 2019). One key problem is the realistic net temporal data resolution which is often significantly reduced due to technical issues, such as image errors and non–existent data (i.e. data availability, completeness, reliability). Other problems include data quality and accuracy in terms of geometric, radiometric and spectral factors (Batini et al., 2017; Barsi et al., 2018). Knowledge of the most useful remote sensing data options is vital for complex, time–critical analyses such as ground motion monitoring and landslide early warning. Timely information extraction and interpretation are critical for landslide early warnings yet few studies have so far explicitly focused on time criticality and the influence of the net temporal resolution of remote sensing data.

- The used data sources (planet and UAV) do not allow optimization of lead time in the context of early warning because of the scarcity of their availability which is reflected in the small number of only three multitemporal data takes between July and September analyzed in this study (Table 3)

  Thank you. With regard to this comment we assume this needs further clarification. First, we have changed the entire phrase on "optimising lead time" to be more precise in the description of our approach (see previous comment). Regarding the data takes, yes, we do have three UAS acquisitions but over the course of more than one year (7/2018–9/2019). For the purpose of this comparison we selected PlanetScope data at a similar time to UAS acquisitions, whereby one Planet image (02.07.2018, see Table 5) showed low quality results why the time interval was excluded (see caption Fig. 4). In both UAS and PlanetScope DIC results we can see the general distinctive hot–spot identification as well as changes in motion behaviour indicating an acceleration for the time intervals I and II. Second, we can obtain a higher frequency of UAS acquisitions if necessary. We have revised our conclusion to be more concise in our work with regard to both, the term optimisation as well as the total number of data takes.

L567–569: This paper presents an innovative concept to compare the lead time for landslide early warnings, ~~utilising~~ of two optical remote sensing systems. We tested this temporal concept by applying UAS and PlanetScope images of temporal proximity as these are currently the sensors with the best spatiotemporal resolution.

[…]

L573–580: Our findings derived from DIC for this steep high–alpine case study show that high resolution UAS data (0.16 m) can be employed to identify and demarcate the main landslide process and reveal its heterogeneous motion behaviour as confirmed by single block tracking. Thus, validated total displacement ranges from 1–4 m and up to 14 m for 42 days. PlanetScope Ortho Scenes (3 m) can detect the displacement of the landslide central core, however, cannot accurately ~~resolve~~ represent its extent and internal behaviour. The signal–to–noise ratio, including multiple false–positive displacements, complicates the detection of hotspots at least in this very steep and heterogeneous alpine terrain.

Coarse temporal data resolution, such as in the case study investigated here, represents an important restriction to the use of optical remote sensing data for landslide early warning applications. Acceleration (and the resulting failure) over short periods of time will likely go unnoticed due to large data acquisition intervals. However, for prolonged acceleration periods, such as observed at the Sattelkar slide and many other relevant hazard sites, the chosen data sources have been demonstrated to represent a formidable early warning approach capable of contributing to an improved risk analysis and evaluation in steep high–alpine regions.

[…]

L589–594: For continuous monitoring and early warning, the warning time window could be shortened by on–site drone ports with autonomous acquisition flights and automatic processing. Our systematic evaluation of the sensor ~~potency~~ capability can be applied ~~and transferred~~ to other optical remote sensing sensors, and the same is true for our conceptual approach ~~optimising~~ which extend~~sing~~ the lead time. Future studies should focus on the applicability of complementary optical data to confirm the detection of landslide displacement and adjust UAS output resolution as this significantly increases the validity of DIC internal ground motion behaviour.

- The missing sound conceptual approach is also reflected in the introduction in form of a lengthy summary of in principle available remote sensing methods and data showing no clear line of arguments (L20-100). Moreover, the new conceptual approach presented in Fig. 1 is very general and not specific to landslide and does not qualify as a novelty in the current form.

  1. Introduction

  We revised the abstract and the introduction , to be more precise with regard to our goal and implementation. In so doing we more clearly defined our approach to lead time and early warning systems for landslides. Further we did our best to improve the line of arguments and to show the historic limitations of optical remote sensing for LEWS up to the recent developments when it comes to options such as high spatiotemporal products and their usage for monitoring, early warning and time-series displacement analyses.

2. The conceptual approach

We decided to keep this concept general, to employ it for other remote sensing techniques and maybe even other kind of instrumentation as well as different use cases of other time challenging issues. We revised and added some sentences to emphasise our approach/idea. Even after intense research we did not find good conceptual approaches challenging remote sensing in the direct context of landslide early warning systems. We therefore consider our approach novel. This concept forms the basis to employ this for the setup of 'a real early warning system'.

L21–102: Landslides are a major natural hazard leading to human casualties and socio–economic impacts, mainly by causing infrastructure damage (Dikau et al., 1996; Hilker et al., 2009). They are often triggered by earthquakes, intense short–period or prolonged precipitation, and human activities (Hungr et al., 2014; Froude and Petley, 2018). In a systematic review Gariano and Guzzetti (2016) report ~~in a review study~~ that 80 % of the papers examined ~~papers~~ show causal relationships between landslides and climate change. The ongoing warming of the climate (IPCC, 2014) is likely to decrease slope stability and increase landslide activity (Huggel et al., 2012; Seneviratne et al., 2012), which ~~. This~~ indicates a vital need to improve the ability to detect, monitor and issue early warnings of landslides and thus to reduce and mitigate landslide risk.

Early warning, ~~as defined by the UN International Strategy for Disaster Reduction (UNISDR),~~ refers to a set of capacities for the timely and effective provision of warning information through institutions, such that individuals, communities and organisations exposed to a hazard are able to take action with sufficient time to reduce or avoid risk and prepare an effective response (UNISDR, 2009). According to UNISDR (2006), an effective early warning system consists of four elements: (1) risk knowledge, the systematic data collection and risk assessment; (2) the monitoring and warning service; (3) the dissemination and communication of risk as well as early warnings; and (4) the response capabilities on local and national levels. ~~Incompleteness or failure of one element can lead to a breakdown of the entire system (ibid.).~~ Lead time as defined in the context of LEWS is the interval between the issue of a warning (i.e. dissemination) and the forecasted landslide onset (Pecoraro et al. 2019) and thus crucially depends on time requirements in phases (1)–(3). The success of an EWS therefore requires measurable pre–failure motion (or slow slope displacement) to allow for sufficient lead time for decisions on reactions and counter measures (Grasso, 2014; Hungr et al., 2014).

While remote sensing has been established for early warnings, remote sensing is not yet used for real early warnings of the onset of landslides in steep-alpine terrain (with a few exceptions), where geotechnical instruments are still preferred. Exceptions include terrestrial InSAR (Pesci et al., 2011; Walter et al. 2020) and terrestrial laser scanning with high repetition rates. However, repeated UAS (unmanned aerial systems) and optical satellite images (PlanetScope) with high repetition rates have so far not been applied for landslide early warning in steep-alpine catchments. In this regard, knowledge of sensor capabilities and limitations is essential, as it determines which rates and magnitudes of pre-failure motion can potentially be identified (Desrues et al., 2019). Our proposed framework refers to mass movements in steep–alpine catchments with significant pre–failure motion ~~operating~~ over ~~a~~ sufficient time periods and thus excludes instantaneous events triggered by processes such as heavy rainfalls or earthquakes.

This study presents a new concept to systematically evaluate remote sensing techniques to ~~optimise~~ estimate and increase lead time for landslide early warnings in these catchments. We do not start from the perspective of available data; instead, we define necessary time constraints to successfully employ remote–sensing data ~~for~~ to provid~~eing~~ early warnings. This approach reduces ~~the~~ to a small number the ~~of~~ suitable remote sensing products

~~to a small~~ with high temporal and spatial resolution. With these constraints, we investigated the application of data from satellites and ~~unmanned aerial systems (~~UAS~~)~~ to allow the assessment of the data, after a spaceborne area–wide but low–resolution acquisition, into a downscaled detailed image recording. In so doing, we analysed the capability of these different passive remote sensing systems focusing on spatiotemporal capabilities for ground motion detection and landslide evolution to provide early warnings.

~~Until~~ Recently, the spatial and temporal resolution of optical satellite imagery has significantly improved ~~requirements for accurate early warning purposes have not been met by optical satellite imagery~~ (Scaioni et al., 2014) and has allowed substantial advances in the definition of displacement rates and acceleration thresholds to approach requirements for early warning purposes. This is essential since spatial and temporal resolution determine~~s~~ whether landslide monitoring is possible with the detection ~~allows defining~~ of displacement rates and ~~the~~ ~~approximation~~ approximate acceleration thresholds, both of which are lacking if information is based solely on post–event studies (Reid et al., 2008; Calvello, 2017). Landslide monitoring offers the potential to significantly advance landslide early warning systems (LEWS) (Chae et al., 2017; Crosta et al., 2017). Previously, high spatial resolution satellite data was obtained at the expense of a reduction in the revisit rates (Aubrecht et al., 2017). Consequently, the return period between two images increased, limiting ground displacement assessment and the range of observable motion rates. The number of useful images was further reduced due to natural factors such as snow cover, cloud cover and cloud shadows. High–resolution remote sensing data was long restricted due to high costs and data volume (Goodchild, 2011; Westoby et al., 2012). Today ~~C~~commercial very high resolution (VHR) optical satellites exist, but tasked acquisitions make them inflexible and very cost intensive, thus limiting research (Butler, 2014; Lucieer et al., 2014). There is a vast spectrum of available remote sensing data with high spatiotemporal resolution (Table 1). Complementary use of different remote sensing sources can significantly improve landslide assessment as demonstrated by Stumpf et al. (2018) and Bontemps et al. (2018), who draw on archive data and utilise different sensor combinations to analyse the evolution of ground motion.

Table 1 Overview of different optical multispectral remote sensors with their corresponding resolution [m] and revisit rate [days]. The sensors are categorised into commercial and free data policy. [1]free quota via Planet Labs Education and Research Program, [2]PlanetScope Ortho Scene Product, Level 3B/Ortho Tile Product, Level 3A (Planet Labs, 2020b), [3]reached end of life, 3/2020, archive data usable, [4]5 m Ortho Tile Level 3A (Planet Labs, 2020a), [5]0.5 m colour pansharpened, [6]self–acquired. Source: (ESA, 2020).

Sensor	Temporal resolution [d]	Spatial resolution [m]	Free/ Commercial
UAS	flexible	0.08	F[6]
WorldView 2	1.1	1.84	C
WorldView 3	<1	1.24	C
WorldView 4	<1	1.24	C
GeoEye 2	5	1.24	C
SkySat	1	1.5	C
GeoEye–1	3	1.64	C
Pléiades 1A/B	1	2.0 (0.5)[5]	C
PlanetScope	1	3.0/3.125[2]	C/F[1]
RapidEye[3]	5.5	5[4]	F
Sentinel–2 A/B	5	10	F
Landsat 8	16	30	F

The latest developments in earth observation programs include both the new Copernicus' Sentinel fleet operated by the ESA, and a new generation of micro cube satellites, sent into orbit in large numbers by PlanetLabs Inc. These ~~PlanetScope~~ micro cube satellites, known as 'Doves'/PlanetScope (from now on referred to as PlanetScope satellites), and Sentinel–2 a/b offer very high revisit rates of 1–5 days and high spatial resolutions from 3–10 m, respectively (Table 1), for multispectral imagery (Drusch et al., 2012; Butler, 2014; Breger, 2017). This opens up unprecedented possibilities based on these These high spatiotemporal resolutions open up unprecedented possibilities to study a wide range of landslide velocities and natural hazards through remote sensing. Future Continuing data access is fostered by PlanetLabs and by Copernicus (via its open data policy) providing affordable or free data for research. This leads to unprecedented possibilities for sturying natural hazards through remote sensing. Examples of landslide activity studies employing multi–temporal datasets of landslide activities based on this access to high spatiotemporal data are include Lacroix et al. (2018), using Sentinel–2 scenes to detect motions of the 'Harmalière' landslide in France, and Mazzanti et al. (2020), who applied a large stack of PlanetScope images for the active Rattlesnake landslide, USA.

As forecasted landslides tend to accelerate beyond the deformation rate observable with radar systems before failure, we concentrate on optical image analysis (Moretto et al., 2016). One advantage of optical imagery is its temporally dense data (Table 1) compared to open data radar systems with sensor visits repeat frequency more than every six days and revisit frequency between three days at the equator, about two days over Europe and less than one day at high latitudes (Sentinel–1, ESA). Optical data allows direct visual impressions impression from the multispectral representation of the acquisition target and the option to employ this data for further complementary and expert analyses. While active radar systems overcome constraints posed by clouds and do not require daylight, data voids can be significant due to layover or shadowing effects in steep mountainous areas (Mazzanti et al., 2012; Plank et al., 2015; Moretto et al., 2016). Moreover, north/south facing slopes are less suitable, thus limit the range of investigation (Darvishi et al., 2018). In general, sensor choice depends on the landslide motion rate with radar at the lower and optical instruments at the upper motion range (Crosetto et al., 2016; Moretto et al., 2017; Lacroix et al., 2019).

However, Aa flexible, cost–effective alternative to spaceborne optical data are airborne optical images taken by UASs (unmanned aerial system). Freely selectable flight routes and acquisition dates prevent enable avoiding shadows from clouds and topographic obstacles, and as well allow avoiding as unfavourable weather conditions and summer time snow cover, all of which frequently impair satellite images (Giordan et al., 2018; Lucieer et al., 2014). UAS–based surveys provide accurate very high resolution (few cm) orthoimages and digital elevation models (DEM) of relatively small areas, suitable for detailed, repeated analyses and geomorphological applications (Westoby et al., 2012; Turner et al., 2015).

In recent years, data provision for users has increased and today data hubs provide easy accessibility to rapid, pre–processed imagery. Knowledge of the most useful remote sensing data options is vital for complex, time–critical analyses such as ground motion monitoring and landslide early warning. Nonetheless, technological advances can be misleading as they promise high spatiotemporal data availability, which frequently does not reflect reality (Sudmanns et al., 2019). One key problem is the realistic net temporal data resolution which is often significantly reduced due to technical issues, such as image errors and non–existent data (i.e. data availability, completeness, reliability). Other problems include data quality and accuracy in terms of geometric, radiometric and spectral factors (Batini et al., 2017; Barsi et al., 2018). Knowledge of the most useful remote sensing data options is vital for complex, time–critical analyses such as ground motion monitoring and landslide early warning.

- L140: General applicability to optical data: This subheading does not fit the content of this section comprising a compilation of rather basic and general steps of remote sensing data processing.
  Thank you for your comment. We agree that it describes general steps of the data processing chain; however, these steps are applied within each phase of the 'time to warning' of our proposed concept. Otherwise the steps would not be explained and thus the basis for the concept would be lacking. We have revised the subheading to "Practical implementation of multispectral data in the concept" which more accurately describes the content of this section.

  2.2. Practical implementation of multispectral data in the concept ~~General applicability to optical data~~

- The study site (starting at L175) represents a very complex landslide case leading to rather erratic mass movements in form of debris flows initiated by changing slope water conditions related to increased atmospheric precipitation. This situation is another obstacle for an early warning approach which is solely based on optical remote sensing data and thus making it impossible to make full use of the in principle daily temporal resolution of the planet data. Taking into account these natural conditions and the constraints introduced by the used imaging constellations, leaves no room for true optimization of lead time in the sense as stated in the overall scientific goal of this paper.
  We agree with your assessment and have replaced the term "optimisation" with a description that hopefully is more accurate in the entire manuscript. The chosen Sattelkar slide is one of the most relevant high-alpine geohazards in Austria and thus represents a compelling study site for natural hazard studies. While we agree that its complexity represents an obstacle, we nonetheless believe that the Sattelkar slide is well-suited for an investigation based on optical remote sensing because (i) we were clearly able to detect significant displacement and (ii) we were able to identify patches of increasing motion. In any case an increase in frequency of UAS flights is possible.

L39–41: This study presents a new concept to systematically evaluate remote sensing techniques to ~~optimise~~ estimate and increase lead time for landslide early warnings in these catchments. We do not start from the perspective of available data; instead, we define necessary time constraints to successfully employ remote–sensing data ~~for~~ to provid~~eing~~ early warnings.

- Any sensible early warning approach for slope movements requires a continuous and reliable high temporal resolution input of observation data related to parameters which are relevant for triggering the potential mass movements. Such information are mostly provided by ground based measurements. In this context, it is surprising that no relevant ground based monitoring information seem to be available to this study despite the longterm history of scientific work at this study site. The mentioned temperature loggers need to be explained in their function for early warning. The GPS measurements seem to only support the remote sensing based analysis. The described setting does not seem to be suitable for identification of precursory signs of ‚slope preparation' related to the triggering of potential mass movements at this site in a way which would be required in the context of early warning.
  Thank you for your feedback. We understand your arguments, yet we are not trying to

create an all-encompassing landslide early warning study that includes all state-of-the-art methods. We have chosen the Sattelkar due to its scientific and societal relevance and its high-alpine location with very limited vegetation. This site was not selected to evaluate a wide range of remote sensing applications. Our goal was to determine if and how our conceptual approach is applicable to this highly complex study site. Due to its topographical characteristics no ground based technique can be implemented. Therefore, only air- and spaceborne sensors can be employed which we believe is the case for numerous potentially hazardous slides/creeps in mountain ranges worldwide. However, we have considered installing a camera on the opposite slope but currently the distance is a problem (3.5 km, selection of camera).

We agree that the temperature data mentioned in the manuscript is not absolutely necessary to understand our conceptual approach. We still think that the (brief) inclusion of the temperature data makes sense as it suggests local permafrost presence/degradation which may be one of the main drivers of the Sattelkar slide. To clarify the role of the temperature data we amended the relevant sections in the study site section.

L175 et seq. […] massive volumes of glacial and periglacial debris as well as rockfall deposits (Fig. 2b, c). ~~Near-surface temperature data indicates sporadic permafrost distribution in the upper part of the cirque.~~

[…] allowing visual block tracking and delimiting the active process area. High displacement was measured between 2012 and 2015 with up to 30 m a^{-1}.

[…]

L200 et seq.: In the Sattelkar cirque, several monitoring components are installed to provide ongoing and long–term monitoring. Nine permanent ground control points (GCPs) measured with a dGPS to provide stable and optimal conditions to derive orthophotos from highly accurate UAS images (GeoResearch, 2018). A total number of 15 near surface temperature loggers (buried at 0.1 m depth) recorded annual mean temperatures slightly above the freezing point (1–2 °C) in the period 2016 to 2019. Ground thermal conditions at depth react with significant lag times to recent warming and therefore are primarily determined by climatic conditions of the past (Noetzli et al., 2019). Significantly cooler climatic conditions in previous decades and centuries (Auer et al., 2007) thus likely contributed to the formation of (patchy) permafrost at the Sattelkar cirque. Recent empirical–statistical modelling of permafrost distribution in the Hohe Tauern Range confirms possible permafrost presence at the study site (Schrott et al., 2012).

~~These components include 30 near surface temperature logger (NSTL) nine permanent ground control points (GCP) measured with a dGPS to provide stable and optimal conditions for the derivation of orthophotos from highly accurate UAS images (GeoResearch, 2018). Field–based mapping and measurements help to delimit the active process area.~~

Correct, the dGPS measurements are only used for repeated UAS campaigns and their data derivation. As described earlier, with our technical approach we were able to not only detect hot spots of total displacement but also to see changes in motion and thus certain areas of accelerating behaviour.

- L210: The complete dismissal of radar data is not justifiable in the current form since the authors only take into account InSAR based deformation analysis and neglect that

the technique of pixel offset tracking can be also be applied to the intensity component of radar data. For the mainly rainfall driven processes at the study site, the integration of radar data seems to be mandatory into any sensible remote sensing based early warning approach, since a combination of optical and radar data is required to establish an as continuous as possible time series of remote sensing observations.
Thank you for mentioning radar data. We have described the application of InSAR/DInSAR in the introduction (L86–91) and placed the argument in section "4.1. Optical Imagery".
For this particular site radar data is not practical. Even if foreshortening and layover effects are a minor issue for this site, the main reason to not include this kind of data is the fact that the velocity shows rates exceeding the limits of radar data leading to a loss of coherence.

L78 et seq.: As ~~forecasted~~ landslides tend to accelerate beyond the deformation rate observable with radar systems before failure, we concentrate on optical image analysis (Moretto et al., 2016). One advantage of optical imagery is its temporally dense data (Table 1) compared to open data radar systems with sensor ~~visits~~ repeat frequency ~~more than~~ every six days and revisit frequency between three days at the equator, about two days over Europe and less than one day at high latitudes (Sentinel–1, ESA). Optical data allows direct visual impressions from the multispectral representation of the acquisition target and the option to employ this data for further complementary and expert analyses. While active radar systems overcome constraints posed by clouds and do not require daylight, data voids can be significant due to layover or shadowing effects in steep mountainous areas (Mazzanti et al., 2012; Plank et al., 2015; Moretto et al., 2016). Moreover, north/south facing slopes are less suitable, thus limit the range of investigation (Darvishi et al., 2018). In general, sensor choice depends on the landslide motion rate with radar at the lower and optical instruments at the upper motion range (Crosetto et al., 2016; Moretto et al., 2017; Lacroix et al., 2019).

- Moreover, taking into account the goal of lead time optimization, I consider it crucial to also include ground-based live-streamed time-lapse imagery in the proposed remote sensing based early warning approach (for an example see the Khan et al. (2021) paper ‚Low-Cost Automatic Slope Monitoring Using Vector Tracking Analyses on Live-Streamed Time-Lapse Imagery' published in Remote Sensing).
  Thank you for this idea and forwarding the information on the article of this useful approach for the 'Rest and Be Thankful slope', Scotland, with PIV on time–lapse imagery. For the Sattelkar we conducted preliminary investigations regarding the installation of a camera on the opposite slope. Due to the steep slope the camera would have to be mounted at the same altitude. This means a camera would have to be able to cover a horizontal distance of about 3.5 km. There is a higher chance of mobile network signal which is otherwise unavailable beginning at the entrance of the valley. Nevertheless, the power supply and issues such as rain drops and general pollution on the lense pose problems as Khan et al. (2021) also acknowledge.

The materials and methods section (4.) as well as the result section (5) are sound and well written. Since reviewer 1 has already focused on this part of the paper as well as the accuracy assessment and made detailed suggestions for improving these parts, I only have a few comments left to make on these aspects of the paper.

- L355: The authors state that core areas of the landslide are surrounded by wide fringes with no data. In this context the meaning of the term ‚no data' is not clear to me.

Please, explain, what do you mean by ‚no data' – either missing results or zero deformation.
Thank you for pointing this out. Here by 'no data' we mean that there is zero deformation and we have revised the text accordingly.

L354 et seq.: No motion was present in a fringe zone along the landslide front (west boundary), similar to results in Fig. 5a and Fig. 5b. In general, the displacement patterns are less smooth than at 0.16 m input resolution. Outside the landslide significant displacements exist at the eastern image border (Fig. 5e) and towards the west (*h*, *i*) (Fig. 5f). In comparison, total displacement ~~rates~~ derived from PlanetScope cover in large parts the active area for Ib (Fig. 5c); however, for II only the core area of the landslide shows displacement. In both results the core areas of the landslide are surrounded by wide fringes with zero deformation.

- L370: Fig 6. The obtained deformation results show a very different degree of detail throughout the landslide. For better evaluation of the reasons for these differences the inclusion of an RGB UAV image of the same area would be helpful in order to be able to include surface texture properties in the evaluation of the obtained differences in the deformation patterns.
  Thank you for your good suggestion. We added the corresponding master and slave image below the presented DIC result. The caption has been adjusted accordingly.

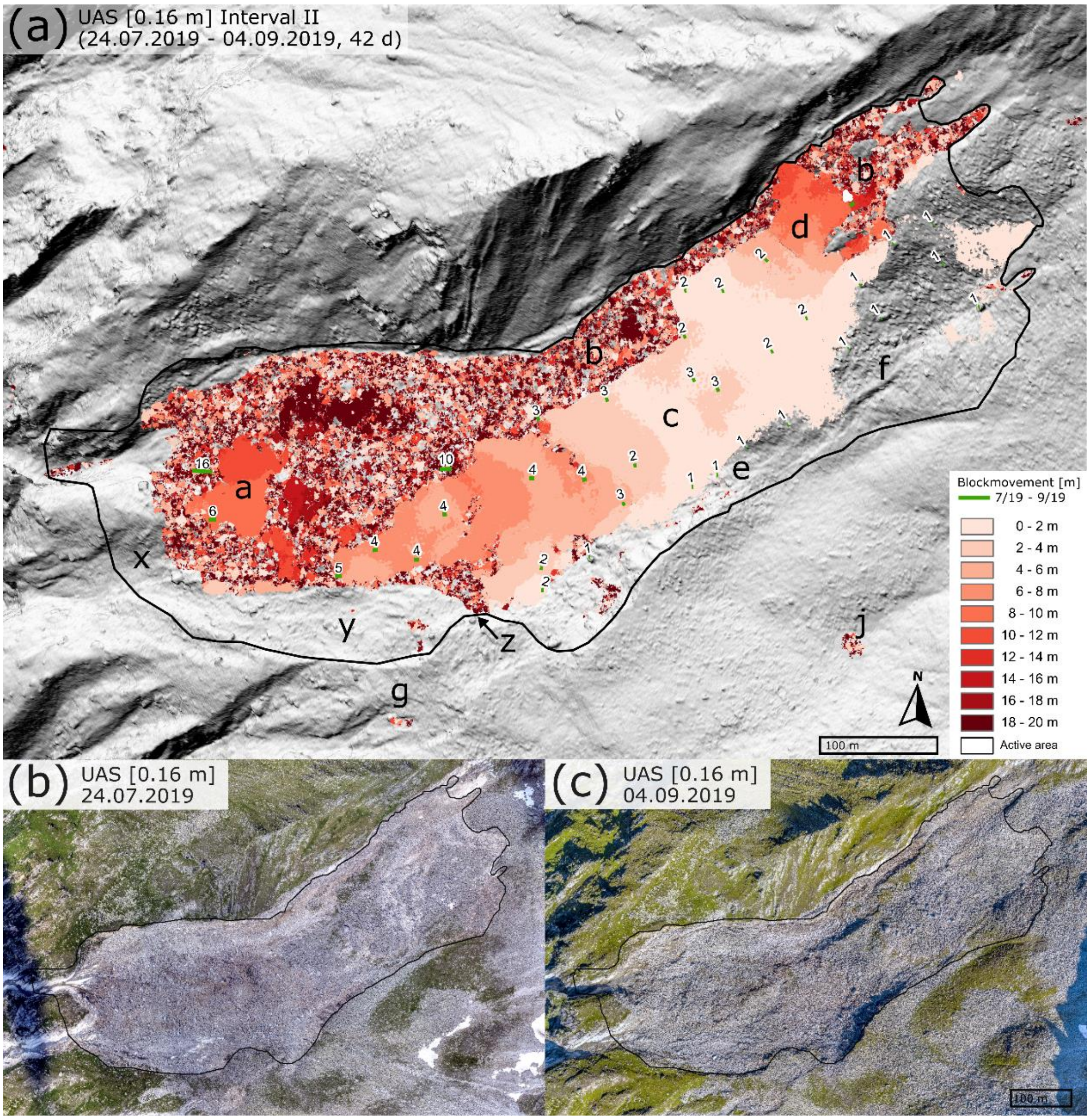

Figure 1 (a) Displacement derived from UAS data at 0.16 m resolution for interval II (24.07.2019–04.09.2019, 42 d) combined with boulder trajectories (in metres) manually measured in the UAS orthophotos in the same time period. The solid black line represents the boundary of the active landslide based on field mapping. Background: UAS hillshade, 24.07.2019 (0.08 m), orientation -3° from north. UAS orthophotos at 0.16 m resolution for the master **(b)** and slave image **(c)** for the corresponding time interval.

- Conclusions related to the results presented until L370: The presented specific deformation results obtained from the analyzed planet and UAV data, represent a valuable contribution towards an improved area-wide process understanding of so far unprecedented detail for this study site. Conceptually, such investigations mainly contribute to the preparedness phase within the disaster management cycle. Continuation of monitoring of the study site using the described approach would represent a very valuable prerequisite for developing and setting up a true early warning system for this site combining ground based and remote sensing observations. However, the results presented in this paper do not allow optimization of lead times within an early warning approach being stated being as the goal of this paper.
  Our approach is not to set up a comprehensive early warning system, which includes all four elements defined by the UNISDR (2006) (see L35–38).
  We agree that optimisation of lead time does not accurately represent what we have done in our study. Thus we have revised our manuscript to make it more precise (see

changes to the manuscript here on p. 1, 3–4). Our concept enables us to evaluate lead time based on our proposed structure.

Introduction, L10–11: We introduce a novel conceptual approach ~~for comprehensive~~ to structure and quantitatively assess lead time ~~assessment and optimisation~~ for LEWS.

[…]

L39–41: This study presents a new concept to systematically evaluate remote sensing techniques to ~~optimise~~ estimate and increase lead time for landslide early warnings in these catchments. We do not start from the perspective of available data; instead, we define necessary time constraints to successfully employ remote–sensing data ~~for~~ to provid~~eing~~ early warnings.

[…]

Conclusion, L578 et seq.: Coarse temporal data resolution, such as in the case study investigated here, represents an important restriction to the use of optical remote sensing data for landslide early warning applications. Acceleration (and the resulting failure) over short periods of time will likely go unnoticed due to large data acquisition intervals. However, for prolonged acceleration periods, such as observed at the Sattelkar slide and many other relevant hazard sites, the chosen data sources have been demonstrated to represent a formidable early warning approach capable of contributing to an improved risk analysis and evaluation in steep high–alpine regions.

- L375: 5.3 Time required for collection, processing and evaluation. The presented analysis is rather meaningless, since the scarcity of the available time steps does not allow the detection of critical process stages. Taking into account the big temporal gaps between the data acquisitions, the time needed for handling the planet and UAV imagery is not really relevant for lead time optimization. The obtained times only allow a relative comparison between planet and UAV based data acquisition within the narrow limits of the chosen approach. However, true early warning would require setting up a *semi-automated processing chain* including automated download and screening of available remote sensing data as well as semi-automated subsequent deformation analysis reducing data handling time to a minimum. Under such conditions, primary remote sensing data availability becomes the crucial decisive factor determined by the data distribution procedures of the satellite data providers and the atmospheric conditions in case of optical imagery. In conclusion, it needs to be stated that the used parameter of time to warning is only applicable under the condition of a near real time continuous data stream of input information which is not available within the presented study.
  Thank you for your comment which helps to clarify your understanding of our text. We did not intend to create a 'true early warning' as you described. This was not the goal of our study. The repeated measurements allow the detection of spatial and temporal acceleration patterns and we believe the repeated measurements can be scaled to early warning demands. With regard to your comment on a *semi-automated processing chain* we do not fully agree. Based on our knowledge, even in case of most geotechnical investigations, the data is analysed by experts prior to issuing an early warning (e.g. https://www.bgu.tum.de/landslides/alpsense/projekt/, Leinauer et al. (2020): DOI: 10.1002/geot.202000027).

- L390: In the current form of the paper the points raised in the discussion (6.) are only relevant in the frame of a process-oriented study and not for early warning purposes

since the latter one requires the identification of precursors for critical process stages – tipping points – which are likely to trigger substantial complex mass movements later turning into potentially catastrophic debris flows.
It is our understanding, we can only provide early warnings for processes we understand. The processual understanding is key to anticipating the magnitude, timing, and reach of alpine hazards, thus processual understanding and early warning cannot be separated.

- L490: Estimating time to warning (6.3). This part of the discussion also suffers from the conceptual limitations which have already been pointed out earlier in this review. A comparison of lead times between the different example landslides would only be meaningful in case of continuous high resolution temporal information on deformation allowing the identification of precursory events which is usually only possible using ground based observations. The presented comparison between potential repeat rates of remote sensing data acquisitions and retrospectively derived lead times is too simplistic (Fig. 8), since the main remaining question is, whether the relevant deformation (cracks etc.) can be first, resolved by the used imagery and second, distinguished from other surface disturbances by the used analysis methods.
  In this paper, in contrast to remote sensing papers, the time scale required for effective early warnings is given by nature, i.e., the typical acceleration patterns of particular landslides.
  With regard to the comparison of historic events, we referred to their natural landslide processes which delimits the possible lead time. Unfortunately, a comparison to these historic examples is limited to a retrospective view. We agree with you regarding the detection of relevant deformations. If the sensors evaluated here could have identified the motion excluded disturbances, then in this temporal concept UAS and PlanetScope would have been able to show an acceleration in a timely fashion.
  We want to keep this concept simple to allow the transfer for required processing times from other sensors. The main question is, if the time is sufficient for the whole processing prior to landslide release.
  L:148–149 Natural processes and ~~natural~~ their developments constantly take place independently, thus dictate the technical approaches and methodologies researchers ~~must~~ can and must apply within a certain time period.

Overall recommendation:
The presented results comprise a very interesting process-oriented study evaluating the use of planet and UAV imagery for the derivation of spatiotemporally differentiated deformation information for a rather large and topographically pronounced terrain affected by complex mass wasting processes. I consider these findings well worth being published in this journal. However, the publication of these specific results requires a major conceptual reframing of the work which is targeted at the real potential usability of these results which cannot be early warning because of the reasons already stated in this review.

However, the work presented in this study has the potential to form an important basis for the development of a true early warning concept / approach in the future combining remote sensing and ground based observations targeting at the same parameters allowing a multi-scale assessment of surface deformation related to triggering potential catastrophic mass movements at the study site.