

# **The single-pair unwrapping ceiling is a property of the track, not of the radar: Sentinel-1 evidence from rock–ice avalanches at Langtang Lirung and Ronti Peak**

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# The single-pair unwrapping ceiling is a property of the track, not of the radar: Sentinel-1 evidence from rock–ice avalanches at Langtang Lirung and Ronti Peak

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**Abstract.** This study asks what single-pair satellite data can detect before rock–ice avalanches, such as the Langtang Lirung (Nepal) and Ronti Peak (Chamoli, India) failures. The single-pair line-of-sight limit of  $0.42 \text{ m yr}^{-1}$  for 12-day Sentinel-1 pairs is treated as a property of the radar, but the downslope ceiling depends on the track. I measure sensitivity to downslope motion  
10 *f* across Copernicus GLO-30 elevation cells using 500 m source discs for four Sentinel-1 tracks and an optical detection floor using Sentinel-2 offset tracking over stable ground. Slope-parallel interferometric synthetic aperture radar ceilings are  $0.46$  versus  $2.77 \text{ m yr}^{-1}$  at Langtang Lirung, and  $0.97$  versus  $1.21 \text{ m yr}^{-1}$  at Ronti Peak. At Langtang Lirung, moving the disc centre gives a factor of  $4.5$ – $5.9$ , and the descending track remains lowest. Non-spanning Sentinel-2 pairs give median optical floors of  $5.55 \text{ m yr}^{-1}$  at Langtang Lirung and  $5.77 \text{ m yr}^{-1}$  at Ronti Peak, whereas pairs spanning the event cannot measure the floor.  
15 Between  $2.77$  and  $5.55 \text{ m yr}^{-1}$ , neither the radar pairs nor the median optical pair can measure motion. Monitoring programmes should select radar tracks based on viewing geometry, report the ceiling per track, and integrate Sentinel-1 with optical offset tracking.

## 1 Introduction

Due to accelerated glacial ablation, heavy rainfall, and permafrost thaw, steep slopes in the Himalaya are becoming unstable,  
20 and rock–ice avalanches are becoming more frequent each year (Ahmed et al., 2026). On 25 April 2015, a catastrophic glacier collapse and avalanche was triggered by the magnitude 7.8 Gorkha earthquake. It swept down into the Langtang Valley, destroying Langtang village and killing at least 350 people (Kargel et al., 2016; Lacroix, 2016). On 7 February 2021, a rock and ice collapse at Ronti Peak, in the Chamoli district of Uttarakhand, India (Shugar et al., 2021), caused a large debris flow that swept away two hydropower plants, and more than 200 people were killed or missing (Ahmed et al., 2026). Wang et al.  
25 (2026) report that on 26 August 2026 at 08:37 local time, a hanging glacier–rock collapse at 5308 m on Langtang Lirung, the same mountain where the 2015 avalanche started (Lacroix, 2016), triggered a debris flow that dropped 4400 m, travelled about 60 km, and reached Syabrubesi about 13 min later. Along its path, it destroyed Gyirong Port, 80 bridges, 42 km of roads, and several hydropower facilities. By 4 September 2026, 1287 people had been confirmed dead and 5083 missing in Nepal, with a further 31 dead and 531 missing in Tibet (Wang et al., 2026). The collapse was sudden, and no warning was given, so there

30 was no time to evacuate and the damage was severe. Catastrophic events like this need to be detected, and nearby communities warned, before the slope fails.

Repeat-pass interferometry cannot measure more than half a fringe of displacement between adjacent pixels within a single interferogram (Massonnet and Feigl, 1998). At Sentinel-1's wavelength of 55.46 mm, this is 13.87 mm of line-of-sight (LOS) motion per pair, or  $0.42 \text{ m yr}^{-1}$  at the 12-day repeat (Torres et al., 2012). This number is treated as a property of the satellite.

35 But it is not. A radar sees only LOS motion, which is what an interferogram measures, but what matters at the source is downslope motion. The radar sees only a fraction of the downslope motion since the two directions are different (Colesanti and Wasowski, 2006; Notti et al., 2014). This fraction is a function of the local incidence angle and the angle between the radar's look direction and the direction the slope faces. Both parameters change from one track to another over the same slope, and both vary across the source within a single pass.

40 I found that no precursor was detected in Sentinel-1 backscatter before the Langtang Lirung failure (Sah, 2026d). In the last image, 50.6 h before the collapse, there was no evidence of an anomaly in the source disc compared with other similar discs, although the same test detected the collapse after the event (Sah, 2026c). A single 12-day pair has a bound of detection with both a floor and a ceiling, as the same measurement at Langtang Lirung and Ronti Peak showed (Sah, 2026b). All six published detections fall outside the single-pair range, three below the floor and three above the ceiling. All were derived from many  
45 images, not from one pair. The ascending track captured the whole source disc but missed the collapse. The ascending data had about four times the variance, and Sah (2026b) did not explain why this track missed the collapse.

An independent study (Wang et al., 2026) reports over 100 m of pre-failure deformation at the same source from optical pixel-offset tracking, with acceleration starting in January 2026. Two different procedures, the same source slope but opposite results. The natural question is where each instrument's sensitivity range actually sits at a real source, rather than at the nominal sensor  
50 specification.

This study answers that question for four Sentinel-1 geometries at two sites, two at Langtang Lirung and two at Ronti Peak, Chamoli (India, February 2021; Shugar et al., 2021), examines whether viewing geometry contributes to the ascending track missing the collapse, and then measures the optical floor at Langtang Lirung and Ronti Peak.

## 2 Data

### 55 2.1 Digital elevation model

Copernicus openly provides the digital surface model (DSM) known as Copernicus Digital Elevation Model (DEM; European Space Agency and Airbus, 2022). The DEM is hosted by Amazon Web Services (AWS) Open Data. It contains three versions, and I used GLO-30 (30 m). These data were acquired before the 2026 collapse by the TanDEM-X mission between 2011 and 2015. The two tiles I selected are N28 E085 and N30 E079. The first tile covers Langtang Lirung, and the second covers Ronti  
60 Peak, where a similar rock-ice avalanche occurred in 2021 in Chamoli district, India.

## 2.2 Source discs

I selected two source discs centred at  $28.2853^\circ$  N,  $85.5252^\circ$  E for Langtang Lirung and  $30.37775^\circ$  N,  $79.72698^\circ$  E for Ronti Peak. Each disc has a radius of 500 m, as in Sah (2026b). The Langtang Lirung centre was chosen in the first days after the event as a working estimate before mapped source outlines were available. It was supported by the radar change being largest within this disc (Sah, 2026d) and by coherence loss being strongest at this centre (Sah, 2026c). Within 500 m of it, 30.0 % of vertical transmit, vertical receive (VV) pixels and 25.4 % of vertical transmit, horizontal receive (VH) pixels changed by more than 6 dB, whereas over the rest of the scene only 0.7 % (VV) and 0.4 % (VH) changed (Sah, 2026d). The change is thus 43 times (VV) and 64 times (VH) more common at the source disc. This change is the largest backscatter change anywhere in the scene. The mapped source from Li (2026) has its centroid at  $28.2886^\circ$  N,  $85.5270^\circ$  E, about 405 m north-north-east of my disc centre. Li's preferred source area is 1.009 km<sup>2</sup>, whereas my disc covers 0.79 km<sup>2</sup>, so my disc covers only part of the failure area. Moving the disc to this centroid and to the collapse point of Wang et al. (2026) gives a ratio between tracks of 4.5–5.9, and the descending track always has the lowest ceiling. Wang et al. (2026) and Adhikari et al. (2026) report that the failure occurred on the northern flank of Tsangbu Ri near Langtang Lirung. Wang et al. (2026) give the location as  $28.2800^\circ$  N,  $85.5497^\circ$  E, about 2.5 km east of the disc centre. Both names describe the same failure; this study keeps the name Langtang Lirung for consistency with Sah (2026b, c, d). I calculated slope and aspect for each cell using GLO-30. The median slope and the circular mean of aspect, which is measured clockwise from north, were calculated over each disc. The circular mean was used because aspect is an angle that wraps around at  $360^\circ$  ( $359^\circ$  and  $1^\circ$  both face north). Langtang Lirung has a median slope of  $39.7^\circ$  and a  $280.5^\circ$  aspect, whereas Ronti Peak has a  $36.6^\circ$  slope angle with a  $17.5^\circ$  aspect. GLO-30 gives a circular-mean aspect of  $280.5^\circ$  at Langtang Lirung against the  $280.8^\circ$  mapped separately by Li (2026). This difference of  $0.3^\circ$  suggests that the disc samples the failure terrain.

## 2.3 Local incidence angles

The incidence angle ( $\theta$ ) is the angle between the incoming radar beam and a line perpendicular (normal) to a flat reference surface. This angle was taken from the incidence maps produced by the Hybrid Pluggable Processing Pipeline (HyP3) of the Alaska Satellite Facility (ASF) as a disc median for each track (Hogenson et al., 2020). The local incidence angle (LIA) is the angle between the incoming radar beam and a line perpendicular (normal) to the slope. The LIA was modelled for each GLO-30 cell using  $\theta$  and the satellite's look direction (Sect. 2.4), alongside the cell's slope and aspect. All four modelled medians agree with the numbers published by Sah (2026b) to within  $1^\circ$  (Table 1).

**Table 1. Comparison of HyP3 angle  $\theta$ , the modelled LIA, and the published LIA of Sah (2026b) for the four tracks, all as disc medians.**

| Site            | Pass, relative orbit | $\theta$ (°) | LIA, modelled (°) | LIA, Sah (2026b) (°) | Modelled – published (°) |
|-----------------|----------------------|--------------|-------------------|----------------------|--------------------------|
| Langtang Lirung | Descending, 19       | 33.92        | 70.7              | 71.0                 | −0.3                     |
| Langtang Lirung | Ascending, 85        | 40.10        | 21.8              | 22.6                 | −0.8                     |
| Ronti Peak      | Descending, 63       | 34.39        | 44.8              | 45.0                 | −0.2                     |
| Ronti Peak      | Descending, 165      | 45.73        | 52.3              | 51.3                 | +1.0                     |

90    **2.4 Look azimuths**

The look azimuth is the horizontal angle that defines the direction the radar looks at a target on the ground. This angle is measured clockwise from true north, following the same convention as aspect (Sect. 2.2). It was obtained from the range edges of Sentinel-1 product footprints in the ASF catalogue (Alaska Satellite Facility, 2026). These edges run across the flight path, in the direction the radar looks, so they give the look azimuth directly. The measured values for Langtang Lirung are 280.9°  
 95 for the descending pass and 80.3° for the ascending pass. The same method gives 280.9° for both Ronti descending tracks (relative orbits 63 and 165). The value is identical across all products of each track (spread  $\leq 0.1^\circ$ ). The two range edges of a footprint differ by about 1°, and using either edge changes the single-pair ceilings (Sect. 3.1) by at most 3 %.

**2.5 Track identity**

Langtang Lirung has a single track per direction, whereas Ronti Peak has two descending tracks in the same direction (relative  
 100 orbits 63 and 165). They pass about 8 min apart from each other, and the orbit direction alone cannot identify them. This ambiguity caused a wrong measurement in earlier work (Sah, 2026b). I checked each product against its acquisition time (about 00:43 UTC for relative orbit 63 and about 00:35 UTC for 165). The relative orbit was used as the identifier of the tracks because frame numbers change between years.

**2.6 Optical data**

105 For the optical part, I used band B04 (red) at 10 m spatial resolution from Sentinel-2 (Drusch et al., 2012) Level-2A surface reflectance. The data were accessed from the AWS open bucket (sentinel-cogs). I searched for scenes on tiles 45RUM (Langtang Lirung) and 44RLU (Ronti Peak) through the Earth Search SpatioTemporal Asset Catalog (STAC) API (Element 84, 2023), which requires no login. Each tile is a fixed square of the Military Grid Reference System (MGRS), so no resampling was needed.

110 I searched for scenes from 15 October to 20 December in each year from 2017 to 2025. These dates were chosen because they fall after the monsoon (less cloud) and before the main winter snow (less snow). Within this window, only scenes with tile cloud cover under 10 % were kept as the first filter. This left 140 candidate scenes at Langtang Lirung and 79 at Ronti Peak.

To choose one scene per year, I used the Level-2A scene classification layer (SCL) over a  $6 \text{ km} \times 6 \text{ km}$  box centred on each source. In the SCL, snow is class 11, and cloud classes are 3, 8, 9 and 10 (cloud shadow and cloud). In each year, the scene with the lowest snow % +  $2 \times$  cloud % was kept as the best scene for analysis because cloud completely blocks the correlation (Sect. 3.2), while snow only weakens it. In addition, a cap of 5 % cloud over the box was applied at Ronti Peak. This removed the only 2017 candidate at either site (40.0 % cloud), so both sites used 2018–2025. As a result, eight scenes per site were left, which gave 28 pairs per site.

The selected scenes fall between 18 October and 20 December. At Langtang Lirung, all eight scenes are from 1–20 December, with 0.0 % cloud over the box in every scene and snow covering 19.5–29.3 % of the box. At Ronti Peak, three scenes are from October (2018, 2019 and 2020), one from late November and four from December, with at most 4.2 % cloud over the box (2018) and snow covering 13.9–49.8 %. The selected scenes are listed in Table A1.

### 3 Methods

#### 3.1 Sensitivity and single-pair ceiling

For each GLO-30 cell, with slope  $\beta$  and aspect  $A$  from Sect. 2.2, I computed two unit vectors, the upward surface normal  $\mathbf{n}$  and the downslope unit vector  $\mathbf{m}$ :

$$\mathbf{n} = (\sin A \sin \beta, \cos A \sin \beta, \cos \beta), \quad (1)$$

$$\mathbf{m} = (\sin A \cos \beta, \cos A \cos \beta, -\sin \beta). \quad (2)$$

The vector  $\mathbf{u}$  points from the ground towards the satellite along the line of sight, with look azimuth  $\alpha$  (Sect. 2.4) and incidence angle  $\theta$  (Sect. 2.3):

$$\mathbf{u} = (-\sin \theta \sin \alpha, -\sin \theta \cos \alpha, \cos \theta). \quad (3)$$

The components of each vector are in the order east, north and up.

The LIA used in Sect. 2.3 and compared in Table 1 follows from  $\mathbf{n}$  and  $\mathbf{u}$ :

$$\text{LIA} = \arccos(\mathbf{n} \cdot \mathbf{u}). \quad (4)$$

I assumed that the slope creeps slowly downhill on the surface along the steepest direction ( $\mathbf{m}$ , Eq. 2). The sensitivity to downslope motion is then

$$f = |\mathbf{m} \cdot \mathbf{u}|. \quad (5)$$

Here the vertical bars denote the absolute value, so the sign of the motion (towards or away from the satellite) is ignored. The sensitivity  $f$  lies between 0 and 1. When  $f = 1$ , the radar sees the whole motion along the downslope direction, but when  $f = 0$ , it cannot see the motion at all when it looks perpendicular to it. The common shortcut formula  $\sin(\text{LIA}) \cdot \cos(\Delta\text{az})$ , where  $\Delta\text{az} = \alpha - A$ , breaks down at near-normal incidence, which is why  $f$  was computed with the full vectors.

The half-fringe limit corresponds to a  $\lambda/4$  (one-quarter wavelength) change in the line-of-sight distance between the sensor and the target. The wavelength is divided by 4 because the radar signal travels a round trip to the target and back, which doubles the path-length change, and a half-fringe corresponds to half a wavelength of that path-length change. Since the Sentinel-1 C-

band wavelength is  $\lambda = 55.46$  mm,  $\lambda/4 = 13.87$  mm for each pair. Annualised for a 12-day pair ( $\times 365.25/12$ ), this becomes  $0.4220$  m yr<sup>-1</sup> in the line of sight. The upper limit of the downslope rate is the single-pair ceiling, which is then calculated by dividing the annual line-of-sight rate by the sensitivity  $f$ :

$$\text{ceiling} = 0.4220 \text{ m yr}^{-1} / f. \quad (6)$$

- 150 The sensitivity  $f$  was computed for every cell within each 500 m disc (Sect. 2.2), and the ceiling was set from the disc median of  $f$  because spatial data often contain extreme anomalies or noise. The spread within the disc was reported as the ratio of the 90th to the 10th percentile of  $f$  (p90/p10).

### 3.2 Optical correlator

- For each site, the eight selected scenes were compared pair-by-pair to generate 28 combinations (Sect. 2.6). I used the 10 m  
155 resolution band B04 within a  $600 \times 600$ -pixel window ( $6 \text{ km} \times 6 \text{ km}$ ) centred on the source. Because all scenes share the same MGRS tile, they align on the same grid with no resampling required. The tiles lie in UTM zone 45N for Langtang Lirung and zone 44N for Ronti Peak.

- I used upsampled cross-correlation in the frequency domain (Guizar-Sicairos et al., 2008), which gave the shift in  $x$  and  $y$  between the two scenes. This was computed on a  $128 \times 128$ -pixel patch moving at a 12-pixel (120 m) node step using the  
160 scikit-image implementation (van der Walt et al., 2014). Patches that contained more than 2 % no-data or had standard deviation (SD) less than 1 in units of the stored B04 values in either scene were skipped. I removed the mean from each patch, divided it by its SD and tapered it with a Hann window. I applied an upsampling factor of 20 to achieve a sub-pixel precision of  $1/20$  pixel.

- I converted the pixel shifts in  $x$  and  $y$  at each node into metres by multiplying by the 10 m pixel size. Then I removed the  
165 scene-wide median shift to reduce co-registration errors between the dates. Finally, I calculated the displacement magnitude using the Pythagorean theorem  $\sqrt{dx^2 + dy^2}$ . Here  $dx$  and  $dy$  are the shifts in  $x$  and  $y$  after the median was removed.

### 3.3 Stable-ground control and detection floor

- I selected nodes on bare rock off the glacier in order to measure the error of the correlator. Because true movement is zero on  
stable ground, the whole shift measured there is error. The size of that error sets the detection floor, the smallest movement  
170 that can be measured. I defined the rules for selecting the control nodes before looking at the displacement results so that the choice could not be influenced by them.

- I selected off-ice nodes where the ITS\_LIVE (Gardner et al., 2025) land-ice mask (120 m grid) is 0, located  $\geq 1000$  m from the source and  $\geq 500$  m outside the measurement area at Langtang Lirung only (the glacier box, Sect. 3.5), on a GLO-30 slope of  $15\text{--}55^\circ$  (Sect. 2.2) that avoids flat valley floors. I also required the patch at each node to be well-lit in both scenes with no  
175 deep shadows, i.e. patch mean B04 above the 10th percentile, and sufficiently textured, i.e. patch SD above the 25th percentile, because the correlator needs texture to find a match.

I took the 68th percentile (p68) of the displacement magnitude over the control nodes for each pair and used it as the detection floor  $\sigma$ , in metres. I used p68 because it corresponds to the 68 % level, which equals one standard deviation if the errors are normal, but it is less affected by outliers like false matches. To compare pairs of different length, I divided  $2\sigma$  by  $T$ , where  $T$  is the time between the two scenes in years.

$$\text{rate floor} = 2\sigma/T. \quad (7)$$

The factor 2 corresponds to the two-sigma level. This gives about 95 % confidence, so a motion above this rate would be detected in that pair.

### 3.4 Ronti Peak pairs spanning the event

The event of the rock–ice avalanche at Ronti Peak on 7 February 2021 falls between some of the scene dates. A pair spans the event if the first scene is before and the second is after 7 February 2021. I used the scenes from 2018 to 2020, before the failure, and from 2021 to 2025, after it. These eight years of data gave 28 pairs, of which 15 span the event and 13 do not. I reported the two groups separately because the event changed the terrain far beyond the 1000 m buffer through a debris flow down the valley, so spanning pairs do not measure the correlator error alone. The floor at Ronti Peak was therefore taken from the 13 pairs that do not span the event, whereas all 28 pairs are pre-event at Langtang Lirung.

### 3.5 Validation and uncertainty

To check that the correlator detects real motion, I placed a glacier box 0.9–1.5 km east of the source at Langtang Lirung only. I compared the rate from my correlator with the ITS\_LIVE annual velocity at 120 m resolution over the same box (Gardner et al., 2025). I defined before scoring that if the glacier rate fell below  $8 \text{ m yr}^{-1}$  (prespecified threshold), no floor would be claimed. Wang et al. (2026) report a pre-failure rate of  $7.4 \text{ m yr}^{-1}$  from the outlet hanging glacier above the source before January 2026. This value was used as published, as a horizontal rate, and was not converted to downslope motion. Because horizontal motion cannot exceed downslope motion, this rate is a lower bound on the downslope rate. This rate is included for comparison with both limits (Sect. 4.4). The two range edges differ by about  $1^\circ$ , and using the other edge changes the ceilings by at most 3 % (Sect. 2.4). The modelled LIA remained within  $1^\circ$  of the published values (Sect. 2.3). The disc covers only part of the failure area (Sect. 2.2), so the ceiling describes the sampled part. If the true motion direction differs from the steepest downslope direction (Sect. 3.1),  $f$  changes.

I reported the median and the range over all pairs rather than a single value because the detection floor  $\sigma$  varies from pair to pair. The floor depends on snow and cloud in the two scenes of each pair (Sect. 2.6). This is why I screened the scenes on snow and cloud.

4.1 Ceilings

At Langtang Lirung, the descending track (relative orbit 19) has  $f=0.914$  and ceiling  $0.46\text{ m yr}^{-1}$ , whereas the ascending track (relative orbit 85) has  $f=0.153$  and ceiling  $2.77\text{ m yr}^{-1}$  (Table 2), yielding a factor of 6.0 between the two tracks at the same source. At Ronti Peak, both tracks are descending, and their ceilings are  $0.97\text{ m yr}^{-1}$  (relative orbit 63) and  $1.21\text{ m yr}^{-1}$  (relative orbit 165), a factor of only 1.25. The spread  $p90/p10$  ranges from  $1.3\times$  (Langtang Lirung descending) to  $13.6\times$  (Langtang Lirung ascending), so on the ascending track,  $f$  varies strongly across the source disc.

**Table 2. Sensitivity to downslope motion  $f$  and single-pair downslope ceiling for the four tracks at the 500 m source discs, computed as the disc median from GLO-30. The ceiling equals the line-of-sight (LOS) limit ( $0.4220\text{ m yr}^{-1}$ )  $\div f$  and spread  $p90/p10$  is the ratio of the 90th to the 10th percentile of  $f$  within the disc.**

| Site            | Pass, relative orbit | $f$ (disc median) | Ceiling ( $\text{m yr}^{-1}$ ) | Spread $f_{p90/p10}$ |
|-----------------|----------------------|-------------------|--------------------------------|----------------------|
| Langtang Lirung | Descending, 19       | 0.914             | 0.46                           | $1.3\times$          |
| Langtang Lirung | Ascending, 85        | 0.153             | 2.77                           | $13.6\times$         |
| Ronti Peak      | Descending, 63       | 0.437             | 0.97                           | $4.7\times$          |
| Ronti Peak      | Descending, 165      | 0.349             | 1.21                           | $10.0\times$         |

215 4.2 Optical detection floor at Langtang Lirung

At Langtang Lirung, the 28 pairs, all pre-event, showed a detection floor  $\sigma$  with a median of 12.47 m, ranging from 2.06 m to 38.46 m, which represents a factor of 18.7 between pairs. Dividing by  $T$  (Eq. 7), the rate floor had a median of  $5.55\text{ m yr}^{-1}$  with a range of 1.23 to  $73.36\text{ m yr}^{-1}$ . The value of  $\sigma$  increased only weakly with  $T$ , approximately as  $T^{0.25}$ , for  $T$  from 0.95 to 7.04 yr. The lowest overall rate floor was  $1.23\text{ m yr}^{-1}$  from a pair with  $T=4.05\text{ yr}$  and  $\sigma=2.50\text{ m}$ , whereas the pair with the lowest detection floor ( $\sigma=2.06\text{ m}$ ) had  $T=1.00\text{ yr}$  and a rate floor of  $4.13\text{ m yr}^{-1}$ . Each pair contained between 440 and 513 control nodes, and in the glacier box (Sect. 3.5), the correlator gave  $13.5\text{--}18.1\text{ m yr}^{-1}$  compared with  $\text{ITS\_LIVE} \approx 14.7\text{ m yr}^{-1}$ . This entire range exceeds the prespecified threshold ( $8\text{ m yr}^{-1}$ ); therefore, the floor is claimed.

4.3 Optical detection floor at Ronti Peak

At Ronti Peak, out of the 28 pairs, 15 span the event and 13 do not; the spanning pairs had a median  $\sigma$  of 91.99 m with a range of 9.74–170.75 m, whereas the non-spanning pairs had a median  $\sigma$  of 4.92 m with a range of 2.24–11.69 m. The rate floor (Eq. 7) for non-spanning pairs had a median of  $5.77\text{ m yr}^{-1}$  compared with  $54.75\text{ m yr}^{-1}$  for the spanning pairs. Two consecutive pairs had a nearly equal  $T$ ; the 2020–2021 pair spanned the event, with  $T=1.11\text{ yr}$  and  $\sigma=122.50\text{ m}$ , whereas the 2021–2022 pair did not span the event, with  $T=1.05\text{ yr}$  and  $\sigma=4.92\text{ m}$ . The non-spanning floor at Ronti Peak of  $5.77\text{ m yr}^{-1}$  was close to the  $5.55\text{ m yr}^{-1}$  measured at Langtang Lirung (Sect. 4.2). Each pair contained between 400 and 640 control nodes.

230 **4.4 Pre-failure rate**

The pre-failure rate of  $7.4 \text{ m yr}^{-1}$  (Wang et al., 2026; Sect. 3.5) exceeds both Langtang Lirung ceilings, 16 times the descending ceiling ( $0.46 \text{ m yr}^{-1}$ ) and 2.7 times the ascending ceiling ( $2.77 \text{ m yr}^{-1}$ ). Against the optical floor (Sect. 4.2), the  $7.4 \text{ m yr}^{-1}$  rate is above the median rate floor of  $5.55 \text{ m yr}^{-1}$ , and 18 of the 28 pairs have a rate floor below  $7.4 \text{ m yr}^{-1}$ . At the same source, the radar ceilings are  $0.46\text{--}2.77 \text{ m yr}^{-1}$  and the optical median floor is  $5.55 \text{ m yr}^{-1}$ , so the optical floor lies above both radar ceilings

235 (Fig. 1).

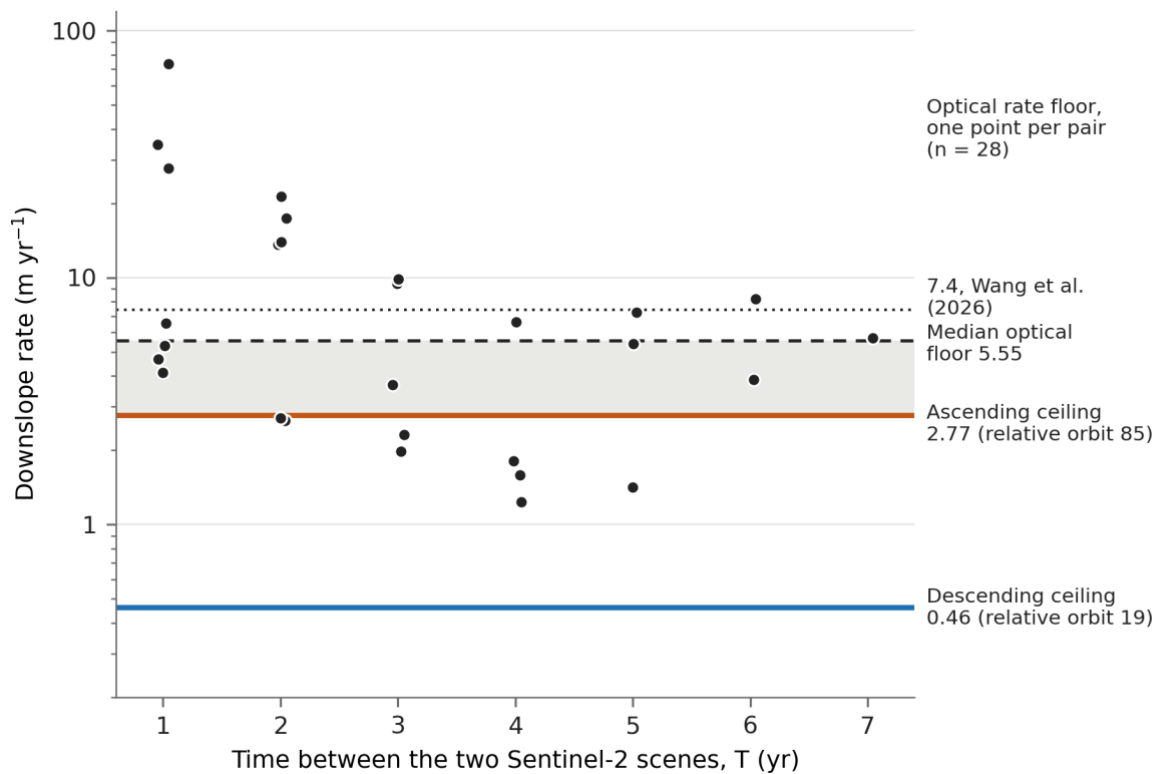


Figure 1. Single-pair detection limits at Langtang Lirung, with the descending ceiling shown as a blue line and the ascending ceiling shown as an orange line ( $0.46$  and  $2.77 \text{ m yr}^{-1}$ ; Table 2). Each Sentinel-2 pair ( $n = 28$ ) is shown as a point, with the optical rate floor for each pair calculated using Eq. (7). The median optical floor ( $5.55 \text{ m yr}^{-1}$ ) is shown as a dashed line. The pre-failure rate ( $7.4 \text{ m yr}^{-1}$ ) from Wang et al. (2026) is shown as a dotted line. The shaded region is between the ascending ceiling ( $2.77 \text{ m yr}^{-1}$ ) and the median optical floor ( $5.55 \text{ m yr}^{-1}$ ). The vertical axis is on a logarithmic scale in  $\text{m yr}^{-1}$ , and the horizontal axis ( $T$ ) on a linear scale in years.

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## 5 Discussion

### 5.1 Viewing geometry and the ceiling

245 All four tracks share the same wavelength and the same LOS limit of  $0.42 \text{ m yr}^{-1}$ . Yet at Langtang Lirung, on the same source, the ceiling of the ascending track ( $2.77 \text{ m yr}^{-1}$ ) differs from that of the descending track ( $0.46 \text{ m yr}^{-1}$ ) by a factor of 6.0. The only difference is  $f$ , which depends on the LIA and on the look direction relative to the slope aspect. At Ronti Peak, by contrast, both tracks are descending, share the same look azimuth of  $280.9^\circ$  and differ only in  $\theta$  ( $34^\circ$  and  $46^\circ$ ), so their ceilings differ by a factor of only 1.25.

250 On the ascending track, the LIA is about  $22^\circ$ , close to normal incidence, and  $f = 0.153$ , so only about 15 % of the downslope motion reaches the LOS. As a result, slow downslope motion produces only a small phase signal, which is harder to separate from noise. In addition, the spread of  $f$  is  $13.6\times$  on the ascending track against  $1.3\times$  on the descending track, so  $f$  is uneven across a single disc.

Sah (2026b) reported that the ascending track covered 100 % of the disc and had about four times the variance of the descending track, but missed the collapse ( $z = -0.52$ ), whereas the descending track registered it ( $z = +3.43$ ). However, that test used coherence (decorrelation), and  $f$  describes phase sensitivity to slow motion. These are two different quantities. The wide spread of  $f$ , which reflects the uneven geometry across the disc, may contribute to the higher variance, but this is not tested here.

### 5.2 Radar and optical detection limits

Radar single-pair ceilings at Langtang Lirung are  $0.46\text{--}2.77 \text{ m yr}^{-1}$ , whereas the optical median rate floor at the same source is  $5.55 \text{ m yr}^{-1}$  and its lowest pair floor is  $1.23 \text{ m yr}^{-1}$ . Between  $2.77$  and  $5.55 \text{ m yr}^{-1}$ , neither the radar pairs nor the median optical pair can measure the motion (Fig. 1). The rate of  $7.4 \text{ m yr}^{-1}$  (Wang et al., 2026) is above both radar ceilings, so a single 12-day radar pair cannot detect it. The  $7.4 \text{ m yr}^{-1}$  rate is above the median optical floor ( $5.55 \text{ m yr}^{-1}$ ), and 18 of 28 pairs have a floor below it, so the motion is large enough for most optical pairs to detect. Wang et al. (2026) measured on the outlet hanging glacier, on ice, not on the rock disc, and they used many images over a long span, which reduces noise, whereas I used one pair at a time on the rock face. The rock disc and ice may move at different rates, so the glacier rate may not equal the rate of the rock source. Therefore, the comparison between the rate of Wang et al. (2026) and my limits (ceilings and floor) is indirect.

### 5.3 Control node stability and pair selection

The control nodes should be on stable ground where true movement is zero, so everything measured there is error. However, at Ronti Peak on 7 February 2021, the event changed the terrain far beyond the 1000 m buffer, so the ground at the control nodes was no longer stable. This means the high  $\sigma$  of the spanning pairs reflects surface change. The two neighbouring pairs, 2020–2021 and 2021–2022, have almost the same  $T$ , and both use the same 27 November 2021 scene. Yet  $\sigma$  is 122.50 m for 2020–2021, whereas for 2021–2022 it drops to 4.92 m. Because the later pair is accurate, the 2021 scene was good, meaning

the event itself caused the large  $\sigma$ . Therefore, the pairs that cross a failure cannot be used to calculate the rate floor. Instead, I  
275 used non-spanning pairs. Once the spanning pairs are excluded, Ronti Peak's non-spanning floor ( $5.77 \text{ m yr}^{-1}$ ) is close to  
Langtang Lirung's ( $5.55 \text{ m yr}^{-1}$ ).

#### 5.4 Seismic and radar monitoring at Langtang Lirung

As reported by Adhikari et al. (2026), the failure at Langtang Lirung on 26 August 2026 at 02:52:16 UTC had a volume of  
about  $10^2 \text{ Mm}^3$ , mostly rock. They also reported that the last small event of  $M_L 2.5$  occurred about 17 min before the failure  
280 and there were more than 60 small events in the preceding two weeks, possibly slide-quakes. The radar saw the slope once  
every 12 days, and the last product was 50.6 h before the failure (Sah, 2026c), so the  $M_L 2.5$  event (17 min before) and anything  
in the final two days happened after the radar's last acquisition. The seismometers record ground vibrations (seismic waves),  
whereas radar interferometry sees LOS surface motion. If the rate exceeded the ceiling in the final days, a single 12-day pair  
could not capture it. This suggests that radar sees motion below its ceiling ( $0.46\text{--}2.77 \text{ m yr}^{-1}$ ), whereas seismometers may  
285 detect short-term activity before the failure.

#### 5.5 Limitations

The sensitivity to downslope motion  $f$  assumes motion parallel to the surface in the steepest downslope direction; no motion  
direction was measured (Sect. 3.1). Meena (2026), using NISAR L-band pixel offsets, measured a mean horizontal motion  
direction at the crown towards  $278^\circ$ , close to my disc aspect of  $280.5^\circ$  and  $280.8^\circ$  in Li (2026). This agreement partly supports  
290 the assumption behind  $f$  (that motion is in the steepest downslope direction), although Meena (2026) assumed zero vertical  
motion and the displacement was not statistically significant. If the true motion were not straight downslope (for example, a  
wedge sliding along a different direction), the ascending track's ceiling would change the most. Because the factor  $f = 0.153$   
is small, a minor shift in the real motion (azimuth or plunge) can cause a large change in sensitivity  $f$ , and therefore a large  
change in the ceiling. By contrast, the descending track's factor is near unity ( $f = 0.914$ ). A small change in motion direction  
295 has a small effect on a value that is already near 1, keeping the descending ceiling stable. That is why the descending ceiling  
( $0.46 \text{ m yr}^{-1}$ ) is the least affected. My disc centre was an initial working estimate covering only part of the failure area ( $0.79$   
 $\text{km}^2$  versus Li's  $1.009 \text{ km}^2$  source). Evaluating the original centre, Li's centroid, and Wang's collapse point reveals a ratio  
between tracks of  $4.5\text{--}5.9$  across the three positions. This result confirms that the descending track has the lowest ceiling in  
each case. The descending track's  $f$  values are stable, varying by  $1.3\times$  within the disc, while the ascending track's  $f$  values vary  
300 by  $13.6\times$ . This difference suggests that the descending track's median ceiling is more reliable.

The optical detection floor was measured on stable ground at least 1000 m from the source (Sect. 3.3), not on the source itself.  
This means the real floor at the source would likely be higher due to the presence of snow, ice, and steep shadowed faces. One  
scene per year was selected during the clearer autumn months (15 October to 20 December) when snow cover at Langtang  
Lirung was limited to  $19.5\text{--}29.3 \%$ . Because the best scene of each year was chosen, the floor is a best-case value, and scenes  
305 from other seasons would give a higher floor. At Ronti Peak, there was no positive control, and the study used only 13 non-

spanning pairs, leaving the 5.77 m yr<sup>-1</sup> floor estimate uncertain. Finally, the scope was limited to testing single pairs, leaving multi-pair methods, time-series stacking, and multi-image inversions as the necessary next steps. Because the radar ceilings ( $\leq 2.77$  m yr<sup>-1</sup>) sit below the optical floor (5.55 m yr<sup>-1</sup>), a higher real floor at the source would widen the gap. This shows that the conclusion of my study survives.

310 **6 Conclusions**

This study shows that the radar line-of-sight (LOS) limit remains identical at 0.42 m yr<sup>-1</sup> for all tracks, whereas the real downslope ceiling depends on the track’s viewing geometry. At Langtang Lirung, the descending and ascending ceilings are 0.46 and 2.77 m yr<sup>-1</sup> (a factor of 6.0), whereas at Ronti Peak they are 0.97 and 1.21 m yr<sup>-1</sup> (a factor of 1.25). This result also survives moving the disc centre: the ratio between tracks is 4.5–5.9, and the descending track remains the lowest in all three  
 315 positions. The optical floor stands at a median of 5.55 m yr<sup>-1</sup> for Langtang Lirung and 5.77 m yr<sup>-1</sup> for Ronti Peak. Pairs spanning an event cannot measure the floor. Instead, non-spanning pairs should be used to measure the rate floor. Between 2.77 and 5.55 m yr<sup>-1</sup>, neither the radar pairs nor the median optical pair can measure motion. Therefore, one must choose tracks based on geometry and also report the ceiling for each track. Finally, monitoring programmes should combine both radar and optical datasets. Future work should focus on multi-pair methods, measured motion direction, and testing at more sites.

320 **Appendix A**

**Table A1. Sentinel-2 scenes selected for each site, one per year from 2018 to 2025. Snow and cloud are given as percentages of a 6 km × 6 km box centred on each source; in the SCL, snow is class 11, and cloud classes are 3, 8, 9 and 10 (cloud shadow and cloud). In each year, the scene with the lowest snow % + 2 × cloud % was kept. At Ronti Peak, a cap of 5 % cloud over the box was also applied.**

| Site            | Year | Acquisition date | Snow over box (%) | Cloud over box (%) | Sentinel-2 granule       |
|-----------------|------|------------------|-------------------|--------------------|--------------------------|
| Langtang Lirung | 2018 | 4 Dec 2018       | 21.8              | 0.0                | S2B_45RUM_20181204_1_L2A |
| Langtang Lirung | 2019 | 9 Dec 2019       | 25.8              | 0.0                | S2B_45RUM_20191209_1_L2A |
| Langtang Lirung | 2020 | 18 Dec 2020      | 19.5              | 0.0                | S2A_45RUM_20201218_1_L2A |
| Langtang Lirung | 2021 | 1 Dec 2021       | 28.8              | 0.0                | S2B_45RUM_20211201_1_L2A |
| Langtang Lirung | 2022 | 18 Dec 2022      | 27.5              | 0.0                | S2A_45RUM_20221218_0_L2A |

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|                    |      |             |      |     |                          |
|--------------------|------|-------------|------|-----|--------------------------|
| Langtang<br>Lirung | 2023 | 3 Dec 2023  | 28.9 | 0.0 | S2A_45RUM_20231203_0_L2A |
| Langtang<br>Lirung | 2024 | 20 Dec 2024 | 21.8 | 0.0 | S2A_45RUM_20241220_0_L2A |
| Langtang<br>Lirung | 2025 | 20 Dec 2025 | 29.3 | 0.0 | S2B_45RUM_20251220_0_L2A |
| Ronti Peak         | 2018 | 19 Oct 2018 | 40.4 | 4.2 | S2A_44RLU_20181019_1_L2A |
| Ronti Peak         | 2019 | 24 Oct 2019 | 43.5 | 0.3 | S2A_44RLU_20191024_1_L2A |
| Ronti Peak         | 2020 | 18 Oct 2020 | 18.7 | 0.0 | S2A_44RLU_20201018_1_L2A |
| Ronti Peak         | 2021 | 27 Nov 2021 | 49.8 | 0.3 | S2B_44RLU_20211127_1_L2A |
| Ronti Peak         | 2022 | 17 Dec 2022 | 42.5 | 0.0 | S2A_44RLU_20221217_0_L2A |
| Ronti Peak         | 2023 | 17 Dec 2023 | 44.1 | 0.1 | S2B_44RLU_20231217_0_L2A |
| Ronti Peak         | 2024 | 6 Dec 2024  | 13.9 | 0.0 | S2C_44RLU_20241206_1_L2A |
| Ronti Peak         | 2025 | 16 Dec 2025 | 21.4 | 0.0 | S2B_44RLU_20251216_0_L2A |

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**Code and data availability**

The scripts named in the Acknowledgements are available on Zenodo at <https://doi.org/10.5281/zenodo.23299807> (version 6.1.1; Sah, 2026a) under a CC BY 4.0 licence. HyP3 incidence maps from Sentinel-1 were obtained from ASF (Hogenson et al., 2020). Sentinel-2 L2A files are freely available from the public sentinel-cogs archive (AWS Open Data; Element 84, 2023), and the Copernicus GLO-30 DEM is freely available from Copernicus (European Space Agency and Airbus, 2022). Contains modified Copernicus Sentinel data 2017–2026.

**Author contributions**

AKS conceived the study and was responsible for developing the methodology, data processing, analysis, verification, interpretation, and writing the manuscript.

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**Competing interests**

The author declares that he has no competing interests.

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