Evaluation of Different Methods for Debris Flow Velocity Measurements at the Lattenbach Creek

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The Lattenbach creek, District of Landeck, Tyrol, is a very active torrent located in a geologic fault zone in the western part of Austria. The channel separates the Northern Limestone Alps in the North from the Crystalline Alps in the South. Aside from the regular flood events with bedload transport, the torrent produced seven debris flows and three debris floods within recent years. Due to the frequent debris flow and debris flood events the torrent is monitored by the Institute of Mountain Risk Engineering since several years. The parameters that are currently measured during an event include meteorological data in the upper part of the catchment and run-off data from the middle and lower reach of the torrent at the villages Grins and Pians. In the last years the monitoring equipment has been constantly improved. Additional to the standard sensors like radar for water level measurements, seismic sensors for ground motion detection and infrasound sensors for acoustic wave identification, a high frequency Pulse Doppler Radar has been installed, which provides the opportunity to measure the instantaneous surface velocity of a debris flow in different range gates. Together with a recently installed 2D-Laser scanner this setup provides the possibility to determine a very precise approximation of the discharge with a high temporal resolution. On this basis different methods to determine the velocity of debris flows were applied and compared. The results show, that the applied concept to record data of debris flows in a high temporal resolution seems to be promising.

Key words: Debris flow, monitoring, surface velocity, surge velocity, Lattenbach

1. INTRODUCTION

The Lattenbach creek, District of Landeck, Tyrol is a very active torrent located in a geologic fault zone in the western part of Austria. Due to the frequent debris flow and debris flood events the torrent is monitored by the Institute of Mountain Risk Engineering for several years. The parameters that are currently measured during an event include meteorological data in the upper part of the catchment (station Dawinalpe) and flow depth, flow surface topography, ground movement and velocities in the middle reach of the torrent.

To get a debris flow hydrograph typically data of channel geometry, flow depth and velocity, derived by time-distance method or particle image velocimetry, are used. To facilitate the calculation of an instantaneous debris flow hydrograph, velocity data collected by a High Frequency Radar utilizising the Doppler effect [*Hübl et al.*, 2017], are applied.

For the September, 16th 2016 debris flow at Lattenbach, these velocities are than compared with velocity estimates by the time-distance method, using either flow height or seismic signals as input.

2. LATTENBACH CATCHMENT

The watershed of the Lattenbach torrent has a catchment area of 5.3 km² and is located westwards the city of Landeck, Austria. The Lattenbach feeds the river Sanna, which is a tributary to the river Inn. The upper limits of the watershed is at around 2900 m above sea level (asl.), the outlet at 840 m asl. Both, the village Grins in the middle reach of the channel and the village Pians at the fan of the catchment, are affected by debris floods and debris flows [*Arai et al.*, 2013].

Geologically the catchment is divided into a northern part, Northern Limestone Alps, and a southern part, Crystalline Alps. The tectonic transition between these geologic units is marked by the incised channel of the Lattenbach. Due to intense mechanical loading of the rock and often unfavorable bedding of the strata parallel to the hillslope numerous mass movements have led to an unlimited debris potential for mass wasting processes. Hence sediment transport processes are supposed to be limited by the availability of a transporting media rather than by the availability of erodible debris.

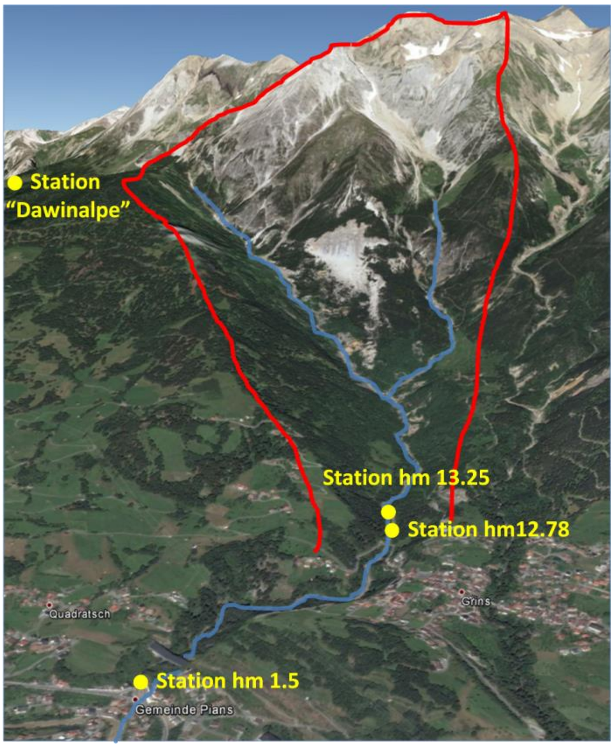

Fig. 1 Catchment Lattenbach and location of the monitoring sites (modified from Google earth, Image©2018DigitalGlobe).

Severe events of debris flows and debris floods are reported in the years 1911, 1912, 1925, 1944, 1949, 1965, 1966, 1973 and 1998, 2005, 2007, 2010, 2015, 2016 and 2017. Analyzing the chronicle, the most probable triggers resulted from short-duration thunderstorms.

Following these major events, structural mitigation measures were continuously constructed along the channel. Since 1908, approximately twenty check dams were built to stabilize the channel bed and to consolidate the slopes. However, until today a considerable number of them had already been destroyed, in particular those situated in the middle reaches of the catchment.

3. MONITORING CONCEPT

The recent monitoring concept is the result of about 10 years of experience. It consists of two sites, one at the apex of the fan at hm 1.5 and one in the middle reach of the torrent (**Fig. 1**) with two stations at hectometer (hm) 12.78 and 13.25. Additionally a meteorological station was set up in the headwater (Dawinalpe).

The discharge in the middle reach is calculated by the measurement of cross-section area and flow velocity with a frequency of 1 Hz. Therefore, three radar sensors for continuous level measurement, a 2D-laser scanner and a High Frequency Radar were chosen to collect the data (**Fig. 2**).

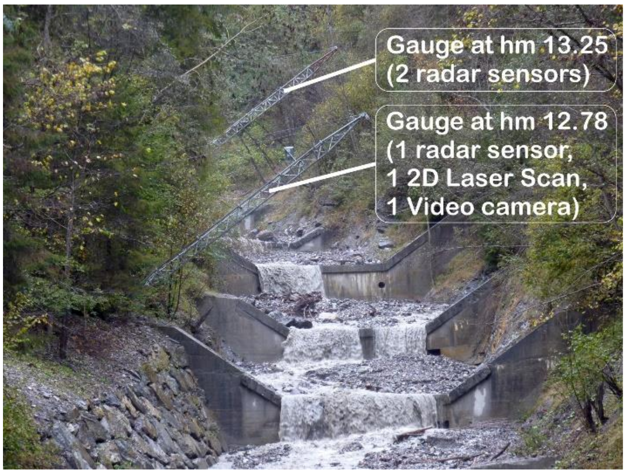

Fig. 2 Monitoring site "Grins" in the middle reach of Lattenbach, consisting of two single steel supports made of Garaventa elements with mounted sensors.

4. VELOCITY ESTIMATION

To demonstrate the velocity calculation by different methods the debris flow on September 10th, 2016 is used. This debris flow with a duration of one hour consisted of about 50 surges, most of them lasting only a few seconds. Obviously the velocities varied according to the surges and the times in-between.

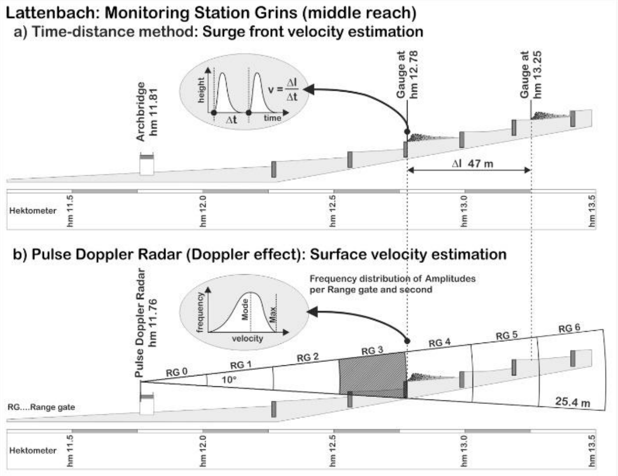

Fig. 3 Velocity estimation concepts for debris flows

4.1 Instantaneous velocity estimation by Radar signal

All radar technologies have in common to get information about distant objects by using electromagnetic waves. The behavior of electromagnetic waves between the transmitter, target and receiver is determined by the laws of wave propagation and strongly depends on the frequency. The used frequency range is from 1 MHz to 100 GHz. Roughly speaking, a low frequency means large wavelength (long antenna needed), has a long range, because of the low atmospheric attenuation and has a poor resolution. High frequency means the opposite. The choice of suitable frequency is determined by these properties on the one hand and on the other hand by the available technology for active and passive components. Additional to that, a frequency range for the operation of the radar must be requested from the public administration office.

The basis for all applications is the radar equation, which establishes a relationship between the specifications of a system and its detection range. To monitor torrential hazards, landslides, rock fall and snow avalanches the detection range should be up to 2 km with a distance resolution of some tens of meters, the temporal resolution should cover the expected speed range from 1 to 100 m/s and the minimal target size to be detected should be about one square meter. The radar should work in any weather conditions at any time continuously with a low power consumption to ensure autonomous energy supply.

A high-frequency signal in the X-band (10.425 GHz) is pulse-modulated in a high-frequency switch, amplified to an output power of about 1 W and radiated from a parabolic antenna to the detection area. The reflected beam from the observed area returns to the antenna and is recorded by the receiver. If an object is moving within the detection area with the velocity v, the reflected signal will experience a frequency shift (Doppler effect). The frequency shift of the reflected radar signal is proportional to the velocity of the moving object. It is positive for approaching objects and negative for objects veering away. The velocity of the moving object can thus be determined via frequency analyses of the reflected radar beam. The resulting velocity spectrum has well defined peaks for compact objects with a single speed and becomes broad banded for avalanches or debris flows where many objects are moving at different speeds. The detection area is devided in so called range gates. For each of these the radar cross section the intensity is measured.

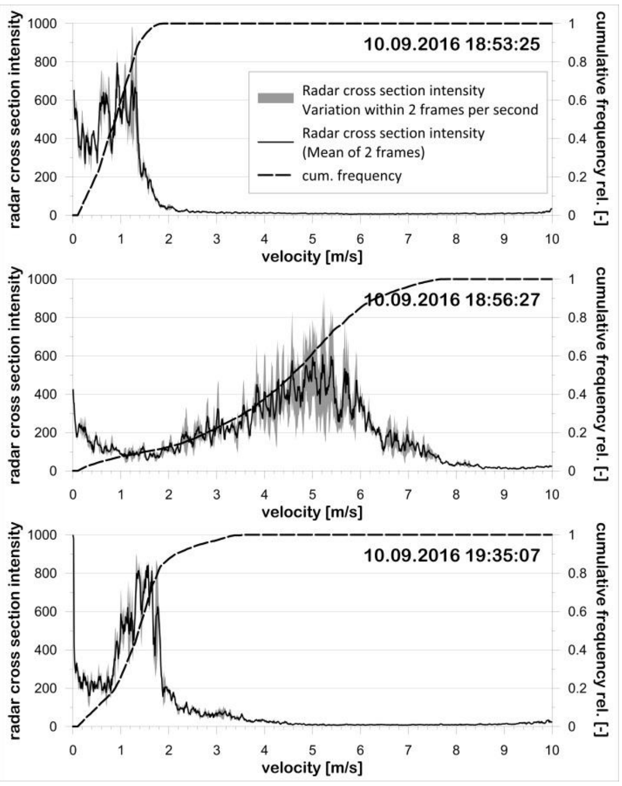

Fig. 4 Typical velocity spectrums of a debris flow surge at different times

The best type of Radar to meet all the above criteria is the Doppler Pulse Compression Radar. The selected radar system was developed by “H&S Hochfrequenztechnik” and already successfully tested for snow avalanches in Sedrun/Switzerland [*Lussi et al.*, 2012] and in Ischgl/Austria [*Kogelnig et al.*, 2012]. The maximum range for detecting moving objects with a cross-section of 1 m² in heavy weather condition (rain/snow) is about 2 km. The range gate length is adjustable between 15 m and 250 m and the detectible velocity ranges from 1 to 300 km/h. The adaption to debris flows was made within the Austrian Research Promotion Agency project (2012-2014) “Automatische Detektion alpiner Massenbewegungen mittels Hochfrequenz Radartechnik: Naturgefahren-Radar” [*Hübl et al.*, 2012].

The aperture of the antenna is 10° with the beam orientation almost parallel to the channel gradient in order to illuminate the maximum range of the slope and to get as many range gates as possible. The space-resolution is equal to the range gate length and therefore a linear function of the duration time of the pulses. The duration time itself influences the signal to noise ratio of the data in such a degree, that the longer the duration time is, the better the signal to noise ratio will be. The pulse repetition frequency of the radar device is up to 90 kHz, resulting in 90,000 pulses per second, giving about 2 frames per second for the analysis.

Within the monitoring area between hm 11.76 and 13.5 seven range gates with a range gate length of 25.4 m give a maximum range of about 175 m. The first two range gates (0, 1) are “blind” gates in air. The radar beam hits the channel in the 3rd range gate, in a distance between 75 and 100 m from the radar (**Fig. 3**). A total of 5 range gates (3-6) provide information of the flow velocity spectrum with a sampling rate of 2 Hz. The radar cross section intensities correspond to the moving objects in each of the velocity classes of 0.01 m/s width. The assumption of this method is, that during a surge the reflectivity of all moving objects does not change and corresponds to the reflectivity of water. This assumption is valid as long as the moving objects are larger with respect to the wavelength of 3 cm. The two spectrums per second are averaged and stored as one spectrum per second (**Fig.4**).

From this averaged velocity spectrum the most frequent value of the radar intensity is considered as average flow surface velocity (v.mod) in the cross-section per second. The maximum velocity of the spectrum is identified as the velocity value, when the radar cross-section intensity falls below 50 (v.max). **Fig. 4** shows the velocity distribution in range gate 3 just before, during and in the recession time of a debris flow surge.

With this method the temporal evolution of surface velocities in the different range gates can be calculated. The relative frequency of the velocities (v.mode and v.max) show a different pattern in the range gates 3 to 4 (**Fig. 5, right**). This may be due to the longitudinal profile of the monitoring sections, because the channel gradient is modified by a series of checkdams, causing a variation of the debris flow velocity inside the range gate.

4.2 Time distance method – flow height

The velocity of a debris flow surge front can be calculated with the elapsed time of the steep increase of the flow height of a surge between two nearby gauging stations. The distance between these sites divided by this timespan yields the velocity of the surge (**Fig. 3**). The recording interval for the flow height was two Hertz. This means, the flow height is recorded each 5 meter if the surge velocity is 10 m/s or each 2.5 meter if the surge velocity is 5 m/s. The onset of clearly identified surges was digitized for the gauging stations at hm 13.25 and 12.78 respectively. The estimated front velocities with this method range from 4 to 11 m/s.

4.3 Time distance method – seismic signal

This method of estimation of the front velocity uses the signals of two installed stations along the channel, recording infrasound and seismic data, whereby one station is located at hm 12.78, and the second station is installed around 90 m upstream

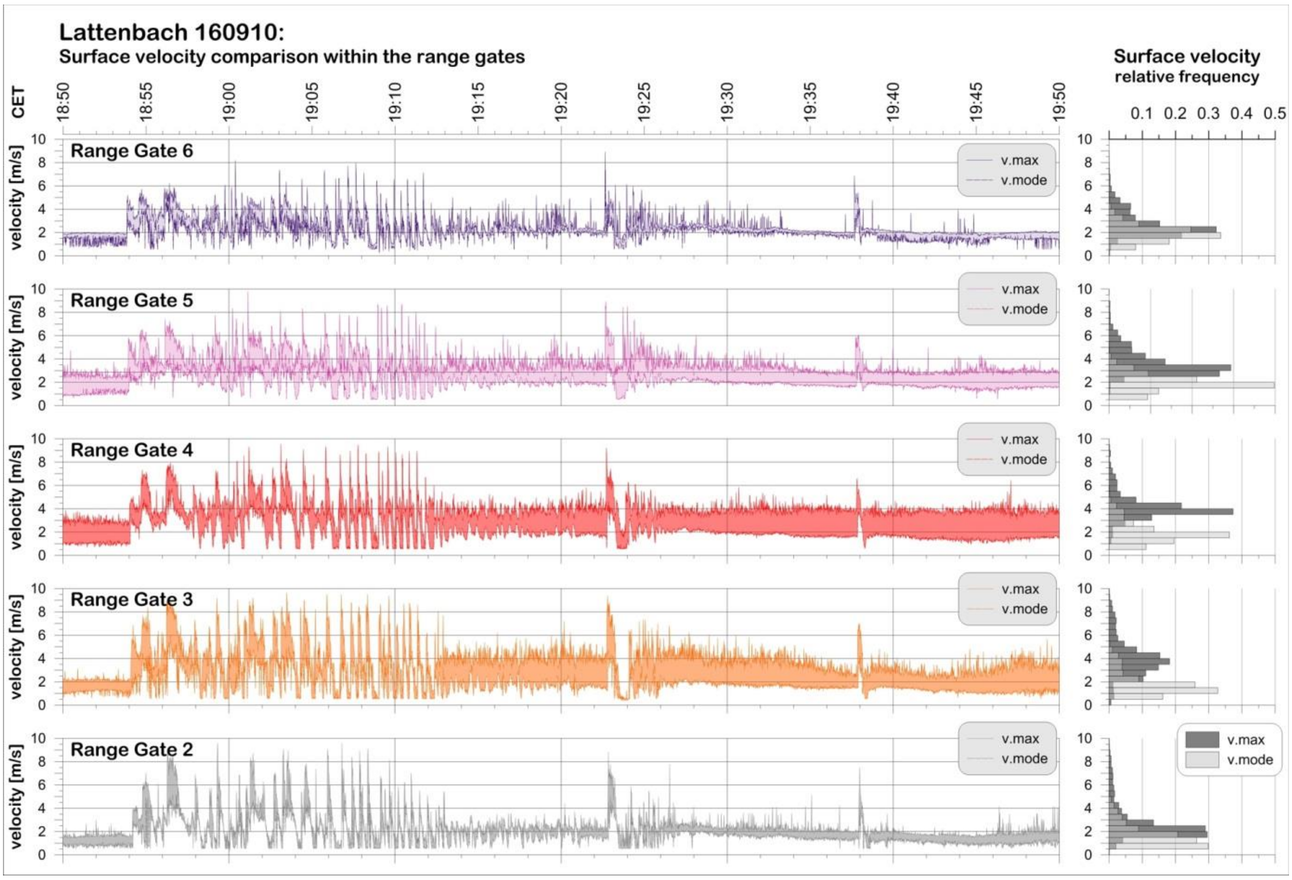

Fig. 5 Surface velocity distribution in the observed range gates (v.max means maximal velocity, v.mode stands for the most frequent velocity in the range gate)

[*Schimmel et al.*, 2016]. For the velocity estimation only the seismic signals are used, since they have a smoother signal sequence than the infrasound signal. The signal progression of the average amplitudes in a 10 to 30 Hz band (which is calculated by fast Fourier transform for every second) has been used to identify the different surges and calculate the time difference between the upper and the lower station. The estimated front velocities derived from seismic signals range from 4 to 11 m/s.

4.4 Particle image velocimetry

Large-scale particle image velocimetry (LSPIV) is a video imagery technique often used in rivers to measure two dimensional velocities from high-resolution images at high frame rates [e.g. *Fujita et al.*, 1998; *Hauet et al.*, 2008; *Le Coz et al.*, 2010; *Muste et al.*, 2014]. Therefore bubbles, ice, debris, and artificial seeding are tracked and cross-correlations are made between time-step imagery within a given search window.

This method can also be used to determine the surface velocity of debris flows [*Theule et al.*, 2018], by tracking specific features of these processes (e.g. fast stage variations or boulders on the flow surface). Because of the poor conditions of illumination the recorded video sequences of the event could not be used for this kind of analysis.

5. RESULTS

The whole debris flow consists of about 50 surges. Each debris flow surge starts with a rapid increase of flow height followed by a recession of several seconds. The largest peaks can be found at the frontal part of the event and again after half an hour. The surface velocities go in phase with flow height (**Fig. 6**). The instantaneous maximum velocity characterizes the surge front velocity. Therefore these measured values can be compared with the velocities derived by the time-distance method (**Fig. 7, 8**).

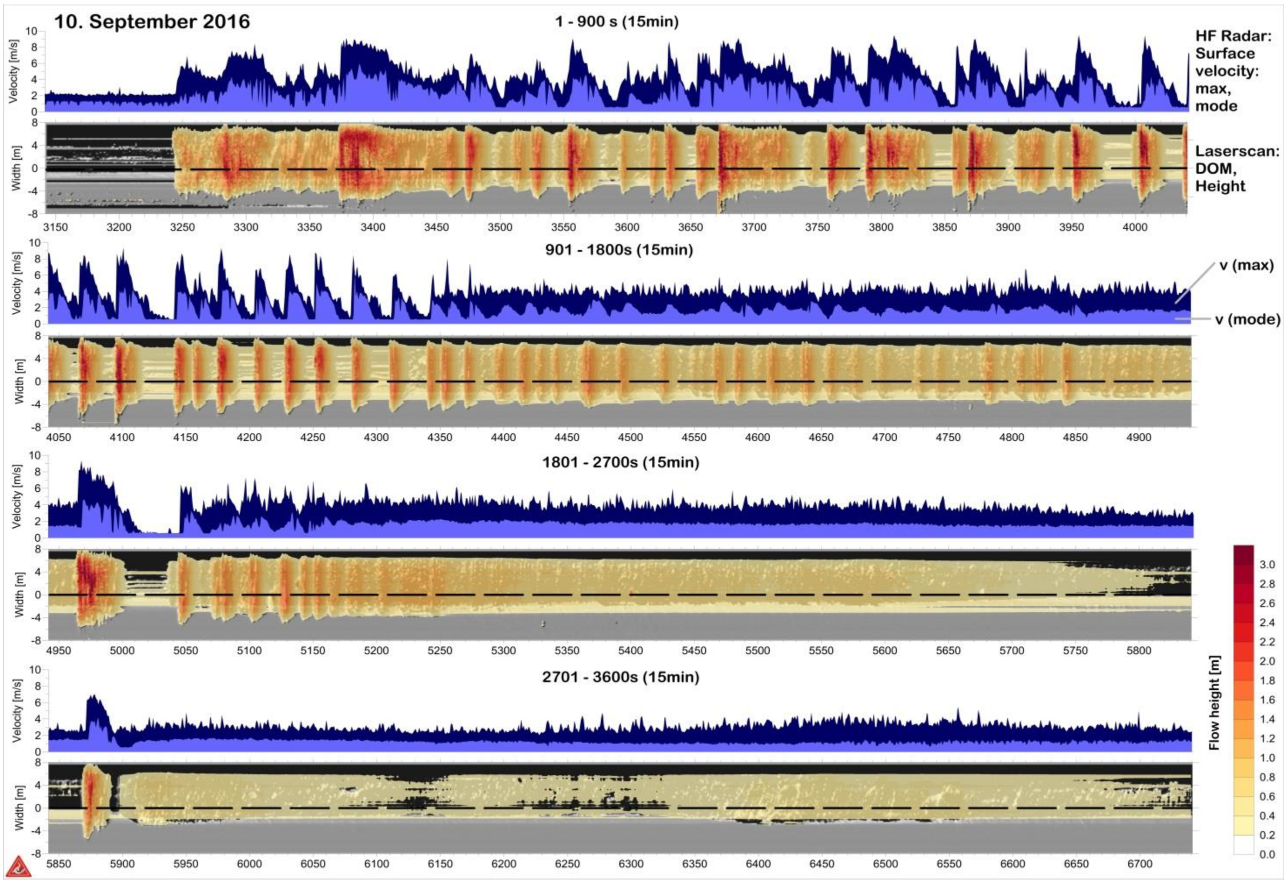

Fig. 6 Surface velocity distribution for the 10.09.2016 debris flow (v.max means maximal velocity, v.mode stands for the most frequent velocity in the range gate) in addition to the recorded flow heights by the 2D Laserscanner; sampling rate: 1 Hz

The peak velocities of the time-distance methods are in the range of 9 to 11 m/s, whereas the surge velocities of smaller ones range from 5 to 7 m/s, independent of the used variable flow height or seismic signal. Although the maximum surge front velocities derived from the radar signal is below 9 m/s, the comparison shows a maximum difference either to the flow height or seismic signal based surge front velocities of less than 1 m/s.

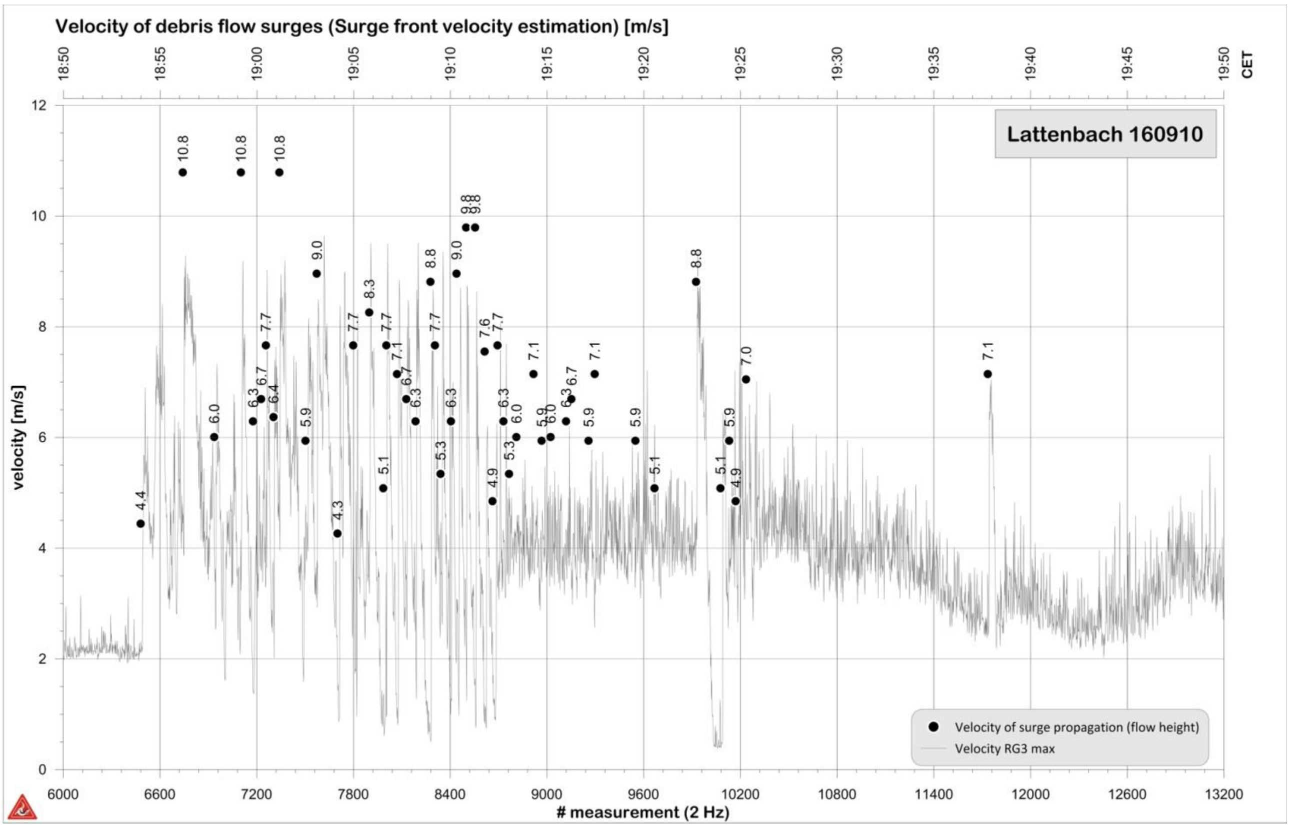

Fig. 7 Surge front velocities calculated by the time-distance method using the flow height as variable in comparison to instantaneous velocity measurement at hm 12.78 applying the maximum velocity

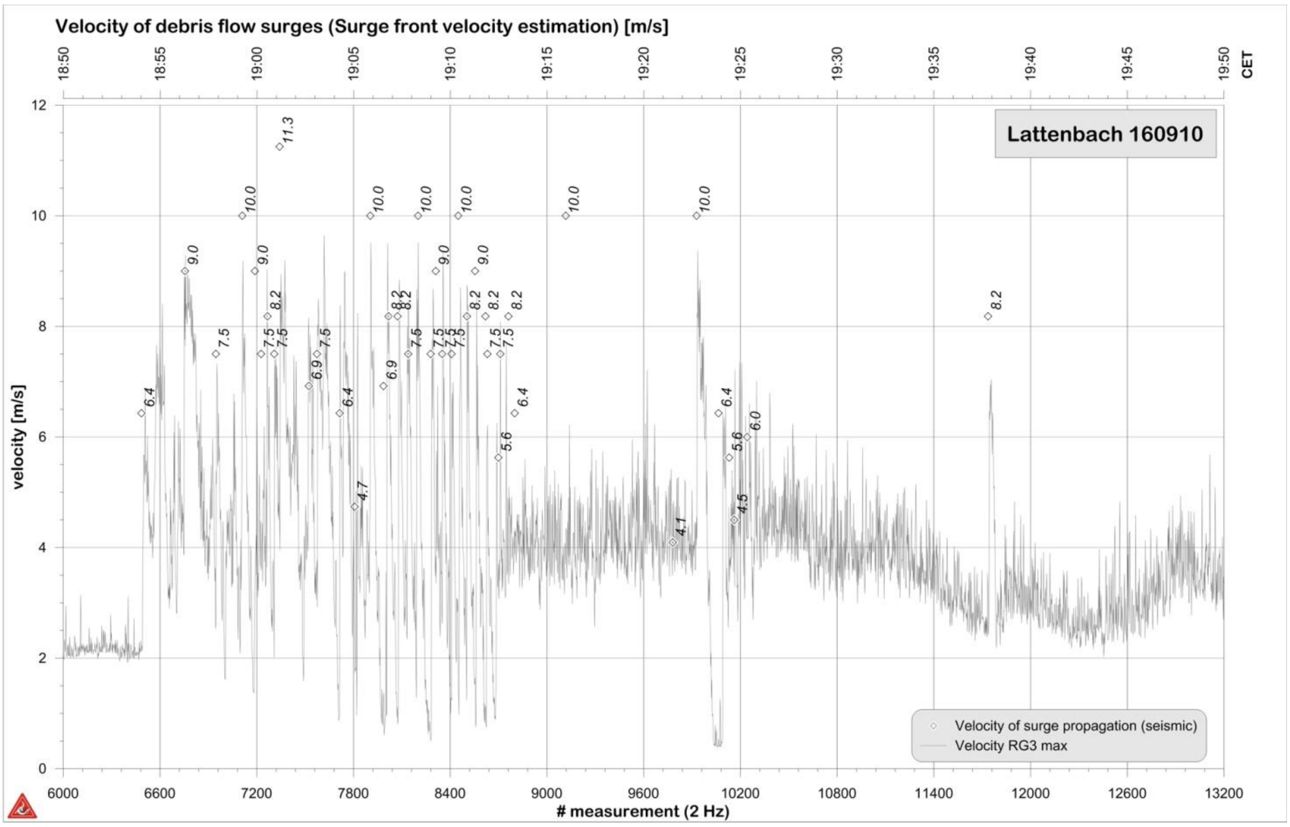

Fig. 8 Surge front velocities calculated by the time-distance method using the seismic signal as variable in comparison to instantaneous velocity measurement at hm 12.78 applying the maximum velocity

6. CONCLUSION

The debris flow velocity estimation using high-frequency radar seems to be a practical way to directly estimate velocities and discharges, but there is still some effort needed to define the proper statistical parameters of the surface velocity distribution. The measured maximum velocity may produce the best result for the surge front velocity and may therefore be used for impact calculations, whereas the most frequent velocity of the measured velocity spectrum may contribute to the instantaneous discharge estimation of a debris flow.

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