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Automated monitoring of subglacial hydrological processes with ground-penetrating radar (GPR) at high temporal resolution: scope and potential pitfalls

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[1] We demonstrate that automated GPR techniques can monitor, at repeat timescales of minutes, hydrological processes beneath glaciers experiencing perennial surface melting. At Grubengletscher, Swiss Alps, melt penetrates into porous near-surface ice during the day, modifying the transmitted radar energy and thus the amplitudes of the targeted subglacial reflections. Normalising these reflections by early-time radar arrivals, integrated over a suitable time window, minimises such artefacts. In mid afternoon peak surface ablation, a diagnostic pulse in englacial reflectivity, sharp increases in subglacial reflectivity and glacier surface uplift precede the onset of transient glacier acceleration. Sliding terminates as the glacier surface lowers and the magnitude of subglacial reflectivity decreases. We infer a prominent episode of basal sliding as subglacial water pressure rises rapidly in response to englacially-routed melt delivery, jacking the glacier off its bed and modifying the observed reflectivity. Quantification of such processes is pertinent for any measurement and interpretation of basal reflection strength or bed reflection power from a GPR dataset. **Citation:** Kulessa, B., A. D. Booth, A. Hobbs, and A. L. Hubbard (2008), Automated monitoring of subglacial hydrological processes with ground-penetrating radar (GPR) at high temporal resolution: scope and potential pitfalls, *Geophys. Res. Lett.*, *35*, L24502, doi:10.1029/2008GL035855.

1. Introduction

[2] The development of automated geophysical techniques for monitoring subglacial hydrological processes at high temporal resolution (e.g. sub-hourly) is a current research priority, as an understanding of the movement of subglacial water, and its impact on ice mass dynamics, is required. Ground-penetrating radar (GPR) is well established as a glaciological tool for the study of the basal environment. Recent reviews by *Woodward and Burke* [2007] and *Bingham and Siegert* [2007], and references therein, have highlighted specifically how the concepts of basal reflection strength (BRS) and bed reflection power (BRP) facilitate detection and delineation of discrete subglacial water bodies and potentially hydrologically active areas of the glacier bed; and, particularly relevant to the present study, how repeat radar profiling can be used to characterise englacial and subglacial hydrological processes. Previous repeat studies typically considered timescales ranging between once a day and a few years, although in one study up to three repeat measurements during individual days could be correlated with changes in glacier velocity, basal water pressure and surface melt rate [*Jacobel and Raymond*, 1984]. Notwithstanding, we appreciate that subglacial hydrological and mechanical processes can change much more rapidly and sometimes abruptly [*Nolan and Echelmeyer*, 1999; *Kavanaugh and Clarke*, 2001; *Mair et al.*, 2003; *Das et al.*, 2008], with significant impact on ice dynamics. This requires development of geophysical monitoring technologies capable of data acquisition at minute-scale temporal resolution that should ideally be automated for reliability and convenience. Specifically in the case of GPR a particular challenge arises since many ice masses experience significant and diurnally variable surface melting, modifying the radar signal in the very near surface.

[3] Based on a case study at the Grubengletscher, Swiss Alps, we address the question ‘Is it possible to monitor hydrological processes beneath glaciers experiencing strong perennial surface melting with automated GPR techniques and on repeat timescales of a few minutes?’, and identify and assess potential pitfalls inherent in GPR monitoring of such processes beneath Alpine and Polar ice masses.

2. Field Site and Methodology

[4] The GPR and GPS monitoring data reported here were collected between 0900 h and 1840 h on August 1st, 2007, in the lower ablation zone of the Grubengletscher, Valais, Switzerland. This study is part of a multidisciplinary project elucidating the dynamic relationship between basal hydromechanical processes and glacier motion using integrated surface geophysical and glaciological methods. The Grubengletscher was chosen for our feasibility study since previous work [*Haeberli and Fisch*, 1984; *Haeberli et al.*, 2001] had demonstrated that (1) it flows at speeds of up to ~45 m/year, which is fast for an Alpine ice mass and thus implies exceptional dynamic behaviour; (2) at least the lower part of the ablation zone is underlain by unlithified sediments up to several tens of metres thick; and (3) up to ~90% of glacier motion is due to processes operating at the glacier bed, although the precise mechanisms involved are not known. The focus of our investigation was the integrated geophysical and glaciological investigation of an area ~36 metres in diameter, located immediately downstream of a prominent break in slope of the glacier surface, in which GPR and GPS monitoring stations were located.

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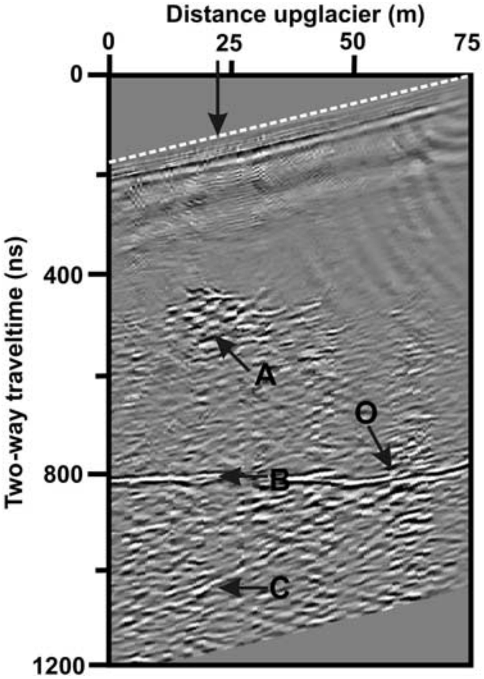

Figure 1. Constant-offset radargram illustrating inferred englacial (A), ice-sediment (B) and sediment-bedrock (C) reflectors. The inferred sediment wedge thickens down-glacier from its onset (O). Spatial sampling interval is 0.5 m, acquisitions are triggered manually. Vertical arrow shows the position of the static GPR survey. Processing involves dewow filter, Ormsby bandpass filter (corner frequencies at 8-16-60-120 MHz), spatial median filter (5 spatial and 11 temporal samples), trace energy gain and Kirchhoff migration (velocity = 0.168 m/ns).

[5] An extensive GPR dataset was collected, using a Sensors & Software Pulse Ekko Pro system with 50 MHz antennas spaced 2 m apart and aligned perpendicular to ice flow. We focus here on monitoring data, where the absolute position of GPR antennas was fixed for all traces of the acquisition; antennas were secured using rocks, and surface melt waters were diverted around them. The acquisition system was programmed to trigger every 10 minutes, upon which 4096 repeat traces were sampled at 0.8 ns and the average stored automatically. Processing of the monitoring data was limited to dewowing and static time shifts to align first-breaks of traces, allowing residual misalignment of events to be attributable to variations in GPR velocity. The survey site was also traversed using constant-offset (CO) GPR antennas, in both up- and cross-glacier directions; the offset was again fixed at 2 m, and the spatial sampling interval was 0.5 m. Additional data processing here involved band-pass and median filters, Kirchhoff migration and energy-decay amplitude correction (detail of the processing stream is given in the caption of Figure 1).

[6] Three LEICA SYSTEM 1200 GPS sensors were permanently deployed across the glacier over a period of ~3 weeks. Data from the sensor located closest to the GPR monitoring station are presented here. Three-dimensional ice displacement was determined at 15 s intervals with reference to an off-ice base station sited at the glacier front less than 1 km away using standard geodetic techniques [*King*, 2004]. Logged L1/L2/L2C data were post-processed under a kinematic solution using Leica GeoOffice proprietary software with precise ephemeris (i.e. the description of the GPS satellite constellation). Solutions with carrier cycle ambiguities were rejected along with solutions that yielded a vertical plus horizontal root-mean-square (rms) positional error of > 3 cm. Horizontal velocities and vertical displacements were subsequently averaged over five-minute intervals. In this paper, we show coincident GPR and GPS records, and an up-glacier CO profile.

[7] To estimate surface-generated melt water input to the sub-glacial hydrological system, ablation was calculated using a local positive degree-day/direct-radiation algorithm [*Hock*, 1999], forced by a 0.5 h time series of temperature and incoming short wave radiation. The meteorological data were obtained from a permanent automated weather station located ~5 km to the south of the Grubengletscher at an elevation of 2810 m a.s.l., matching the elevation of our study site well. All parameters were calibrated against seasonal melt measurements and yielded results in good agreement with those derived by *de Woul et al.* [2006].

3. Results

[8] Common-midpoint GPR analyses and seismic reflection profiling (to be published in a companion paper) revealed that the ice in the study area is ~52 m thick. On application of topographic corrections, elevation changes of the ice-substrate interface beneath the study area are negligible (Figure 1). Thus we are confident that our GPR monitoring data do not suffer from artefacts generated either by an inclined ice-substrate interface, or by interference from offline ice-substrate reflections generated at distance. Three englacial and subglacial reflection events are dominant in the CO and monitoring GPR data; in the following description, all travel-times are with respect to those of topographically-corrected first-breaks (dashed, white line in Figure 1). Based on comparison of the arrival time of these events with the CO GPR profile (Figure 1) and seismic reflection data we infer that they indicate an englacial reflector (labelled A in Figure 1), centred around ~450–500 ns; the interface between glacier ice above and unlithified subglacial sediments below ~700 ns (B in Figure 1); and a deeper reflection at ~890 ns (C in Figure 1).

[9] CO GPR data suggest a spatially complex distribution of englacial reflectivity, both at this location and, more generally, within the ice body in the ablation zone. In our experience, such complexity can cause GPR reflections to superpose, with the resulting interference producing a complicated waveform. This is observed for the first of these events; we therefore do not attempt to identify the material properties of the englacial reflector based on echo phase and polarity, but speculate that it could be an air- or fluid-filled englacial flow channel or fracture. The third, deepest, event is weak hence its polarity is difficult to ascertain; it is interpreted, however, as originating from the interface between unlithified subglacial sediments above and bedrock (mica schist) below. This interpretation is based on the combined arguments that (1) it coincides with a diagnostic reflecting interface observed in our seismic reflection data; (2) coherent inter-sediment reflecting horizons appear above it (see e.g. the reflection that traces

approximately from 950 ns at 0 m to 800 ns at 50 m) but no coherent events appear below it; and (3) it appears to mark the base of a sediment wedge that has its onset at ∼60 m (Figure 1), whence it thickens downglacier.

[10] *Middleton* [2000] proposed that ice porosity (decreasing from 0.27 % at the surface to 0.037 % at ∼8 m depth) and hydraulic permeability (averaging 0.6 m d^{-1}) were elevated within the uppermost few metres during the summer melt season at Haut Glacier d'Arolla, Swiss Alps, compared to winter; this increased significantly radar attenuation. We therefore separated the early and later arrival-time portions of our radar monitoring data, and chose 160 ns as the threshold because it is a suitable compromise between sampling adequately the early-time energy whilst avoiding interference from deeper reflection events.

[11] Since we are only concerned with relative temporal changes during the day we present all data in percentage change relative to the 1500 h reference value in each case (Figures 2a and 2b); the choice of 1500 h as the temporal reference is justified a-posteriori below. Apart from a transient increase between 1200 h and 1400 h the average rms amplitude of the early-time arrivals decreases during the day (Figure 2a). The amplitude of the dominant half-cycle of the englacial reflection increases rapidly between the start of the survey period and ∼1245 h, and later mirrors the decrease of the amplitudes of the early-time arrivals (Figure 2a). Intermittently this reflection experiences uniquely extreme transients exceeding ±20 % change centred at 1230 h and at 1400 h. The maximum half-cycle amplitude of the ice-sediment reflection decreases on average during the day, although the period between 1130 h and 1530 h is characterised by some variability that includes smaller transient increases (Figure 2a). The maximum half-cycle amplitude of the sediment-bedrock reflection is dominated by a minimum between 1250 h and 1350 h and a persistent increase from 1450 h until the end of the survey period.

[12] The average daily trend of elevation reflects net lowering of the glacier surface (Figure 2c). Superimposed on this trend are three periods where the elevation of the glacier surface increases, respectively initiated at ∼1000 h, 1300 h, and 1520 h. We also observe a net increase in average horizontal velocity during the day (Figure 2c). Superimposed on this trend are two anomalously sharp increases in horizontal velocity in the periods 1035–1040 h and 1535–1610 h. Ablation increased markedly from ∼0800 h in the morning of 1st August, peaking above 18 cm d^{-1} equivalent between

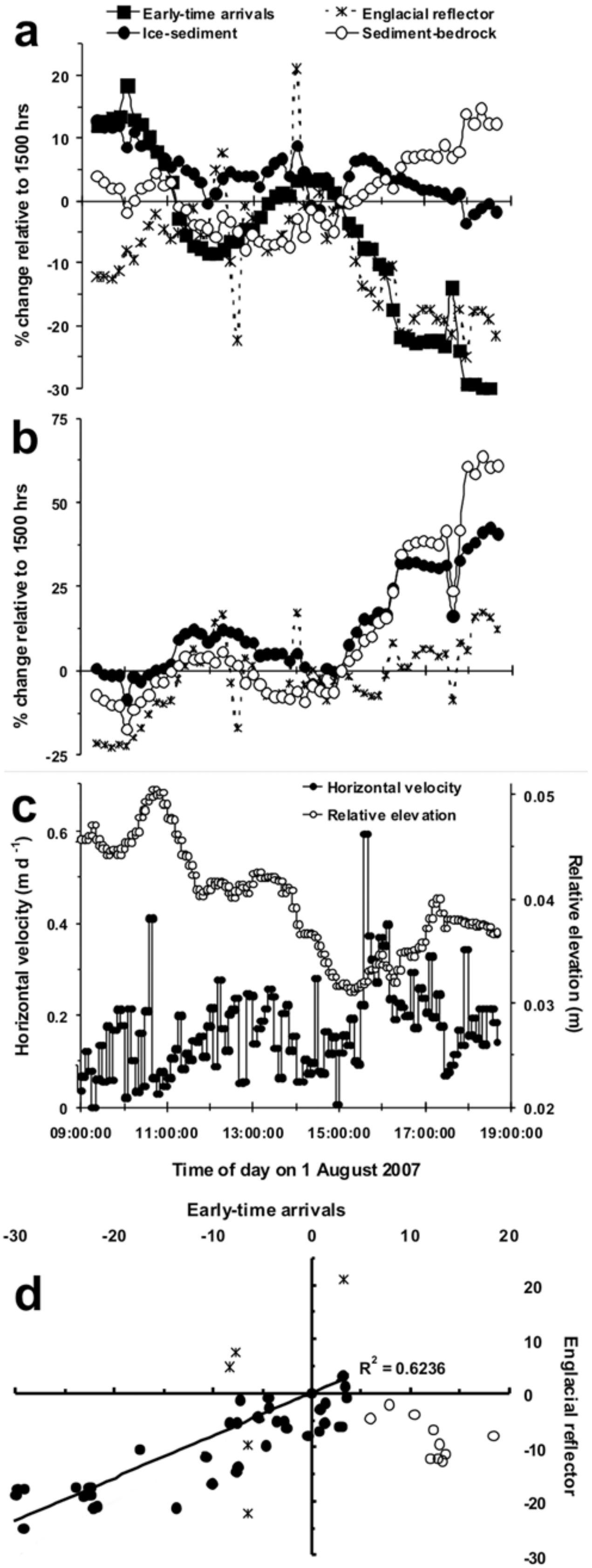

Figure 2. Percentage change in the amplitudes of (a) the early-time arrivals and the englacial and subglacial reflectors; and (b) the englacial and subglacial reflectors normalized by the amplitudes of the early-time arrivals. 1500 h is used as the temporal reference. (c) Horizontal velocity and relative elevation ∼ 30 m to the southwest of the GPR monitoring station. (d) Scatterplot of percentage change in englacial reflector amplitude against that of the early-time arrivals, relative to the 1500 h reference. Filled and open circles respectively represent the data after and before 1100 h and stars correspond to the extreme englacial transients. The solid line represents the best-fit linear regression to the data after 1100 h (filled circles).

1330–1500 h (maximum 19 cm d^{-1} at 1400 h) and decreasing thereafter to 3.5 cm d^{-1} equivalent by ~2000 h.

4. Interpretation

[13] The amplitude of a subsurface radar reflection depends principally on (1) the amount of energy transmitted into the ground; (2) attenuation along the wave path; and (3) the contrast in dielectric permittivity (and thus radar velocity) between the two media involved; hydrologically-forced changes of the ice-bed dielectric contrast are the targets of the present study. Although we have minimised electrical noise affecting energy transmission we need to be concerned about diurnal changes in attenuation along wave path, particularly if ingress of surface melt waters into anomalously porous near-surface ice in late morning and afternoon produces significant increases to signal attenuation [*Middleton*, 2000].

[14] After 1100 h, and excluding the extreme englacial transients, the temporal changes in the amplitude of the englacial reflector are statistically significantly ($R^2 = 0.62$) related to those of early-time arrivals (Figure 2d), prominently including the persistent decrease between ~1500 h and the end of the survey period (Figure 2a). This suggests that ingress of surface melt waters into anomalously porous ice near the surface modifies strongly the amplitudes of the early-time arrivals during the day, by attenuation and/or tuning effects, and thus also those of the deeper englacial and subglacial reflections. We propose that normalising the amplitude of deeper reflections by the rms amplitude of early-time arrivals (i.e. dividing by the early-time rms amplitude) can minimise such artefacts. The normalised amplitudes of the englacial and subglacial reflections fluctuate typically between zero and ~17 % change through the entire survey period (Figure 2b). Only the normalised amplitudes of the englacial reflector earlier in the morning (up to 23 % change) and those of the subglacial reflectors later in the afternoon (up to 42 and 63 % change) exceed the 17 % threshold.

[15] Since modelled ablation in the study area commenced at ~0800 h, it is likely that the pronounced rise in englacial radar reflectivity before 1100 h indicates that surface melt penetrates existing flow pathways in the ice. Indeed, this interpretation is supported by observations of fractures and moulins around the survey area, and similar results have been reported in pertinent previous work [*Fountain et al.*, 2005]. Consistently the presence of such pathways is confirmed by the spatial complexity in englacial radar reflectivity (Figure 1), although it is impossible to identify their exact geometrical nature from our radar data alone. However, given the established drainage network, we expect water transit times from the surface to the bed to be short. Intriguingly, each of the three intervals of glacier surface uplift is preceded by anomalous englacial reflectivity (Figures 2b and 2c) that is consistent with sequenced influx (initial transient increase in reflectivity) and flushing (subsequent transient decrease in reflectivity) of melt waters (Figure 2).

[16] The significant enhancement of subglacial reflectivity later in the afternoon implies a persistent increase in the dielectric permittivity of the subglacial sediments that commences at 1430 h (Figure 2b) and is preceded by the second (1400 hr) englacial transient that coincides temporally with the maximum ablation rate of 19 cm d^{-1} equivalent. Shortly after the transient attenuates and the permittivity starts to rise, the glacier surface experiences a significant and persistent uplift that commences at 1520 h. Some 15 minutes thereafter a dramatic transient increase in the glacier's horizontal velocity occurs that rapidly reaches the highest values of horizontal velocity observed during the day (Figure 2c). We interpret this sequence of events as indicative of hydraulically efficient influx of melt waters through the ice body at this time of peak ablation, causing subglacial water pressures to rise. Rising (rather than high) water pressures eventually jack the glacier off the bed initiating a pronounced sliding event [e.g., *Anderson et al.*, 2004, and references therein]. This event terminates about half an hour later (~1610 h, Figure 2c), coincident with a transient drop in surface elevation (Figure 2c) and preceded by a transient decrease in the gradient of subglacial reflectivity (Figure 2b).

[17] Closer inspection of Figure 2b reveals (1) increasing relative amplitudes at the ice-sediment interface through the morning and the early afternoon; (2) steady relative amplitudes between 1430 h and 1620 h; and (3) stronger relative amplitudes at the sediment-bedrock interface from 1620 h onwards. Following from point 1 it appears that the hydromechanical changes (i.e. where the presence of water impacts the mechanical regime) that give rise to the corresponding increases in reflectivity are relatively concentrated at or near the ice-sediment interface prior to and during the speed-up event. The termination of this accelerated flow and the instant at which the sediment-bedrock amplitudes become larger than the ice-sediment amplitudes occur at almost the same time (~1620 h, Figure 2b). Since there is no marked decrease in the reflectivity of the ice-sediment interface it is unlikely that the sediment-bedrock reflector becomes dominant as a result of more energy being transmitted to and through this interface (e.g. due to some system variation). Instead it appears that the area of water-filled pore space exposed to the radar energy deeper within the sediments begins to increase during the pronounced sliding event, although we cannot infer the governing hydromechanical processes from our radar data alone.

5. Discussion and Conclusions

[18] Radar monitoring of subglacial hydrological processes needs to avoid two potential pitfalls. Rapid temporal changes in both (1) hydrologically-forced radar attenuation in anomalously porous near-surface ice, and (2) subglacial reflectivity must be recognised and accounted for. Normalisation of subglacial reflectors by the amplitudes of the early-time arrivals, integrated over a suitable time window, is a simple and robust approach to address potential pitfall 1. Here we have demonstrated the usefulness of radar monitoring for analysing relative temporal changes in subglacial reflectivity by focusing on percentage amplitude variation. We envisage that judicious scaling could allow quantification of temporal changes, e.g. in terms of BRS or BRP, although more research is required before such changes can be used to quantify reliably subglacial hydrological properties and temporal changes thereof. Potential pitfall 2 could become significant where 'one time only'

surveys are conducted, yielding a snapshot of BRS or BRP at a particular point in time which could be misinterpreted if significant temporal hydrological changes occur in the subglacial environment. This could even be a problem at warm-based portions of polar ice masses.

[19] Joint interpretation of normalised subglacial radar reflectivity, surface elevation and horizontal velocity derived from co-located GPS data as well as estimates of melt input to the glacier bed, allowed reconstruction of subglacial hydromechanical processes in our study area. Our inferences involve increasing subglacial water pressures following peak surface ablation supplying englacially-routed delivery of water to the ice-sediment interface, eventually jacking the glacier of the bed and thus allowing it to slide. Prior to the sliding event the radar reflectivity of the ice-sediment interface consistently exceeds that of the sediment-bedrock interface. This situation is reversed following the termination of this event, although the hydrological or mechanical changes that occur within the sediments, and potentially therefore also the reasons for the termination of sliding, remain uncertain in the absence of direct subglacial observations. The a-posteriori justification of 1500 as the reference amplitude is that it marks the instance at which a rapid and persistent rise in subglacial reflectivity is initiated, marking the commencement of the most significant subglacial hydromechanical process we infer.

[20] In conclusion, the answer to our central research question is yes, it is possible to monitor hydrological processes beneath glaciers experiencing strong perennial surface melting with automated GPR techniques and on repeat timescales of a few minutes. It is however important to be aware of and avoid several potential pitfalls as demonstrated here. Future work should combine surface radar monitoring with direct subglacial observations, and pay particular attention to characterising adequately the hydrological properties of anomalously porous ice near the surface. Future work should also consider the potential effects of decreasing battery power over time, especially where absolute, rather than normalised, amplitudes are to be analysed.

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