Supplement for article: Tracking coarse sediment in an Alpine subglacial channel using radio-tagged particles

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This document provides a literature review supporting the methodology and rationale behind the method developed to track subglacial radio-tagged particles. Additional results exploring the choice of the bandwidth and weighting parameters used in the kernel density estimation technique are presented.

PARTICLE TRACKING TECHNOLOGIES: A BRIEF REVIEW

From Einstein's (1937) pioneering research tracking painted particles in a flume to contemporary experimental applications of RFID technology in large-scale river systems (e.g. Lamarre and others, 2005; Cassel and others, 2017), field studies that track individual tagged particles through hydrological systems have produced invaluable insights into: sediment transport rates and volumes, particle entrainment, flow competence, the timing of periods of rest and motion, step lengths, overall transport distance and virtual velocity, particle dispersion, the impact of particle morphology on transport, sediment sources and zones of deposition (e.g. Hassan and Roy, 2016). These insights have revolutionised understanding of coarse sediment transport dynamics in rivers. To contextualise the methodological development we propose, we review the set of technologies that underpin our approach.

RFID tags

Radio-frequency identification (RFID) tags have been widely used to locate and track individual particles through fluvial systems using either a roving (or mobile) receiving antenna, or stationary antennas placed over or alongside rivers (Hassan and Roy, 2016). The primary advantage of RFID tags is that they transmit unique ID codes in the low frequency (LF) to ultra-high frequency (UHF) radio bands (generally 125 KHz to 868 MHz), which can be detected over short to medium distances through water, sediment and rock using receiving antennas, eliminating the need to identify each tagged particle visually. Passive RFID tags (transponders) are activated in the magnetic field of a powered antenna, which also acts as a receiving antenna, while active RFID tags (transmitters) are powered by an internal battery and their radio signals are received by unpowered antennas. RFID tags can be inserted into natural particles by excavating a cavity with a drill, then sealing the tag inside with epoxy or silicone.

Passive RFID tags are small (~20-30 mm), inexpensive (1-2 USD), long-lasting (years), simple to deploy in a large number of natural particles and emit low frequency (KHz) signals that are minimally attenuated in the natural environment. The majority of bedload tracking studies have utilised Passive Integrated Transponder (PIT) tags across a wide range of grain sizes with minimal impact on particle density. However, PIT tags are limited by a short maximum detection range of ~1 m (e.g. Lamarre and others, 2005; Bradley and Tucker, 2012; Liébault and others, 2012; Chapuis and others, 2014) and are therefore unsuitable for use in large, turbulent meltwater rivers. Detecting multiple tags transponding simultaneously with the same antenna is also generally not possible. By contrast, active RFID tags operating in the high frequency (HF) to UHF radio bands can be detected from distances of 50-100 metres in the open field and from several metres water depth (Ergenzinger and others, 1989; McNamara and Borden, 2004; May and Pryor, 2014; Hassan and Roy, 2016; Cassel and others, 2017). Despite the comparatively high attenuation of their shorter wavelength signals, especially in water, the increase in detection range results from an increase in the transmission power enabled by the internal battery. Active tag reader systems (signal decoders) generally use signal anti-collision protocols that enable the detection of multiple tags transmitting simultaneously in the antenna's sensing field.

Active RFID tags are relatively large (~30-80 mm) due to their electronic components so their insertion into a natural particle may reduce particle density and alter their centre of mass, with consequences for particle transport behaviour. The size of modern active tags therefore limits their application to particles >~40 mm (coarse pebble to cobble size fractions). Particles made of a synthetic material may be created to control morphology and density (e.g. Nichols, 2004; Olinde and Johnson, 2015; Cassel and others, 2017). The use of a very dense material may allow the production of smaller synthetic particles than is feasible with natural particles. The time and cost of production (days per particle) make this method impractical where a large number of tagged particles is required. Active tags also have a limited operational life typically of some months to years depending on transmission power and timing. The cost per unit of commercially available active tags used in particle tracking studies is higher at ~5-10 USD, although the cost of the basic antenna systems is generally less than for PIT tags (100s vs 1000s USD).

Wireless sensor technologies and applications in ice

Also noteworthy are wireless sensor platforms developed to obtain hydrological and glaciological measurements of the englacial and subglacial environment in the form of borehole sensors or Lagrangian drifters (Martinez and others, 2004, 2005; Hart and others, 2006; Bagshaw and others, 2012; Smeets and others, 2012; Bagshaw and others, 2014; Alley and others, 2019; Alexander and others, 2020; Prior-Jones and others, 2021). In wireless sensor platforms, probes typically transmit data in the very high frequency (VHF) to UHF radio bands to receiving antennas located on the glacier surface or proglacial channel banks. VHF frequencies are preferred since their wavelengths are longer than most water, air and sediment bodies in temperate ice that scatter and attenuate radio signals (Smeets and others, 2012). However, a balance must be struck between radio frequency and antenna size, which increases with increasing wavelength and affects the overall size of the sensor housing. The housing should be small enough to allow particles of a reasonable density to be constructed. The absorption of radio signals in pure, cold, uniform ice is insignificant at frequencies up to 800 MHz (UHF band) (Budd and others, 1970) and signals from wireless sensor probes have been received from ice sheet depths of up to 2500 m (Smeets and others, 2012; Prior-Jones and others, 2021). However, temperate glacier ice contains impurities in the form of water, air and sediment which significantly degrade UHF radio signals. Despite the lossy propagation media, the reported maximum range of wireless probes operating in heterogeneous, temperate glacier ice and basal till is 40 m at 433 MHz (Martinez and others, 2005) (and 70 m at 151 MHz (VHF) in Hart and others, 2019), indicating the potential to detect subglacially deployed particles tagged with simple a-UHF RFID transmitters through shallow temperate ice.

Localisation of RFID-tagged particles

Following deployment in fluvial and glacial systems, RFID-tagged particles can be repeatedly localised using roving or stationary receiving antennas to track their transport. Tagged particles may be localised within a Lagrangian frame of reference, in which the displacement of individual particles is followed over time, typically by surveying a given area with a roving (or mobile) antenna. Lagrangian monitoring can provide a spatially well-resolved location estimate at the expense of temporal resolution, given the time required to perform surveys. By contrast, in an Eulerian frame of reference the passage of tagged particles is observed past a fixed point, producing a temporally well-resolved record of particle location in a given zone at the expense of spatial coverage (e.g. Ballio and others, 2018). The combination of roving and stationary antennas can therefore effectively capture both particle location and timing of motion.

Geometrical, range-based techniques such as multilateration can be used for the Lagrangian localisation of radio transmitters (e.g. Greco and others, 2015; Yiu and others, 2017; Li and others, 2019). However, they are based on theoretical relationships between signal strength at the receiving antenna and absolute distance from the transmitter, which are inevitably subject to large, unknowable errors caused by radio signal attenuation and scattering in complex outdoor environments. Alternatively, it is possible to analyse the spatial distribution of received transmissions from an RFID transmitter in a geostatistical framework to determine the particle's position. This approach assumes that the RFID points (an RFID transmission assigned to the point location at the time of reception) obtained for a single a-UHF RFID-tagged particle located in a glacial or riverine environment will be spatially distributed around the point location of the tagged particle (assumed stationary) with the signal strength and detection rate of received transmissions generally increasing with proximity to the particle. Although the actual distribution of received transmissions will be affected by unknowable signal propagation effects, this general, spatially averaged relationship is assumed to apply over large, relatively flat survey zones without major topographical or artificial barriers to signal propagation.

Cassel and others (2017) localised a-UHF RFID-tagged particles located on a river bar with a roving antenna by identifying the point location with the highest signal strength. They also identified the grid square with the highest interpolated signal strength value obtained using Inverse Distance Weighting (IDW), achieving sub-metre accuracy with very dense survey line spacing. The use of a flexible, probabilistic smoothing technique such as density estimation would permit the application of this type of geospatial analysis in larger survey areas with less dense survey lines and greater distances between the transmitting and receiving antennas, and would also produce an estimate of uncertainty alongside the most likely planimetric location of the particle. A weighting parameter may also be used to account for variability in the speed and track of the roving antenna during a survey which can lead to bias in and across localisation estimates due to variation in the amount of time spent surveying in a given area.

Active RFID-tagged particles may also be localised in an Eulerian sense by using stationary antennas located over or adjacent to the particle transport path, provided the along-channel detection range of the antenna is known or approximated. Signal strength information may also be used to assess the particle's proximity to a stationary receiving antenna in a given reach, provided in-field calibration between signal strength and distance is achieved across the range of flow conditions (e.g. Cassel and others, 2021). Using a network of stationary antennas can provide information on the within-reach timing of particle transport. Once the position of the tagged particle is determined, it may then be converted into downstream transport distance, provided the transport path is known or approximated. A record of the change in transport distance over time can then be analysed to describe particle transport dynamics. On the basis of this review, we propose the development of a method using a-UHF RFID technology and a probabilistic localisation technique to track particles under shallow temperate ice and in large proglacial rivers, complemented by stationary antenna arrays.

ROVING ANTENNA DATA

Table S1 shows the dates on which roving antenna surveys were performed. Surveys were conservatively considered incomplete if multiple survey lines were missed in a given area (glacial or proglacial) due to weather or time constraints. Only complete surveys that covered the entire glacial and proglacial zones (GP, n=16) were used in the calculation of the roving antenna detection rate.

Table S1. Roving antenna survey dates (n=26). The area that was completely surveyed is labelled with "G" for "Glacial" or P for "Proglacial"

Date			
16.08.21 G	23.08.21 G	31.08.21 GP	07.09.21 P
17.08.21 GP	24.08.21 G	01.09.21 GP	08.09.21 GP
18.08.21 G	25.08.21 P	02.09.21 GP	10.09.21 GP
19.08.21 P	26.08.21 GP	03.09.21 GP	28.09.21 GP
20.08.21 GP	27.08.21 P	04.09.21 GP	17.10.21 GP
21.08.21 GP	28.08.21 G	05.09.21 GP	
22.08.21 GP	30.08.21 P	06.09.21 GP	

The kernel density estimates (KDEs) were weighted by a heuristic index (product of normalised detection rate and mean rescaled signal strength (RSSI) per grid square) to reduce bias related to the roving antenna spending more time in a given grid square than in others, and to account for information on particle proximity provided by the RSSI measurements. The effect of weighting was particularly apparent in KDEs characterised by sub-optimal or incomplete survey lines, such as those situated in the crevassed region of the lower glacier snout, shown in Fig. S1a. The KDE is biased to the east where the spread of RFID points is greatest. The weighted KDE produced a KDE_{max} point reflecting the increased rate and strength of received transmissions towards the glacier terminus, 20 m west of the unweighted point Fig. S1b. The effect of weighting was less pronounced where RFID points were distributed radially around a point, rarely changing the KDE_{max} point location by >5 m (1 grid square). Weighted KDEs were also more symmetrical and concentrated within a distinct region with a greater likelihood of containing the tagged particle.

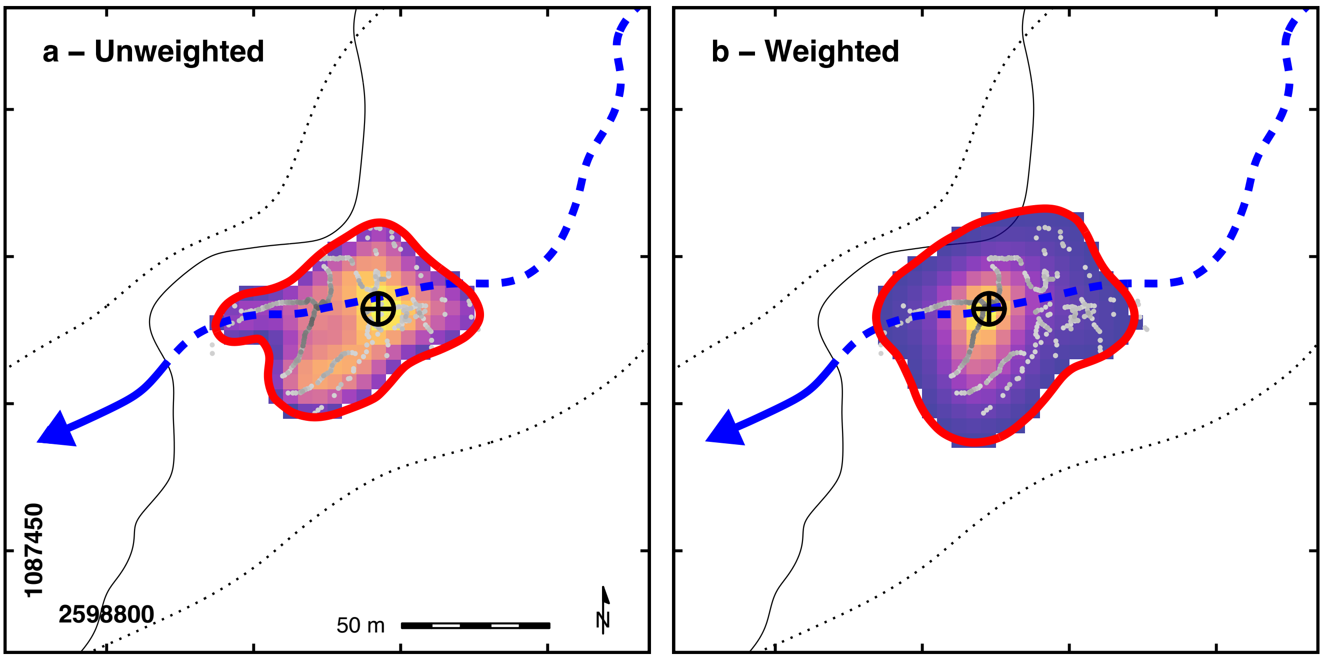

Fig. S1. a) Unweighted and b) weighted KDEs derived from the RFID points from single tagged particle (P2) on 21 August 2021. Weighting was performed using a heuristic index accounting for detection rate and mean RSSI per grid square. RFID point RSSI values shown in greyscale (black = high). Glacier outline (black line), subglacial and proglacial channel (blue line).

The kernel bandwidth in a KDE determines the degree of smoothing of the probability density function being estimated. It controls the amount of data points that influence the density estimate at each point, with a larger bandwidth resulting in a smoother and more generalised estimate and a smaller bandwidth resulting in a more detailed and localised estimate. A careful selection of kernel bandwidth is important because it affects the accuracy and reliability of the density estimate. Choosing a bandwidth that is too small can result in an overly complex estimate that is heavily influenced by noise in the data or an incomplete point cloud, whereas a bandwidth that is too large can result in an oversimplified estimate that misses important features and trends in the data.

Bandwidths were compared using the range of selectors in the ks package for R (Duong, 2007) and a diagonal bandwidth matrix since no correlation between the X and Y dimensions was observed: 1) Smoothed Cross-Validation (SCV); 2) Least-Squares Cross-Validation (LSCV); 3) Biased Cross-Validation (BCV); 4) Plug-in selector; 5) Normal scale bandwidth and 6) fixed bandwidth corresponding to the estimated detection range of the antenna (38 m) (Fig. S2).

From a qualitative perspective, the change in the KDE_{max} point and 95% confidence interval contour locations was generally minimal, exemplified for a single tagged particle (P1). This overall lack of

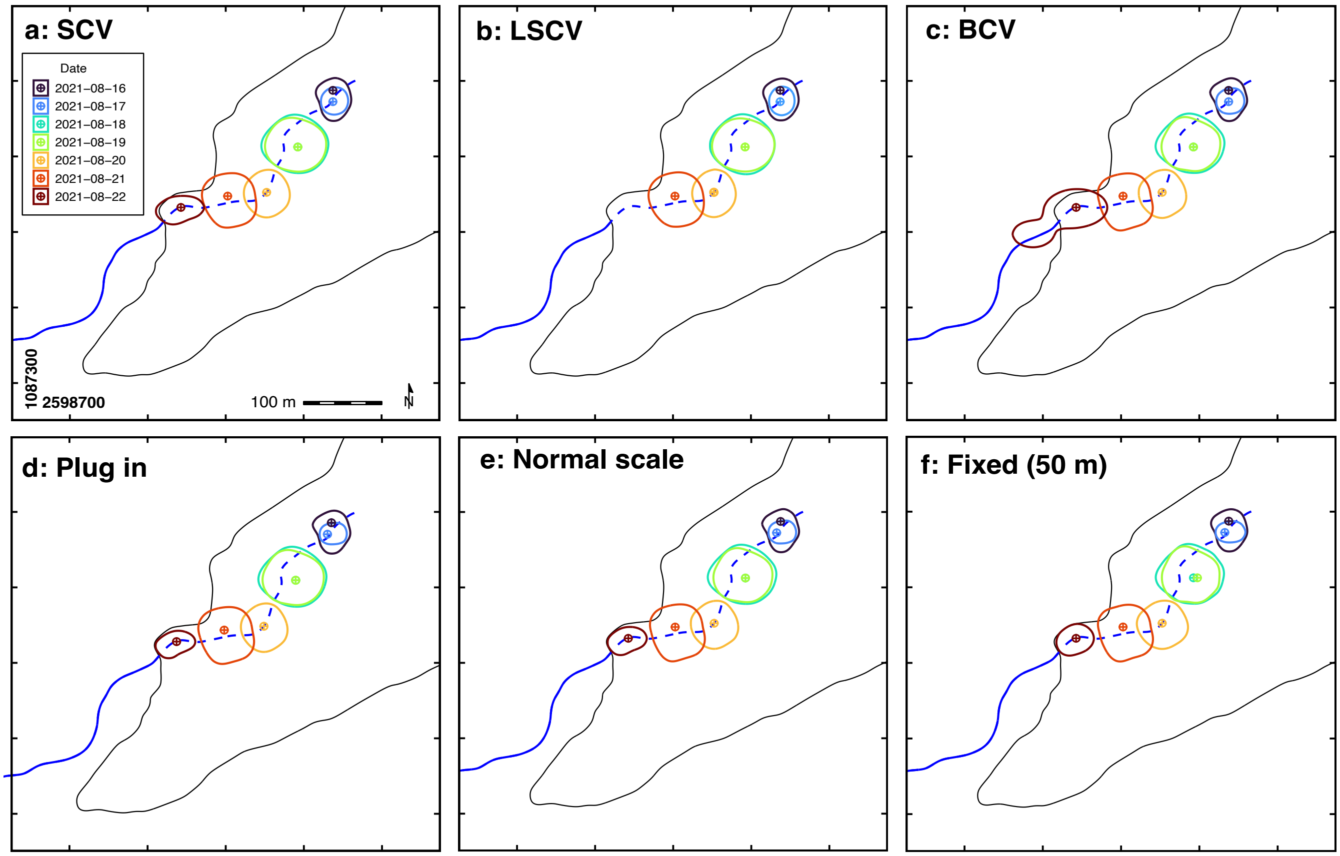

Fig. S2. The variation in the subglacial localisation of particle P1 across different kernel bandwidth selectors: a) Smoothed Cross-Validation (SCV), b) Least-Squares Cross-Validation (LSCV), c) Biased Cross-Validation (BCV), d) Plug-in selector, e) Normal scale bandwidth and f) Fixed bandwidth of 38 m. KDE_{max} point (coloured point) and 95% confidence interval (coloured lines), glacier outline (black line), subglacial and proglacial channel (blue line).

sensitivity to the bandwidth selector indicates that the RFID point data are largely robust, particularly when reduced to the heuristic index. In some cases where the survey lines were constrained (i.e. 22 August 2021) the LSCV bandwidth selector failed to localise the particle, and BCV overestimated the positional uncertainty given the heuristic data accounting for signal strength and detection rate. This indicates that these selectors were too sensitive to the spatial distribution of limited RFID point clouds and highlights the need for exploratory analysis of KDE bandwidth. SCV was identified as the most robust of the data-adaptive selectors based on cross-validation and was therefore selected for use in this study.

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