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Towards a common terminology in radioglaciology

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Abstract

Over the past 70 years, many different components of the cryosphere have been imaged with a variety of radar systems using increasingly sophisticated processing techniques. These systems use various pulse lengths, signal frequencies and, in some cases, modulated signals. The increasing diversity of radar systems has created the potential for confusion due to the use of non-consistent terminology. Here we provide an overview of state-of-the-science radar technologies and suggest a simplified and unified terminology for use by the cryosphere community. We recommend a terminology that is target independent but specifies the characteristics of the signal. Following this recommendation, commercial impulse systems that penetrate the subsurface should be referred to as ground-penetrating radar (GPR), and pulse radars as radio-echo sounding (RES). Continuous-wave (CW) radar systems should be referred to as ground-penetrating CW radars. We further suggest any additional characterisation of the system be expressed using descriptors that specify the platform it is mounted on (e.g. airborne) or the frequency range (e.g. HF (high frequency)) or modulation (e.g. FM (frequency modulated)).

Introduction

With the increasing societal impact of global warming, interest in mapping and understanding the ice masses on our planet has increased. While the earliest surveys focused largely on mapping ice thicknesses, sophisticated radar surveying and processing techniques have since been developed to infer the structure and rheological properties of the ice and substrate. The propagation of electromagnetic (EM) waves through glacial materials in the radio frequency spectrum of 3 kHz–300 GHz depends on their electrical conductivity and dielectric properties (Bogorodsky and others, 1985). Changes in these EM properties along the wave's travel path cause energy to scatter back to the surface, whereby radar signal modifications are diagnostic of the physical properties of the ice and its substrate and of any inherent structural interfaces.

Cold ice is often described as being electromagnetically transparent because penetration depths are large and signal attenuation is small. Penetration depth of EM waves in any material is limited due to absorption and scattering losses and, thus, the material's EM properties, whereby signal attenuation scales with frequency (Joseph, 2005). High frequency (HF, 3–30 MHz) is used to image the bed and coarse ice-internal layering, very high frequency (VHF, 30–300 MHz) to estimate ice thicknesses and higher-resolution layering in ice and firn, ultra high frequencies (UHF, 300–3000 MHz) for thinner ice bodies and layering of firn and snow, and finally, super high frequency (SHF, 3000–30 000 MHz) in radio altimeters to measure aircraft heights above ground (Fig. 1). Such radar altimeters use a sufficient high-frequency range to ensure very low penetration into the ice and snow.

Although the *IGS Radioglaciology symposia* in 2013 and 2019, and prominent reviews such as those by Schroeder and others (2020); Navarro and Eisen (2009); Bingham and Siegert (2007); Dowdeswell and others (2004); Zirizzotti and others (2010) and Plewes and Hubbard (2001) are powerful testimonies to the development of radar methodologies and applications over the past six decades, a common radar terminology has not been developed, and the potential for confusion prevails. The aim of this letter is to suggest a unification of radar terminology within the cryosphere community resulting in a much reduced and global radar vocabulary.

Variety of radar terminologies and principles

The variety in radar terminology in radioglaciology is partly linked to historical developments, different communities and different applications. In the following, we provide a brief review of some of the differences between different terminologies. We hope to raise awareness of which distinctions are still to be made and which are unnecessary and misleading. However, this letter is focused solely on active radar systems; passive radar sounders such as those used by Peters and others (2021) and Howat and others (2018) are not considered in the following.

Frequency		Literature Name	Target
3 MHz – 30 MHz	HF	Deep-looking radar[1], RES[2], ice-penetrating radar[3], ice radar[4], ice-sounding radar[5]	Ice thickness, layering, anisotropy
30 MHz – 0.3 GHz	VHF	Ice-penetrating radar[3], ice radar[4], RES[2]	Ice thickness, layering, anisotropy
0.3 GHz – 3 GHz	UHF	Accumulation radar[6], Snow-penetrating radar[7]	Layering, anisotropy, seasonal snow depth, snow depth on sea ice
3 GHz – 30 GHz	SHF	Snow-penetrating radar[7], Snow radar[8]	Shallow surface characteristics, snow depth on sea ice

Fig. 1. Frequency range for different radar applications. [1] DELORES; King and others (2007); Schlegel and others (2022), [2] Young and others (2018); Jordan and others (2020); Kingslake and others (2014), [3] Mingo and Flowers (2010); Matsuoka and others (2004); Hawkins and others (2020), [4] Reeh and others (2003); Fountain and Jacobel (1997); Christensen and others (2000), [5] Pritchard and others (2020); Reeh and others (2003), [6] Lewis and others (2017); Culberg and Schroeder (2020), [7] Chen and others (2017); Schroeder and others (2020), [8] Richardson and others (1997); Newman and others (2014); Jenssen and Jacobsen (2020).

Differences in the radar systems and radar signals

Within the scope of this letter, we differentiate modern-day radar systems by the characteristics of their emitted signals into pulse, impulse and continuous-wave (CW) radar (Fig. 2), where the latter can be modulated (e.g. in frequency or phase). These radars differ in the emitted signal length and bandwidth. The first radar systems used in glaciology were pulse radars, which emit powerful pulses or bursts (several 10 s–100 s of nanoseconds long). The emitted signal is characterised by a narrow bandwidth, which limits resolution in ice. For impulse radars, the signals are short (up to 1.5 cycles) and emitted individually. The short signal has a broad bandwidth and is designed such that the bandwidth roughly corresponds to the centre frequency. This greatly improves resolution compared to pulse-limited radars. CW radars emit a long signal (quasi-continuous), a so-called sweep or burst. The components of this sweep can be modulated over the time of the sweep, thus contributing to a broader frequency content, i.e. bandwidth. In the case of linear frequency modulation, the radar is referred to as frequency modulated- (FM-)CW radar. Systems which modulate the frequency along a stepped function are referred to as stepped frequency- (SF-)CW radar. For further information on these systems, we refer to the reviews by Navarro and Eisen (2009); Zirizzotti and others (2010) and Plewes and Hubbard (2001). Furthermore, we consider a radar system as coherent if during acquisition and processing the phase and magnitude of the signal (equivalent to imaginary and real part or in-phase and quadrature of the signal) are recorded and preserved. Radar data are considered as phase-sensitive if, during acquisition and/or stacking, signals are summed coherently (using magnitude and phase of the signals).

Radar terminology in the literature

Often the characteristics of the emitted signal are not specified in the terminology of radar systems, and the same terminology is used to refer to CW, pulse and impulse radars in the literature (Fig. 2). Instead, the terminology of radar systems that penetrate the subsurface has often been adapted to describe their target material so that studies on snow might be conducted using a **snow-penetrating radar** (Chen and others, 2017; Schroeder and others, 2020) or **snow radar** (Richardson and others, 1997; Newman and others, 2014; Jenssen and Jacobsen, 2020). Studies that use systems that penetrate further into the subsurface, such as the basal environment, might use a **ground-penetrating radar** (GPR) (Eisen and others, 2011; Miége and others, 2013; Bauder and others, 2018), **surface-penetrating radar** (Leuschen and others, 2002; Pettinelli and others, 2015), **ice-penetrating radar** (Matsuoka and others, 2004; Mingo and Flowers, 2010; Hawkins and others, 2020), **ice radar** (Fountain and Jacobel, 1997; Christensen and others, 2000; Reeh and others, 2003) or **georadar** (Maurer and Hauck, 2007; Bradford and others, 2009; Kitov and others, 2020). Furthermore, some studies refer to sounding rather than penetrating the subsurface using **ice-sounding radar** (Reeh and others, 2003; Rignot and others, 2004; Pritchard and others, 2020). These terminologies effectively describe the same system (either pulse, impulse or CW), with the main difference being the frequency content of the emitted signal, which constrains the target investigated (Fig. 1). However, a specification of the emitted signal is lacking.

Radar, ground-penetrating radar (GPR) and radio-echo sounder (RES)

Specifically, the terms RES and radar are often used as synonyms for the same system. For instance, the ApRES system, originally defined as an autonomous phase-sensitive radio-echo sounder (Nicholls and others, 2015) is referred to as a radar (Gillet-Chaulet and others, 2011; Brisbourne and others, 2019; Case and Kingslake, 2022) or RES (Kingslake and others, 2014; Young and others, 2018; Jordan and others, 2020), similarly for the DELORES system (King and others, 2007; Schlegel and others, 2022).

Generally speaking, an instrument that images the subsurface by emitting and receiving EM signals is referred to as radio detection and ranging (radar). The term RES was introduced in glaciology to describe the first applications of EM waves on glaciers and ice sheets (e.g. Bogorodsky and others, 1985). Those initial airborne systems were based on analogue electronics and were only able to graphically record the rectified amplitude of the signal, i.e. its magnitude, but not its phase. Owing to this limitation, the term RES was often used to refer to such classical systems, even after introducing digitisation techniques for recording and storage.

Following the observation that radar waves can penetrate the ice, other radar systems, such as commercially available GPR systems, have been introduced in glaciology. In the conventional sense, GPR refers to impulse systems used to characterise the subsurface in the frequency range from megahertz to gigahertz. A variety of systems are readily available as off-the-shelf products from commercial manufacturers.

Initially, RES was referring to (analogue) airborne radar systems, while GPR was mainly operated on the ground. However, nowadays, GPRs are also operated underneath helicopters or drones, and systems on the ground are also referred to as RES.

Sounder and imager

Additional to the difference between GPR and RES from a historical point of view, the incorporation of the term 'sounding' into RES systems was used to specify the system as a sounder rather than an imager. A sounder refers to the classical concept of radar to measure the two-way travel time of a radar signal to a reflector or scatterer and the return of its echo, in other words, the distribution of backscattered energy as a function of time, a 1-D measurement of the whole recording. Putting together several 1-D measurements produce the familiar 2-D radargrams, which approximate vertical cross sections of the subsurface. Imaging radars are designed and operated to provide a 2-D map of the most prominently reflecting interface in the subsurface. In the case of radioglaciology, this means producing from a single flight line a 2-D map of the ice–bed interface and, at the same time, also mapping the reflectivity of that interface.

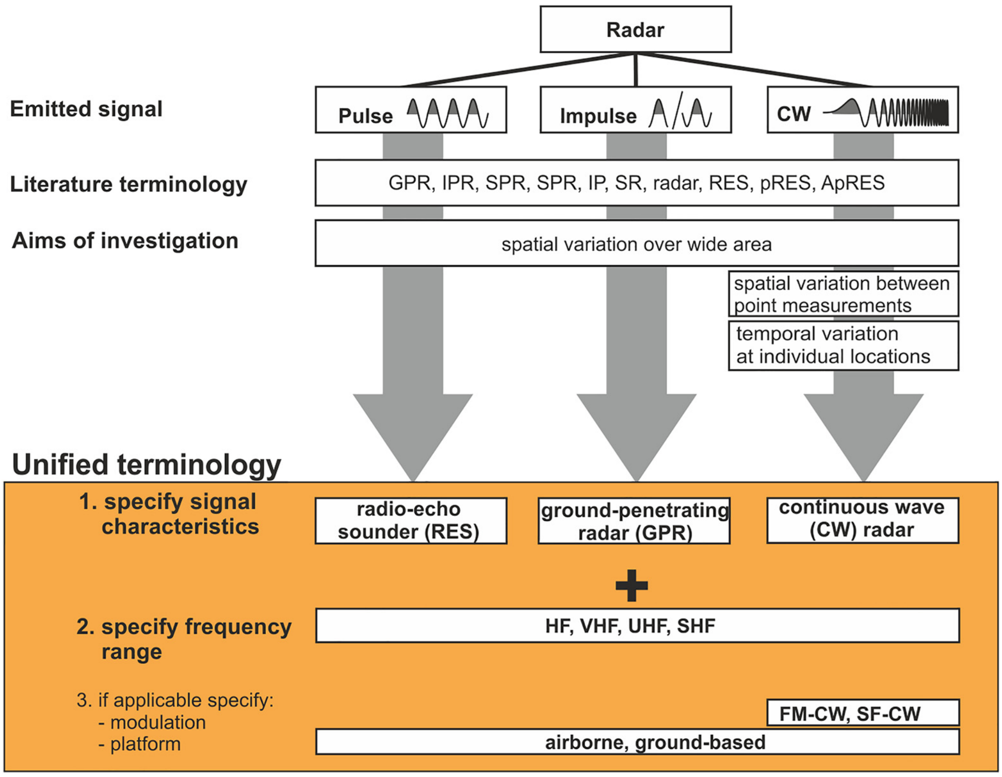

FIG. 2. Illustration of the variety of radar terminologies. ApRES = autonomous phase-sensitive radio-echo sounder; CW = continuous-waves; FM = frequency modulated; GPR = ground-penetrating radar; HF = high frequency; IPR = ice-penetrating radar; IR = ice radar; pRES = phase-sensitive radio-echo sounder; RES = radio-echo sounder; VHF = very high frequency; SPR = snow-penetrating radar; SPR = surface-penetrating radar; SF = stepped frequency; SR = snow radar; UHF = ultra high frequency; SHF = super high frequency. 'Aims of investigation' applies to the primary objective of the deployment. All radars can be used to target temporal variations by repeat measurements.

Differences in data acquisition, processing and analysis

Real and synthetic aperture radar

Depending on the spatial area investigated (Fig. 2), radar systems are designed to be moved during the acquisition to cover a wide area (e.g. GPR, RES), deployed in various locations to investigate spatial variations between these locations (e.g. pRES) or deployed in one location over a certain period of time to record temporal changes in that location (e.g. ApRES). The acquisition principle and the system (pulse, impulse or CW) can be used in all three cases, whereas a so-called **synthetic aperture radar** (SAR) refers to a specific acquisition and processing technique that either requires the antennas to be moved during acquisition or several antennas mounted next to each other creating a gridded SAR (e.g. MIMO; Young and others, 2018); thereby densely sampling the subsurface, followed by migration. An acquisition that does not allow the creation of an SAR, which is the case for point measurements, is theoretically referred to as **real aperture radar** (RAR). The significant difference between RAR and SAR data is in the along-track resolution of the data after processing.

For RAR, the along-track resolution is dependent on the beamwidth, which depends on (1) the distance to the target and (2) the aperture size of the antenna (i.e. the size of the reflecting element). Maintaining the same signal characteristics, an improved along-track resolution could be obtained by a larger antenna aperture (Joseph, 2005; Lillesand and others, 2015). However, increasing the physical size of antennas complicates the acquisition or even makes it unfeasible, where large antennas cannot be mounted on aeroplane wings or towed behind snowmobiles. To overcome the unfeasibility of long RAR, a SAR can be created. This allows the relatively short radar aperture synthetically to be extended by (1) moving the antennas along track or (2) having several distributed antennas that are linked during acquisition, creating a longer synthetic aperture.

SAR data acquisition allows several emitted signals to sample individual points. Reflected signals can then be relocated to their true origin in the subsurface by the application of a migration algorithm, which then reduces scattering and thus improves resolution (Lindsey, 1989; Leuschen and others, 2000; Yilmay, 2001). The creation of a synthetic aperture and applying migration allows the along-track resolution to be improved, independent of the target depth, being dependent only on the antenna aperture size (Lindsey, 1989; Leuschen and others, 2000; Yilmay, 2001). We refer to migration as the process of summation of amplitudes along a diffraction trajectory. This allows reflected signals to be relocated (i.e. corrected of range effects) in a 2-D or 3-D space, depending on the migration algorithm and acquisition characteristics of data. Acquisition with a phase coherent system, allows phase changes, e.g. due to steeply dipping reflectors, to be corrected before the summation along the hyperbolic trajectory, which we refer to as focused SAR processing. Simple migration of data without the correction of phase changes (e.g. Doppler effects, steeply dipping reflectors), such as often implemented in seismic or ground-based radar processing, is comparable to unfocused SAR processing, where the phase of the data is included but not corrected for different effects.

The use of these processing terminologies in different communities, such as geophysicists vs remote sensors, has led to some ambiguity in the past. Although the implementation of a velocity model for air and ice in the migration is crucial to reconstruct the subsurface using signals that penetrate the subsurface, in remote-sensing studies, which aim to image a surface (e.g. the snow surface) a migration of data with a layered velocity model might not be necessary. The latter processing could be referred to as unmigrated focused SAR processing, assuming phase effects have been taken into account. Other authors (e.g. Peters and others, 2007; Schroeder and others, 2019) refer to the latter as 1-D focusing, while 2-D focusing is including migration with a velocity model to correct for range effects (in the time dimension, e.g. Peters and others, 2007). This highlights an ambiguity in the terminology of processing; however, it is not within the remit of this letter to provide a review of the processing techniques.

The way forward: common terminology for future studies

All systems considered in this letter refer to radar systems that penetrate into the subsurface. We propose a terminology that focuses on the technical system used for data acquisition rather than on the target that is investigated by such a system. Therefore we suggest referring to 'ground penetrating' in all cases. Incorporating the term 'penetrating' has the additional advantage of distinguishing clearly between radar systems that penetrate into the subsurface and radars that do not penetrate deep and instead aim to characterise a surface, such as e.g. the snow surface examined by a so-called snow radar (e.g. Lemmetyinen and others, 2016).

Furthermore, we propose individual terminologies for the three categories of radar systems (Fig. 2): (1) impulse systems, (2) pulse systems and (3) continuous wave (CW) systems. All impulse systems, especially commercially available impulse systems that penetrate into the ground, should be referred to as **ground-penetrating radar (GPR)**. They are distinct from pulse systems which should be referred to as **radio-echo sounders (RES)**, irrespective of whether they use rectified signals, as the older systems do, or also retrieve phase. CW systems should be referred to as **ground-penetrating CW radar**. Further specification (Fig. 2) of the systems can be achieved by adding the frequency range (e.g. HF, UHF; Fig. 1), the platform, phase sensitivity, coherency or modulation (e.g. frequency modulated (FM), stepped frequency (SF)) as a prefix. Regarding the platform on which the radar is used, we suggest that only attributes such as airborne (whether helicopter-borne, drone-borne or fixwing) and ground-based should be used. We suggest not including processing techniques in the terminology of the systems.

Examples for unified terminology

BAS DELORES system (e.g. King and others, 2007) emits an impulse signal in the frequency range of 1–4 MHz, which classifies it as a ground-penetrating radar in the lower HF range, we, therefore, recommend referring to it as HF ground-penetrating radar (Fig. 2). The pRES systems (Nicholls and others, 2015) such as those used in the MIMO system (Young and others, 2018) emit a frequency modulated continuous wave (FM-CW) in the range of 200–400 MHz; we recommend referring to it as a ground-penetrating VHF FM-CW radar. The AWI airborne system (Nixdorf and others, 1999) emits a burst of either 60 or 600 ns long with a centre frequency of 150 MHz. Due to these characteristics, we recommend referring to this system as a VHF radio-echo sounder.

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