

A FRAMEWORK FOR CONSIDERING RECEIVER SATURATION TRADE-OFFS IN ICE-PENETRATING RADARS

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ABSTRACT

We explore and present a range of strategies for quantifying and mitigating the effects of receiver saturation in ice-penetrating radars. Ice-penetrating radars must be able to detect very weak reflected signals while maintaining dynamic ranges greater than 120 dB or more. Historically, ice-penetrating radars have done this by increasing pulse length, increasing transmit power, and interleaving short and long pulses to improve dynamic range. In most ice-penetrating radar architectures, steps are taken to prevent receiver saturation. Here we investigate the performance trade-offs associated with receiver saturation, and explore techniques to impact the negative effects of receiver saturation.

Index Terms— Saturation recovery, radar sounding, radar design

1. INTRODUCTION

Ice-penetrating radars are nadir-looking radar sounders that have been used since the 1970s to investigate Earth's ice sheets [1]. They have been used to observe basal topography, englacial layers, basal thermal state, depth-averaged englacial temperature, and firn properties [1]. The most prevalent of these systems are coherent, chirped airborne radar sounders that transmit linear frequency-modulated (FM) pulses. Recently, additional ground-based coherent radar systems have been developed, but they have not yet been widely deployed [2].

The primary target for these radar systems is the ice-bed interface, located under 1-3 km of ice in most of Greenland, and under 1-4 km of ice in most of Antarctica [3, 4]. The bed echo can be a very dim target and ice-penetrating radars must be intentionally designed to maximize the signal-to-noise ratio (SNR) of this echo in the face of englacial attenuation (which increases in areas of warm ice), scattering of the signal due to interface roughness, and basal material reflectivities as low as -30 dB. To observe the bed echo, ice-penetrating radars may be designed to have high transmit powers (e.g. [5, 6]) and/or to coherently sum many pulses together in order to decrease additive noise levels and elevate the reflected coherent signal [7]. Increasing the transmitted pulse length is

also commonly used to increase the total amount of energy transmitted by the system without increasing the maximum instantaneous power (e.g. [7]).

However, the bed echo is not the only target of interest for glaciologists who use ice-penetrating radar data to conduct investigations of ice sheet state and behavior. There are many englacial and near-surface targets of interest as well. Englacial targets include semi-contiguous englacial layers that can be used as isochrones to map past ice sheet conditions [8], as well as mechanisms of englacial water storage such as moulins and fracture networks that hydraulically connect the ice sheet surface to the bed [9]. Near-surface targets include firn properties and processes, such as firn compaction [10] and refrozen layers [11]. Radars designed to image these near-surface targets often use higher frequencies, larger bandwidths, and notably, shorter pulse lengths so that shallower returns are not stepped on by a long transmit pulse.

Radar design techniques used to increase the bed echo are often opposite the techniques used to increase the near-surface echoes. Techniques to increase the bed echo often obfuscate near-surface and englacial targets, while techniques for increasing near-surface echoes often lack the SNR necessary to observe a bed echo. For instance, increasing the transmit power of the radar increases the direct path leakage incident upon the receiver, potentially masking weaker near surface returns. Similarly, increasing the transmitted pulse length will mask more near-surface and englacial reflections, making them significantly harder to detect.

In both cases, the receiver may be saturated, creating nonlinearities in the receive chain of limiters, filters, amplifiers, and digitizers. If the receiver saturates, an important question is how does the receiver behave while it is recovering from this saturation and returning to its ideal linear state? In this paper, we investigate how different components recover from saturation and seek to provide a framework for radar receiver design when the goal is to detect echoes from throughout the entire ice column. We discuss the recovery performance of different front-end components, both in terms of temporal recovery time, as well as repeatability of the saturation recovery response. Additionally, we discuss the trade-offs associated with different receiver architectures with the goal of detecting echoes during the period of receiver saturation recovery.

2. AIRBORNE VERSUS GROUND-BASED SYSTEMS

Airborne ice-penetrating radars flown on crewed platforms typically fly at altitudes of 100-500 m above the surface of the ice [5]. At these altitudes, the echo of a pulse off of the ice surface returns to the receiver in 0.66-3.3 μs , giving the receiver that much time to recover from any direct path saturation that may have occurred on transmit. For short pulses and higher platform altitudes, the radar receiver can recover from any saturation on transmit and return to its linear operating region prior to echoes from within the ice being received. However there is often not enough energy transmitted in short pulses for them to be able to see through kilometers of ice (and the attenuation it creates) to the bed beneath it. For that reason, airborne radar sounders are often operated by interleaving short and long pulses to improve dynamic range [5]. Short pulses are usually around 1 μs in length, while long pulses range anywhere from 5-50 μs [5]. The short pulses are used to observe near-surface reflections, while long pulses are used to observe the bed echo. The data are combined in post-processing to produce a single radargram that spans the full depth of the ice column.

For ground-based ice-penetrating radar systems, interleaving a short pulse is still not an effective way to image the near-surface. While a short pulse will reduce the amount of time the receiver is saturated, therefore reducing the “blind depth” of the system, a blind region will always exist in a ground-based system. This is also a problem, albeit to a somewhat lesser extent, for radars flown at low altitudes (20-80 m) on uncrewed aerial vehicles (UAVs), such as [12]. Furthermore, for stationary ground-based coherent ice-penetrating radars, there are a subset of applications that necessitate maximizing the radar’s ability to detect the weakest possible signal. In these applications self-interference from the radar, multiplicative noise sources such as speckle, and clutter may become more important than in typical ice-penetrating radar applications where reasonable SNRs are reached prior to reaching these different noise regimes.

Our interest in this paper is to explore the trade-offs in different hardware designs for a mobile ground-based, stationary ground-based, or low altitude UAV-borne ice-penetrating radar that allow faint signals to be reliably detected in the face of receiver saturation. We explore the radar’s ability to recover from saturation and our ability to correct for saturation effects, both with hardware/architecture choices, and in processing. We focus particularly on the time after the saturating signal has ceased, but while the receiver front-end is still returning to its steady state behavior. This region is referred to as the saturation recovery region.

3. RADAR RECEIVER DESIGN

Achieving high dynamic range is critical for ice-penetrating radars, as the difference in power between echoes from the ice surface and ice bed can be as high as 120 dB or more. In order to be sensitive to such a low-power bed echo, most ice-penetrating radars utilize low-noise amplifiers on the receive side and power amplifiers on the transmit side, in combination with processing techniques such as coherent summation and synthetic aperture focusing. If we increase the transmitted signal power, we must consider the effects of high power transmitter leakage and the effects of the direct path signal on the receiver. In ice-penetrating radars, these effects are likely to be relevant on every pulse.

To a first order, we must ensure that our increase in transmit power does not damage the front-end RF components in the receiver. We must also ensure that the expected power levels presented at the system’s analog-to-digital converter are not high enough to saturate the ADC and create clipping in the digitized signal. In some ice-penetrating radar architectures, preventing damage to the front-end components is done by placing limiters after the receive antenna and in front of the LNAs [13]. When input powers to a PIN diode limiter exceed its threshold value (i.e. the limiter is saturated), output powers are typically limited to within a few dB of that value. Most PIN diode limiters have saturation recovery times on the order of 100s of nanoseconds, after which they allow low-power signals to pass through the device as normally expected [13, 14].

In ice-penetrating radar architectures without limiters, or those using limiters with non-optimal threshold values for the system, it is possible that the LNA input will be subjected to very high power signals. In the case of direct path leakage, these signals may be 100 dB or more stronger than the weak englacial echoes the LNA is typically designed to amplify. LNAs are not necessarily designed to have fast saturation recovery times, and their saturation recovery behavior is often not well characterized, or released publicly, by manufacturers.

For ice-penetrating radar architectures where the separation between transmit and receive antennas is fixed, concerns over preventing RF front-end damage and saturation at the ADC input can limit the maximum transmit power. For these systems, understanding the trade-offs of saturating will provide needed insight into the performance impacts and the radar’s ability to detect weak subsurface targets.

Many ice-penetrating radars rely on coherent summation of received signals to decrease the contributions of thermal (and other additive) noise and improve SNR and dynamic range. Coherent summation on the order of 10^5 or 10^6 pulses is not uncommon in ice-penetrating radars [15]. When the received signal is dominated by additive (i.e. incoherent) white noise, coherent summation produces increases in SNR proportional to the number of coherent summations, N . However, coherent summation is an ineffective way to improve

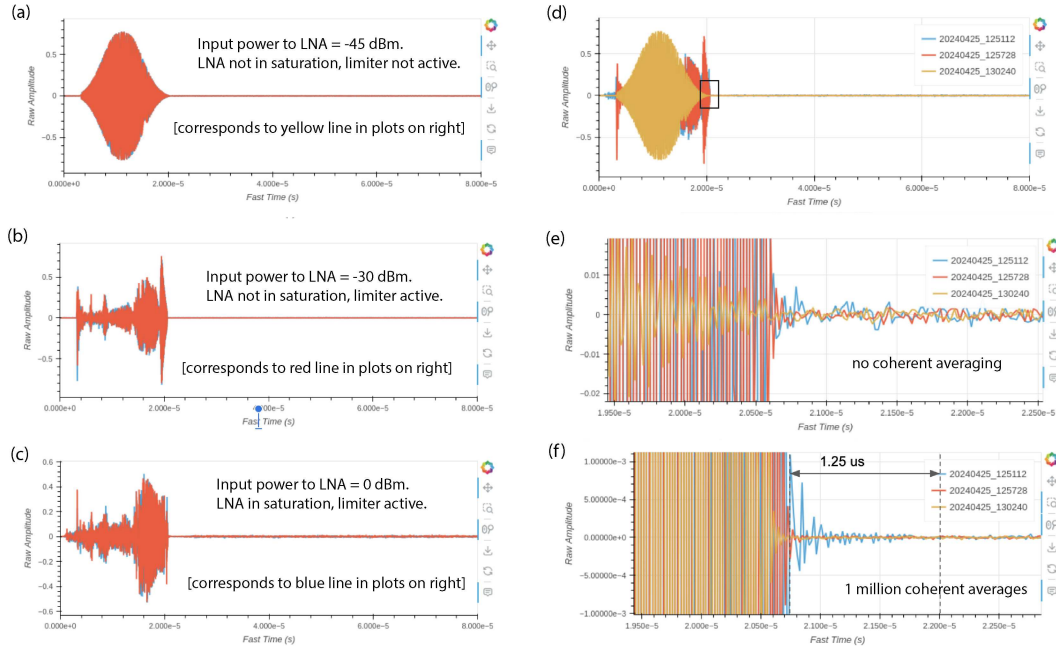


Fig. 1. Example of saturation recovery behavior in an ice-penetrating radar with an LNA and limiter in the receive chain. (a-c) Raw time domain data of received pulse under different limiting and saturating cases. Red is real part of data, blue is imaginary part. (d) The three cases from the left column shown on top of each other. (e) A zoom on the end of the pulse, black box in (d), after no coherent averaging. (f) A zoom on the end of the pulse, black box in (d), after 1 million coherent averages.

SNR when the dominating noise source is coherent (i.e. multiplicative). In these cases, coherent summation effectively amplifies the noise as well as the signal. Our work explores the cases where recovery from receiver saturation becomes a limiting factor for an ice-penetrating radar's ability to detect weak subsurface echoes once thermal noise contributions have been removed, for instance when additional coherent summation serves to amplify the saturation and receiver recovery behavior, in addition to weak signals of interest.

4. SATURATION RECOVERY MITIGATION

Figure 1 demonstrates the effects of receiver saturation in an software-defined ice-penetrating radar system, which is built using the codebase described in [16]. The radar is run in a loopback configuration with the transmitter connected to a 10 km fiber optic delay line, then directly to the receiver. The receiver consists of an LNA followed by a limiter, followed by the software-defined radio. In the left column of Fig. 1, the raw time domain of a received pulse is shown for three cases: (a) where the LNA is not saturated and the limiter is not triggered (i.e. limiting), (b) where the LNA is not saturated, but the limiter is triggered, and (c) where the LNA is saturated, and the limiter is triggered. Triggering the limiter and saturating the LNA both significantly affect the overall shape of the received pulse. Figure 1(d) shows the three pulses from the left column together for comparison. In Fig. 1(e) and (f),

we zoom in on the end of the pulse to observe the recovery behavior for (e) an individual pulse, and (f) 1 million pulses coherently averaged together. After sufficient coherent averaging, a decaying-amplitude, sinusoidal response is observed for the case where the LNA saturated and the limiter was triggered. This response takes approximately 1.25 us to decay into the noise floor.

We explore and present a range of strategies for quantifying and mitigating the effects of receiver saturation recovery in ice-penetrating radars. Broadly, we explore how the receiver recovery response can be characterized and its effects mitigated. For ice-penetrating radars in particular the large dynamic ranges, likelihood of self-induced saturation, and need to detect extremely dim targets make receiver saturation recovery a very important problem to understand. Our future efforts include characterizing the receiver recovery behavior in the time and frequency domains, removal of the recovery response from saturated data and quantification of our ability to recover a small amplitude signal that would otherwise be masked by the saturation recovery. We additionally aim to explore how the saturation recovery response of limiters and LNAs evolves (or does not evolve) with increasing levels of saturation and the variance of saturation recovery behavior between different LNA models and designs.

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