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DECOMPRESSION-BASED RECEIVER DESIGN FOR RADAR ICE SOUNDING APPLICATIONS

Utsa Dey Sarkar, Shravan Kaundinya, Lee Taylor, Fernando Rodriguez-Morales, John Paden

Center for Remote Sensing and Integrated Systems, The University of Kansas, USA

ABSTRACT

This work describes the design and development of a radar receiver with a large dynamic range by means of carefully designed compression. The receiver is designed for ice sounding applications on the Antarctic and Greenland ice sheets and is designed to be usable over a large frequency range (VHF and UHF) and with multiple analog-to-digital converters with only minor modifications. We present the receiver design, in which we have implemented an RF-power limiting feature so that the output power is monotonically increasing with respect to the input power over a large dynamic range. This allows the receiver to operate in the non-linear region to compress the high-power returns into the dynamic range of the analog to digital converter while still achieving good sensitivity (low noise figure) for low power signals. We discuss design considerations, hardware description, initial lab test results, the architecture of the design and results from recent field deployments. Lastly, we discuss the future work on the decompression mechanism to recover the uncompressed signals.

Index Terms— Radar receiver, decompression, VHF, UHF, radar sounding, radioglaciology.

1. INTRODUCTION

In radioglaciology, the application of radar remote sensing to ice and snow, the targets of interest have a very wide dynamic range. The scattering from the ice surface and *shallow* internal reflecting horizons (IRHs) are generally much larger than the scattering from the ice bottom and *deep* IRHs close to the ice bottom due to the signal extinction in ice. Therefore, most radar receivers used for ice sounding applications require a wide dynamic range. Maintaining the required gain profile of the received signal necessitates having sufficient gain to optimize detection of deep IRHs and the ice-bed while ensuring that the power levels from the ice surface and shallow IRHs are not above the saturation level of the receiver. RF switches or variable attenuators are commonly used to toggle between two or more different-gain paths [1][2][3] and time division multiplexing is used to capture low and high gain signals. There is a reduction in the signal to noise ratio of 3 dB since the two gain paths share a single receiver. Another possibility is to switch between gain states during the data collection. However, there is a discontinuity and nonlinear behavior where the switch and/or attenuators are changed between states resulting in partial loss of information. This work describes the design and first results of a radar receiver that attempts to solve the problem mentioned above. The paper is organized as follows. Section 2 presents the overview of the receiver architecture. Section 3 covers the receiver performance. Section 4 presents field results with some discussion. Section 5 discusses future work on how to numerically decompress or complete the companding operation needed to recover the original signal. Our concluding remarks are given in Section 6.

2. OVERVIEW OF THE RECEIVER ARCHITECTURE

The operating principle of this receiver architecture relies on de-compressing the signal in post-processing to extend the dynamic range. It uses a power limiter with a near monotonic power profile. For low power returns, the power limiter behaves as a linear device. For high-power returns, the device saturates, but we operate in a region where the compressed output power levels are still increasing with increasing input power so that the original signal can be uniquely recovered.

The design was intended to be used as a modular setup where each channel would use one receiver module. The receiver has been used in two different multi-channel radars deployed to Antarctica and Greenland for ice sounding measurements. These two radars are configured to operate at 600-900 MHz. A third multichannel radar system is being developed for 140-215 MHz based on the same receiver architecture. The components in the receiver are wideband and the operating bandwidth is determined by pre-select and anti-aliasing filters, with the pre-select filter being external to the receiver block and designed as a drop in board.

The receiver architecture uses PE45361 RF power limiters, to create the non-linear portion of the gain-profile, where the output power is monotonically increasing with respect to the input power levels. The pSemi™ PE45361 limiter allows several control voltages to adjust the limiting function.
To increase the dynamic range further than is possible with just compression, we have introduced two high speed RF

switching stages that enable 1) reception of the received signal from a directional coupler that is inline with the antenna feed and 2) to choose between low and high gain settings. The second SPDT switch allows the receiver to operate in the same way as earlier designs. The simplified block diagram of the receiver is shown in Figure 1. The "Cal Switch" in the diagram is used for calibration, monitoring the transmit signal, and monitoring the antenna reflection. This path significantly attenuates the received signal and is critical for ground-based operation because the surface and shallow layer reflections are very large considering the >1000W transmit power of the radar systems. Because of the high-speed nature of the switches, they can be used as a rudimentary sensitivity timing control that allows the receiver gain to be changed as a function of time *during* recording; this does result in the aforementioned loss of information during the switching event.

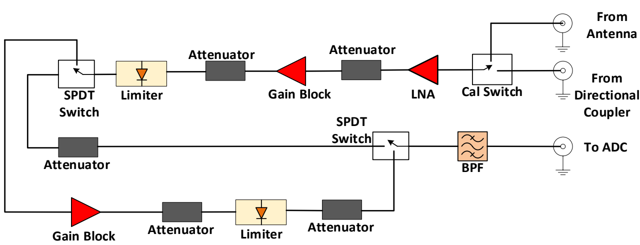

Figure 1: Receiver block diagram

The receiver modules were used in two different radar systems, in a multichannel configuration. Figure 2 shows photographs of a single receiver module (left) and one of the radars with 8 receive channels, one receiver module per channel. Receivers are mounted vertically underneath the power distribution wiring with cooling fans mounted across sets of four receivers.

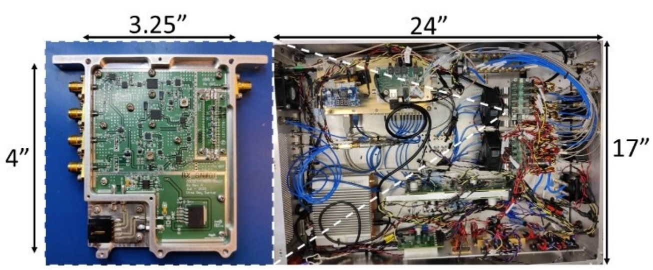

Figure 2: Modular structure of receiver in a radar chassis

3. PERFORMANCE CHARACTERIZATION

The receivers were each characterized in the lab. We present measurements of the gain profile, output power versus input power, noise figure, and power consumption. One point should be mentioned before proceeding: as the limiters begin to compress, their return loss degrades. While this is important to analyze, we plan to study the impact of input power on the full scattering parameters or S-parameters in a future work.

3.1. Gain Measurement

Figure 3 shows the receiver gain versus frequency. The measurements of the receiver S-parameters are in agreement with the EM/circuit co-simulations performed in Keysight Advanced Design System. The gain profile is visible for the passband of the filter, 600-900 MHz. We measured and calculated the gain for the receiver to be 32 dB for the passband. This gain was chosen to raise the receiver output noise 6-10 dB above the quantization noise of each radar's analog-to-digital converter (ADC). The two switching stages allow the gain to be decreased below this level, but Section 3 focuses on the high gain path results.

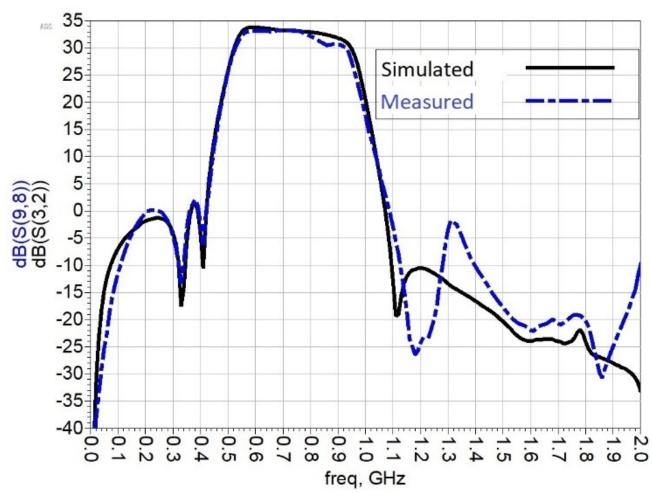

Figure 3: Measured vs. co-simulated gain versus frequency

3.2 Power Sweep Measurement

We characterized the output power with respect to the input power across the frequency band using a power-sweep vector-network-analyzer measurement. For several control voltage levels applied to a single RF limiter, the output power vs. input power curves are plotted in the Figure 4 inset. We decided to use the 0.4 VDC control voltage since the response was monotonically increasing up to ~24 dBm of input power. Figure 4 shows the power curves for several receiver modules with the 0.4 VDC control voltage. The plot shows the compression due to the entire RF chain. The results are favorable since the output power increases monotonically over our range of interest. The monotonic nature is necessary to uniquely recover the original uncompressed signal.

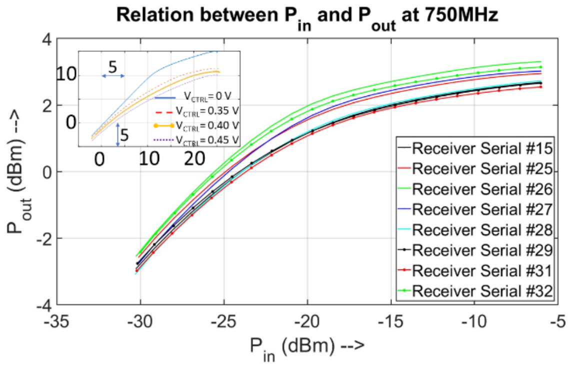

Figure 4: Input power vs. output power for various receiver modules

3.3 Noise Figure Measurement

We have also measured the noise figure for the receiver modules that we have manufactured, by using the standard Y-factor method. We used a calibrated noise source (ENR=15.1 dB) and a power meter. Because of the receiver gain, we used an additional amplifier and calibrated to remove the effect of this additional stage. Across the receiver modules, the noise figure was measured to have an average value of 2.4 dB. The plot for different receiver modules is displayed in Figure 5.

We used the following rule to calculate the noise figure:

$$F = 10\log_{10}\frac{10^{ENR/10}}{10^{Y/10}-1}$$

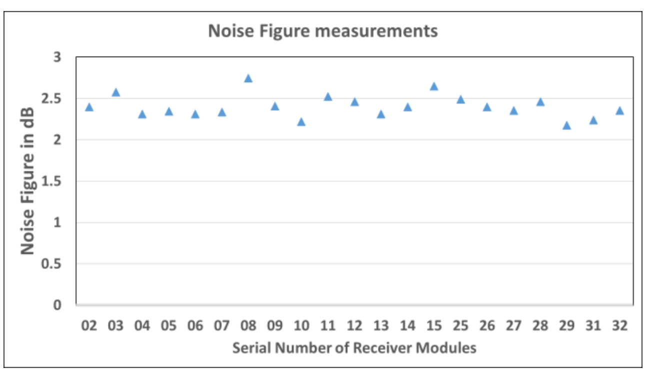

Figure 5: Noise figure measurement for each receiver module

3.4 Power Consumption

The amount of power consumed by each receiver module was 9.9 W. In comparison, the earlier radar receivers only used 2-3 W. The limiters used in the present work were selected based on their limiting properties, but they require a higher amplifier power to compress and the amplifiers consume significantly more power than previous designs. While this increased power may be a concern in some situations, the receiver power is still a small fraction of the overall power budget for the high-power radar systems that these receivers are deployed in.

4. FIELD EXPERIMENT RESULTS

Two radars using these receivers were deployed to Antarctica during the past field season and we present preliminary radar images from each system [4]. Figure 6 presents a ground based HH-polarization radar echogram from the McMurdo Ice Shelf. An example A-scope (image column) is presented on the side with references to the ice surface and bottom. Figure 7 shows an airborne echogram from near the South Pole collected with the second radar.

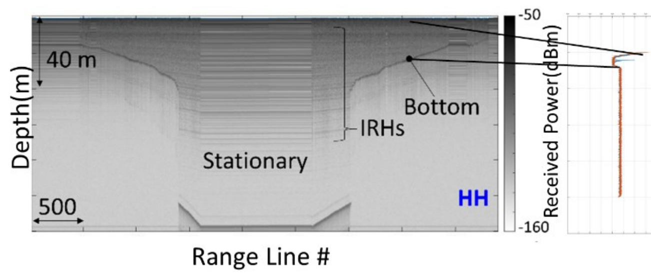

Figure 6: Ground-based radar echogram, 600-900 MHz, from the McMurdo Ice Shelf. Darker signals indicate larger signals.

5. APPLICATION OF COMPANDING IN RADAR

In radar receivers used in ice sounding applications, it is customary to use multiple gain architectures. It is usually sufficient to use two receiver gain profiles to cover the dynamic range of the desired signal. Having two gain settings to recover the signal requires that two separate channels of data need to be recorded for each input signal path. One approach is to use a single receiver with digitally controlled gain and time multiplex the capture of the signals. With this approach, the receiver is operated in low gain mode and high gain mode according to some schedule. The downside of sharing a single receiver is that the along-track sampling rate is reduced for each mode meaning that, either less averages are done or the maximum along-track spatial bandwidth is reduced. Another approach is to use two separate receivers to capture the low and high gain channels. This produces the best results but doubles the required hardware. For radar systems with many channels (e.g. one of the deployed radars has 22 antenna channels), doubling the receiver requirement has significant size, weight, power and cost impacts. The approach here utilizes a receiver with a combination of companding and rudimentary sensitivity timing control. In the literature, there are previous applications on nonlinear receiver compression in the domain of ultrasonic sounding in biomedical applications (e.g. [6]). However, companding [7] for radar applications appears to be an unexplored approach to recover signals.

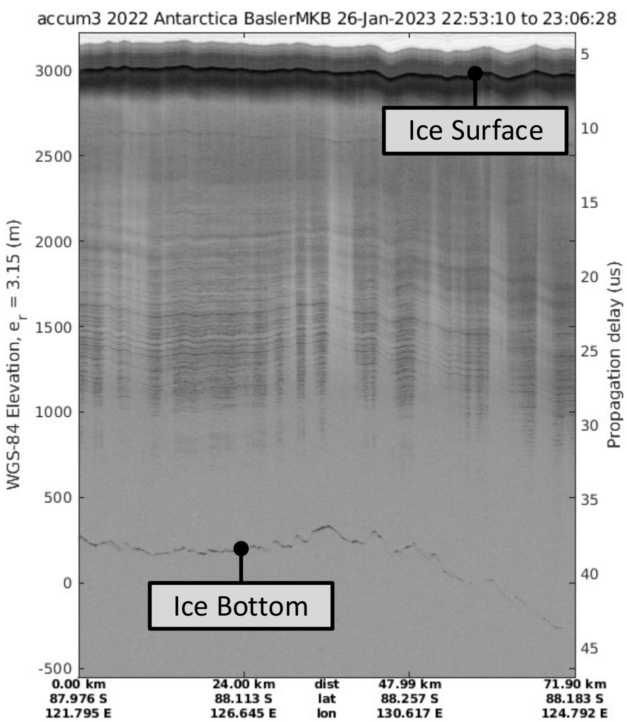

Figure 7: Airborne echogram collected near the South Pole. The signal trend from high SNR at the surface to low SNR near the ice bottom due to ice loss is apparent.

6. CONCLUSIONS

This work covers the design and characterization of a radar receiver with a large dynamic range achieved with a monotonically increasing gain/compression profile. Data processing results are presented from recent field experiments utilizing these receivers. In our future work, we plan to utilize machine learning techniques to numerically solve the decompression problem in order to recover the original uncompressed signals and undo the non-linear RF limiting operation. We plan to first try fully-connected neural networks. We will use neighboring samples and nonlinear activation functions to model the nonlinear and frequency dependent nature of the compression. We will train the network with data collected in the lab using an arbitrary waveform generator fed into the receiver to produce a large training set: the waveform generator will be run through many random sequences and the corresponding outputs from the receiver will be recorded. The ability to easily collect millions of training samples in this way lends itself to the neural network problem.

7. ACKNOWLEDGMENT

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