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Attenuation of Spurious Impulses from an Ultra-Wideband Radar: A High-Speed Switch for the Synchronous Impulse Reconstruction (SIRE) Frontend

by Gregory Mazzaro, Marc Ressler, Gregory Smith, and Francois Koenig

ARL-TR-5750 **September 2011**

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Gregory Mazzaro, Marc Ressler, Gregory Smith, and Francois Koenig
Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT

The performance of ultra-wideband (UWB) radar systems suffers from reflections between frontend components caused by impedance mismatch. The Synchronous Impulse Reconstruction (SIRE) radar built by the U.S. Army Research Laboratory (ARL) is no exception. While most of the radio frequency (RF) energy in each impulse is transmitted by the radar as desired, a portion of the RF energy reflects within the radar frontend. Undesired impulse echoes arrive back at the transmit antennas and are emitted from the radar. These undesired transmissions reflect from the radar environment and produce echoes in the radar image. The proposed solution for eliminating these echoes is to dissipate impulse reflections in a matched load before they are emitted. A high-speed switch directs the desired impulse to the antenna and redirects the undesired reflection from the antenna to a matched load. This report reviews the current SIRE frontend design and describes the solution for eliminating the echoes. The consequences of inserting each portion of the new circuit into the radar frontend are explained. Measurements on the new frontend show an attenuation of the undesired impulse transmissions of more than 18 dB at the expense of an attenuation in the desired impulse transmission of less than 3 dB.

15. SUBJECT TERMS

Radar, ultra-wideband, front-end, reflection, attenuation, high-speed switching, relay

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1. Introduction

Pulse reflection between frontend components is a common problem for impulse radar systems. Such reflections arise because radio frequency (RF) components are rarely impedance-matched over an ultra-wide bandwidth (UWB). Any mismatch between components causes a portion of the impulse to reflect within the radar frontend. If the reflection couples into the transmit antenna, the radar emits an unintended, delayed, and distorted replica of the intended radar transmission.

The performance of the U.S. Army Research Laboratory's (ARL) synchronous impulse reconstruction (SIRE) radar has suffered from this problem. Because the transmit antenna is only reasonably well-matched to the system impedance, an attenuated, distorted replica of the impulse is reflected toward the impulse generator, which is poorly matched to the system impedance after making an impulse. Thus, most of this distorted signal is reflected from the transmitter and radiated by the antenna. Upon reflection of the undesired impulses by the environment and reception of these signals by the receiver circuit, echoes from the radar environment appear in the radar image. Since an undesired reflection is recorded after each desired reflection, a weak target echo appears behind every actual target. These echoes generate false alarms during target detection and mask weak targets in their vicinity.

The proposed solution for eliminating the echoes is to dissipate impulse reflections from the antenna in a matched load. The solution requires placing a high-speed solid-state switch between the impulse generator and antenna. The switch initially connects the antenna to the generator, and immediately after the UWB pulse is transmitted, connects the antenna to a 50-Ω termination. In this way, the undesired reflection is dissipated before it can be transmitted.

Section 2 presents the current SIRE frontend design, the origin of the undesired impulses, and the solution for eliminating these impulses: a high-speed switch, a 15-ft cable, and a 50-Ω load. Section 3 shows the effects of adding a 15-ft cable to the signal path. Section 4 compares the performance of four solid-state switches for transmitting desired impulses while dissipating undesired impulses. Section 5 provides the printed circuit board (PCB) layout for the switch and its control circuit, as well as the timing signals necessary to transmit the desired radar impulses with minimal attenuation and dissipate the undesired impulses with maximum attenuation. Section 6 summarizes the performance improvement.

2. Current ARL SIRE Frontend and Proposed Upgrade

The frontend of the SIRE radar consists of the following components: the Timing & Control board, a pair of Avtech AVB-1-3 pulse generators, a pair of transverse electromagnetic (TEM) horn antennas, an array of 16 Vivaldi-notch antennas, and a receiver circuit for each antenna. The Timing & Control board triggers the Avtech generators for each UWB pulse. Each Avtech generator sends large-amplitude short-duration pulses to its transmit antenna. The TEM horns transmit the wideband pulses into free-space. The Vivaldi-notch antennas receive pulse reflections from the radar environment and the receiver circuit reconstructs received signals into a time waveform. A two-dimensional (2-D) radar image is generated from the collection of the 16 antenna signals. A block diagram of the SIRE radar frontend, for a single transmit-receive path, is shown in figure 1. A sample pulse, as generated by the Avtech source and applied to the TEM horn, is shown in figure 2.

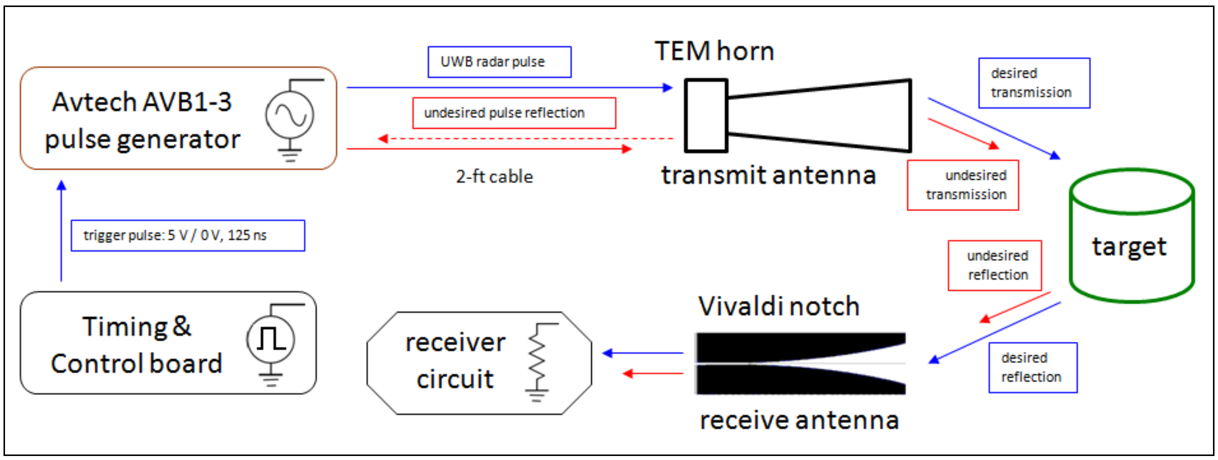

Figure 1. SIRE radar frontend: single transmit-receive path.

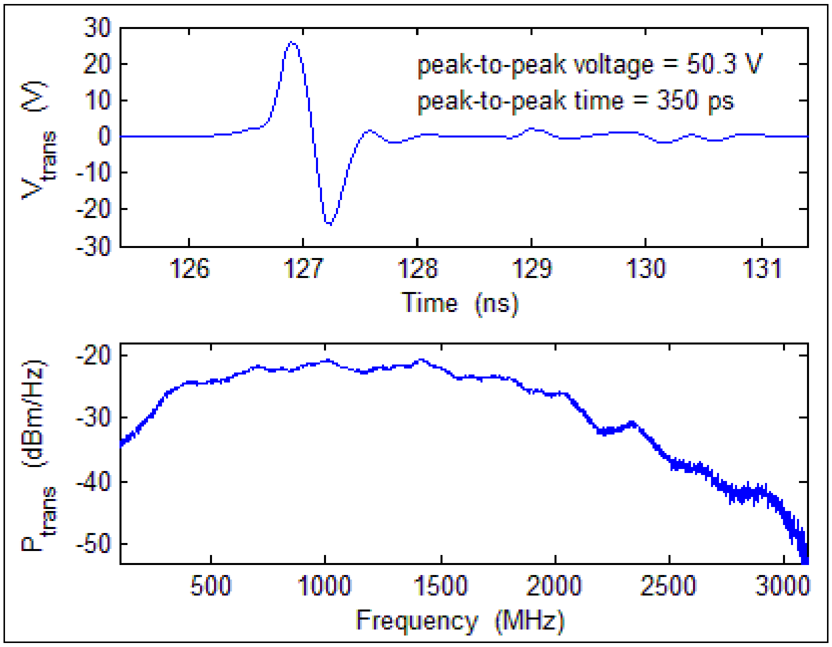

Figure 2. SIRE UWB radar pulse sample from Avtech generator: (a) time domain and (b) frequency domain.

As illustrated in figure 1, part of the pulse is transmitted into free-space and part of the pulse is reflected back towards the Avtech generator because the TEM horn is not matched to the system impedance (50 Ω) over the entire bandwidth of the pulse. The antenna's impedance mismatch, displayed as its reflection coefficient, is shown in figure 3a.

The reflection coefficient of the TEM horn generally ranges from –35 to –10 dB over the operating range of the radar. At the frequencies where $|S_{11}|$ reaches its peaks, approximately 10% of the radar pulse power is reflected from the antenna. The signal reflected from the horn antenna returns to the output of the Avtech generator, where it encounters an output circuit that has changed state to a "quasi-open" circuit as a result of outputting the impulse. This impedance mismatch (higher reflection coefficient), after the radar trigger has fired, is shown in figure 3(b). The output reflection coefficient of the Avtech source generally ranges from –10 to –2 dB. Over the operating range of the radar, the source re-reflects 10% to 60% (frequency-dependent, see figure 3b) of the power that arrives back at its output.

The forward and reverse transmission coefficients for the 2-ft cable, which currently connects the Avtech pulse generator to the TEM horn antenna, are given in figure 3c. The cascaded coefficient of retransmission, which is the sum of the traces in figures 3a, b, and c, is given in figure 3d. The trace in figure 3d shows that, at some frequencies, as much as 4% of the initial radar pulse that arrives at the transmit antenna (a) reflects from the antenna input, (b) is transmitted back to the pulse generator, (c) reflects from the generator output, and (d) is transmitted back to the antenna, where this process begins anew.

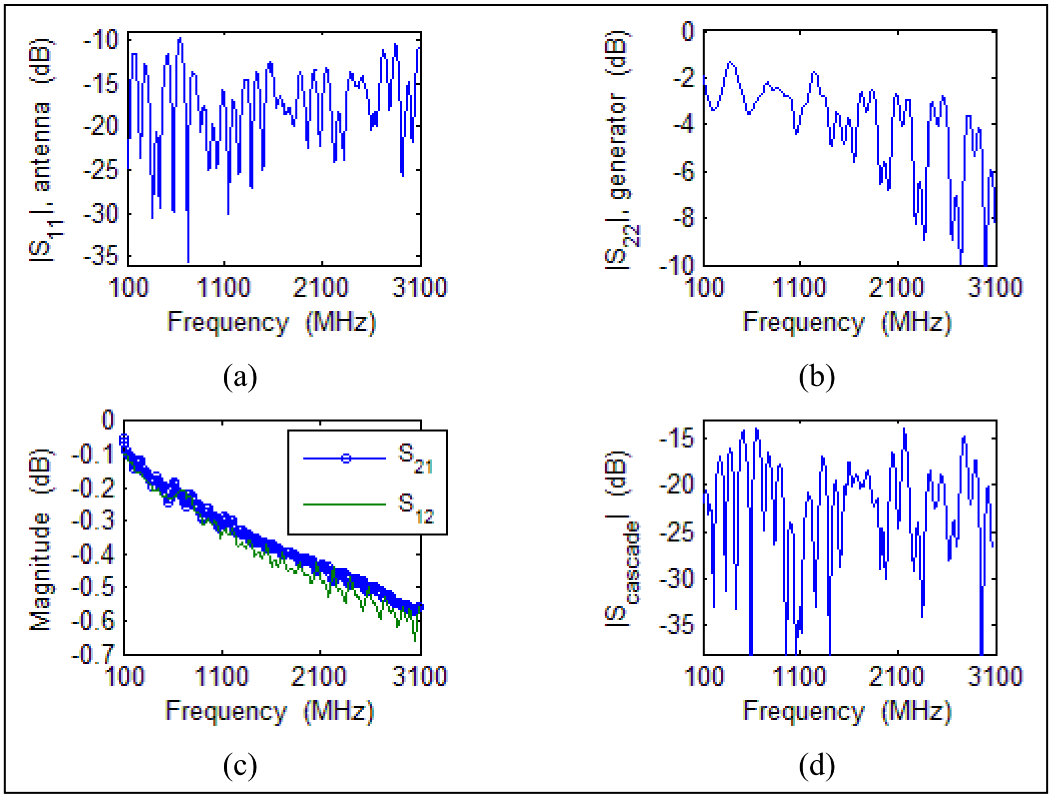

Figure 3. Reflection and transmission coefficients for SIRE frontend components: (a) reflection from TEM horn input, (b) reflection from Avtech pulse generator output, (c) transmission through MiniCircuits 2-ft cable, and (d) sum of $|S_{11}|$, $|S_{22}|$, $|S_{21}|$, and $|S_{12}|$.

The distorted, delayed version of the initial pulse is transmitted by the TEM horn and produces undesired target echoes. A sample SIRE radar image of a wooden stump and a water-filled plastic barrier, taken in a field of grass and brush, is shown in figure 4. The pulse reflection from the stump is weak, so it appears only once in the image before being reduced to the noise floor of the image. The pulse reflection from the water barrier is strong, and it generates multiple returns: the true target image (whose left/right edges are depicted as red circles) and echoes behind the image, with decaying amplitude. The echoes appear to be targets, which would register false alarms in a radar environment having a dense collection of targets.

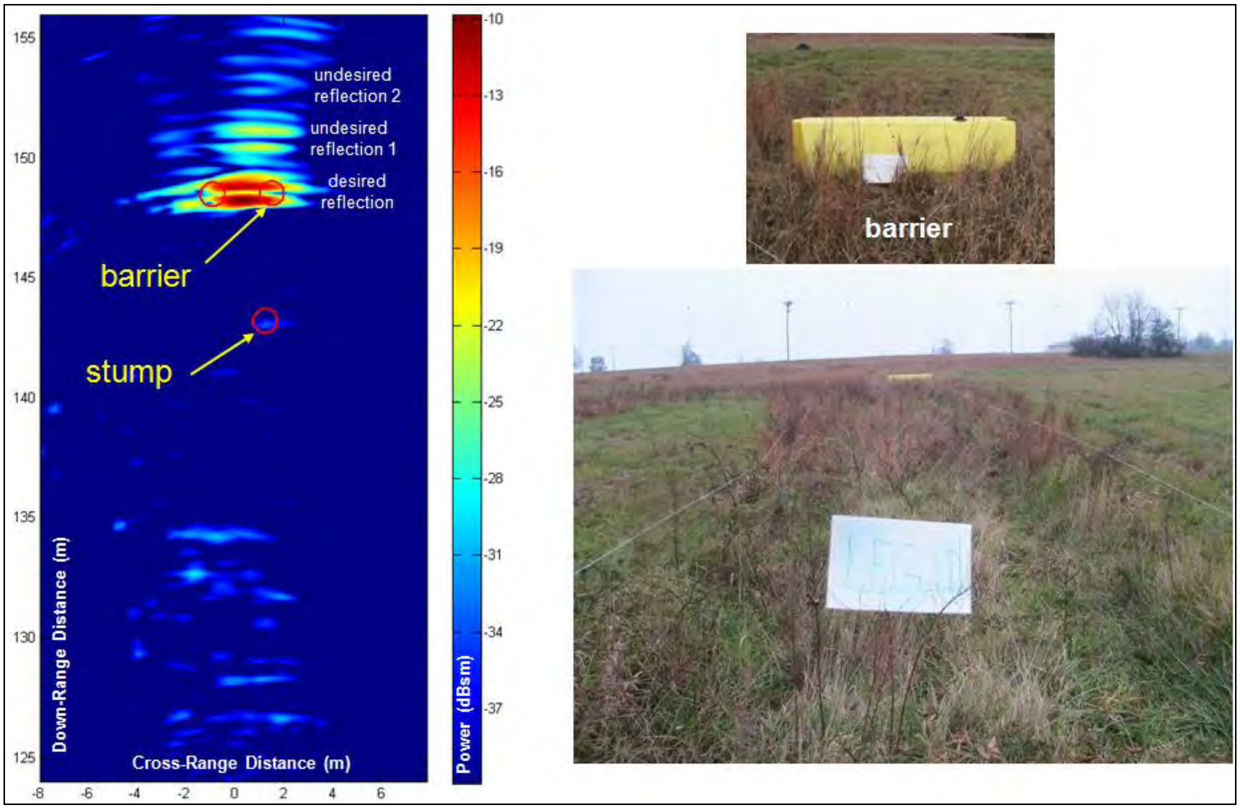

Figure 4. Sample radar image displaying target echoes. The true image of the barrier appears due to the desired reflection of the radar pulse. Echoes of the barrier appear behind the target due to the undesired reflection of the radar pulse.

An acceptable solution for eliminating these echoes must attenuate each undesired pulse by more than 10 dB while attenuating each desired radar pulse by less than 3 dB. A block diagram of the solution that will achieve these two goals is shown in figure 5.

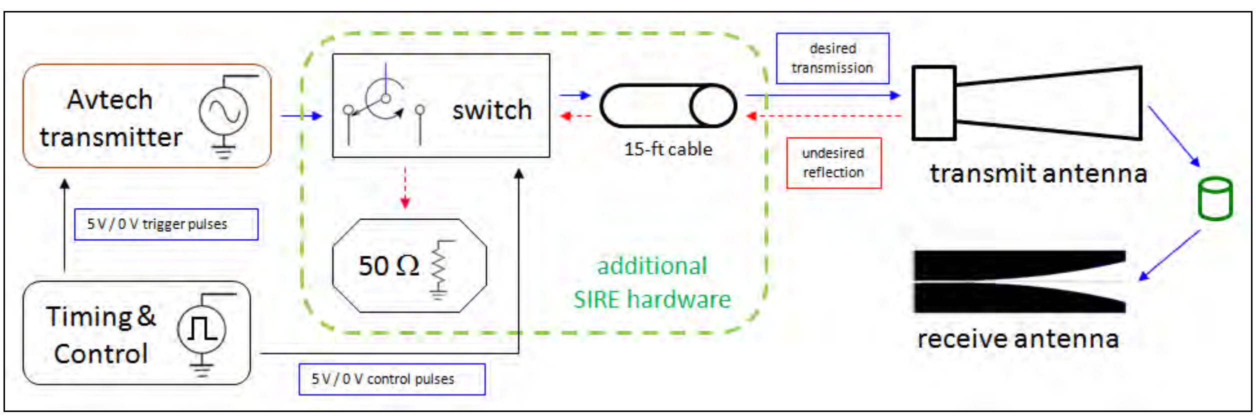

Figure 5. New SIRE radar frontend, incorporating a high-speed switch and 15-ft cable.

The additions to the SIRE frontend are the switch, the 15-ft cable, and the 50-Ω load. The switch initially connects the 15-ft cable to the Avtech source, passing the radar's UWB pulse to the transmit antenna. Soon after the pulse passes into the 15-ft cable, the switch connects the cable input to the 50-Ω load. As the radar pulse reflects from the TEM horn back towards the source, the switch redirects this undesired signal into the 50-Ω load. A cable length of at least 15 ft is chosen in order to delay the arrival of the undesired reflection back at the switch until after the switch has transitioned from the antenna/source connection to the antenna/termination connection.

This switch-cable-load circuit dissipates the undesired reflection so that almost none of the original radar pulse re-reflects towards the transmit antenna. Retransmissions are significantly attenuated and echoes are removed from the radar image.

3. Signal-delay Cable

Inserting a 15-ft cable between the pulse generator and its antenna introduces loss and distortion to the radar signal. In this section, the severity of these effects is investigated.

3.1 Frequency-domain, Small-signal

The insertion losses of three types of 15-ft cables are plotted in figure 6.

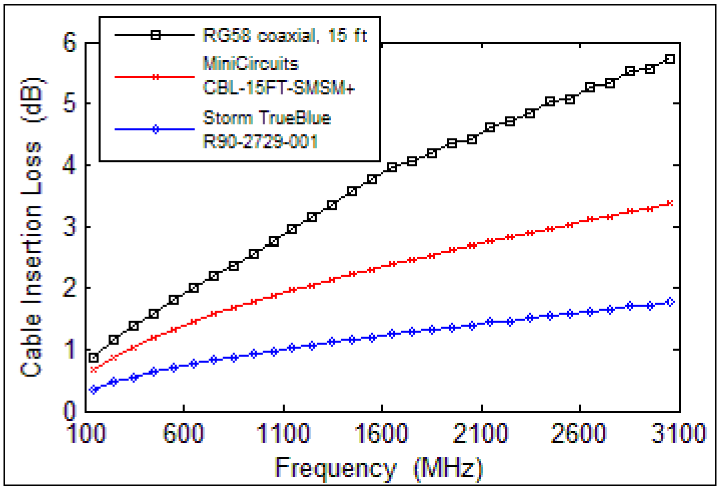

Figure 6. Losses incurred by placing a 15-ft cable between the pulse generator and antenna, measured using the Rohde & Schwarz ZVB-8 network analyzer.

The loss of a typical 15-ft RG58 coaxial cable is more than 3 dB for most of the radar's operating band, so it is unsuitable for use in the frontend redesign. The MiniCircuits and Storm TrueBlue cables both attenuate the input signal by less than 3 dB for most of the radar's operating band. However, the loss of the Storm TrueBlue cable is approximately 1 dB less than that of the MiniCircuits cable, for the same 15-ft length, over these same frequencies.

3.2 Time-domain, Large-signal

Time-domain captures of the radar pulse from the Avtech AVB1-3 generator, comparing the MiniCircuits 2-ft cable used in the current radar design against the aforementioned 15-ft cables, are given in figure 7.

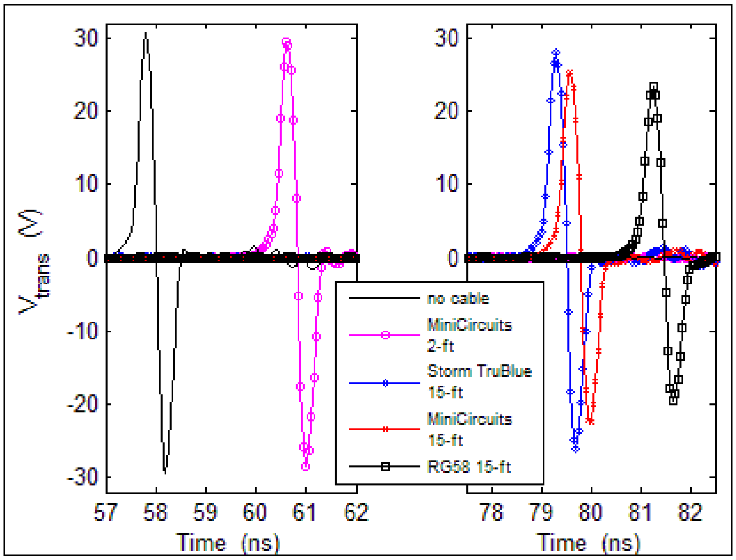

Figure 7. Time-domain traces for cable comparison using the radar waveform: recorded using the Lecroy Wavemaster 8300A oscilloscope (with 40-dB front-panel attenuation).

The peak-to-peak amplitude of the radar pulse is attenuated by 0.9 dB when using the Storm TrueBlue cable (compared to no cable), by 2.0 dB when using the MiniCircuits 15-ft cable, and by 2.9 dB when using ordinary RG58 coaxial line. If the radar waveform is approximated as a single-cycle sinusoid at 1100 MHz, this peak-to-peak loss is consistent with the measurements taken near 1100 MHz as reported in figure 6.

The one-way pulse transit time through the 15-ft Storm TrueBlue cable is 21.5 ns, through the 15-ft MiniCircuits cable is 21.8 ns, and through the 15-ft RG58 cable is 23.5 ns. Because the delay difference between the three cables is minimal and because the Storm TrueBlue cable provides lower loss than both the MiniCircuits and RG58 cables, the Storm TrueBlue is chosen to follow the switch in the frontend redesign.

4. High-speed Switch

Inserting a high-speed switch between the pulse generator and its antenna will also introduce loss and distortion to the radar signal. In this section, the effects of adding the switch alone to the SIRE frontend are investigated. The performance of four switches is compared.

The requirements for the high-speed switch to be used in the SIRE radar are (a) a wide bandwidth to pass the UWB radar pulse with negligible linear distortion, (b) a power-handling capability greater than the power generated by the Avtech AVB1-3 to pass the radar pulse with negligible nonlinear distortion, (c) a quick transition between states with a switching time less than twice the propagation delay of the 15-ft cable, and (d) low loss, preferably less than 2 dB, to maintain a reasonable signal-to-noise ratio in the final radar images.

4.1 Power Handling: Peak versus Average

The power of the radar pulse while it is on, P_{pulse}, is approximately

$$P_{\text{pulse}} = \frac{1}{2}\left(V_{\text{peak}}^2/R\right) = \frac{1}{2}\left[\left(25\,V\right)^2/50\,\Omega\right] = 6.25\text{ W} \tag{1}$$

where the pulse is approximated as a sinusoid with a maximum/minimum voltage $V_{\text{peak}} = \pm 25$ V. Since the pulse is approximately $T_{\text{ON}} = 800$ ps long and it is transmitted once per µs, the average power of the radar signal, measured at the output of the Avtech generator, is

$$P_{\text{avg}} = \frac{T_{\text{ON}}}{T_{\text{ON}} + T_{\text{OFF}}} P_{\text{pulse}} = \left(\frac{800\text{ ps}}{1\,\mu\text{s}}\right)\left(6.25\text{ W}\right) = 5\text{ mW}\,. \tag{2}$$

Few commercially available switches are capable of transmitting 6.25 W with an ON/OFF transition time under 43 ns (twice the Storm TrueBlue cable delay). There are many more switches capable of transmitting a lower power with a shorter transition time. Hittite manufactures several switches capable of transmitting 5 mW average power with a transition time under 10 ns. Four such switches are tested:

- HMC221: max power = 0.1 W, transition time = 3 ns, control-to-switch time = 6 ns
- HMC232LP4: max power = 1.0 W, transition time = 3 ns, control-to-switch time = 6 ns
- HMC536: max power = 0.8 W, transition time = 15 ns, control-to-switch time = 30 ns
- HMC484: max power = 10.0 W, transition time = 15 ns, control-to-switch time = 40 ns

It is unclear from their datasheets whether or not these switches will, with minimal loss and distortion, pass the SIRE radar pulse whose peak power is greater than its average power by more than a factor of 1000. It appears that the HMC484 switch will be able to pass the 6.25-W pulse and switch off within the required 43 ns, but it is unknown if the pulse will be attenuated or distorted by passing the signal and turning the switch off in rapid succession.

4.2 Radar Pulse Transmission: Pass-through, Without ON/OFF Transition

To determine which of the four Hittite switches are able to transmit the 6.25-W peak-power radar pulse, the following test was conducted:

1. the switch was turned ON (i.e. the "common" and "RF1" ports were connected while the "common" and "RF2" ports were disconnected) from $t = 0$ to $t = 500$ ns,
2. the radar pulse was applied to the "RF1" port after the Avtech AVB1-3 was triggered at $t = 100$ ns,
3. the switch was turned OFF (i.e. the "common" and "RF1" ports were disconnected while the "common" and "RF2" ports were connected) from $t = 500$ ns to $t = 1000$ ns, and
4. the voltage at the "common" port was recorded. The results of this test are reported in figure 8.

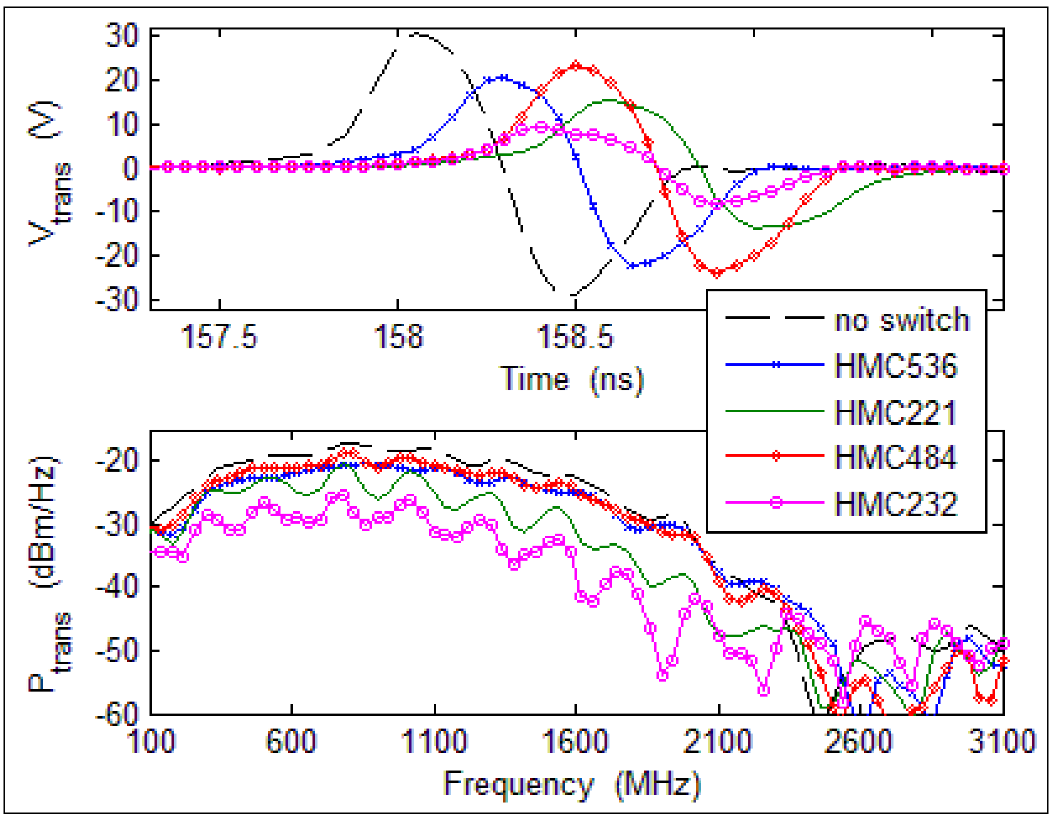

Figure 8. Time and frequency-domain traces for switch comparison using the radar waveform.

The peak-to-peak voltage of the pulse is attenuated by 1 dB through the HMC484, by 2 dB through the HMC536, by 5 dB through the HMC221, and by 9 dB through the HMC232. The shape of the pulse is distorted somewhat by the HMC221 and HMC232, while the pulse is only minimally distorted by the HMC484 and HMC536. In the frequency domain, considerable attenuation and distortion is observed for the HMC221 and HMC232, while minimal attenuation and distortion are observed for the HMC484 and HMC536. The HMC221 and HMC232 are unsuitable for passing the radar signal. Only the HMC484 and HMC536 are considered in further analysis.

4.3 Reflection Attenuation

The experiment used to compare the HMC484 and HMC536 for attenuating undesired pulse retransmissions is shown in figure 9. The Highland P400 pulse generator outputs two complementary 5-V pulses to control the state of the HMC switch and triggers the Avtech pulse generator. The GW GPS-3303 unit provides 15-V power to the Avtech source and 5-V power to the HMC536 and HMC484 switches. To attenuate a realistic reflection from a transmit antenna, a 15-ft Storm TrueBlue cable connects the common port of the switch to a SIRE TEM horn antenna. The Hewlett Packard 11607-60001 coupler samples the signal applied to the antenna by the switch/cable configuration. The Lecroy Wavemaster 8300A oscilloscope records the radar pulses applied to the transmit antenna (attenuated by 40 dB).

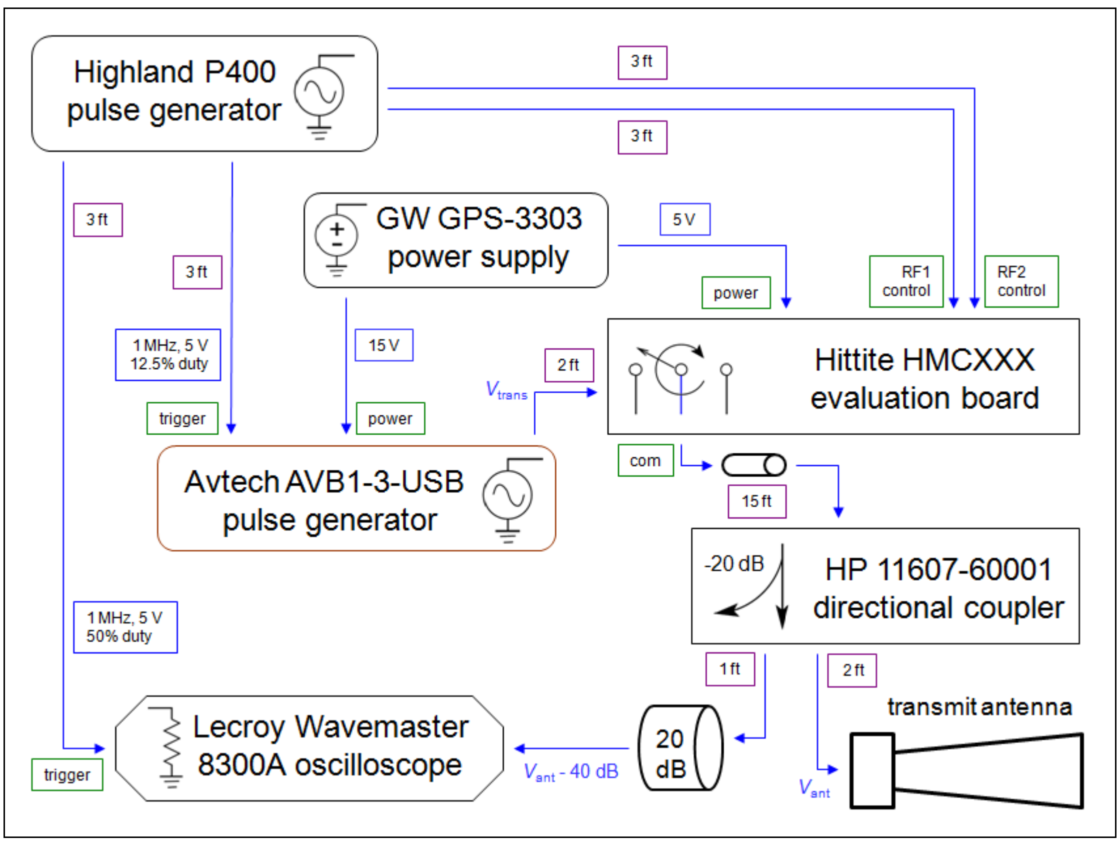

Figure 9. Measurement setup for comparing switches by attenuating antenna retransmissions.

Plotted in figure 10 are (a) the peak-to-peak attenuation of the desired pulse transmission and (b) the peak-to-peak attenuation of the undesired pulse retransmission, as a function of the time at which the switch is turned off after the radar trigger is fired. Each data point represents a separate run of the experiment, with the switch transition time specified by the horizontal axes of figure 11. The switch has been turned "on" (connecting the antenna to the pulse generator) for more than 100 ns; this time is the same for each run. The switch is turned "off" (connecting the antenna to the 50-Ω load) at a different time for each run. Each data point represents the attenuation of the desired/undesired pulse for the different locations of the switch control-pulse transition, referenced to the radar trigger-pulse transition.

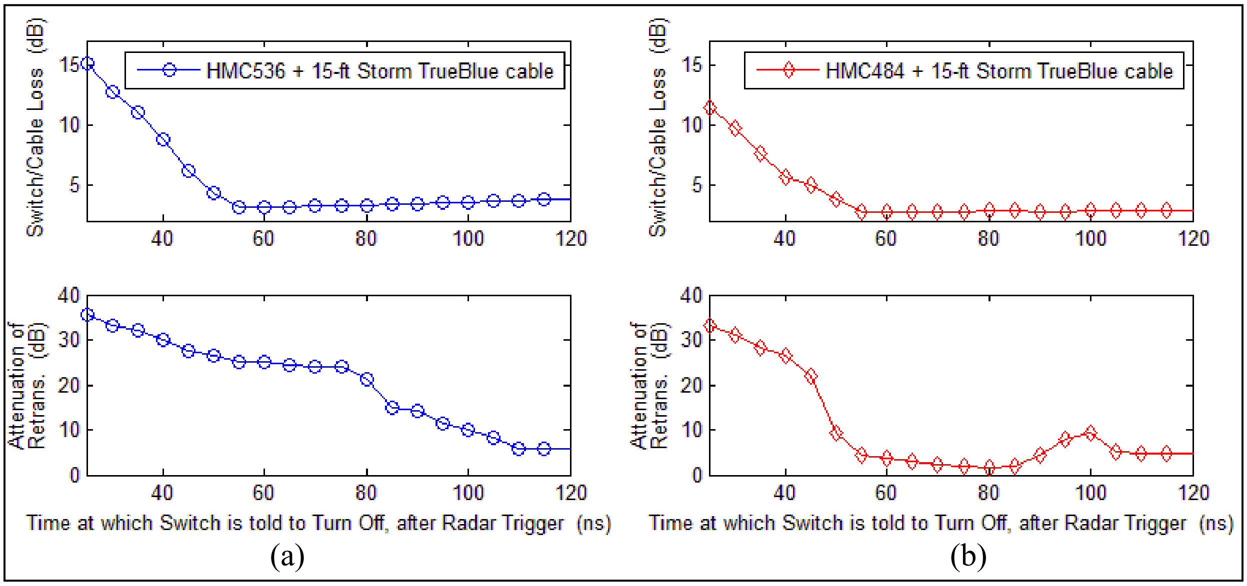

Figure 10. Signal loss and retransmission attenuation vs. switch turn-off timing: (a) HMC536 switch and (b) HMC484 switch.

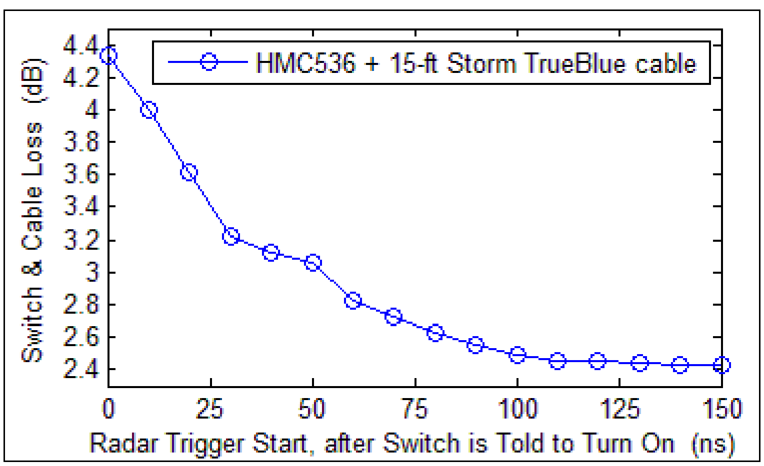

Figure 11. Desired-pulse loss vs. switch turn-on timing.

First, the peak-to-peak voltage of the coupled output of the desired radar pulse, *without* the switch or cable inserted in the signal path, was recorded: $V_{\text{des}}(t)$. Next, the peak-to-peak voltage of the coupled output of the desired radar pulse, *with* the switch and cable inserted in the signal path, was recorded: $V'_{\text{des}}(t)$. The ratio of the two appears in the upper plot of figures 10a and b: switch/cable loss = $20\log\left[V_{\text{des}}(t)/V'_{\text{des}}(t)\right]$.

The peak-to-peak voltage of the coupled output of the undesired radar pulse (the next largest pulse to reach the antenna), *without* the switch or cable in the signal path, was recorded: $V_{\text{und}}(t)$. Next, the peak-to-peak voltage of the coupled output of the undesired radar pulse, *with* the switch and cable in the signal path, was recorded: $V'_{\text{und}}(t)$. The ratio of these two appears in the lower plot of figures 10a and b: attenuation of retransmission = $20\log\left[V_{\text{und}}(t)/V'_{\text{und}}(t)\right]$.

If the HMC536 were selected for use in the radar frontend, its turn-off signal should take place between 55 and 75 ns after the radar trigger. During this time-period, the switch/cable loss is at a minimum (under 3 dB), while the antenna retransmission is attenuated by more than 25 dB. If the switch transitions before 55 ns, the desired pulse is attenuated, and because the desired pulse is weak, the retransmission is weak. If the switch transitions after 75 ns, the desired pulse remains strong, but the undesired pulse returns to (and reflects from) the switch before it can transition completely, and so the retransmission is also strong.

For the HMC484 switch, there is only a small window of time during which the desired pulse is relatively strong and the retransmission is relatively weak: between 40 and 50 ns. However, at 40 ns the attenuation of the desired pulse is 6 dB, which is unacceptable, and at 50 ns the attenuation of the retransmission is 10 dB, which is marginal. Considering the transmission of the desired radar pulse and the attenuation of its undesired retransmission simultaneously, the HMC536 switch outperforms the HMC484 switch. The HMC536 switch is selected for further testing.

4.4 Radar Pulse Transmission: Pass-through, With ON/OFF Transition

To determine the minimum amount of time required for the HMC536 switch to settle before it passes the radar pulse completely, the switch-and-cable loss is plotted as a function of the time at which the radar trigger fires after the switch is told to turn on. This data is given in figure 11.

If the switch transitions too soon after the radar pulse is triggered, the switch will not be completely open and the desired signal will be attenuated. Given additional time between the radar trigger and the switch transition, the switch will settle into a more open state and the desired signal will pass with less attenuation. The loss due to the switch and cabling is less than 3 dB if the radar trigger fires at least 100 ns after the switch is told to connect the pulse generator to the antenna.

5. Printed Circuit Board

To evaluate the performance of the switch-cable-load circuit as part of the SIRE frontend more realistically, the HMC536 switch and its controller are placed on a PCB and inserted between the Avtech source and the TEM horn antenna. This section discusses the switch controller, provides a block diagram of the new SIRE hardware, and shows the performance improvement measured when this hardware is added to the SIRE frontend.

5.1 Switch Control: Dual-output Comparator

Since the HMC536 requires dual complementary control signals and only a single switch-control line is available on the Timing & Control board, the Maxim MAX963 comparator is selected to convert a single 5-V control signal into two complementary 5-V control lines.

The 5-V control signal from the Timing & Control board is connected to the inverting input of the comparator, while a constant 2.5 V (generated using a resistive divider) is connected to the non-inverting input of the comparator. When the inverting input is 5 V, the inverting output is 5 V and the non-inverting output is 0 V. When the inverting input is 0 V, the inverting output is 0 V and the non-inverting output is 5 V. The DC voltage tied to the non-inverting input is selected halfway along the inverting input voltage swing to minimize logic errors.

5.2 PCB Diagram and Performance

A block diagram of the PCB containing the HMC536 switch, MAX963 comparator, 50-Ω load, associated coupling capacitors and resistors, and the connection to the Storm TrueBlue 15-ft cable is shown in figure 12. A picture of the corresponding fabricated PCB is given in figure 13. This PCB contains both the solid-state switch and an electromechanical relay that connects a single Avtech unit to the two transmit antennas. The relay circuit is discussed in the appendix.

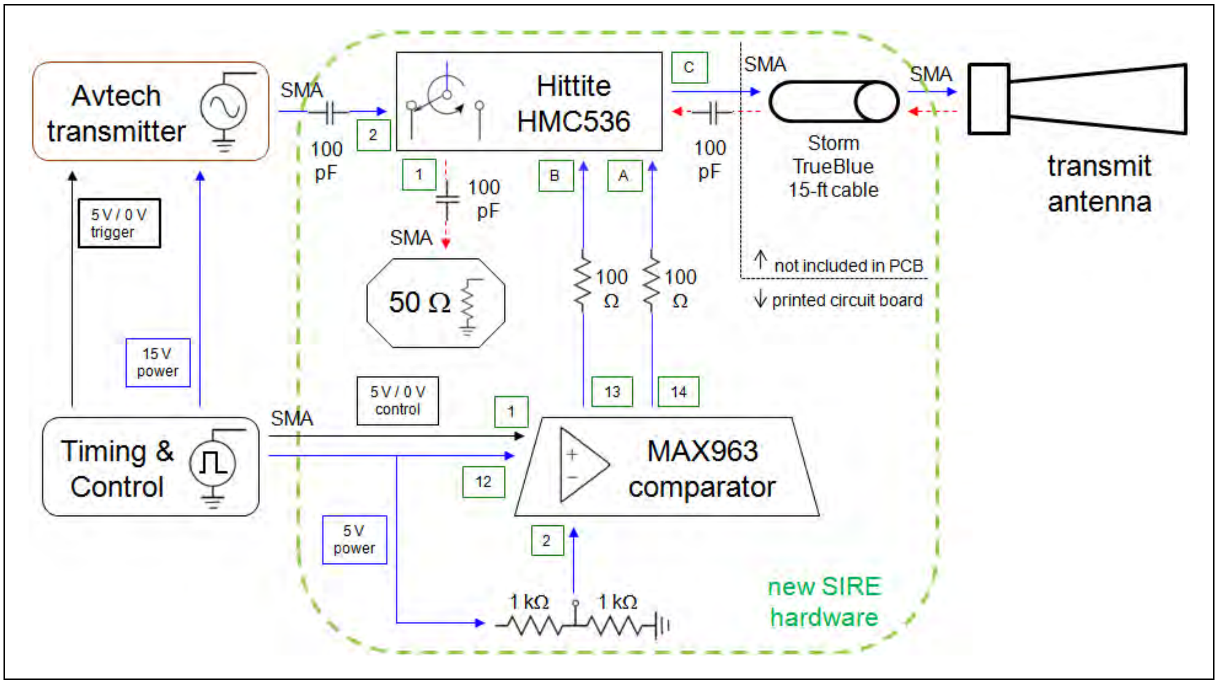

Figure 12. SIRE frontend redesign block diagram.

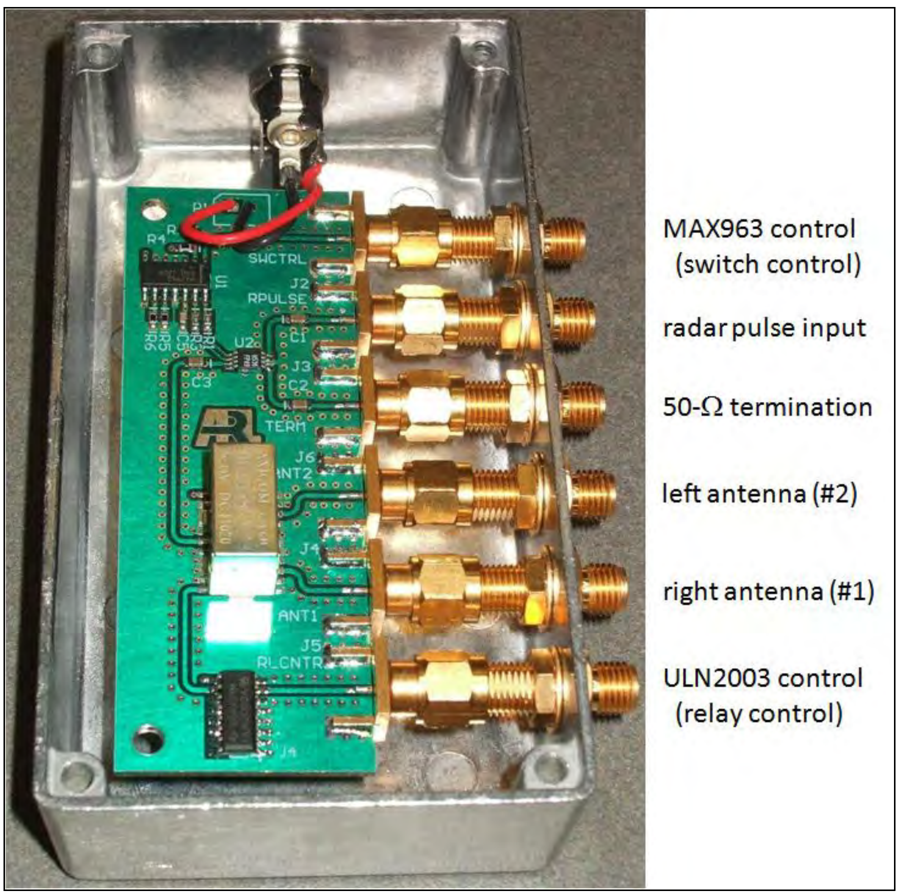

Figure 13. PCB containing the parts shown in figure 12.

In section 4.4, it was found that the radar trigger should take place at least 100 ns after the comparator's control pulse changes from 0 to 5 V (turning the switch on). In section 4.3, it was found that the switch turn-off should take place between 50 and 80 ns after the radar is triggered. Given these two constraints and maintaining a radar trigger length of 125 ns from the current SIRE design, the signals required from the Timing & Control board to achieve low loss in the desired transmissions and high attenuation of the undesired retransmissions are as depicted in figure 14.

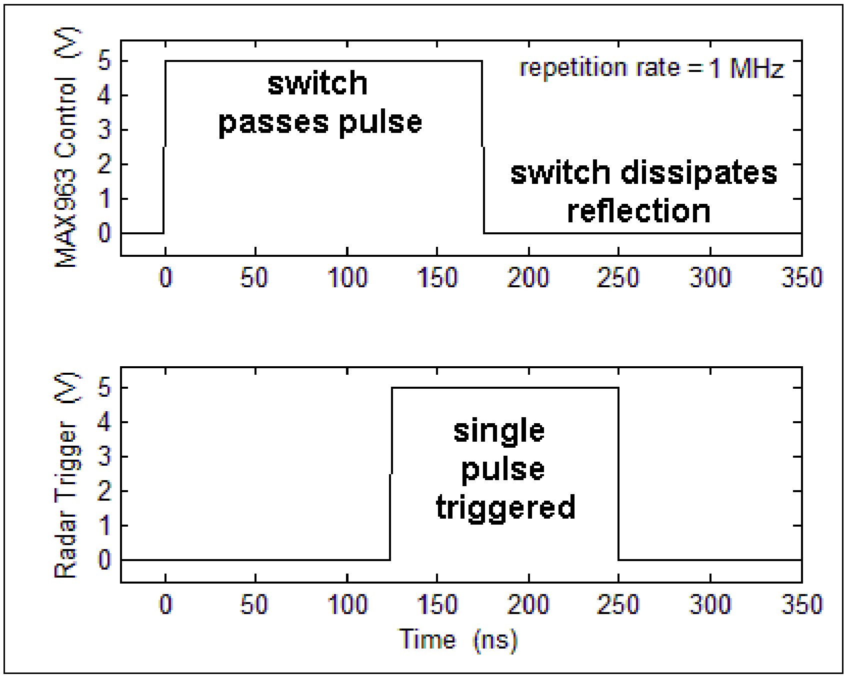

Figure 14. Timing diagram for the new transmitter configuration, incorporating the HMC536 switch.

The performance of the PCB and cabling when added to the SIRE frontend is evaluated using figure 15. Using the "old frontend," without the switch-cable-load circuit, the radar pulse is transmitted with a peak-to-peak amplitude of 48.1 V, and the first reverberation between the antenna and pulse generator is retransmitted with a peak-to-peak amplitude of 3.3 V. Using the "new frontend," inserting the switch-cable-load between the antenna and pulse generator, the radar pulse is transmitted with an amplitude of 35.5 V, and the reverberation is retransmitted with an amplitude of 0.40 V. The loss in the desired transmission is 2.6 dB, while the attenuation of the retransmission is 18.4 dB.

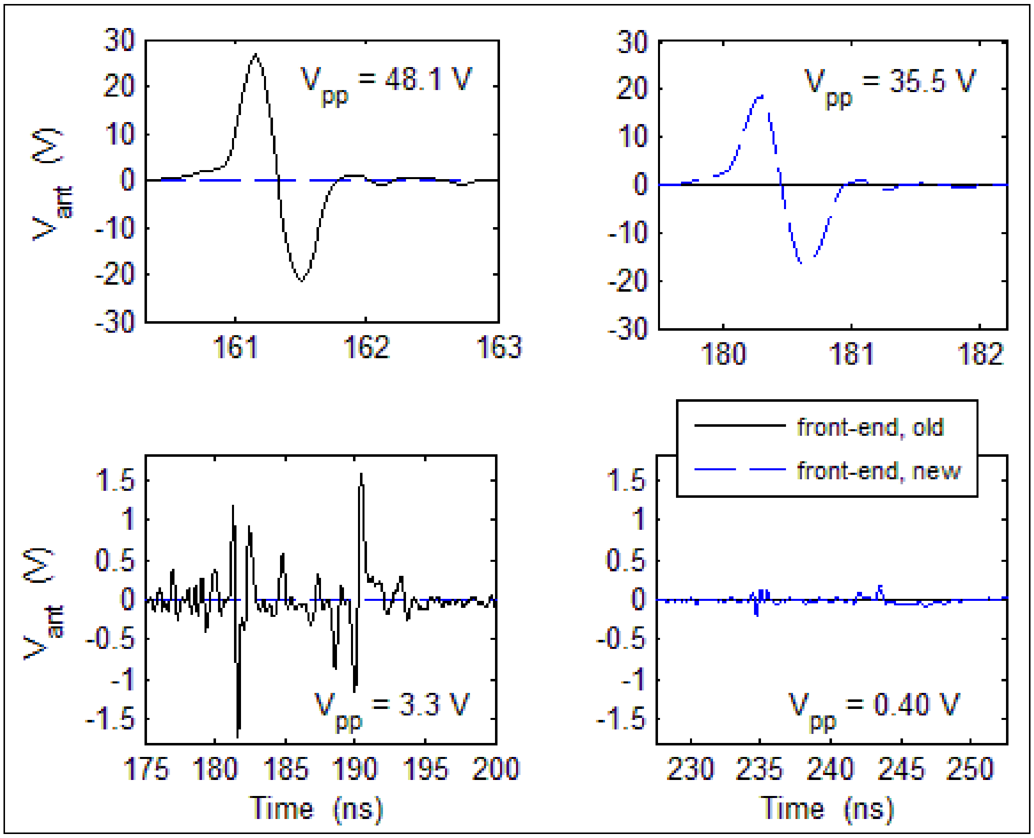

Figure 15. Comparison of the new SIRE frontend design (with switch and 15-ft cable) against the old design: radar pulse transmitted to antenna (above) and retransmission to antenna (below).

6. Conclusions

A method for reducing frontend pulse reflections from an impulse-based radar system was presented. The high-speed switching solution permits impedance mismatch of frontend components and the generation of undesired replicas of the desired transmit pulse, but it dissipates the undesired replicas in a matched load before they can be emitted from the transmit antenna.

A PCB, which implements the circuit solution, was fabricated and tested as part of the ARL SIRE radar. Measurements showed attenuation of the undesired pulse transmissions greater than 18 dB at the expense of an attenuation in the desired pulse transmission under 3 dB.

7. References

1. Ressler, M.; Nguyen, L.; Koenig, F.; Wong, D.; Smith, G. The Army Research Laboratory (ARL) Synchronous Impulse Reconstruction (SIRE) Forward-Looking Radar. *Proceedings of the SPIE*, Vol. 6561, 2007.

2. Nguyen, L. *Signal and Image Processing Algorithms for the U.S. Army Research Laboratory Ultra-Wideband (UWB) Synchronous Impulse Reconstruction (SIRE) Radar*; ARL-TR-4784; U.S. Army Research Laboratory: Adelphi, MD, April 2009.

3. Koenig, F.; Ressler, M.; Smith, G.; Nguyen, L.; Harris, R. *Synchronous Impulse Reconstruction (SIRE) Radar Sensor*; ARL-TR-4661; U.S. Army Research Laboratory: Adelphi, MD, November 2008.

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Appendix. Single-Transmitter Operation using an RF Relay

In addition to reflections caused by mismatch between each pulse generator and its transmit antenna, the performance of the SIRE radar suffers from another problem: imbalance between its two transmitters.

The radar transmits UWB pulses from two antennas, left and right, as seen in figure A-1a. Currently, each antenna is fed by its own Avtech pulse source, as seen in figure A-1b. A block diagram of this transmitter configuration is given in figure A-2.

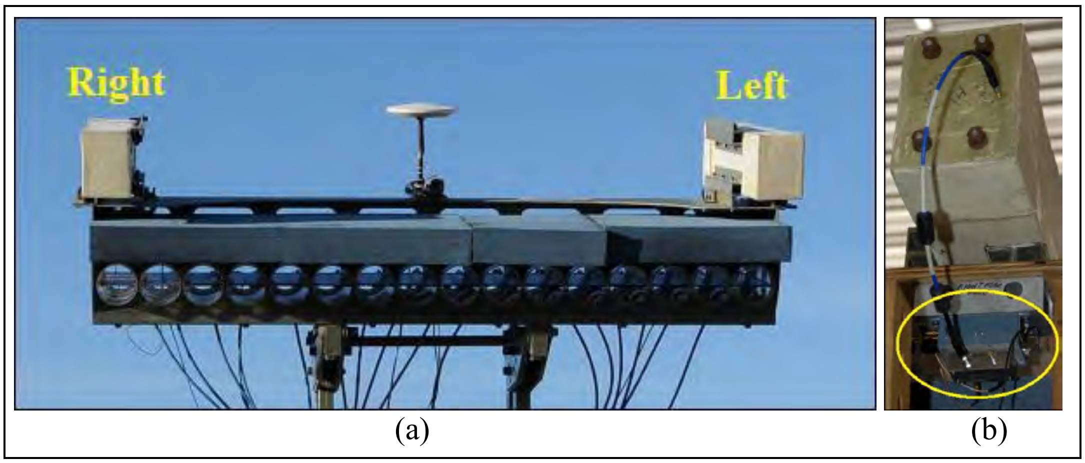

Figure A-1. Transmit antenna configuration for SIRE radar: (a) full antenna array, as seen from the front of the radar and (b) right transmit antenna, as seen from behind the radar, with its Avtech source circled.

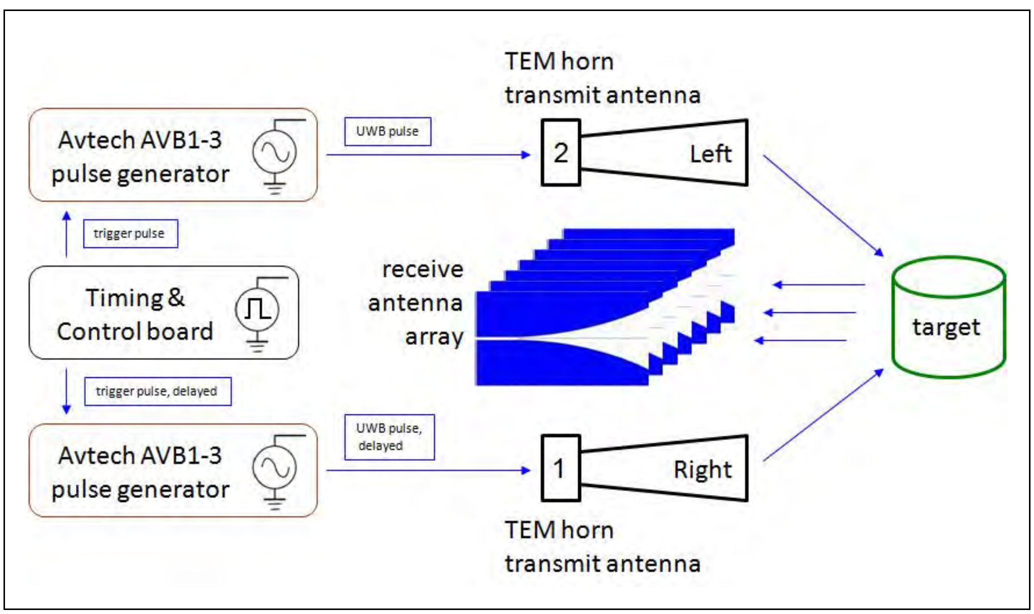

Figure A-2. SIRE radar frontend: two transmit paths, two Avtech pulse generators.

The two sources output pulses with unequal delays and frequency responses, which produce an imbalance between the two transmit channels. Sample outputs from the Avtech AVB1-3-USB generators with serial numbers 10455 and 10456 are plotted in figure A-3. Figure A-3a shows the UWB pulses in the time domain. When both Avtech units are given identical trigger pulses (applied at $t = 0$), the 10456 output trails the 10455 output by 2.3 ns. Figure A-3b shows the UWB pulses in the frequency domain. Below 2.2 GHz, the two sources track each other fairly well. Between 2.2 and 2.9 GHz, the 10455 source is generally about 5 dB stronger than the 10456 source.

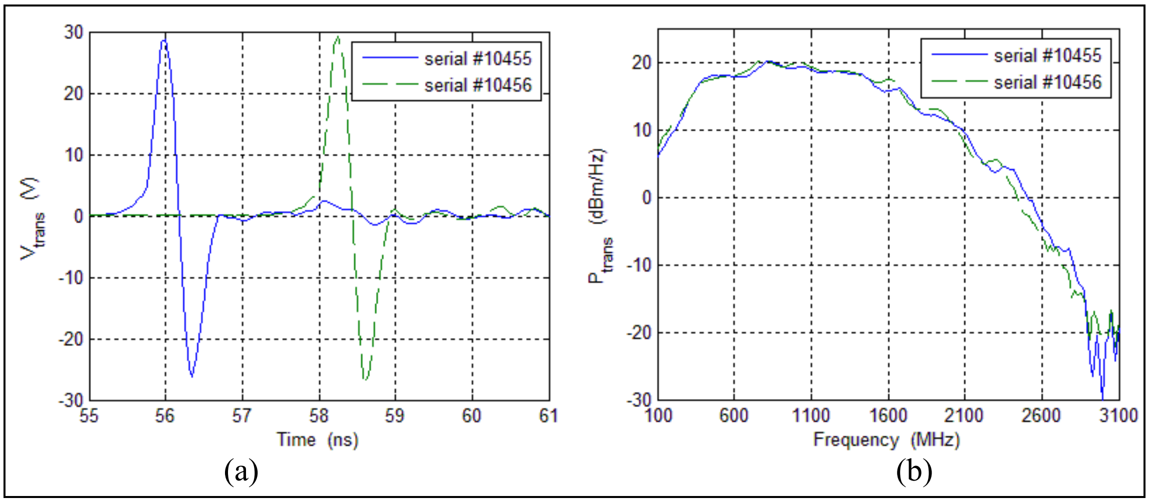

Figure A-3. Output from two Avtech pulse sources: (a) time domain, (b) frequency domain.

A-1. Balancing the Two Transmit Paths

To equalize the two transmit paths, a relay connects a single pulse generator to the two transmit antennas. A block diagram of the new transmitter configuration is given in figure A-4. The relay initially connects the Avtech unit to the left transmitter. After a set of pulses is transmitted, the relay connects the Avtech unit to the right transmitter and another set of pulses is transmitted. Then the relay reconnects the Avtech unit to the left transmitter. The relay in this configuration switches back and forth between the left and right transmit antennas at the same rate that the Timing & Control board in the previous configuration switched its control pulses back-and-forth between the left and right pulse generators. Instead of outputting two sets of trigger pulses on two channels, the Timing & Control board now outputs radar-trigger pulses on its first channel and relay-control pulses on its second channel.

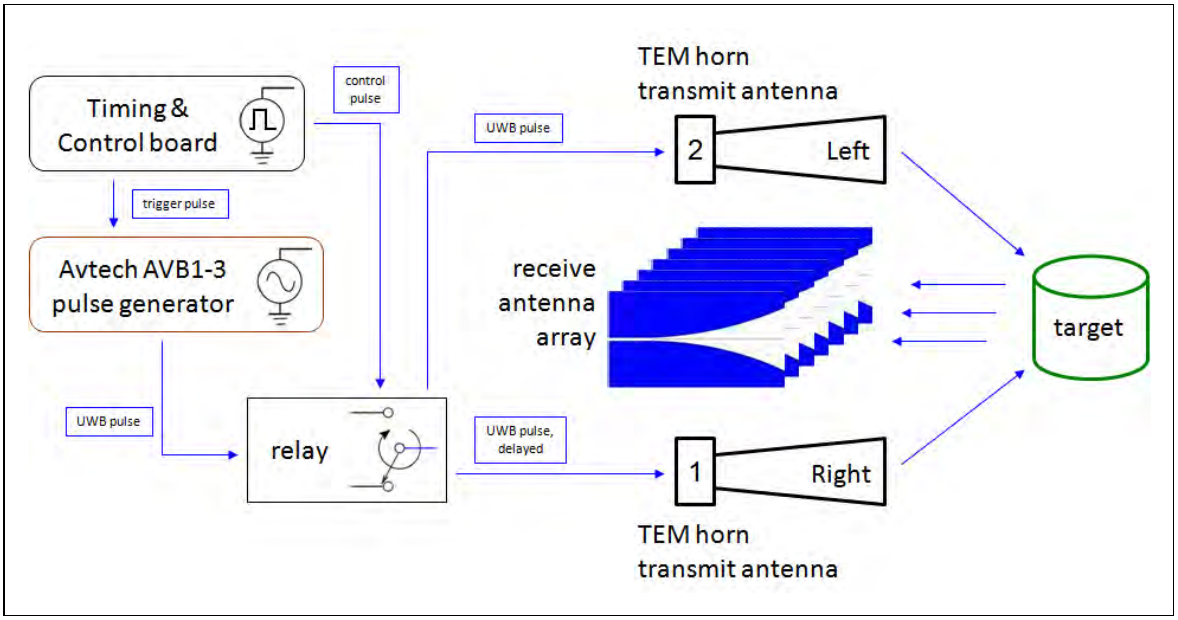

Figure A-4. New SIRE radar frontend: two transmit paths, one Avtech generator and one relay.

For the relay to function adequately as part of the SIRE radar front-end, it must satisfy the following:

1. operate between 300 MHz and 3 GHz (i.e., over the bandwidth the radar),
2. attenuate the transmitted signal by less than 1 dB over this frequency range,
3. be controlled with 5 V/0 V (the same logic as the solid-state switch),
4. be 50 Ω nominal impedance (i.e., equal to the system impedance),
5. pass at least a 6.25-W peak and 5 mW average power (calculated in section 4.1), and
6. be able to perform more than 1 million operations before it must be replaced.

The Tyco Axicom HF353S electromechanical relay appears to meet these specifications.

A-2. Electromechanical Relay Steady-State and Transient Responses

To confirm the utility of the Tyco Axicom relay as part of the new SIRE frontend configuration, the steady-state and transient responses of an HF353S were measured. The steady-state insertion loss is plotted in figure A-5 for the two relay transmit paths (two antennas) and the different switch and relay states.

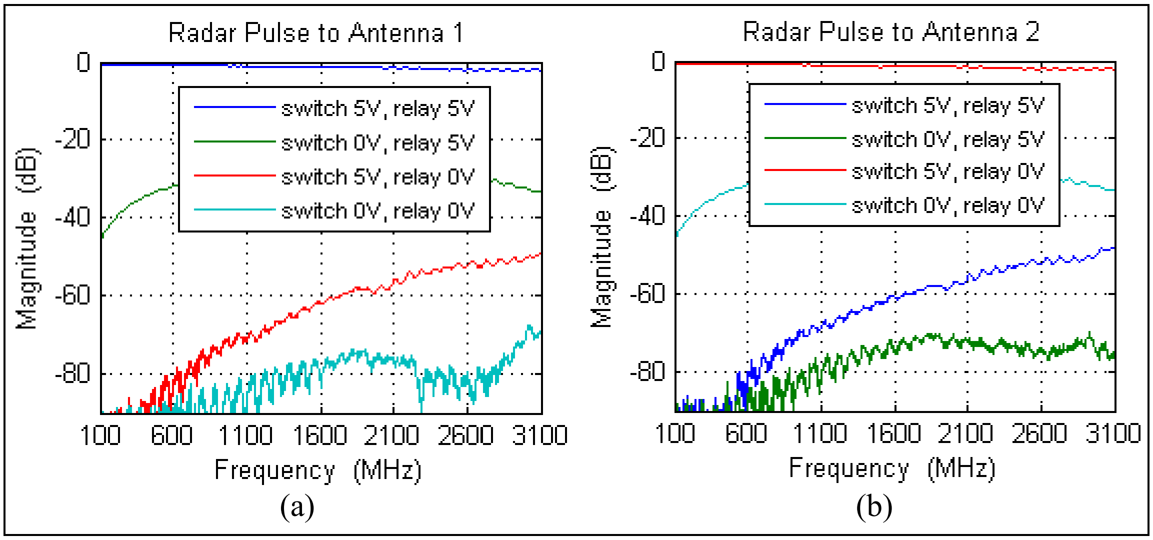

Figure A-5. Insertion loss and isolation for the HF353S relay: (a) radar pulse input to Antenna 1 connection and (b) radar pulse input to Antenna 2 connection.

When the relay is passing a signal from the radar pulse input to Antenna 1 (i.e., when 5 V is applied across the coil and 5 V is applied to the switch), the insertion loss of the switch-and-relay board is under 3 dB. At this time, the relay is blocking the signal to Antenna 2 with an isolation greater than 50 dB. When the relay is passing a signal from the radar pulse input to Antenna 2 (i.e., when 0 V is applied across the coil and 5 V is applied to the switch), its insertion loss is again under 3 dB. At this time, the relay is blocking the signal to Antenna 1, with a loss greater than 50 dB. This data indicate that the relay will pass the SIRE radar pulse with minimal loss after it has settled and only 0.001% of the radar pulse will leak into the input of the antenna that is not currently transmitting.

To measure the transient response of the relay, a sine-wave at 1 GHz and 10 dBm was applied to the radar pulse input port and the control voltage across the coil was switched between 0 and 5 V. Depending upon the control-signal level, the sine-wave is passed to either Antenna 1 or Antenna 2.

First, the control voltage was switched from 0 to 5 V and held at 5 V. Captures of the control signal and Antenna lines are shown in figure A-6. The control transitions from 0 to 5 V at 0 ms. The time required for the Antenna 2 signal to turn off is approximately 2.36 ms. The time required for the Antenna 1 signal to turn on is approximately 3.25 ms.

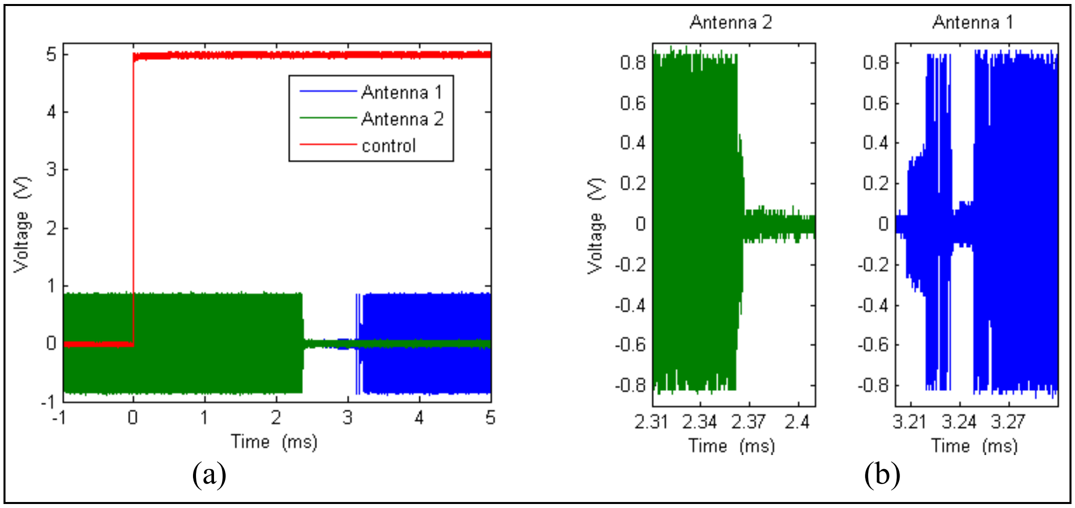

Figure A-6. Measured HF353S transient response: (a) control signal (0 to 5 V) and RF signal transitions, zoomed out, and (b) RF signal transitions, zoomed in.

Next, the control voltage was switched from 5 to 0 V and held at 0 V. Captures of the control signal and Antenna lines are shown in figure A-7. The time required for the Antenna 1 signal to turn off is approximately 1.68 ms. The time required for the Antenna 2 signal to turn on is approximately 2.69 ms.

The longest time interval required to turn the relay on or off is 3.25 ms. This time is the minimum interval required to swap the Avtech source from one antenna to the other.

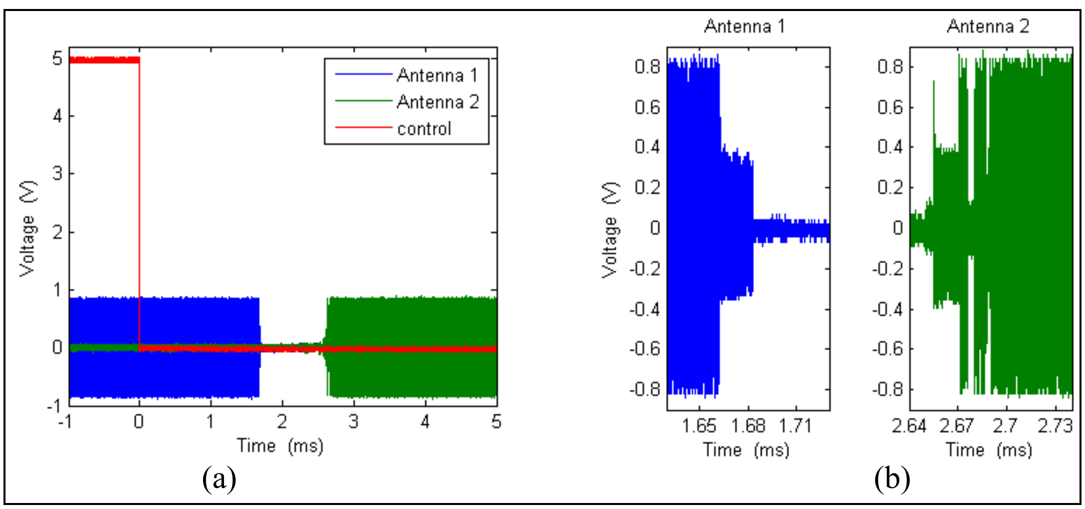

Figure A-7. Measured HF353S transient response: (a) control signal (5 to 0 V) and RF signal transitions, zoomed out, and (b) RF signal transitions, zoomed in.

A-3. Relay Control and Required Timing

To latch the connection between the radar pulse input and Antenna 1 closed and the connection to Antenna 2 open, the HF353S relay requires 28 mA driven through its coil. The Timing & Control board cannot provide this amount of current, so an integrated circuit for converting a low-current control signal to a high-current driver signal must be installed between the Timing & Control board and the relay. The circuit chosen to perform this function is the Texas Instruments ULN2003A: a high-current Darlington transistor array, capable of operating from a 5-V supply, with a 1-mA input and a 500-mA maximum output.

The Timing & Control board applies 5 or 0 V to the input of a single transistor on the ULN2003A, and the output of this transistor is connected to one side of the HF353S coil (Pin 11). A constant 5 V is applied to the other side of the coil (Pin 1). When 5 V is applied to the ULN2003A input, the transistor pulls one side of the coil down to ground with current sufficient to latch it. When 0 V is applied to the ULN2003A input, the transistor releases its side of the coil to 5 V (such that both Pin 1 and Pin 11 are at 5 V) and the coil is unlatched.

A-4. Printed Circuit Board Layout: Solid-State Switch + Electro-Mechanical Relay

A diagram of the PCB layout, which incorporates both the solid-state HMC536 switch and the electromechanical HF353S relay, along with the switch control (MAX963) and relay driver (ULN2003A), is given in figure A-8.

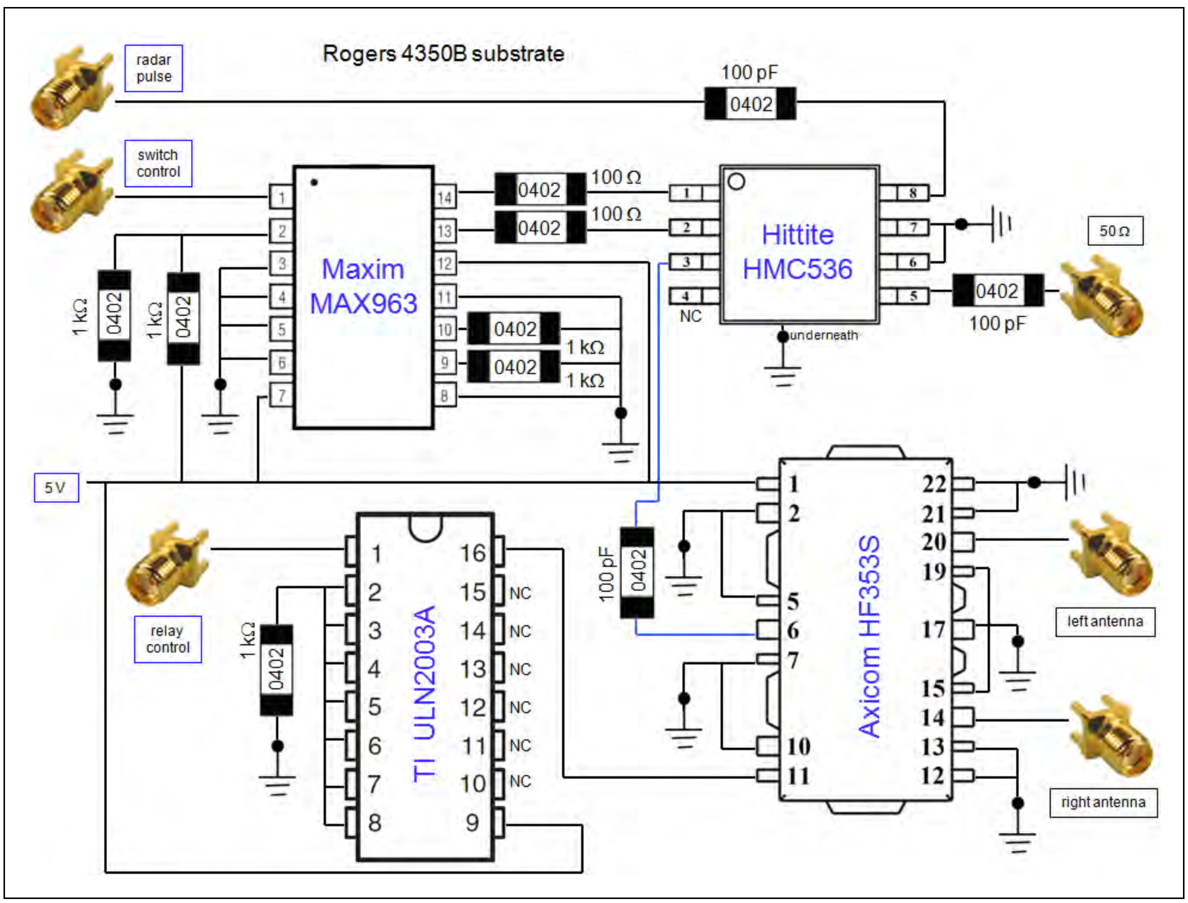

Figure A-8. PCB layout for the complete switch-and-relay circuit: Hittite HMC536 switch and Maxim MAX963 comparator, Axicom HF353S relay and Texas Instruments ULN2003A driver.

The timing signals required for the Timing & Control board to operate the HF353S relay and trigger each radar pulse are shown in figure A-9a. The timing signals required to operate the HMC536 switch (from figure 14) are reproduced in figure A-9b.

Figure A-9a shows the control signals required for the relay to swap the Avtech generator between the two transmit antennas: left ($t = 0$ to 20 ms) and right ($t = 20$ to 40 ms). Radar pulses are applied in sets, each 15 ms long ($t = 5$ to 20 ms, $t = 25$ to 40 ms). Figure A-9b shows the control signals required to transmit each individual radar pulse and dissipate antenna reflections using the switch. Within the 15-ms-long sets, the switch and radar-trigger pulse repeat at a rate of 1 MHz.

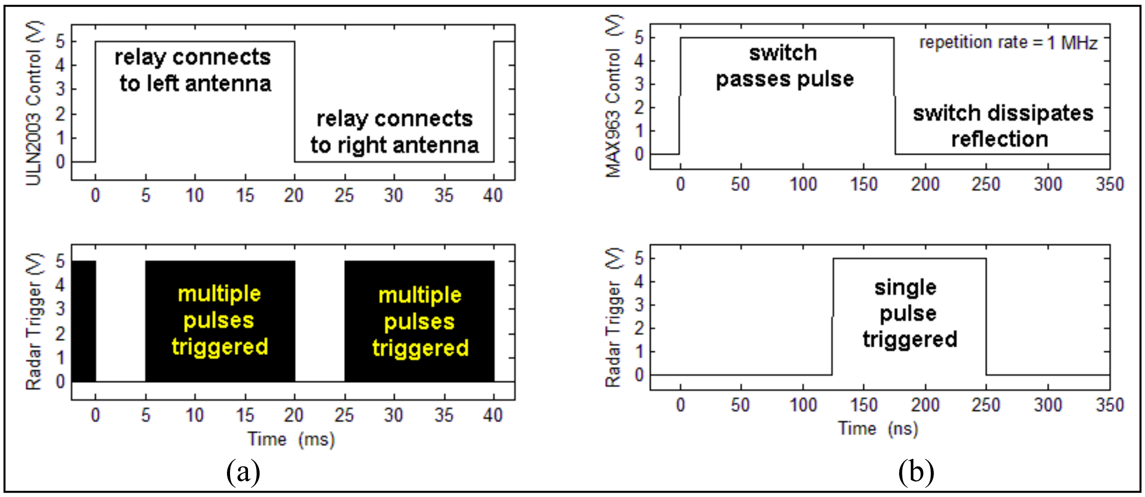

Figure A-9. Timing diagram for the new transmitter configuration, incorporating both the solid-state switch and the electro-mechanical relay: (a) HFS353S-control timing and (b) HMC536-control timing.

The signals provided to the relay must account for the delays between the control signal transition and the RF pass/block transitions, each of which is under 4 ms. According to the HF353S data sheet, however, these transition times can be as high as 5 ms; thus, after each relay-control transition, a 5-ms wait time occurs before the first radar pulse of the set is triggered.

At the highest rate of transition of the relay (every 20 ms), the radar can transmit 15,000 pulses from each antenna between transitions:

$$N_{\text{pulses}} = \frac{T_{\text{relay}} - \tau_{\text{wait}}}{T_{\text{switch}}} = \frac{20\ \text{ms} - 5\ \text{ms}}{1\ \mu\text{s}} = 15{,}000\ . \tag{A-1}$$

Each pulse trigger is accompanied by a pair of switch transitions (one before and one after the trigger) as described in section 4 and illustrated in figure A-9b.

Using the complete switch-and-relay circuit, the radar pulses are

a. transmitted from a single Avtech generator,

b. swapped between the Left and Right antennas at a maximum rate of $1/20\ \text{ms} = 50\ \text{Hz}$,

c. each delayed 125 ns so that they are transmitted completely by the switch, and

d. each cut off 50 ns after triggering so reflections from both antennas are dissipated in 50 Ω.

List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
PCB	printed circuit board
RF	radio frequency
SIRE	Synchronous Impulse Reconstruction
TEM	transverse electromagnetic
UWB	ultra-wideband

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TOTAL: 15 (1 ELEC, 14 HCS)