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Modeling and Experimental Support for Detection of Linear Conductors
Task Authorization 2: Multispectral Measurement of Scattered Radiation from Linear Conductors

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1 Introduction

There is an ongoing research program at Defence Research and Development Canada (DRDC) Suffield Research Centre (SRC) to explore electromagnetic (EM) scattering from linear conductors to better understand the physical phenomena governing this effect. The purpose of this contract is to provide technical expertise to supplement the efforts at DRDC by furthering the research on EM scattering through experimental and theoretical means.

The need to detect linear conductors is pertinent to military and commercial interests. A number of commercial applications would benefit from a reliable method to detect buried infrastructure such as wires, pipes, rods and other infrastructure critical to the delivery of crucial services to consumers. Detection of these conductors would help to significantly reduce the number of occurrences resulting in interruptions to power, water and communications services that result from excavation operations. This would directly result in time and money savings for businesses and consumers alike and help alleviate associated safety and environmental concerns.

The goal of this contract is to further the work done in previous contracts through continued model development and focused experiments that provide new insights into scattered field detection. In particular, there is a need to investigate the feasibility of detection schemes which are able to sense scattered fields over significant distances (>10 m). While much of the previous work has been centered on a portable detection system, more recent work has been looking at vehicle mounted detection concepts. There are numerous advantages of having a vehicle-based method of detection. A detector mounted on a vehicle can cover more territory than a handheld detector carried on foot. For military applications, an armoured vehicle offers a degree of protection from hostile fire. Finally, a vehicle based system is not as limited with regards to the amount of battery energy and processing power required to implement a successful detection scheme. Taking this a step further, the potential for airborne mounted systems, particularly unmanned versions, may further reduce risk to personnel and equipment.

Ultimately, the primary objective of this work is to move the research forward to the final goal of developing a reliable system that has sufficient stand-off detection range and is deployable on vehicle or airborne platforms.

This report is an assessment of using higher frequencies, in particular the frequency modulation (FM) band, in order to detect linear conductors. Under previous contracts, a prototype portable detector was designed and constructed (C-CORE 2013, 2014) which made use of amplitude modulation (AM) transmitters of opportunity in order to detect linear conductors with lengths on the order of 75 m. There has been interest in the possibility of detecting shorter lengths of wire (20m and below) with a similar approach. Shorter lengths of wire are less receptive of long EM wavelengths at AM frequencies and therefore create weaker re-radiated fields. Hence a switch to a higher frequency, and therefore a shorter wavelength, should allow the shorter wire to absorb more of the radiated energy, and hence create a stronger reradiated field.

The equipment used for this proof-of-concept demonstration was a software defined radio (SDR) which is capable of frequencies up to 1.8 GHz. This allows testing for not only AM and FM bands, but ultra-high

frequency (UHF) and L-band frequencies. A series of tests were devised for measuring the reradiated fields. These tests were then conducted and the results are presented. The feasibility of detecting linear conductors of shorter lengths at different frequencies is then assessed.

This work has been carried out under Task Authorization (TA) 2 entitled "Multispectral measurement of scattered radiation from linear conductors." This TA is authorized under contract No. W7702-175832/001/EDM with DRDC Suffield.

1.1 Scope

This report provides an overview of the work carried out to develop and test a sensor capable of measuring EM fields around shorter wires (< 20m) in order to determine the feasibility of detection. The sensor style is described and the experimental plan and results are presented, along with a discussion as to the overall feasibility of the detection scheme.

1.2 Definitions

Acronym	Definition
AGC	Automatic Gain Control
AM	Amplitude Modulation
AMN	Narrowband AM
AMS	Synchronous AM
API	Application Programming Interface
COTS	Commercial Off-The-Shelf
dBm	Decibel-milliwatt
DRDC	Defence Research and Development Canada
DSB	Double Side Band
EM	Electromagnetic
FM	Frequency Modulation
FMW	Wideband FM
HF	High Frequency
IF	Intermediate Frequency
ISB	Independent Side Band
LSB	Lower Side Band
PC	Personal Computer
RSSI	Real Signal Strength Indicator
SDK	Software Development Kit
SDR	Software Defined Radio
SRC	Suffield Research Centre
TA	Task Authorization

Acronym	Definition
UHF	Ultra-High Frequency
USB	Upper Side Band

2 Background

Under prior contracts (C-CORE 2013, 2014), it had been demonstrated that detecting long linear conductors, with lengths on the order of 75m, was feasible by making use of local AM transmitters of opportunity such as commercial radio stations. The primary field generated by an AM transmitter would induce currents in the wire. The currents then generated secondary fields which could then be detected with a magnetic field sensor. This scheme works in part because the wire length is an appreciable fraction of the wavelength at AM frequencies and acts as an antenna.

There has been an increasing interest in the feasibility of detecting shorter wires of lengths less than 20m. Transmitters radiating higher frequencies, and hence shorter wavelengths which are amenable to reception by these shorter wires, must be considered. For the proof-of-concept considered in this contract, transmitters of opportunity in the FM band (such as local commercial radio stations) will first be considered. Then UHF transmitters of opportunity will be considered depending on their availability and strength.

The experiment is based on measuring re-radiated fields in the proximity of a linear conductor for different frequencies, with a focus on FM band. A SDR is capable of performing signal strength measurements over a broad range of frequencies and is hence selected as the multispectral measurement device for this proof-of-concept experiment. Details about this sensor type and setup are found in Section 3. The fields will be measured around the wire, following different paths of the sensor, for different wire lengths and frequencies. Details of the experiment methods, along with the generated results, are found in Section 4.

3 Experiment Apparatus and Sensor Construction

The selected sensor comprises the SDR, the sensor head, and a personal computer (PC) to accept the data stream and record it to a file for later processing. These components are described in greater detail in the following subsections.

3.1 Software Defined Radio

The WiNRADiO WR-G305e, shown in Figure 1, is a commercial off-the-shelf (COTS) SDR from WiNRADiO and was selected for its vast feature set, well-established track record, and availability of convenient accessories.

Figure 1. WiNRADiO WR-G305e SDR

The salient features of the WR-G305e are:

- Frequency range of 9 kHz to 1.8 GHz;
- Optional downconverter expanding the upper range to 3.5 GHz;
- Tuning in 1 Hz increments;
- Demodulation modes: AM, narrow band AM (AMN), synchronous AM (AMS), lower sideband (LSB), upper sideband (USB), 6 kHz FM, 15 kHz FM;
- Additional demodulation modes: Wideband FM (FMW), independent sideband (ISB), and double sideband (DSB);
- Software control panel; and
- Readily available software development kit (SDK) for specific applications.

The accessories acquired in addition to the SDR are also listed in the below subsections.

3.1.1 Battery Pack

A convenient accessory for the WR-G305e is a lithium-ion battery pack (Figure 2) which allows the SDR to become portable. This is essential for the experiment plan as outlined since the presence of power cables with similar length to the wires being considered may comprise the obtained readings.

Figure 2. Battery pack.

3.1.2 Downconverter Module – WR DNC 3500

Another accessory is the downconverter module (WR DNC 3500), which allows measurement of signals of up to 3.5 GHz. Such signals were ultimately not considered in the tests outlined in this contract: it was found that transmitters of opportunity at UHF were much lower in received power and hence the reradiated fields observed were much lower (Section 4.5). However, this module allows the possibility of future experiments involving a dedicated local transmitter at these frequencies.

Figure 3. WR DNC 3500 downconverter module

3.2 Sensor Head

WiNRADiO provides a telescopic receiving antenna for use with its WR-G305e SDR. For convenience, this AX-06B antenna was selected as the pickup antenna to be used in the multispectral measurement device.

The antenna has a length of 604mm when fully extended and is rated for operating frequencies of 20 to 1800 MHz with a typical gain of 2.1 dB.

Figure 4. WiNRADiO AX-06B Telescopic Antenna

3.3 Personal Computer and Software

A portable laptop computer is used to log the data generated by the SDR. There is a SDK available for the SDR that provides an Application Programming Interface (API) containing a number of functions that allow the PC to configure the SDR and record signal strength data. The relevant functions are summarized in Table 1.

For the purposes of the functional tests, a console software application was developed to record the signal strengths reported by the device over time for a provided frequency. Functions are provided to access the signal strength in both dBm and an internal format used by the SDR consisting of real signal strength indication (RSSI) and automatic gain control (AGC) values. The sampling rate for the received signal strength readings is 128 Hz.

In all tests, the recorded values were analyzed for artifacts or anomalies to determine if any indication of a linear conductor or other object was observed.

Table 1. WR-G305e API function list.

Function	Description
OpenRadioDevice	Establish connection with the WR-G305e and obtain device handle.
CloseRadioDevice	Release the device handle.
SetPower	Turns the SDR on and off
SetFrequency	Tunes the SDR to the given frequency.
SetAtten	Turns the attenuator on and off
SetAGC	Sets the AGC speed
CodecStart	Starts the intermediate frequency (IF) streaming input. Note that the codec output is not required in this application, but the function is required to enable GetInternalRSSI and GetSignalStrengthdBm below.
GetInternalRSSI	Returns the RSSI and AGC values
GetSignalStrengthdBm	Returns the signal strength in decibel-milliwatts (dBm)

4 Operational Testing

To demonstrate the performance of the constructed multispectral measurement system, a number of functional, or proof-of-concept tests were performed. The tests were primarily designed to observe the ability of the system to detect and/or measure the scattered field from linear conductors due to a nearby transmitter of opportunity operating in the FM broadcasting band. Additional tests investigated the possibility of using the system to detect alternative metallic objects and at higher operating frequencies.

4.1 Available Transmitters of Opportunity

To determine the optimum operating frequency for the primary tests as well as suitable higher frequencies for supplemental experiments, a survey of nearby transmitters of opportunity was performed. The swept spectrum analyzer feature of the SDR was used to measure the strength of signals received over its operating frequency range. Figure 5 shows the measured spectra for frequencies up to 1000 MHz. Frequencies above 1000 MHz are omitted as no signals were observed.

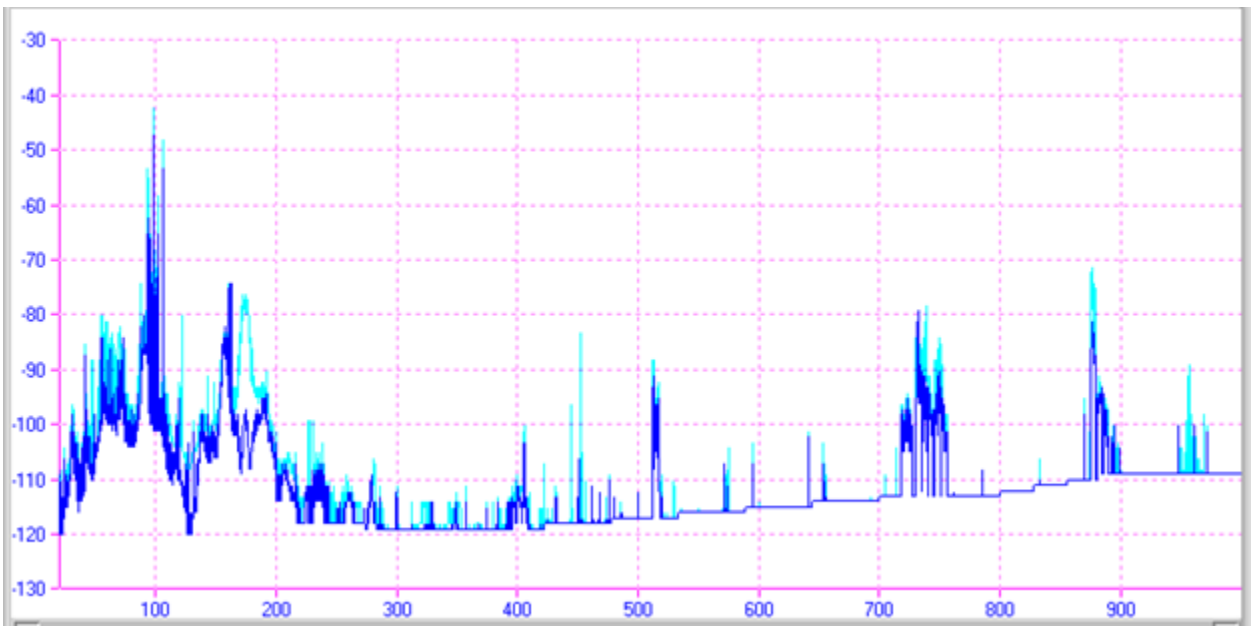

Figure 5. Received signal strength measured at C-CORE's facility.

In Figure 5, the dark blue trace indicates the received signal strength for the current measurement, while the light blue trace indicates the maximum measured signal over multiple measurements. A number of potential transmitters of opportunity can be seen within the FM radio band; however, the signal measured at 99.1 MHz was noted to be consistently strongest. For this reason, it was selected as the operating frequency for the primary tests.

Also indicated in Figure 5 are a number of transmitters operating at UHF with varying bandwidths that may be suitable for experiments. Operating frequencies of 514.8 MHz and 879 MHz were selected to

represent the midpoint and maximum of the available signals and their signal strengths were greater than alternatives. It should be noted that the received signal strengths from these transmitters were approximately 40 dB below that observed at 99.1 MHz and that this preliminary survey did not account for the frequency-dependence of the dielectric constant and conductivity of the underlying ground. It is expected that these will reduce the strength of the scattered field for these increased operating frequencies.

4.2 Preliminary Tests

A few preliminary tests were conducted to establish a baseline of the performance of the multispectral measurement system. First, the system was carried across a long wire (50 m) and configured to record the AGC and RSSI values of the received signal for an AM commercial station broadcasting at 800 kHz. Figure 6 shows the output of this trial. A feature in the recorded signal is clearly discernable as the sensor crosses the wire. This demonstrates that the system is capable of producing a feature as noticed in prior contracts (C-CORE 2013, 2014), before proceeding to the FM band. Note that while the antenna used (Section 3.2) has a lower frequency of 20 MHz, it is still capable of receiving AM signals for the purposes of this preliminary test.

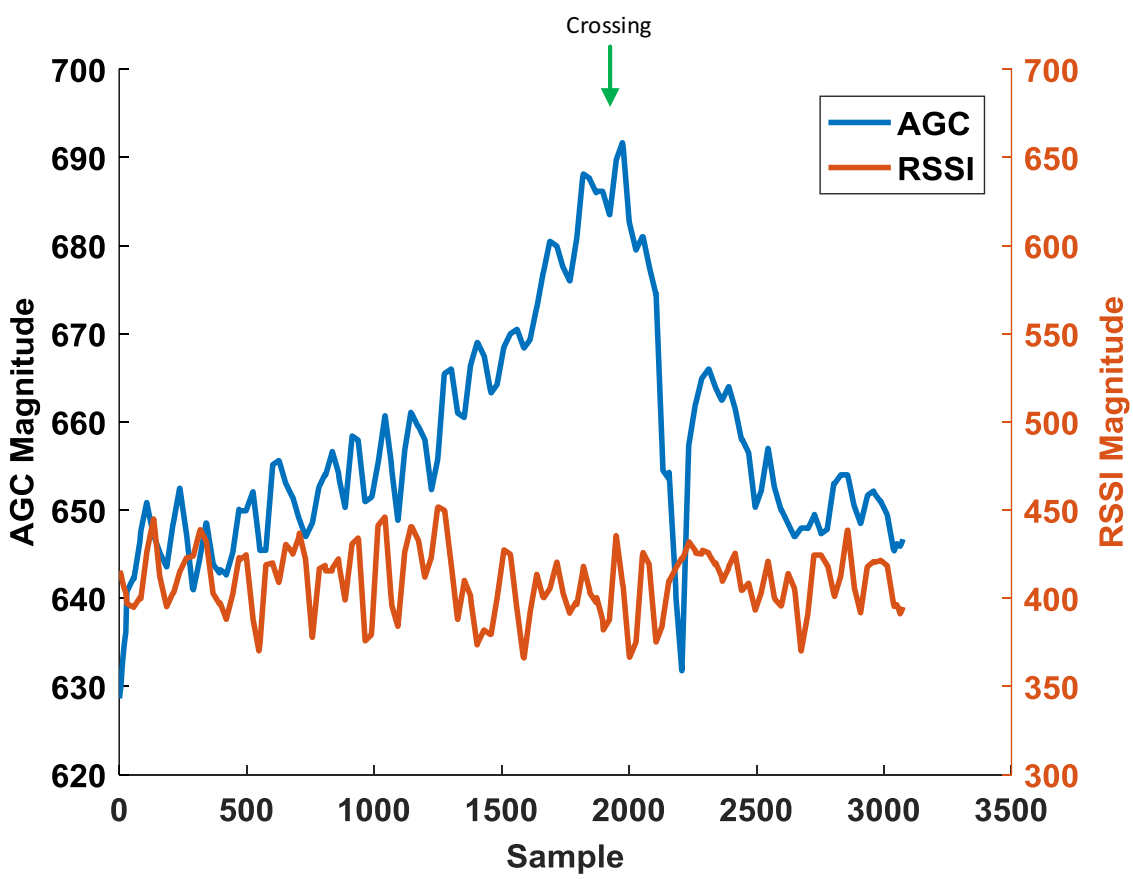

Figure 6. Preliminary center crossing measurement at 800 kHz, wire length of 50m.

After this, another preliminary test was conducted at 99.1 MHz for crossing the same length of wire, the results are shown in Figure 7. A feature is also distinguishable in this case. Note that the first iteration of the software for these tests only recorded the AGC and RSSI values. An improved version also recorded the dBm values for signal strength. A more detailed explanation of all of these value types is provided in Section 4.3.1.1. The intention of these preliminary tests was simply to demonstrate the feasibility of the system producing a feature.

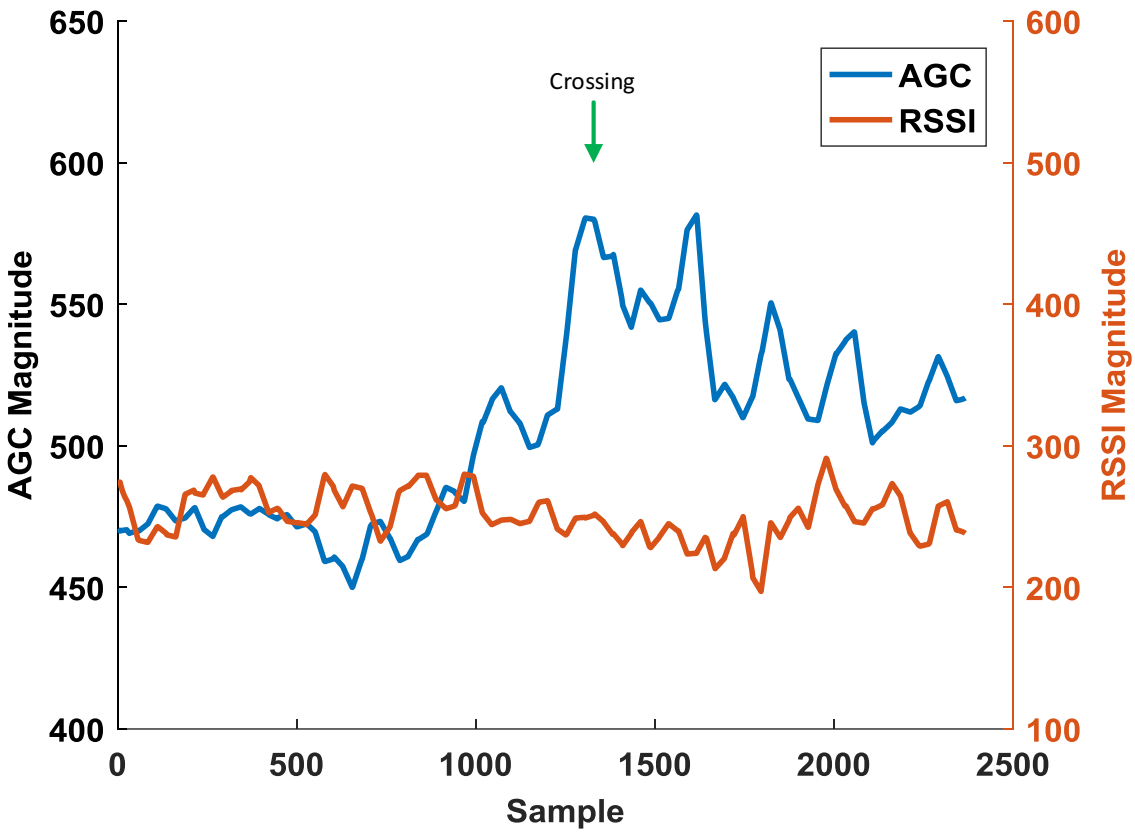

Figure 7. Preliminary center crossing measurement at 99.1MHz, wire length of 50m.

4.3 Linear Conductor Tests

Following the results of the preliminary tests, a more detailed set of experiments were developed. These tests were conducted with an operating frequency of 99.1 MHz and measured the received signal strength from a linear conductor placed on top of the ground at C-CORE's test facility. These experiments were repeated for wire lengths of 12, 6, and 3 meters. As an initial functional test, these lengths were selected to allow for an order-or-magnitude estimate of minimum conductor length. To minimize ground conduction losses, the tests were performed for ground conditions that were as dry as practical.

4.3.1 Centre Crossing Measurement

The first test consisted of recording the signals produced by the SDR as the measurement system was carried over the conductor's midpoint as depicted in Figure 8. The starting point of the experiment was approximately 3 meters from the conductor and the device was carried in a two-way path (forward and back) perpendicular to the conductor. During measurements, the pick-up antenna was held parallel to the linear conductor approximately 30 cm above the ground. The objective of the test was to determine if any distinguishable artifact could be observed in the recorded signal due to the presence of a linear conductor.

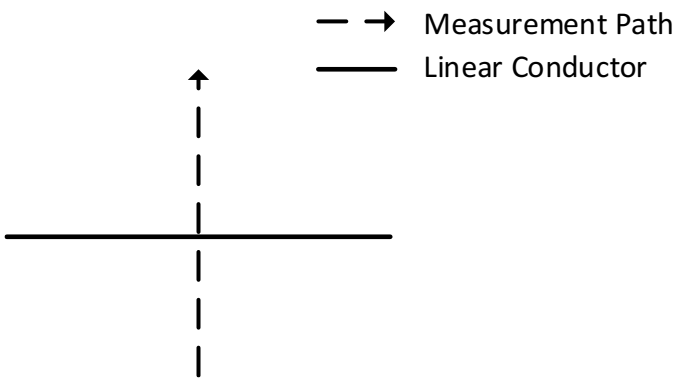

Figure 8. Test 1 Configuration

4.3.1.1 12 Meter Conductor Crossing

The results recorded while crossing the 12m conductor are plotted below in Figure 9. The received signal strength values are plotted for each sample as the measurement was taken. The AGC and RSSI values are shown in blue and orange respectively, with their magnitude indicated on the left y-axis. The received signal power in dBm is plotted in yellow with its magnitude shown on the right y-axis. The green arrows indicate the approximate time of the wire crossing. The dBm values show two broad peaks as the device crossed the conductor and are separated by a strong null. It is noted that the variation in field strength is reflected in the AGC value, and not the RSSI. The AGC values appear to vary inversely proportional to the received signal strength, while the RSSI values are approximately constant, excluding a few sporadic spikes. A 50-point moving average filter has been applied to all signals to reduce some sporadic variations that were observed in signal strength.

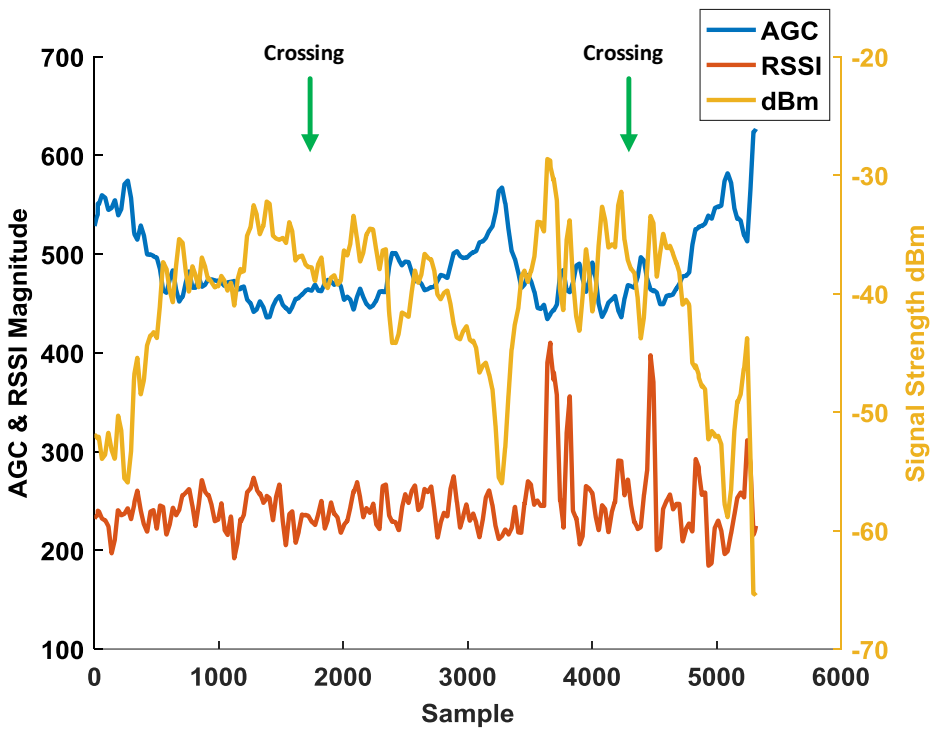

Figure 9. 12m Conductor Crossing Results

4.3.1.2 6 Meter Conductor Crossing

The results recorded while crossing a 6m conductor are plotted below in Figure 10. In this experiment, the wire crossings appeared to be indicated by a decrease in signal strength as seen in the dBm measurement and its corresponding peak in the AGC value. As shown in Section 4.3.2, this is a result of the standing wave pattern on the wire; it is possible that the effect of the wire on the field strength is to produce a null. It is also noted here that the variation in signal strength attributed to the presence of the conductor is significantly less than that for the 12m case.

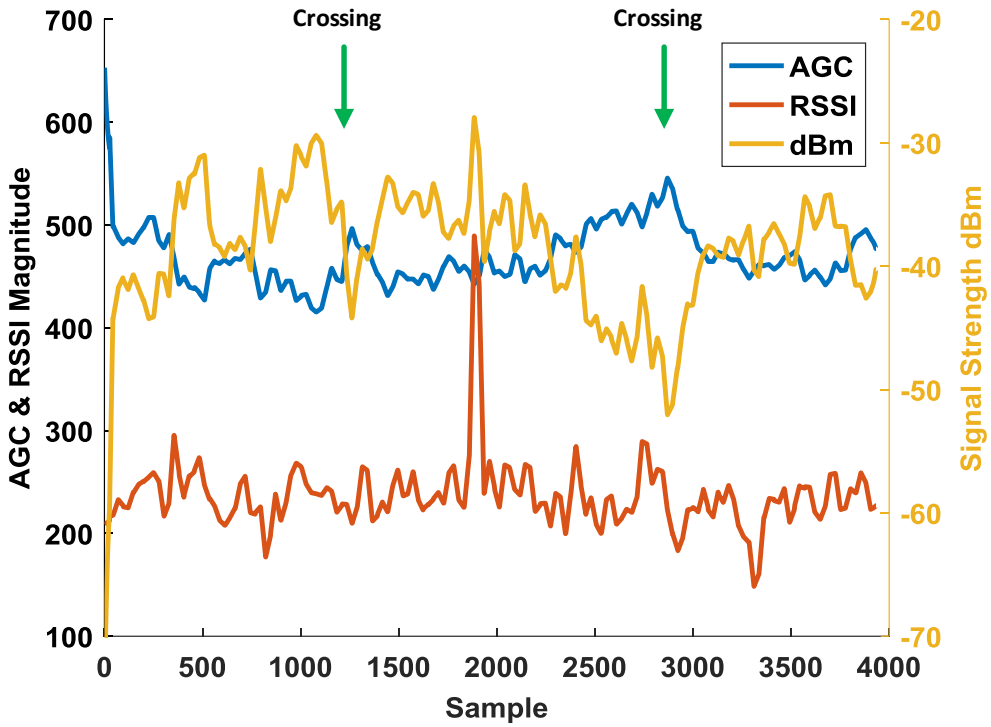

Figure 10. 6m Conductor Crossing Results

4.3.1.3 3 Meter Conductor Crossing

The results recorded from the 3m case are plotted Figure 11. Little variation in signal strength was observed as the measurement device crossed the conductor. For this reason, 3m was chosen as the smallest length for experiments.

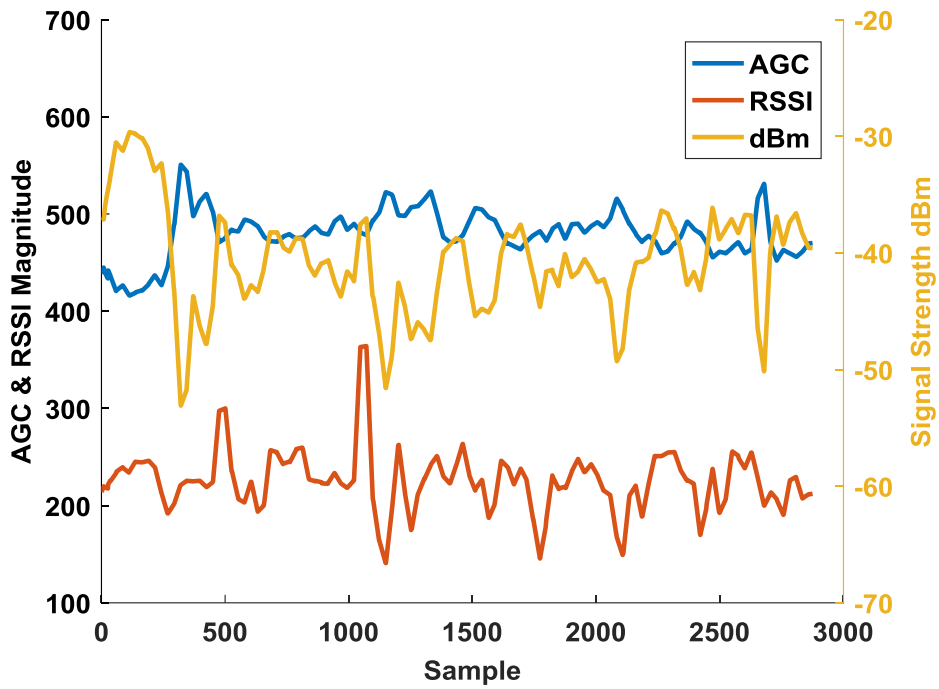

Figure 11. 3m Conductor Crossing Results

4.3.2 Along Axis Measurement

As a second test, signals produced by the SDR as the pick-up antenna was held parallel to the linear conductor and carried in a path approximately 30cm above the conductor as depicted in Figure 12. This test was expected to produce a standing wave pattern corresponding to induced currents on the wire; a representative example of this standing wave pattern is shown in Figure 13.

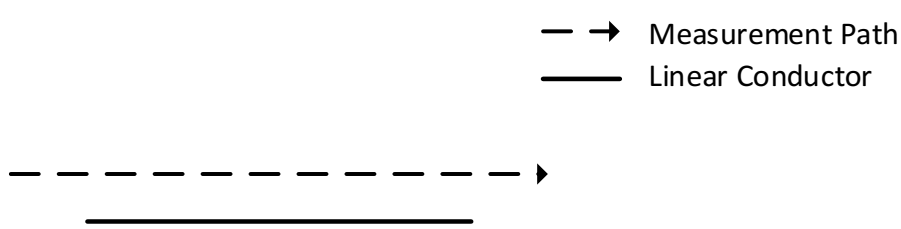

Figure 12. Test 2 Configuration

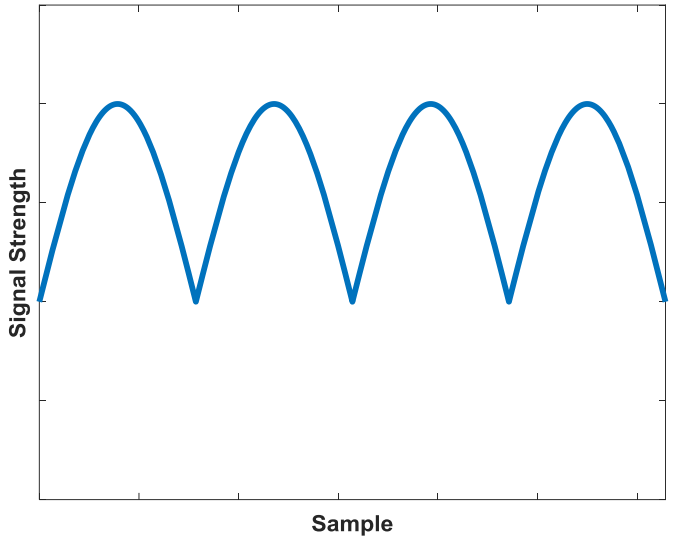

Figure 13. Test 2 expected output

4.3.2.1 12 Meter Conductor Results

Again, the 12m conductor was used for the first set of measurements, with the results plotted below in Figure 14. The signal strength values recorded in dBm, as well as the AGC values, suggest a slight standing wave pattern as expected: that is, there are peaks and nulls along the axis as anticipated.

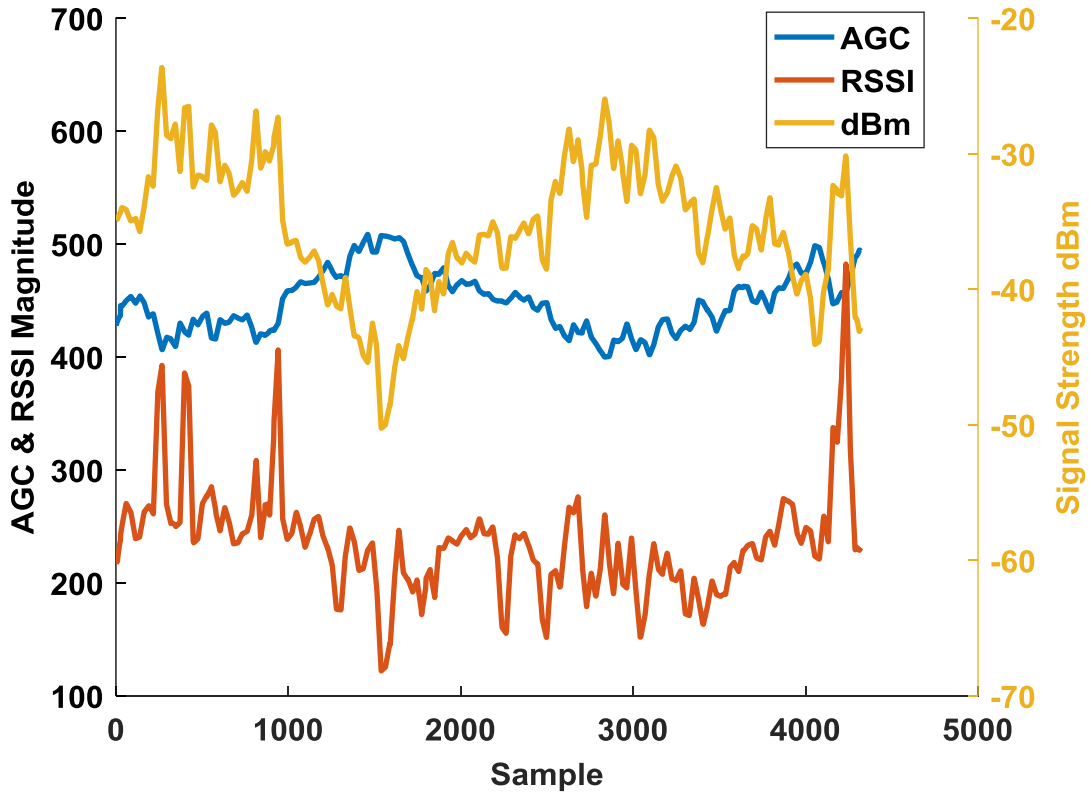

Figure 14. 12m Conductor Along Axis Results

4.3.2.2 6 Meter Conductor Results

The results using the 6m conductor also indicate another slight standing wave pattern (Figure 15). The shorter length of the wire is noticeable as less of a standing wave pattern was observed than was the case with the 12m conductor.

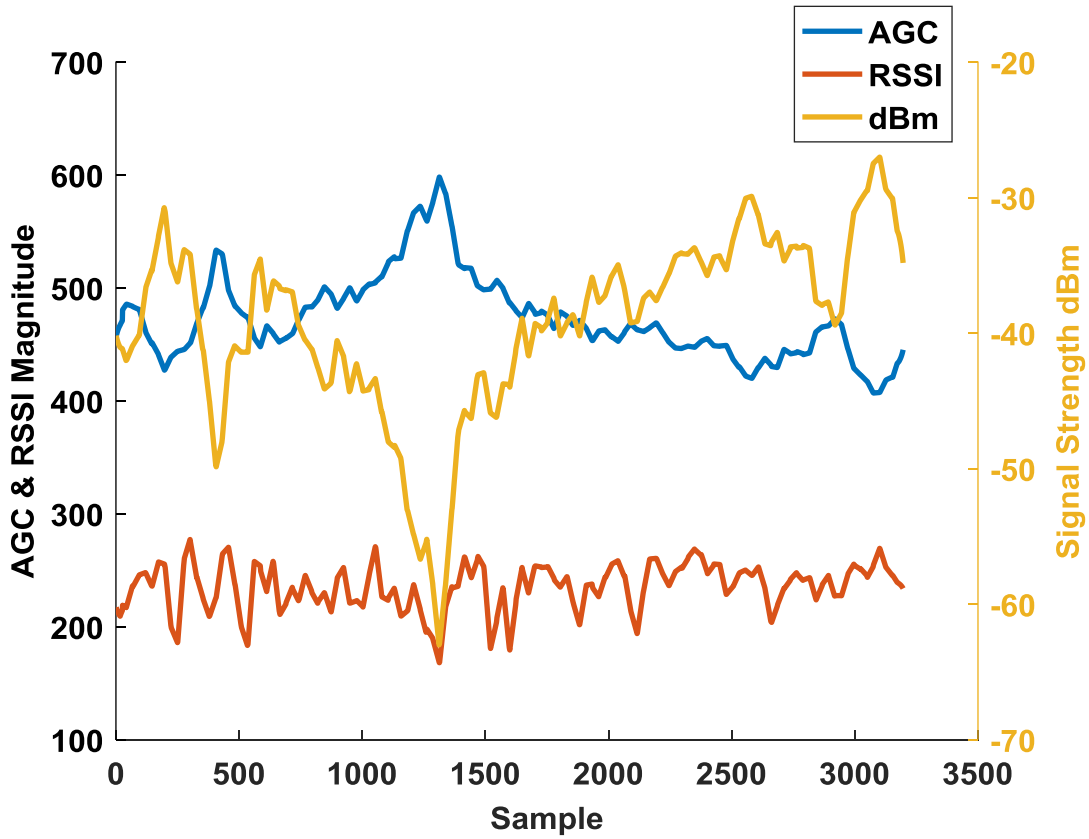

Figure 15. 6m Conductor Along Axis Results

4.3.2.3 3 Meter Conductor Results

In contrast to the first center crossing test, the measured signal strength along the length of the 3m wire produced observable results (Figure 16). A short section of a standing wave pattern was observed, including a strong null near sample number 500. At approximately sample 1700, the sensor had completely passed the conductor. The sharp decrease seen at the end of the measurement was attributed to this and not considered part of a standing wave pattern.

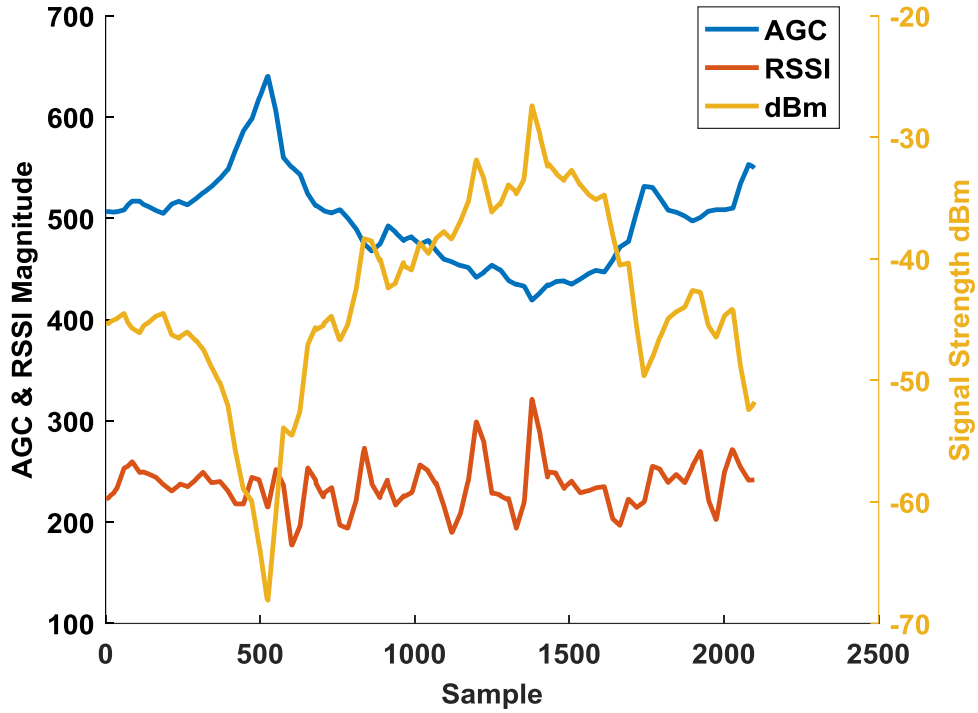

Figure 16. 3m Conductor Along Axis Results

4.4 Alternative Object Detection Tests

Additional tests were performed to evaluate the measurement device's ability to detect and/or measure the scattered field from metallic objects other than linear conductors. The two objects tested were an aluminum plate and rod pictured in Figure 17 and Figure 18. The plate measures 61x61cm^2 while the rod has a diameter and length of 2.54 cm and 1 m respectively. These experiments followed a procedure similar to that described in 4.3.1, where the sensor was carried in a path crossing the center of each object (for the rod, the long axis was crossed, as if it were a short linear conductor in Figure 8).

The received signal strength as the sensor was carried over the square plate are plotted in Figure 19. The results show a noticeable reduction in signal strength while the sensor was directly above the plate.

The results from the one meter rod are plotted in Figure 20 and indicate little variation in signal strength. This may be expected when compared to the 3m conductor center crossing results, however a clearly distinguishable null around sample number 2000 was observed.

Figure 17. Aluminum Plate

Figure 18. Aluminum Rod

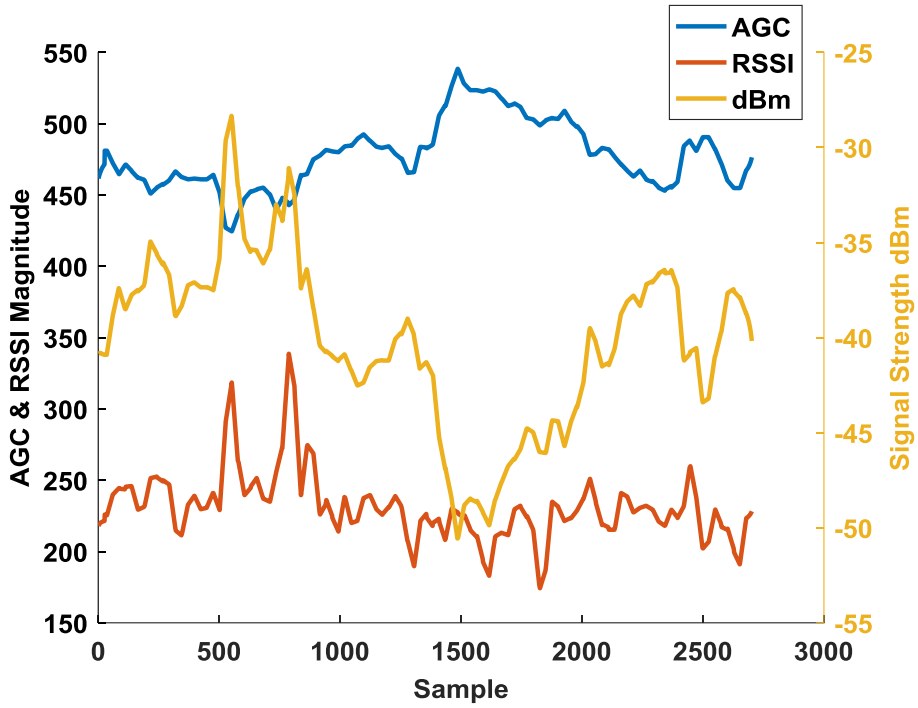

Figure 19. Aluminum Plate Field Strength Measurements

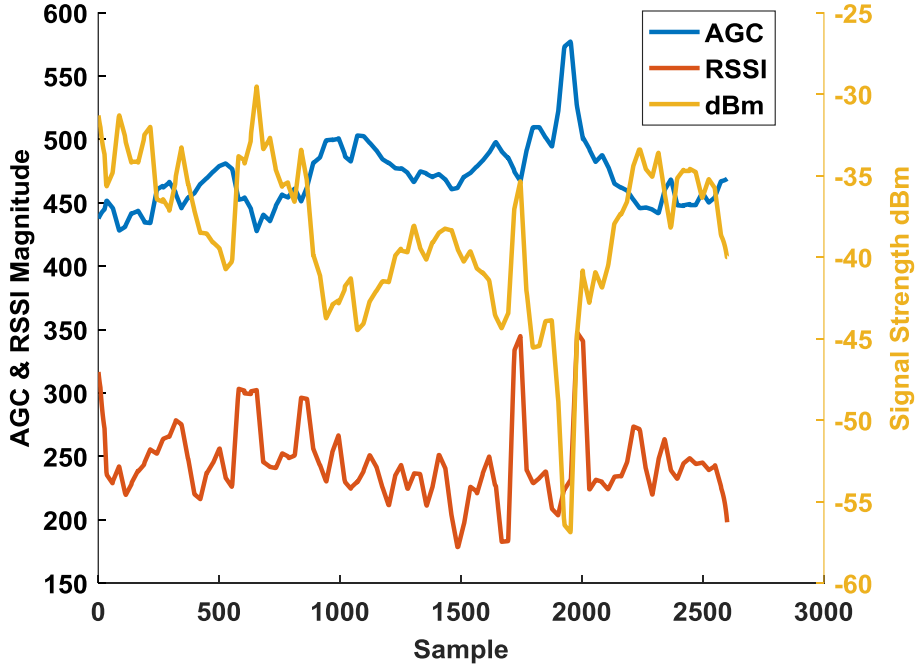

Figure 20. Aluminum Rod Field Strength Measurements

4.5 UHF Measurements

As a preliminary evaluation of the linear conductor detection concept at higher frequencies, the center crossing test described in Section 4.3.1 was repeated with the 12m conductor for operating frequencies of 514.8 MHz and 879 MHz. The results are plotted in Figure 21 and Figure 22 respectively. In both results, some variation in signal strength is observed; however, peaks and nulls are less prominent than observed at 99.1 MHz.

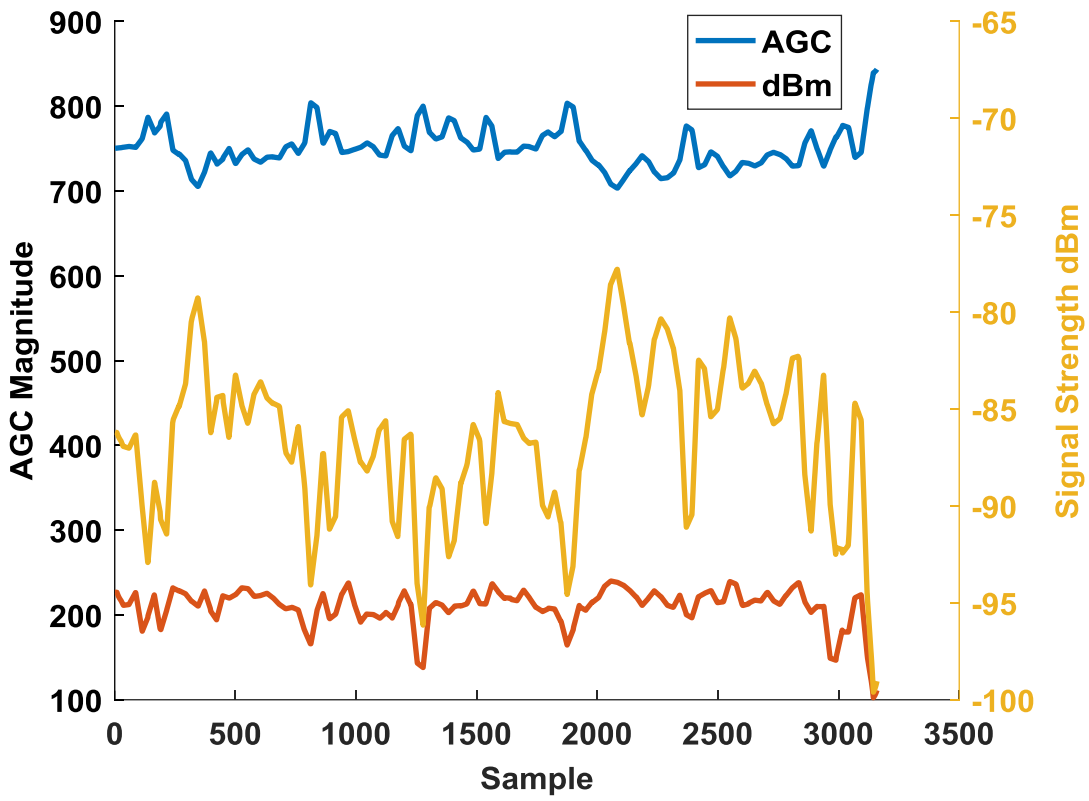

Figure 21. 12m Conductor Centre Cross at 514.8 MHz

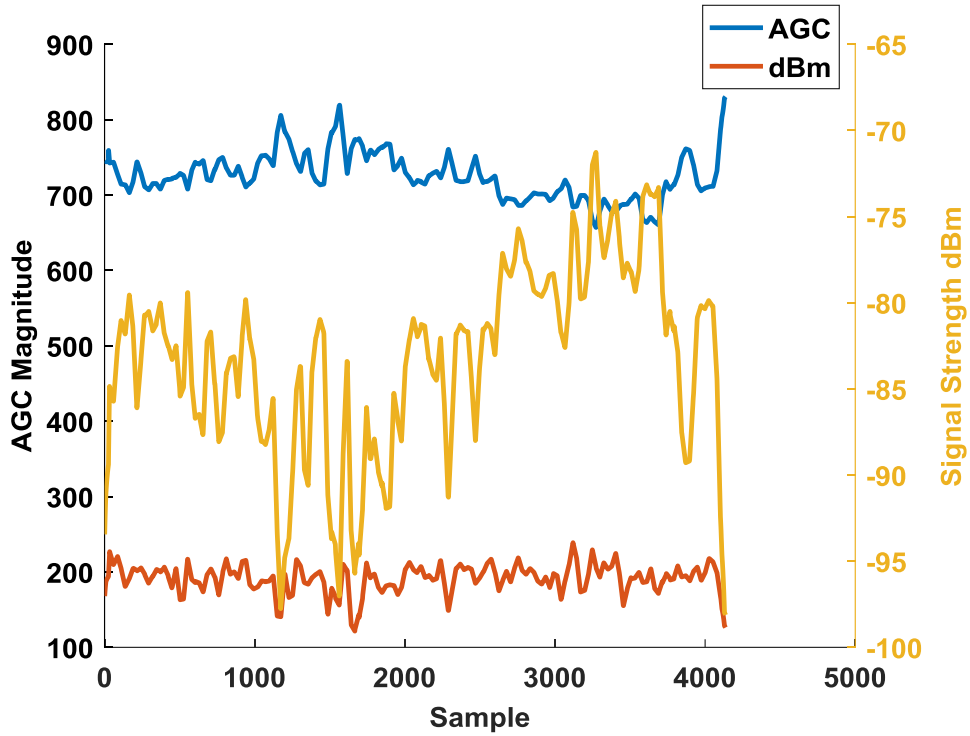

Figure 22. 12m Conductor Centre Cross at 879 MHz

4.6 Additional Linear Conductor Measurements

Following the initial set of tests, it was decided to perform the center crossing and along axis measurements with a 20m linear conductor to produce more distinguishable results. Both tests were repeated for the previous operating frequency of 99.1 MHz. The along axis measurement was also repeated at an additional FM frequency of 94.7 MHz to determine if the slightly longer wavelength produced any noticeable difference in the standing wave pattern.

To more clearly indicate the effect of the linear conductor's presence on the measured field strength, the center crossing experiments were performed for a single pass (i.e., one wire crossing) and started from an increased initial separation of approximately 6 meters. In addition, the measurement system was held stationary for approximately 20 seconds before and after the experiment.

The results from the center crossing experiment with the 20m linear conductor are plotted in Figure 23. The starting and ending stationary periods are clearly seen as well as a large peak in the AGC data set corresponding to the wire crossing.

The results from the along axis measurement from the 20m conductor for an operating frequency of 99.1 MHz are plotted in Figure 24. As expected, when compared to the previous along axis measurements in Section 4.3.2, more of a standing wave pattern is observed. In this case, approximately three each of peaks

and nulls are clearly distinguishable in the AGC data set, and two peaks and three nulls are distinguishable in the dBm data set.

The results of the along axis measurement for the 20m conductor taken at 94.7 MHz are plotted in Figure 25. Again, the results suggest a standing wave pattern, however peaks and nulls are harder to distinguish when compared to the results measured at 99.1 MHz. This is attributed to the weaker signal strength of the transmitter of opportunity at 94.7 MHz.

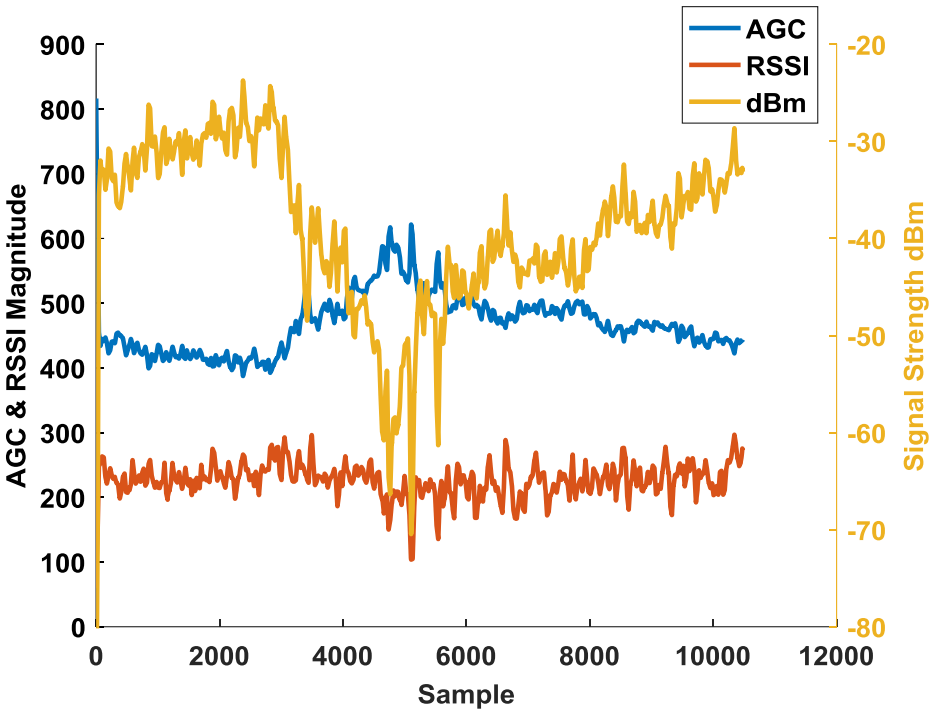

Figure 23. 20m Conductor Center Crossing at 99.1 MHz

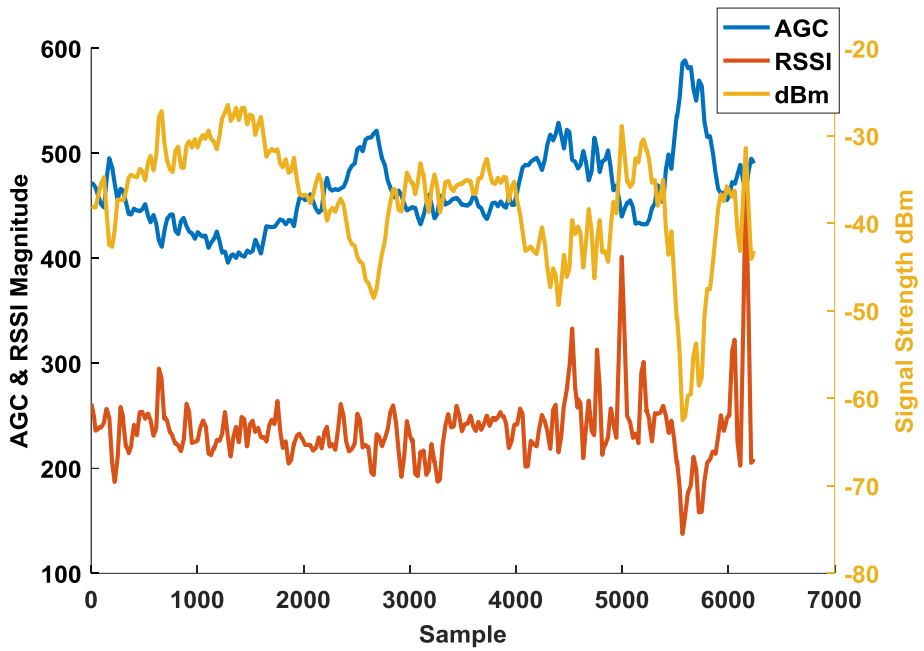

Figure 24. 20m Conductor Along Axis Results at 99.1 MHz

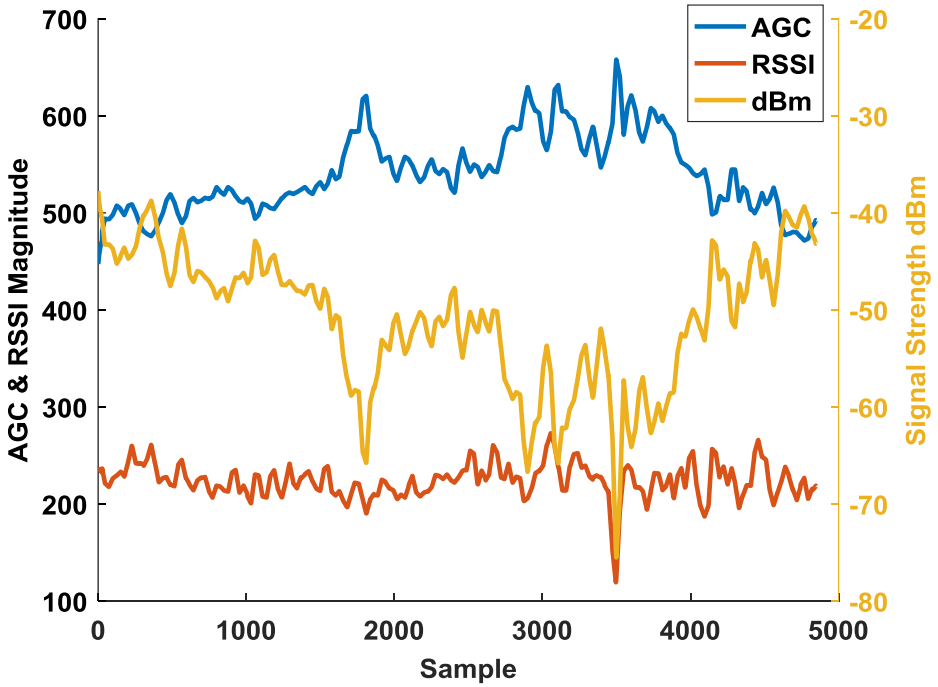

Figure 25. 20m Conductor Along Axis Results at 94.7 MHz

5 Conclusions and Future Considerations

The objective of this work was to implement and evaluate a multispectral measurement device for the detection of linear conductors. A prototype measurement device was assembled to examine reradiated fields arising because of currents induced by nearby transmitters of opportunity operating in the FM frequency band and also at UHF frequencies. Functional testing was performed and suggested the feasibility of the core concept, agreeing with previous studies performed at AM band frequencies (C-CORE 2013).

The multispectral measurement device comprised an SDR, sensor head, and a laptop. With the API released for the SDR, an application was created to sample the received signal strengths. The API is comprehensive and allows for recording of demodulated data (WiNRADiO 2007). One possible enhancement to be explored further is to examine this demodulated signal for irregularities. For example, the addition of the re-radiated field to the primary field may introduce a phase shift in the demodulated data which may be detectable.

The results of both the center crossing and along axis measurements suggest the core concept of linear conductor detection is possible at FM band frequencies. With the exception of the 3 meter wire center-crossing, all tests produced one or more observable artifacts in their recorded output that could be attributed to the presence of the conductor. The results illustrate potential advantages and challenges attributed to the relatively shorter wavelengths of the FM radio band when compared to the AM band. In particular, the wave-like nature of the current induced on the conductor results in a spatial distribution of peaks and nulls along the length of the wire as demonstrated in the along axis measurements. One advantage of this spatial distribution is the additional information it provides regarding the properties of the linear conductor and its surroundings, such as soil permittivity and conductivity. This distribution however, complicates the detection of a linear conductor as the magnitude of an observed artifact will be dependent on where the measurement is taken.

While this work was successful in demonstrating the feasibility of a multispectral measurement device for the detection of linear conductors, there are a number of opportunities to further characterize, optimize, and test the performance of successive designs. The implemented measurement device utilized a standard, commercial collapsible FM antenna as a pick-up transducer. A specialized or custom, electric near-field probe may be able to more accurately measure the reradiated field from a linear conductor. This can be through reduced coupling to the linear conductor or by providing a more localized field measurement with a more compact design. Additionally, future designs may be calibrated to known field strengths to determine a relationship between the reradiated field strength and the device's recorded signal strength.

The results of the functional tests also indicate the benefits of further developments in the modelling of reradiated fields from linear conductors that arise due to transmitters of opportunity. As previously suggested, the standing wave pattern observed in the field strength along the axis of the conductor is likely to be impacted by the conductor properties as well as its environment. A detailed understanding of this phenomenon may produce a relationship whereby some or all of these properties could be obtained from the standing wave pattern observed at one or more frequencies.

6 References

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There has been interest in the possibility of detecting shorter lengths of linear conductor (20m and below) using transmitters of opportunity, similar to what has been previously examined for longer conductors at AM frequencies. A switch to a higher frequency, and therefore a shorter wavelength, should allow the shorter wire to absorb more of the radiated energy, and hence create a stronger reradiated field. The equipment used for this proof-of-concept demonstration was a software defined radio (SDR) which is capable of frequencies up to 1.8 GHz. This allows testing for not only AM and FM bands, but ultra-high frequency (UHF) and L-band frequencies. A series of tests were devised for measuring the reradiated fields. These tests were then conducted and the results are presented.