Power Line Detection for UAVs using mmWave RADAR

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Power line detection for UAVs is an important problem to consider in light of how much they rapidly taking over a wide array of industries across the world. There are many ways to try solving this problem, and we present using a mmWave RADAR to detect the wires from a safe enough distance. The RADAR would not require the wires to be carrying current, like some detection methods do (for example, using gaussmeters). In addition, they have a better range and resolution than most cameras in adverse weather and bad lighting conditions. We test the hypothesis by simulating a current carrying wire and measuring its magnetic field as well as detecting it using a RADAR. The maximum range of detection will be a function of the RCS, or the radar cross section of the object.

Additional Key Words and Phrases: Radar Cross Section,UAV,mmWave RADAR

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1 INTRODUCTION

UAVs, or unmanned aerial vehicles are rapidly permeating different sectors, like combat, surveillance, logistics, and even inspections. The issue is very straightforward. There are many high tension cables including power lines in the general path of a UAV which it may not be able to detect. There have been several reports of drones crashing into power lines and causing power outages for many hours. One of the more recent incidents was in Brisbane in September 2022, where a drone accidentally flew into a power line and subsequently melted, causing a power outage in the vicinity for about 4 hours and cost the city tens of thousands of dollars. There have been reports in California as well, in Mountain View and West Hollywood, where drones have caused both accidents and power outages. Hence, the ability of drones to detect power lines is a pressing and worthwhile issue to consider solving.

Drones are usually fitted with IMUs and high speed cameras, which control its motion and what it sees. However, cameras don't work too well in low visibility and bad weather conditions. Some IMUs have gyroscopes inbuilt which can be leveraged to detect the magnetic field around current carrying wires, but the resolution of these gyroscopes is nowhere close to what is needed to detect the mostly weak magnetic fields. Hence, we propose the use of a mmWave RADAR. This would solve the low visibility issue, and the wire detection can be treated as a simple object detection problem.

2 BACKGROUND AND RELATED WORK

Previous works [1], [2] have shown promising results in detecting power lines using LiDAR in UAVs. However, LiDARs have limitations in their performance in bad weather conditions such as rain or smoke. The use of mmWave RADAR would be more reliable in such scenarios. Furthermore, the range of detection of a mmWave RADAR is higher than that of a LiDAR, which would enable us to detect objects and power lines from farther.

The US army [4] has developed power line sensors for small drones in the recent past, touting the fact that radars and LiDARs in general are computationally heavy and bulky instruments to mount on UAVs. This method of detection focuses on detecting the magnetic field generated by the current carrying wires. However, the ubiquitous nature of radar and the fact that it is commercially more easily available and integratable into UAVs than a gaussmeter make it an attractive option to consider. However, gaussmeters are not only more expensive on average (they cost about $ 1500 as compared to budget RADARs that cost anywhere between $20 and $400) but also do not provide the range and resolution that is necessary to detect current carrying wires at a safe enough distance. The latter point will be illustrated in our simulations.

Previous works have also used mmWave RADAR to detect power lines [3], [5], but these ([5] specifically) use high end mmWave RADARs in combination with RGB cameras to detect the wires. [5] provides a range of 10m and costs $780 and we believe that a simpler chip of mmWave RADARs would provide a much larger range (20m-40m) and also be cheaper.

In this project, we propose to use mmWave RADAR to detect power lines in the environment. The radar cross section of an object is a useful tool to exploit for this problem as it measures the amount of backscatter an object provides when electromagnetic waves are incident on it. This problem can be modeled as an object detection problem with the limiting factors being the resolution of the radar on the drone, the distance between the drone and the wire, and the diameter of the wire.

The goal of the project is to determine the maximum distance from which a drone can successfully detect a wire given a specific radar, and the diameter of the wire. The amount of backscatter is directly dependent on the frequency of the radar waves, and we also intend to conduct an analysis of which center frequencies are best suitable for detection (ie, which band of operation would be ideal for the radar to detect the wire).

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3 DESIGN AND METHODOLOGY

3.1 Setup

All the simulations have been done on HFSS, using either HFSS or SBR solution set up. The wire that has been constructed is 4.2mm in diameter, with length 60 mm. It is a coax cable with a core made up of aluminum, a dielectric of vaccum surrounding it, and an outer sheath of copper. Fig 1. shows the setup for the coaxial cable in Ansys.

3.2 Methodology

For our RADAR, we have considered a monostatic setup with one transmitter and one receiver antenna. The position of the RADAR has been varied to get different RCS plots. The analyses we have conducted can be summarized into 3 categories given below:

- Finding the Electric Field E induced at different points on the wire by the RADAR setup.
- Finding the Magnetic Field H because of the induced current in the wire at a distance from it.
- Finding RCS plots of the wire by varying phi of the incident wave (Fig **??** shows the geometric view of phi).
- Shooting rays from the RADAR and detecting the backscatter to reconstruct the image of the wire. (done using SBR setup).

3.3 RCS evaluation

Radar Cross Section of an object is defined as the cross-sectional area of a perfectly radiating sphere that produces the same strength of power at the radar. It is the measure of how well an object is detectable from the RADAR. The RCS mainly depends on the size,shape,material and orientation of the object with respect to the radar source. This can be easily evaluated from the simulations and is one of the major factors influencing the radar system performance. Given below is the mathematical formula for RCS :

$$\sigma = 4\pi r^2 \frac{|E_s|^2}{|E_i|^2} \tag{1}$$

Hence, the received power can be expressed as :

$$P_R = P_T \frac{4\pi A}{\lambda^2} \frac{1}{4\pi R^2} \sigma \frac{1}{4\pi R^2} A\tau \tag{2}$$

where, P_T = Transmit power
$\frac{4\pi A}{\lambda^2}$ = Transmit Gain
$\frac{1}{4\pi R^2}$ = Spread factor
σ = RCS
A = Receive aperture
τ = Dwell time

3.4 Range calculation using RCS

As mentioned previously, we can exploit the RCS to give us the maximum range that the wire can be detected from. We can look at the calculation of maximum range in two ways: from the perspective of the RADAR, and from the perspective of the object being detected. From the RADAR's perspective, the max range is limited by the sampling rate F_s:

$$d_{\text{max, RADAR}} = \frac{c}{2F_s} \tag{3}$$

However, we know that the range will also vary depending on the RCS of the object (an object with low RCS will have a lower max range than an object with higher RCS). Hence we can find this range with a constraint. The received power must simply be greater than the noise floor that is tolerable by the RADAR being used. If we denote the range by d, the time of flight is τ, the received power is P_R and the bandwidth of the RADAR is B,

$$d_{\text{max, RCS}} = \frac{c\tau}{2} \tag{4}$$

Subject to: $P_R > kTB$, where kTB is the thermal noise floor.

The ideal maximum range can be calculated as:

$$d_{\max} = min(d_{\text{max, RADAR}}, d_{\text{max, RCS}}) \tag{5}$$

In the next section, we describe how the project has been implemented and observe the results.

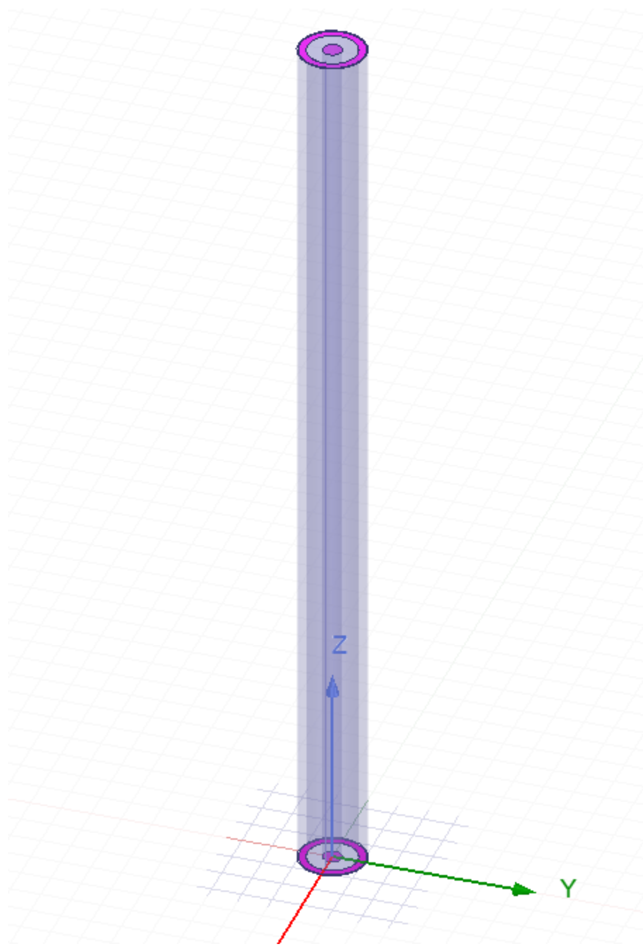

Fig. 1. Ansys setup for Coaxial cable

4 IMPLEMENTATION

In this project, we have performed our analysis in two stages which are discussed in detail in the following sub-sections. In the first stage, we performed a simulation experiment and SBR analysis to identify whether the wire is detectable. In the second stage, we have thoroughly studied the RCS of a coaxial cable and the electric field behaviour at different ranges. Further, we have performed a magnetostatic analysis in Ansys Maxwell 3D for the current carrying wire to analyse the magnitude of magnetic field emitted by the wire.

4.1 SBR analysis and RADAR Imaging for Wire detection

We have done an SBR analysis to visualise the shooting and bouncing rays from the antennas to the object of interest. We have used two parametric beams to represent 1 transmit and 1 receive antenna and a cylindrical wire made of a perfect electric conductor to represent the wire. Since this is a mere object detection experiment, we have not introduced any current through the wire at this stage. Fig 2 shows the SBR setup for the cylindrical conducting wire. The antennas are placed along the y-axis, and the wire is placed at a variable distance ’d’ on the x-axis aligned along the y-axis.

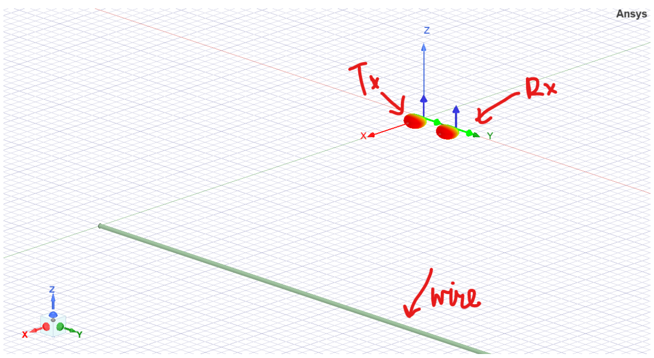

Fig. 2. SBR setup with 1 Tx 1 Rx

RADAR Imaging : To identify if the wire is detectable, we use a RADAR Imaging method. For this, we extract the s-parameter between Rx and Tx and input these real and imaginary values into a program, that returns the RADAR image of the object. As seen in the reference[7], we observe high contrast images indicating the presence of wire. Figures 3,4 and 5 are the radar imaging results for the cylinder wire of radius = 1mm,10mm and 100mm respectively. In these figures, the vertical axis represents the Y-axis and the horizontal axis represents Z-axis. As expected, we see an object along the Y-axis.

Visual Ray Tracing : Next, we observe the behaviour of incident rays onto the wire for linear and rotational motion of the antennas. To achieve the linear motion, the position of antennas is varied in the Y and Z direction,i.e., in the plane perpendicular to the line joining the Tx-Rx antennas to the wire. To mimic rotational motion of radar around the wire, the axis of the cylinder has been rotated. The ray tracing for both the cases been visualised in the figures (6) and (7).

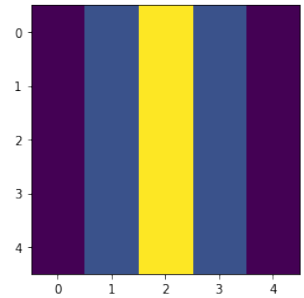

Fig. 3. RADAR Image for cylindrical wire of radius 1mm

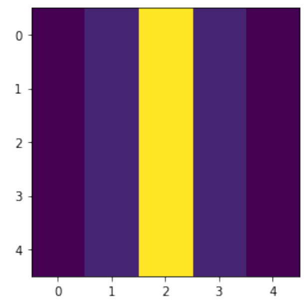

Fig. 4. RADAR Image for cylindrical wire of radius 10mm

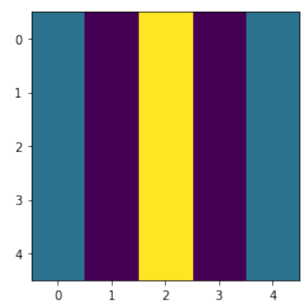

Fig. 5. RADAR Image for cylindrical wire of radius 100mm

4.2 Magnetic Field Analysis

To perform a fair comparison between detection of power lines using RADAR vs magnetometers, we have analysed the simulations to observe the magnitude of field observed around a coaxial cable. Shown below in the figures (8) and (9) are the magnetic field evaluated at 1m range and at 10m range from the wire.

4.3 RCS Analysis and E-field evaluation

The RCS of an object can be obtained from the Monostatic RCS report in HFSS. To achieve this, we use the coaxial cable model described in 3.1 with an incident electric field at varying incident angles ϕ and θ. Fig (10) illustrates the incident wave on the coaxial cable for varying ϕ. The figure (11) depicts the incident electric field intensities on different parts of the cable when there is no

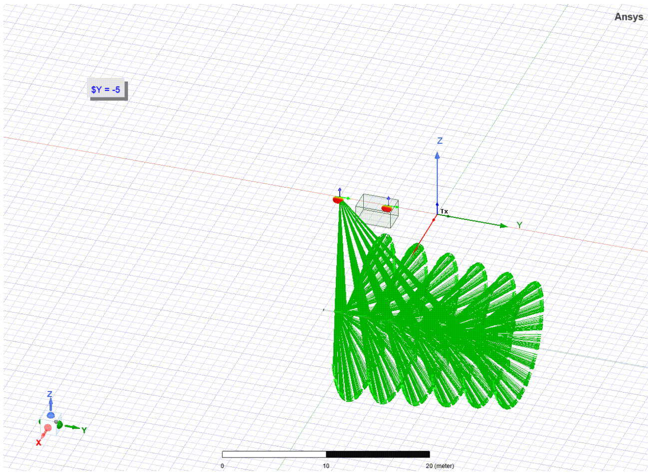

Fig. 6. VRT plot for linear motion

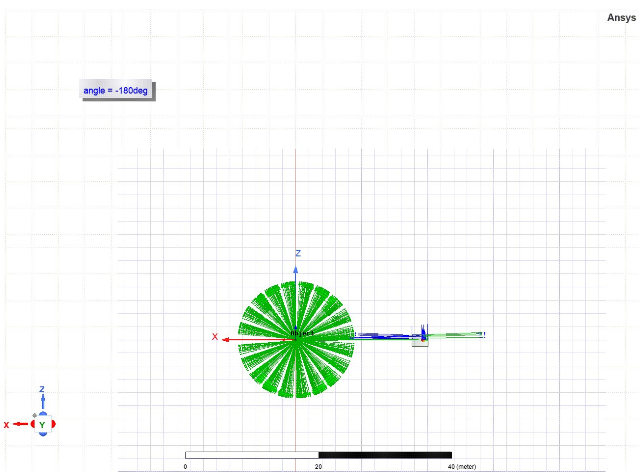

Fig. 7. VRT plot for rotational motion

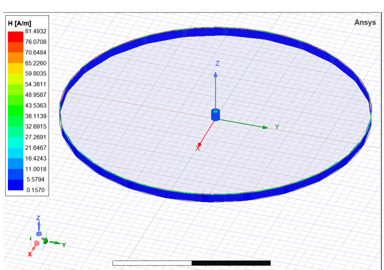

Fig. 8. Magnetic Field around a current carrying coaxial cable at 1m distance

current passed through it and (12) shows the E-field when there is current flowing through the wire. The assigned current flows in the +z direction in the inner conductor and in the -z direction in the outer conductor. These plots help us visualise the variation in the incident electric field and the field values can be used in calculating

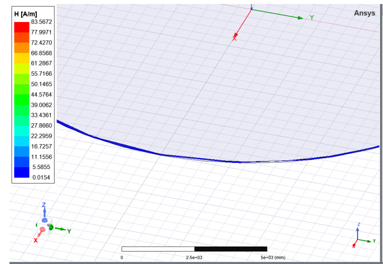

Fig. 9. Magnetic Field around a current carrying coaxial cable at 10m distance

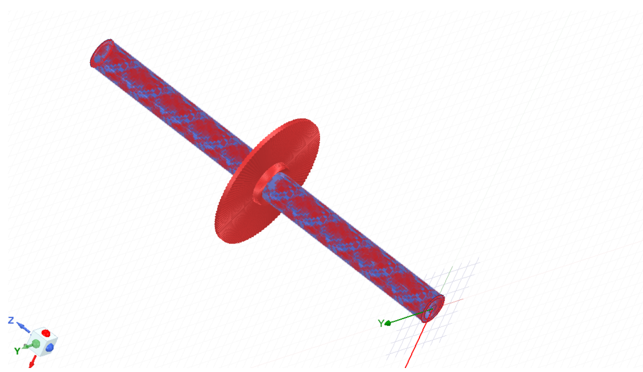

Fig. 10. Incident wave with varying angle ϕ

the magnitude of scattered field using equation 1.

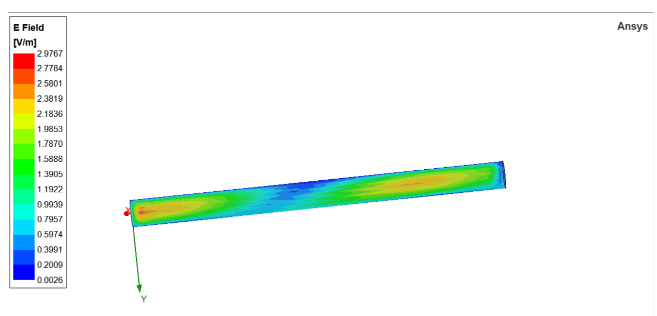

Fig. 11. Incident Electric field on coaxial cable with 0 current

Electric Field Calculations :
To evaluate the electric field induced by the RADAR waves at a certain distance, we simulated a microstrip patch antenna and a horn antenna and calculated the E-field magnitude and phase at different ranges. Figure 13, The current simulations are limited to a frequency of operation at 24GHz and have the ability to output the magnitude and phase of electric field only upto a few millimeters. In the next section, we present the monostatic RCS reports at different frequencies of operation, which are further used in our evaluations.

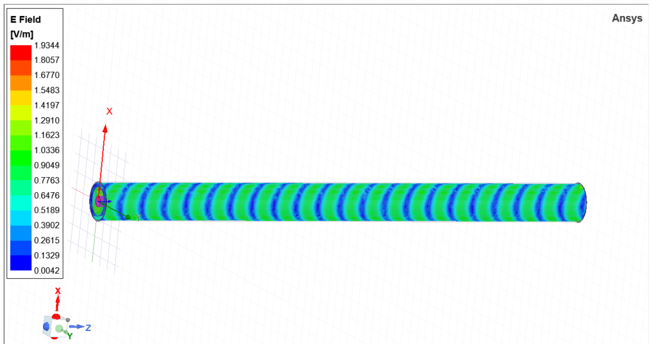

Fig. 12. Incident Electric Field on coaxial cable with current

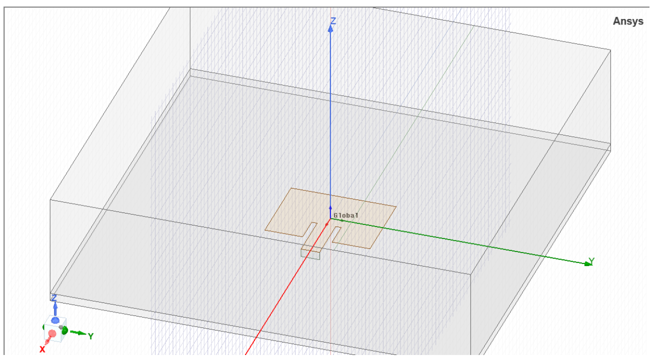

Fig. 13. Patch antenna setup

5 RESULTS AND INFERENCES

5.1 Magnetic Field Analysis

The magnetic field values obtained from the simulations are high compared to the real-life values observed near actual power-line cables.

Simulating the wire however still gives us a good way to evaluate the metrics if the insulation is simulated perfectly. Magnetometers do away with the problems of bad weather and low lighting, and in general are not very power consuming. However, they come with their own problems. From 14 we know that the magnetic field values are often in the order of a few mG at 10m-20m from the wire. As we can see, the magnitude rapidly falls off with increasing distance, and the distribution lines only have 2mG at 20 meters from the wire. So unless you have magnetometers or gaussmeters with a resolution of 1mG, it won't be possible to detect these fields. For context, the common gaussmeters commercially available have a resolution of 0.1G or 1G, and these are pocket sized. There are gaussmeters that have a resolution in the range of 0.1mG but these are huge bulky oscilloscopes that will never fit onto a small drone. In contrast, mmWave RADARs are ubiquitous, easily available, and can have a very good range and resolution, making this object detection problem much easier. Hence we arrive at the conclusion that mmWave RADARs are a good solution to the problem of power line detection.

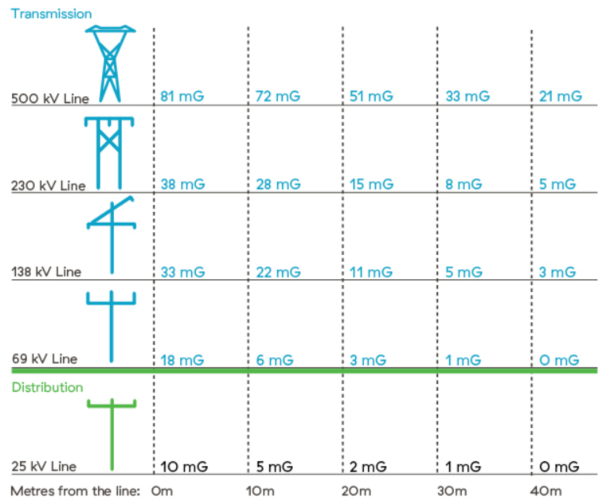

Fig. 14. Real world data of magnetic flux around a current carrying wire for different lines.

5.2 RCS results

The plots below depict the variation in RCS at different ϕ angles for the frequencies 10GHz, 24GHz and 77GHz. This is relevant since the angle of incidence ϕ equates to the AOD from the RADAR if the drone is aligned parallel to the ground. The analysis has been done for 3 different frequencies to isolate a suitable frequency of operation. At 10GHz, the RCS is around -66dB and varies very minimally (0.2dB) with varying ϕ(fig.15,16). Peaks in RCS occur at -150° and 50°. At 24 GHz, the RCS is around -60dB and peaks occur in the range of $+-150^{\circ}$ to $+-180^{\circ}$(fig.17,18). At 77GHz, the peak RCS is similar to at 20GHz, at -58dB. The peaks occur at multiple different angles as seen in figures 19,20.
Now,the value of scattered electric field from the cable can be calculated using the RCS equation in 1 by inputting the value of RCS obtained from the previous results, and the magnitude of incident electric field at different ranges calculated from the antennas. With this calculation, we can estimate the maximum range of detection. By our preliminary calculations, we can see that the reflected electric field is roughly -30dBm, in comparison to the noise floor which is approximately -100dBm for a 77GHz RADAR. Hence in these simulations, the wire is easily detectable using a mmWave RADAR.

6 CONCLUSIONS

From our results and observations, we conclude that 77GHz is the best frequency of operation as it allows the most freedom in terms of choosing ϕ or the angle of incidence of the transmitted radiation from the antenna. There are several directions we want to explore further in this area. Firstly, we hope to modify the patch antenna architecture to meet the design specs of a 77GHz mmWave RADAR and concurrently find the maximum detection range using the electric field calculations mentioned previously, and we hope to do this once we gain access to the lab's cloud RAM. Secondly, it is possible

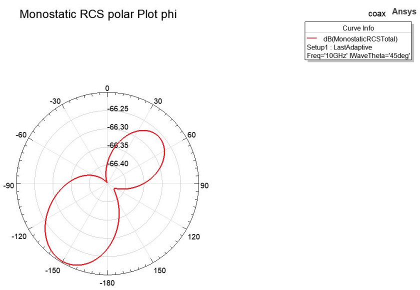

Fig. 15. Monostatic RCS polar plot for 10GHz

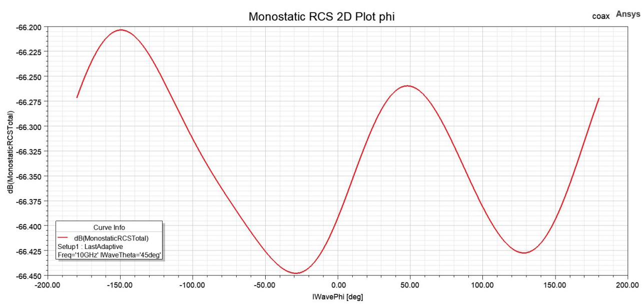

Fig. 16. Monostatic RCS plot for 10GHz

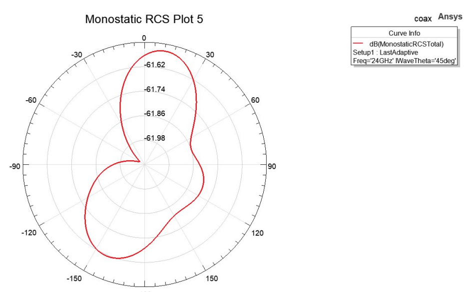

Fig. 17. Monostatic RCS polar plot for 24GHz

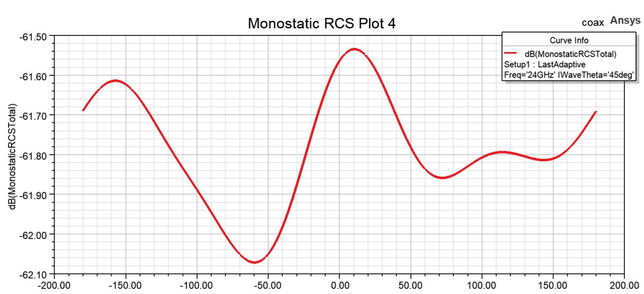

Fig. 18. Monostatic RCS plot for 24GHz

to develop a convolutional neural network to detect and classify wires as current carrying or non current carrying, and we want to

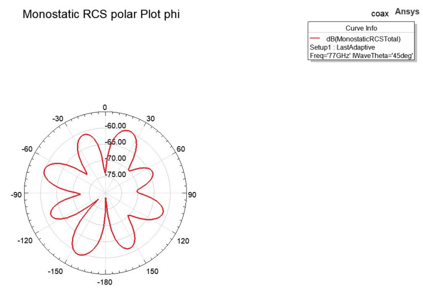

Fig. 19. Monostatic RCS polar plot for 77GHz

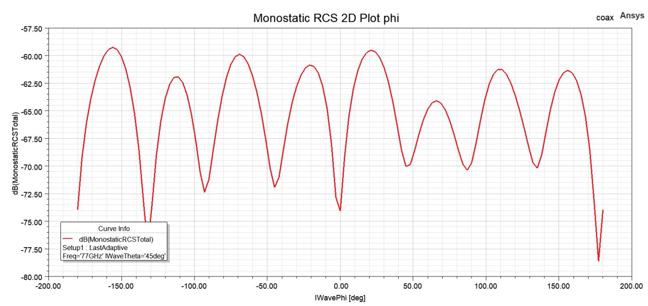

Fig. 20. Monostatic RCS plot for 77GHz

look into this, using [6] as a reference. We also want to look into the possibility of exploiting the 50Hz radiation emanating from the wire due to the current, and see if there is a coupling possible in lower band RADARs that can be accomplished with some hardware changes. Finally, we want to explore the possibility of using microdoppler to detect vibrations that come from electric poles and generators (also called the 50Hz hum).

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