

# Daredevil: Ultra-wideband radar sensing for small UGVs

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## ABSTRACT

We are developing an ultra wideband (UWB) radar sensor payload for the man-portable iRobot PackBot UGV. Our goal is to develop a sensor array that will allow the PackBot to navigate autonomously through foliage (such as tall grass) while avoiding obstacles and building a map of the terrain. We plan to use UWB radars in conjunction with other sensors such as LIDAR and vision. We propose an algorithm for using polarimetric (dual-polarization) radar arrays to classify radar returns as either vertically-aligned foliage or solid objects based on their differential reflectivity, a function of their aspect ratio. We have conducted preliminary experiments to measure the ability of UWB radars to detect solid objects through foliage. Our initial results indicate that UWB radars are very effective at penetrating sparse foliage, but less effective at penetrating dense foliage.

**Keywords:** UGV, robotics, ultra wideband, radar, sensors

## 1. INTRODUCTION



Fig. 1. Daredevil PackBot with polarimetric UWB radar array (concept)

For the Daredevil Project, iRobot Corporation is integrating the output of inexpensive, low-power, ultra wideband (UWB) radar sensors with higher-resolution range imaging devices (such as LIDAR and stereo vision) to provide sensing for our PackBot small unmanned ground vehicles (UGVs). Daredevil is funded by the US Army Tank-Automotive Research, Development, and Engineering Center (TARDEC). For this project, iRobot is partnering with Multispectral Solutions, Inc. (MSSI), a world leader in UWB technology. We are using MSSI's RaDeKL (Radar Developer's Kit Lite) UWB radar as the basis for our sensor payload.

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A unique feature of our approach is the use of polarimetric (dual-polarization) radar to distinguish foliage from solid objects. For certain types of foliage – such as tall grass, open fields, and crop fields – most of the vegetation (e.g. blades, stalks) will be approximately vertical in orientation. These types of foliage will return provide strong radar returns for vertically-polarized radar pulses and weak radar returns for horizontally-polarized radar pulses. In contrast, objects such as rocks will tend to reflect radar roughly equally regardless of pulse orientation. By computing the differential reflectivity of the target object, we expect to be able to reliably distinguish vertically-oriented vegetation from other solid objects.

We also plan to fuse the sensor returns from the UWB radar sensors with the high-resolution range data from a SICK LIDAR. For foliage that is not vertically oriented, such as bushes or underbrush, we plan to distinguish vegetation from solid objects using a density metric from the LIDAR returns, such as the one developed by Macedo, Manduchi, and Matthies<sup>1</sup> for the PackBot's predecessor, the Urban Robot. LIDAR will provide sparse returns from vegetation and dense returns from solid objects. A sparse LIDAR return in a particular direction will indicate that the objects detected (by LIDAR or radar) are likely to be vegetation and thus passable for the UGV.

The goal of the Daredevil Project is to advance the state-of-the-art in UWB radar perception systems for small UGVs. Such radar systems have a number of key advantages over existing perception systems based on LIDAR, vision, sonar, and other sensor modalities. These include the ability to see obstacles through foliage and the ability to operate effectively in adverse weather conditions. When fused with high-resolution range data from LIDAR and vision, the combined system will provide unprecedented capabilities for small UGVs to operate in environments beyond those currently navigable by small UGVs.

For example, a small UGV equipped only with LIDAR and/or stereo vision would find it difficult or impossible to navigate through a field covered with tall grass (e.g. 1 meter tall) that also contained solid obstacles such as boulders or tree trunks. In contrast, the Daredevil UGVs will be able to see the solid obstacles through the foliage and navigate around those obstacles.

In addition, sensor systems based on LIDAR and vision have greatly diminished capability in low-visibility weather conditions, such as rain and snow. Using UWB radar, the Daredevil UGVs will be able to navigate effectively through adverse weather conditions.

The combination of these advantages will enable UGVs with Daredevil technology to be useful in a broad range of environments and weather conditions. This will extend the benefits of UGVs (e.g. reduced risk to warfighters, force multiplication, increased reconnaissance range) to warfighters engaged in operations in dense foliage and poor weather and increase the mobility, survivability, and lethality of the Future Force.

## **2. BACKGROUND**

### **2.1 Multispectral Solutions (MSSI) RaDeKL UWB Radar**

The Radar Developer's Kit Lite (RaDeKL) is the next generation design of Multispectral Solutions, Inc.'s (MSSI's) UWB pulse radar technology<sup>2</sup>. The radar is compliant to Federal Communications Commission (FCC) Part 15 Subpart f rules permitting unlicensed use.

The maximum range of the RaDeKL sensor is 1152 feet (351 m). At any given time, the sensor will return an array of range values covering a span of 256 feet (78 m). In this way, the sensor can return ranges from 0-256 feet, 128-384 feet, 256-512 feet, et cetera. Each range bin is 12 inches (30 cm) long, which determines the range resolution of the sensor. Detection range depends upon radar cross section of target. Human detection range is 90 feet (27 m) nominal. The RaDeKL kit includes the radar hardware, supporting software drivers, and a graphical user interface (GUI) application for simple radar operation and control. The application allows viewing of radar return data and data logging for additional return signal post-processing.

Fig. 2 shows a RaDeKL UWB sensor unit. The dimensions of each sensor are 7.75" (20 cm) x 4" (10 cm) x 3.125" (8 cm) not including antennas and 7.75" (20 cm) x 4.875" (12 cm) x 4.75" (12 cm) including antennas. Table 1 shows the technical specifications for the sensor.



Fig. 2. MSSSI RaDeKL UWB radar (front view)

Table 1. RaDeKL UWB radar sensor specifications

<b>RADEKL UWB RADAR SENSOR SPECIFICATIONS</b>	
Radio Technology	Ultra Wideband (UWB)
Frequency of Operation	6.0 – 6.6 GHz
Transmitter Output Power	FCC Part 15 Subpart f Compliant
Receiver Antenna	14 dBi gain with 40 x 40 degree field-of-view
Receiver Sensitivity	-75 dB at 10 dB S/N
Receiver Dynamic Range	40 dB above noise floor
Range Resolution	12 inches (30 cm)
Number of Range Bins	256
Range Extent	Selectable in 4-foot increments from 128 – 1,152 feet (39 – 351 meters)
Operating Voltage	12 V DC, 110 V power supply provided
Current Consumption	100 ma
Temperature Range	0 – +50 deg C
Frequency of Update Rate	Selectable single return by command or 20 Hz streaming
Interface	USB 2.0 compliant

## 2.2 PackBot Platform

iRobot's PackBot is a highly-robust, all-weather, all-terrain, man-portable mobile robot. PackBot was developed under the DARPA Tactical Mobile Robotics program (contract F04701-01-C-0018). PackBot is equipped with two main treads that are used for locomotion and two articulated flippers that are used to climb over obstacles. PackBot can travel at sustained speeds of up to 4.5 mph. On a full set of batteries, PackBot can drive at 4.5 mph continuously for 8 hours, for a total range of 36 miles (58 km). Standing still, PackBot can run its computer and sensor package for 36 hours.

PackBot is 27 inches (69 cm) long, 16 inches (41 cm) wide, 7 inches tall (18 cm), and weighs 40 pounds (18 kg). All of a PackBot's electronics are enclosed in a compact, hardened enclosure. These electronics include a 700 MHz mobile Pentium III with 256 MB SDRAM, a 300 MB compact flash memory storage device, and a 2.4 GHz 802.11b radio Ethernet. Each PackBot can withstand a 400G impact, equivalent to being dropped from a second story window onto concrete. Each PackBot is also waterproof to 3 meters. Three modular payloads fit into the rear payload bay. Each payload connector provides power, Ethernet, and USB connections from the PackBot to the payload module for a highly-flexible mission capability.

PackBot is at home in both wilderness and urban environments, outdoors and indoors. In the wilderness, PackBot can drive through fields and woods, over rocks, sand, and gravel, and through water and mud. In the city, PackBot can drive on asphalt and concrete, climb over curbs, and climb up and down stairs while carrying a payload. PackBot can also climb up, down, and across surfaces that are inclined up to 60 degrees. In addition, PackBot can climb up and down inclines of up to 55 degrees, and across inclines of 45 degrees, while carrying a 22.5 pound (10 kg) payload. Heavier payloads can be carried over less steep terrain.



Fig. 3. US Army soldier uses a PackBot to explore a cave complex in Afghanistan

Over 700 PackBots have been deployed in Iraq and Afghanistan as part of Operation Iraqi Freedom and Operation Enduring Freedom. Fig. 3 shows a US Army soldier using a PackBot to explore a suspected al Qaeda cave in eastern Afghanistan.

In previous work, as part of the Wayfarer Project funded by TARDEC, we developed a fully-autonomous version of the PackBot capable of performing urban reconnaissance missions<sup>3</sup>. The Wayfarer PackBot used a combination of LIDAR and stereo vision sensors to avoid obstacles and build maps, in combination with an INS/GPS system for localization.

## 3. POLARIMETRIC (DUAL-POLARIZATION) UWB RADAR

Unlike most other sensor modalities (e.g. LIDAR, vision), UWB radar has the ability to penetrate dense foliage and detect objects in the foliage. Since the UWB radar receives radar returns from both the foliage and the solid objects in the foliage, a key question is how to classify returns as either foliage (passable) or solid objects (impassable). The UGV will then be able to traverse terrain covered by passable foliage and steer around solid objects, significantly increasing vehicle mobility as compared to vehicles that are unable to sense and pass through foliage.

We propose to use polarimetric (dual-polarization) radar to transmit UWB pulses that are vertically polarized along with separate pulses that are horizontally polarized. Since most vegetation (e.g. tall grass, open fields, crop fields) has large features roughly aligned with the vertical axis and smaller (if any) features aligned with the horizontal axis, these forms of vegetation will return stronger UWB pulses in the vertical direction than the horizontal direction.

We can then compute the differential reflectivity of the UWB returns with vertical and horizontal polarization:

$$Z_{DR} = 10\log\left(\frac{P_h}{P_v}\right)$$

Where  $Z_{DR}$  is the differential reflectivity in dB,  $P_h$  is the returned backscattered power received from the horizontally-polarized radar pulse, and  $P_v$  is the returned backscattered power received from the vertically-polarized radar pulse.

A positive value of  $Z_{DR}$  indicates that the objects reflecting the radar pulse are horizontally-aligned, while a negative value of  $Z_{DR}$  indicates that the objects reflecting the radar pulse are vertically-aligned. A value of  $Z_{DR}$  near zero indicates the reflecting objects have horizontal and vertical axes that are roughly equal.

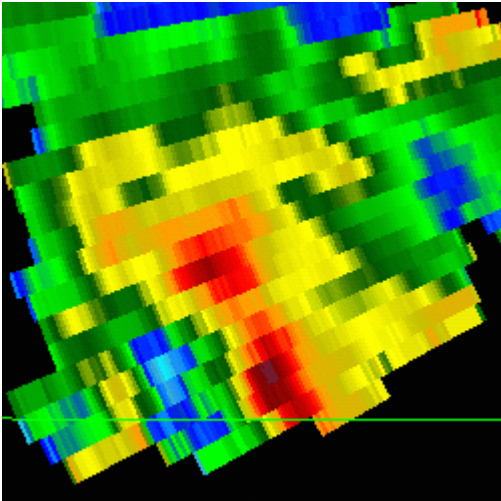


Fig. 4. Differential reflectivity from hail-producing supercell thunderstorm (blue = low  $Z_{DR}$ , red = high  $Z_{DR}$ )

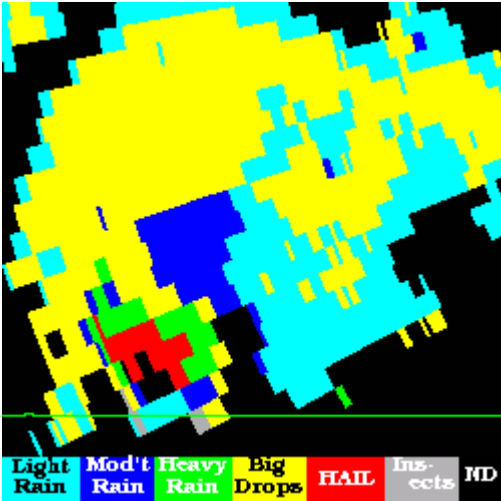


Fig. 5. Precipitation map from NSSL Hydrometer Classification Algorithm (HCA)

Meteorologists at the National Oceanographic and Atmospheric Administration (NOAA) National Severe Storms Laboratory (NSSL) have used polarimetric radar to classify precipitation based on the shape of the falling water<sup>4</sup>. Large

raindrops tend to fall in an oblate configuration, wider along the horizontal axis than the vertical. In contrast, hailstones are approximately spherical, with similar horizontal and vertical axis lengths. As a result, large raindrops tend to have a large positive  $Z_{DR}$  while hailstones tend to have a near-zero  $Z_{DR}$ . Using this technique, NSSL meteorologists were able to successfully determine whether regions of precipitation were rain or hail.

Fig. 4 shows the differential reflectivity map for a hail-producing supercell thunderstorm produced by the NSSL polarimetric radar<sup>5</sup>. The blue regions correspond to areas with low  $Z_{DR}$ , and the red regions correspond to areas with high  $Z_{DR}$ . The “ $Z_{DR}$  hole” of blue readings in the lower portion of the map, just left of center, is characteristic of a hail-forming region. The NSSL Hydrometer Classification Algorithm (HCA) uses this data to accurately distinguish hail from rain and generate a classified precipitation map (Fig. 5).

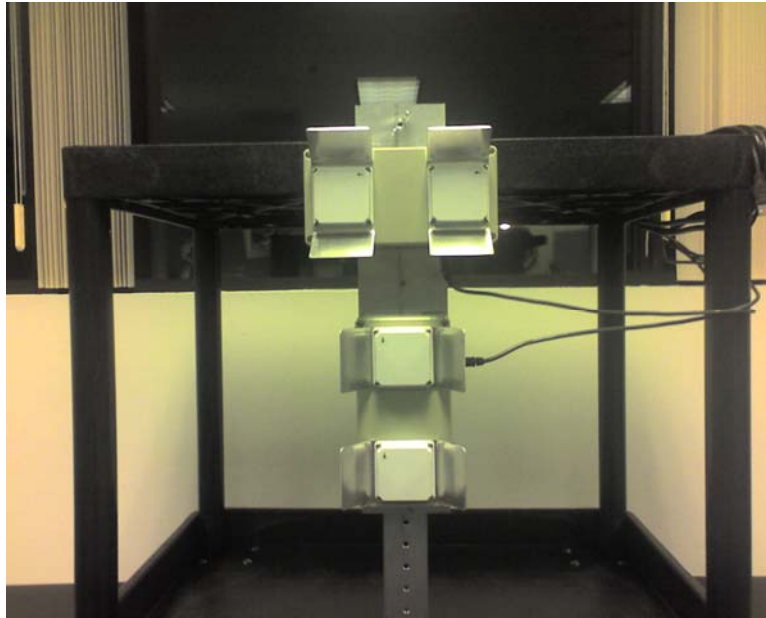


Fig. 6. Polarimetric UWB radar array mobile test rig

For the Daredevil Project, we are developing a polarimetric radar array for the PackBot using two RaDeKL UWB radar sensors. One of the radar sensors is mounted with a vertical orientation, and one of the sensors is mounted with a horizontal orientation. For the initial experiments described in this paper, we have mounted the polarimetric radar array on a test rig on the mobile cart shown in Fig. 6.

#### 4. EXPERIMENTAL RESULTS

For our initial experiments, we measured the ability of the UWB radar sensor array to detect a solid building wall (concrete and glass) through foliage (bushes and trees). We moved the sensor array test rig parallel to the wall at a distance of approximately 20 feet (6 m) for the entire length of the wall (approximately 70 m).

These tests were conducted during the winter, and the foliage included two types of bushes, deciduous and evergreen. The deciduous bushes lost their leaves for the winter and consisted of a dense thicket of bare branches. We refer to this as “sparse foliage”. The evergreen bushes retained all of their leaves and provided a dense obstacle with no openings. We refer to this as “dense foliage”. The bushes blocked most, but not all, of the radar field-of-view relative to the building wall. Unlike tall grass, the branches and leaves of bushes are not vertically aligned, so methods other than differential reflectivity (such as density measures) will need to be used to differentiate bushes from solid obstacles.

Our experiments indicate that the UWB sensors can detect solid obstacles through sparse foliage, but may have difficulty detecting obstacles through very dense foliage. While this is a limitation for long-range mapping, it is an advantage for obstacle avoidance, since the dense bushes that block the UWB radar pulses are too dense for the PackBot to drive through and must be treated as solid obstacles.

Fig. 7 shows the return signal amplitude from a single sample from the horizontal (left) and vertical (right) RaDeKL sensors. Signal strength is plotted along the vertical axis for each range bin between 0 and 60 feet (18 m). Each range bin corresponds to a 1 foot (30 cm) range interval, and ranges are marked along the horizontal axis in feet.

The peak at 10 feet clearly shows that the sensors can detect a strong radar return from the building wall through the sparse foliage. (The peak at range zero is present in all radar samples, due to close-range reflections, and can be ignored.)

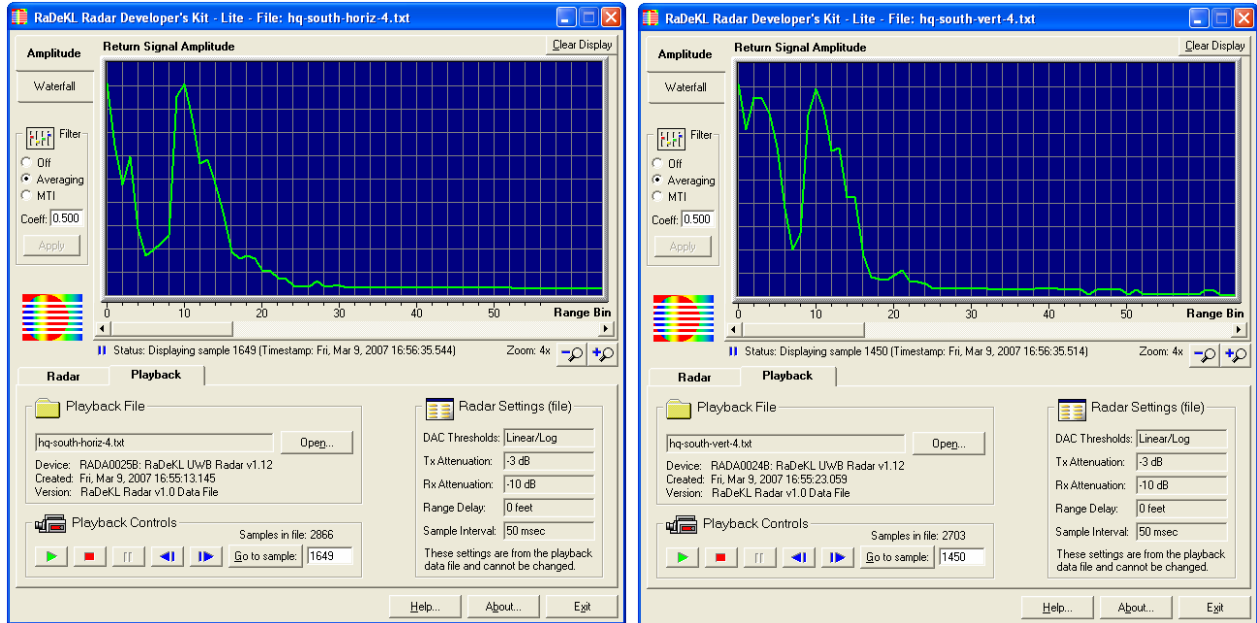


Fig. 7. Radar return signal amplitude through sparse foliage for horizontal (left) and vertical (right) sensors (range in feet)

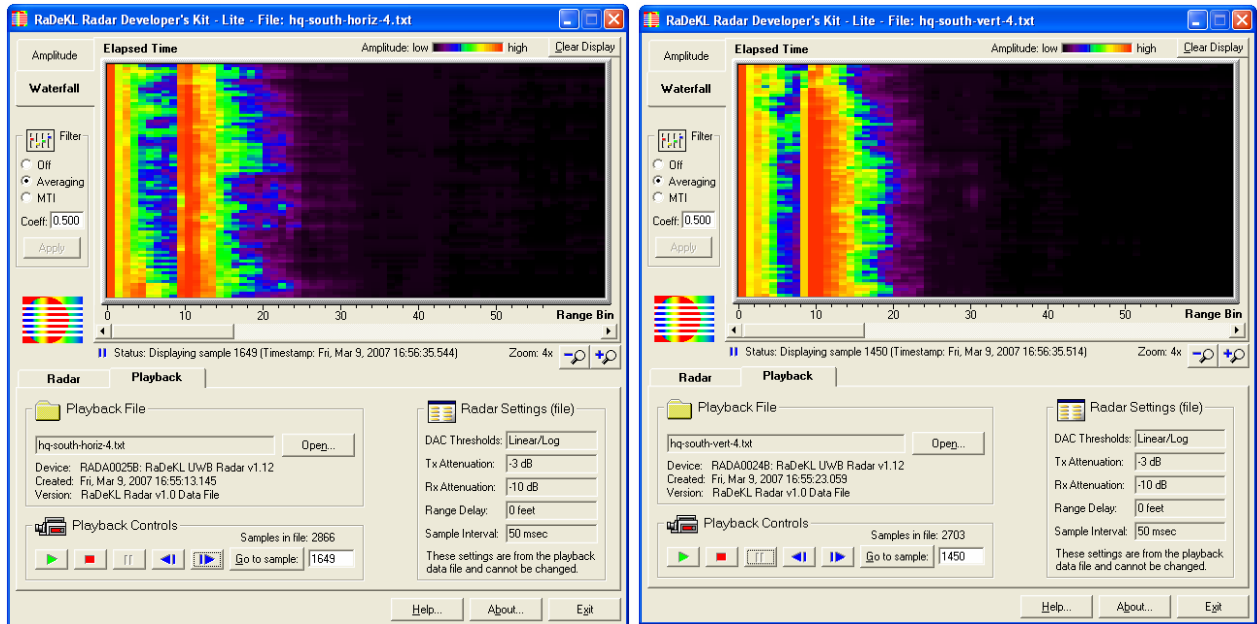


Fig. 8. Waterfall plot through sparse foliage for horizontal (left) and vertical (right) sensors (black/blue = low, red = high)

Fig. 8 shows waterfall plots for radar samples over time for the horizontal (left) and vertical (right) sensors. In these plots, the vertical axis represents time (with the current time at the top of each plot); the horizontal axis represents range; and the color of each point corresponds to the strength of the radar return signal. Black indicates no return or a very

weak return; purple and blue indicate weak returns; yellow and orange indicate moderate-strength returns; and red indicates a strong return. In these plots, the vertical red line at 10 feet (3 m) shows the strong signals received from the wall through the sparse foliage at 3-6 feet (1-2 m).

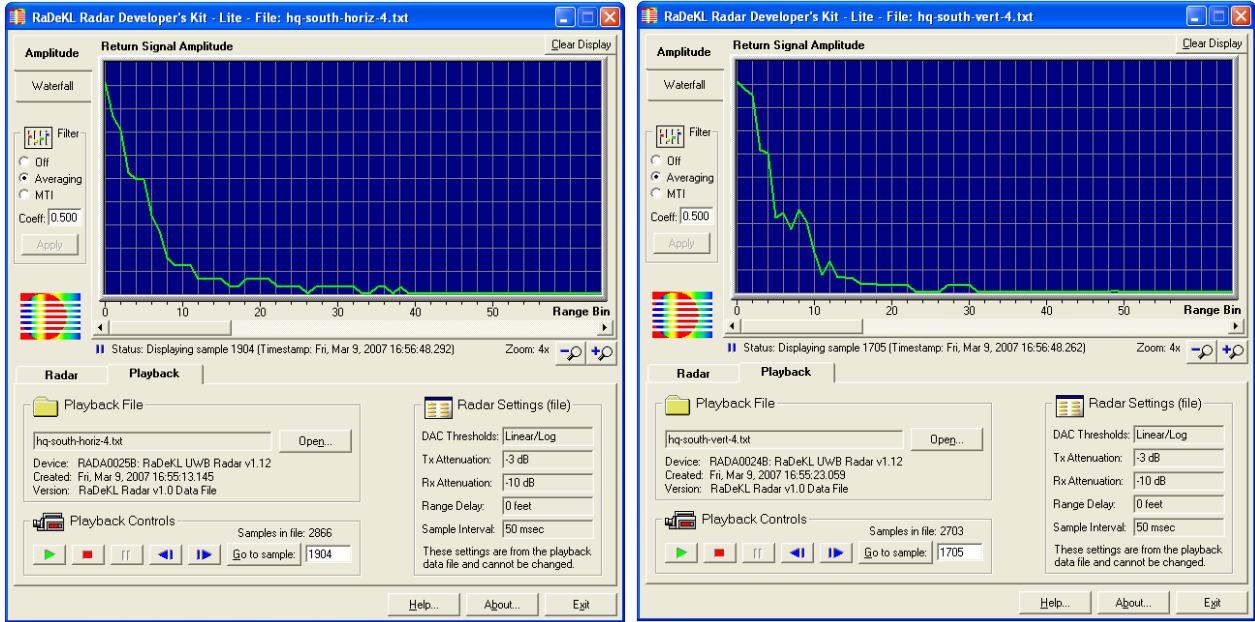


Fig. 9. Radar return signal amplitude through dense foliage for horizontal (left) and vertical (right) sensors (range in feet)

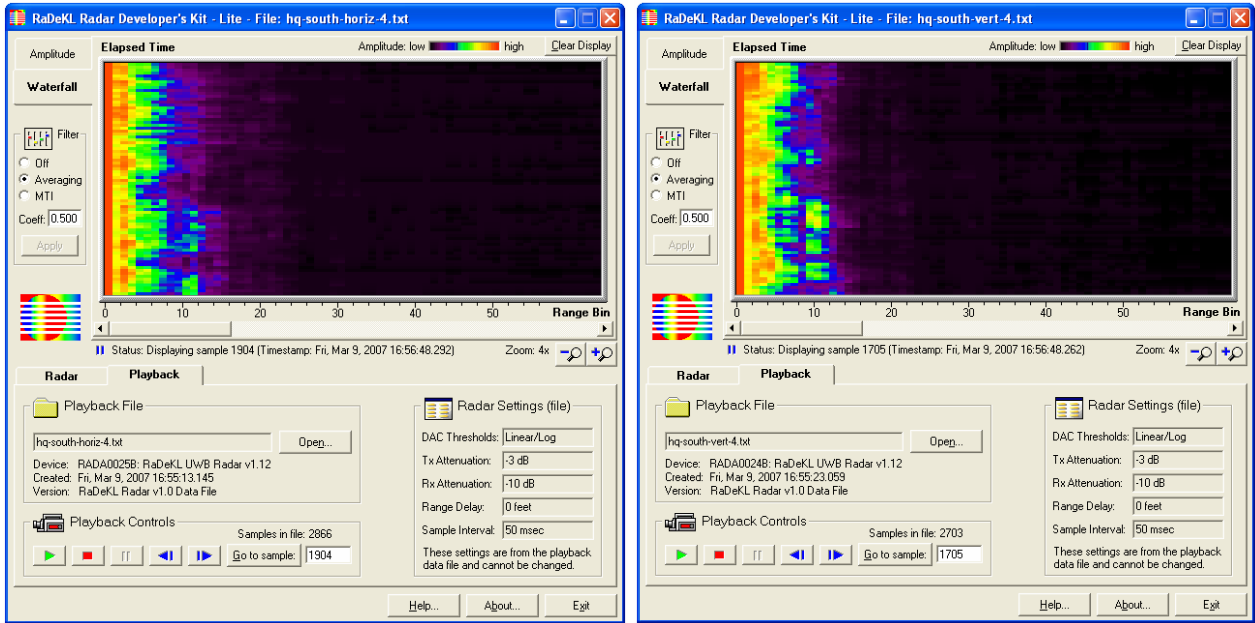


Fig. 10. Waterfall plot through dense foliage for horizontal (left) and vertical (right) sensors (black/blue = low, red = high)

Fig. 9 shows the radar return amplitude from the dense foliage located between the horizontal (left) and vertical (right) sensors and the wall. These graphs show that the UWB sensors are not able to penetrate the dense foliage to detect the building wall at 10 feet.

Fig. 10 shows waterfall plots for the horizontal (left) and vertical (right) sensors as they were moved parallel to the dense foliage. These plots also show that the sensors are only detecting the foliage and not the wall beyond.

For these experiments the transmit signal was attenuated at -3 dB from maximum, and the receiver sensitivity was attenuated -10 dB from maximum. We experimented with greater transmit power and greater receiver sensitivity, but found that reflections from the environment would swamp the return signal, making the data useless. We also experimented with lower transmit power and less receiver sensitivity, and found that these settings were fine for detecting solid obstacles in open space, but were insufficient for penetrating sparse foliage and detecting the building wall.

## 5. CONCLUSIONS

For the Daredevil Project, we are developing a UWB radar payload for the man-portable iRobot PackBot UGV. Our objective is to develop a sensor array that is effective at detecting solid objects through foliage, and can be used in combination with higher-resolution sensors such as LIDAR and stereo vision to allow a small UGV to navigate through foliage.

We plan to use a polarimetric array of one horizontally-polarized sensor and one vertically-polarized sensor to differentiate vertically-aligned foliage (e.g. tall grass) from solid objects. Other methods and sensors, such as density metrics and LIDAR, will be used to differentiate non-vertically-aligned foliage from solid objects.

In our initial experiments, we tested the ability of UWB to detect solid objects through (non-vertically-aligned) foliage. Our results show that UWB can effectively penetrate sparse foliage (such as deciduous bushes without leaves) but not very dense foliage (such as evergreen bushes with leaves). This is a potential advantage for obstacle avoidance since the PackBot is able to drive through sparse foliage, but must treat dense bushes as obstacles.

Our next step will be to test our UWB sensor array in other forms of vegetation, such as tall grass, which we expect to have an intermediate density between sparse foliage and dense foliage. In this environment, we will test our polarimetric radar classification algorithm to determine whether it can effectively classify radar returns as coming from foliage versus solid objects. We will then mount our UWB sensor array on a PackBot and use it to construct a map of terrain including both foliage and solid objects.

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