Performance analysis of a RADAR FMCW sensor developed for plant height measurement in agricultural and comparison with an NDVI sensor

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Abstract. *This paper presents the preliminary analysis of a low cost RADAR FMCW System developed for plant height measurement. It was tested under controlled conditions and then shipped on an agricultural machine with an infrared reflectance sensor (NDVI) on a millet crop (Pennisetum glaucum) for the proper comparison of dynamically obtained responses during agricultural operations. The system was georeferenced and the results demonstrated the potential of the technique used. However, boundary conditions must be implemented to remedy noise encountered in the field and provide greater accuracy in the responses of the developed sensor system.*

1. Introduction

The use of detailed information through the insertion of electronics in agricultural machines allows the application of inputs in small portions of the crops. Among the possibilities for determining the need for localized applications, is the use of sensors to measure parameters related to plant development, such as their height. NDVI reflectance sensors can be used for this purpose, but tend to have saturation of readings from the moment plants begin to overlap. Ultrasound-based sensors are also used, but they are sensitive to environmental conditions, such as the presence of wind, and do not allow measuring the distance between their anchor point in the machines and the ground, being possible to only measure the distance between the sensor and the top of the plants. LIDAR sensors can provide height parameters through three-dimensional images, based on the time it takes laser pulses to return from the target to the sensor. The drawback is that the systems are more sensitive to weather and other conditions that interfere with thw laser pulse. Cost is another factor that limits its large-scale expansion. Active sensors use radiation that can penetrate the canopy of plants have advantages over others, with radars being an option. Syntetic Aperture Radar (SAR) sensors, which can be embedded in aircraft or satellites, are ground-sensing technologies that provide better resolution data, however these technologies can reach high values depending on their configuration, making them unviable use in smaller scale operations. Frequency Modulation Continuous Wave (FMCW) radars can be a versatile alternative for crop applications, where close-to-crop sensing is sought, with the advantage of simpler setup and lower cost.

FMCW sensors respond almost instantaneously, allowing actuators to be deployed and triggered quickly during agricultural operations. Thus, there may be greater precision in the responses and the inputs can be applied in a timely and controlled manner.

In this context, this paper aims to demonstrate the potentiality and the relationship between the RADAR FMCW sensor developed and a commercial sensor that allows obtaining the normalized difference vegetation index (NDVI), through a case study in a millet crop, in full development.

2. Background

2.1. Precision Agriculture

Precision Agriculture (PA) is the use of a set of technological tools that can be used for crop management, allowing treatment according to existing variability, demonstrating their potential for economic development and environmental benefits that can be visualized through the reduction of water, fertilizers, herbicides, pesticides among others (MOLIN, 2015).

Recently, (PA) relies on proximal remote sensing methods that use sensors embedded in drones (ANTHONY, 2014) or agricultural machines (SANTOS, 2019), which use LIDAR and RADAR, respectively. Such sensors are responsible for the analysis of plant growth when in agricultural operations and describe detailed information about their condition, also allowing an assessment of plant tolerance to abiotic stress, such as drought, heat or nutrient deficiency. Therefore, proximal sensing enables information to be improved and accurate through crop monitoring, enabling management and decision-making in an agile and integrated manner with other systems, automatically, thus improving the cost-benefit ratio (MULLA, 2013).

2.2. Remote Sensing

According to Elanchi and Van Zil, (2006) the term remote sensing indicates the acquisition of information about an object without physical contact between them. Such information can be obtained through active sensors, which are responsible for the emission and reception of their signal, or passive ones, which depends on an external signal source.

The development of remote sensing tools has been heavily influenced by the advances in Global Navigation Satellite Systems (GNSS) consisting of a constellation of satellites designed to provide position, velocity and time data for use on Earth and to some extent, in space, which provides greater accuracy of data obtained by remote sensors (ZAVOROTNY et al., 2014).

Currently sensors embedded in satellites provide dynamic information about global patterns such as clouds, surface vegetation cover and their seasonal and structural variations, among others. The capability of wide and rapid coverage enables the monitoring of rapid change of phenomena in the atmosphere, so long-term and repetitive capabilities allow for observation of seasonal, annual and long-term changes. With the development of technologies and the reduction of sensor size and costs, there is a greater demand for implementation in embedded systems such as tractors, implements and also in unmanned aerial vehicles. When compared to satellites or airplanes, they provide higher spatial resolution in addition to real-time imaging, improving crop monitoring (VEGA et al., 2015).

2.3. Radio Detection and Ranging (Radar)

RADAR, acronym for Radio Detection and Ranging, is an active sensor that has the property and autonomy to produce electromagnetic waves at microwave frequencies, which range from 0.3 to 300 GHz, allowing them to cross certain objects, thus providing relevant information of the structures analyzed (SKOLNIK, 2009).

The intensity and transmission of RADAR signals are described based on the characteristics of the analyzed surface and also the technology adopted for its construction, as seen in Equation 1.

$$P_r = \frac{A_e \, G P_t \, \sigma^0 \, A}{(4\pi)^2 R^4} \tag{1}$$

Where, P_r is the received signal power, A_e is the RADAR antenna area in m^2, G determines the RADAR gain, P_t defines the transmitted power and A describes the surface reflection area of the target in m^2. The distance from RADAR to the target analyzed and described by parameter R, in meters. The factor $(4\pi)R^2$ indicates the total area of a sphere where power will be distributed. The backscatter coefficient σ^0 is one of the most important factors, being dimensionless and most often expressed in dB.

The accuracy of the information depends on some factors, such as orientation, geometry of the dielectric constant target of the material and also the band used, being the most common bands L (1 to 2) GHz, C (4 to 8) GHz and X (8 at 10) GHz. Radars become appropriate sensors for monitoring the earth's surface, as microwaves are able to penetrate clouds, canopies and even the topsoil, thus describing relevant information on the current stage of the targets analyzed. SAR cameras currently have the most advanced technologies for remote sensing imaging, which can be taken at high altitudes and covering large areas. This is due to the simulation of a large antenna synthesized from a smaller antenna array, but this advantage increases the cost of this type of system. FMCW radars are the most viable alternatives when working with shorter distances and covering smaller areas, since the carrier signal is frequency modulated and therefore require lower power and consequently there is a reduction in costs (SCHEER, HOLM, 2010).

2.4. Normalized Difference Vegetation Index (NDVI)

One of the parameters obtained through the remote sensing technique commonly used in (PA) is the Normalized Difference Vegetation Index (NDVI). This technique consists of measuring the energy reflected by the canopy of the crop under study in two bands. For this purpose, both active sensors, which have their own energy source, or passive sensors, which refer to natural sunlight, can be used. NDVI correlates with various plant attributes such as growth, biomass and leaf nitrogen content (AMARAL et al., 2015).

NDVI optical sensors can be installed on a variety of platforms, such as satellites, on board airplanes or also on agricultural machines. The conditions and quantities in the vegetation are described by the ratio between the difference of reflectivity in the near infrared and visible red bands and that resulting from the sum of these same reflectivities, and the values may vary between -1 and 1, with greater plant vigor, in values close to 1 (GAMEIRO et al., 2016).

3. Related work

Radar work has been developed for a variety of purposes. A short range distance meter for agricultural applications and in particular for measuring the depth of work in tillage was developed by Rouveure, Faure and Monod (2002). A sensing device was fixed at a distance of 0.75 m from the ground with an accuracy of around 5 mm. The authors reported that operating environment restrictions such as dust, rain, mud or turbulence did not affect FMCW radar making the tool viable and yet inexpensive.

To analyze crop growth, Haagsma (2015) used NDVI data and SAR-type RADAR satellites to compare the growth of four crop types. There was a strong correlation between NDVI indices when compared with RADAR parameters for analyzes performed on corn, canola and soybean crops, but low correlations were obtained for wheat, which, according to the author, is due to the high crop variability. RADAR was sensitive to different materials and was therefore sensitive to culture structure, water content and incidence angle, which varied according to the culture analyzed. Nevertheless, the results presented in the paper demonstrate that radar is able to provide valuable information on crop development, such as height and biomass accumulation, an analysis of great importance for crop monitoring.

Henry et al. (2017) used a RADAR FMCW to estimate the volume of grapes in a vineyard. The system worked at a frequency of 24 GHz, where it was shifted between the lines of the grapevines approximately 1m from the crop and with it performed a scan of the irradiated beam in 3D. After the scan, a parameter called scattering factor was established, which allowed the classification of the echo levels of the microwave signal after returning from the culture. Subsequently an algorithm for contour detection was developed and applied in the processing of the image generated by RADAR, which according to the authors, obtained an R^2 of 0.947, with a standard error of 0.02, being considered a tool that allows the estimation. the volume of grapes after the microwave signal treatment detected, which occurs even in the presence of natural disorders such as leaves and twigs, or artificial, such as irrigation hoses present in the crop.

4. Methodology

A RADAR FMCW sensor system was developed and tested in the Electronic Instrumentation (LIE) Laboratory at ESALQ / USP. The project was designed to be embedded in agricultural machinery to measure plant height. The work consisted of three distinct stages: in the first stage there was the development, testing and calibration of the sensor system, containing an electronic circuit of modulation and demodulation of signals from the microwave sensor (*AgilSense*), HB 100, which operates in Band X, 10 GHz. The second stage was performed in a controlled and dynamic field at the Department of Biosystems Engineering of ESALQ / USP, using cardboard boxes of known sizes and shapes to simulate the plant canopy. In the third step, the system was tested in crop condition, to know its responses in dynamic situations. Figure 1 shows the steps performed.

Figure 1. In A, developed eletronics, in B, field stage and in C, tillage stage.

In the farming stage, an optical reflectance sensor was also used to obtain the NDVI to analyze and correlate with the data of the developed system (Figure 1 C).

An Arduino microcontrolled platform (Figure 1) was used for acquisition, sharing and storage of signals from the sensors. Subsequently, an algorithm was implemented to collect sensor data in a systematic and joint manner. The acquisition of data related to the optical sensors and the developed RADAR FMCW were properly georeferenced.

The system determines the height of the plants operating with two sensors working in different modulations: 1560 Hz, responsible for the distance between the sensor and the canopy; and 500 Hz, responsible for the distance between the sensor and the ground (Figure 2).

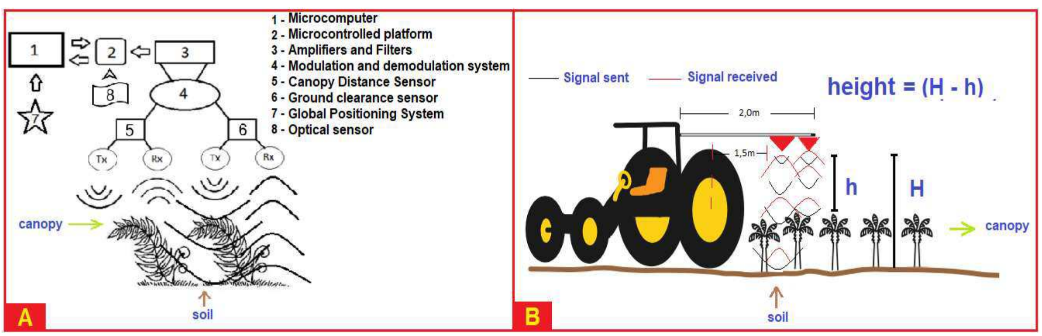

Figure 2. In A, system block diagram, in B, implementation on tractor.

The modulated signal from both sensors reaches the targets and returns, allowing the calculation of the number of beats of the signal. For determination of plant height, the system makes the difference between the number of beats obtained and compares it with the values of the calibration step in the laboratory. Figure 2 in B demonstrates the method used.

4.1. General System Architecture

The laboratory stage 1 consisted of evaluating the electronics performance, validating the proposed technique and characterizing the sensor. The sensor system developed was mounted on a movable platform in front of a masonry wall, used to simulate the ground, and then, between the wall and the sensor, were marked positions from 0.5m to 4m, where the platform was moved and the response signal referring to frequency beat has been properly recorded. A high density chipboard with dimensions of 1.3m x 1.8m and thickness of 0.03m in front of the sensor was added to simulate the crop canopy. The plate has been moved in front of the sensor at some known distances between sensor, plate and wall. Three repetitions were performed for each described situation, obtaining R^2 determination coefficients of 0.99 and 0.77 to measure the distance in the conditions without and with the plate respectively.

To perform the field experiment, in step 2, a compact Massey Fergusson 4283 model tractor with 63 KW of power was used, where the FMCW sensor system was installed on a metal rod, and later fixed to the rollover protection structure of the tractor. The sensor was at a height of 2.3m from the ground and at a distance of 1.5m from the outermost point of the tractor side. Figure 2 in B illustrates the above. Along a 50-meter course, 7 cardboard box targets were arranged to simulate the plants. The tractor traveled the course at speeds of $1ms^{-1}$, $2ms^{-1}$ and $3ms^{-1}$. Three repetitions were performed for each velocity.

An algorithm was developed to compare and correlate signals coming from FMCW radar in real time. It also allows capturing the optical reflectance sensor signals simultaneous, as well as the geographic coordinates generated by a GPS receiver, thus reflecting the georeferenced state of the crop, which allows the generation of crop maps.

5. Case study

The third step consisted of a case study for validation in crop conditions, evaluating the sensor performance in a real situation and dynamically, with the interference and noise in the field. The experiment took place in a millet (*Pennisetum glaucum*) crop in full vegetative development at a speed of 1.3 ms^{-1}. They were then passed side by side along a portion of the farmland from the outside into the culture (Figure 3).

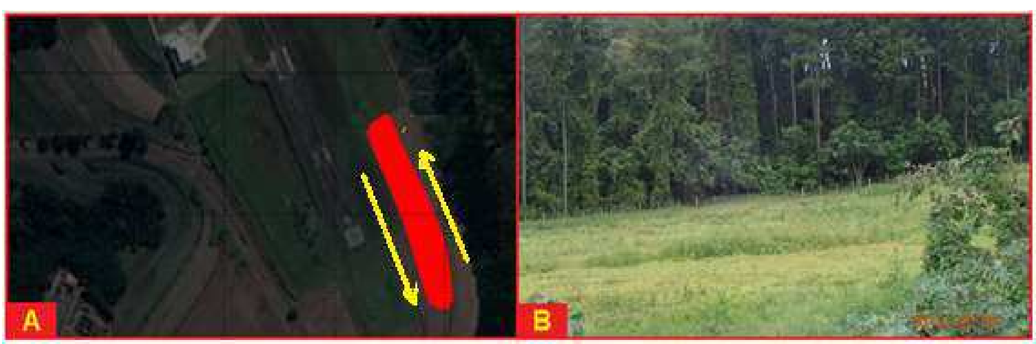

Figure 3. In A, region analyzed, in B, region details

On the same support where the RADAR FMCW system was fixed, the Crop Circle® ACS-210 (*HOLLAND SCIENTIFIC, USA*) optical device was used to obtain the NDVI. It provided canopy reflectance readings at the wavelengths of 590 nm (amber) and 880 nm (near infrared). This procedure aimed at comparing and correlating the developed system and its responses with those of a commonly used sensor. The sensors, microwaves and NDVI were fed with positioning data through a Novatel GNSS receiver with submetric accuracy and operating at a 5 Hz acquisition frequency.

Discrepant values of reflectance data were eliminated by discarding values above average plus three standard deviations and those below average minus three standard deviations. Spatial data were processed using the Quantum GIS Geographic Information System (GIS), applying a subtitle classifier called natural breaks, in order to minimize variability within the classes. Nine classes were generated through which nine delimitations were obtained from polygons manually defined in the GIS.

The data thus obtained were processed in a spreadsheet for correlation and regression analysis.

6. Results and discussion

In the sensor testing and calibration step it was possible to establish a direct correlation between the distance from the target to the sensor and the number of beats of the signal (Figure 4).

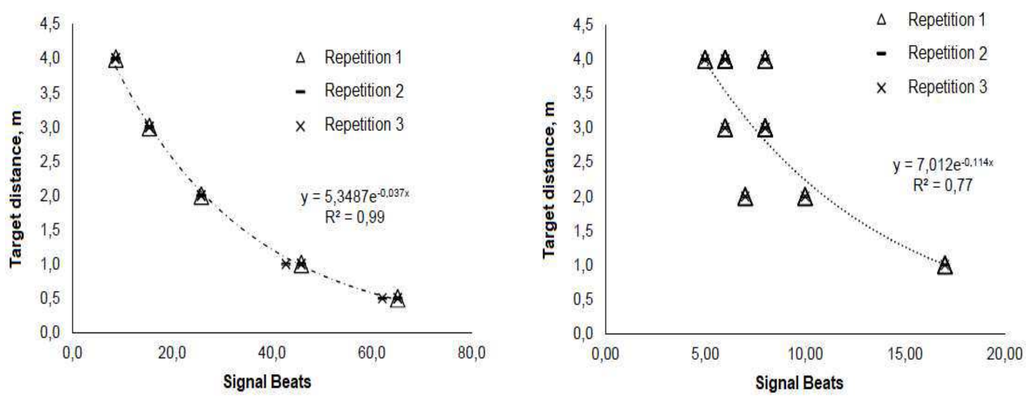

Figure 4. Relationship between sensor signal beats and distance for 1560 Hz and 500Hz.

Analyzing Figure 4, to the left of the representation is presented the relationship between the frequency beats of the sensor signal and the distance measured between the sensor and the target, without the presence of the obstacle, demonstrating excellent accuracy in the results. In the figure on the right, generated by the addition of an obstacle between the masonry wall and the sensor, to simulate the plant canopy, we can see that there was repeatability, but there is a dispersion of the results and thus, there is a reduction in the coefficient of determination. Such identified information serves for future implementations, adjustments and improvements of the developed system (FERREIRA, 1991).

In the field stage, there was a greater influence of the geometric characteristics of the targets, where those with larger area respond better. At the smallest targets, for a speed of $3ms^{-1}$ with boxes measured between 0.20 and 0.23m, there was a response in the sensor beats difference between 12.5 and 12.4 respectively. In the highest target analyzed, a beating difference of 18.8 were obtained and this information represents a box with a measured height of 1.15m. Table 1 provides the results of the field trip experiments, with box height and size measurements and sensor responses at a speed of $3ms^{-1}$.

Table 1. Descriptive statistics for the difference between the number of signal beats and the target characteristics and speed.

Targets	Velocity	Height	Longitudinal dimension	Transverse dimension	Area	Difference Between Signal Beats		
	($m\ s^{-1}$)	(m)	(m)	(m)	(cm^2)	Average	Standard deviation	C.V.** (%)
1°	3,0	0,30	0,45	0,32	1440	13,5	1,7	11,6
2°		0,35	0,37	0,58	2146	15,0	2,5	16,9
3°		0,64	0,25	0,30	700	16,1	2,1	13,3
4°		0,62	0,20	0,35	700	17,8	1,2	8,3
5°		0,35	0,37	0,58	2146	14,9	1,4	9,3
6°		0,20	0,25	0,30	700	12,5	0,2	1,4
7°		0,23	0,35	0,35	1225	12,4	1,8	14,7
8°		1,15	0,18	0,18	324	18,8	2,7	14,5

* Standard deviation of repetitions of differences between signal beats **C.V. Coefficient of variation of repetitions between the differences between signal beats.

Looking at the table, we realize that the values of the coefficients of variation are less than 20%, so there is an average dispersion of the values and thus an acceptable accuracy of the results (SANTOS, 2007).

In step 3, the correlation between the developed sensor and a commonly used reflectance sensor was evaluated. The regions selected through the polygons manually located through the GIS showed average NDVI values ranging from 0.120 to 0.685 with a mean of 0.214 and a coefficient of variation of 45%, indicating a condition of variability. Plant height measurements were performed punctually. A manual GNSS (GARMIN-62S) provided the location of the determined points. The adopted method can be seen in Figure 5.

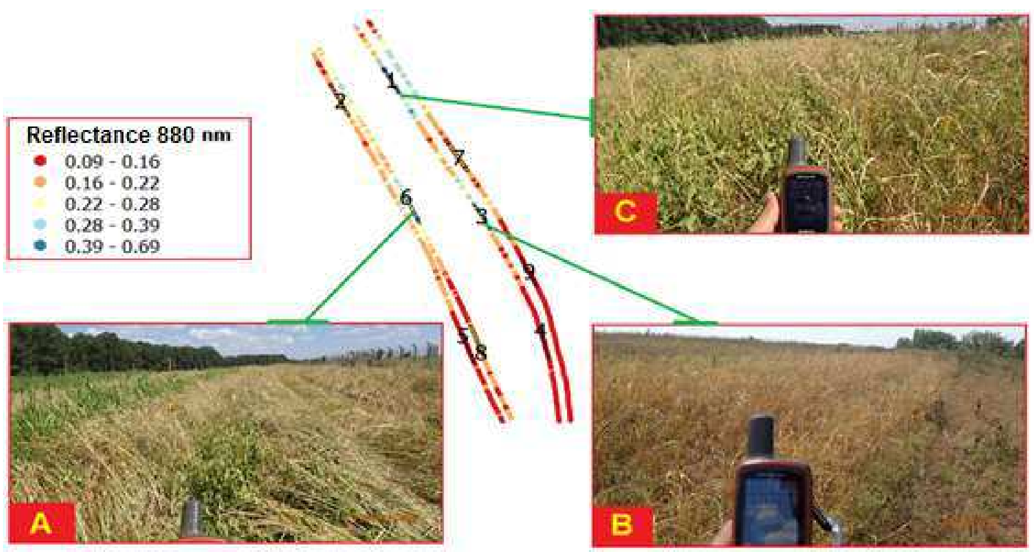

Figure 5. In the center: Image obtained from the sensor (NDVI) and its corresponding response in the field.

In Figure 5A, the culture had a high reflectance index of 0.65. However, it was noted that it was bedridden, with much biomass to which the reflectance sensor was sensitive, but with low heights and average values of 0.76 m.

In 5B, the reflectance index was 0.35, with less biomass, but there was a considerable height at plant height, with average values of 0.64 m. In the third case, selected in 5C, there was an intermediate reflectance index of 0.58, which may be related to the presence of broadleaf weeds in the middle of the millet, and which may respond better to the microwave sensor.

It was noted that, although there is a difference between the smallest and highest rates of vegetation in the crop, the size oscillated only 0.07 m, with an average value of 0.88 m. Due to the diversity of field situations, reflectance was not effectively sensitive to plant height.

Subsequently the data concerning the microwave sensor were processed through the Fourier transform. The values found after processing provided the signal beats from the selected region. Data were compared with reflectance values characteristic of the defined regions (Figure 6).

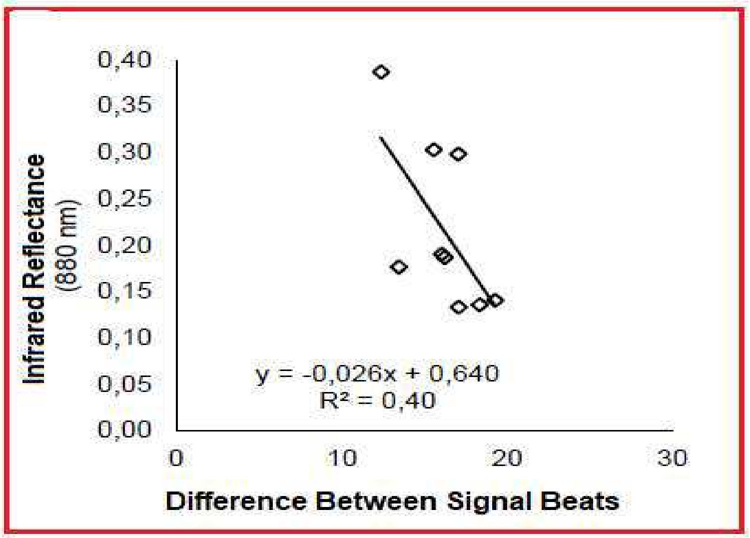

Figure 6. Regression between infrared reflectance and signal beats difference.

In Haagsma (2015) work using SAR-type radar and NDVI optical sensors in various types of crops, it was observed that for wheat, which resembles millet, there is a preference for signal beam mode which is where the waves can penetrate the canopy vertically, because with smaller angles of incidence the crop canopy behaves like a flat surface and with this there is a phenomenon of radiation scattering, where the signal does not have the opportunity to interact with the crop canopy, which may have caused lower correlations of the optical and RADAR sensors.

When plants are at a full stage of development, infrared reflectance may not be effective in obtaining indicators of their size (PAYERO, NEALE and WRIGHT, 2004). Therefore the intrinsic characteristics of the crop may have influenced the results, observing a high dispersion when looking for the relationship between reflectance and the height sensor signal, as shown in Figure 6.

For the correlation analysis between the signal beat difference and reflectance a value of (-0.63) was obtained. Such correlation is considered reasonable but negative. In the works by Mulla (2013), there is a direct relationship between the reflectance signal and plant biomass.

7. Conclusion

This study presented the development, analysis and preliminary testing of a low cost RADAR FMCW system, where the measurement of the distances between the sensor and representative ground and canopy targets proved to be efficient in controlled laboratory environments. The system allowed vegetation sensing to be performed when agricultural machinery and / or implements are conducting agricultural operations in near real time, which would allow actuator systems to be activated during operations, reducing operating costs. The RADAR FMCW sensor developed for controlled laboratory testing provided the distances between sensor and target with R^2 of 0.99. When an obstacle was placed to simulate the plant canopy, an R^2 of 0.77 was obtained, which is a considerable response, due to the extreme characteristic chosen for the target, which will hardly be found in the field. For a controlled field stage, using cardboard boxes as targets and under dynamic conditions, a sensor response proportional to the height of the targets was obtained, with better results for targets with larger contact areas. The developed sensor was also compared with a commercial reflectance sensor, and the results indicate that the response obtained from the developed sensor demonstrated sensitivity to the variability of the analyzed crop, but with inverse correlation with NDVI.

Future works are necessary for the full knowledge of the factors that caused the noise presented in the farming stages. Implementations should be made seeking boundary conditions for the best results. Also to improve accuracy, it has been observed that analog filters can be implemented in the developed sensor hardware and later, to better suit and adjust the system to other environments, digital filters can ensure appropriate improvements more quickly.

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