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# A NEW RADAR SENSOR FOR CUTTING HEIGHT MEASUREMENTS IN TREE HARVESTING APPLICATIONS

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**Abstract.** Shear cutting heads are standard devices in the domain of energy wood harvesting, that can be easily implemented on hydraulic excavators. In order to increase the operational flexibility of these machines, it could be interesting to be able to separate the lower part and the upper part of standing trees. Currently, the use of shear cutting heads for this application is limited, because it does not exist reliable sensors able to measure the distance between the cutting head and the soil. We present in this paper the development of a range sensor based on microwave radar. Due to the harsh functioning conditions in forest environments, the microwave radar technology is an interesting solution for harvesting applications, and it allows to overcome the limitations of classical optical sensors. The radar has been positioned on a tree harvesting machine, and results obtained in real conditions are presented.

**Keywords:** radar; height measurement; tree harvesting

## 1 Introduction

In recent years, wood has been used more and more as an energy resource to replace fossil fuel, in France as well as in Europe. This evolution implies the development of new agricultural equipment for wood harvesting in order to be able to use forestry biomass. Main research activities are related to the development of new harvester heads such as shear cutting heads, with the objective of mechanization of the wood harvesting task.

For energy wood heads, the shear cutting heads can be an advantageous solution. They can be implemented on standard hydraulic excavators, which are cheaper and easier to drive than specialized tree harvesting machines. In a classical energy wood harvesting process, a skidder is used for pulling logs or trees out of the forest. The chipping process can then be realized at roadside after a drying period of about 3 to 6 months. For some forest stands, it could be interesting to separate the lower part and the upper part of the tree, because the lower part of the tree can be used for industrial purposes and not only for energy generation. In that case, it is necessary to cut the tree at a specific height: this operation is not possible with shear cutting heads because currently no one sensor is available to measure the distance between the cutting head and the ground.

Classical solutions for distance measurements are based on optical (laser) or ultrasound technologies. But the sensors have to deal with functioning conditions which are often harsh in a forest environment: light variations, dust, turbulences, fog, presence of intermediate branches or vegetation on the ground, etc., can lead to false or completely unavailable distance measurements. For that reason we have developed a solution based on a microwave radar to measure the distance between the ground and the cutting head.

The developed sensor is based on the Linear Frequency Modulated Continuous Wave (LFMCW) principle. This technology is more adapted than the classical pulse radar technology to measure short distances. With a high-frequency transmitted signal (24GHz frequency, i.e. 1.25cm wavelength), the microwave radar is not affected by the harsh conditions of forest environment. And due to the size of the antenna beam (typically several degrees), the radar can detect simultaneously different targets present in its line of sight (for example the ground and intermediate branches). The radar-target distances are computed from spectral analysis of the radar signal. In order to deal with nearby targets, this process is based on high resolution frequency analysis such as MUSIC algorithm.

In section 2, we present in more detail the architecture and the functioning of the microwave radar, with a focus on the problem of distance resolution. Results obtained in real conditions are presented and discussed in section 3.

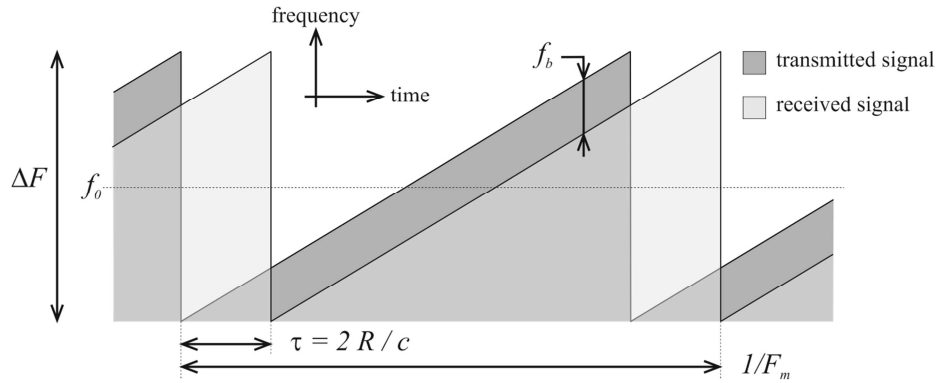
## 2 Distance Measurement with a LFMCW Radar

### 2.1 LFMCW Radar Principle

In classical pulse radars, distance measurements are achieved through time of flight (TOF) measurements of short radar pulses. For short range applications, this technology is not the best adapted solution because it implies (i) the measurements of very short time of flight  $\tau$ , and (ii) the generation of very short radar pulses. The developed radar is based on the Linear Frequency Modulated Continuous Wave technology (Skolnik 1980, Monod 1995, Rouveure 2009). The principle of LFMCW radars consists in transmitting a continuous frequency modulated signal, and measuring the frequency difference (called beat frequency  $f_b$ ) between the transmitted and the received signals. With the carrier frequency  $f_0$ , two main parameters characterize LFMCW radars: the sweep frequency  $\Delta F$  and the frequency modulation  $F_m$  (see Figure 1).

The radar antenna beam width cannot be considered punctual, so several targets can be detected at the same time. If  $i$  targets are located at range  $R_i$  in front of the radar, the measured beat signal  $S_b$  results from the sum of the  $i$  reflected signals. Without radial velocity, the beat signal  $S_b$  can be written as (Monod 2009):

$$S_b = k \sum_i V_e V_{ri} \cos \left( 2\pi \left( 2 \Delta F F_m \frac{R_i}{c} \right) t + \Phi_i \right) \quad (1)$$

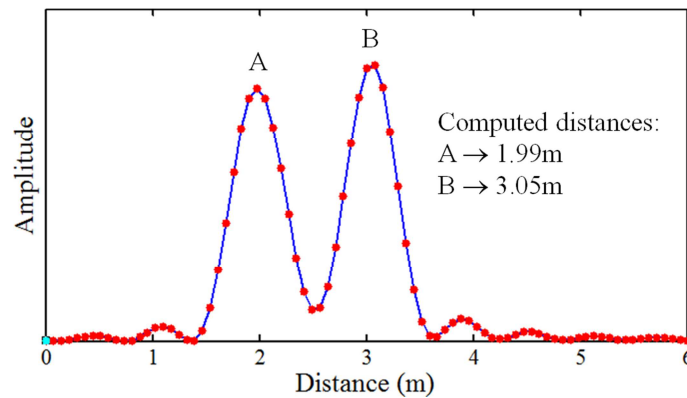


**Fig. 1.** Linear modulation principle. Example of received signal with one static target located at range  $R$  from the radar.  $f_0$  is the carrier frequency,  $\Delta F$  the sweep frequency, and  $F_m$  the modulation frequency.

$V_e$  is the amplitude of emitted signal,  $V_{ri}$  and  $\Phi_i$  respectively the amplitude of received signal and a phase term depending on target  $i$ ,  $c$  the light velocity and  $k$  a mixer coefficient. One can see that  $S_b$  contains a sum  $\sum f_{bi}$  of frequency components, each of them corresponding to a particular target  $i$ :

$$f_{bi} = 2 \Delta F F_m \frac{R_i}{c} \quad (2)$$

The range  $R_i$  to each target may be determined by measuring the individual frequency components by the mean of a spectral analysis. An example of simulated radar spectrum, using the model of signal described in Eq. (1), is presented in Figure 2. Two targets  $A$  and  $B$  are located at ranges 2m and 3m. The FFT spectral analysis allows to separate both frequency components used to compute the radar-target distances.



**Fig. 2.** Simulation of radar spectrum with 2 targets located at ranges 2m and 3m. Radar parameters:  $f_0 = 24.125\text{GHz}$ ,  $\Delta F = 250\text{MHz}$ ,  $F_m = 100\text{Hz}$ .

## 2.2 Distance resolution

Different elements such as branches, bushes, etc., can be positioned between the radar and the soil. So, it may be necessary to detect several objects in front of the radar. And as these objects can be close to each other, it is necessary to have an accurate distance resolution.

With a classical FFT frequency analysis, the frequency resolution  $\delta f$  is determined solely by the observation time  $T_{obs}$ :

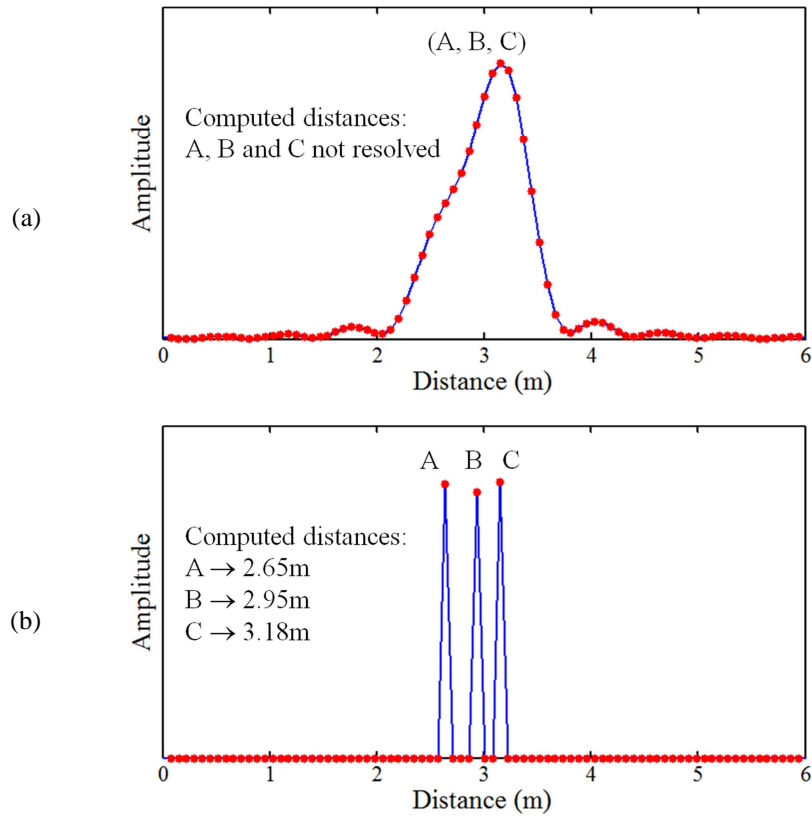
$$\delta f = 1 / T_{obs}, \text{ with } T_{obs} = 1 / F_m \quad (3)$$

Considering a LFM CW radar, the increase of  $T_{obs}$  (while maintaining the same sweep frequency  $\Delta F$ ) leads to a more accurate  $\delta f$ , but the distance resolution  $\delta r$  remains the same because at the same time the maximum range is increased. With LFM CW radars, the distance resolution  $\delta r$  is solely determined by the sweep frequency  $\Delta F$  (Skolnik 1980):

$$\delta r = c / (2 \Delta F) \quad (4)$$

It means that two targets separated by distances lower than  $\delta r$  cannot be resolved when using a FFT spectral analysis. An example is given in Figure 3(a), considering three close targets located at range 2.7m, 3m and 3.2m. With  $\Delta F = 250\text{MHz}$ , the theoretical resolution  $\delta r$  is equal to 0.6m: the FFT analysis is not able to detect the three targets.

From Eq. (4), one can see that it is necessary to increase the sweep frequency  $\Delta F$  to obtain a more accurate distance resolution  $\delta r$ . But even if this increase is technologically possible, we have to deal with the International Telecommunication Union (ITU) which is in charge of the allocation of global resources such as radio-frequency spectrum. In France, the use of the radio-frequency spectrum is controlled by the French Telecommunications Regulatory Authority (ARCEP). We are using the Industrial, Scientific and Medical (ISM) radio band at 24 GHz (K-band) for our application. This ISM band defines a free bandwidth of 250MHz (24.000-24.250GHz) for industrial, scientific and medical purposes other than telecommunications, completed with a limitation in transmitted power (Agence Nationale des Fréquences 2013). As the current bandwidth of our radar is already 250MHz, a second solution must be found to improve the distance resolution. If the FFT is the basic tool for spectrum analysis due to its robustness and noise resistance, different methods exist for high resolution spectrum estimation which overcome the limitations of FFT approach. For example, parametric methods such as MUSIC (*Multiple Signal Classification*) or ESPRIT (*Estimation of Signal Parameter via Rotational Invariance Technique*) take advantage of known parameters of the signal such as the number of spectral components (Schmidt 1986; Shahbazpanahi et al 2001). In Figure 3(b), one can see that the ESPRIT algorithm is able to detect the three closed targets.



**Fig. 3.** Simulation of radar spectra with three close targets located at ranges 2.7m, 3m and 3.2m. Radar parameters:  $f_0 = 24.125\text{GHz}$ ,  $\Delta F = 250\text{MHz}$ ,  $F_m = 100\text{Hz}$ . (a) FFT radar spectrum: the targets A, B and C are not resolved. (b) The ESPRIT algorithm allows to detect the targets A, B and C.

### 3 Experiments

#### 3.1 LFMCW Radar

The developed microwave radar is based on a Voltage Controlled Oscillator (VCO). Lightweight and small sized, it has been integrated in a radome in order to provide sufficient protection during the experiments (the radome is constructed of material that minimally attenuates the electromagnetic signal transmitted or received by the antenna). A general view of the radar is presented in Figure 4.



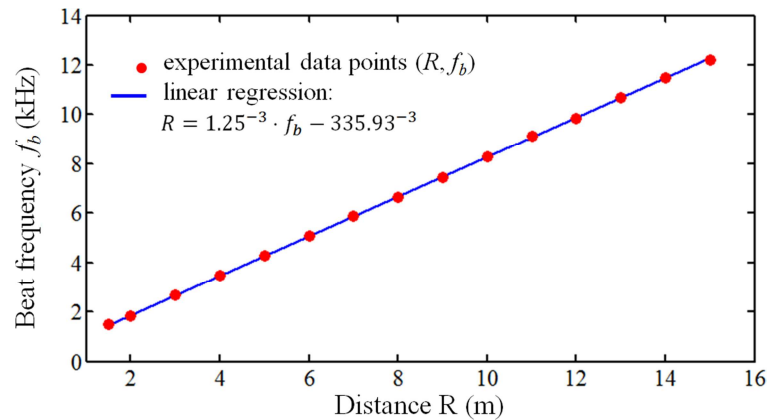
**Fig. 4.** LFM CW radar integration. Left: the microwave VCO is equipped with a lens horn antenna. Right: transparent to radar waves, the radome is a mechanical protection for the radar.

The radar is equipped with a lens horn antenna. The antenna beam width is about  $14^\circ$  (half-power aperture): the surface illuminated by the radar (radar footprint) can be represented by a circle with diameter 2.4m considering a distance of 10m. This aperture allows to detect simultaneously several obstacles in front of the radar. The radar operates by transmitting a signal with a center frequency  $f_0$  (24.125GHz, K-band) linearly swept over a bandwidth  $\Delta F$  of 250MHz during a modulation period of 10ms. The transmitted power of the radar is about 3mW (5dBm).

The linear modulation law is an essential point with LFM CW radars. In order to obtain a constant beat frequency during the modulation period, the frequency variation of the transmitted signal must be as linear as possible. The main problem with VCO is that the relationship between the driving voltage and the output frequency is always nonlinear. A specific modulation must be applied to the VCO in order to take into account this non linearity, and to obtain a linear variation of the frequency vs time. This modulation law (which is specific to the used VCO) has been integrated in an electronic card. A second electronic card has been developed for filtering and amplification of the beat signal.

The acquisition of the beat signal is achieved with a National Instruments data acquisition device (DAQ NI USB-6211). The data acquisition device is connected to a laptop for the control of the process and data storage.

A calibration step has been realized in order to determine the relationship between the distance  $R$  and the measured beat frequency  $f_b$ . Canonical targets such as metallic trihedral corner or Luneburg lens have been used for this calibration. The experimental data points and the computed linear regression are presented in Figure 5.



**Fig. 5.** Radar calibration. The experimental data points ( $R, f_b$ ) highlight a linear relationship between the radar-target distances and the measured beat frequency.

The experimental data points highlight a linear relationship between the radar-target distances  $R$  and the measured beat frequency  $f_b$ . This linear regression is of the form:

$$R = 1.25^{-3} \cdot f_b - 335.93^{-3} \quad (5)$$

### 3.2 Results

A series of test was carried out under field conditions. The radar has been positioned on a hydraulic excavator used for wood harvesting purposes (see Figure 6). The hydraulic excavator was equipped with a shear cutting head from VIGNEAU Society. The radar was placed at the rear of the shear cutting head, in order to avoid collisions with trunks or branches. The laptop, equipped with the data acquisition device and a graphical interface, was placed in the cabin of the hydraulic excavator (see Figure 7).



**Fig. 6.** General view of the hydraulic excavator used during the experiments in the forest. The excavator is equipped with a shear cutting head from VIGNEAU Society.





**Fig. 7.** Positioning of the equipment. (a) Rear position of the radar, fixed on the shear cutting head. (b) A graphical interface on the laptop allows to control the process.

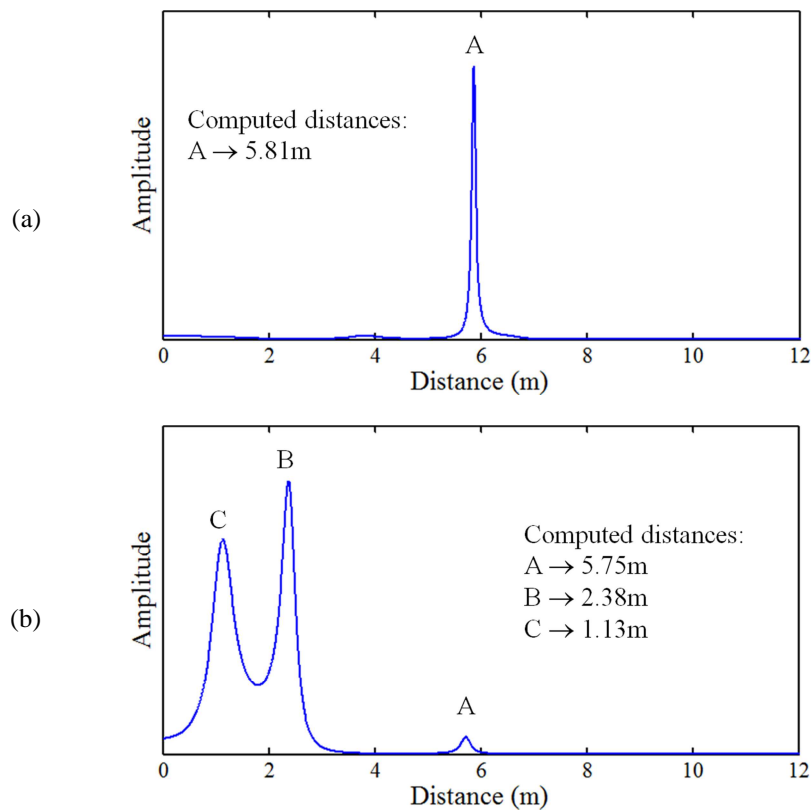
Figure 8 shows a typical use of the shear cutting head. The objective of the radar fixed on the cutting head is to measure the distance to the soil surface, even if obstacles such as branches or bushes are present.



**Fig. 8.** General view of the experiment realized in the forest. The radar must be able to detect the ground even if obstacles such as branches or bushes are present.

Two spectra provided by the radar are presented in figure 9. Figure 9(a) is an example of measurement without obstacle between the radar and the ground. The spectrum highlights only one spectrum component, which allows to determine the radar-soil distance.

In Figure 9(b), one can observe three components in the radar spectrum. The farthest component (reference A) indicates the radar-soil distance. Two other components with higher amplitudes are also detected (references B and C). They correspond to intermediate branches present between the radar and the soil. The amplitudes of the different components of the spectrum are related to the sizes and orientations of the obstacles with regard to the radar. It means that the echo from the ground can be highly attenuated if a lot of intermediate branches or bushes are present. Specific signal processing techniques are studied in order to provide a robust and repeatable measurement of the radar-soil distance considering various environments.



**Fig. 9.** Examples of distance measurements with the LFMCW radar. (a) Without obstacle between the radar and the ground, the reference A indicates the radar-ground distance. (b) The radar spectrum indicates the position of the ground (reference A, the farthest frequency component in the spectrum), but also the positions of obstacles between the radar and the ground (references B and C, intermediate branches).

## 4 Conclusion

The cutting height measurement for standing trees has to deal with functioning conditions that are often harsh in forest environments. Microwave radar is an interesting solution because it is not affected by light changes, rain, fog, etc. Moreover, due to the antenna aperture, several obstacles can be detected simultaneously in the line of sight of the radar. The objective of the developed radar range sensor is to measure the distance between a shear cutting head and the ground. The radar is based on LFM principles which are well adapted for short-range distance measurements. Simulations and measurements in real conditions have been achieved to validate the approach. The experiments have pointed out the necessity to provide an accurate distance resolution in order to deal with nearby obstacles such as branches on the soil.

The current research activities are related to signal processing, with the aim to provide robust and repeatable radar-soil distance measurements. The development of a 10GHz radar (X-band) is also considered, in order to increase the robustness of soil detection.

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