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An analysis of a radio frequency sensor as a means to remotely sense selected surface topographies in an agriculture environment

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AN ANALYSIS OF A RADIO FREQUENCY SENSOR AS A MEANS TO REMOTELY SENSE SELECTED SURFACE TOPOGRAPHIES IN AN AGRICULTURE ENVIRONMENT

A Dissertation
Submitted
in Partial Fulfillment
of the Requirements for the Degree
Doctor of Industrial Technology

Approved:

Dr. Mohammed F. Fahmy, Chair

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Dr. Teresa J. K. Hall, Committee Member

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University of Northern Iowa
December 2001

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John W. Somervill

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ABSTRACT

Remote sensing is the science and art of obtaining information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation. The remotely sensed data can be of many forms, including variations in force distribution, acoustic wave distribution, or electromagnetic energy distribution. Information thus acquired can be used for observing, monitoring, and studying planetary surfaces and environments.

Because there are many ways to acquire data about targets of interest, there are many types of remote sensors that can be used, including visible, infrared, and active and passive microwave radio frequency (RF) sensors. This research specifically addresses active RF remote sensing.

When one investigates RF sensors for agriculture (Ag) applications, the investigator finds very limited production use of RF technology. The limited use stems from the fact that RF applications for Ag equipment are usually driven by automotive desires and not by Ag needs.

The hypotheses of this exploratory study was to determine the signal return profile (radiated return output

power) or Radar Cross Section (RCS) are within the FCC Article 47 guidelines of three surface topographies. The three surfaces are tilled soil, grass, and concrete. Additionally, to a certain extent, this study tried to identify the capability of the radio frequency sensor as a means to measure ground speed of an Ag vehicle.

The purpose of this exploratory study was to provide technical data (i.e., RCS) on the three surface topographies of tilled soil, grass, and concrete. Additionally, the purpose of the study was to investigate and provide information on four radio frequency radar principles that could be used in Ag applications, and to determine which of the four radar principles provide the optimum RCS over the selected surface topographies.

Based upon the analyses of data, it was concluded that the correlation between multiple faceted surface topographies (e.g., tilled soil and grasses) was more statistically significant as to true ground speed than that of a smooth surface (i.e., concrete). Further, it was concluded that the correlation or feasibility of use between radio frequency technology and agriculture applications was again statistically significant. Given the outcomes of the study, recommendations for further study were warranted and may be utilized to further define the relationship between radio frequency sensor development and agricultural applications.

It was recommended that this exploratory study be replicated. In addition, other recommendations for further study were also made.

ACKNOWLEDGEMENTS

In taking this opportunity to reflect back over the several years of work, I want to take a moment to thank those who have given of their time and effort to help make this dissertation something of which I can be proud. With that thought in mind, I express my deepest appreciation to the following people.

First and foremost to my wife Glenda Lee, who made many personal and professional sacrifices to ensure a stable household and a positive environment for me to study. Additionally, to our children, Adrianne Jeanette, Yale Michael, and Ian Joseph, who all endured my late night classes, weekend studying, and most of all, their understanding as to why Dad could not attend many of their school plays, recitals, and athletic contests. My heart goes out to all of you for your love and understanding.

I would like to thank with deep gratitude the Industrial Technology Department Head and Advisor Dr. Mohammed F. Fahmy for his guidance and unfailing support while attending classes and in preparation of this dissertation. You truly are a friend and guiding light throughout this entire project.

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To Dr. Mahoney, for his sharp wit and his direction that ensured the data acquisition system and field-testing would provide guidance to future researchers of RF technologies.

A special thanks to Dr. Rogers of the Department of Educational Psychology and Foundations for his direction and statistical expertise, and for providing the time to advise and discuss the latest sensing technology under development in industry and the military.

In closing, I want to recognize the life long support and love of both my parents. They instilled within me the drive and persistence necessary to complete a task. I love you Mom and Dad.

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CHAPTER 1

INTRODUCTION

The potential applications created through the use of remote non-mechanical sensors, such as induction, capacitance, and radio frequency (RF) sensors, challenge both engineers and technologists in agriculture environments. In its least intrusive form, remote non-mechanical sensing technology results in changes in how an agricultural (Ag) application is viewed. On closer look, one could conclude that the most successful remote sensing devices are those that have replaced older technologies.

For example, Ag vehicles of the past relied on rear wheel revolution as an indicator of ground speed--today's vehicles use remote non-contact RF ground speed radars as a means for true vehicle speed. "Although in recent years a plethora of remote sensor concepts have been demonstrated, only an insignificant fraction of them can qualify as potentially viable devices from a business perspective" (Gutierrez, 2000, p. 4). Summarizing the works by Alfredo Gutierrez (2000) and Anatolij Shutko and Eugenij Novichikhin (1999), successful mass produced remote sensing devices of commercial importance are mainly those in automotive near-infrared presence detection, airbag accelerometers, and global positioning systems (GPS). Bjorkquist and Evans (1996), stated,

> Technology is often created to make work possible and to extend the capability of the worker. The hoe of the farmer, the net of the fisher, the stove of the cook, the order pad of the meal server, the automated machine of the manufacturing worker, the paint brush of the artists, the price tag of the retailer, the lesson pad of the teacher, and the planning committee of the executive representing technologies that are the result of the need to accomplish tasks in the work setting. (p. 424)

Based on this observation, the Agritechnica environment could be well positioned to apply diverse remote sensing technologies to existing agriculture applications.

The ease or complexity of a remote sensing device for an Ag application relies much on the technology used to create the level of acceptable performance. The avenues available to reduce or eliminate mechanical sensing devices are limited by the possibility of applying the wrong technology to the wrong application. The old axiom of "if you have a hammer, all problems look like a nail," would come into play if all one is attempting to do is implement remote sensing devices for all Ag vehicle applications. As a result, the scope of the readily available technology may not enable remote sensing of non-mechanical sensors for all contact or mechanical applications.

Statement of Need

The need for this study was based on the lack of a descriptive analysis of remote sensing radio frequency radar sensors (viz., namely remote non-mechanical sensors) and their relationship to Ag applications. Although there have been studies on applications in automotive (Knox 2000; Ulaby, Moore, & Fung, 1982; Williams, 1999), few studies have been published on Ag applications of RF. There was also a need for an empirical study of remote non-mechanical sensors in this specific typological environment to better understand the adequacy of performance and to guide application decisions in this field in the future.

Statement of Problem

The problem of this research study was to determine the performance output of radiating return power of remote sensing radio frequency sensors and their relationship to various surface topographies (e.g., tilled soil, grass, and concrete).

Statement of Purpose

The purpose of this research study was to describe the differences in remote sensing radio frequency sensor performance with respect to field conditions for Ag applications (e.g., tilled soil, grasses, and concrete). Therefore, to expand the body of empirical knowledge on remote sensing radio frequency sensor, the main objectives were as follows:

1. To study selected surface topographies as seen in Ag environments (i.e., tilled soil, grasses, and concrete).

2. To investigate and provide a working understanding of four radio frequency radar candidates that could be used in Ag applications.

3. To determine which of the four radio frequency radar principles provide the optimum signal return over the selected surface topographies as seen in Ag environments (Addressed in Review of Literature).

Research Questions

The aim of this research was to study and provide the necessary information on the signal return profile of a selected radio frequency sensor as it relates to various Ag surface topographies (e.g., tilled soil, grass, and concrete). The radio frequency sensor, within termed "radar," is regulated by the Federal Communication Commission (FCC). The Telecommunications Act, Article 47 of the FCC, Parts 2.106, 2.997, 15.33, and 15.249, identifies three elements as acceptable guidelines for this radar environment; radar band, signal return profile, and frequency allocation. For further definition of FCC Telecommunications Act Article 47, reference Appendix A. The radar band used in this study was K-band, signal output return or radar cross section was termed radiated output power measured in decibels (dB), and the frequency allocation was 24.125GHz.

The research questions were as follows:

1. What was the signal return profile between the selected remote sensing radio frequency radar and tilled soil? Reference Definitions of Common Terms page 9 for a definition of tilled soil.

2. What was the signal return profile between the selected remote sensing radio frequency radar and grass?

3. What was the signal return profile between the selected remote sensing radio frequency radar and concrete?

Research Hypotheses

1. It was hypothesized that the signal return profile (radiated return output power) is within the FCC guidelines for tilled soil.

2. It was hypothesized that the sign return profile (radiated return output power) is within the FCC guidelines for grasses.

3. It was hypothesized that the signal return profile (radiated return output power) is within the FCC guidelines for concrete.

Limitations of the Study

The following limitations were inherent in this research study:

1. This study was limited to the surface topographies of tilled soil, grasses, and concrete as the only reflected surface for radiated return of radar signals.

2. This study included the limited use of a test "mule" (i.e., Ag vehicle) as a means to carry and house the selected radio frequency radar.

3. This study was limited to only the selected outdoor test fields where tilled soil, grasses, and concrete are available in aggregate.

Assumptions

In this study, certain assumptions were considered that served as the basis for the ensuing analysis:

1. It was assumed, with respect to surface topographies, that the conditions of preparation, handling, and maintainability, to which the tests were performed, were adequately observed for the purpose of this research.

2. It was assumed, as based on definitions that the test surface topographies were uniformly constant throughout the testing and analysis.

3. It was assumed that all testing apparatus and material used were consistent and of good quality.

4. It was assumed that the output energy of the remote sensing radio frequency sensor was uniform and consistent throughout testing and analysis.

Definitions of Common Terms

Certain terms that were used, although not unique to this study, have been defined in order that readers have a common basis for understanding their use within the context of this research. The following terms are defined:

Amplitude Modulated Continuous Wave (AMCW)--"variation in the amplitude of an alternating current signal or radio wave. May be introduced by pulse modulating a radar's transmission" (Stimson, 1983, p. 593).

Aperture--"an opening, the area normal to the axis of the antenna's mainlobe, over which the radiation is distributed" (IEEE Standard, 1978, p. 28).

Bandpass Filter--"a filter designed to pass only those input signals that fall within a specified band of frequencies" (Stimson, 1983, p. 594).

Bandwidth--"the width of the band of frequencies passed by a filter or an electrical, electromechanical, or mechanical system. The band of frequencies occupied by the central lobe of the spectrum of an alternating current signal" (Toomay, 1998, p. 85).

Coherent Pulsed Radar--"a coherent pulsed radio frequency signal that has been translated to the video frequency range and tin the process resolved into in-phase (I) and quadrature (Q) components so as to retain the phase information contained in the original signal" (Stimson, 1983, p. 596).

Concrete--"a mixture of inorganic material of claylike and lime-bearing materials. The claylike material furnish SiO_2 and the calcined mass consists primarily of silicates of calcium" (D. K. Dewey, Deere & Co., personal communication, June, 2001). For purposes of this study the term concrete and content of concrete were held constant.

Continuous Wave (CW)--"a radar, which transmits continuously and simultaneously listens for the reflected echoes" (Dictionary of Technical Terms for Aerospace Use, 1965, p. 64).

Doppler Frequency--a shift in the radio frequency of the return from a target or other object as a result of the object's radial motion relative to the radar. "It is equal to $-2R/\lambda$, where R is the object range and λ is the wavelength of the transmitted radio" (Stimson, 1983, p. 597).

Echoes--"radar signal returns received from a given object" (Stimson, 1983, p. 598).

Electromagnetic Wave--"wave that is propagated by the mutual interaction of electric and magnetic fields" (Stimson, 1983, p. 598).

Freshly Tilled Soil--"Blackhawk County soil that has been tilled using a chisel plow with a twisted shank under wet conditions produce soil not larger than 4"-6" wide clods of soil" (M. Rolles, USDA/NRCS, personal communication June, 2001).

Fourier Transform--mathematical expression that translates the equation for an ac signal (such as pulse modulated radio wave) from the time domain to the frequency domain. "Converts the equation for the amplitude of the signal as a function of time to the corresponding equation for the amplitude as a function of frequency-the signal's spectrum" (Stimson, 1983, p. 599).

Frequency--"number of cycles per second which a pure unmodulated sine wave completes per second" (Dictionary of Technical Terms for Aerospace Use, 1965, p. 115).

Frequency Modulated Continuous Wave (FMCW)--"variation of the frequency of an ac signal or radio wave (i.e., range measurement or convey information)" (Stimson, 1983, p.599).

Gigahertz--"a unit of frequency: 1 gigahertz = 1000 megahertz" (Toomay, 1998, p. 189).

Grass--Black Hawk County of Iowa registers the following grass types: smooth brome, Viva Kentucky Bluegrass, Envicta Kentucky Bluegrass, majesty ryegrass, orchard grass, reed canary-grass, and tall fescue. For the purposes of this study all grass were considered and termed, as grass (USDA, HTTP://WWW.NHQ.NRCS.USDA.GOV/WSRI, 2001).

Homologation--"compliance between foreign governments on manufacturing, electronics or end products" (D. K. Dewey, Deere & Co., personal communication, May, 2000).

IF Amplifier--"in a superheterodyne receiver, an analog bandpass amplifier (or chain of amplifiers) whose bandpass generally is just wide enough to pass the received pulses" (Stimson, 1983, p. 600).

Propagation--"the outward spreading (travel) of an electromagnetic wave-radio wave" (Dictionary of Technical Terms for Aerospace Use, 1965, p. 218).

Pulsed Radar--Pulsed radar whose transmission is noncoherent. Measurement range by pulse delay techniques. May have a limited moving target indicator (MTI) capability, but generally cannot measurement Doppler frequencies.

Radar Cross Section (RCS)--"a factor relating the power of the radio waves that a radar target scatters back in the direction of the radar to the power density of the radar's transmitted waves at the target's range" (Toomay, 1998, p. 194).

Real Beam Ground Mapping--"pulsed radar. Makes maps whose azimuth resolution is limited by the length of the antenna and the wavelength of the transmitted radio waves. For some applications, the resolution may be increased by increasing the length of the antenna or by using shorter wavelengths (at the expense of reduced range)" (Stimson, 1983, p. 40).

Sidelobe--"in an antenna radiation pattern, the lesser lobes of progressively decreasing amplitude on either side of the mainlobe" (IEEE Standard, 1978, p. 640).

Soil--soil taxonomy in the contexts of this study refers to Black Hawk County in the state of Iowa. Reference Chapter 3 Methodology and Design for further description of Black Hawk County Soil used in this study.

Vehicle Hop--the presence of vehicle oscillation over undulating or rough terrain in the Z-axis during speeds while performing an application (i.e., cultivating, planting, or spraying).

Summary

Business and industry will continue to experience radical and rapid technological changes in remote radio frequency radar sensory devices. In addition to the new technologies, improved skills and knowledge will be required to understand not only the "traditional" applications (i.e., automotive), but also the non-traditional applications of self-propelled agricultural vehicles.

The aim of the research study was to guide the study in order to determine which one of the four remote radio frequency radar candidates (e.g., frequency amplitude continuous wave, frequency strike key, short pulse, and amplitude modulated continuous wave radars) are perceived as optimum for selected Ag applications. The data could be used as a base line to validate the decision as to whether or not current remote radio frequency radar research efforts should be directed towards traditional contact sensing devices on selected Ag applications. Herein, the term remote non-mechanical sensor is replaced by Radio Frequency, known as RF.

Chapter II, discusses the basic principle of RF or radar, briefly touches on a sensor system analysis of potential RF applications in the Ag environment, points out two principals within radar, and covers four candidate RF sensor technologies (e.g., frequency modulated continuous wave, frequency strike key, short pulse, and amplitude modulated continuous wave radars). The discussion continues with the role of RF as used in agriculture or automotive applications, a brief explanation on how certain members of the animal kingdom use RF, and identification of an Ag application where RF is used as a remote sensor (i.e., ground speed radar capability).

The results of said research supports the understanding of how and where a remote sensing RF sensory device can be implemented on selected Ag applications. In addition, this study addressed the four RF candidate sensor technologies and provided a working knowledge of remote sensing RF sensors.

CHAPTER 2

REVIEW OF RELATED LITERATURE

Introduction

In the review of related literature, a wide variety of materials, laboratory, and field tests were examined. The review of related literature has been delineated under seven major headings. Those headings are: (a) Radio Frequency principle, (b) Radio Frequency applications on self-propelled agricultural vehicles, (c) Sensor System Analysis, (d) Two Categories within Radar Design, (e) Radio Frequency as a means for remote sensing, (f) Four Candidates RF Sensor Technologies, and (g) Radar Backscatter Studies.

Radio Frequency-RF Radar Principle

The principal of using sound waves to detect objects and determining distance (range) based on the echoes reflected by objects is a technique used by human and animal alike. For example, "Tapping the sidewalk repeatedly with his cane, a blind man makes his way along a busy street, keeping a fixed distance from the wall of a building on his right-hence also a safe distance from the curb and the traffic whizzing by on his left" (Stimson, 1983, p. 3).

Another example is the bat darting through the sky as it avoids obstacles based on its high pitch shrill or beeps. The bats as well as the blind man with his cane are using sound waves to determine the range to objects. The principal used for ground speed by Ag vehicles, airborne fighters or commercial airlines is not too much different from that of the bat.

However, the Ag vehicle, the fighter, and the commercial airline rely on radio waves to determine range and distance to objects. The concept of radio waves or radio frequency (RF) to detect targets, measure their range and angular position is based on the phenomenon known as the Doppler effect.

Radio detection and ranging or Radar provides the means to deliver a RF signal either from the underside of an Ag vehicle, a nose cone of a fighter or from a tracking station located on the ground. Stimson (1983) states, "radar can not only measure range rate but also differentiate between echoes from moving targets and echoes from stationary objects, such as ground" (p. 3).

A primary consideration in the design of virtually every radar is the frequency of the transmitted radio waves and its use within the frequency spectrum. Stimson (1983, p. 122) observes,

> Most radars, however, employ frequencies lying somewhere between a few hundred megahertz and 100,000 megahertz. To make sure large values more manageable, it is customary to express them in gigahertz. One gigahertz, you recall, equals 1000 megahertz. A frequency of 100,000 megahertz, then, is 100 gigahertz.

For an illustrative example of frequency spectrum and its applications in both commercial and military environments reference Figure 1. It should be noted that the area of study for this research resides approximately between 22,000 megahertz and 26,000 megahertz or 22 gigahertz to 26 gigahertz (see Figure 1, "area of study").

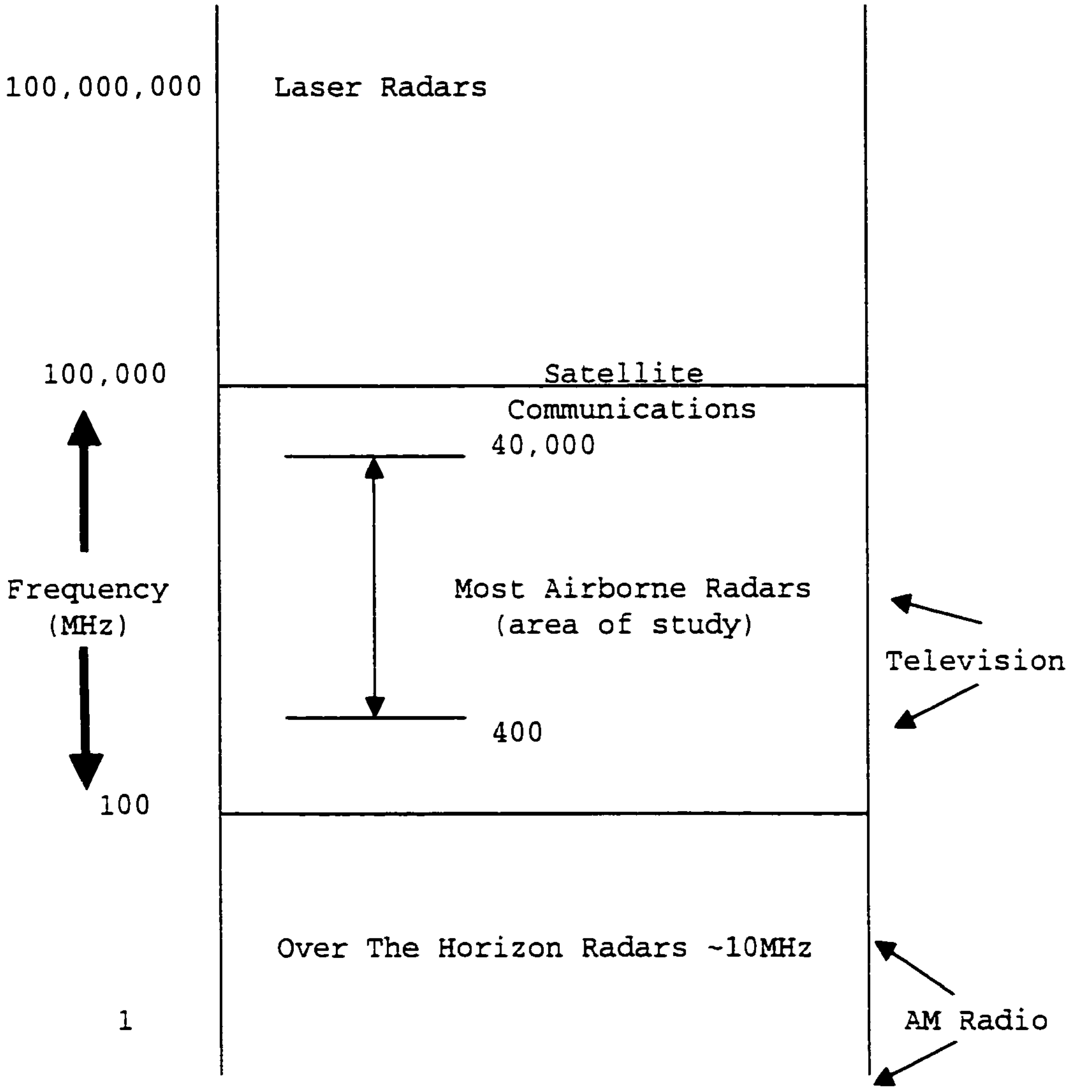


Figure 1. Portion of frequency spectrum. Adapted from Stimson, 1983, p. 121.

Frequency Bands

Besides being identified by discrete values of frequency, radio waves are also broadly classified as falling within or on another of several arbitrarily established regions of the radio frequency spectrum--high frequency (HF), very high frequency (VHF), and ultra high frequency (UHF). The frequencies commonly used by radar fall in the VHF, UHF, microwave, and millimeter wave regions. "During World War II, these regions were broken into comparatively narrow bands and assigned letter designations for purposes of military security: L-band, S-band, C-band, X-band, and K-band" (Stimson, 1983, p. 122). Reference Figure 2, Radar Band Letter Designations, for an illustrative view of the various frequency bands.

It should be noted that K-band turned out to be very nearly centered on the resonant frequency of water vapor, where absorption of radio waves in the atmosphere is high. Consequently, the band was divided. The central portion retained the original designation, K-band. The lower portion was designated the Ku-band; the higher portion, the Ka-band (Gutierrez, 2000; Knox, 2000; Stimson, 1983).

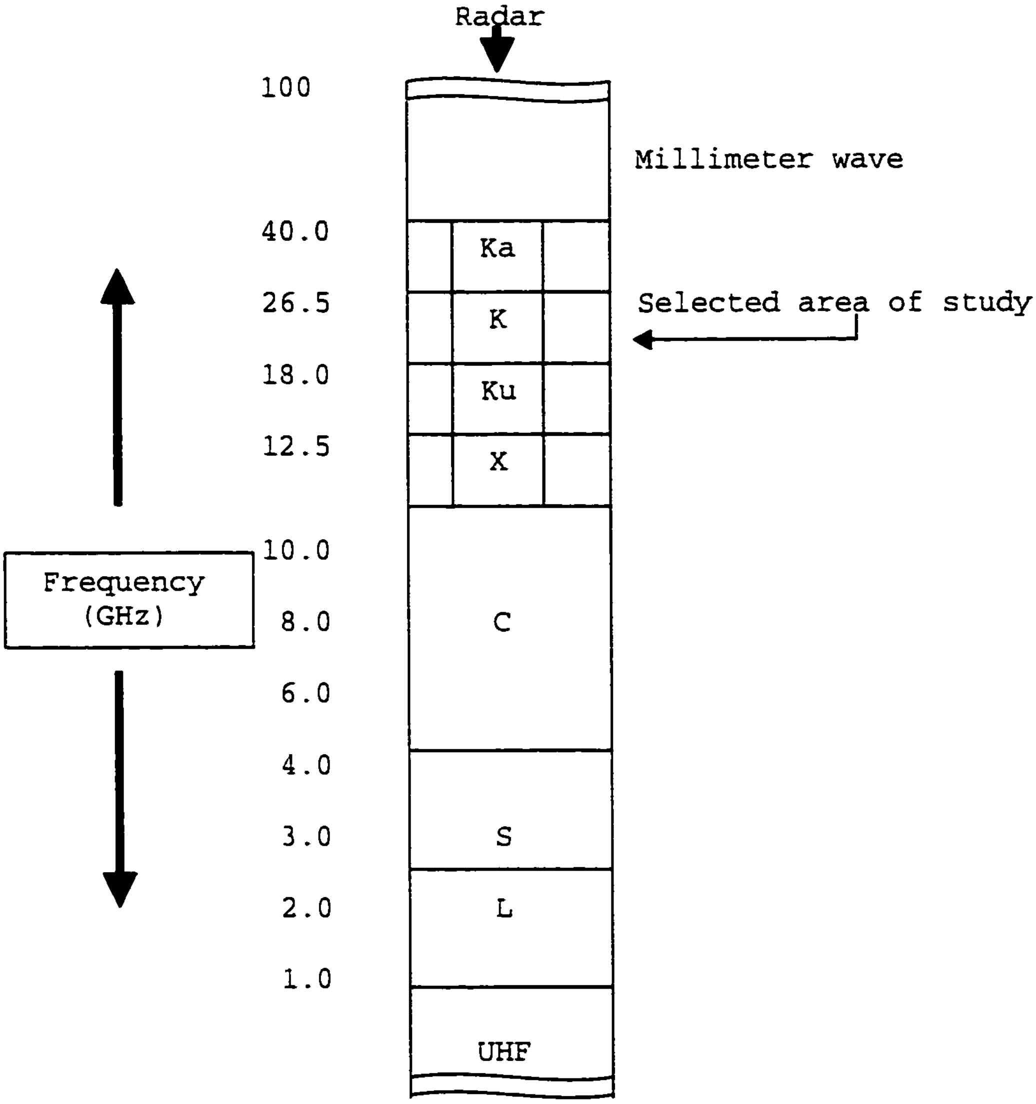


Figure 2. Radar band letter designations. Adapted from Stimson, 1983, p. 123.

Radio Frequency (RF) as a Means for Remote Sensing

"Over the past two decades, RF or radar remote sensing has evolved into an important tool for monitoring Earth surfaces" (Singcaster, 1999, p. 2). The application of radar as a remote sensing device is well known in the Ag industry, law enforcement agencies, and the National Aeronautics and Space Administration (NASA) communities.

The need for RF sensors as a means to solve applications in both the automotive and agricultural industries are under investigation by automobile companies, agricultural equipment manufacturer's, and government agencies alike. Applications such as, adaptive cruise control, ground (truth) speed radar, height of harvester cutter head off ground, and forward looking obstacle detection/obstacle avoidance sensors are examples currently in use by both the automotive and Ag industries. Scientists such as Anatolij Shutko and Eugenij Novichikhin of the Russian Academy of Sciences, and Robert Knox of Epsilon Lambda Inc., to name a few, are currently pursuing one or more of these applications for the U.S. government and automobile companies (A. Shutko and R. Knox, personal communications, March, 1999).

According to Epsilon Lambda's CEO Robert Knox, a leading radar and millimeter wave manufacturer for 25 years, "today's design of RF sensors will need to incorporate both emitter and detector called a transceiver to function in the cost conscience world of farming" (2000,

p. 9). The discrete components for a cost conscience design would entail an oscillator, a circulator, an amplitude modulator, a receiving mixer, a band pass filter, an antenna and amplifier, a diode mixer, and for RF energy a gun diode.

Knox stated, "the Amplitude Modulator (AM) is one of the unknown components and most costly and high risk design" (2000, p. 12). The frequency allocation for the most efficient and reliable forward-looking AM radar (FLR) is 35.5GHz (Ka-Band), which is only used in military applications, and, per the FCC not authorized for commercial use. Knox and others are currently lobbying the US Congress to review current commercially open FCC frequency bands and expand the frequency spectrum from Ka (35.5GHz) and W-bands (76.5GHz).

Additionally, Knox (2000, p. 35) stated,

> Today, before the FCC and US Congress there is a bill to expand the frequency allocation bandwidth to 60 Ghz. Most European countries, except England, operate at 24.124 GHz while Germany and the rest of Europe are in-line with America at 24.125 Ghz. As a result homologation of K-band between America and Europe is not an issue for Ag vehicles. Whereas in England, engineering redesign of the emitter is necessary in order to use or sell the 24.125 GHz RF sensors for Ag applications.

At the time of this literature review, England's radio frequency industry had not adopted the American and European frequency allocation/bandwidth for radar.

Sensor System Analysis

Several studies (Knox, 2000; Shutko & Novichikhin, 1999) observed, the single most useful description of the factors influencing radar performance is the radar equation that gives the range of radar in terms of the radar characteristics. Knox (2000), as had others, use the Equations 2.1 and 2.2, to measure the range of radar that is proportional to the fourth root of the transmitter power. Additionally, Figure 3 illustrates a depiction of the factors necessary to determine the received signal energy from the target (i.e., σ-radar cross section-of ground). The radar equations are:

$$P_r = \frac{P_t G_t G_r \ \sigma \ \lambda^2}{(4\pi)^3 \ R^4 L_s} \qquad (2.1)$$

and

$$R^4 = \frac{P_t G_t G_r \ \sigma\lambda^2}{(4\pi)^3 \ kTBF_n(S_0/N_0)L_s} \qquad (2.2)$$

where,

P_r:	Minimum receiving power (mW)
P_t:	Transmitting power (mW)
G_t:	Transmit antenna gain (mV)
G_r:	Receiver antenna gain (mV)
σ:	Radar cross section (RCS, mm^2)
λ:	Free space wavelength of operating frequency
R:	Detect distance (mm/inches)
kTBF:	White noise level (generated based on λ)
L_s:	System loss (mW)
F_n:	System noise figure (dB)
S_0/N_0:	Signal to noise ratio (dB)
$P_{avg}G$:	Average power gain (dB)

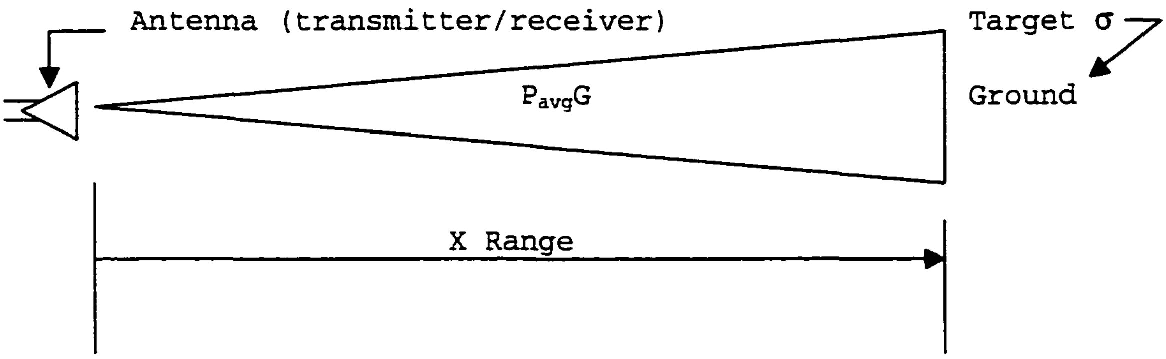


Figure 3. Factors determining the received signal energy.

Two Categories Within Radar Design

"In 1886, Heinrich Hertz demonstrated the basic radar principle (reflection of radio waves), and shortly after the turn of the century a German engineer patented the proposed use of radio echoes as an aid to ship navigation" (Stove, 1992, p. 343). Stimson noted, "yet except for the development of pulsed radio frequency sounders for measuring the height of the ionosphere, it was not until the 1930's that work was begun in earnest on practical radar applications" (1983, p. 39). With World War II came many advances in radar technology and an increase in the number of variety of applications. Stimson observed, "by war's end, radar had become vital to all ground, ship, and air operations" (1983, p. 40). When peace came, many of the wartime radar developments were applied to civil uses (e.g., weather radar, search and rescue radar, and radar altimeters).

As there are many different tasks and applications for radar designs, there are a huge variety of radar systems that are fitted to special characteristics. Frequency, polarization, power, and range are some of the most important characteristic values of a classical radar system. As a result, radar devices may be divided into five categories, Pulsed Doppler, Real Beam Ground Mapping, High Resolution Ground Mapping, Continuous Wave (CW) Radar, and Pulse-Radar (Gutierrez, 2000; Knox 2000; Stimson, 1983). For purposes of this study, only two of the five categories were investigated, they were: CW Doppler radar and pulsed-radar.

The CW procedure uses two different principles, Doppler radar and pulsed radar. The Doppler radar uses a fixed sending frequency, and measures the Doppler-shift between transmitted and received signal to determine the speed. The pulsed radar, "whose transmission is non-coherent, measures the range by pulse delay techniques. The pulsed radar may have a limited moving target indicator

(MTI) capability, but generally cannot measure Doppler frequencies" (Stimson, 1983, p. 307).

CW Doppler Radar

In an CW radar, the sampling rate must at least equal the width of the band of frequencies to be passed by the Doppler filter bank. If the rate is less than this, the sampling will introduce frequency ambiguities. The reason is that sampling converts the CW signal into a pulsed signal whose repetition frequency is the sampling rate. Reference Figure 4 for an illustration of a CW signal converted to a pulsed signal.

Further, Knox (2000) notes,

> the spectral lines of a pulsed signal, recur at intervals equal to the repetition rate. Consequently, if two signals are received whose true Doppler frequencies differ by more than the sampling rate, the observed differences in their frequencies will be the true difference *minus* the sampling rate. (p. 22)

In a pulsed radar, sampling corresponds to the range gating performed in analog. If only one sample is taken during each interpulse period, the radar is said to have a single range gate.

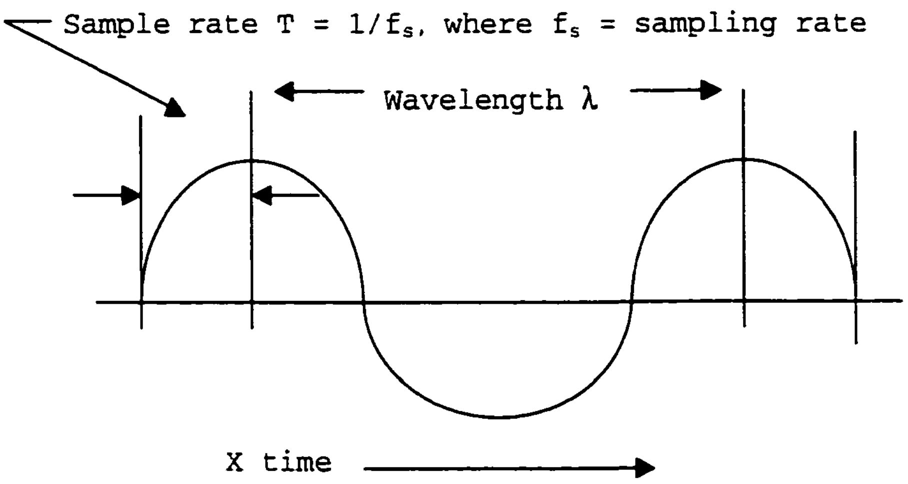


Figure 4. CW signal after conversion to a pulsed signal (e.g., sine wave).

CW Pulsed Radar

When compared to Doppler radar, pulsed radar transmits its radio wave in pulses and listens for the echoes (signal returns) during the periods between transmissions. Pulsed radar has four major areas of concern for radio frequency engineers: (a) it uses time domain reflectometry, (b) measures large distances, (c) requires wideband equipment, and (d) has reduced efficiency when contrasted to Doppler (Knox, 2000; Stimson, 1983).

To overcome some of these shortcomings, pulse-radar uses only one short sending impulse and receives the echo of the target while the transmitter is turned off. In that way, a high uncoupling between send and receive path is achieved. Uncoupling the send/receive signal is a common problem for earlier technology CW radar devices because the echoed signal is often much weaker than the internal or external over coupling. The weaker signal is possibly due to lack of power/gain from the gun oscillator and or the aperture/antenna interface to power source.

Radar Design Process

The design process for radar begins with the definition of the desired measured variable and the decision whether a CW radar system or a pulse radar system can be used. The expenditure for the High Frequency (HF) or microwave parts are highly dependent on this system definition. If only speed measurement is of interest, the development of an CW Doppler radar should be sufficient. But if distance and velocity are to be measured, complex and expensive coherent pulse radar should be highly considered.

The necessary signal-to-noise ratio of the measured signal, the expected level of the RF signal and the internal noise of the receiver define the detection range and determine if a heterodyne receiver or a homodyne receiver might be used. The parameters of frequency, power, and the geometrical dimensions define the circuit technology. For a fixed base radar device, size is not an issue. However, mobile applications require the designer (engineer) to consider size as a limiting factor in the radar design process.

Four Candidate RF Sensor Technologies

Many different technologies exist or have been proposed for the determination of distance measurement using microwave radiation. For purposes of this research (e.g., ground speed radar sensing), the sensing technologies will be limited to the four radio frequency technologies listed below. Essentially, the radar sensor must have the capability to sense true ground at a distance from platform of ~1m, and mounted to an angle of ~45°, while on a moving vehicle.

There are four common types of radar sensor technologies typically used for accurate distance measurement. They are:

- Frequency Modulated Continuous Wave (FMCW) Radar
- Short Pulse Radar
- Frequency Strike Key (FSK) Radar
- Amplitude Modulated Continuous Wave (AMCW) Radar

FMCW Radar

This technology uses a voltage-controlled oscillator (VCO) to linearly sweep the frequency of the transmitter through a range of frequencies. Since the received signal will be slightly delayed in time with respect to the transmitted signal, mixing the transmitted and received signals gives a difference frequency proportional to the distance from the transmitter. Target distance can be measured with FMCW radar by frequency modulating the spectrum at a known rate and comparing the return signal from the target with that of the transmitter.

Basically, the FMCW radar transmits energy to a target; as a result there is time delay or a time interval, which passes before the reflected electromagnetic wave returns. Therefore, the transmitting oscillator already changed its frequency and the phase difference can be used to determine the distance. This technique of phase difference to determine distance provides FMCW radar four positive attributes: (a) the carrier wave is frequency modulated, (b) better resolvability, (c) measurement of relative velocity, and (d) improved efficiency (over the pulsed radar technique; Knox, 2000; Stimson, 1983; Toomay, 1998).

Detukowski states, "the distance is proportional to the frequency change, but if the target distance is small (i.e., 0.5m), a transmitter frequency-tuning rate of more than 1GHz is required" (2000, p. 12). This concept is commonly used for military and industrial applications in which the target is at least several meters from the sensor. As the distance to the target decreases, however, the required bandwidth becomes very high. Sophisticated signal processing may enable a system to work at K-band (24.125 GHz), where there is 250 MHz of allowable bandwidth. A full 1GHz bandwidth would not be feasible for long distances while meeting the Federal Communication Commission (FCC) requirement in the 24GHz-frequency band. Figure 5 illustrates the FMCW signal in time domain or rate of change (frequency-f versus time-t; Knox, unpublished raw data, 2000).

"Experiments with straw bale quickly showed however, that low-power K-band radar does not penetrate biomass very well" (Copper, 2000, p. 3). Because of the fact that there is not enough bandwidth to realize an FMCW system at a shorter wavelength (which would penetrate the biomass), this technique is usually not appropriate for ground speed sensing.

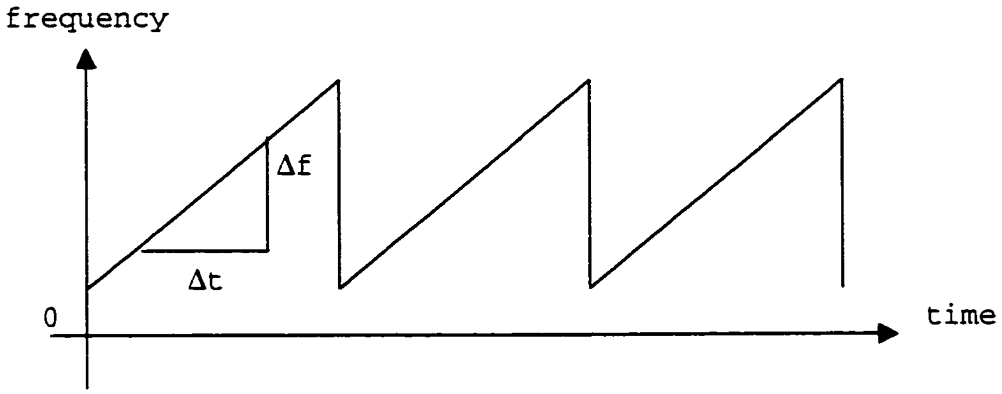


Figure 5. FMCW signal in time domain. Rate of change of transmitted frequency k = Δf /Δt.

Short Pulse Radar

Target distance can also be accurately measured by determining the time for a radar pulse to go to and return from the target, but to measure short distances (down to 1-2 inches) requires accurate time measurement to approximately 50 picoseconds and a receiver bandwidth as large as 7.5GHz. This is available, but in the cost conscious world of agriculture it is too expensive. Figure 6 illustrates the pulse signal in time domain, where t = time (e.g., t1 represents first time delay and t2 represents second time delay; Knox, unpublished raw data, 2000).

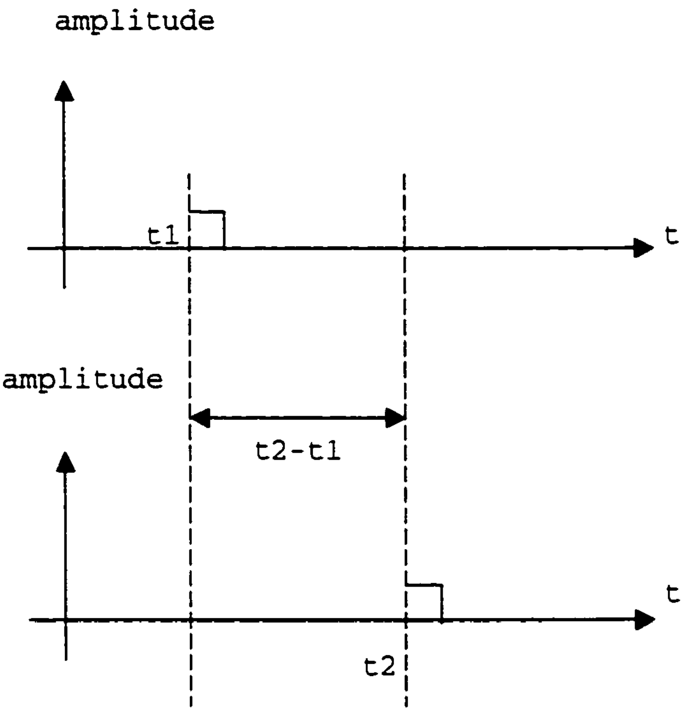


Figure 6. Pulse signal in time domain.

FSK Radar

A switched frequency radar can also be used for measuring distances by switching between two transmitter frequencies and measuring the phase difference between the two pulses at the down converted frequency. This type of distance sensor is very accurate if the two transmitter frequencies are controlled carefully and the phase angles of the down converted intermediate frequencies (IF) are measured accurately. If one wished to measure very short distances (<1m), the spacing of the two transmit frequencies must be large. It would be difficult to keep the two radar frequencies within the allowed 250Mhz band at 24 Ghz. Figure 7 illustrates the FSK signal in frequency domain, where f1 = first frequency transmitter and f2 represents the second frequency transmitted (Knox, unpublished raw data, 2000).

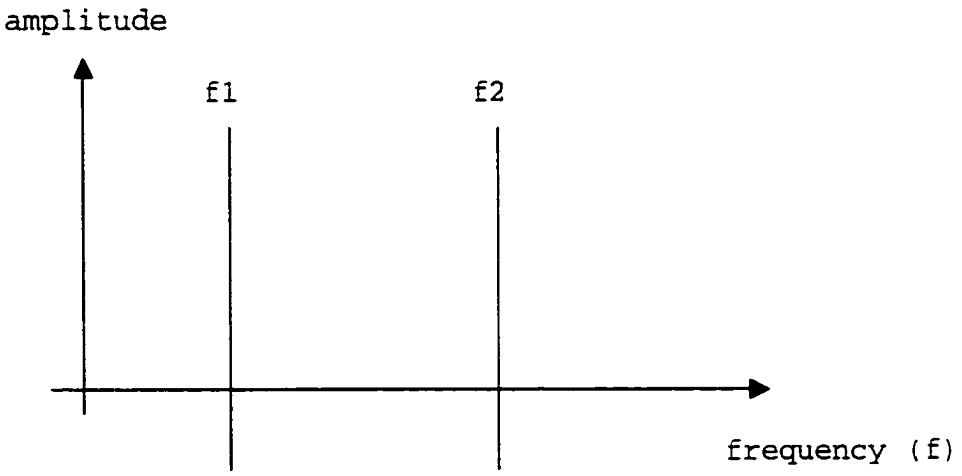


Figure 7. FSK signal in frequency domain.

AMCW Radar

An AMCW radar uses a fixed frequency transmitter. The transmitter signal is amplitude modulated with a switch. The switch should have sinusoidal change in impedance with modulation drive to minimize unwanted higher order modulation products. The transmitter's modulation index is kept relatively low to minimize the higher order side bands. This system is very accurate in short-range applications. It cannot detect a long-range target due to the phase repeatability. Figure 8 depicts the AMCW signal in frequency domain, where the carrier frequency (f_c), is modulated at a lower frequency (Stimson, 1983, p. 99).

Whenever the amplitude of a signal of a given frequency (f_c) is modulated at a lower frequency (f_m), two new signals are invariably produced. Since the frequencies of these signals lie on either side of f_c, the signals are called sidebands or sidelobes.

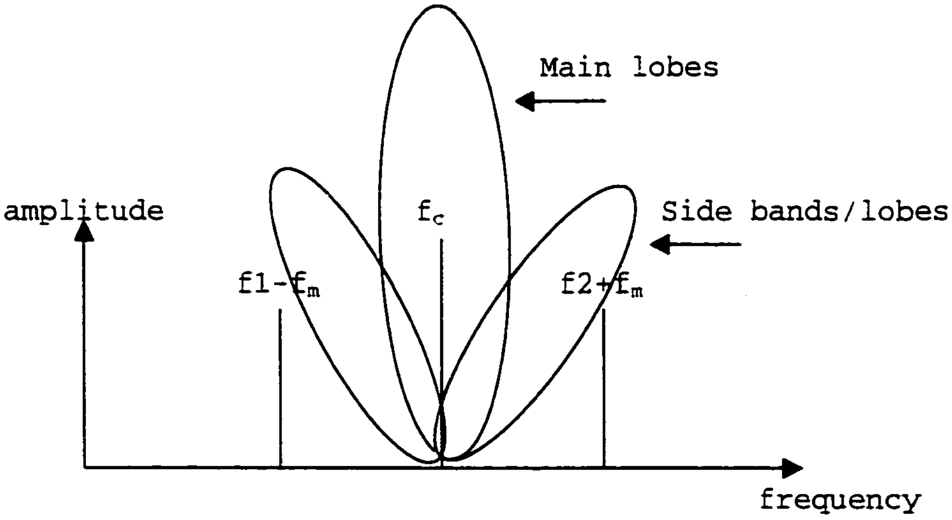


Figure 8. AMCW signal in frequency domain.

RF Antenna Configuration

The configuration of the RF sensor antenna is dictated by the Ag application, the antenna could be parabolic or a printed flat panel array, all due to issues such as packaging and location on the vehicle. The block diagram of the proposed AMCW Radar System is shown in Figure 9, where fc = carrier frequency and two side band frequencies fc±fm (fm is the modulate frequency at about 60 MHz). Shutko & Novichikhin (2000, p. 10) states, "most designs today are near-field flat panel arrays, flat panel design offers reduced physical size and hybrid/monolithic component packaging." Additionally, the antennas of flat panel arrays offer good gain, low sidelobes, excellent producibility, and choice of beam width.

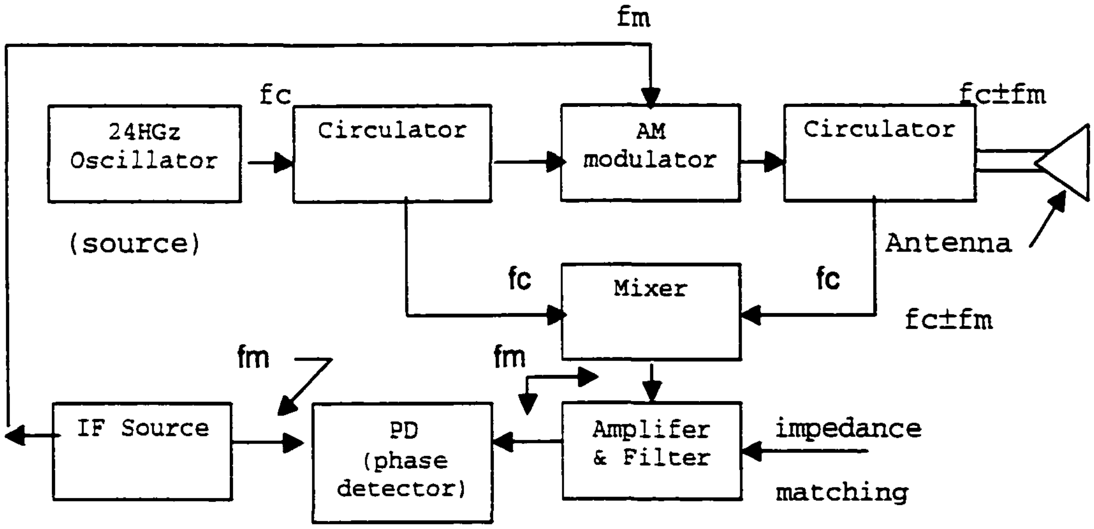


Figure 9. Block diagram of the proposed AMCW radar system.

Currently the commercial and automotive industry is in the process of introducing its first model of Forward Looking Radar (FLR) for obstacle detection applications. Two such companies, DaimlarChrysler and BMW offer an RF sensor FLR to support adaptive cruse control. According to Knox, "there are more complex issues associated with FLR versus Rear Looking Radar such as, slow speed stop/go operation; detecting short-range cut-in vehicles; recognizing stopped objects for reliable path prediction and collision warning" (2000, p. 35).

Limited Deere Field Test Results

Current AMCW RF 24.125 GHz K-band radar used on today's Ag self-propelled vehicles for monitoring ground speed experience accuracy fluctuations or variations in operation over various ground terrains (e.g., earth, asphalt, concrete, and ground stubble). As observed in John Deere Product Engineering Center-PEC field tests, typical ground variations can be ±15% over concrete and ±5% over soil. Additionally, "drop out of signal and reacquisition of signal over similar terrain will occur over long usage periods of 400 to 500 hours" (Potter, unpublished raw data, 2000).

Based on John Deere Product Engineering Center field test data, the signal drop out at approximately 400 hours to 500 hours can be traced to either the physical component alignment of the gun diode oscillator to the mixer diode or to the size of "key hole" emitter opening.

The alignment of gun oscillator to mixer diode is important when determining the amount of RF energy returning to its source. Therefore, if the emitter source or gun diode receives a large percentage of returned RF energy over long periods of time, the repeated saturation-release cycle and absorption of energy to the gun diode will result in a reduced ability to interpret the electrical current during emitter operation. Figure 10 illustrates current degradation/saturation curve phenomena.

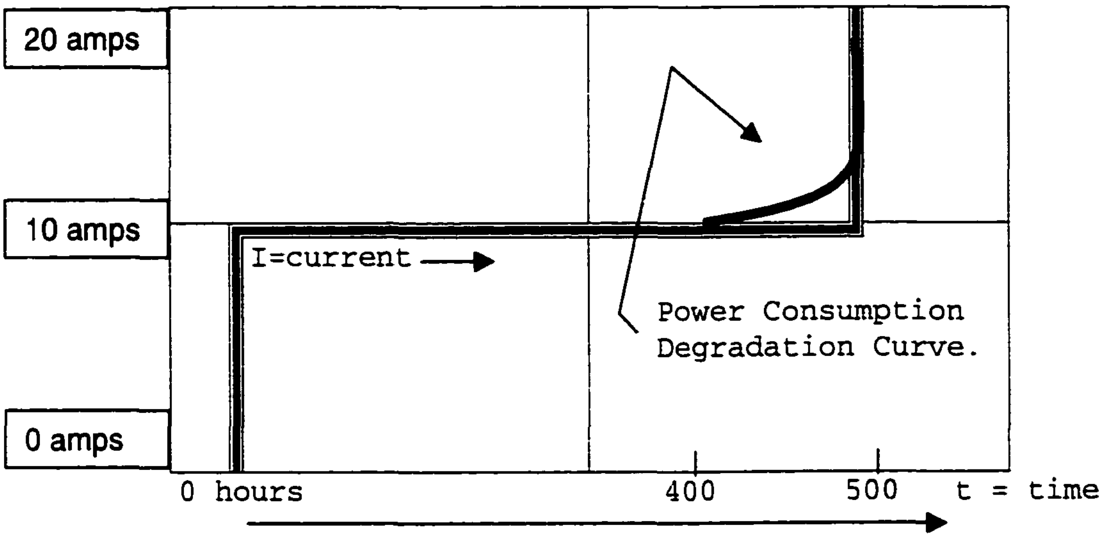


Figure 10. Current degradation/saturation curve phenomena. Curve represents current degradation.

Radio Frequency (RF) Applications on Self-Propelled Agricultural Vehicles

A K-band (24 GHz) radar is currently used in Ag applications as a ground (truth) speed sensor for self-propelled vehicles, in law enforcement agencies as a vehicle rate of speed detection sensor, and by NASA to sense various conditions of the Earth's surface such as nutrient levels, crop health or flood damage (Shutoko & Novichikhin, 1999; Ulaby et al., 1982).

As with many radar applications or tasks such as those stated above, there are a large variety of radar remote sensing characteristics, which are fitted to special applications. The radar characteristics of frequency types, polarization, power and range are some of the most important values of classical radar used as a remote-sensing device.

Ground Speed Radar

An ideal speed sensor would be able to indicate a vehicle's true ground speed instantaneously on any surface. It should be able to perform under any acceleration or deceleration event as well as under steady state conditions. In reality, it is difficult for any one sensor to perform flawlessly under all conditions.

Microwave speed sensors rely on scattered radiation from the ground to be detected by the transceiver in order to generate the Doppler effect sensor signal. Consequently, rough surfaces tend to provide better performance than smooth surfaces. "Doppler effect speed sensors are ideal for field stubble, plowed fields, gravel roads, but show a degradation in performance on concrete or blacktop roads" (Copper, 2000, p. 4).

Copper (2000) and Knox (2000) both conducted research using ground speed radars on rough and smooth surfaces. Both noted a significant level of degradation to the return signal on smooth wet surfaces. Doppler effect ground speed sensors do not function at peak performance if the incident surface is standing water or a pool of water (Copper, 2000; Knox, 2000).

It is important to note that the ground speed sensor can only measure it's own speed. Knox (2000), as had others, conducted sensor speed tests to reveal the sum of all movement for any distance of the reflector target is given by Equation 2.3: where,

$$R = \alpha + \frac{\lambda\theta}{4\pi}. \qquad (2.3)$$

Where, Knox (2000) noted,

> R is the distance from the target, α is the experimentally determined range delay constant for the sensor's electronic circuits and the phase shift from the target, λ is the wavelength at the modulation frequency and θ is the phase difference between the modulation signal and return signal. (p. 22)

The directionality or phase shift of the reflection from the target is determined by the characteristics of the target. For example, a sphere reflects equally in all directions. A flat plate reflects the majority of the energy in a direction determined by the orientation of the plate. That portion of the reflected energy that propagates in the direction of the radar's receiving antenna is called backscatter. It is the only reflected energy that matters to the radar.

Radar Backscatter Studies

Scatter of electromagnetic radiation results from the interaction of the electromagnetic wave with bulk media it encounters. This interaction is governed by the dielectric properties of the media, specifically the capacitance and conductance of the media. "These dielectric properties are defined by the complex dielectric constant (ε) of the media, the real component (ε') is referred to as the permittivity and the imaginary component (ε'') as the loss factor" (Hallikainen, Ulaby, Dobson, El-Ray, & Wu, 1985, p. 23). The permittivity is comprised of two components, that due to alignment of permanent dipoles with the electric field of the electromagnetic radiation and that due to the creation of induced dipoles.

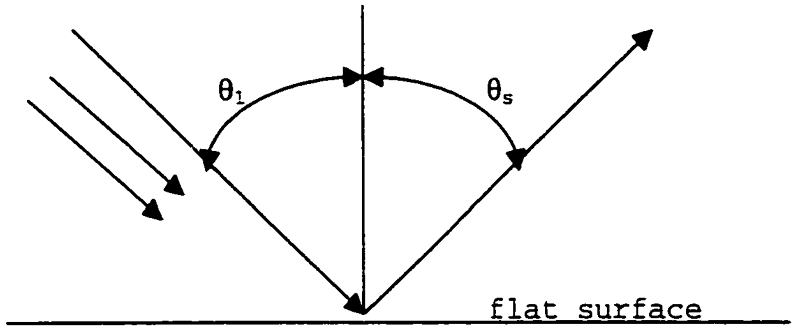
For example, at a rough surface boundary, an incident wave is partially transmitted through the boundary and partially reflected from the surface. The reflected portion can be separated into a spectral component and a diffuse component, where the spectral component is often referred to as the coherent component while the diffuse component is referred to as the non-coherent component. "The coherent component (as highlighted in figure 11 by a jagged wave form) is reflected symmetrically in relation to the incident wave while the non-coherent component is scattered in all directions as demonstrated in Figure 11, titled, relative contributions of coherent and non-coherent (diffuse) components" (Hallikainen et al., 1985, p. 27).

For relatively smooth surfaces the reflection is predominately coherent while rough interfaces result in mostly non-coherent of diffuse reflections. Backscatter is defined as the component of radiation that returns in the direction of the source. The backscatter component consists of coherent and non-coherent scatter.

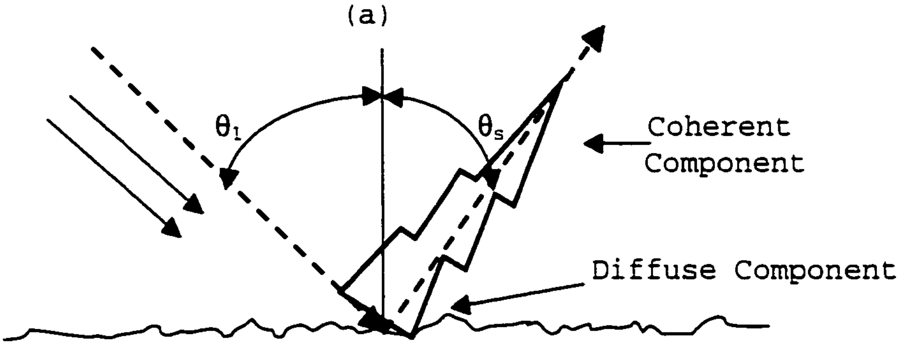
Figure 12, illustrates the angular variation of the backscatter coefficient for different surface roughness. Ulaby, Moore, and Fung (1982) state,

> The means of specifying smooth or rough surfaces are somewhat arbitrary, generally smooth means the root mean square (rms) surface height is substantially less than the incident wavelength and rough means the rms surface height is substantially larger than the wavelength. (p. 49)

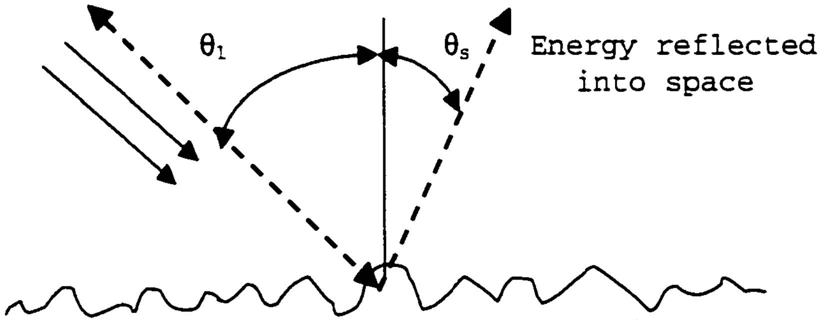
Thus, the proportion of non-coherent component of the reflected wave is a fairly reliable measure of surface topography.



Reflected Power is Entirely Coherent and
$\theta_s = \theta_1$. Scattering Pattern is a Delta Function
(a)



Scattering Pattern Consists of Large
Coherent Component and Small Diffuse Component
(b)



Scattering Pattern is Composed Entirely of
Diffuse Component
(c)

Figure 11. Relative contributions of coherent and non-coherent (diffuse) components: (a) smooth surface resulting in spectral reflections, (b) slightly rough with coherent and non-coherent components, shown as jagged line, (c) very rough with only non-coherent reflection.

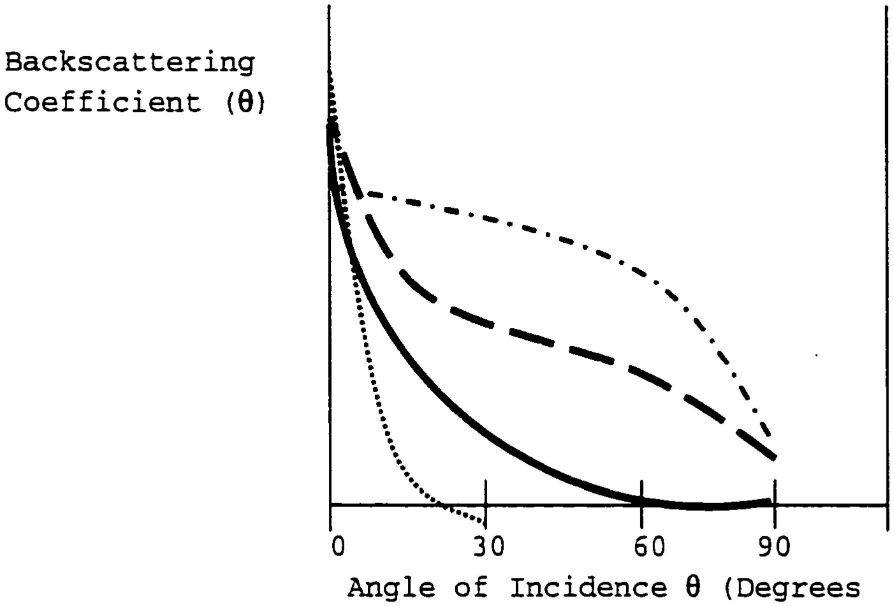


Figure 12. Angular variation of the backscattering coefficient for varying surface roughness conditions.

Legend of Backscattering Coefficient

…………… Coherent Component of Slightly Rough Surface

▬ ▬ . Coherent Component of Medium Rough Surface

▬▬▬ Non Coherent Component of Slightly Rough Surface

▬ . ▬ . Non Coherent Component of Very Rough Surface

Inhomogeneities of the dielectric value within the media result in local reflections of the electromagnetic waves. In soil these inhomogeneities are random in shape, orientation, and location (Gutierrez, 2000; Hallikainen et al., 1985; Knox, 2000). "The dielectric value may assume a gradual change with depth, as is the case with soil moisture which generally increases with depth" (Ulaby et al., 1982, p. 77). These inhomogeneities cause the wave to scatter in all directions, undergoing multiple reflections or scattering. Some of this scattered radiation may return to the detector in the form of backscatter. Backscatter, as stated earlier, is a portion of a radar's transmitted energy that is intercepted by a target or other object and reflected (scattered) back in the radar's direction.

Radar Cross Section (RCS)

As defined in Chapter 1, radar cross section (RCS) is a factor relating to the power of the radio waves that a radar target scatters back in the direction of the radar in direct proportion to the power density of the radar's transmitted waves at the target's range. That said, a target's geometric cross-sectional area, reflectivity, and directivity are combined into a single factor, called radar cross section (RCS). It is expressed by the Greek letter sigma, σ, and it's value is usually expressed in square meters.

The power density of the waves scattered back in the radar's direction, then can be found by multiplying the power density of the transmitted waves when they reach the target by the target's radar cross section. Since the directivity of the target can be quite high. For example, some target aspects of the radar cross-section could be many times the geometric cross-sectional area. For others the reverse may be true, this depends on the reflectivity of the target.

The geometric cross-sectional area and the energy of the target signal support basic factors of electromagnetic radiation and absorption. As observed by Stimson (1983, p. 170), "there are four basic factors to determine the amount of energy a radar will receive from a target during any one period of time, while the antenna beam is trained on it." Those basic factors are:

- The average power--rate of flow of energy--of the radio waves radiated in the target's direction
- The fraction of the wave's power which is intercepted by the target and scattered back in the radar's direction
- The fraction of that power which is captured by the radar antenna
- The length of time the antenna beam is trained on the target.

When the antenna is trained on a target, the power density of the radio waves radiated in the target's direction is proportional to the transmitter's average power output, P_{avg}, times the gain, G, of the antenna's mainlobe.

In transit to the target, the power density is diminished as a result of two things: absorption in the atmosphere and spreading. As waves propagate toward the target, their energy spreads--like the surface of an expanding soap bubble--over an increasingly large area.

Stimson states, "at the target's range, say R miles, the power density is only $1/R^2$ time what is was a range of 1 mile" (1983, p. 171). The amount of power intercepted by the target equals the power density at the target's range time the geometric cross-sectional area of the target, as viewed from the radar (the projected area).

Further, Stimson (1983), stated,

> As the waves propagate back from the target, they undergo the same geometric spreading as on their way out. Their power density, which has already been reduced by a factor of $1/R^2$ is again reduced by $1/R^2$. The two factors are compounded, so the power density when the waves reach the radar is only $1/R^2 \times 1/R^2 = 1/R^4$ times what it would be if the target were at a range of only 1 mile (or whatever other unit of distance R is measured in). (p. 172)

What fraction of the intercepted power is scattered back toward the radar depends upon the target's reflectivity and directivity. The reflectivity is simply the ratio of total scattered power to total intercepted power. The directivity-like the gain of an antenna-is the ratio of the power scattered in the direction of the radar to the power, which would have been scattered in that direction had the scattering been uniform in all directions.

Summary

To summarize, this chapter discussed a review of literature on remote radio frequency sensors. Specifically, the chapter focused on both published by text books and unpublished raw data generated during field testing of various RF sensors. The discussion continued on the RF principle as it relates to frequency of the transmitted radio waves within its frequency spectrum and various frequency bands (e.g., megahertz to gigahertz, and L-band to millimeter wave radar). Further, the chapter provided examples of radio frequency as a means for remote sensing as used by various industries (i.e., NASA, automobile, and Ag); continuing with a discussion on limited field tests using a RF sensor; the radar backscatter as it relates to targets, both coherent and non-coherent components; the radar cross section of targets (i.e., geometric cross-sectional area); its reflectivity and directivity; and a review of the four candidate RF sensor technologies (e.g., FMCW, short pulse radar, FSK, and AMCW radars).

CHAPTER 3

METHODOLOGY AND DESIGN

Introduction

Remote sensing is the science and art of obtaining information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation. The remotely sensed data can be of many forms, including variations in force distributions, acoustic wave distribution, or electromagnetic energy distribution.

This research specifically addresses radio frequency (RF) remote sensing. The need for this research was based on the lack of a descriptive analysis of remote RF sensing and the need for empirical study of RF in specific typological environments. This chapter describes the use of the experimental research design and test plan (reference Appendix B Test Plan and Procedures) of the remote radio frequency sensor and the surface topographies used for this study (e.g., tilled soil, grass, and concrete).

Research Design

Background

The design of this study was experimental. The goal of the study was to collect radar cross sectional (RCS) data with respect to three specific field conditions in an agriculture (Ag) environment (e.g., tilled soil, grasses, and concrete). To accomplish this, a test platform (i.e., tractor) was utilized for the testing of the radar. The tractor was equipped with the ground speed radar per block diagram on page 37. The radar housed a digital signal processor (DSP) and interface with the electronics on the vehicle and test equipment.

The testing runs/sampling followed a procedure whereby the vehicle covered the three selected surface topographies (tilled soil, grasses, and concrete) in three separate passes. A "pass" consisted of approximately 600 feet at a set velocity over all three surfaces. During each pass, vehicle wheel speed, radar radiating return power, and radar target were collected, recorded, and stored from all three surfaces. The stored data sets were reduced and analyzed off-line to determine radiating power output of each surface.

Test Equipment

The radar/transceiver system: The radar used consists of a K-band, 24.125 GHz Doppler transceiver. Incorporating a Single Beam, Dielectric Resonator Oscillator (DRO) with I (in-phase) & Q (quadrature) mixers. The transceiver's power, tuning frequency band, and DRO power, all are within the Federal Communication Commissions Telecommunication Act, Article 47 (reference Appendix A for Article 47). For calibration purposes, all performance parameters were tested at room temperature.

The data acquisition systems tool/field computer system used for this research was the SOMAT EASE version 3 (herein termed SOMAT). The SOMAT tool is a complete data analysis system for time and frequency domain analysis. In short, the SOMAT system provides frequency analysis in the form of fast fourier transform (FFT; i.e., an FFT can be performed on an entire history of tests). Additional SOMAT features include: auto power function analysis--scaling of auto power function as linear, power spectral density, and energy spectral density. Reference Appendix C for detail description of the SOMAT system.

Digital Signal Processing System

The Digital Signal Processing (DSP) unit used baseline or off-the-shelf software. The bias error and variation error correction factors were not custom tailored to the units at this time. The DSP unit was functionally tested on a small-scale towed trailer apparatus to verify function and operation prior to testing on a large or different platform. Note: The DSP has two data output streams. The TTL output was the standard OEM interface for use on the tractor. The second interface was a serial data port for monitoring the performance of the DSP system. The serial data port was for the initial testing only. It allowed monitoring of signal strength, averaging calculations, and other processor characteristics.

Test Method

The test conditions for the initial trial were over a 600 foot measured distance of straight tilled soil, grass, and a level concrete road. The DSP serial output was connected to a laptop PC for data collection. The engine governor kept the vehicle speed constant during the entire run. Axle speed variations were monitored visually to record the maximum and minimum values during the run.

The test method consisted of multiple runs (~20 at three pre-selected speeds) over the selected topographies, while recording true ground speed (via axle), radar speed, and radiating output power. The output of ground speed, radar speed, and radiating output power was then correlated to determine true speed and radiating power loss.

Accuracy of vehicle velocity was measured at the following speeds: 4 mph, 8 mph, and 16 mph. The speeds were maintained to ±10%. The vehicle was set up once and all measurements taken. Note: the vehicle speeds of 4, 8, and 16 mph were selected based on current knowledge of tilling (4 mph), harvesting/planting/cultivating (~8 mph), and spraying (16 mph), respectively. The speed of 8 mph, encompasses the majority of agricultural processes and thus was defined as the optimum vehicle velocity for calculating cost of seeding and harvesting yield data.

To assist in the calibration of test equipment and vehicle preparation was Zachary Bonefas, a University of Iowa Electrical Engineering graduate student working as a summer intern for Deere & Co., Advanced Sensor Development Department. Bonefas support included: SOMAT calibration, radar installation onto vehicle(s), visual confirmation of true vehicle speed via rear wheel revolution, and the printing of SOMAT charts.

The test course was 600 feet long and the radar output pulse rate for one pass was 128,536 pulses. The pulse counter measured the output pulses with 0.01% accuracy. The pulse count was based on an initial mounting angle for the radar at 37°.

Test Method: Wheel Speed Calibration

1. Set vehicle tire pressures at the recommended setting. Vehicle should be ballasted or loaded only per the manufacturer's recommendations.

2. Measure a set distance approximately equal to 10 tire circumferences. Use a concrete or asphalt test site.

3. Place a mark on the tire sidewall that extends down to the tread.

4. Connect in data acquisition to count wheel speed sensor pulse.

5. Align the mark on the tire with the start of the known test distance.

6. Turn on data acquisition equipment and start vehicle. Drive the vehicle at a slow rate of speed so the wheel revolutions can be counted by an outside observer.

7. When the wheel hits the end marker of the calibration track. Stop the data acquisition equipment. Do not allow the vehicle to roll backwards.

8. Count the number of pulses and calculate the pulses/wheel revolution.

9. Repeat the test three times and average the result.

Test Method: Radar Speed Tests

1. Determine the necessary acceleration distance required to accelerate the vehicle to the desired steady state speed. Park the vehicle at that spot in front of the test track.

2. Turn on tractor and make sure system voltage is functioning within vehicle specification.

3. Initialize data acquisition equipment. Do not take data at this time.

4. Turn on Radar and timing equipment.

5. Activate data acquisition equipment, verify that it is recording.

6. Select and record gear information and engine rpm.

7. Declutch tractor and accelerate tractor to speed. Verify that target speed is matched prior to reaching the start marker of the test course.

8. Verify that timing equipment activated when tractor crossed the start marker. If it did not match timing and marker, abort run.

9. Observe speed readouts during run.

10. As the tractor nears the end of the test track, verify that the timing system has triggered at the end marker.

11. Slowly stop the tractor.

12. Stop the data acquisition system

13. Store the acquired data; log the file name in a notebook.

14. Repeat steps 20 times for each vehicle speed (4 mph, 8 mph, and 16 mph) and each surface topography (tilled soil, grass, and concrete). Specific details of the testing methodology and procedure can be found in reference Appendix B.

Radar Sensor Description

The radar sensor used for the research and test was K-band Doppler technology. The emitter frequency (e.g., 24.125 GHz), was used to sense the ground speed and the on board DSP processes this signal to give a pulsed voltage output with a frequency proportional to the speed of the vehicle.

The true ground speed radar sensor used the Doppler effect to sense the difference in frequencies between the transmitted signal and the reflected signal received from the ground (or other objects in its path). This difference is the Doppler frequency shift and it is proportional to the speed of the vehicle.

The Doppler shift frequency (f_d) is given by the Equation 3.1:

$$f_d = 2 \times v \times (f_o / c) \times \cos \phi \qquad (3.1)$$

where,

v: Velocity of the vehicle in meters per second(m/s)

f_o: Transmitter frequency (Hz)

c: Speed of light (2.99792458×10^8 m/s)

ϕ: Angle below horizontal of the center of the beam.

Atmospheric Conditions

It was proposed that all testing occur at or fall within a range of similar conditions such as: proposed minimum temperature 60° Fahrenheit to 75° Fahrenheit, relative humidity of approximately 60%, clear to partly clear sky, and with no standing water from rain or other sources of water on any of the three surface topographies.

Sensitivity

The gain of the sensor was adjusted to allow operation in selected surface topographies. The sensor did not have any loss of signal in any mode. The sensor was not expected to behave normally on standing water. Any loss of radiating signal return during test (field operation) constituted a failure. The data acquisition system (viz., namely SOMAT) was used in field operating conditions where there was no signal output loss for periods longer than 0.125 seconds on a course 600 feet long. This was determined by monitoring the output of the radar.

Signal deviations that cause the radar accuracy to fall outside of the field accuracy requirements constituted a failure. The radio frequency sensor was not able to filter out the effects of grass movement, vehicle vibration, and bounce.

Radio Frequency Microwave Output

The radar unit met all applicable FCC regulations concerning RF emissions and possessed the following characteristics:

Frequency: 24.125 GHz ±250 MHz licensed for North America and European (except UK). Note: the UK frequency allocation and licensing for radar is 24.124 GHz ±250 MHz.

Power: Output power did not exceed 10 mW average power.

Maximum output power: Was 500 mW EIRP (Effective Isotropic Radiated Power).

-3dB beam width (azimuth): ± 12 degrees (beam angle measured at 3dB point of main beam).

-3dB beam width (elevation): ± 12 degrees (beam angle measured at 3dB point of main beam).

Side lobe: -15dB for both azimuth and elevation.

Size and Mounting Specification

The radar sensor was compatible with existing mounting hardware on John Deere tractors and equipment. The bolt-hole pattern was unsymmetrical.

Height: 46 cm to 122 cm. (18" to 48") from center of lens vertical to ground.

Angle: 37° from horizontal.

Black Hawk County Soil and Surface Topography

The soil in Black Hawk County, per the USDA and Iowa Cooperative Soil Survey are registered and cataloged through the use of the Soil Map Unit (SMU). The SMU, which is used to describe soil types, registers Black Hawk County as Dinsdale-Tama (DT). The Black Hawk soil is registered as LEAG Farmland Unit (LEAGFMLND) and is defined by: clayey over loamy, monotmorillonitic, mesic.

Type of Tilled Soil

The percentage of organic matter was estimated for tilled surface horizons of 0 to 7 inches, as a result the organic matter was approximately 1.5 to 2.5%. A measure of acidity or alkalinity of soil, expressed as pH, was medium acid (5.6 to 6.0 pH). The silty clay loams are less than 35% clay and less than 5% finely divided calcium carbonate. These soils are very slightly erodible. The content of mineral soil particles was <0.002mm in diameter. The sand size and content was <0.25mm and <15%, respectively. Based on clay content, organic matter, drainage class, sand size, and sand content the tilth rating is 1 (one as being the best).

Type of Grasses

For the purposes of this study, as defined in the Definition of Terms, grass was considered constant and termed as grass.

Type of Concrete

For the purpose of this study, the term concrete was considered as multi-purpose concrete. It is suitable for all uses where the special properties of other types are not required. The concrete used in Black Hawk County includes pavements, floors, reinforced concrete buildings, bridges, railway structures, tanks and reservoirs, pipe, masonry units, and other precast products.

Analysis of Test Data

After the data was collected, a statistical analysis was conducted using the Statistical Package for the Social Sciences (SPSS) and Microsoft Excel Statistical Program. Nominal vehicle velocity (speed), wheel speed bias, and radiated output power (dB) were stored, analyzed, and calculated.

Summary

The AMCW radio frequency sensor for ground speed applications should be able to indicate a vehicle's true ground speed instantaneously and radiating signal return profile on the three surface topographies of tilled soil, grass, and concrete. The AMCW sensor should able to perform under any acceleration/deceleration event as well as under steady state conditions. In reality, it is difficult for any one sensor to perform flawlessly under all conditions. The test (results in Chapter 4) were designed to test the performance of a non-contact speed sensor, specifically, the Doppler effect speed sensor.

A near range radio frequency sensor concept was proposed based on the literature research of radar sensor technology and FCC regulations. The test vehicle carried a 24.125GHz radar sensor, meeting the FCC regulations of 250MHz allowable bandwidth. This same frequency is available for industrial applications in most European, Pacific Rim, and North American countries. An AMCW method was suggested due to its advantage of detecting the dynamic near range targets (i.e., surface topographies of tilled soil, grasses, and concrete).

In order to collect the results of the tests, a data acquisition system tool, (trade name: SOMAT) was used and was capable of counting the number of pulses output by the radar sensor and also capable of event timing with ~1 millisecond resolution if necessary. In addition, a complementary speed/distance sensor was required, such as monitoring wheel revolution over known distance to calculate true ground wheel speed.

CHAPTER 4

PRESENTATION AND ANALYSIS OF DATA

This chapter presents the results of the research on using a radio frequency radar sensor (e.g., 24.125GHz radar) to measure a consistent vehicle speed over selected surface topographies of tilled soil, grasses, and concrete. The radio frequency sensor was mounted on a test vehicle at a predetermined distance of 39" above all three surface topographies throughout all phases of the test.

The objective of the test results was to determine, from previous research reports (i.e., review of literature), the signal return profile or radar cross section (RCS; reference Chapter 1, page 7 for definition of terms) from the selected surface topographies. Reference Chapter 3, page 52 and Appendix B, page 102 for details on the administration of experimental research design and testing, methodology, and procedures.

A set of three research questions (Chapter 1, p. 4) were used as the basis of this research. The aim of this research was to study and provide the necessary information on the signal return profile of a selected radio frequency sensor as it relates to various Ag surface topographies (e.g., tilled soil, grass, and concrete). The radio frequency sensor within, termed "radar," is regulated by the Federal Communication Commission (FCC). The FCC Telecommunications Act, Article 47, Parts 2.106, 2.997, 15.33, and 15.249, identifies three elements as acceptable guidelines for this radar environment; radar band, signal return profile, and frequency allocation. For further definition of FCC Article 47, reference Appendix A.

The radar band used in this study was K-band. Signal output return or radar cross section was termed radiated output power measured in decibels (dB). Frequency allocation was at 24.125GHz.

The research questions were as follows:

1. What was the signal return profile between the selected remote sensing radio frequency radar and tilled soil (i.e., freshly furrowed soil not larger than 4"-6" wide clods of soil present)? Reference Definitions of Common Terms page 9 for a definition of freshly tilled soil.

2. What was the signal return profile between the selected remote sensing radio frequency radar and grass?

3. What was the signal return profile between the selected remote sensing radio frequency radar and concrete?

With a goal to answering these research questions, the methodology of the study was developed, data collection sequences were ordered, and actual data collected from field tests were recorded and analyzed.

Conceptual Notion of Operation

Method of Data Collection

The field-testing set consisted of 20 runs covering 600 feet at speeds of 4 mph, 8 mph, and 16 mph over three surface topographies of tilled soil, grass, and concrete. The test data was then collected from 180 field test runs.

Based on the field-testing, the mean and standard deviation were calculated for radiated reflected power (i.e., radar cross section--RCS). Additionally, true vehicle wheel revolution, and indicated radar speed were calculated and stored. Reference Appendix B and E for test preparation and data collection approach, and the associated raw data from wheel speed, radar speed, and RCS, respectively.

Radar Operation

The radio frequency sensor, including a fixed beam antenna, was mounted on the vehicle at a convenient height above average ground level. Terrain below the vehicle was illuminated from a down-look angle of 37 degrees.

Radiating energy return is the Doppler shifted signal produced by the instantaneous line-of-site velocity of the sensor toward the illuminated patch of ground. The Doppler spectrum of radiating reflected power at any instant is determined by instantaneous vehicle speed, vehicle tilt, and reflection characteristics of the illuminated ground patch. In addition to radiating reflected power, the Doppler power spectral density includes spectral components produced by spurious harmonics, self and target noise produced by transmitter frequency instability, vehicle vibration, and signal return from rotating or other moving parts of the vehicle.

AMCW Radar Components

Based on the block diagram, reference Figure 9, page 37, that illustrates the amplitude modulated continuous wave (AMCW) radio frequency sensor used during the field tests and the field test results, the following list highlights the final components, which were required for the sensor to operate. They include an IF (intermediate frequency) oscillator, Gunn oscillator, AM (amplitude modulated) modulator, circulator, antenna, mixer, IF amplifier, IF filter, and phase detector. Details of the

AMCW radio frequency component specifications and sections can be found in Appendix F.

Analysis of Data Collection for Research Questions

During a period of four weeks, research was conducted at the Deere & Company Product Engineering Center (PEC) facility, located in Waterloo, Iowa. During the first two weeks of this research, the three surface topographies (tilled soil, grasses, and concrete) were "conditioned" (i.e., soil freshly tilled, and grasses and concrete were cleared of debris). Additionally, the data acquisition device was calibrated; the test vehicle was outfitted with radio frequency sensor in preparation of ensuring ground speed tests; and mock dry runs were conducted.

The following two weeks of this research were used to identify which days provided the optimum atmospheric conditions (via National Weather Forecast predictions) for performing the test(s), followed by the collecting of data, and analyzing the results. Throughout the field tests, the three research questions were used as a guideline (i.e., compare and contrast), to gain a better understanding of the radar signal return profile or RCS and speed bias over the selected surface topographies.

Physical Changes

After the initial assembly of the radio frequency sensor to the test vehicle and initial dry runs, the following phenomena occurred: as the test vehicle was driven across the terrain, the vehicle experienced either or all of the dynamic conditions of pitch, roll, and yaw. As a result, the angle between the radio frequency sensor and the tilled soil changed in an unpredictable manner.

Based on the review of literature, it was known that the Doppler frequency is proportional to the sensor-ground angle. The Doppler frequency or shift, due to undulating surface texture and multiple variations in vehicle attitude in relation to incident angles of return signal, is known to offer an unpredictable change to velocity error. Integrating the sensor readings over time can average out this error, but the technique increases the time needed by the operator to respond to variations in velocity.

A common solution to the phenomena mentioned above, as stated by Williams (1999, p. 36), "is to use a second sensor mounted at the same angle as the first, but facing in the opposite direction." Since both radio frequency sensors are pointed in opposite directions, the instantaneous pitch angle is plus and minus in relation to the vehicle velocity. As a result, the signal-processing algorithm averages these two frequencies when it converts them to velocity readout, then pitch error is effectively eliminated.

Analysis of Research Question 1, 2, and 3

The main research questions addressed by this study were as follows:

1. What is the signal return profile--RCS--between the selected remote sensing radio frequency radar and tilled soil, (i.e., freshly tilled soil consisting of but not larger than 4"-6" wide clods of soil present)?

2. What is the signal return profile--RCS--between the selected remote sensing radio frequency radar and grass?

3. What is the signal return profile--RCS--between the selected remote sensing radio frequency radar and concrete? Reference definition of terms, page 8 for clarification on the usage of the term "concrete."

These three questions were used to guide the collection of data throughout the field tests over tilled soil, grass, and concrete at relative constant speeds of approximately 4 mph, 8 mph, and 16 mph, respectively (reference p. 52 for definitions of the various speeds and their significance). To ensure all three speeds experienced the same or like surface conditions, special care was taken so that the tilled soil, grass, and concrete were consistent throughout the entire test runs and data collection phases.

Analysis of RCS or Spectral Noise

In aggregate, the responses to Research Questions 1-3 are outlined below in Tables 1-3. The research questions essentially state, what are the radiated reflected power over tilled soil, grass, and concrete by the radar frequency sensor? The radiated reflected power, or RCS so outlined by FCC Article 47 for surfaces such as tilled soil, grass, cement is recommended to be between ~8dB and 10dB. Tables 1-3, depict the results of $\underline{n} = 20$ runs for each surface at each speed.

It's important to note, that radar speeds are used to support Ag applications (i.e., accurate seeding or planting). To achieve radar speed accuracy, long sampling periods are required to evaluate whether or not the vehicle speed is 4.12 mph or 4.13 mph.

In comparison, the on-vehicle sensors achieve finer speed resolution at shorter sampling rates (i.e., ~600 feet). As a result, the sampling period/time could explain the deviation between vehicle speed and the radar speed so indicated on Tables 1-3. Reference Appendix B for further information.

Table 1

Results of n = 20 Test Runs for Each Speed Over the Surface Topography of Tilled Soil.

Tilled Soil Speed (mph)	True Radar Speed (mph)	Spectral (RCS) Noise--Mean (dB)	Spectral (RCS) Noise--SD
4.21	4.32	9.55	1.23
8.32	8.18	8.00	0.97
16.40	16.21	8.60	0.50
n = 60			

Note. Variable is spectral noise (dB) as measured by RCS, for each surface.

Table 2

Results of n = 20 Test Runs for Each Speed Over Surface Topography of Grass.

Grass Speed (mph)	True Radar Speed (mph)	Spectral (RCS) Noise--Mean (dB)	Spectral (RCS) Noise--SD
4.15	4.22	9.45	0.51
7.91	8.00	8.35	0.48
16.48	16.64	9.75	0.44
n = 60			

Note. Variable is spectral noise (dB) as measured by RCS, for each surface.

Table 3

Results of n = 20 Test Runs for Each Speed Over Surface Topography of Concrete.

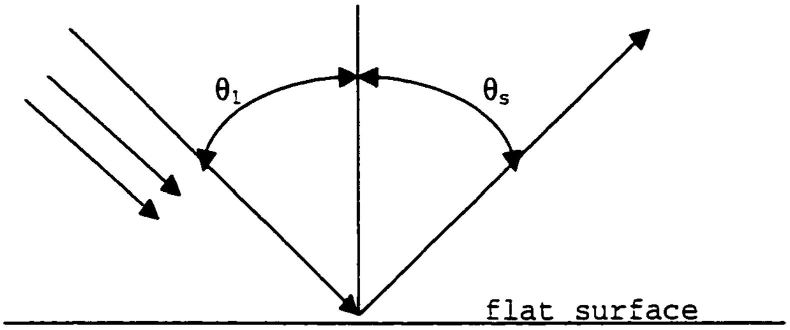
Concrete Speed (mph)	True Radar Speed (mph)	Spectral (RCS) Noise--Mean (dB)	Spectral (RCS) Noise--SD
4.18	4.42	10.50	1.19
7.97	9.08	10.40	0.59
16.50	17.98	9.60	0.59
n = 60			

Note. Variable is spectral noise (dB) as measured by RCS, for each surface.

Tables 1-3 synthesizes 180 test runs (= 60 runs x 3 surfaces) of the vehicle carrying the radio frequency sensor traversing 600 feet over all three surface topographies at three speeds of 4, 8, and 16 mph, respectively. The outcome of the aforementioned tests, suggest the radar frequency sensor over tilled soil and grass displayed a consistent RCS, well within the FCC requirements at all three speeds of 4, 8, and 16 mph, respectively.

Conversely, the smooth flat surface of concrete exhibited a RCS larger than recommended by the FCC due to the high angle of incident or deflection away from the radar power source. As a result, the RCS or radiating return power was higher due to the scattering of the emitting radar signal by the surface (i.e., concrete). Based on the high angle of incident (or scatter) for concrete, the RCS results were consistent with the findings of other research conducted over similar or like surfaces.

Reference Figure 13 (depicting former research findings) for an example of how radiating return power reacts on a relatively smooth surface. The reflection (backscatter) is predominately coherent while rough interfaces result in mostly non-coherent or diffuse reflections. Backscatter is defined as the component of radiation that returns in the direction of the source. The backscatter component consists of coherent and non-coherent scatter.



Reflected Power is Entirely Coherent and
$\theta_s = \theta_I$, Scattering Pattern is a Delta Function

Figure 13. Spectral reflections: a smooth surface resulting in spectral reflections (Hallikainen, et al., 1985, p. 27).

Generally, based on the RCS consistency over tilled soil and grass, the RCS return or radiating return power of the radar sensor, equates to the expected state of the spectral properties for these surfaces (reference Figure 11 Section c, p. 45).

Specifically, the reduced RCS over tilled soil at 8 mph correlates to optimum vehicle efficiency (i.e., vehicle center of gravity and vehicle attitude is in balance). In order to maintain uniform planting and or harvesting, this "balance" or equilibrium is necessary to ensure reduced vehicle hop over tilled soil at an operating speed of 8 mph.

Vehicle hop (reference Definition of Terms, p. 12), which needs to be controlled or eliminated, will create unequal spacing of seeds during planting and will introduce errors in harvesting yield data. The vehicle equilibrium usually represents minimum vehicle hop, depending on surface and speed, but other factors need to be considered. These factors include: vehicle rotation, axial load, angular motion, and surface angle(s). Based on the data, 8 mph could represent optimum vehicle dynamics and RCS data over the surface topographies of tilled soil, grass, and concrete.

Analysis of Data

Figure 14, Spectral Noise (RCS) as a Function of Speed, illustrates the mean versus RCS of three topographies at three speeds. Figure 14 depicts that at 8 mph all three RCS's dip or are reduced when compared to 4 and 16 mph, respectively.

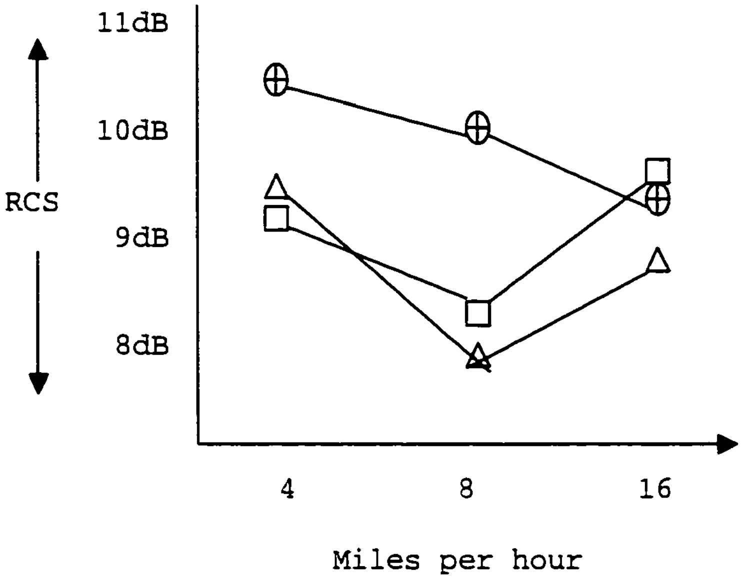


Figure 14. Spectral noise (RCS) as a function of speed for 3 types of surface topographies: tilled soil △, grass □, and concrete ⊕ .

The RCS mean was calculated to understand central tendency within the sample (i.e., tilled soil), and as a comparison to the other two surface topographies of grass and concrete. The central tendency or mean is the sum of the total test runs, N = 180. For further clarification, Hurlburt (1998, p. 53), defines the mean as, "the measure of central tendency appropriate for interval/ratio variables; it is equal to the sum of all values of a variable divided by the number of values."

Aside from the reduction of the RCS mean at 8 mph, the RCS range was well within the FCC guidelines for 24 GHz radar operating over the three selected topographies. Furthermore, the largest RCS mean reduction--8.6dB spectral noise--at 16 mph over tilled soil would suggest diminishing returns occur when tilled soil is "too rough" or the vehicle operating velocity is too fast a speed for a particular surface.

As stated previously, surface roughness must be present to ensure a larger portion of the transmitted energy is reflected back to the target. Smooth surfaces (i.e., concrete), have a tendency to deflect the transmitted energy away from the source, thus affecting the RCS.

Theoretical System Error Analysis

Evaluating the basic radar equation for the Doppler signal shows that there could be three basic errors that may be attributed to the radar front end: (a) antenna mounting angle errors, (b) frequency deviation errors, and (c) vehicle attitude deviations. Of the three, the largest uncontrolled deviation is the vehicle attitude.

1. Antenna mounting angle--A one-degree mounting error can cause a 3.5% relative error at 5 mph. This error would diminish to 0.8 % at 20 mph.

2. Frequency deviation errors--The instability or drift of the oscillator (source) would induce this error. Typical frequency drift of an oscillator is from 2.4MHz to 50 MHz worst case. This would cause an error in the Doppler signal of 0.5 to 1 Hz. This would not be detectable as the Doppler frequency at 5 mph velocity is 254 Hz (0.2-0.39 % error). This was the smallest error of the three described here.

3. Vehicle Attitude--The vehicle attitude may vary as much as ± 20° under normal operating conditions. It was suspected that the change in the beam angle with respect to the ground was severe when crossing undulating surfaces of rolling grasses or fields. As vehicle speed increases over the three test surfaces, a phenomenon called vehicle hop occurred. Prior to the phenomena, the vehicle experienced a harmonic conversion of vehicle resident frequencies where there was leveling of the vehicle. This is akin to an automobile being driven/accelerating onto the expressway where the vehicle is audibly louder until the

vehicle reaches peak efficiency and levels out both in noise and performance.

Summary

Microwave speed sensors rely on scattered radiation from the ground reflecting back towards the sensor in order to generate the Doppler effect speed sensor signal (e.g., signal return profile). As a result, rough surfaces provide higher quality of return signal performance than grasses and concrete (moving surfaces and smooth surfaces).

Based on the analysis of data, Pulse Doppler effect speed sensors yielded lower RCS--8dB--at speeds of approximately 8 mph but degraded in performance as measured by--8dB to 10.5dB--over tilled soil, grass, and concrete at speeds of 4 mph and 16 mph, respectively. The degradation of the RCS via Doppler speed sensor signal control was particularly evident when the smooth incident surface was concrete.

Additionally, the findings suggest the dynamic range and reflected signal loss (i.e., radiated reflected power or RCS), with multiple surface topographies (i.e., tilled soil, grasses, and concrete), displayed a varied spectral noise from 5dB to 15dB.

The spectral noise--8dB--at 8 mph over tilled surface is well within the FCC guidelines, and suggests rough textured surfaces are well suited for Radio Frequency Sensors as a means to monitor vehicle speeds.

CHAPTER 5

CONCLUSIONS, RECOMMENDATIONS, AND SUMMARY

In the previous chapter, the findings were reported and the supporting data were presented. The results of the aforementioned tests, suggest the radar frequency sensor over tilled soil and grass displayed a consistent radiating return power or radar cross section (RCS), well within the FCC requirements at all three speeds of 4 mph, 8 mph, and 16 mph, respectively.

Conversely, the smooth flat surface of concrete exhibited a RCS larger than that of tilled soil and grass, which was due to the high angle of incident or deflection away from the radar power source. As a result, the RCS or radiating return power was higher due to the scattering of the emitting radar signal by the surface (i.e., concrete).

Based on the high angle of incident (or scatter) for concrete, the RCS results were consistent with the findings of other research conducted over similar or like surfaces. Generally, based on the RCS consistency over tilled soil and grass, the RCS return or radiating return power of the radar sensor, equates to the expected state of the spectral properties for these surfaces (reference Figure 11 Section c, p. 45).

Specifically, the reduced RCS over tilled soil at 8 mph correlates to optimum vehicle efficiency (i.e., vehicle center of gravity and vehicle attitude is in balance). In order to maintain uniform planting and or harvesting, this "balance" or equilibrium is necessary to ensure reduced vehicle hop over tilled soil at an operating speed of 8 mph.

In Chapter 5, using the research questions of the study as a guide, a discussion will follow on the efficiency of the RCS as measured by the radio frequency ground speed sensor over different surface topographies. This chapter includes the following headings: Research Questions of the Study, Discussion of Relative Error Measurement, Conclusion of Observations, Recommendations for Future Study, and Conclusion of Study.

Research Questions of the Study

A set of three research questions were used as the basis of this research. The aim of this research was to study and provide the necessary information on the signal return profile of a selected radio frequency sensor as it related to various Ag surface topographies (e.g., tilled soil, grass, and concrete). The radio frequency sensor within, termed "radar," is regulated by the Federal

Communication Commission (FCC). The FCC Telecommunications Act, Article 47, Parts 2.106, 2.997, 15.33, and 15.249, identifies three elements as acceptable guidelines for this radar environment; radar band, signal return profile, and frequency allocation. For further definition of FCC Article 47, reference Appendix A. The radar band used in this study was K-band, signal output return or radar cross section was termed radiated output power measured in decibels (dB), and frequency allocation is 24.125GHz.

The research questions were as follows:

1. What was the signal return profile between the selected remote sensing radio frequency radar and tilled soil.

2. What was the signal return profile between the selected remote sensing radio frequency radar and grass?

3. What was the signal return profile between the selected remote sensing radio frequency radar and concrete?

Based on the analysis of data, Pulse Doppler effect speed sensors yielded lower RCS--8dB--at speeds of approximately 8 mph but degraded in performance as measured by--8dB to 10dB--over tilled soil, grass, and concrete at speeds of 4 mph and 16 mph, respectively. The degradation of the RCS via Doppler speed sensor signal control was particularly evident when the smooth incident surface was concrete.

Additionally, the findings suggest, the dynamic range and reflected signal loss (i.e., radiated reflected power or RCS), with multiple surface topographies (i.e., tilled soil, grasses, and concrete), displayed a varied spectral noise from 5dB to 15dB.

The spectral noise--8dB--at 8 mph over tilled surface was well within the FCC guidelines, and suggested rough textured surfaces are well suited for Radio Frequency Sensors as a means to monitor vehicle speeds.

Conclusions of Relative Error Measurement

It was noted in the testing, the pulse Doppler systems had difficulty measuring velocity over the concrete surface (i.e., smooth surfaces). "Doppler effect speed sensors are ideal for field stubble, plowed fields, gravel roads, but show a degradation in performance on concrete or blacktop roads" (Copper, 2000, p. 4).

The limiting factor as to why signal degradation occurred was due to inadequate dynamic range, caused by the selection of the DSP A/D converter. Potentially, a design update to a 12-bit A/D converter from the existing 10-bit

A/D unit could improve the performance of the system as measured the radio frequency pulse Doppler system.

It was noted in the testing that there was a bias between the hand-timed runs and the wheel speed sensor. It is likely that there was wheel slip present. Hand timing would introduce a potential error of 0.1-0.6%, but the wheel speed deviations were on the order of 2-3%. There is some scatter in the bias data due to the use of the hand-timed data. The use of automated timing equipment with photoelectric triggering would increase the precision of the measurement of elapsed time.

Conclusions on Observations

Several unique observations can be made from this data:

1. The radio frequency sensor and digital signal processing (DSP) system performed well over tilled soil at 8 mph. There was degradation of RCS at velocities of 4 and 16 mph over all three surfaces. This is possibly due to a dynamic range limitation of the existing development level product and the phenomena called vehicle hop.

2. Wheel speed should not be used as a definitive basis in any of the testing due to the possibility of wheel slippage. An error analysis should be done on the data to

determine the variation in the hand timing process. It is recommended that an automatic timer interfaced into the data recording equipment be implemented for future testing.

3. The relative error of the radio frequency sensor was a function of the design of the signal processing. The units with digital signal processing may demonstrate less variation than the analog processing systems.

4. In order to give the experiment the ability to make precise speed variation measurements, it is necessary to improve speed control.

5. The radar sensors reacted in a similar fashion over tilled soil and grass at 8 mph. This may be to say that the spectral properties of these surfaces are similar at that velocity. The deviations seen may be attributable to vibration/harmonics or variations in wheel speed.

Recommendations for Future Research

It is recommended that there is a need for future research into the following areas: maintaining consistent vehicle velocity through all phases of test; radar speed versus monitored ground speed; an investigation into operator variance using the same vehicle; and the determination as to what speed is optimum between 8 mph and 16 mph.

Future research could include improved speed monitoring devices on the transmission or wheels in an attempt to eliminate wheel slippage being calculated within the field data. Wheel slippage can influence the data causing an increase or decrease in vehicle speed. Vehicle speed error could promote the operator to increase or decrease the application of media (i.e., seeding, herbicide, or pesticide) at too low or too high concentrations. Therefore, it adds cost per acre or damage to crop or field.

Further research is warranted due to possible variance between operators (i.e., vehicle drivers) when using the same vehicle in conducting the test runs. The operator variance could be the result of experience versus lack of experience in operating the same vehicle. Experience in acceleration, maintaining a straight and steady vector, and experience in shifting the transmission from gear to gear and over various terrains affect the outcome of speed and media application.

Additional research is suggested in the area of establishing the optimum speed between 8 mph and 16 mph. The previous research was limited to specific speeds of 4, 8, and 16 mph, respectively. The research did not allow the researcher to explore whether or not the vehicle peak efficiency is attained at 9 or 10 or 11 mph. The field results indicate that 8 mph is close to ideal for tilled soil; there possibly could be an improvement above 8, but below 16 mph.

It is recommended that further research is necessary to determine if there is an optimum speed for planting and harvesting between 8 mph and 16 mph, respectively.

Upon closer examination, there is a possibility that external forces did affect the test runs over tilled soil at 4 mph. The RCS deviations detected at 4 mph can be attributed to vehicle vibration and operator variance (i.e., acceleration and/or deceleration by operator) or this could be where the vehicle and radar do not operate at the optimum balance and frequency.

Finally, it is recommended that this research study be replicated either incorporating the suggestions listed above or possible new technology that may be developed in the future.

Summary of the Study

This research presented results from field tests using an amplitude modulated continuous wave (AMCW) radio frequency sensor as a means to monitor the radar cross section (RCS) of three distinct surface topographies of freshly tilled soil, grasses, and concrete. Radio frequency (RF) sensors were tested at speeds of 4, 8, and 16 mph over the three surface topographies.

It was found the optimum frequency of the RF sensor to be 24.125GHz. The radar cross sections produced over the three surface topographies, using the RF sensor was within the FCC guidelines for radiating return spectral power.

Additionally, it was found that 8 mph was the optimum speed over tilled soil--arguably the most common of the three surfaces--where the vehicle harmonics were in equilibrium at the optimal speed. Whereas, concrete displayed a high angle of incidence causing the emitting signal to deflect away from the source and increase its radar cross section (RCS). The high angle of incidence thereby increased the radar cross section or spectral noise of cement beyond that of the other two surfaces at 8 mph.

Grass, with its multifaceted surface displayed a radar cross section in close proximity to that of freshly tilled soil. The spectral noise as a function of speed over grass, at all three speeds, displayed similar characteristics as tilled soil. The characteristic of lower RCS at 8 mph--8.35dB for grass, as compared to 8.0dB for tilled soil--warrants further study at speeds between 8 and 16 mph, respectively. Possibly, the increased speeds above 8 mph but below 16 mph will result in an improvement to future radio frequency radar sensors for monitoring vehicle speed.

In conclusion, the basis of any research study is to identify a problem, collect data, report on the data, analyze data, and draw conclusions (Clover & Balsley, 1984). Additionally, it is known that no research can be truly conclusive without constant revision and scrutiny. Although this study has been brought to closure within the boundaries of this chapter, this author will continue to conduct research in regard to radar frequency technologies.

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APPENDICES

APPENDIX A

FCC Title 47 Telecommunications Act

TITLE 47--TELECOMMUNICATION

CHAPTER I--FEDERAL COMMUNICATIONS COMMISSION

PART 15--RADIO FREQUENCY DEVICES--Table of Contents

Subpart A--General

Sec. 15.33 Frequency range of radiated measurements.

(a) For an intentional radiator, the spectrum shall be investigated from the lowest radio frequency signal generated in the device, without going below 9 kHz, up to at least the frequency shown in this paragraph:

(1) If the intentional radiator operates below 10 GHz: to the tenth harmonic of the highest fundamental frequency or to 40 GHz, whichever is lower.

(2) If the intentional radiator operates at or above 10 GHz and below 30 GHz: to the fifth harmonic of the highest fundamental frequency or to 100 GHz, whichever is lower.

(3) If the intentional radiator operates at or above 30 GHz: to the fifth harmonic of the highest fundamental frequency or to 200 GHz, whichever is lower, unless specified otherwise elsewhere in the rules.

(4) If the intentional radiator contains a digital device, regardless of whether this digital device controls the functions of the intentional radiator or the digital device is used for additional control or function purposes other than to enable the operation of the intentional radiator, the frequency range shall be investigated up to the range specified in paragraphs (a)(1) through (a)(3) of this section or the range applicable to the digital device, as shown in paragraph(b)(1) of this section, whichever is the higher frequency range of investigation.

(b) For unintentional radiators:

(1) Except as otherwise indicated in paragraphs (b)(2) or (b)(3) of this section, for an unintentional radiator, including a digital device, the spectrum shall be investigated from the lowest radio frequency signal generated or used in the device, without going below the lowest frequency for which a radiated emission limit is specified, up to the frequency shown in the following table:

Highest frequency generated or used in the device or on which the device operates or tunes (MHz)	Upper frequency of measurement range (MHz)
Below 1.705	30.
1.705-108	1000.
108-500	2000.
500-1000	5000.
Above 1000	5th harmonic of the highest frequency or 40 GHz,whichever is lower.

(2) A unintentional radiator, excluding a digital device, in which the highest frequency generated in the device, the highest frequency used in the device and the highest frequency on which the device operates or tunes are less than 30 MHz and which, in accordance with Sec. 15.109, is required to comply with standards on the level of radiated emissions within the frequency range 9 kHz to 30 MHz, such as a CB receiver or a device designed to conduct its radio frequency emissions via connecting wires or cables, e.g., a carrier current system not intended to radiate, shall be investigated from the lowest radio frequency generated or used in the device, without going below 9 kHz (25 MHz for CB receivers), up to the frequency shown in the following table. If the unintentional radiator contains a digital device, the upper frequency to be investigated shall be that shown in the table below or in the table in paragraph (b)(1) of this section, as based on both the highest frequency generated and the highest frequency used in the digital device, whichever range is higher.

Upper frequency Highest frequency generated or used in the device or on of which the device operates or tunes (MHz) measurement range (MHz)

Below 1.705	30
1.705-10	400
10-30	500

(3) Except for a CB receiver, a receiver employing superheterodyne techniques shall be investigated from 30 MHz up to at least the second harmonic of the highest local oscillator frequency generated in the device. If such receiver is controlled by a digital device, the frequency range shall be investigated up to the higher of the second harmonic of the highest local oscillator frequency generated in the device or the upper frequency of the measurement range specified for the digital device in paragraph (b)(1) of this section.

(c) The above specified frequency ranges of measurements apply to the measurement of radiated emissions and, in the case of receivers, the measurement to demonstrate compliance with the antenna conduction limits specified in Sec. 15.111. The frequency range of measurements for AC power line conducted limits is specified in Secs. 15.107 and 15.207 and applies to all equipment subject to those regulations. In some cases, depending on the frequency(ies) generated and used by the equipment, only signals conducted onto the AC power lines are required to be measured.

(d) Particular attention should be paid to harmonics and subharmonics of the fundamental frequency as well as to those frequencies removed from the fundamental by multiples of the oscillator frequency. Radiation at the frequencies of multiplier states should also be checked.

[54 FR 17714, Apr. 25, 1989, as amended at 61 FR 14502, Apr. 2, 1996; 63
FR 42278, Aug. 7, 1998]

APPENDIX B

Testing Methods and Procedures

The basic radar signal is used with precision farming equipment to gauge the application of chemical/seed over a long distance of field row. This means that the signal pulses from the radar are integrated (counted and averaged) over long periods of time. Long sampling periods are required when trying to evaluate if the vehicle is going 4.12 mph or 4.13 mph.

The only signal available to evaluate was the output signal at 57.42 Hz per mile per hour. It is very difficult to measure such small changes in speed when using short sample periods. The output signal is constant for a given distance, a pulse every 8 millimeter or 128.74 pulse per meter traveled. The signal is independent from velocity due to the pulses. When counting and averaging pulses (this is the function of the charge coupled device--CCD--bus interface), the number of significant figures the CCD bus uses in the calculation are too few when it samples for 0.25 seconds.

As a comparison to the CCD bus, the wheel speed sensor measures about 5000 pulses per revolution at about 20 linear feet of distance per wheel revolutions. It is calibrated by rotating the wheel 10 revolutions over several hundred feet. This is the way to get 4 significant figures for the calibration factor. The wheel speed sensor gives approximately a sensor pulse every 1.3 millimeters, or 6 times finer resolution than the ground speed radar.

The wheel speed signal can achieve a finer resolution than the radar signal. Even with the wheel speed sensor, pulses must be counted over a long period of time to determine the difference between 4.12 mph and 4.13 mph.

If the sensor output is used to measure a short-term event like momentary wheel slip or instantaneous speed, it is highly unlikely that one will get a speed determination that is better than one decimal in significant figure. This is due to the resolution of the CCD bus sampling and the method in which the sensor output pulses are counted. When calculated the sensor sends out one pulse every 8 mm of vehicle travel. This constant is independent of vehicle speed.

Data Acquisition Unit Installation

The data acquisition unit was installed with the following list of minimum sensors required: System voltage, Wheel speed, Wheel pulse count, Radar Speed, Radar pulse count, Timing marker input. Minimum sample rate on the speed data was 5 KHz, the pulse count channels should be at 40 KHz. The data files should be checked after download to verify that data is captured properly. A hand log of the data files should also be kept to correlate the data.

Radar unit installation

The Device Under Test (DUT) should be installed on the test vehicle per the manufacturer's recommendacions. The installation height and angle of installation should be documented. The DUT power, ground and signal wires should be routed.

Auxiliary timing device

There are several methods to verify the ground speed over the test course. The least accurate test method is to use a hand stop-watch. This can place a timing error of 0.3-0.8 seconds in the run. The hand stop-watch method can be attenuated by using a very long test track. The second method is to use a beam-breaking timer with the data either independently recorded or transmitted to the data acquisition unit in the test vehicle.

Logging the data into the data acquisition system is preferable. The third method involves tracking the timing actively during the entire run. Using a video device, laser radar device, or special slow speed radar (i.e., radar speed gun). The radar gun device must be interfaced into the data acquisition system. It is known that unless special care is taken in selecting the device, many radar guns do not work below 10-20 mph.

Test Method--Wheel Speed Calibration

1. Set vehicle tire pressures at the recommended setting. Vehicle should be ballasted or loaded only per the manufacturer's recommendations.

2. Measure a set distance approximately equal to 10 tire circumferences. Use a concrete or asphalt test site.

3. Place a mark on the tire sidewall that extends down to the tread.

4. Connect in data acquisition to count wheel speed sensor pulse.

5. Align the mark on the tire with the start of the known test distance.

6. Turn on data acquisition equipment and start vehicle. Drive the vehicle at a slow rate of speed so the wheel revolutions can be counted by an outside observer.

7. When the wheel hits the end marker of the calibration track, stop the data acquisition equipment. Do not allow the vehicle to roll backwards.

8. Count the number of pulses and calculate the pulses/wheel revolution.

9. Repeat the test three times and average the result.

Radar Speed Tests

1. Determine the necessary acceleration distance required to accelerate the vehicle to the desired steady state speed. Park the vehicle at that spot in front of the test track.

2. Turn on tractor and make sure system voltage is functioning within vehicle specification.

3. Initialize data acquisition equipment. Do not take data at this time.

4. Turn on Radar and timing equipment.

5. Activate data acquisition equipment, verify that it is recording.

6. Select and record gear information and engine rpm.

7. Declutch tractor and accelerate tractor to speed. Verify that target speed is matched prior to reaching the start marker of the test course.

8. Verify that timing equipment activated when tractor crossed the start marker. If it did not, abort run.

9. Observe speed readouts during run.

10. As the tractor nears the end of the test track, verify that the timing system has triggered at the end marker.

11. Slowly stop the tractor.

12. Stop the data acquisition system.

13. Store the acquired data, log the file name in a notebook.

14. Repeat steps 20 times for each vehicle speed (4 mph, 8 mph, and 16 mph) and surface topography (tilled soil, grass, and concrete).

Calculations

The following list of data is calculated for each run.

Elapsed time--from timing equipment;

Mean Radar Speed;

Mean Wheel speed;

Radar Speed Standard Deviation;

Wheel speed standard deviation;

Radar output pulse counts;

Wheel speed % relative error;

Radar % relative error;

Total wheel pulse counts;

Wheel speed bias vs. timing equipment speed;

Radar speed bias vs. timing equipment speed.

Most of this data can be extracted from the data acquisition system software, or the data can be imported into Microsoft Excel for calculation in a spreadsheet format.

To calculate the mean speed:

Elapsed timing equipment = Distance of test track/(elapsed time to cover the distance).

Wheel speed mean = Average of all wheel speed readings taken during the test run.

Radar speed mean = Average of all radar speed reading taken during the test run.

To calculate speed bias:

Wheel speed bias determines if wheel slip is present = (average wheel speed)/(elapsed time calculated speed). Radar speed bias = (average radar speed)/(elapsed time calculated speed).

Relative error = $2*\sigma$/(average value). Multiply by 100 to get % relative error.

The data run is considered valid only if the following conditions are met:

No wheel speed deviations > 10% due to bumps or wheel slip.

Engine rpm deviations more than 40 rpm.

No radar signal fallouts.

Vehicle did not tilt more than 2 degrees longitudinally during run.

The calculated values should be averaged over the triplicate runs and reported.

Precision Calculation

The wheel speed sensor may or may not determine the correct distance. It is useful to calculate the theoretical distance to determine if wheel slip is in the measurement system.

Distance traveled by wheel = number of wheel pulses/[wheel pulse/rev] * Distance for 10 wheel revs/10

If this number is more than 1% different from the surveyed test course, there was wheel slip.

Radar Unit Precision

Calculate the theoretical number of pulse over the length of the test track, and compare to the number actually measured. Radar calibration factor is generally considered to be 57.42 Hz/mph for 24.125 GHz ground speed radar. If the manufacture recommends another factor, use that in the calculation.

Pulse counts over the test distance =

$$\frac{\text{57.42 Hz } * \text{ Average MPH of radar } * \text{ Elapsed Time of Run}}{\text{MPH}}$$

The pulse count error would then be: *% error of pulse counts = Actual pulse counts/Theoretical pulse counts.

APPENDIX C

SOMAT Data Acquisition System

SOMAT data modes are the basic building blocks of SoMat test control software. They determine how the data will be recorded and stored. Effectively using DataModes helps you reduce the time, effort and expense of your data analysis. You can specify how incoming data is analyzed, reduced, and stored. DataModes allow the Field Computer System to retain the important content of the data while optimizing the use of memory and computational resources. Multiple DataModes can run concurrently. The different types of DataModes are as follows:

Time History--This is the fundamental DataMode. It sequentially stores data for specified input channels at a fixed sampling rate. It is analogous to collecting data on a tape recorder.

Sequential Peak/Valley History--Peak/Valley History is a reduced data version of Time History where only the peaks and valleys are recorded. You specify the hysteresis value which determines the points that are stored as reversal points. This DataMode is typically used for recording maximum and minimum values over time.

Time History--This is the fundamental DataMode. It sequentially stores data for specified input channels at a fixed sampling rate. It is analogous to collecting data on a tape recorder.

Sequential Peak/Valley History--Peak/Valley History is a reduced data version of Time History where only the peaks and valleys are recorded. You specify the hysteresis value which determines the points that are stored as reversal points. This DataMode is typically used for recording maximum and minimum values over time.

Burst Time History--This allows your field computer to act like a transient data recorder. It stores data before and after the triggering condition is met. You control the number of bursts, total time and pre-trigger time of each single or multichannel burst.

Time at Level Matrix--A Time at Level Matrix records the amount of time spent at discrete values of one or more input channels. This results in a matrix having as many dimensions as input channels. Up to six dimensions are supported. For example, a matrix containing the amount of time spent at unique combinations of torque, engine RPM and gear shift position is useful in determining customer usage profiles for a transmission. Standard single dimensional Time at Level Matrices are also supported.

Peak/Valley & Rainflow Matrices--Peak/Valley matrices are used to categorize load histories statistically. Rainflow matrices categorized load histories according to the amount of fatigue damage they can cause. Each counts the number of transitions between discrete peak-valley pairs of an input history. They are functionally identical except that the methods for pairing peaks and valleys differ.

Output DataMode--This DataMode is used to control the Status Indicator Module in the 2100.

Real-time Display--Channels listed in this DataMode can be viewed in real-time during data collection for the 2100.

Stop Criteria--This DataMode can be used to stop and start a 2100 test when a specified condition is met.

APPENDIX D

Soil Identification of Black Hawk County, The State of Iowa

Iowa Soil Properties and Interpretations Database (ISPAID)

Soil Map Symbol (SMS)

The symbol as used on the soil map sheets.

2 Soil Map Unit [SMU]

The Soil Map Unit (SMU) symbol identifies the soil type, the slope class, and the erosion phase. A statewide legend has been developed to include all SMUs that have been correlated in modern county soil surveys (Fig. 1). Soil maps that are coded with alphabetic symbols for the soil type identification require conversion to the numeric symbols for use of the database.

The statewide legend for soil type identification is developed according to the following numbering system. (NOTE: 7000, 8000, and 9000 numbers are not used as a publication symbol. These numbers were assigned to their respective publication symbol, the sms, to help account for yield differences in soils mapped statewide.)

Slope: The standard slope classes are as listed. A few exceptions occur. For example,
for some depressional units the "A" is 0-1%, and for some "B" slopes units are 1-4%.
A = 0-2% = Level and nearly level
B = 2-5% = Gently sloping
C = 5-9% = Moderately sloping
D = 9-14% = Strongly sloping
E = 14-18% = Moderately steep (western Iowa = 14-20%)
F = 18-25% = Steep (western Iowa = 20-30%)
G = 25-40% = Very steep

Interpretations assigned to complexes are either the complete range of all soils identified in the name or are the most limiting value. Please refer to each field definition. Interpretations assigned to complexes which have a nonsoil component (i.e., gullied land, rock outcrop, etc.) are values only of the named soil.

LEAG Farmland Units [LEAGFMLND], Representative of Black Hawk County, Iowa

LEAG farmland units are a refinement of the USDA prime farmland units. The LEAG definition of prime farmland is based on land capability classes and native productivity. The LEAG farmland units are:

P1 = Most SMUs listed in capability classes 1 and 2 but does not include those soils that have profile features that limit rooting depth and water-holding capacity. All are on slopes of 0-5%.

P2 = Those SMUs with profile features that limit rooting depth or water-holding capacity and have slopes of 0-5%.

P3 = Highly productive soils on slopes of 5-9% that can be major sediment producers if they are intensively used for row crop production without conservation practices.
Includes prairie-derived soils that are in erosion classes slight and moderate and transitional and forest-derived soils that are in erosion class slight.

P4 = Those SMUs protected from flooding or that do not flood more than once in 2 years during the growing season.

S1 = SMUs that generally are sloping (5-9%), that are severely eroded prairie soils, or are moderately or severely eroded transition and forested units. Includes some less productive soils on slopes less than 5-9%.

S2 = SMUs with desirable profile characteristics but occur on slopes 9-14%. Erosion classes 1 and 2 are included. Includes some less productive soils on slopes less than 9-14%.

S3 = All other units that have more desirable properties than land of local importance.

O = SMUs of local importance.

U = Organic soils and some sandy soils that are suited for vegetable crops under high-level management resulting in high yields.

APPENDIX E

Raw Field Data of Test Runs, Nominal Velocity, RCS, Calculated Radar Speed, Means, and Standard Deviations

600 feet of tilled soil, at 4 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	Surface Type	Distance Traveled (~feet)	Raw Field Data-Tilled Soil True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	RCS - Radiated Reflected Power (dB)	Radar Speed (~mph)	Radar Bias = True Wheel Speed / Radar Speed
1	Tilled Soil	600	4.223	AMCW	10	4.223	1.025811035
2	Tilled Soil	600	4.21	AMCW	9	4.21	1.002850356
3	Tilled Soil	600	4.201	AMCW	10	4.201	1.034039514
4	Tilled Soil	600	4.203	AMCW	12	4.203	1.159409945
5	Tilled Soil	600	4.211	AMCW	12	4.211	1.158157207
6	Tilled Soil	600	4.168	AMCW	10	4.168	1.055422265
7	Tilled Soil	600	4.177	AMCW	12	4.177	1.143643763
8	Tilled Soil	600	4.183	AMCW	10	4.183	1.035620368
9	Tilled Soil	600	4.181	AMCW	9	4.181	1.009567089
10	Tilled Soil	600	4.172	AMCW	9	4.172	1.011505273
11	Tilled Soil	600	4.164	AMCW	8	4.164	0.989193084
12	Tilled Soil	600	4.165	AMCW	9	4.165	1.013445378
13	Tilled Soil	600	4.308	AMCW	8	4.308	0.956128134
14	Tilled Soil	600	4.316	AMCW	9	4.316	0.977988879
15	Tilled Soil	600	4.299	AMCW	9	4.299	0.981856246
16	Tilled Soil	600	4.31	AMCW	9	4.31	0.979582367
17	Tilled Soil	600	4.239	AMCW	9	4.239	0.996225525
18	Tilled Soil	600	4.234	AMCW	8	4.234	0.97118564
19	Tilled Soil	600	4.221	AMCW	10	4.221	1.000947643
20	Tilled Soil	600	4.199	AMCW	9	4.199	1.005477495
Standard Deviation			0.050		1.234	0.050	0.060209418
Average Speed			4.219		9.55		1.02540286

600 feet of tilled soil, at 4 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	Surface Type	Distance Traveled (~feet)	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	RCS - Radiating Output Power (dB)	Radar Speed (~mph)	Radar Bias = True Wheel Speed / Radar Speed
1	Tilled Soil	600	8.81	AMCW	9	8.81	1
2	Tilled Soil	600	8.99	AMCW	10	9.01	1.002224694
3	Tilled Soil	600	8.005	AMCW	10	8.009	1.100562149
4	Tilled Soil	600	8.848	AMCW	11	7.858	0.888110307
5	Tilled Soil	600	8.882	AMCW	11	7.082	0.797342941
6	Tilled Soil	600	8.91	AMCW	11	8.919	1.001010101
7	Tilled Soil	600	8.911	AMCW	10	8.911	1
8	Tilled Soil	600	8.906	AMCW	10	8.01	0.899393667
9	Tilled Soil	600	7.926	AMCW	10	8.026	1.012616705
10	Tilled Soil	600	7.838	AMCW	10	8.01	1.021944374
11	Tilled Soil	600	7.875	AMCW	10	8.075	1.025396825
12	Tilled Soil	600	7.894	AMCW	10	7.991	1.012287814
13	Tilled Soil	600	8.106	AMCW	10	8.106	1
14	Tilled Soil	600	8.171	AMCW	11	8.171	1
15	Tilled Soil	600	8.155	AMCW	11	8.201	1.005640711
16	Tilled Soil	600	8.005	AMCW	11	8.101	1.011992505
17	Tilled Soil	600	8.016	AMCW	11	8.1	1.010479042
18	Tilled Soil	600	8.006	AMCW	11	8.006	1
19	Tilled Soil	600	8.099	AMCW	11	8.1	1.000123472
20	Tilled Soil	600	8.169	AMCW	10	8.21	1.005018974
Standard Deviation			0.438		0.598	0.440	0.062178896
Average Speed			8.326			8.185	0.989707214

600 feet of tilled soil, at 4 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	Surface Type	Distance Traveled (~feet)	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	Radiating Output Power (dB)	Radar Speed (~mph)	Radar Bias = True Wheel Speed / Radar Speed
1	Tilled Soil	600	16.355	AMCW	8	15.906	0.972546622
2	Tilled Soil	600	16.38	AMCW	10	15.908	0.971184371
3	Tilled Soil	600	16.331	AMCW	10	15.92	0.974833139
4	Tilled Soil	600	16.479	AMCW	9	16.068	0.975059166
5	Tilled Soil	600	16.529	AMCW	9	16.061	0.971686127
6	Tilled Soil	600	16.36	AMCW	9	16.077	0.982701711
7	Tilled Soil	600	16.196	AMCW	10	16.299	1.006359595
8	Tilled Soil	600	16.161	AMCW	10	16.288	1.007858425
9	Tilled Soil	600	16.163	AMCW	10	16.294	1.008104931
10	Tilled Soil	600	16.356	AMCW	10	16.298	0.996453901
11	Tilled Soil	600	16.344	AMCW	9	16.278	0.995961821
12	Tilled Soil	600	16.351	AMCW	9	16.29	0.996269341
13	Tilled Soil	600	16.972	AMCW	10	16.455	0.969538063
14	Tilled Soil	600	16.935	AMCW	10	16.457	0.971774432
15	Tilled Soil	600	16.975	AMCW	10	16.449	0.969013255
16	Tilled Soil	600	16.35	AMCW	10	16.351	1.000061162
17	Tilled Soil	600	16.339	AMCW	10	16.358	1.001162862
18	Tilled Soil	600	16.201	AMCW	10	16.115	0.994691686
19	Tilled Soil	600	16.186	AMCW	10	16.143	0.997343383
20	Tilled Soil	600	16.219	AMCW	9	16.201	0.998890191
Standard Deviation			0.257		0.598	0.177	0.014562754
Average Speed			16.409			16.210	0.988074709

600 feet of tilled soil, at 4 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	Surface Type	Distance Traveled (~feet)	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	RCS - Radiated Reflected Power (dB)
1	Tilled Soil	600	4.223	AMCW	10
2	Tilled Soil	600	4.21	AMCW	9
3	Tilled Soil	600	4.201	AMCW	10
4	Tilled Soil	600	4.203	AMCW	12
5	Tilled Soil	600	4.211	AMCW	12
6	Tilled Soil	600	4.168	AMCW	10
7	Tilled Soil	600	4.177	AMCW	12
8	Tilled Soil	600	4.183	AMCW	10
9	Tilled Soil	600	4.181	AMCW	9
10	Tilled Soil	600	4.172	AMCW	9
11	Tilled Soil	600	4.164	AMCW	8
12	Tilled Soil	600	4.165	AMCW	9
13	Tilled Soil	600	4.308	AMCW	8
14	Tilled Soil	600	4.316	AMCW	9
15	Tilled Soil	600	4.299	AMCW	9
16	Tilled Soil	600	4.31	AMCW	9
17	Tilled Soil	600	4.239	AMCW	9
18	Tilled Soil	600	4.234	AMCW	8
19	Tilled Soil	600	4.221	AMCW	10
20	Tilled Soil	600	4.199	AMCW	9
Standard Deviation			0.050		1.234
Mean dB					9.55

600 feet of tilled soil, at 8 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	Surface Type	Distance Traveled (~feet)	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	RCS - Radiated Reflected Power (dB)
1	Tilled Soil	600	8.81	AMCW	10
2	Tilled Soil	600	8.99	AMCW	10
3	Tilled Soil	600	8.005	AMCW	8
4	Tilled Soil	600	8.848	AMCW	8
5	Tilled Soil	600	8.882	AMCW	8
6	Tilled Soil	600	8.91	AMCW	10
7	Tilled Soil	600	8.911	AMCW	10
8	Tilled Soil	600	8.906	AMCW	11
9	Tilled Soil	600	7.926	AMCW	8
10	Tilled Soil	600	7.838	AMCW	8
11	Tilled Soil	600	7.875	AMCW	8
12	Tilled Soil	600	7.894	AMCW	8
13	Tilled Soil	600	8.106	AMCW	8
14	Tilled Soil	600	8.171	AMCW	9
15	Tilled Soil	600	8.155	AMCW	9
16	Tilled Soil	600	8.005	AMCW	8
17	Tilled Soil	600	8.016	AMCW	8
18	Tilled Soil	600	8.006	AMCW	8
19	Tilled Soil	600	8.099	AMCW	8
20	Tilled Soil	600	8.169	AMCW	9
Standard Deviation			0.438		0.97
Mean dB					8.0
Variance Entire Population			0.182		0.91

600 feet of tilled soil, at 16 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	Surface Type	Distance Traveled (~feet)	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	RCS - Radiated Reflected Power (dB)
1	Tilled Soil	600	16.355	AMCW	8
2	Tilled Soil	600	16.38	AMCW	8
3	Tilled Soil	600	16.331	AMCW	8
4	Tilled Soil	600	16.479	AMCW	8
5	Tilled Soil	600	16.529	AMCW	8
6	Tilled Soil	600	16.36	AMCW	8
7	Tilled Soil	600	16.196	AMCW	9
8	Tilled Soil	600	16.161	AMCW	9
9	Tilled Soil	600	16.163	AMCW	9
10	Tilled Soil	600	16.356	AMCW	9
11	Tilled Soil	600	16.344	AMCW	9
12	Tilled Soil	600	16.351	AMCW	9
13	Tilled Soil	600	16.972	AMCW	9
14	Tilled Soil	600	16.935	AMCW	9
15	Tilled Soil	600	16.975	AMCW	9
16	Tilled Soil	600	16.35	AMCW	9
17	Tilled Soil	600	16.339	AMCW	9
18	Tilled Soil	600	16.201	AMCW	8
19	Tilled Soil	600	16.186	AMCW	8
20	Tilled Soil	600	16.219	AMCW	9
Standard Deviation			0.257		0.502
Mean dB					8.6
Variance Entire Population			0.063		0.24

600 feet over grass, at 4 mph, using a 24GHz K band radar, with RCS of 12 dB

			Raw Field Data				
Run #	Surface Type	Distance Traveled (~feet)	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	Radiating Output Power (dB)	Radar Speed (~mph)	Radar Bias = True Wheel Speed / Radar Speed
1	Grass	600	4.173	AMCW	9	4.167	0.998562185
2	Grass	600	4.204	AMCW	9	4.173	0.99262607
3	Grass	600	4.187	AMCW	9	4.169	0.995700979
4	Grass	600	4.188	AMCW	9	4.17	0.995702006
5	Grass	600	4.111	AMCW	9	4.168	1.01386524
6	Grass	600	4.11	AMCW	9	4.169	1.014355231
7	Grass	600	4.112	AMCW	9	4.167	1.013375486
8	Grass	600	4.111	AMCW	9	4.168	1.01386524
9	Grass	600	4.185	AMCW	10	4.347	1.038709677
10	Grass	600	4.192	AMCW	10	4.355	1.038883588
11	Grass	600	4.174	AMCW	10	4.352	1.042644945
12	Grass	600	4.184	AMCW	10	4.352	1.040152964
13	Grass	600	4.127	AMCW	10	4.235	1.02616913
14	Grass	600	4.125	AMCW	10	4.235	1.026666667
15	Grass	600	4.124	AMCW	10	4.23	1.025703201
16	Grass	600	4.125	AMCW	10	4.233	1.026181818
17	Grass	600	4.173	AMCW	10	4.212	1.009345794
18	Grass	600	4.133	AMCW	9	4.196	1.015243165
19	Grass	600	4.132	AMCW	9	4.211	1.019119071
20	Grass	600	4.144	AMCW	9	4.206	1.01496139
Standard Deviation			0.032		0.510	0.069	0.015233372
Average Speed			4.150			4.225	1.018091692

600 feet over grass, at 4 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	Surface Type	Distance Traveled (~feet)	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	Radiating Output Power (dB)	Radar Speed (~mph)	Radar Bias = True Wheel Speed / Radar Speed
1	Grass	600	7.956	AMCW	8	7.922	0.995726496
2	Grass	600	7.965	AMCW	8	7.925	0.994978029
3	Grass	600	7.977	AMCW	8	7.926	0.993606619
4	Grass	600	7.966	AMCW	8	7.924	0.994727592
5	Grass	600	7.787	AMCW	8	7.974	1.024014383
6	Grass	600	7.794	AMCW	8	7.966	1.022068258
7	Grass	600	7.791	AMCW	8	7.97	1.022975228
8	Grass	600	7.791	AMCW	8	7.973	1.023360288
9	Grass	600	8.02	AMCW	8	7.97	0.993765586
10	Grass	600	7.998	AMCW	8	7.966	0.995999
11	Grass	600	8.015	AMCW	8	7.948	0.991640674
12	Grass	600	7.856	AMCW	8	7.96	1.013238289
13	Grass	600	7.859	AMCW	8	7.958	1.012597023
14	Grass	600	7.861	AMCW	9	8.017	1.019844803
15	Grass	600	7.858	AMCW	9	8.017	1.020234156
16	Grass	600	7.859	AMCW	9	8.025	1.02112228
17	Grass	600	7.991	AMCW	9	8.004	1.00162683
18	Grass	600	7.899	AMCW	9	8.015	1.014685403
19	Grass	600	7.99	AMCW	9	8.275	1.035669587
20	Grass	600	7.977	AMCW	9	8.275	1.037357403
Standard Deviation			0.083		0.489	0.099	0.014896485
Average Speed			7.910			8.000	1.011461896

600 feet over grass, at 4 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	Surface Type	Distance Traveled (~feet)	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	Radiating Output Power (dB)	Radar Speed (~mph)	Radar Bias = True Wheel Speed / Radar Speed
1	Grass	600	16.577	AMCW	9	16.495	0.995
2	Grass	600	16.474	AMCW	9	16.499	1.002
3	Grass	600	16.68	AMCW	9	16.478	0.988
4	Grass	600	16.577	AMCW	9	16.491	0.995
5	Grass	600	16.144	AMCW	10	16.634	1.030
6	Grass	600	16.153	AMCW	10	16.648	1.031
7	Grass	600	16.143	AMCW	10	16.631	1.030
8	Grass	600	16.147	AMCW	10	16.638	1.030
9	Grass	600	16.324	AMCW	10	16.892	1.035
10	Grass	600	16.326	AMCW	10	16.852	1.032
11	Grass	600	16.324	AMCW	10	16.874	1.034
12	Grass	600	16.325	AMCW	10	16.873	1.034
13	Grass	600	16.696	AMCW	9	16.493	0.988
14	Grass	600	16.681	AMCW	10	16.544	0.992
15	Grass	600	16.716	AMCW	10	16.517	0.988
16	Grass	600	16.698	AMCW	10	16.518	0.989
17	Grass	600	16.694	AMCW	10	16.694	1.000
18	Grass	600	16.68	AMCW	10	16.68	1.000
19	Grass	600	16.693	AMCW	10	16.693	1.000
20	Grass	600	16.689	AMCW	10	16.689	1.000
Standard Deviation			0.225		0.444	0.140	0.019
Average Speed			16.487			16.64	1.018

600 feet over grass, at 4 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	RCS - Radiated Reflected Power (dB)
1	4.173	AMCW	9
2	4.204	AMCW	9
3	4.187	AMCW	9
4	4.188	AMCW	9
5	4.111	AMCW	9
6	4.11	AMCW	9
7	4.112	AMCW	9
8	4.111	AMCW	9
9	4.185	AMCW	10
10	4.192	AMCW	10
11	4.174	AMCW	10
12	4.184	AMCW	10
13	4.127	AMCW	10
14	4.125	AMCW	10
15	4.124	AMCW	10
16	4.125	AMCW	10
17	4.173	AMCW	10
18	4.133	AMCW	9
19	4.132	AMCW	9
20	4.144	AMCW	9
Standard Deviation	0.032		0.510
Mean dB			9.45
Variance Entire Population	0.001		0.247

600 feet over grass, at 8 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	RCS - Radiated Reflected Power (dB)
1	7.956	AMCW	8
2	7.965	AMCW	8
3	7.977	AMCW	8
4	7.966	AMCW	8
5	7.787	AMCW	8
6	7.794	AMCW	8
7	7.791	AMCW	8
8	7.791	AMCW	8
9	8.02	AMCW	8
10	7.998	AMCW	8
11	8.015	AMCW	8
12	7.856	AMCW	8
13	7.859	AMCW	8
14	7.861	AMCW	9
15	7.858	AMCW	9
16	7.859	AMCW	9
17	7.991	AMCW	9
18	7.899	AMCW	9
19	7.99	AMCW	9
20	7.977	AMCW	9
Standard Deviation	0.083		0.489
Mean dB			8.35
Variance Entire Population	0.006		0.227

600 feet over grass, at 16 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	RCS - Radiated Reflected Power (dB)
1	16.577	AMCW	9
2	16.474	AMCW	9
3	16.68	AMCW	9
4	16.577	AMCW	9
5	16.144	AMCW	10
6	16.153	AMCW	10
7	16.143	AMCW	10
8	16.147	AMCW	10
9	16.324	AMCW	10
10	16.326	AMCW	10
11	16.324	AMCW	10
12	16.325	AMCW	10
13	16.696	AMCW	9
14	16.681	AMCW	10
15	16.716	AMCW	10
16	16.698	AMCW	10
17	16.694	AMCW	10
18	16.68	AMCW	10
19	16.693	AMCW	10
20	16.689	AMCW	10
Standard Deviation	0.225		0.444
Mean dB			9.75
Variance Entire Population	0.048		0.187

600 feet over concrete, at 4 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	Surface Type	Distance Traveled (~feet)	Raw Field Data True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	Radiating Output Power (dB)	Radar Speed (~mph)	Radar Bias = True Wheel Speed / Radar Speed
1	Concrete	600	4.203	AMCW	10	4.258	1.013
2	Concrete	600	4.182	AMCW	10	4.23	1.011
3	Concrete	600	4.186	AMCW	11	4.406	1.053
4	Concrete	600	4.19	AMCW	11	4.489	1.071
5	Concrete	600	4.202	AMCW	12	4.512	1.074
6	Concrete	600	4.2	AMCW	11	4.453	0.943
7	Concrete	600	4.182	AMCW	8	4.003	1.045
8	Concrete	600	4.195	AMCW	12	4.995	0.840
9	Concrete	600	4.222	AMCW	12	4.966	0.850
10	Concrete	600	4.244	AMCW	12	4.653	0.912
11	Concrete	600	4.22	AMCW	12	4.687	0.900
12	Concrete	600	4.229	AMCW	10	4.374	0.967
13	Concrete	600	4.124	AMCW	10	4.378	0.942
14	Concrete	600	4.176	AMCW	11	4.427	0.943
15	Concrete	600	4.169	AMCW	9	4.186	0.996
16	Concrete	600	4.156	AMCW	9	4.185	0.993
17	Concrete	600	4.166	AMCW	9	4.162	1.001
18	Concrete	600	4.176	AMCW	10	4.22	0.990
19	Concrete	600	4.17	AMCW	11	4.477	0.931
20	Concrete	600	4.171	AMCW	10	4.369	0.955
Standard Deviation			0.027		1.192	0.254	0.061
Average Speed			4.188			4.421	0.971

600 feet over concrete, at 4 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	Surface Type	Distance Traveled (~feet)	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	Radiating Output Power (dB)	Radar Speed (~mph)	Radar Bias = True Wheel Speed / Radar Speed
1	Concrete	600	7.984	AMCW	9	8.223	0.971
2	Concrete	600	7.987	AMCW	10	8.981	0.889
3	Concrete	600	8.01	AMCW	10	8.979	0.892
4	Concrete	600	7.994	AMCW	11	9.973	0.802
5	Concrete	600	8.036	AMCW	11	9.981	0.805
6	Concrete	600	8.021	AMCW	11	9.982	0.804
7	Concrete	600	8.019	AMCW	10	8.978	0.893
8	Concrete	600	8.025	AMCW	10	8.893	0.902
9	Concrete	600	7.981	AMCW	10	8.984	0.888
10	Concrete	600	7.943	AMCW	10	8.878	0.895
11	Concrete	600	7.936	AMCW	10	8.985	0.883
12	Concrete	600	7.954	AMCW	10	8.999	0.884
13	Concrete	600	7.967	AMCW	10	8.982	0.887
14	Concrete	600	7.942	AMCW	11	9.001	0.882
15	Concrete	600	7.941	AMCW	11	9	0.882
16	Concrete	600	7.95	AMCW	11	8.996	0.884
17	Concrete	600	7.966	AMCW	11	8.995	0.886
18	Concrete	600	7.941	AMCW	11	8.995	0.883
19	Concrete	600	7.941	AMCW	11	8.993	0.883
20	Concrete	600	7.949	AMCW	10	8.877	0.895
Standard Deviation			0.033		0.598	0.421	0.038
Average Speed			7.974			9.083	0.879

600 feet over concrete, at 4 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	Surface Type	Distance Traveled (~feet)	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	Radiating Output Power (dB)	Radar Speed (~mph)	Radar Bias = True Wheel Speed / Radar Speed
1	Concrete	600	16.645	AMCW	8	17.92	1.077
2	Concrete	600	16.544	AMCW	10	18.02	1.089
3	Concrete	600	16.814	AMCW	10	18.877	1.123
4	Concrete	600	16.668	AMCW	9	17.481	1.049
5	Concrete	600	16.273	AMCW	9	17.224	1.058
6	Concrete	600	16.579	AMCW	9	17.216	1.038
7	Concrete	600	16.721	AMCW	10	18.207	1.089
8	Concrete	600	16.721	AMCW	10	18.118	1.084
9	Concrete	600	16.674	AMCW	10	18.113	1.086
10	Concrete	600	16.696	AMCW	10	18.118	1.085
11	Concrete	600	16.635	AMCW	9	17.796	1.070
12	Concrete	600	16.4	AMCW	9	17.791	1.085
13	Concrete	600	16.577	AMCW	10	17.778	1.072
14	Concrete	600	16.322	AMCW	10	18.235	1.117
15	Concrete	600	16.321	AMCW	10	18.23	1.117
16	Concrete	600	16.375	AMCW	10	18.228	1.113
17	Concrete	600	16.339	AMCW	10	18.126	1.109
18	Concrete	600	16.3	AMCW	10	18.127	1.112
19	Concrete	600	16.3	AMCW	10	18.127	1.112
20	Concrete	600	16.248	AMCW	9	17.874	1.097
Standard Deviation			0.185		0.598	0.376	0.023
Average Speed			16.507			17.983	1.089

600 feet over concrete, at 4 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	RCS - Radiated Reflected Power (dB)
1	4.203	AMCW	10
2	4.182	AMCW	10
3	4.186	AMCW	11
4	4.19	AMCW	11
5	4.202	AMCW	12
6	4.2	AMCW	11
7	4.182	AMCW	8
8	4.195	AMCW	12
9	4.222	AMCW	12
10	4.244	AMCW	12
11	4.22	AMCW	12
12	4.229	AMCW	10
13	4.124	AMCW	10
14	4.176	AMCW	11
15	4.169	AMCW	9
16	4.156	AMCW	9
17	4.166	AMCW	9
18	4.176	AMCW	10
19	4.17	AMCW	11
20	4.171	AMCW	10
Standard Deviation	0.027		1.192
Mean dB			10.5
Variance Entire Population	0.000		1.35

600 feet over concrete, at 8 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	**True Wheel Speed Nominal Velocity (~mph)**	**Radar Type K-band 24GHz**	**RCS - Radiated Reflected Power (dB)**
1	7.984	AMCW	9
2	7.987	AMCW	10
3	8.01	AMCW	10
4	7.994	AMCW	11
5	8.036	AMCW	11
6	8.021	AMCW	11
7	8.019	AMCW	10
8	8.025	AMCW	10
9	7.981	AMCW	10
10	7.943	AMCW	10
11	7.936	AMCW	10
12	7.954	AMCW	10
13	7.967	AMCW	10
14	7.942	AMCW	11
15	7.941	AMCW	11
16	7.95	AMCW	11
17	7.966	AMCW	11
18	7.941	AMCW	11
19	7.941	AMCW	11
20	7.949	AMCW	10
Standard Deviation	0.033		0.598
Mean dB			10.4
Variance Entire Population	0.001		0.34

600 feet over concrete, at 16 mph, using a 24GHz K band radar, with RCS of 12 dB

Run #	True Wheel Speed Nominal Velocity (~mph)	Radar Type K-band 24GHz	RCS - Radiated Reflected Power (dB)
1	16.645	AMCW	8
2	16.544	AMCW	10
3	16.814	AMCW	10
4	16.668	AMCW	9
5	16.273	AMCW	9
6	16.579	AMCW	9
7	16.721	AMCW	10
8	16.721	AMCW	10
9	16.674	AMCW	10
10	16.696	AMCW	10
11	16.635	AMCW	9
12	16.4	AMCW	9
13	16.577	AMCW	10
14	16.322	AMCW	10
15	16.321	AMCW	10
16	16.375	AMCW	10
17	16.339	AMCW	10
18	16.3	AMCW	10
19	16.3	AMCW	10
20	16.248	AMCW	9
Standard Deviation	0.185		0.598
Mean dB			9.6
Variance Entire Population	0.032		0.34

9400 & 8000 Series Tractor Testing at PEC

Date	Run #	Surface	Steady State?	Radar 24GHz	Dist.	Data Collection	Gear	Engine RPM	Notes
6/23/2001	1	Grass/Concrete Mix	Yes	AMCW 'K'	400 ft	HT, Somat	Various		test run/set up
6/23/2001	2	Grass/Concrete Mix	Yes	AMCW 'K'	400 ft	HT, Somat	Various		test run/set up
6/23/2001	3	Grass/Concrete Mix	Yes	AMCW 'K'	400 ft	HT, Somat	Various		test run/set up
6/23/2001	4	Grass/Concrete Mix	Yes	AMCW 'K'	400 ft	HT, Somat	Various		test run/set up
6/23/2001	5	Grass/Concrete Mix	Yes	AMCW 'K'	400 ft	HT, Somat	Various		test run/set up
6/23/2001	7	Concrete	Yes	AMCW 'K'	400 ft	HT, Somat	Various		test run/set up
6/23/2001	8	Concrete	Yes	AMCW 'K'	400 ft	HT, Somat	Various		test run/set up
6/23/2001	9	Concrete	Yes	AMCW 'K'	400 ft	HT, Somat	Various		test run/set up
6/23/2001	10	Concrete	Yes	AMCW 'K'	400 ft	HT, Somat	Various		test run/set up
6/23/2001	11	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	B2L	1470	test run/set up
6/23/2001	12	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	B2L	1470	test run/set up
6/23/2001	13	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	B2L	1470	test run/set up
6/23/2001	14	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	C3L	1470	Incorrect speed
6/23/2001	15	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	C3L	1800	test run/set up
6/23/2001	16	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	C3L	1800	test run/set up
6/23/2001	17	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	C3L	1800	test run/set up
6/23/2001	18	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	D2L	1810	test run/set up
6/23/2001	19	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	D2L	1810	test run/set up
6/23/2001	20	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	D2L	1810	test run/set up
6/23/2001	21	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	D3L	1810	test run/set up
6/23/2001	22	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	D3L	1810	test run/set up
6/23/2001	23	Tilled Soil	Yes	AMCW 'K'	600 ft	HT, Somat	D3L	1810	test run/set up
6/23/2001	1	Concrete & Grass	Yes	AMCW 'K'	Varies	HT, Somat			Check new parameter file
6/23/2001	2	Concrete & Grass	Yes	AMCW 'K'	Varies	HT, Somat			Check Function of wires
6/23/2001	3	Gravel Road	Yes	AMCW 'K'	600 ft	HT, Somat	D3L	1810	test run/set up
6/23/2001	4	Gravel Road	Yes	AMCW 'K'	600 ft	HT, Somat	D3L	1600	Low RPM setting
6/23/2001	5	Gravel Road	Yes	AMCW 'K'	600 ft	HT, Somat	D3L	1812	test run/set up
6/23/2001	6	Gravel Road	Yes	AMCW 'K'	600 ft	HT, Somat	D3L	1813	test run/set up
6/23/2001	7	Ditch crossing	No	AMCW 'K'		HT, Somat	C3H		Tilt sensor not powered
6/23/2001	8	Hill climb	No	AMCW 'K'		HT, Somat	C2L	1780	Tilt sensor not powered
6/23/2001	9	Sil-soe field	No	AMCW 'K'		HT, Somat	B2L	1580	Tilt sensor not powered
6/23/2001	10	Sand wash	No	AMCW 'K'		HT, Somat	C3H	1770	Tilt sensor not powered
6/23/2001	11	Ditch crossing	No	AMCW 'K'		HT, Somat	C3H		Tilt sensor not powered
6/23/2001	12	Hill climb	No	AMCW 'K'		HT, Somat	C3L	1780	Tilt sensor not powered
6/23/2001	13	Hill climb	No	AMCW 'K'		HT, Somat	C2L	1750	Tilt sensor not powered
6/23/2001	14	Sil-soe field	No	AMCW 'K'		HT, Somat	B2L	1580	Tilt sensor not powered
6/23/2001	15	Sil-soe field	No	AMCW 'K'		HT, Somat	B2L	1580	Tilt sensor not powered
6/23/2001	16	Sand wash	No	AMCW 'K'		HT, Somat	C3H	1770	Tilt sensor not powered

6/23/2001	17	Ditch crossing	No	AMCW 'K'		HT, Somat	C3H		Tilt sensor not powered
6/23/2001	1	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	2	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	3	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1471	Begin test runs
6/23/2001	4	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	5	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	6	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	7	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Begin test runs
6/23/2001	8	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Failure & Declutch
6/23/2001	9	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Begin test runs
6/23/2001	10	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1811	Begin test runs
6/23/2001	29	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	30	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	31	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	32	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	33	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	34	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	35	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1809	Begin test runs
6/23/2001	36	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Begin test runs
6/23/2001	37	Tilled Soil	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1811	Begin test runs
6/23/2001	19	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Begin test runs
6/23/2001	20	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	w/Param4.txt
6/23/2001	21	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	22	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	23	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	24	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	25	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	26	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1809	Begin test runs
6/23/2001	27	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Begin test runs
6/23/2001	28	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1811	Begin test runs
6/23/2001	48	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	49	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	50	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	51	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	52	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	53	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	54	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1809	Begin test runs
6/23/2001	55	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Begin test runs
6/23/2001	56	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1811	Begin test runs
6/23/2001	33	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	34	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	35	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	B2L	1470	Begin test runs
6/23/2001	36	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	37	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	38	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs

6/23/2001	39	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Begin test runs
6/23/2001	40	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Begin test runs
6/23/2001	41	Concrete	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Begin test runs
6/23/2001	42	Concrete	No	AMCW 'K'	800 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	43	Concrete	No	AMCW 'K'	800 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	17	Lateral Tilt, Grass	No	AMCW 'K'	800 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	18	Lateral Tilt, Grass	No	AMCW 'K'	800 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	19	Lateral Tilt, Grass	No	AMCW 'K'	800 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	20	Log Obst., Grass	No	AMCW 'K'	800 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	21	Log Obst., Grass	No	AMCW 'K'	800 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	22	Log Obst., Grass	No	AMCW 'K'	800 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	28	Grass	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	29	Grass	Yes	AMCW 'K'	800 ft	HT, Somat	D1L	1530	Begin test runs
6/23/2001	30	Grass	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Begin test runs
6/23/2001	31	Grass	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Begin test runs
6/23/2001	32	Grass	Yes	AMCW 'K'	800 ft	HT, Somat	D3L	1810	Begin test runs
6/23/2001	2	Ditch	No	AMCW 'K'		HT, Somat	C3H	1940	Begin test runs
6/23/2001	3	Ditch	No	AMCW 'K'		HT, Somat	C3H	1940	Begin test runs
6/23/2001	4	Hill Climb	No	AMCW 'K'	70 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	5	Hill Climb	No	AMCW 'K'	70 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	6	Hill Climb	No	AMCW 'K'	70 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	7	Sil-soe	No	AMCW 'K'	135 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	8	Sil-soe	No	AMCW 'K'	135 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	9	Sil-soe	No	AMCW 'K'	135 ft	HT, Somat	B2L	1580	Begin test runs
6/23/2001	10	Sand Wash	No	AMCW 'K'		HT, Somat	C3H	1940	Begin test runs
6/23/2001	11	Sand Wash	No	AMCW 'K'		HT, Somat	C3H	1940	Begin test runs
6/23/2001	12	Sand Wash	No	AMCW 'K'		HT, Somat	C3H	1940	Begin test runs
6/23/2001	13	Tall Grass	No	AMCW 'K'		HT, Somat	Park	900	Begin test runs
6/23/2001	14	Tall Grass	Stopped	AMCW 'K'		HT, Somat	Park	2240	Begin test runs
6/23/2001	15	Soy Beans	Stopped	AMCW 'K'		HT, Somat	Park	900	Begin test runs
6/23/2001	16	Soy Beans	Stopped	AMCW 'K'		HT, Somat	Park	2240	Begin test runs

APPENDIX F

AMCW radio frequency component specifications and sections

The AMCW radio frequency sensor components used during the field tests are listed below. Included are an IF oscillator, Gunn oscillator, AM modulator, circulator, antenna, mixer, IF amplifier, IF filter, and phase detector. The component specifications are listed in the following sections.

1. IF Oscillator

a) Frequency	60MHz (+/-30MHz)
b) Stability	10ppm
c) Power	0dBm+/-3dB
d) Power tuning range	20dB

2. Gunn Oscillator

a) Frequency	24.125GHz+/- 10MHz
b) Power	7dBm+/-3dB
c) Frequency shift	<110MHz (50MHz
goal) over temp range	(-40 C to 85 C)
d) Phase noise	<-80dBc/Hz @ 10KHz

3. AM modulator

a) Frequency	Carrier 24.125GHz
Modulation	60MHz (+/-30MHz)
b) Insertion loss	7dB+/-1dB
c) Modulation index	-20dB +/- 2dB
d) Harmonics (third)	<-42dB
e) Spurious	<-50dB

4. Circulator

a) Frequency	24.125GHz
b) Bandwidth	>500MHz
c) Isolation	>20dB
d) Insertion loss	<0.8dB

5. Antenna

a) Frequency	24.125
b) Bandwidth	>500MHz
c) Gain	15dB +/- 2dB
d) Return loss	<-15dB
c) Side lobe	<-13dB
e) Beamwidth	23 +/- 2degree
f) Diameter	1.5 in.

6. Mixer

a) Frequency (RF & LO)	24.125GHz +/-200MHz
IF	60MHz +/-30 MHz
b) Conversion loss	<15db
c) Sensitivity	<-90dbm
d) Pumping power	0 to -10dbm

7. IF Amplifier

a) Frequency range	[60MHz +/-30MHz]
+/- 10MHz	
b) Gain	>80dB
c) Input/output impedance	50 ohm

8. IF Filter

a) Pass band	[60MHz +/-
30MHz] +/- 10MHz	
b) Insertion loss @ 2 x f_m	>50dB
c) Input/output impedance	50 OHM

9. Phase Detector

a) Kp	0.16V/rad
2.8mV+/-0.1mV/degree)	
b) Max input frequency	>125MHz
c) Input level	-25dbm - 10dbm
d) Tolerance	<3mV (1degree)