IF-TH-63

A Novel Signal Processing Approach for Microwave Doppler Speed Sensing

Norbert Weber, Stefan Moedl and Michael Hackner

Fraunhofer-Institut für Integrierte Schaltungen, 90411 Nuernberg, Germany

Abstract - **Systems for ground speed measurement usually determine a peak in the measured microwave spectrum of a reflected Doppler-shifted transmit signal. Ground speed is calculated from the frequency offset of this peak and the incident angle between the microwave antenna and ground. In this paper a Doppler measurement system is described that does not need to know the exact angle under which the antenna is radiating and receiving the signal with respect to ground if a specific condition is met. Furthermore, no Janus antenna configuration is needed for this system.**

I. Introduction

Microwave ground speed measurement systems have been discussed and optimised by a large number of authors (see e.g. [1]). The dependence of the Doppler shifted frequency on the angle of incidence has always been a severe problem, although speed measurements down to 0,03 m/s have been performed with some effort [2]. In most practical systems the angle dependence limits the accuracy because of statistical changes of the angle due to movements of the sensor relative to ground. Moreover, the median value of this angle has to be known to allow for calculations of the velocity from the Doppler shift.

In this paper a method is described that relaxes exact knowledge of the angle and allows for a significant change in angle without lowering accuracy. For such a system an antenna with a broad aperture angle is utilised together with a novel signal processing procedure.

II. Theory

A. Conventional Doppler Sensors

Conventional Doppler systems are usually realised in a monostatic or bistatic arrangement with antenna(s) for transmitting and receiving the back-scattered signal. For ground speed measurements the transmit antenna has to radiate to ground under an angle α (see fig. 1).

The relevant Doppler shift of the received signal that contains speed information is nearly proportional to the radiated signal or – in other words – the Doppler shifted frequency f_D is

$$f_D = f_T \cdot (c+v\cos\alpha)/(c-v\cos\alpha) \qquad (1a)$$

or with the approximation $v \ll c$

$$f_D \approx f_T\ (1+2\cos\alpha \cdot v/c) \qquad (1b)$$

where f_T is the transmitted signal frequency, v is the ground speed to be measured and c is the speed of

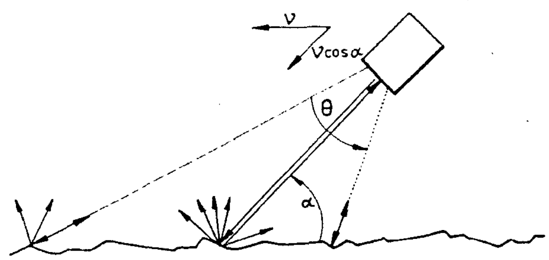

Fig. 1 Antenna configuration for Doppler measurement

light. Under realistic conditions it has to be considered that

- the aspect angle α may not be constant due to up and down motions of the vehicle to which the antenna is attached
- due to a non-zero aperture angle θ of the antenna the reflected signal has a relatively broad spectral bandwidth

These limitations will cause a measured microwave spectrum that has a spectral bandwidth dependent on the aperture angle of the antenna and a peak at a frequency value which will depend on motions of the antenna. Therefore, in practical systems, designers tend to use antennas with very small aperture angles in order to get a slim peak in the spectrum; the angle-dependent frequency shift can be compensated by using a Janus-type antenna, which consists in fact of two antennas that are looking to ground in the forward and backward directions, respectively, to correct the errors due to varying angles because of vehicle movements [1].

B. Proposed Method

The method the authors propose is to use an antenna with a very broad aperture angle in order to make sure that there are signal components transmitted in a horizontal direction parallel to ground. For demonstrating the operating principle an antenna with isotropic radiation was used for calculation of the Doppler spectrum. The antenna configuration is shown in fig. 2.

0-7803-7239-5/02/$10.00 © 2002 IEEE

The expected Doppler spectrum of the signal will be much broader than before because of the isotropic radiation. The frequency will shift even to frequencies lower than the transmit frequency because of radiation in backward direction. For this configuration the Doppler spectrum was calculated assuming ideal diffuse backscattering from ground (Lambert transmitter).

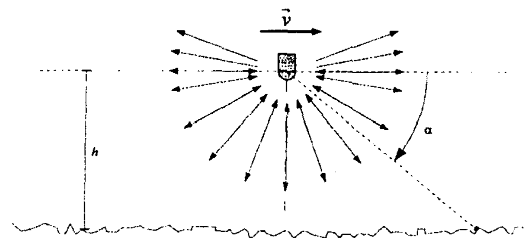

Fig. 2. Doppler system with isotropic antenna configuration

The calculated spectrum for a speed of 15 m/s is shown in fig. 3 where the reflected amplitude is plotted vs. the normalized frequency.

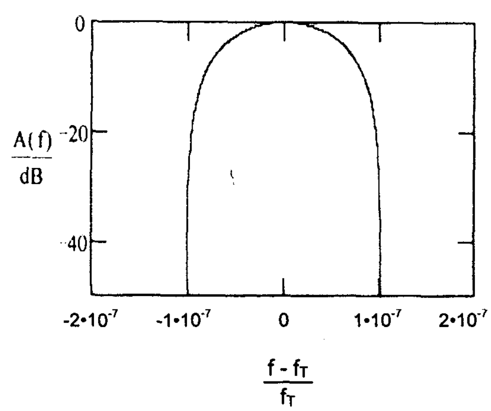

Fig. 3 Calculated Doppler spectrum

As expected, the spectrum is very broad and symmetric with respect to the transmit frequency. For evaluation with the goal to calculate the speed over ground, no longer the maximum of the spectrum can be used. From eq. (1b) and fig. 4 one can see that the Doppler shifted frequency will adopt a maximum value in case that there are signal components transmitted in horizontal direction where $\alpha = 0$ and $\cos\alpha = 1$ and becomes

$$f_D \approx f_T \ (1+2\ v/c). \qquad (2)$$

From this equation a speed value of

$$v \approx (c/2) \cdot (f_D - f_T)/f_T \qquad (3)$$

can be calculated. Theoretically, at this maximum frequency there is no reflection from ground because this frequency corresponds to a signal transmitted in a direction parallel to ground. Thus, for evaluating the received spectrum one has to search for the maximum frequency

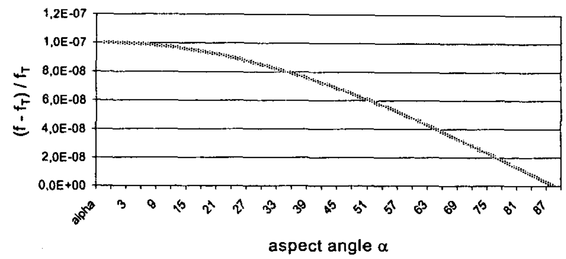

Fig. 4 Doppler frequency vs. aspect angle

component with theoretically zero signal level. Therefore the falling edge of the spectrum has to be evaluated, i.e. the highest frequency that occurs. This falling edge is a direct measure for speed and does not have to be corrected with any angle information as long as the above conditions are met and there are signal components corresponding to $\alpha = 0$. Within this condition angular movements of the transmitter or receiver are irrelevant; the falling edge in the spectrum will not change its position if such movements occur. Moreover, from fig. 4 it is clear that there is a flat maximum in the cosine-shaped dependence of the Doppler frequency from the aspect angle. Thus, even if α were slightly greater than 0 up to about 10 degrees not a large error will result in evaluating the falling edge of the spectrum.

In practical applications, no isotropic transmitter can be used but it can be ensured that signal components parallel to ground are transmitted. This is the case if the condition

$$\theta > 2\alpha \qquad (4)$$

is met where θ is the aperture angle of the antenna (see fig. 1). As long as the above equation is fulfilled there will always exist received frequencies for which $\cos\alpha = 1$. Therefore this method is independent of the incident angle α if eq. (4) is fulfilled.

In contrary to the state of the art, where system designers are using antennas with small aperture angle θ, the result of the considerations above is to use an antenna with a rather large aperture angle, depending on the angle under which the antenna is looking towards ground.

III. Measurement Setup

In order to proof this theory a bistatic Doppler radar system was built using a sensor system operating at 24 GHz. The antennas (developed by InnoSent GmbH) were two microstrip array antennas with 2x4 radiating elements each (one 2x4 array for transmit and one for receive) and had aperture angles θ of 30° in horizontal and 50° in vertical direction, respectively (see fig. 5: here, the antenna is rotated by 90°). The antenna was mounted in a way that α was nearly 20° to ground, so that the condition of eq. (4) holds true.

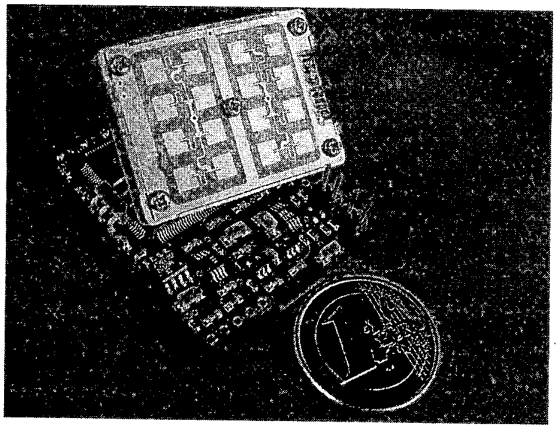

Fig. 5 Antenna for a bistatic Doppler system with large and small aperture angles and PCB for signal processing

The signal processing algorithm including averaging, FFT and some calculations of the threshold value and finally the cut-off-frequency was implemented in a digital signal processor. The power consumption of the whole system is about 5 mA at a 3 V supply voltage.

IV. MEASUREMENT RESULTS

The sensor system was used for measuring speed of jogging people, so the Doppler shifts were rather small. The sensor was mounted in front or in back of the running persons. A typical measured spectrum (after some averaging) in this application with a speed of approximately 3.1 m/s is shown in fig. 6. The x-axis represents the Doppler shifted frequency f_D - f_T, the scaling of the y-axis is in arbitrary units.

As expected, a significant falling edge can be observed in this spectrum. In order to extract the speed information a cut-off-frequency f_c is determined from the intersection of an amplitude threshold T with the measured curve, where T is calculated out of the noise amplitude of the spectrum above the expected cut-off-frequency. In the above example a value of 500 Hz was determined for f_c. From eq. (3) the speed value can be calculated to be v = 3.125 m/s which corresponds very well with the actual speed.

Recently, the first commercial solution of the sensor was released as a prototype version (see fig. 7). From the first measurements an accuracy for determination of speed was estimated to be within a few percent for jogging.

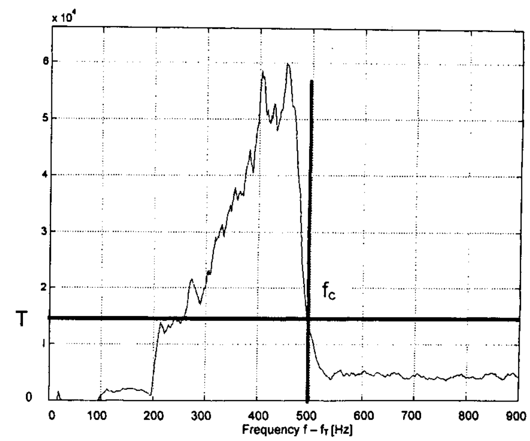

Fig. 6 Averaged measured Doppler spectrum (arb. units)

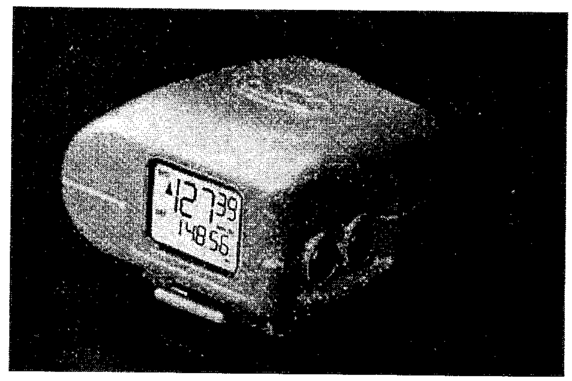

Fig. 7 Prototype of speed sensor for jogging

V. CONCLUSIONS

In this paper the authors propose a novel method for performing microwave Doppler measurements for ground speed sensing. A short overview of the theory was given and the relevant conditions were shown under which a speed signal can be extracted out of the microwave spectrum that is independent of the aspect angle of radiation towards ground. This system is very promising for a wide variety of applications and has been tested for jogging, downhill skiing, inline skating and in motor cars. We are looking forward to publish even more results in the near future.

REFERENCES

[1] H. Meinel, "Commercial applications of millimeter-waves – History, Present Status and Future Trends", *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1639-1653, July 1995

[2] M. Weinberger, *Eigengeschwindigkeitsmessung für Kraftfahrzeuge mit dem Doppler-Effekt im Millimeterwellenbereich*, Doctoral Thesis, Institute for microwave technology, Technical University of Munich, 1993