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Microwave Doppler Sensors Measuring Vehicle Speed and Travelled Distance: Realistic System Tests in Railroad Environment

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ABSTRACT

A high-performance 24 GHz microwave Doppler sensor system for non-contact ground speed measurement is presented. Its potential for positioning tasks, as well as slippage control in railway applications has been demonstrated in extended measurement campaigns. The microwave front-ends are based on highly stabilised dielectric resonator oscillators and low-cost patch antennas. Employing model based algorithms implemented on signal processor an accuracy of about 1 % for the speed measurement and of about 2 m / 1000 m for the distance measurement has been obtained.

INTRODUCTION

With increasing traffic flow better traffic management systems for railway, as well as for automotive applications are needed [1]. As a consequence, the interest for a precise non-contact measurement of speed and position of vehicles has been stimulated. Due to the robustness of microwaves against changing environmental conditions, radar sensors are superior to sensors employing optical or ultrasonic principles. Microwave sensors operating in the 24 GHz band provide high sensitivity and good reliability [2]. For the measurement of speed and position a microwave beam is emitted obliquely to the ground [3]. A small part of the wave is scattered back into the antenna by statistically distributed scattering objects. The frequency of the backscattered signal is shifted in frequency relative to the emitted signal due to the Doppler effect. The difference of the two frequencies is the Doppler frequency f_d, which is proportional to the vehicle speed and the cosine of the radiation angle α with respect to the horizontal plane:

$$f_d = f_0 \cdot (2v/c) \cdot \cos \alpha$$

f_0	microwave frequency
v	vehicle speed
c	speed of light
α	radiation angle

Principal problems of this measurement technique arise from the fact, that the Doppler signal does not consist of only one frequency component. Due to the statistical backscattering properties of the ground together with the antenna radiation pattern a broad frequency spectrum is generated. For precise, reliable measurements an optimisation of the microwave front-end as well as the Doppler signal processing is necessary.

SYSTEM CONFIGURATION

Fig. 1 shows a schematic of the set-up, which was used during the measurement campaigns. In the trapeziform sensor box (Fig. 2) three independent microwave front-ends are installed with different antenna radiation patterns (front-end 1: so-called Janus configuration with two antenna beams, $\alpha = 45°$; front-end 2,3: single antenna beam, $\alpha = 15°$). Along an on-line evaluation on digital signal processor (DSP), the Doppler signals of all three front-ends are recorded simultaneously on digital tape (DAT) together with the signal of a precision wheel transducer. The speed value given by the wheel transducer is used as a reference enabling an investigation of the absolute measurement accuracy of the Doppler system. Both the speed value calculated on DSP and the speed measured by wheel motion can be monitored on PC.

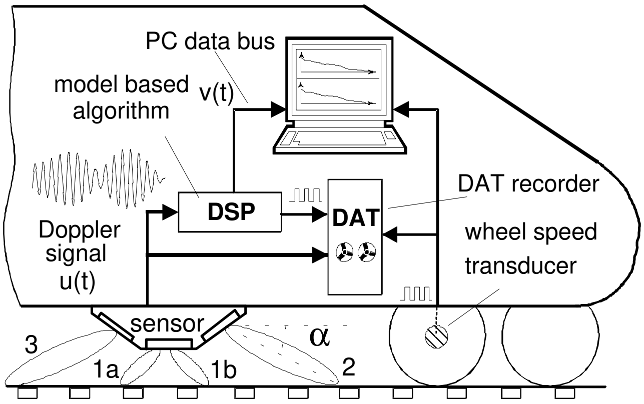

Fig. 1: Measurement set-up.

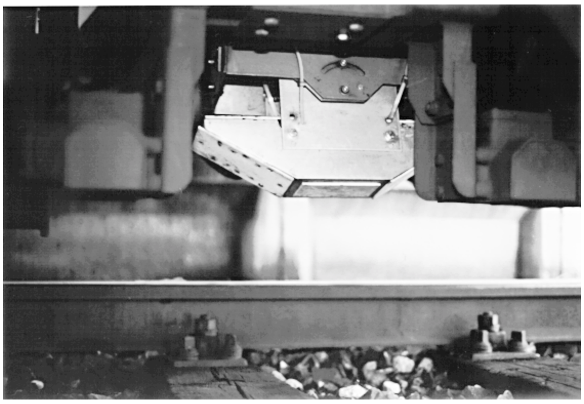

Fig. 2: 24 GHz Doppler sensor on locomotive.

Thus, it is possible to compare the performance of the different hardware configurations under exactly the same measurement conditions. Furthermore, an analysis of the backscattering properties of different ground types is done by comparing the signals of the three microwave front-ends, which individually illuminate the ground with different radiation patterns. This multiple beam configuration also gives the opportunity to investigate data processing concepts evaluating more than just one Doppler signal in order to increase the accuracy and reliability of the speed measurement, an aspect of particular interest for railway applications.

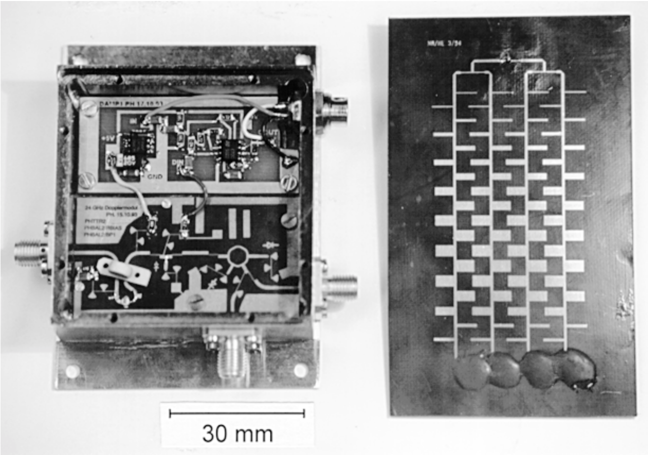

Fig. 3: 24 GHz radar front-end comprising of a fundamental-frequency dielectric resonator oscillator, a schottky diode detector and a travelling-wave patch antenna.

The basic component of the Doppler sensor is a highly stabilised 24 GHz fundamental-frequency dielectric resonator oscillator. The use of a higher-order mode of the dielectric resonator has led to a new type of oscillator with high spectral purity (phase noise level: -95 dBc/Hz @ 100 kHz) and good temperature stability (+10 ppm/K). Adding a schottky diode detector as a homodyne receiver and a patch antenna [4], a low-cost compact CW Doppler sensor has been built. Fig. 3 depicts the 24 GHz radar front-end built in low-cost hybrid microstrip technology [5]. The compact-sized module (60 x 80 x 25 mm) is already prepared for different kinds of modulation, which allow to achieve a range selectivity, to reduce noise, and to avoid cross-sensor interference.

The signal processing is done by model based algorithms [6,7], which give much better accuracy than conventional methods, as they take into account a priori knowledge of the whole sensor configuration [8]. Regarding the two especially investigated radiation angles (α = 45°, α = 15°) and the resulting Doppler spectra (Fig. 4) two specific algorithms have been developed. The data evaluation for α = 45° is based on an AR (= autoregressive) signal model, for α = 15° on an ARMA (= autoregressive moving average) signal model. The algorithms, written in assembler code, are implemented on digital signal processor (type: MOTOROLA 56001). The prototype signal processing unit also contains the power supply for the microwave front-ends, several output interfaces and an LED-display indicating the estimated speed value and the system status.

MEASUREMENT RESULTS

In first practical tests promising results were achieved, although some track types demanded further investigations. The influence of some ground types on the Doppler spectrum are analysed in more detail. In accordance with system theory [9, 10], the Doppler spectrum of a ground speed radar is a product function of two terms: the sensor system function, corresponding to the Doppler spectrum obtained from an isotropically scattering surface and a second term, representing the angular dependency of the backscattered amplitude. Fig. 4 shows typical Doppler spectra measured with front-ends 1 and 2 on tracks with wood or concrete sleepers. The shape of the spectra are as expected for an isotropically scattering surface. Similar Doppler spectra are obtained on tarmac covered roads in car measurements.

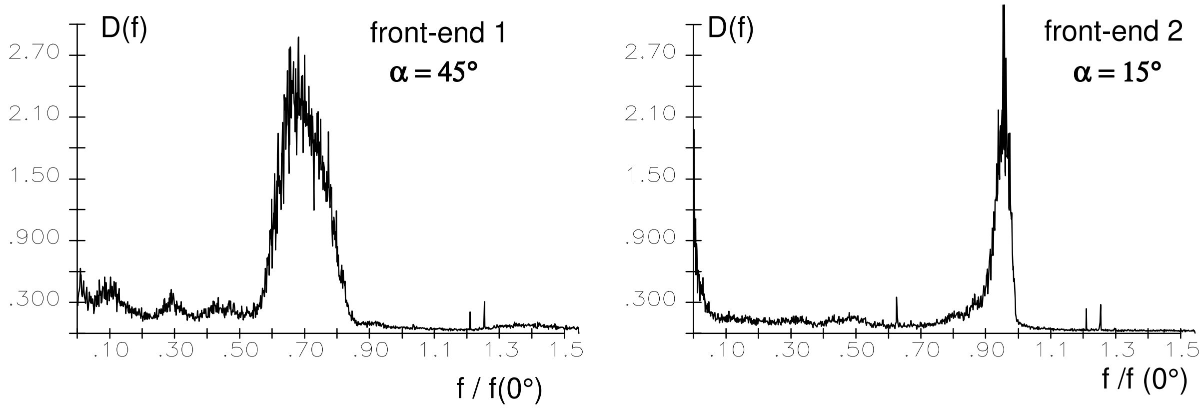

Fig. 4: Typical Doppler spectra on wood or concrete sleepers (frequency scale normalised to upper theoretical frequency value corresponding to horizontal radiation α = 0°).

Fig. 5 shows spectra measured on tracks with metal sleepers. In the Doppler spectrum of front-end 1 there is a significant enhancement of three frequency components (arrows), which is caused by specular reflection of the microwaves on the metal sleepers. The backscattering cross-section of the metal sleepers in the direction perpendicular to the flat surfaces is very high. Therefore, the basic assumption of an isotropically scattering surface is no longer valid. However, the Doppler spectrum for α = 15° is much less influenced by the metal sleepers.

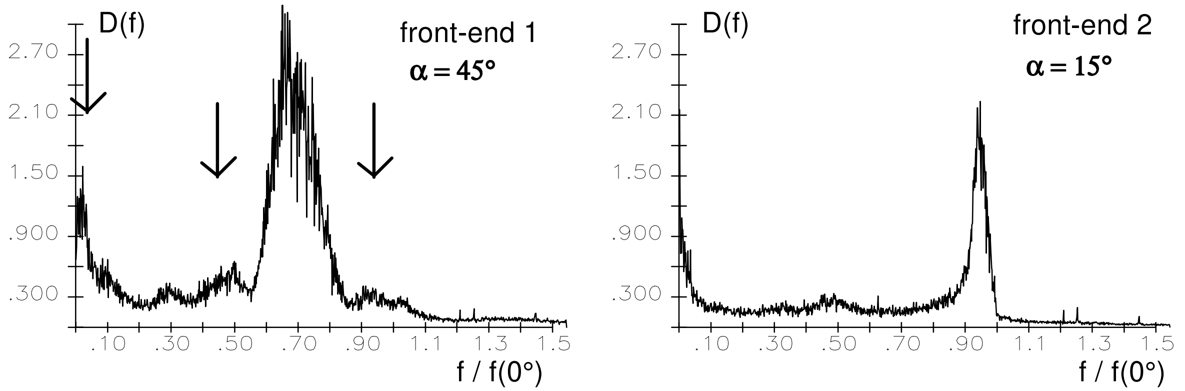

Fig. 5: Typical Doppler spectra on metal sleepers: The arrows indicate frequency components caused by specular reflection.

On level crossings covered by tarmac, a small reduction in the amplitude of the Doppler signal occurs, the shape of the spectrum staying virtually unchanged. On level crossings covered by concrete, a marked reduction in the signal amplitude is observed. The overall shape of the spectrum is not changed, although there is a slightly increased amplitude for low frequencies and a slightly reduced amplitude for high frequencies due to the much smoother surface in comparison to gravel. On tracks with the whole area between the rails being covered by metal sheets (mainly used on bridges), a variety of distortions of the Doppler signal are observed, depending on the structure and the surface properties of these metal sheets. In rare cases, almost a complete loss of the signal occurs. The influence of snow covering the tracks depends very much on its consistency. For dry powder snow no influence on the Doppler signal is detected. Frozen and crusty snow leads to an increase, wet snow to a marked reduction in signal amplitude. In both cases there is virtually no change in the shape of the spectrum. The reduction in signal amplitude on wet snow is due to the high absorption coefficient of water. The increase in signal amplitude on icy snow is not fully clear.

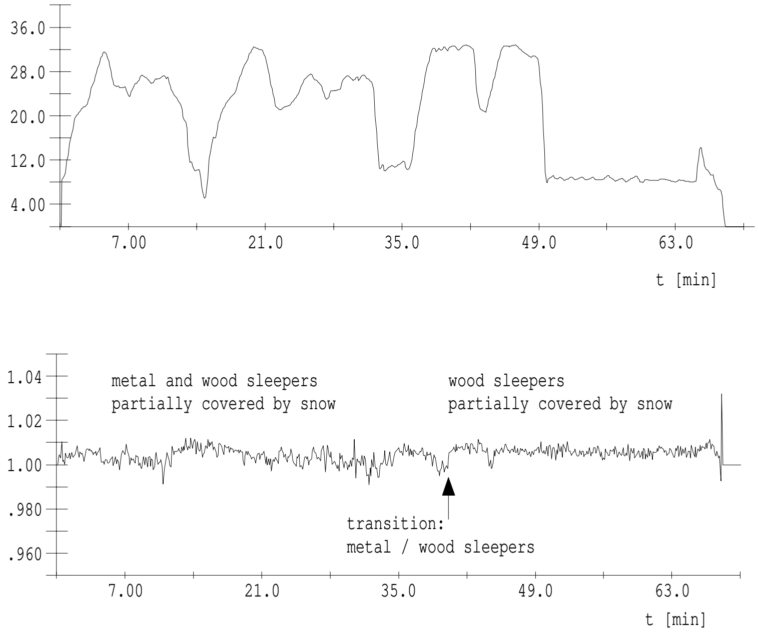

Fig. 6: Speed measured with front-end 1 ($\alpha = 45°$) (upper trace) and ratio of this speed and the reference value measured by the wheel speed transducer (lower trace).

Fig. 6 depicts the estimated vehicle speed obtained with the signals of front-end 1 during a test ride of about one hour (upper trace). The lower trace gives the ratio of the speed measured by the Doppler system and the wheel speed transducer. The overall error is about 1 %. In the first part of the test ride changing sleeper types (metal/ wood) and a partial snow coverage lead to a fairly large standard deviation, whereas for the rest of the track with wood sleepers only, the measurement accuracy is highly satisfactory. The arrow indicates a transition from metal to wood sleepers. The smaller speed value measured on metal sleepers is caused by a shift of the centre of gravity of the Doppler spectrum (Fig. 5, left). Fig. 7 demonstrates the significant improvement obtained using the signals of a front-end with a flat radiation angle and an appropriate signal processing. The narrow spectrum obtained for flat radiation is much less sensitive to changing ground types than the broad spectrum obtained for steep radiation. Thus, an algorithm extracting speed information only from a very small, but highly significant part of the spectrum will give a very precise measurement.

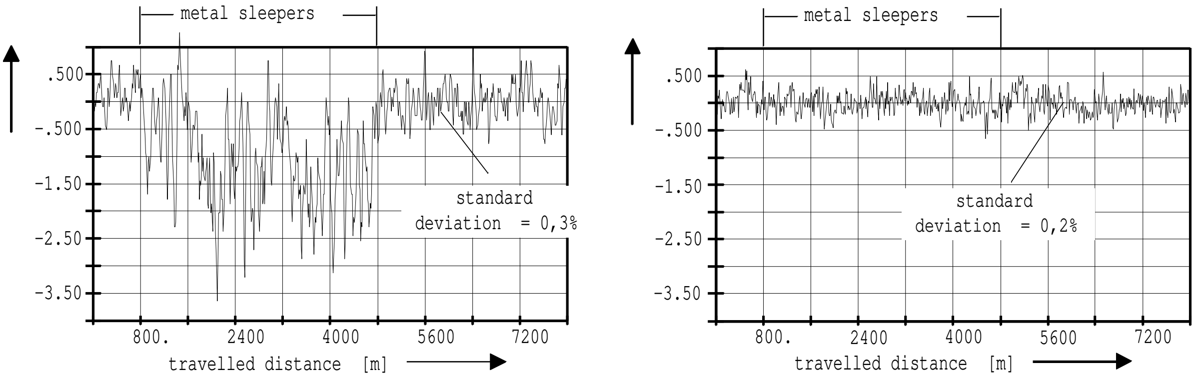

Fig. 7: Relative error for speed measurement (critical ground condition). Left: radiation angle $\alpha = 45°$ (front-end 1); right: radiation angle $\alpha = 15°$ (front-end 2).

Altogether, the system has been tested on several thousands of kilometres of railway track. The overall precision is about 1 % for the speed measurement and of about 2 m / 1000 m for the distance measurement. The functioning of the system was not influenced by falling rain or snow. In almost all situations where the accuracy obtained with front-end 1 was reduced due to changing ground properties, front-end 2 (very flat radiation angle) gives reliable measurement results. In test rides on the French high speed train TGV, the Doppler radar proved to work reliably at speeds up to 350 km/h. On a prototype locomotive (Euro-Sprinter [11]) its potential for slippage control has been shown, although some refinements in the signal processing would still be necessary for this application.

OUTLOOK

The reported 24 GHz Doppler radar for speed and distance measurements proved to work well in extended measurement campaigns with the German and French railways. Another promising application is the speed measurement on magnetically levitated vehicles as for example the German TRANSRAPID, where a measurement by wheel motion is not feasible.

A low-cost version of the system with just one microwave front-end is well suited for automotive applications. In order to further increase the reliability and accuracy of the system, the outputs of the different microwave front-ends could be combined in one signal processing unit. As discussed above, a flat radiation angle leads to a very high measurement precision. In some cases however, the lower amplitude of the backscattered signal and the increased probability of spurious reflections in comparison to a steep radiation angle can counterbalance this advantage. New modulation techniques [12] increase the signal-to-noise ratio and establish a range selectivity, such that these shortcomings are overcome. For applications demanding both high accuracy and high up-date rates, a further reduction of the error is obtained by including an accelerometer [7].

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