# 77 GHz TRAFFIC RADAR SENSOR FOR SPEED ENFORCEMENT MEASURING SPEED AND DISTANCE

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## INTRODUCTION

All existing traffic radars to be used for speed enforcement measure the speed of the passing vehicles on the basis of a CW technology. A new prototype of a traffic radar sensor has been developed that not only measures the speed of the vehicle but also its distance to the radar device, photograph see figure 1. The measured distance enables the police to unambiguously assign the measured speed to a vehicle shown in a picture, even in special cases. The prototype is based on a 77 GHz pulse radar technology that has so far been used only for driver assistance systems. In a first step, the accuracy of an existing sensor was analysed by comparing the results with a reference system for speed measurements. In a second step, the sensor was modified in order to optimise it for speed enforcement, and tested again. The concept of the prototype, the modifications and the results of the comparison are described.

Figure 1: Photograph of the new radar sensor, a German Pfennig coin (∅ 16,5 mm) illustrates the dimensions of the sensor

## LIMITATIONS OF EXISTING TRAFFIC RADARS FOR SPEED ENFORCEMENT

All existing traffic radars to be used for speed enforcement are based on a simple CW Doppler technology. This means that the system continuously emits a radar wave (frequency $f$) which is partly reflected by the passing vehicle with a frequency shift $\Delta f$ in compliance with the Doppler effect, which is proportional to the speed $v$ of the vehicle ($\Delta f = 2 f v/c$ $c$: velocity of light). The system determines $v$ by measuring the frequency shift $\Delta f$. If, however, the radar wave is reflected by more than one vehicle, the radar signal delivers no information which makes unambiguous assignment of the measured speed to a single vehicle possible. This means that hand-held systems aimed at the vehicle along the road are not useful for dense traffic. The beam of most systems used in Europe is, therefore, aligned at a fixed angle $\alpha$ (typically 20°) to the direction of motion; the angle is automatically taken into account by correcting the formula for the Doppler effect by a factor $\cos\alpha$. This technique should enable the police, at least on roads with only a single lane per direction, to correctly assign the measured speed to the vehicle shown in a photograph in the range where the beam crosses the road. It is well known, however, that there are some very special situations where erroneous assignment or corrupted speed measurement may occur, see e.g. Michel [1], Mira [2] or Fisher [3].

Figure 2 illustrates the standard situation of correct measurement and assignment (part A) and the three most important special cases (parts B, C and D).

Part B illustrates the so-called double reflection: the radar beam is first reflected by the vehicle (with a frequency shift $\Delta f$), then by a retroreflector (without a frequency shift), and finally reflected again by the vehicle (with a second frequency shift $\Delta f$). In this situation the frequency of the radar beam received by the instrument is shifted by $2\Delta f$ so that the instrument will calculate a speed $2v$. For several reasons such situations are very infrequent. The most important conditions to be fulfilled are:

- The retroreflector must be big enough to be hit during the complete passage of the vehicle.
- The amplitude of the doppler signal corresponding to the beam part that is directly reflected according to the situation A must be smaller than the amplitude corresponding to the double reflection though the distance for latter is much bigger.

Part C shows the situation of so-called cracked beam reflection (german: “Knickstrahlre-flexion”). The radar beam is first reflected by a reflector similar to a mirror (e.g. a traffic sign, without frequency shift) and then by vehicle I with a frequency shift $\Delta f$ corresponding to it´s speed $v_{\mathrm{I}}$. If by chance a second vehicle (II) exists near the standard position but not hit by the beam erroneous assignment may occur. If the speed $v_{\mathrm{II}}$ is lower than $v_{\mathrm{I}}$ such assignment is a disadvantage for the driver of vehicle I. For several reasons such situations are rather infrequent, too. The most important conditions to be fulfilled are (two are similar to those for double reflection):

- The reflector must be big enough to cover a significant area of the beam.
- The amplitude of the doppler signal corresponding to the beam part that is directly reflected according to the situation A must be smaller than the amplitude corresponding to the cracked beam reflection though the distance for latter is much bigger.
- The position of vehicle II must be such that by chance it fits to the standard situation.
- The position of vehicle I must be such that the angle between the beam reflected by this vehicle and the axis of the radar antenna is small enough for a significant antenna sensitivity (typically not more than 3 °).

Part D shows the most frequent special situation. Two vehicles (I and II) with similar or different speed ($v_{\mathrm{I}}$, $v_{\mathrm{II}}$) are passing the radar beam at the same time. In this case the doppler signal in the traffic radar is characterised by a spectrum consisting of two frequencies corresponding to the frequency shifts caused by $v_{\mathrm{I}}$ and $v_{\mathrm{II}}$. Most existing traffic radars automatically analyse the doppler signal, the software will annul the complete measurement if specified criteria are exceeded. Others deliver an acoustic signal indicating the user that the measured speed may not be assigned to one of the vehicles. This means that an effective use of traffic radars is not possible for highways with more than one lane if the traffic is dense.

The most important consequences of the three special effects mentioned above are – at least in Germany – that the systems may no be used at places with strong reflectors (e.g. iron bridges) and that the police officers are obliged to permanently watch the situation in order to annul all questionable cases. Only with this inconvenient restriction is an exclusion of erroneous measurements or assignments possible.

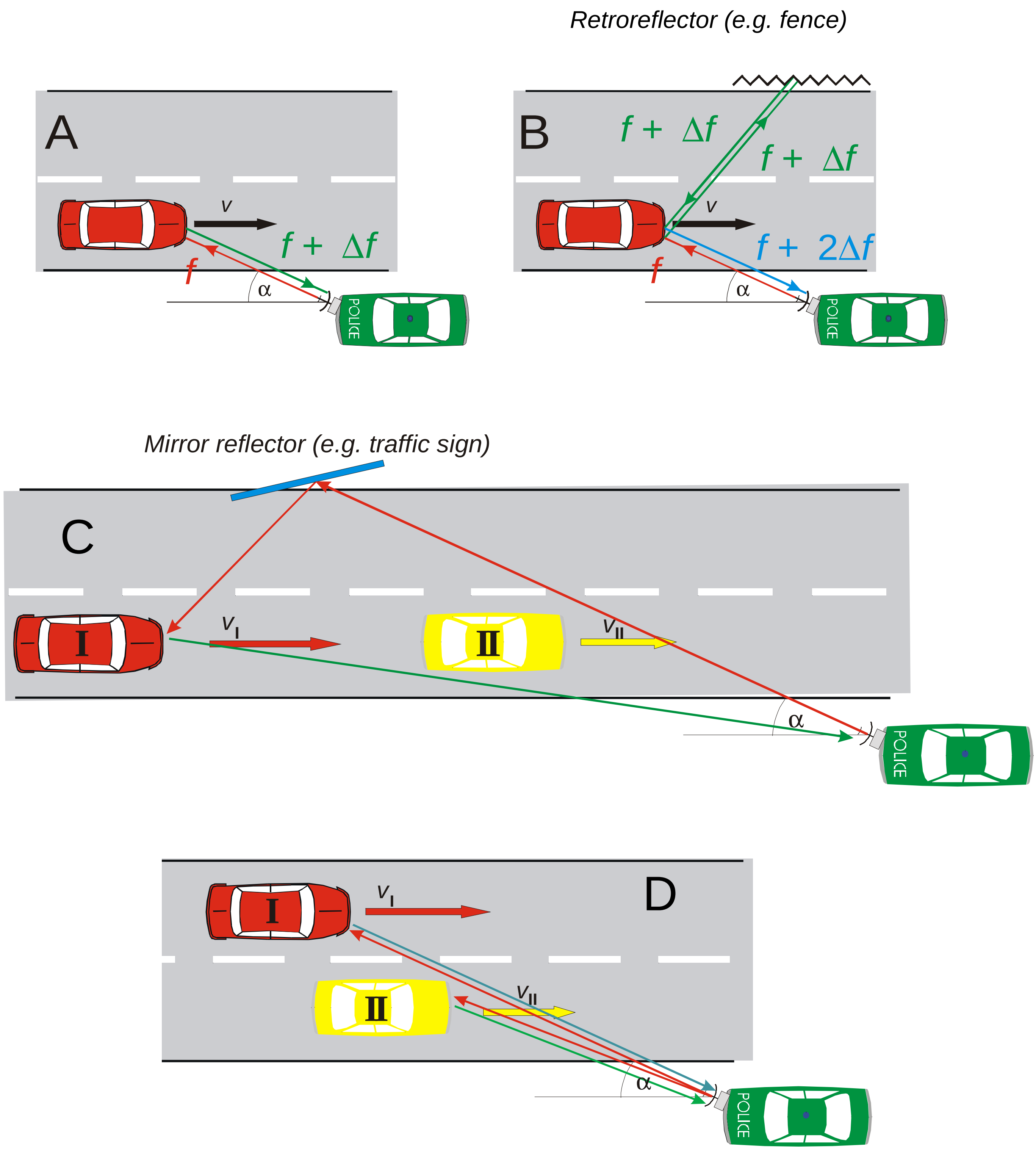


Figure 2: Situation with traffic radar used in Europe; part A shows the standard situation of a speed measurement, part B illustrates double reflection, C cracked beam reflection and D the situation of two vehicles hit by the beam at the same time (details see text above).

## CONCEPT OF THE NEW SENSOR

If a radar sensor was able to measure not only the speed but also the distance of the reflecting object, unambiguous assignment of the measured speed to a single vehicle would be possible in the case of two or more lanes per direction and also in all those cases mentioned above. Simultaneous measurement of the range and speed of objects in multi-target situations is is, however, not possible with simple CW-radars. For this purpose different radar principles, such as FMCW or Pulse-Doppler radars, can be used, see e.g. Mende [4]. The authors of this paper decided to use a very advantageous combination of both for the first tests of the new generation of speed enforcement radars. Thus, the applied radar unit used pulsed operation with frequency modulated waveforms.

It is also necessary to introduce a certain angular resolution to the sensor system to make it easier to decide which car drives on which lane and to classify the measured speed values as belonging to the different detected objects. The chosen system uses three beams with a beam width of about 3° and a beam offset in the same order.

Typical ACC (Adaptive Cruise Control Radars), like the new Distronic System of Daimler Chrysler, which has recently been introduced in the new Mercedes-Benz S-Class, are designed to measure distance and speed of objects in a small angular section in front of a driving vehicle. Powerful signal processing algorithms are usually applied to resolve the radar echoes coming from the reflection objects ahead.

For the first measurements the RF front end of the mentioned ACC was used and similar algorithms have been developed by s.m.s smart microwave sensors GmbH.

The new feature of the new sensor is the additional possibility to measure the distance between the instrument and the reflecting object. The upper part of figure 3 shows measured distance raw data for a sequence of several minutes with more than 30 vehicles most of which are approaching the sensor. The question arises, however, if such data can be used to automatically separate and track vehicles even if they drive with only short gaps. To optimise this function hardware and software of the sensor have been modified. One of the most important modifications covers the tracking algorithm taking into account raw data of distance and speed. To demonstrate the success of the new sensor a traffic situation with 5 approaching vehicles with short gaps was analysed. The result for this sequence using the modified sensor is shown in the lower part of figure 3. For illustration of the tracking (e.g. on a monitor) the algorithm automatically allocates different colours for the separated vehicles. As can be seen, vehicles can clearly be separated automatically, even if their gap is only about 5 m.

This means that in all three special traffic situations mentioned above the sensor will help the police in their work for speed enforcement. A decision whether a falsification of the speed measurement by double reflection or an erroneous assignment by cracked beam reflection has occurred can even been made automatically by a traffic radar before triggering of a photo, if the police officer inputs the distance of the standard situation before starting with the series of speed measurements. The measured distance also helps to correctly assign the measured speed to one vehicle if two vehicles pass the beam at the same time in dense traffic. Probably it will even be possible to measure, document and assign the speed of both vehicles.

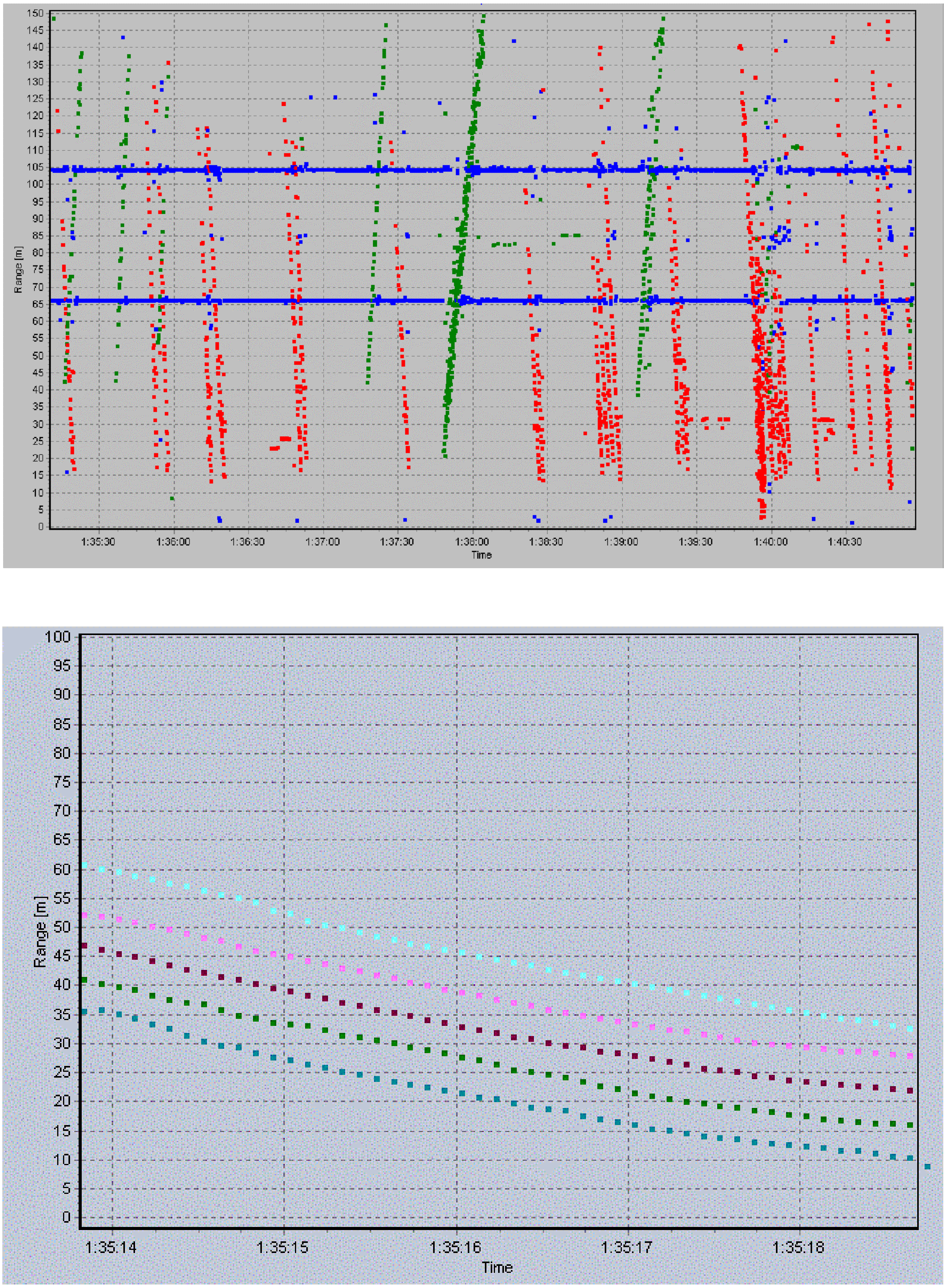


Figure 3: Measured distance in m versus time. Upper part: Raw data of a sequence lasting several minutes (red: approaching vehicles, blue: stationary objects, green: departing vehicles). Lower part: tracked distances of a sequence lasting some seconds with 5 vehicles approaching the sensor with short gaps.

## COMPARISON OF THE MEASURED SPEED WITH REFERENCE VALUES

All systems to be used for speed enforcement by the German police need a type approval, for which the PTB is responsible. The core of each type test is a comparison of the speed values measured by the sensor under test with those measured by a PTB reference system. For such tests, the PTB uses either the system that has been described by Jäger [5] and that is based on light beams, or a system based on three piezoelectric cables fastened on the road surface. In Germany, as in most other countries, the maximum permissible errors for such tests are 3 km/h (3% of the measured value for a value above 100 km/h). These error limits are specified in the so-called German Verification Ordinance (Eichordnung) and have been recommended world wide by [6]. The police has to take into account this error limit for each measurement in favour of the offender. It must, however, be ensured that no single value exceeds these limits during the tests. Otherwise an offender might argue that just in his case the system made an error exceeding these limits.

Such tests were carried out with the prototype of the new radar sensor using the PTB system with piezoelectric cables as a reference, both installed on a road with real traffic. Only approaching vehicles and only a single lane were covered by this test. The radar sensor was mounted on the road side at a distance of 40 m to the second piezoelectric cable. The axis of the beam was aligned nearly parallel to the direction of motion, the angle $\varphi$ being only 2,7° to reduce the systematic error of the speed measurements caused by $\cos\varphi$. The axis of the radar sensor crossed the middle of the corresponding lane exactly at the second piezoelectric cable.

Only the results from the middle antenna were evaluated. For a correct comparison it must be ensured that the device under test and the reference system measure the speed of the vehicle simultaneously. To fulfil this requirement we used the measured speed value of the time which corresponded to the measured distance of 40 m. The small systematic error caused by $\cos\varphi$ was taken into account by multiplying the result by $\cos\varphi = 0{,}999$ afterwards. Figure 4 shows the results as a histogram of the distribution function.

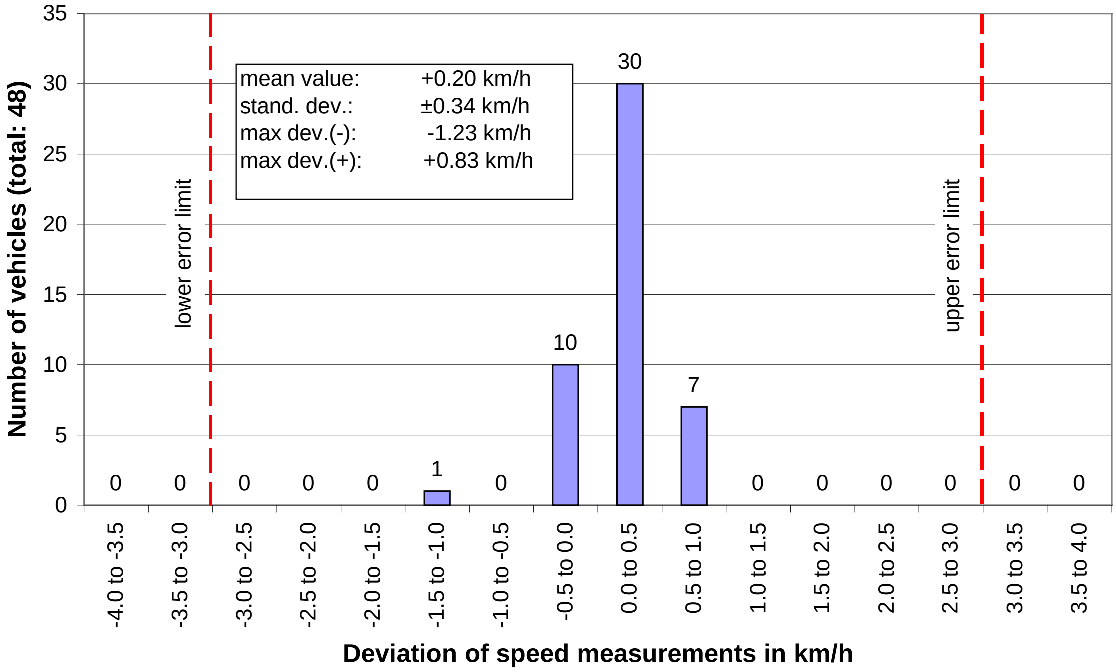


Figure 4: Comparison of the speed values measured by the new radar sensor with those measured by the PTB reference system.

The red broken lines show the error limits mentioned above. In metrology the histogram is mainly characterised by the deviation of the mean value and by the standard deviation. The number of compared values is limited (48 vehicles) but sufficient to estimate the standard deviation of 0,34 km/h. This means that the difference between the mean value and the error limit in favor of the offender equals more than 8 standard deviations. This very good result clearly fulfils the requirements of type tests in Germany and clearly shows that the technology of the new sensor promises to be suitable also for speed enforcement purposes. Of course more detailed tests and, in particular, a larger number of vehicles would be required for type approval.

The data obtained from the first measurements were found to be very promising, although only minor modifications were made. The optimisation of the analog and digital signal processing has not been finished by far. For the final design of the radar system under development, it can be estimated that for the standard deviations of distance and speed values of less than 1 m and about 0.2 km/h can be achieved.

## CONCLUSIONS

The novel feature of the new sensor is that the sensor not only measures the speed of a passing vehicle but also its distance to the radar device. This is done by separately measuring the frequency shift caused by the doppler effect and the length of the radar beam path between the sensor and the reflecting object. This promises to help the police in their work for speed enforcement because it enables them to correctly assign the measured speed to a vehicle shown in a photograph even in those special traffic situations that cause inconvenient measures for existing traffic radars. In situations of double reflection the falsification of the speed measurement can easily be detected by checking the measured distance. The same is true for the possibility of erroneous assignment caused by cracked beam reflection. The new sensor also helps to correctly assign the measured speed to one vehicle if two vehicles pass the beam at the same time in dense traffic, as a separation of two vehicles is possible even if their distance is lower than 5 m. Comparison tests of the sensor´s speed measuring function with a PTB reference system showed that the accuracy requirements for a type approval in Germany can be fulfilled. The technology of the new sensor has, therefore, proved to be advantageous as the core of future radar systems to be used for speed enforcement.

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