Polarimetric RCS Analysis of Traffic Objects

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***Abstract*—Polarimetry capable antennae, with a unique design feature, are presented which were used to perform radar cross section (RCS) measurements of traffic signs at 77 GHz. An analysis of the results in the light of near field phenomena is presented and compared with previous work.**

It has also been shown, that guide posts have a unique RCS signature and that this can be used to discriminate them from metal posts.

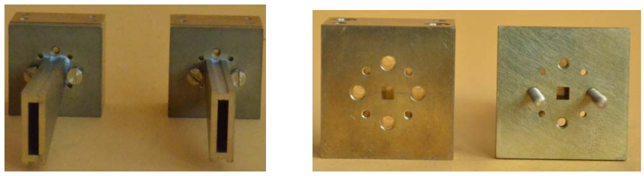
I. Introduction

While polarimetry has long been used in aerospace and space industry, there has not been a significant application of it in the automotive sector. Additionally, the number of publications investigating traffic objects are limited. [1] and [2] have measured the radar cross sections (RCS) of traffic objects, however they have not carried out any polarimetric analysis. Polarimetry offers the opportunity to obtain additional information, as opposed to non-polarimetric sensors, which may make the system more robust. This paper thus presents both co and cross-polarised RCS patterns of traffic signs with detailed discussion. Near field RCS patterns of metal plates have also been reported in literature. Published in [3] are extensive near field RCS measurements of circular as well as square metal plates. Results of simulations and RCS measurements of metal plates are also published in [4]. The results presented in this paper are backed by publications [4] [3]. Additionally, new results are also presented where the cross-polarised returns are shown and discussed.

In this work, horn antennae have been designed and fabricated for polarimetry and subsequently fixed to an FMCW radar sensor, working in the 77 GHz band with a bandwidth of 5 GHz, which was used to perform RCS measurements of traffic signs.

II. Antenna Design

In order to carry out a thorough investigation of traffic signs using polarimetry, an important requirement was for the antennae to provide strong decoupling between the co and cross-polarised radar returns. Hence it was decided to design a couple of horn antennae since they offer good polarisation decoupling and are relatively easily designed. One important factor to consider was the fact that, the aperture of the antennae be identical to ensure that both the antennae probe the same volume in space. This requirement of identical apertures, however, created a challenge where the orientation of the feeds of the antennae would have to be rotated 90° with respect to each other due to the orthogonal polarisation. But then the apertures would be rotated as well. It was therefore decided to make a square feed for the horn antennae which would ensure that there is rotational symmetry and then to design a transition which would gradually taper from an E-band (WR-12) waveguide to the square feed of the horn antennae.



(a) Horns with identical aperture. (b) Square feed of horns.

Fig. 1. The fabricated horn antennae.

In Fig. 1a, the two horns with identical apertures can be seen. The narrow opening in the azimuth plane causes the beam to be quite wide in azimuth. This ensures that the targets (also larger ones) lie completely in the main beam. Fig. 1b shows the square feed of a horn antenna on the right and on the left, the transition can be seen with its horn compatible side. On the opposite side of the transition is an E-band waveguide compatible opening which may be oriented either in the E-plane or the H-plane by a rotation of 90°. Shown in Fig. 2 are the co and cross-polarised patterns. Both horns have a measured gain of 17 dB.

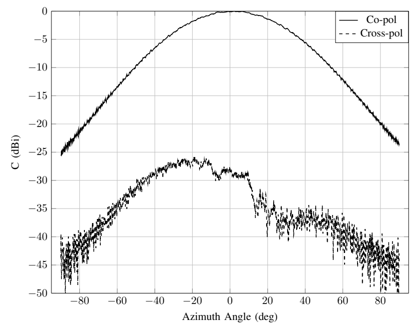


Fig. 2. Measured beam patterns of the fabricated horns.

III. Measurement Set-up & Calibration

The RCS measurements were carried out in an anechoic chamber where the target was fixed on a rotary stand which was programmed to rotate in steps of 1° starting from 0° and ending at 359°, with the radar taking a measurement after every step. The measurement set-up is illustrated in Fig. 3a where the positions of the target and the sensor are shown. The range to the target was approximately 5.8 m. The orientation

TABLE I
RCS CALIBRATION VALUES.

Calibration Object	Dimensions (cm)	Theoretical RCS (dBsm)	Measured RCS (arb. u.)
Sphere	⌀ 30	−11.51	−97.1
Test Object	Dimensions (cm)	Theoretical RCS (dBsm)	Measured RCS (dBsm)
Plate	9.1 × 7.1	15.4	13.3
Plate	8 × 8	15.3	11

of the traffic sign with respect to the azimuth angle can be inferred with help of Fig. 4.

(a) Schematic of measurement setup. (b) Warning sign placed on rotary stand (shown here at 180° position).

Fig. 3. RCS measurements setup.

For the calculation of the RCS of the traffic objects, the radar had to be first calibrated. For this purpose, three simple targets were employed; a metallic sphere and two metal plates. The sphere was chosen for the actual calibration where it's reflected signal power was measured and then used together with the theoretical RCS of a sphere (RCS: $\sigma = \pi \cdot r^2$) to measure the RCS of two metal plates [5]. This way the measurement set-up and procedure was tested to be accurate. The results of the calibration are summarised in Table I.

An important point to be noted here is that the RCS measurements carried out within the scope of this paper were performed in the near field region. This makes sense as the traffic signs are almost exclusively in the near field for all relevant purposes, as even the smallest traffic signs have at least one dimension of approximately 50 cm which would mean the far field region is at a distance of more than 128 m. This distance is at the edge of the operational range of an automotive radar. For larger signs, the far field region is even further away.

IV. MEASUREMENT RESULTS

Fig. 5 shows the co and cross-polarised RCS patterns of guide (dielectric material, photo embedded) and metal posts. The metal post was the same as that used for the placement of traffic signs. However, for this measurement the sign was removed, only the cylindrical post was the target. The metal post has a uniform co and cross-polarised RCS signature

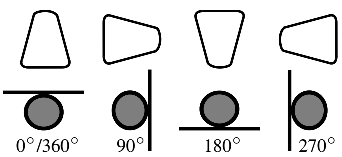


Fig. 4. Orientation of guide post (top) and traffic signs (bottom).

owing to it's symmetry. The guide post, though it has a lower RCS signature due to it being composed of a dielectric material, has two distinct sharp peaks at 105° and 255° in both the co and cross-polarised pattern. These two angles correspond to the point where the two broader sides of the post were aligned such that their specular reflection's main lobe coincided with the position of the radar. At all other angles, the curved surfaces of the post reflected the incident waves away from the radar.

Based on this knowledge, it is possible to differentiate between a guide and a metal post. The metal post must not necessarily be just the pole used to hold up a traffic sign, rather it could also be the bottom part of a traffic or street light for example. The emphasis is on the bottom bit because this effect is best utilised at close ranges where the traffic sign is too high to lie in the main beam of the automotive radar which is normally placed low in the front bumper of the car. Hence, if the received power exhibits narrow sharp peaks in both co and cross-polarised channels, one can be certain that the object is a guide post. Otherwise, if the received power does not fluctuate, rather maintains a uniform profile, the target must be a cylindrical object.

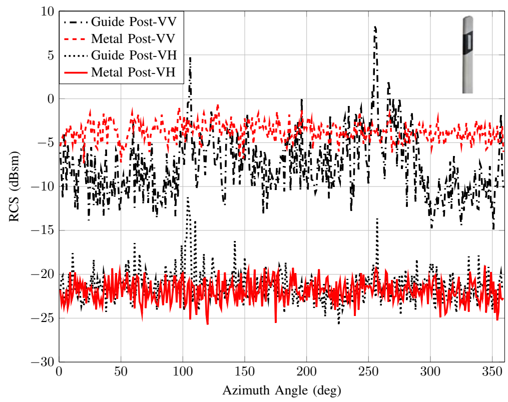
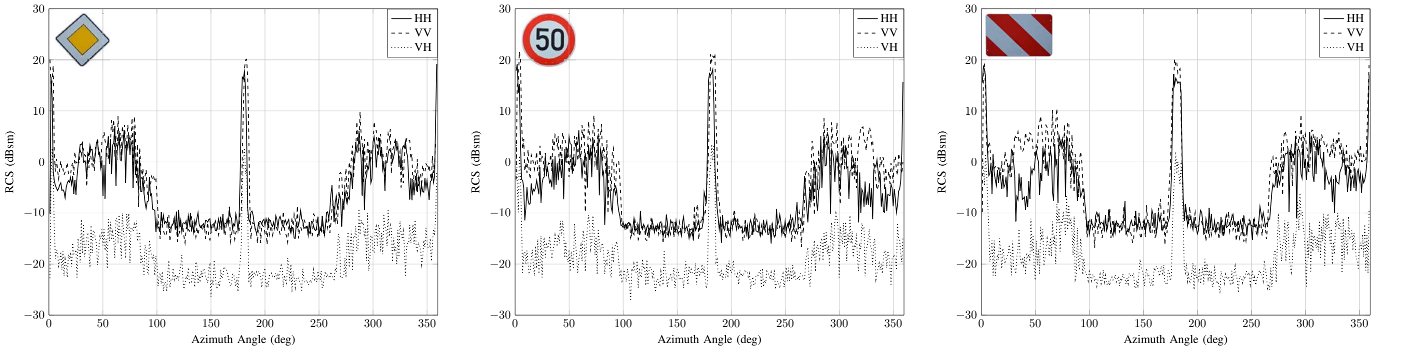


Fig. 5. RCS of metal and guide post (height of guide post = 173 cm, height of metal post = 210 cm).

The RCS patterns of traffic signs are shown in Fig. 6. In Fig. 6a is the RCS pattern of a priority sign which is the smallest traffic sign to be measured. Depicted in the plot are the two co-polarised patterns, HH and VV, as well as the cross-polarised pattern, VH. All three patterns in Fig. 6 (HH, VV and VH) are very similar other than the amplitude offset except in the vicinity of 180°. The offset between HH and VV is roughly 3 dB while between co and cross-polarised is about 15 dB. At 180° the radar return is the strongest because the traffic sign is aligned directly toward the sensor and a maximum amount of the incident energy is reflected back towards the source. However, when the traffic sign is rotated, the plate deflects the incident energy away from the source and thus a minimum of energy is reflected back towards the radar [6]. This effect is illustrated in Fig.7a. When the traffic sign is rotated past 270° (or before 90°) the pole on which the traffic sign has been fixed and the back of the sign form a simple dihedral corner,



(a) Priority sign (57 × 57cm).
(b) Speed limit sign (⌀ = 60 cm).
(c) Warning sign (75 × 50cm).

Fig. 6. RCS measurement results.

as can be seen in Fig. 7b, which reflects a significant portion of the energy back towards the radar. This behaviour is quite well documented by previously published RCS measurements [1]. Next in Fig. 6b, the RCS pattern of the speed limit sign can be seen, which is slightly larger than the priority sign. And finally in Fig. 6c, the RCS pattern of the warning sign is plotted.

(a) Sign deflecting incident energy.
(b) Corner formed by sign and pole.

Fig. 7. Behaviour of traffic sign dependent on orientation.

A few observations can be made when the region in the vicinity of 180°, is considered. Firstly, the peaks are not smooth as would be expected from a metal plate [6], rather they exhibit peak splitting and this effect is strongly pronounced for the cross-polarised pattern. The second point is the broadening of the main lobe of the RCS pattern for larger traffic signs as compared to the smaller ones. The main lobe of the priority sign shown in Fig. 6a is the slimmest and it gradually becomes broader for the speed limit sign shown in Fig. 6b and is the broadest for the warning sign shown in Fig. 6c. However according to previous scientific studies, the main lobe of an RCS pattern of large metal plates is slimmer than that of smaller plates [6]. These observations are looked into in detail in the next two subsections.

A. Influence of Near Field on RCS Measurements

To better analyse the behaviour of the traffic signs, the measurement was re-done for the warning sign with more samples between 170° and 190°, in steps of 0.1°. The RCS pattern obtained from this measurement is shown in Fig. 8.

From Fig. 8 it is possible to see the profile of the RCS pattern as the traffic sign rotates through the point where it is aligned to the boresight (at 180°) of the radar. The RCS pattern for HH and VV are very similar except for the difference in amplitudes of roughly 3 dB. The HH and VV plots plateau between approximately 177° and 184°. This is contrary to what is expected when a large metal plate is rotated and it's RCS measured. However, for all such measurements it is usually assumed that the RCS measurements are performed where the far field condition for the target has been fulfilled. This does not hold true in this case, though. To fulfil the far field criterion, the distance between the radar and target would have to be increased to more than 290 m, which is neither realistic nor possible for the reasons mentioned earlier in Section III. Similar near field RCS patterns for metal plates have been reported in literature [3] [4].

To confirm the results illustrated in Fig. 8 and to validate the reason for such results, more measurements were carried out to measure the RCS of three metal plates of differing sizes to see if the behaviour seen above can be explained due to the near field measurement of RCS. The largest plate is actually a highway location sign which has been used here to validate results. The set-up for this measurement remained the same as mentioned in Section III. The results of the measurement are illustrated in Fig. 9. The dimensions of the metal plates as well as the distance to their respective far field regions (**Fraunhofer distance**) are summarised in Table II.

From Fig. 9, it can be seen that the profile of the near field RCS of the medium and large metal plate are very similar to the traffic signs. That of the small metal plate, however, is very different and resembles a metal plate in the far field. The results validated here are cogent, as in the near field the

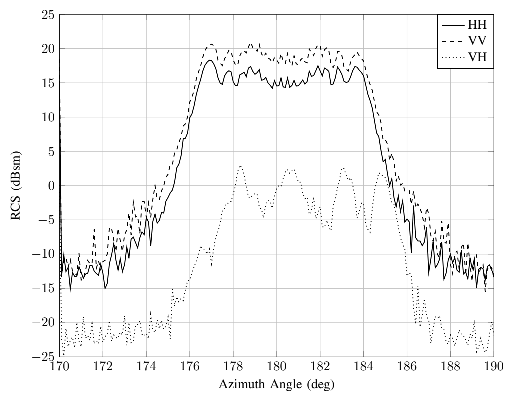


Fig. 8. RCS of warning sign zoomed in between 170° and 190°.

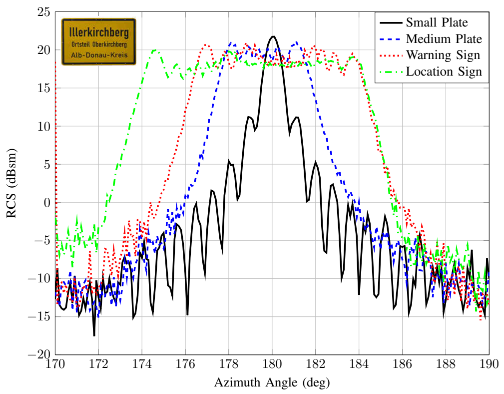


Fig. 9. Zoomed RCS of metal plates of varying sizes (co-polarised: VV).

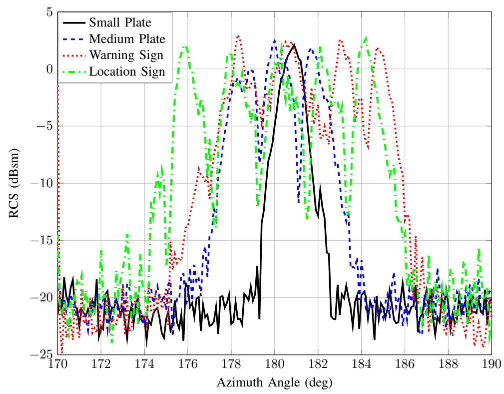


Fig. 10. Cross-polarised (VH) RCS patterns of the metal plates and the warning sign.

TABLE II
FAR FIELD REGION OF METAL PLATES (& TRAFFIC SIGNS).

Object	Dimensions (cm)	Fraunhofer Distance (m)
Small Plate	13.5×12.5	9.4
Medium Plate	50×30	129
Warning Sign	75×50	281
Large Plate (Location Sign)	100×65	500

waves are spherical and cannot be assumed as plane waves. This is more true as the target object becomes larger. Hence, the tips of the wave reflected from the target travel a distance which is different from what the middle part of the wave travels. This leads to a phase difference and thus to stronger interference effects at the radar. In the far field region, the waves are no longer spherical but plane and hence a narrow lobe corresponding to the direction of specular reflection is formed [6] as there is only a negligible phase difference between the tips and the centre of the wave. In summary, it has been shown with measurement results and previous publications that the traffic signs can be modelled as metal plates.

B. Effects of Edges on Cross-Polarised Returns

So far in the paper the cross-polarised returns from the targets have not been discussed. The cross-polarised pattern can be seen for the warning sign in Fig. 8. There is a prominent pattern here of sharp peaks and troughs occurring periodically. To analyse this effect, one has to keep in mind that the plot shows the depolarised return from the target, that is the incident polarised waves, in this case horizontally polarised, whose polarisation was rotated to be vertical when they interacted with the object. In the region between 170° and 190°, the edges of the traffic sign are responsible for the rotation of the polarisation [7]. The metal plate itself only reflects co-polarised waves back, however, the edges can cause depolarisation. The peaks are the locations where the waves interfere constructively and at the troughs, they interfere destructively.

Another interesting phenomenon which deserves to be mentioned is that the larger the plate, the larger the number of peaks and troughs. This is due to the fact that even small rotations of a large plate cause large changes in the path differences of reflected waves and hence more opportunities or locations where the conditions of interference are fulfilled. This is shown in Fig. 10 where the cross-polarised return from the three plates are shown together with the warning sign. The medium plate is smaller than the warning sign and hence it has a smaller number of peaks and troughs. The warning sign in turn is smaller than the location sign, thus the warning sign has a smaller number of peaks. The location sign has the broadest pattern and the most number of peaks owing to it's large dimensions.

V. CONCLUSION

Based on the RCS measurements of traffic objects shown and the analysis thereof, it has been argued that a metal and a guide post can be differentiated based on their RCS signatures. Evidence, that the dimensions of the target have a direct effect on the cross-polarised RCS pattern, was also presented.

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