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Convergence of Scattering Parameters and $H\alpha A$-Features of Road Surfaces

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***Abstract*— The convergence of polarimetric scattering parameters and H, α and A features of road surfaces under various conditions is analysed. It is shown that the number of radar measurements used for surface classification can be traded off with accuracy of the estimation of the mean value and covariance of S-parameters and H, α and A features. Furthermore, it is shown that the H, α and A features converge at the same rate, independent of antenna orientation angles or considered road surface conditions.**

***Keywords*— Polarimetric radar, automotive, classification, surface scattering.**

I. Introduction

To enhance road safety, vehicles are often equipped with automotive radar systems. With the transition to the 77 GHz band from the longer wavelengths found at 24 GHz, new opportunities arise to also use radar to detect road surface conditions in front of the vehicle, as the shorter wavelengths result in more powerful backscattering from the road surface.

Currently, all commercial automotive radar systems operate with single polarisation. However, fully polarimetric radar can increase situational awareness and classification performances by using polarimetric information [1]–[4]. In [4], classification of road surfaces using polarimetric radar and the $H\alpha A$ decomposition was proposed. With that statistical method, the classification accuracy is dependent, among other factors, on the number of measurement samples. Hence, this paper analyses the convergence of the scattering parameters and the H, α and A features. This aspect affects the refresh rate of a road surface classification system and the distance a radar platform needs to move along the surface to complete surface classification. This study on convergence helps to minimise the amount of required measurements, which maximises the refresh rate and minimises the distance the radar platform must travel.

The rest of the paper is organised as follows: section II introduces the $H\alpha A$ decomposition, while sections III and IV present the measurement setup/procedure and the experimental results respectively. Section V discusses the relevance of the convergence and section VI concludes the paper.

II. Theoretical Background

The $H\alpha A$ decomposition was originally introduced for synthetic aperture radar [5] to determine the existence and the characteristics of a dominant scattering mechanism within an ensemble of cells. This statistical approach operates on the eigenvalues of the coherency matrix T, computed using (1):

$$T = \left\langle \vec{k}\vec{k}^{\dagger} \right\rangle . \tag{1}$$

In (1), the vector $\vec{k}$ is the so-called target vector and is defined as in (2). The dagger symbol represents the conjugate transpose operator and the angled brackets indicate spatial averaging. To prevent averaging over scattering with different statistical properties due to large variations in incident angles at the rough surface that occur in automotive scenarios, the averaging in this study is done over multiple range profiles instead of over ranges within the same profile.

$$\vec{k} = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{XX} + S_{YY} & S_{XX} - S_{YY} & 2S_{XY} \end{bmatrix}^{T} \tag{2}$$

In (2), S_{XX} indicates the scattering parameters as measured in a XX polarimetric basis. In this paper, a horizontal/vertical polarisation basis is used, thus X corresponds to V polarisation while Y corresponds to H polarisation.

By performing an Eigendecomposition on T, the eigenvalues λ_i and corresponding eigenvectors $\vec{u_i}$ are found, with $i = 1$ corresponding to the largest eigenvalue and $i = 3$ to the smallest. From these three eigenvalues, three features can be computed: entropy, denoted by H, the angle α, and anisotropy, denoted by A. More details on the developed signal processing pipeline to extract these features in automotive applications and how the averaging of the coherency matrix is performed in these scenarios can be found in [4].

The *entropy* characterises the randomness of backscattering from a target, with low values indicating scattering from a discrete target and high values from highly random targets like tree canopies. The *feature* α provides information on the character of the average scattering mechanism. A value of 45° corresponds to scattering from a cloud of anisotropic particles, while 90° corresponds to scattering from dihedral reflectors. The *anisotropy* measures the relative importance of the smallest and the second-largest eigenvalues. This helps to distinguish between targets that show completely random scattering, i.e. equal eigenvalues, and targets which have two dominant scattering mechanisms. Based on the combination of the values of H, α and A, a classification of the scattering of a target can be made. For example, scattering with low α and H features can correspond to Bragg sea surface scattering for L-band synthetic aperture radar. [5]

III. Experimental Measurements

Measurements were performed using an N5242A Vector Network Analyser (VNA) with frequency extenders to cover the 75-85 GHz band and a dual polarised horn antenna. The setup was mounted on a support structure enabling to adjust the antenna orientation angle, with values of 60° and 90° used in this work. The antenna orientation angle is defined as the angle between the antenna broadside direction and the surface normal vector. A picture of the measurement setup is shown in Fig. 1, with more details presented in [4].

The setup was calibrated using a short-open-load-through procedure. To further remove measurement errors introduced by the antenna, due to i.e. length differences between the horizontal and vertical polarised channels, reference measurements were performed on a metal sphere. As the scattering parameters of a metal sphere are known, the reference measurements can be used to correct these errors.

To collect statistically relevant measurement data of different road surfaces, the following measurement procedure was used. Firstly, the road surface was prepared to represent the desired conditions, which were dry asphalt, wet asphalt and asphalt covered with basalt in this work. Subsequently, the setup was positioned such that a different uncorrelated part of the surface was measured compared to previous measurements. This was done by moving the measurement setup a few centimetres along the surface, as a previously performed study on statistical properties of asphalt surfaces showed that the correlation length of their surface roughness is about 2 mm. This procedure was repeated 50 times for each road surface condition. Finally, the measured range profiles were divided by a normalised range profile. This normalised range profile was computed using a numerical procedure outlined in [6], where a surface is discretised into many uncorrelated scattering points with normalised radar cross sections of 1. Dividing by the normalised range profile compensates for the imbalance of returned power due to different antenna gain and propagation losses between parts of the surface that are close to the antenna, and parts of the surface that are located far away.

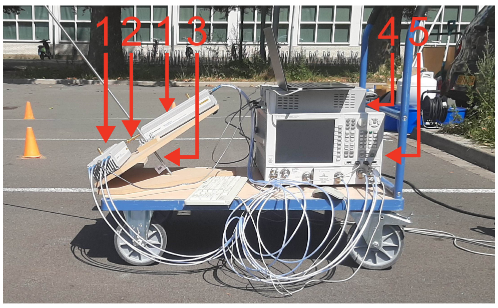

Fig. 1. Measurement setup with VNA (5), frequency extenders (1) powered by auxillary power supplies (4), and dual polarised horn antenna (2) mounted on a support structure (3) to measure various road surface patches under various antenna orientation angles.

IV. Experimental Results

In this section, the convergence of the measured scattering parameters is considered. To do this, the difference between a statistical quantity Q, denoted by ΔQ, calculated based on N measurements, indicated by $Q(N)$, and the same statistical quantity Q based on $N-1$ measurements, denoted by $Q(N-1)$, is computed as shown in (3). The statistical quantity Q can for example be the mean value of the magnitude of S_{VV}, denoted by $\langle |S_{VV}| \rangle$, or the covariance of $|S_{VV}|$ and $|S_{HH}|$.

$$\Delta Q(N) = Q(N) - Q(N-1) \tag{3}$$

Furthermore, ΔQ can be normalised to make the comparison of multiple statistical quantities possible, e.g. $\langle |S_{11}| \rangle$ & $\langle |S_{22}| \rangle$.

Fig. 2 shows the trend of the convergence of the mean value of the measured scattering parameters of dry asphalt measured with an antenna orientation angle of 60°. The difference is normalised by the largest computed difference within the corresponding range bin. As expected, it can be seen that the computed mean value converges with the normalised difference going to zero as the measurements are uncorrelated. It can also be seen that including more and more measurements leads to diminishing returns due to incoherent summing and division by the number of measurements. Another important observation is that the difference does not reduce gradually, but sometimes experiences a peak within a range bin. This can be explained by a measurement that has a particularly high or low value compared to previous measurements. The mean convergence rate, C, is then computed, which is the mean value taken over the range bins for a number of included measurements N as shown in (4).

$$C(N) = \sum_{i=1}^{M} \frac{\overline{\Delta Q_i}(N)}{M} \tag{4}$$

Here, M indicates the number of range bins over which the mean is computed and $\overline{\Delta Q_i}(N)$ is the normalised difference of the statistical quantity ΔQ in the range bin i, computed from N measurements.

Fig. 3 shows the mean convergence rate for the mean values of the measured scattering parameters of dry asphalt, measured with an antenna orientation angle of 60°. All scattering parameters converge on average at the same rate. Furthermore, this figure can be used to determine the number of measurements that must be taken to achieve a difference in the computed $\langle |S| \rangle$ that is on average less than a specified threshold. For example, to achieve a mean difference of less than 10% compared to the previous N measurements, at least 19 measurements need to be performed.

A similar analysis can be performed for the covariance of the 4 scattering parameters in Fig. 4. Compared to the mean values, these values converge faster. To achieve a mean difference of less than 10%, 15 measurements are required.

Next, the convergence of the H, α and A features is considered, introduced for road surface classification in [4]. Figs. 5 to 7 show the mean convergence rates of these features for dry asphalt, wet asphalt and asphalt covered with gravel, all measured with an antenna orientation angle of 60°. From these figures, it can be seen that overall, the anisotropy feature is the slowest to converge. This can be caused by the coherency

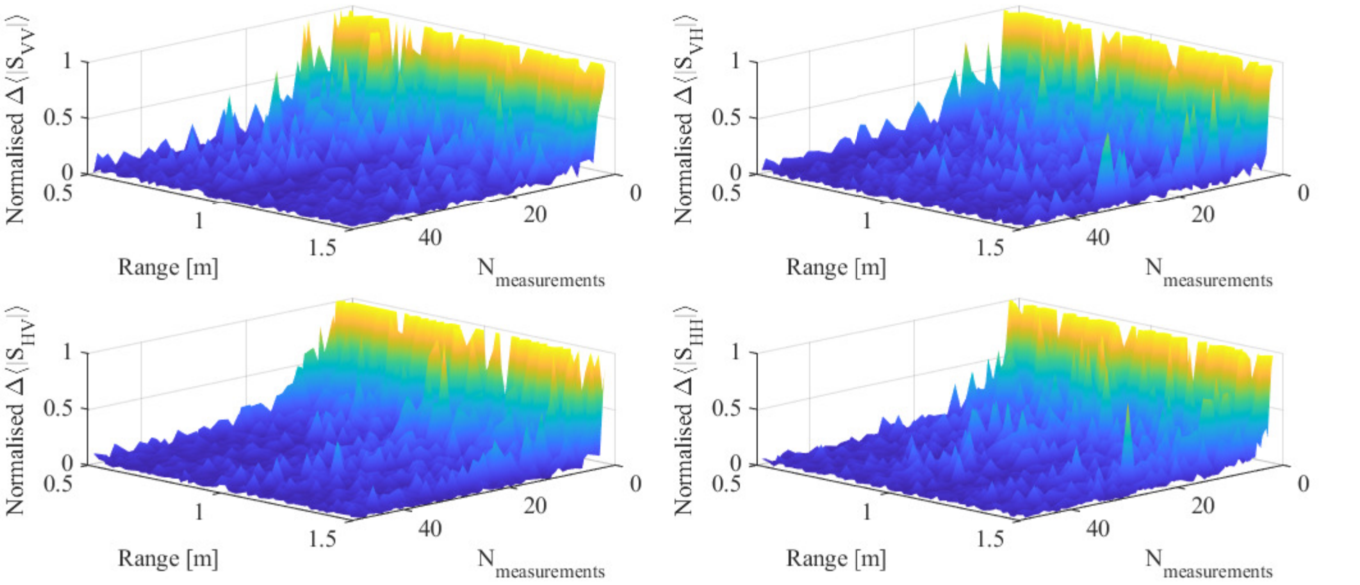

Fig. 2. Convergence of the mean value of the measured scattering parameters of dry asphalt, measured with an antenna orientation angle of 60° as function of range and number of included surface measurements.

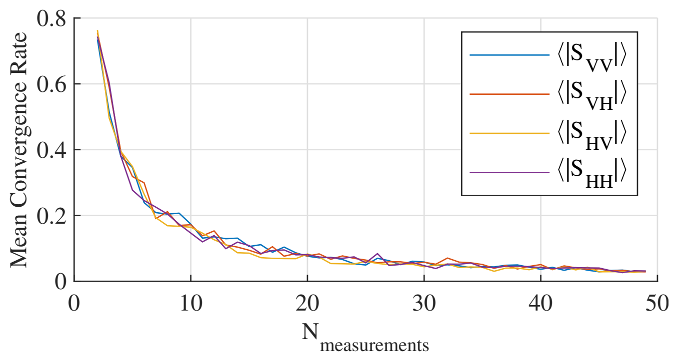

Fig. 3. Mean convergence rate of the mean values of the measured scattering parameters of dry asphalt, measured with an antenna orientation angle of 60°.

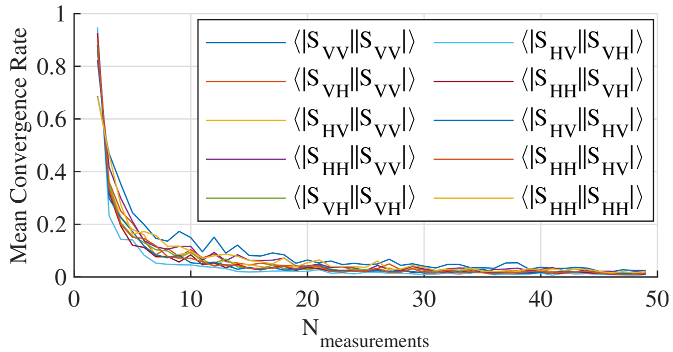

Fig. 4. Mean convergence rate of the covariances of the measured scattering parameters of dry asphalt, measured with an orientation angle of 60°.

matrix having a low eigenvalue which is sensitive to noise and thus more measurements are required to average out its effect. Also, for wet asphalt, the mean convergence rate shows sharper deviations from the general decreasing behaviour. This can be explained by the measured scattering parameters of this class

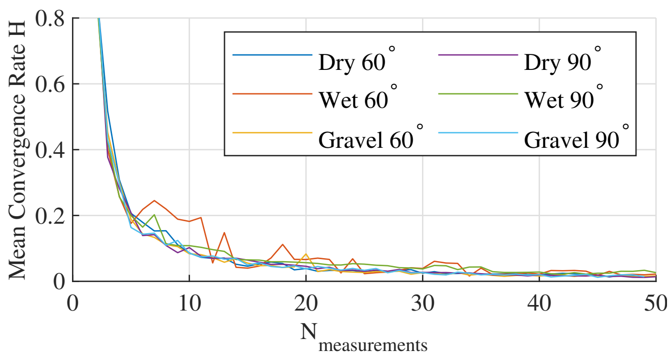

Fig. 5. Mean convergence rate of the entropy H feature of dry asphalt, measured with antenna orientation angles of 60° and 90°.

being closer to the noise floor of the VNA, and thus being more influenced by noise.

It can be seen that about 36 measurements are required to achieve mean convergence rates below 0.1 for the wet asphalt condition. When an occasional mean convergence rate slightly above 0.1 is acceptable, 25 measurements may suffice.

Similarly, for the case of the measurements that were performed with a 90° orientation angle, the mean convergence rate of the H, α and A features can be considered. Figs. 5 to 7 show that these converge at a similar rate as the feature values measured with an orientation angle of 60°. Thus, in general, a similar number of measurements as with the 60° orientation angle is required to achieve a specified mean convergence rate.

V. Discussion on the Relevance of Convergence

The analysis of the convergence is important as it is related to the number of measurements of road surface scattering needed for an accurate classification. This has two implications. First, the measurement time with the resulting

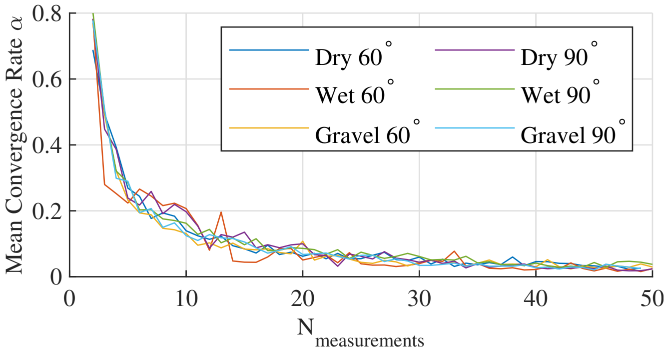

Fig. 6. Mean convergence rate of the α feature of dry asphalt, measured with antenna orientation angles of 60° and 90°.

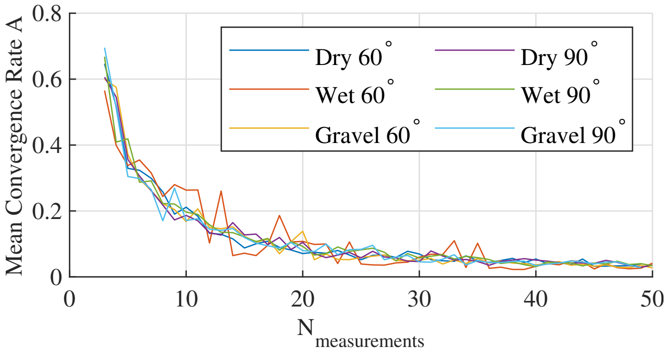

Fig. 7. Mean convergence rate of the anisotropy A feature of dry asphalt, measured with antenna orientation angles of 60° and 90°.

distance that is covered by a vehicle. If e.g., the measurement time of the radar system is 50 µs and 50 measurements are required to achieve the required level of convergence, then the total time to classify a surface condition is 2.5 ms. If a car is moving at 100 km/h (27.8 m/s), the distance travelled during the measurement time is about 6.9 cm. Depending on the measurement time and the amount of required measurements, the distance travelled by the car during the measurement period may become significant enough to reduce the effectiveness of the road condition estimation.

The second implication is related to the requirement that each road surface measurement should be uncorrelated with the previous one. This means that each surface measurement should be spaced one or more correlation lengths from the previous sample. For example, when the longest correlation length of a road surface condition is 5 mm, then the total distance that needs to be covered is 25 cm in the case of 50 required measurements. This means that a puddle of water or a patch of ice or other road surface condition needs to be at least 25 cm in length.

These two cases show that it is important to analyse the convergence of the H, α and A features, as it determines the distance a car travels during a road surface classification measurement and the length of surface that needs to be covered to achieve accurate results. Namely, by reducing the number of required measurements as much as possible, the refresh rate of the surface classification system can be increased, while the distance travelled by the vehicle and the required road surface condition size can be minimised.

VI. Conclusion

In this paper, the convergence of the polarimetric decomposition for radar-based road surface measurements was investigated. It is crucial to investigate the convergence of the measured statistical quantities as it places bounds on the accuracy of the computed statistics. Furthermore, the required level of convergence determines also the number of measurements that need to be practically acquired. This in turn influences the refresh rate of a road surface classification system and determines the amount of surface area that must be covered by the platform in the process.

To provide insights in the convergence of S-parameters and polarimetric H, α and A features, measurements of various road surface conditions were performed using a VNA. The considered road surface types were dry asphalt, wet asphalt and asphalt covered with basalt. The mean convergence rates of the mean and covariance of the S-parameters were computed, as well as the mean convergence rates of the H, α and A features. It was found that the covariances of the S-parameters converge faster than their mean values, and out of the three considered features, the entropy feature is the fastest to converge. Finally, it was shown that the features of the three road surface classes converge at the same rate, independent of the antenna orientation angle they were measured with, or the road surface condition they were calculated for.

Acknowledgement

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