Progress In Electromagnetics Research, PIER 104, 125–143, 2010

DISCUSSION ON VALIDITY OF HADAMARD SPECKLE CONTRAST REDUCTION IN COHERENT IMAGING SYSTEMS

F. Qi, V. Tavakol, D. Schreurs, and B. Nauwelaers

Division ESAT-TELEMIC
Katholieke Universiteit Leuven
Kasteelpark Arenberg 10, Leuven-Heverlee 3001, Belgium

Abstract—Hadamard speckle contrast reduction (SCR) is considered to be an effective approach to deal with speckle problems in coherent imaging systems. A Hadamard SCR system is divided into two sub-systems, which implement phase patterns projection and reflected waves imaging respectively. The performances of both sub-systems are discussed with numerical simulations and linked to certain parameters so as to give more insights of this approach. For generality, both optical and millimeter wave imaging systems are discussed. To distinguish from former literature based on Fourier optics, the simulation is implemented via wave optics, which is more physical and more accurate. Moreover, considering the fact that the Hadamard method originates from statistics, the effectiveness of Hadamard SCR is in the first place linked to the texture of the object's surface. Statistical optics is also adopted during qualitative analysis of the results. It is shown that the ratio between the dimension of a resolution cell and the granular size of the object's randomly rough surface is closely linked to the performance of Hadamard SCR. Differences in the roughness model in imaging cases of optical and millimeter waves are discussed, which would help to evaluate the validity of the Hadamard SCR approach in practice. The purpose of this paper is to clarify the misunderstandings of Hadamard SCR in previous literature and to give a guideline to apply this approach.

1. INTRODUCTION

The history of speckles is almost as long as that of lasers [1]. However, the phenomenon does not only appear in optics, but also in the area

Corresponding author: F. Qi (feng.qi@esat.kuleuven.be).

of ultrasound [2], microwave [3] and millimeter waves [4]. So speckle is a universal topic for all the researchers who work on coherent imaging systems. From physics point of view, speckles result from coherent illumination and the rough surface of the object. The reflected waves interfere and the propagated fields are distorted. Detectors on the image plane sense the non-uniform field distributions. By coupling the incident power on sensors, detected signals fluctuate and speckles appear on the attained images. Speckles generally blur the image, making information extraction quite difficult even by image post-processing techniques [5]. In some serious cases, images are totally blurred and can not be recognized at all [1].

A lot of efforts have been spent to deal with speckles for decades, in which researchers in optics have contributed a lot. So the experience in optics forms a good starting point nowadays for understanding speckles and exploring speckle reduction techniques. Hadamard SCR is considered to be a phase diversity technique, which aims at reducing speckles. By using Hadamard 64, Trisnadi firstly presented a successful experiment at 532 nm with a nice agreement compared to theoretical predictions [6]. The working principle is explained based on the concept of point spread function (PSF) and geometrical optics. In [5], the Hadamard SCR system is simulated by Fourier optics at 100 GHz with corresponding SCR performance of 75% for Hadamard 4 and 62% for Hadamard 16 compared to the theoretical values of 2 and 4 respectively. In [7], the experiment setup at 100 GHz shows 80% SCR compared to the theoretical value by applying Hadamard 4. Moreover, Hadamard phase patterns are considered to be able to destroy the coherence of the illumination [8, 9] and even transform coherent millimeter illumination into incoherent illumination [9]. In existing literature, the performance of Hadamard SCR is quite positive and basically agrees with theory in both optical and millimeter wave cases. The question we will address is under which conditions the method can function and how good the performance should be. During the shift from optical to millimeter wave imaging systems, there are some other issues that should be considered.

This paper will be structured as follows: the principle of Hadamard SCR in coherent imaging systems is briefly reviewed first; next, by dividing a Hadamard SCR system into the sub-systems which implement the functions of phase projection and reflected waves imaging we discuss the performance of each sub-system in both optical and millimeter wave cases at selected wavelengths of 500 nm and 3 mm respectively. Objects with random roughness of different granular sizes are investigated. The results are analyzed qualitatively by wave optics and statistical optics respectively and we link the performance of Hadamard SCR to the ratio between the granular size of the random roughness and the dimension of a resolution cell In Section Four, objects' roughness models at optical and millimeter wave frequencies are compared both physically and mathematically, which would help to judge the validity of Hadamard SCR approach. After pointing out the improper statements in previous literature, conclusions are given in the end.

2. PRINCIPLE OF HADAMARD SCR OPERATION

Hadamard matrix was firstly proposed by researchers in statistics, and it is considered to be the optimum weighting design for extracting information from random noise [10]. It has been applied successfully in optical measurements for decades, but its application in coherent imaging systems started only recently [1, 11].

Mathematically, the Hadamard matrix is made up of 1's and −1's only and it can be constructed in a recursive way [10]. For coherent waves, its practical implementations are no more than the regular arrangement of the binary phase shifts of 0 and pi. The trick is that the Hadamard matrix realizes orthogonality between any two columns and rows in the simplest way [11].

In coherent systems, waves interfere based on amplitudes rather than intensities, indicating that it allows minus operations of amplitudes. Consequently, for given field distributions in imaging systems, we can make use of phases to modulate the detected intensity

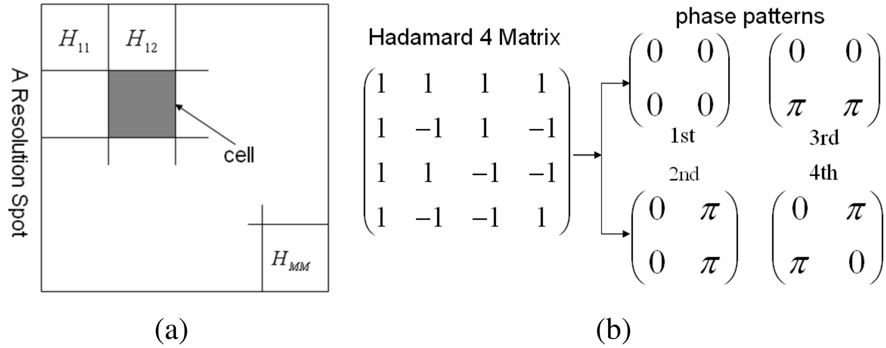


Figure 1. Illustration of a resolution spot and how to map a 4th-order Hadamard matrix to 4 Hadamard phase patterns as four two by two matrices; (a) a resolution spot (one pixel) is made up of M^2 cells, M is the square root of the order of the Hadamard matrix; (b) four Hadamard phase patterns are generated from the Hadamard 4 matrix.

inside a pixel. The sketch map for a resolution spot is shown in Figure 1(a). In Figure 1(b), we show how the Hadamard phase patterns are generated from the Hadamard 4 matrix.

For a power detector, without using the Hadamard phase patterns, the detected signal is described as (1) in [1, 6, 11]. Due to the orthogonality of the Hadamard matrix, the cross-terms will vanish during the expansion of formula (2). So formula (1) transforms into formula (2) after applying the phase patterns during the integration time of the detector. It means that the detected power is changed and for an ensemble of resolution spots, the speckle contrast will change correspondingly. Mathematically, the integral of the fields in terms of complex numbers is implemented in an N times' smaller dataset. Physically, interaction between adjacent cells is eliminated during power coupling from incident waves to a detector pixel. The M^2 cells decorrelate from each other and their contributions to the detected intensity of a resolution spot become independent. As a result, the image may suffer from less speckles.

$$I_0 = \left| \sum_{j=1}^{M} \sum_{i=1}^{M} A_{ij} \right|^2 \tag{1}$$

$$I = \frac{1}{N} \sum_{a=1}^{N} \left| \sum_{j=1}^{M} \sum_{i=1}^{M} H_{ij} A_{ij} \right|^2 = \sum_{j=1}^{M} \sum_{i=1}^{M} |A_{ij}|^2 \tag{2}$$

DENOTIONS: N: the order of the Hadamard matrix; M: the square root of N; A: integral of electrical fields inside a cell; i, j: row and column number to locate a cell inside a resolution spot; I_o: intensity of a resolution spot without applying the Hadamard operation; I: intensity of a resolution spot by applying the Hadamard phase patterns; H: weighting coefficients for each cell, as assigned by the Hadamard matrix, which is 1's and −1's only.

3. HADAMARD SPECKLE CONTRAST REDUCTION SYSTEM

A system setup for Hadamard SCR is reported in [11] and a similar system setup at millimeter wave frequencies is proposed in Figure 2. Essentially, there are two sub-systems: the Hadamard phase patterns projection system and the reflected waves imaging system. In this section, we will discuss the two sub-systems separately so as to evaluate the system performance properly.

We have developed two system modeling approaches to help understanding the imaging system, based on Fourier optics and wave

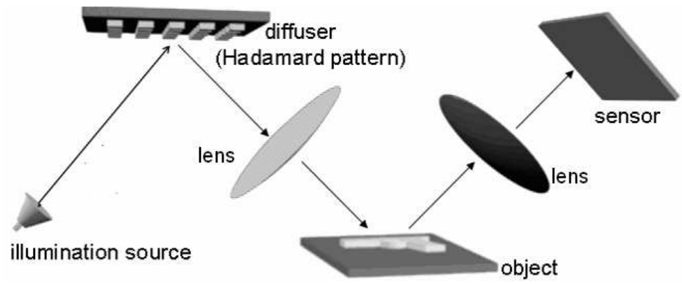


Figure 2. Hadamard speckle contrast reduction system setup at millimeter wave frequencies.

optics respectively. The latter one is selected for simulations, since it is more accurate mathematically and provides more information physically than Fourier optics [12]. The interaction between objects and incident waves is considered to be phase and amplitude modulations in our simulations, which follows the optical routine [1]. It is desirable to check the accurate scattered fields by the possibly rough objects. There are numerous papers on this topic in quite diverse scenarios from radar cross section study [13], wave propagation in troposphere [14], to indoor wireless channel modeling [15]. Numerical methods for rough surface scattering are reviewed in [16]. To sum up, the calculations are complicated and can be very heavy when good accuracy is pursued. Considering the calculation ability of common workstations nowadays, it is still too heavy to implement full-wave calculations at the system level in case of imaging studies, which forms the impetus for us to apply wave optics in the Hadamard SCR discussions. The coming analysis is completely wave-oriented and therefore the description of the problem in terms of electrical size is essential. Consequently, we should not be limited by the working frequencies. In what follows, we will check how well the phase patterns can be projected by calculating field distributions on the image plane and the performance of the reflected wave imaging system at both millimeter wave and optical frequencies. Unlike [6, 11], in which only the final synthesized image can be attained, we show all the partial images. In case of millimeter wave imaging systems, we emphasize the non-paraxial features during wave propagation by calculating diffractions, which can work beyond the limitations of Fourier optics which is applied in [5]. To quantize the discussions of speckle reduction, we follow the optical concept of speckle contrast [1], which is the ratio of the standard deviation and the mean value of all the pixels in terms of intensities.

3.1. Hadamard Phase Patterns Projection Sub-system

The phase patterns projection sub-system includes an illumination source, a Hadamard diffuser, which can be either transparent or reflective, and a projection lens. In optics, the projection sub-system is discussed with the following conclusions: if the diffuser does not overfill the projection lens, the phase patterns would be perfectly mapped to the image plane; while if the diffuser overfills the projection lens, the projection process would contribute to speckles itself [1]. It is a description from geometrical optics (GO). By applying wave optics, we will see how well practical systems can perform.

First, the projection lens is not only larger than the dimension of the diffuser, but also it can capture most radiated power from the diffuser with the main beam folded inside the lens' aperture. In this case, the performance of the projection sub-system should be attributed to the phase patterns themselves rather than other factors. According to antenna array theory, fast phase shifts are generally with large diffraction angles. So the pattern with the fastest phase shift generates the most dispersive waves. For simplification, the discussions here are limited to Hadamard 4 with different cell sizes: two wavelengths and six wavelengths respectively, among which the second one is applied in the optical experiment by Trisnadi [11]. Once the number of cells inside a resolution spot is fixed, the cell size would influence the resolution of the imaging system directly. In figure captions, the f-number of the system is expressed by $f/\#$. In Figure 3, field distributions on the imaging plane are displayed in case of a millimeter wave system at 100 GHz, including both amplitude and phase information. The fourth pattern of Hadamard 4 is selected since its spatial frequency is the highest among all the four phase patterns. By checking the radiation pattern, the lens size can be decided so as to guarantee sufficient power collection [17]. In Figures 3(a) and (b), amplitude distributions after projection are not flat, but with certain fluctuations. This phenomenon is caused by serious interference of the waves due to small dimension of a cell in terms of electrical size. In Figure 3(a), the amplitude distribution inside a cell seems like a Gaussian function. In Figure 3(b), the Gibbs ringing effect, which is the physical response of any practical system to a Dirac function, is obvious. So whenever the pi phase hop happens, it would always exist. Considering the small adopted f-numbers of 1/2 and 1/3, which are already much better than practical millimeter wave imaging systems which have an f-number around one [5], we can conclude that practical field distributions for the projected Hadamard phase patterns can not be absolutely flat. As shown in Figure 3(c), phase projections are good in case of small cells. Distortion happens when cells are large as shown

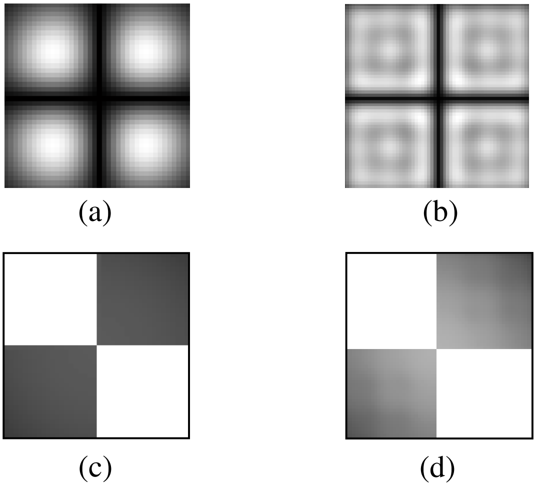
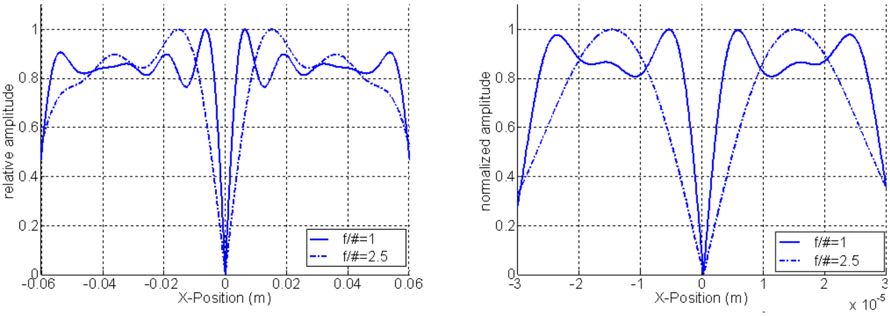


Figure 3. At 100 GHz, field distributions of the fourth pattern of Hadamard 4 on image plane in case of main beams folded inside the lens' aperture, amplification ratio is one (a) $f/\# = 1/3$, amplitude distribution for a cell size of two wavelengths; (b) $f/\# = 1/2$, amplitude distribution for a cell size of six wavelengths; (c) phase distribution for a cell size of two wavelengths; (d) phase distribution for a cell size of six wavelengths. In (a) and (b), black and white stand for 0 and 1, respectively. In (c) and (d), black and white correspond to 0 and pi, respectively.

in Figure 3(d). Essentially, it is due to the non-paraxial features and more compact system scale in term of electrical size of millimeter wave imaging systems compared to general optical systems [12].

To distinguish from the discussions above, the size of the lens is now decreased. It is still larger than the geometrical dimension of the Hadamard diffuser, but the main beams spill over the aperture of the lens. 1D simulations are implemented. At millimeter wave frequencies, the cell size is set to be 20 wavelengths and the amplification ratio of the system is one. In the optical case, the cells size is six wavelengths so as to match the experiment in [11] and the amplification ratio of the system is ten. The f-numbers of the projection lens are 1 and 2.5 and the wavelengths are 3 mm and 500 μm respectively. An f-number of 1 is typical for practical millimeter wave imaging systems and an f-number of 2.5 corresponds to a good optical imaging system in reality. Simulations are implemented to examine the influence of the lens. As shown in Figures 4(a) and (b), when the f-number is around one, the amplitude fluctuations are generally less than 20%. However, when it



(a) (b)

Figure 4. Hadamard phase patterns projection when the main beams partially spill over the lens' aperture (a) at 100 GHz, amplification ratio = 1, $f/\#$ = 1 and 2.5; (b) at optical frequency, lambda = 500 nm, amplification ratio=10, f/#=1 and 2.5. X-axis implies the physical position on image plane.

is increased to 2.5, the amplitude fluctuations can be much larger. In Figure 4(b), the shading of the amplitude on the border of the image is even -8 dB.

These examples validate that the performance of the Hadamard phase projection sub-system is influenced by both the electrical size of a cell and the f-number of the lens. Rather than simple geometrical descriptions of the Hadamard diffuser in term of "overfill" or "non-overfill" the lens, the simulations above based on wave optics show that the phase projection process is not as clean as in previous discussions [5, 6]. Generally, phase patterns can be projected well, but amplitude modulations occur due to the Gibbs ringing effect, interference of the waves accompanied with aberrations during diffraction [17], and power loss. A larger lens with a smaller f-number can always help if it does not introduce serious aberrations in practice. However, the first two points can not be overcome conceptually even by an ideal lens. For cells of a small electrical size, waves interfere more seriously. Physically, it means that during the pattern projection, fields on the surface of the object are not flat. Or in other words, it is equal to the case by which the object's reflectivity is modulated, which is quite undesirable. In this way, speckles may be introduced during the phase patterns projection, which originally aims at decreasing speckles in the final image. Mathematically, the dataset which corresponds to the object is weighted unexpectedly, thus the system performance decades.

3.2. Reflected Waves Imaging Sub-system

In this section, Hadamard phase patterns are supposed to be perfectly projected on the surface of the object, so that we only evaluate the performance of the imaging sub-system. In our simulations, the object's rough surface is defined as follows: we first define a set of random phases in [−pi, pi], which follow a uniform distribution and correspond to height fluctuations between zero and half a wavelength in case of reflective surfaces. The points corresponding to the assigned phases are called scattering points in the text. Next, we make interpolation with a fixed grid size between adjacent scattering points so as to cover the whole object's surface. The interval between adjacent scattering points is called the granular size of random roughness. It can be tuned so that different roughness models can be defined. So for a set of scattering points with fixed values, a larger granular size of random roughness corresponds to a smoother surface in this case. In what follows, simulations are implemented at both optical and millimeter wave frequencies. The influence of the granular size of the object's rough surface will be investigated.

The experiment in [11] is implemented by a projector system. The diameter of the imaging lens is 3 mm so as to match the human eyes. The investigated object is a very rough surface and the selected wavelength is 532 nm. A 1D simulation of a similar system setup is implemented at 500 nm. The diameter of the lens is also 3 mm and the focal distance is 2 cm, which correspond to human eyes. The object has a randomly rough surface, with a granular size of 0.2 wavelengths. We aim at simulating the human's vision when looking at a rough object in practice. The length of the linear object is 1.15 cm, which is a very large electrical size. The distance between object and lens is 0.5 m. The cell size is 6 wavelengths and Hadamard 64 is applied. The system works in pixel scanning mode, which is also applied in [11]. In Figure 5, a direct integral of the 64 partial images gives a smoother intensity distribution as the dashed curve shows, thus a clearer image is sensed by the eyes with less annoying speckles. Speckle contrast is reduced from 0.96 to 0.12. The value of SCR is 7.88. In [11], the speckle contrast is reduced by 7.78 in the experiment. Theoretically, SCR is expected to be 8 by applying Hadamard 64. Both simulation and measurement results match the theoretical prediction well. So at optical frequencies, Hadamard SCR theory can hold.

Active millimeter imaging systems also suffer from speckles, which may be one of the most difficult problems for this technology nowadays. The original impetus for us to study the Hadamard SCR is to move the successful optical experience to millimeter wave systems, since we are doing projects on millimeter wave imaging. High resolution is

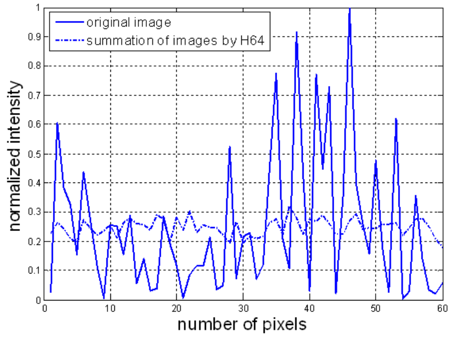
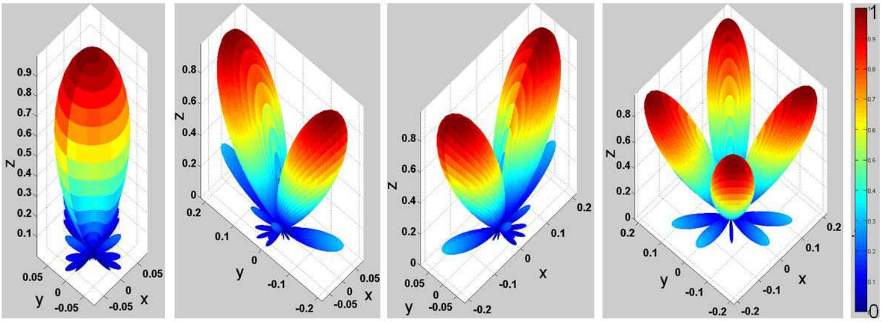


Figure 5. The effect of Hadamard SCR by applying Hadamard 64 to a randomly rough surface at 500 nm, with a granular size of random roughness of 0.2 wavelengths.

important for imaging systems generally. However, considering the possible amplitude modulation effect and possible difficulties for power collection, the cell size can not be infinitely small. In practice, there should be a threshold of the cell size, which forms a basic limitation of the Hadamard SCR technique. In [17], the minimum cell size is recommended to be two wavelengths and we will apply this value in the following simulations. Theoretically, a higher-order Hadamard matrix has better SCR ability. But the physical limitation of the cell size would lead to a larger resolution spot, thus lower resolution. Moreover, high-order Hadamard phase patterns make the system more complicated. So in the following discussions, only Hadamard 4 is discussed. In Figure 6, we show the 3D radiation patterns of Hadamard 4 inside one resolution spot, which correspond to the four phase patterns in Figure 1(b) respectively. The calculation is based on antenna array theory. By considering each Hadamard phase pattern as an aperture source of certain physical dimensions, the array factor is calculated. The diffuser is located in the x-y plane. In later discussions, the Hadamard phase patterns are replicated so as to cover the whole object's surface. However, radiation patterns can be calculated in the same manner and for each Hadamard phase pattern, they are no more than the repetition of the radiation patterns in Figure 6, accompanied with corresponding interference effects [18].

The object has the shape of a gun. The reflectivity contrast between object and the background is 9 dB, which corresponds to the contrast between metal and skin at 100 GHz [19]. For simplification, the amplification ratio of the imaging system is set to be one. The f-number of the lens is one and the focal distance is 0.5 m. The size of the object is 0.24 m. The area of a cell is two by two wavelengths,



(a) (b) (c) (d)

Figure 6. Normalized 3D Radiation patterns of the four phase patterns of Hadamard 4; (a)–(d) correspond to the 1st to 4th Hadamard phase patterns in Figure 1(b).

thus the resolution spot is 1.2 cm by 1.2 cm. The image contains 400 pixels and we are interested at the region of the gun.

First, the granular size of the randomly rough surface is set to be 0.2 wavelengths. As shown in Figure 6, field distributions by applying the four Hadamard phase patterns are similar with typical features like granular noise, which is quite similar to optical speckles [20]. But they are not the detected images, which are not only decided by the field distributions, but also by the power coupling mechanism of the field to the detectors. The gray level of the pixel is proportional to the intensity inside the integral region which is in fact the detector's aperture in this case. As Figure 7(b) shows, without applying Hadamard SCR, the original image seems like a random noise and there is no clear description of the shape of the gun. By using Hadamard 4, a much more understandable image is attained, as shown in Figure 7(c). The shape of the gun is obvious. The speckle contrast is reduced from 1.07 to 0.54, which means that the SCR performance is 99 % of the theoretical value.

Second, the granular size of the object's randomly rough surface is enlarged to be 3 wavelengths and interpolation is applied to the phase definition. As Figure 8 shows, field distributions of the four partial images are obviously different, two of which are quite regular with vertical and horizontal dark lines. This phenomenon can be explained by the radiation patterns of different Hadamard patterns. As shown in Figures 6(b) and (c), repetition of the two phase patterns of Hadamard 4 can make the radiating fields similar to the fields diffracted by the grating structures, thus generating the lines. In Figure 8(b), without applying Hadamard SCR, the image of the gun is still understandable.

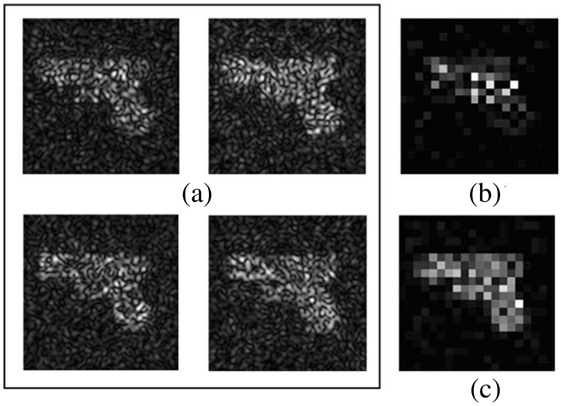


Figure 7. At 100 GHz, the granular size of the random roughness is 0.2 wavelengths; (a) field distributions on image plane, corresponding to the phase patterns in Figure 1(b), by applying Hadamard 4; (b) original image without applying Hadamard SCR; (c) enhanced image by applying Hadamard SCR (Hadamard 4).

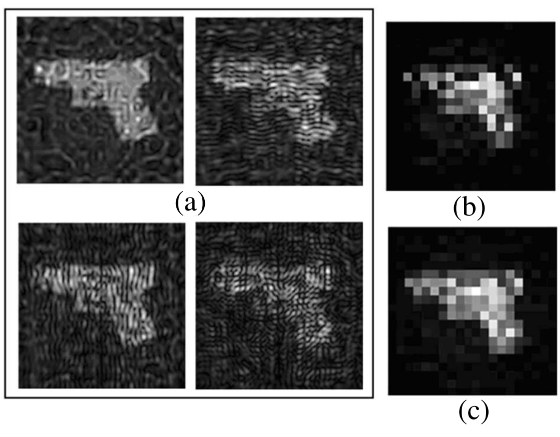


Figure 8. At 100 GHz, the granular size of the random roughness is 3 wavelengths; (a) field distributions on image plane, corresponding to the phase patterns in Figure 1(b), by applying Hadamard 4; (b) original image without applying Hadamard SCR (c) enhanced image by applying Hadamard SCR (Hadamard 4).

While by applying Hadamard SCR, some lost information is recovered and the object is described better, as shown in Figure 8(c). The speckle contrast is reduced from 0.73 to 0.46 by applying the Hadamard SCR method. Compared to the theoretical value, the improvement is 79%.

So the original image is enhanced, although it is not as good as in the previous example.

3.3. Discussions on Simulation Results

Mathematically, the principle of the Hadamard SCR approach means that phase patterns are applied to a fixed dataset sequentially, and the integral of partial results corresponding to different patterns may generate a flattened data distribution when examining an assemble of pixels [21]. In the ideal case, different Hadamard phase patterns are expected to be applied to the same field distribution sequentially. The function of the diffuser is to partition a resolution spot into a set of cells and to assign each cell an according phase. The discussions by Trisnadi [6, 11] seem to be perfect based on point spread function and geometrical optics. In the papers, it is assumed that interference happens at the detector side. Meanwhile, the phase modulation is assumed not to influence amplitude distributions of the fields on image plane but only a phase shift. However, the practical case is that waves always interfere during propagation, and it is quite possible that field distributions are distorted due to phase modulations, which means the requirements for the Hadamard SCR may not be satisfied in practice. So the question is how much the Hadamard phase patterns influence on the incident fields on the object's surface, thus whether the dataset to be manipulated can be assumed constant by applying different Hadamard phase patterns. In what follows, we will explain the simulation results in Figures 7 and 8 via wave optics and statistical optics, respectively.

According to wave optics, except for the first Hadamard pattern which contains 1s only, all the rest patterns would modulate the phase of reflected or penetrated waves which leave the object due to the superimposed pi phase differences among cells. As a result, the radiation is not strictly the same after modulating by different Hadamard patterns. When the Hadamard cell size is much larger than the granular size of the random roughness, as shown in Figure 7(a), the field distributions are robust by applying different Hadamard patterns. In this case, reflected waves of the object are quite dispersive, and the interaction between adjacent cells has little influence on the overall radiation patterns. Consequently, the Hadamard SCR matches the theoretical assumption well. When the cell size is smaller than the granular size of the random roughness, by applying the Hadamard patterns, reflected waves by the object would be strongly affected, as Figure 7(a) shows. Following our previous roughness definition, the relatively large granular size of the random roughness means a relatively flat surface locally compared to the Hadamard phase patterns, thus the scattered fields would be mainly in broadside direction. When the pi phase shift happens inside this region, the radiation would be deviated from the broadside and move towards the endfire direction. Moreover, the previously lost radiation may also be moved to broadside to some extent so that it can be collected by the imaging lens. In this way, the previously escaped waves may be captured and new content would appear on the image plane. This is the reason why we see some improvements in Figure 7(c). However, the performance deteriorates compared to the theoretical value.

According to statistical optics, during the derivation of the Hadamard SCR approach, there are two basic assumptions: first, the random variables inside different cells are statistically independent; second, the rough surface is supposed to generate a "fully developed speckle" with a speckle contrast of one. In [1], this is a basic assumption that the theoretical value of Hadamard, which is the square root of the order of the Hadamard matrix, can be achieved. However, a larger granular size of the random roughness compared to the cell size would introduce correlation of the data in adjacent cells, making the first assumption failed. However, when the granular size of the roughness is much smaller than the cell size, it means that there are more independent data inside a cell so that the cell has better statistical properties. Moreover, the terminology of "fully development speckle" corresponds to an extremely random case with a signal to noise ratio (SNR) of one, which is the reason why the Hadamard SCR approach requires an extremely random rough surface. To evaluate the number of scattering points, we should go back to statistics. In [1], the statistical property of the summation of random phasors is evaluated and the conclusion is as follows: when the number is larger than five, the summed phasor has a similar possibility density function to the case when the number is infinite. It means that to develop a "fully developed speckle", there should be at least five random phasors to sum up inside a cell which accounts for the expected statistical property. By repeating the simulations based on Fourier optics in [5], we found that by simply increasing the amount of random numbers or what we called the scattering points in our previous definition inside a cell from 2 to 4, the SCR can be improved from the reported value of 1.5 to around 1.9, which means 95% compared to the theoretical value. Moreover, by tuning the lens' aperture, it is possible to reach the theoretical prediction of Hadamard SCR at millimeter wave frequencies. So we conclude that to let the Hadmard SCR theory work, there should exist a limitation on the granular size of the object's randomly rough surface and the cell size should be large enough so as to cover sufficient independent regions.

4. SPECKLES FORMULATION AND VALIDITY DISCUSSIONS

In previous section, it has been shown that the performance of the Hadamard SCR is influenced by the roughness definition of the object's surface and in some cases the Hadamard SCR follows the theory perfectly. Here we want to point out that general speckles in optics and millimeter waves are not the same either in case of mathematical description or physical sources, although they share the same terminology of "speckle".

In optics, speckle is attributed to the integral of a set of random phasors [1]. In case of strong scattering surfaces, a basic assumption is the uniform distribution of phase between −pi and pi. Moreover, statistical independency is assumed. First, two phasors are independent; second, the amplitude and phase of a phasor are independent. Once these conditions are satisfied, a fully developed speckle is generated with a speckle contrast of one. In practice, it is possible to make the surface smooth by using fine polishing processing techniques, accompanied with a speckle contrast of less than one. Following the discussions in [1, 22], for surfaces whose phase difference is larger than half a wavelength, the speckles are fully developed. Considering the optical wavelengths which are hundreds of nanometers, the condition for fully developed speckles is generally satisfied in our daily life. In practice, except mirrors, most materials encountered in the real world are rough on the scale of an optical wavelength. So the randomness of the object's surface at micro-scale is the source for optical speckles.

At millimeter wave frequencies, the roughness of the surface is electrically small considering the fabrication techniques nowadays. So the object is locally flat compared to the wavelengths and the material itself does not contribute to random speckles. In this case, we can not give a uniform mathematical description of speckles on the image plane [23]. So the macro-scale features of the object are the sources for speckles essentially. In Figure 9(a), a practical pistol is shown. The characteristic features include flat parts, gratings, slop structures and scattering points. The scattered or reflected waves are closely linked to the features in term of electrical size above, which can range from 0.1 wavelength to tens of wavelengths in practice. Such a large dynamic range makes the imaging more difficult than general optical cases. In optics, the intensity distribution follows a negative exponential distribution in case of strong scattering surfaces [1]. However, for an image attained by millimeter wave imaging systems, it is more likely that a discrete distribution in which certain intensity components

(a) (b) (c)

Figure 9. Imaging simulation of a practical gun (a) optical image of the gun; (b) field distribution of the gun model; (c) image of the gun, resolution: 1.2 cm at 100 GHz, (b) and (c) follow the gun model in Figure 7 and Figure 8.

dominate, due to regular features of the object's surface.

In practice, the performance of the Hadamard SCR approach is closely linked to the field distribution on the image plane. By applying Hadamard phase patterns, formula (1) is changed into (2) automatically by assigning Hadamard phase patterns on the image plane perfectly. As we learned from previous section, without a random dataset and a large enough cell size compared to the granular size of object's randomly rough surface, the theoretical value of Hadamard SCR should not be considered as the natural result. At optical frequencies, optical speckles generally satisfy the requirements regarding the granular size of random roughness and the cell size, that is why in [6, 11], theoretical predictions are realized so well. However, at millimeter wave frequencies, the speckle model is different from optics, and the requirements discussed above fail. Whenever the field distributions are substantially different by applying different Hadamard phase patterns, the working principle of Hadamard SCR has broken, and possible improvements should be attributed to lost information recovery due to the modulation of object's spectrum by interaction with Hadamard phase patterns. In [17], when the spectrum of the object and the Hadamard phase patterns match, it is possible to see some improvement and to realize a better "intensity transfer function". Unlike the explanations in [7], we contribute the improvement of Hadamard SCR to this case. The statements in [8, 9] are not correct. Hadamard phase patterns can not change the coherent illumination to incoherent, since waves still interfere based on amplitudes. It can only lead to a smaller coherent area physically in case of good a phase pattern projection without serious amplitude modulations. In [5], it is concluded that Hadamard SCR can not reach the theoretical prediction in millimeter wave imaging systems. But we have shown in Figure 7 that by setting the parameters which satisfy the validity requirements of Hadamard SCR, equally good results can be attained compared to optical cases. Moreover, practical indoor active millimeter wave imaging systems do not follow Fourier optics very well [12], thus discussions based on f-numbers in [5] are not quite accurate. In [24], it is concluded that by Hadamard SCR, the image of flat objects are still flat. However, considering principle of Hadamard SCR, it is not reasonable to apply it to smooth objects, since there are no speckles in this case. Some of the conclusions in previous papers are really misleading. There is no guarantee that Hadamard SCR can always work for all kinds of surfaces in any case.

5. CONCLUSIONS

In this paper, we go back to statistical optics, based on which the Hadamard speckle contrast reduction approach originates. Considering the phase patterns projection, we check the influence of the electrical size of a cell. The projection process is not as clean as previous optical analysis, since amplitude modulations may happen, accompanied with Gibbs ringing effects. A lens with a small f-number and a large cell size can improve the performance, while the latter one directly limits the resolution of the imaging system. A parallel simulation of Hadamard 64 is implemented at optical frequencies so as to help understanding the previous successful experiment. At millimeter frequencies, by tuning the ratio between the granular size of random roughness and the cell size, it is possible to do equally well as in the optical cases. However, due to the different speckle models in case of millimeter wave imaging, the Hadamard SCR is not as promising as in optics. In practice, speckle contrast around one is a good starting point to consider applying Hadamard SCR. In summary, Hadamard SCR can be useful in case of an extremely rough surface with a small enough granular size of random roughness, but we should not exaggerate its performance. The performance SCR on Gaussian surfaces will be investigated in our future work.

REFERENCES

1. Goodman, J. W., *Speckle Phenomena in Optics: Theory and Applications*, Roberts & Co., Publishers Englewood, CO, 2006.
2. Nascimento, J. C., J. M. Sanches, and J. S. Marques, "Tracking the left ventricle in ultrasound images based on total variation

denoising," *Lecture Notes in Computer Science*, Vol. 4478, 628–636, 2007.

3. Xia, Z. G. and Y. Sheng, "Radar speckle: Noise or information?" *IEEE International Conference on Geoscience and Remote Sensing Symposium IGARSS*, Vol. 1, 48–50, 1996.
4. Huegenin, G. R., C. T. Hsieh, J. E. Kapitzky, E. L. Moore, K. D. Stephan, and A. S. Vickery, "Contraband detection through clothing by means of millimeter wave imaging," *Proc. SPIE*, Vol. 1942, 117–128, 1993.
5. Koers, G., I. Ocket, F. Qi, V. Tavakol, I. Jager, B. Nauwelaers, and J. Stiens, "Study of active millimeter-wave image speckle reduction by Hadamard phase pattern illumination," *Journal of Optical Society America. A*, Vol. 25, 312–317, 2008.
6. Trisnadi, J. I., "Hadamard speckle contrast reduction," *Optics Letters*, Vol. 29, 11–13, 2004.
7. Jager, I., J. Stiens, G. Koers, G. Posen, and R. Vounckx, "Hadamard speckle reduction for millimeter wave imaging," *Microwave and Optical Technology Letters*, Vol. 48, 1722–1725, 2006.
8. Islam, S., J. Stiens, G. Poesen, R. Vounckx, J. Peeters, I. Bogaert, D. de Zutter, and W. de Raedt, "Simulation and experimental verification of W-band finite frequency selective surfaces on infinite background with 3D full wave solver NSPWMLFMA," *Progress In Electromagnetics Research*, PIER 101, 189–202, 2010.
9. Islam, S., J. Stiens, G. Posen, I. Jager, and R. Vounckx, "Passive frequency selective array as a diffuser for destroying millimeter wave coherence," *Active and Passive Electronics Components*, Vol. 2008, 1–6, 2008.
10. Hawit, M. and N. J. A. Sloane, *Hadamard Transform Optics*, Academic Press Inc., 1979.
11. Trisnadi, J. I., "Speckle contrast reduction in laser projection displays," *Proc. SPIE*, Vol. 4657, 131–137, 2002.
12. Qi, F., V. Tavakol, I. Ocket, P. Xu, D. Schreurs, J. Wang, and B. Nauwelaers, "Millimeter wave imaging system modeling: spatial frequency domain calculation versus spatial domain calculation, " *Journal of Optical Society America. A*, Vol. 27, 131–140, 2010.
13. Chen, K. S., L. Tsang, and J. C. Shi, "Microwave emission from two-dimensional inhomogeneous dielectric rough surfaces based on physics-based two-grid method," *Progress In Electromagnetics Research*, PIER 67, 181–203, 2007.

14. Oraizi, H. and S. Hosseinzadeh, "A novel marching algorithm for radio wave propagation modeling over rough surfaces," *Progress In Electromagnetics Research*, PIER 57, 85–100, 2006.
15. Cocheril, Y. and R. Vauzelle, "A new ray-tracing based wave propagation model including rough surfaces scattering," *Progress In Electromagnetics Research*, PIER 75, 357–381, 2007.
16. Warnick, K. F. and W. C. Chew, "Numerical simulation methods for rough surface scattering," *Waves in Random Media*, Vol. 11, 1–30, 2001.
17. Qi, F., V. Tavakol, I. Ocket, D. Schreurs, and B. Nauwelaers, "Discussion on the functions of Hadamard phase pattern in millimeter wave imaging," *European Radar Conference*, 52–55, 2008.
18. Qi, F., I. Ocket, V. Tavakol, D. Schreurs, and B. Nauwelaers, "Millimeter wave imaging: System modeling and phenomena discussion," *International Conference on Applied Electromagnetics and Communications (ICEcom)*, 1–4, 2007.
19. Appleby, R. and H. B. Wallace, "Standoff detection of weapons and contraband in the 100 GHz to 1 THz region," *IEEE Trans. on Antennas and Propagation*, Vol. 55, 2944–2956, 2007.
20. Rojas, J. A. M., J. Alpuente, E. Bolivar, P. López-Espí, S. Vignote, and M. I. Rojas, "Empirical characterization of wood surfaces by means of iterative autocorrelation of laser speckle patterns," *Progress In Electromagnetics Research*, PIER 80, 295–306, 2008.
21. Qi, F., V. Tavakol, I. Ocket, S. Islam, I. Jager, D. Schreurs, J. Stiens, and B. Nauwelaers, "Hadamard speckle contrast reduction for imaging systems: Comprehension and evaluation," *European Radar Conference*, 401–404, 2009.
22. Persson, U., "Roughness measurement of machined surfaces by means of the speckle technique in the visible and infrared regions," *Optical Engineering*, Vol. 32, No. 12, 1993.
23. Qi, F., D. Schreurs, V. Tavakol, and B. Nauwelaers, "Comparison of optical and millimeter wave imaging on speckle," *IEEE International Symposium on Antenna and Propagation (AP-S)*, 1–4, 2008.
24. Ocket, I., B. Nauwelaers, G. Koers, and J. Stiens, "Fast modeling and optimization of active millimeter wave imaging systems," *European Radar Conference*, 1559–1562, 2006.