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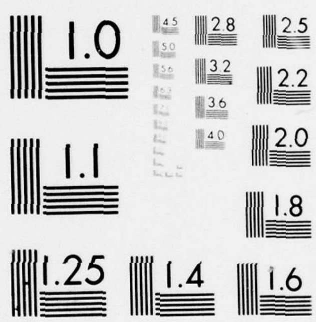
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DIRECT ELECTRONIC FOURIER TRANSFORMS (DEFT) FOR CAMOUFLAGE SIGNATURE MEASUREMENT (CSM)

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FORT BELVOIR, VA

11 JUN 1978

12 15p.

INTRODUCTION: This paper presents the theoretical basis and initial experimental results of a new concept, technique, and method for measuring and evaluating camouflage in a scientific and quantitative manner. Although methods for precise measurement of color and contrast have existed for some time, the evaluation of the combined effect of contrast reduction, patterns, natural foliage, and other shape disruption methods has remained a subjective judgment on the part of the camouflage specialist. Thus, the quantitative evaluation of camouflage on a scientific basis will provide an important and valuable solution to a unique military problem.

The concept, technique, and method presented herein can be used to provide the Army with a new capability to scientifically measure and evaluate this heretofore subjective quantity. It is expected to provide a valuable tool to the research camouflage specialist in its present state of development and with further development should provide essential and valuable information to the military commander in the field.

The concept and technique is based on the Fourier transform of an image, and the method uses one of the most recent advances in surface acoustic wave (SAW) technology together with modern communications technology to obtain the camouflage signature measurement (CSM) of military objects. This SAW device produces an analog (RF) electrical signal containing the Fourier transform (including amplitude, frequency, and phase) of the spatial frequencies contained in a conventional image.

This work originated and was performed in-house at the U. S. Army Engineer Topographic Laboratories, under the ILIR program. It is actually a by-product of what has become a long-range program on feature extraction and image analysis. Camouflage is treated as the inverse of feature extraction. It has become difficult to treat one to the exclusion of the other. Hence, reference at time will be made to feature extraction as well as camouflage signature measurement.

CAMOUFLAGE SIGNATURE MEASUREMENT (CSM): A definition of "camouflage" is "the disguising of an installation, vehicle, gun position or ship with paint, garnished nets, or foliage to reduce its visibility or conceal its actual nature or location from the enemy." (1)

The hypothesis taken in this paper is that camouflage is the hiding or disquising of the shape and characteristic features which provide a characteristic signature of a feature or object. In other words, those camouflage measures which cause a change in the spatial frequency pattern of the object are considered in this paper.

The reasoning which led to the concept presented herein is that camouflage and feature extraction are mutual inverses, and that both are signal-to-noise problems. In communications terminology, camouflage is the addition of noise and/or the distortion of the characteristic signature signal of an image while feature extraction is the extraction of a desired signature signal from a noisy signal. Thus, feature extraction becomes a very difficult cross-correlation problem while the measurement of camouflage becomes a relatively less difficult problem of measuring the amount of noise and distortion added to the known signature spectrum, i.e., the overall reduction of the signal-to-noise ratio and the addition or deletion of pronounced spatial frequencies in the signature spectrum.

If a theoretical basis and physical means for measuring the characteristic signature of a feature or object, and the change in the characteristic signature resulting from camouflage can be found and demonstrated; then we will have justified the hypothesis and will have established the basis for a quantitative measurement of camouflage.

THEORETICAL BASIS: The theoretical basis for the concept is the Fourier Theorem and the Fourier transform. Fourier's Theorem has been described as "not only one of the most beautiful results of modern analysis, but also furnishes an indispensable instrument in the treatment of nearly every recondite question in modern physics." (2)

The key Fourier relationships which provide the basic groundwork for camouflage signature measurement (CSM) will be presented. Proofs of and details on the Fourier transform and its properties can be found in various texts. A few references are (2) thru (6). Hence, complete details are omitted in order to take the key formulas and properties essential to this paper as a point of departure.

The Fourier Theorem states that a function f(x), of spatial period λ, can be synthesized as a sum of harmonic functions whose wavelengths are integral submultiples of λ (i.e., λ, $\lambda/2$, $\lambda/3$. etc.) In other words, if f(x) is a periodic function of wavelength λ, it can be represented by a Fourier series of the form:

(1) $$f(x) = C_o + C_1 \cos(2\pi x/\lambda + \phi_1) + C_2 \cos(4\pi x/\lambda + \phi_2) + \ldots$$

Another representation of the Fourier series is:

(2) $$f(x) = (A_o/2) + \sum_{m=1}^{\infty} A_m \cos mkx + \sum_{m=1}^{\infty} B_m \sin mkx$$

where A_m, B_m are the amplitudes of the various harmonic components as indicated by "m" which has the values 0,1,2,..., and the wave number $k = 2\pi/\lambda$ where "λ" is the wavelength or spatial period of the periodic function, not an optical wavelength.

Another, more compact representation using exponential notation is:

(3) $$f(x) = \sum_{m=-\infty}^{m=+\infty} C_m \exp(jmkx)$$

where C_m represents the amplitude of each harmonic component.

The Fourier integral and the Fourier series are alternative expressions, the integral being the limiting case of the series. It can be approached from the side of the series by allowing the spatial repetition to extend to infinity and considering only one period of the function. Thus, we can write any function, no matter how complex, as:

(4) $$f(x) = (1/2\pi) \int_{-\infty}^{\infty} F(k) \exp(jkx)\, dk$$

remembering that we are integrating over submultiples of a single period, i.e., all k-values become the higher and higher harmonics required to represent one period of the function.

Now F(k) is referred to as the Fourier transform of f(x) and is written as:

$$\text{(5)} \quad F(k) = \int_{-\infty}^{\infty} f(x) \exp(-jkx)\, dx$$

The one-dimensional Fourier transform is an important tool and is sufficient for many scientific applications. However, some problems are multidimensional in nature, e.g., image analysis and processing. Therefore, we generalize the Fourier transform to the two-dimensional spatial domain as follows:

$$\text{(6)} \quad f(x,y,) = [1/(2\pi)^2] \iint_{-\infty}^{\infty} F(k_1, k_2) \exp[j(k_1 x + k_2 y)]\, dk_1\, dk_2$$

and

$$\text{(7)} \quad F(k_1, k_2) = \iint_{-\infty}^{\infty} f(x,y) \exp[-j(k_1 x + k_2 y)]\, dx\, dy$$

where k_1 is the wave number in the "x" direction and k_2 is the wave number in the "y" direction.

We now present the Addition Theorem, or superposition property, and the linearity property of Fourier transforms. Any two functions, af(x), and bg(x), will have Fourier transforms aF(k), and bG(k), respectively. Also, the sum of the functions, af(x) + bg(x), has the Fourier transform, aF(k) + bG(k).

$$\text{(8)} \quad \int_{-\infty}^{\infty} [af(x) + bg(x)] \exp(-jkx)\, dx = \int_{-\infty}^{\infty} af(x) \exp(-jkx)\, dx + \int_{-\infty}^{\infty} bg(x) \exp(-jkx)\, dx = aF(k) + bG(k)$$

This superposition property means that the spectrum of a linear sum of functions is the linear sum of their spectra. If the spectra are complex, the usual rules of addition of complex quantities apply. Further, any function, as in our case an image, can be regarded as a sum of component parts and the spectrum is the sum of the component spectra.

These separate frequency components, each with their individual specific amplitudes and phases, make up the spatial frequency signature of the function. Note Eq. (1). Therefore, if the function is an image, we have the signature of the image. By applying the superposition principle to the camouflage situation, we take the view that a military object is one generalized function and camouflage is another generalized function. Hence, the signature spectrum of the "camouflage," (e.g., patterns, foliage, other shape disruption measures) is added to the signature spectrum of the object. That is, the camouflage spatial frequencies, with their individual amplitudes and phases, are added to the spatial frequencies of the original object. Note Eq. (8). Actually, some of the original image will probably be obscured (by foliage, for example). In any case, the result will be the addition of new frequency components; and, because of phase relationships and obscuration, the amplitudes of old frequency components will be increased, decreased, or perhaps eliminated entirely. This change is a direct result of the addition of the camouflage measure.

Thus, if an image is changed by the addition of shape disruptive camouflage measures, then the Fourier transform, i.e., the spectrum of the image, will also be changed accordingly. Hence, if the frequency signature components can be identified and the change in amplitude of each signature frequency component can be measured quantitatively, then the sum of these changes can be used as a quantitative measure of the overall effect of the camouflage on the signature of the object.

This key point is fundamental to this concept. It is based on Eqs. (1) thru (8); where any function even one as complicated as an image, can be specified by a summation of frequencies each having specific amplitudes and phases. The theoretical basis for the scientific and quantitative measurement of "camouflage" has now been presented.

METHOD: At this point, we switch from Fourier transform theory to communications theory and technology. It is now assumed and later demonstrated that the spatial frequencies of the image can be converted into real RF sinusoidal frequencies as used in standard RF communications systems. The powers, i.e., the amplitudes and changes in amplitudes, of RF frequencies for communications applications are conveniently measured in terms of signal-to-noise ratios (SNR) in decibels (db). Hence, if we wish to know the strength of a signal after operating on it in some way, as with an antenna of a certain size, we simply add the gain of the antenna in db to the strength of the signal which impinges on the antenna; and conversely, if a receiver amplifier has a certain noise figure (NF), we simply subtract the NF in db from the strength of the signal. This same approach can now be adopted in the case of camouflage signature measurement.

However, since we are dealing with a complete spectrum of frequencies, we should measure the effect on each frequency in the spectrum of the image. This would be logical if the complete image was to be reconstructed. Returning to Fourier theory, we know that the magnitude of any given spatial frequency is an indication of its importance in the image. Therefore, if we select only those frequencies which have a significant amplitude or change in amplitude, we will have reduced the total amount of data, i.e., the spectrum, to be considered, and still have retained the most significant information about the image. Just as we added the separate Fourier frequencies, again recall Eqs. (1) thru (8), to get the original function, we will now add the changes in each principal Fourier frequency component in db to get the "overall" change in the image due to camouflage (i.e., patterns, foliage, etc.). "Overall" is placed in quotation because only the principal frequencies are used.

The method for applying this concept is illustrated schematically in Figure 1. It anticipates the DEFT device and presents the experimental results in an idealized manner based on the theory. In this idealized case, the noncamouflaged tank has seven principal Fourier spectral components, whose amplitudes in db are: 3, 5, 5, 8, 7, 10, and 10. When camouflage is added, the amplitudes of the original spectral components become: 0, 3, 7, 6, 4, 8, and 8 db. In addition, four new components are created as indicated by the dashed lines. These spectral components have amplitudes 3, 5, 6, and 6 db.

The general amplitude reduction of the majority of the original spectral components is attributed to an overall contrast reduction, while the elimination of one spatial component and the addition of four new components is attributed to the addition of new spatial frequencies by the camouflage. The amplitude increase of one component (i.e., the third component went from 5 db to 7 db) is attributed to a reinforcement of that spatial frequency by the camouflage. Since this is a change in the original spatial frequency spectrum, it is considered to be beneficial as far as camouflage, i.e., signature distortion, is concerned. Hence, the total spatial frequency change in the image signature due to camouflage is 36 db. This quantitative measurement could also be expressed as a percentage change due to camouflage, i.e., (36 db) / (48 db) = 75%.

It is anticipated that future work in feature extraction may be able to convert these numbers into a "visibility range" in meters. This would be the distance beyond which the unaided eye would not be able to "see" the target. The method for a quantitative measurement of camouflage has now been described in an idealized manner.

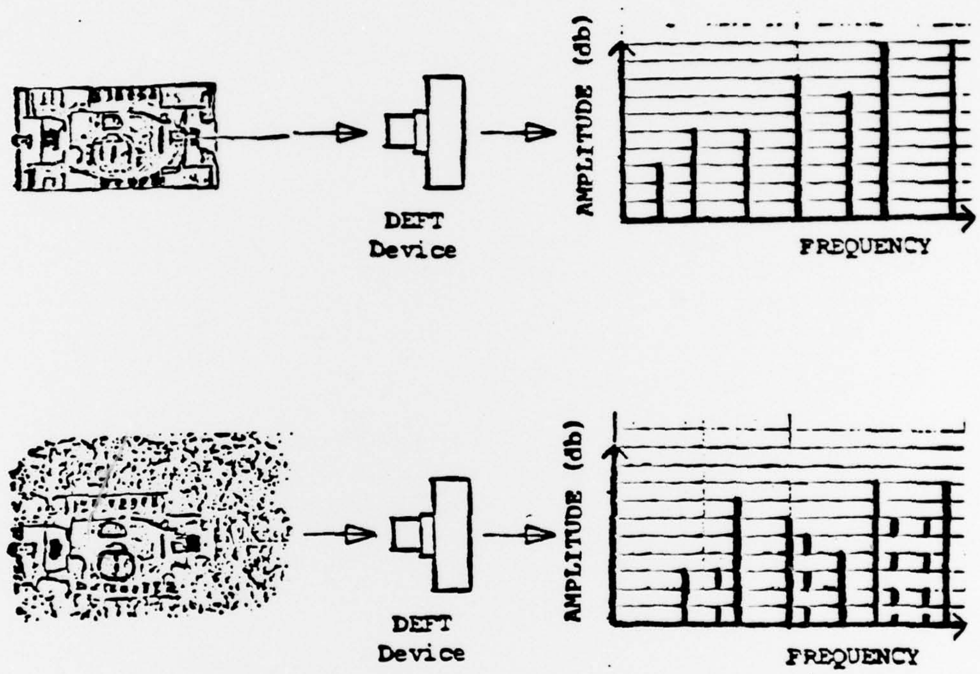


Figure 1. Camouflage Signature Measurement (CSM) Concept. A non-camouflaged tank and a camouflaged tank are viewed by a Direct Electronic Fourier Transform (DEFT) device about the size of a 35-mm camera to obtain the spatial frequency signature of each image. The total change in spatial frequency signature is a quantitative measurement attributable to camouflage.

DEFT TECHNOLOGY: DEFT technology combines acoustics, optics, and electronics in a unique manner to produce the Fourier transform of conventional images directly in the form of an analog (RF) electrical signal. This technology is believed to have a multitude of potential applications in addition to camouflage signature measurement.

The discovery and advancement of DEFT technology is a result of the work of two professors, Dr. P.G. Kornreich and Dr. S.T. Kowel at Syracuse University. Their work was recommended for Army sponsorship by the Advanced Concepts Team (ACT), D.A. The sponsoring agency is the Night Vision Laboratory with technical support from the US Army Engineer Topographic Laboratories. A schematic of a device which represents an early experimental prototype of this technology is illustrated in Figure 2. This type of device was used for experimental results in this paper.

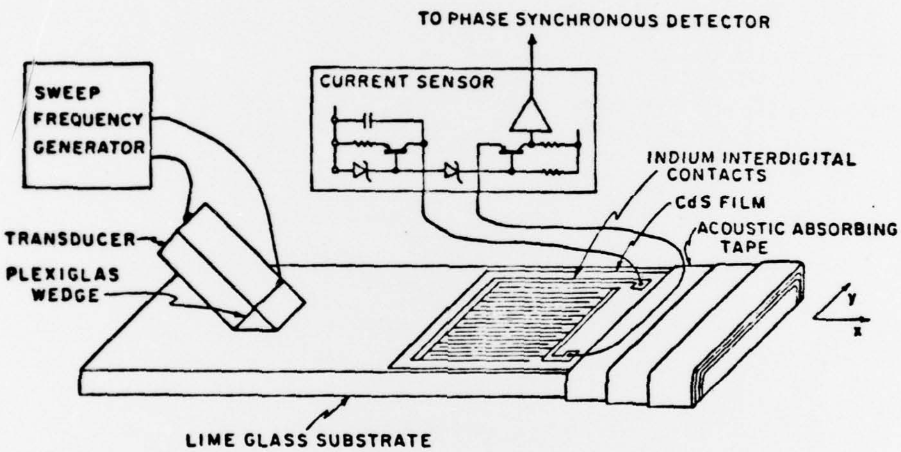


Figure 2. Schematic of an early experimental Direct Electronic Fourier Transform (DEFT) device. (After Kornreich, P.G., Kowel, S.T., et al, "*DEFT: Direct Electronic Fourier Transforms of Optical Images*," Proc. IEEE, vol. 62, PP 1072-1087, Aug. 1974).

Significant advances in this technology beyond that illustrated in Figure 2 have already been made. Devices have been fabricated with piezoelectric substrates and with dual SAW's for two-directional scanning at higher frequencies, i.e., 30-MHz range as compared to the 6.0-MHz limit of devices as shown in Figure 2. It can also be recognized that all solid-state construction and low power requirements for DEFT devices offer great potential for use in the Army field environment. Present DEFT devices can operate on a 9-volt transistor battery.

Space does not permit detailed discussion on DEFT technology. However, technical details can be found in references (7) thru (10). A very concise description would be to say that the strain induced by a propagating SAW causes a variation in the conductance of a photoconductive material. This variation in conductance is spatial over the whole surface of the photoconductor and also temporal in accordance with the speed of sound on the surface of the substrate. When the spatial frequency pattern of the conductance matches that of one of the component frequencies of the image, then an incremental analog, a.c. photocurrent at that frequency is generated. These incremental currents are picked up by a very fine grid of interdigital electrodes which are deposited with integrated circuit technology. If the SAW is sinusoidal, swept in frequency, and if synchronous detection is used, such as a sweep generator together with a network analyzer, the resulting output is an RF signal with frequencies corresponding to the spatial frequencies of the image. This output is shown in references (7) thru (10) to be the Fourier transform of the image intensity pattern $I_{(x,y)}$. It is obtained in "real time" and of the form:

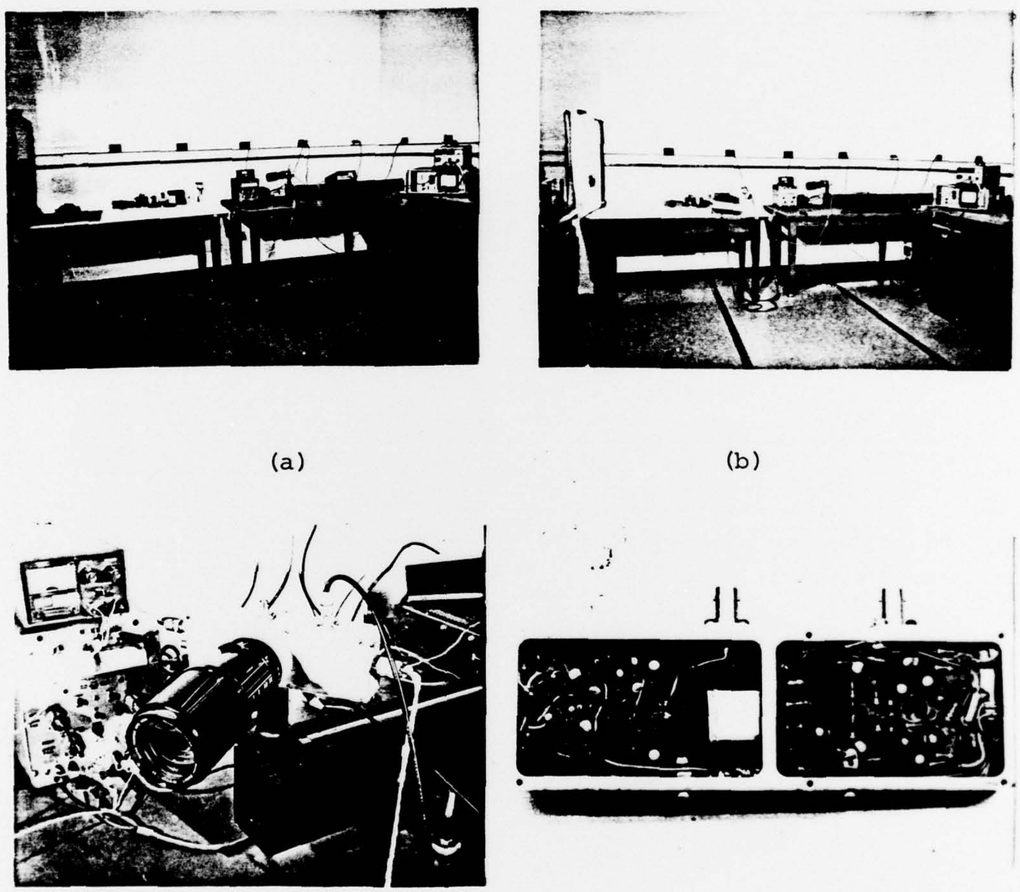
$$(9) \quad i_{(ac)} \propto \iint I_{(x,y)} \exp[-j(k_1 x + k_2 y)] \, dx \, dy$$

NOTE: Other technologies, such as computer or coherent optical technologies, are not precluded but have not been investigated for this application. The Digital Image Analysis Laboratory (DIAL) and the Recording Optical Spectrum Analyzer (ROSA) could provide candidate methods for investigation. The size, cost, and complexity of such systems seem to make them more appropriate for laboratory use than for general use in the Army field environment.

EXPERIMENTAL RESULTS: The experimental arrangement and close-up views of the experimental DEFT device are shown in Figure 3. Experiments were performed with scale models (Figure 3.a) and also with photographs of scale models (Figure 3.b) with varying amounts of camouflage. The measurement equipment consists of the DEFT device, the sweep generator, and the network analyzer which can be seen on the right sides of Figures 3.a and b. A close-up view of the DEFT device is shown in Figure 3.c, and an internal view is shown in Figure 3.d.

Sample results obtained with this experimental device are illustrated in Figure 4. This figure shows a tank with increasing amounts of camouflage from the worst case situation of "zero camouflage," i.e., maximum contrast situation of a dark tank against a white background, to a reduced contrast situation of a dark tank against a dark background, then a textured background and "camouflage foliage" covering the corners of the tank. The "camouflage foliage" is lichen and the textured background consists of shredded sponge used by model builders.

The Fourier spatial frequency spectrum (i.e., camouflage signa-



(a) (b)

(c) (d)

Figure 3. Experimental arrangement and close-up views of the experimental DEFT device used for making Camouflage Signature Measurements in the laboratory with scale models (a) and with photographs of scale models (b). The sweep generator and network analyzer are on the extreme right of (a) and (b). A close-up view of the DEFT device is shown in (c) and an internal view is shown in (d).

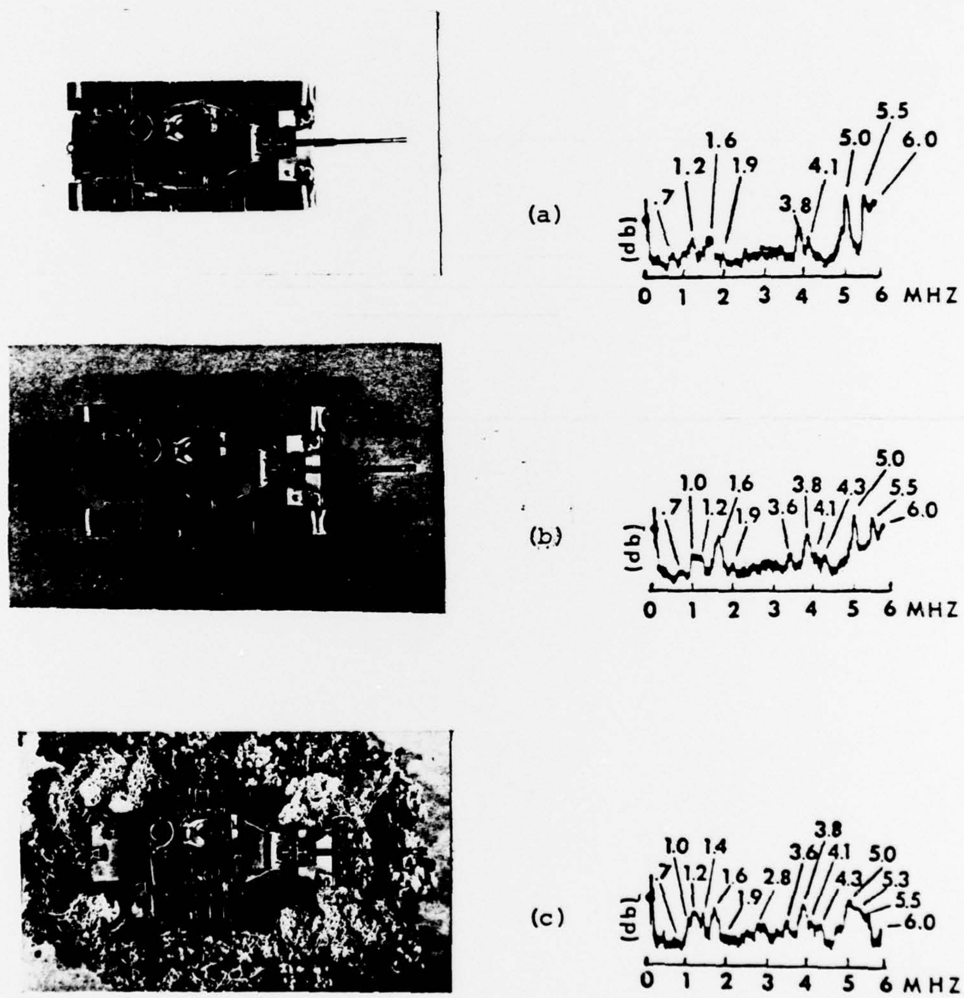


Figure 4. Tanks and corresponding signatures (i.e., Fourier spatial frequency spectra) for Camouflage Signature Measurement: (a) Worst case (zero camouflage) dark tank with white background; (b) Dark tank with dark background; (c) Dark tank with "foliage" background and camouflage foliage on corners.

ture) is shown beside each camouflage configuration. The horizontal axis is frequency from 0.1 to 6.0 MHz which is the bandwidth limit of the DEFT and the vertical axis is amplitude in decibels (db). These camouflage signatures are photographs of the CRT display of the network analyzer. Unfortunately, the graticule is not visible and a great amount of detail is lost in the reduction and reproduction processes. Therefore, the principal frequencies are identified in Figure 4. Only those frequencies whose amplitudes or changes in amplitude are 5 db or more were selected as the principal spatial frequency components.

Table 1 contains a list of the principal spatial frequency components, their amplitudes in terms of SNR based on adjacent noise levels, and the change in SNR of each spatial frequency component. Parentheses are used to indicate certain frequency components that were not considered significant until they became stronger and more significant under the influence of camouflage measures. The initial value, marked with an asterisk, given for these frequencies is based on the initial signal level, i.e., the "noise" level at that frequency, in order to provide a reasonable reference level for subsequent comparison. The need for such a reference is apparent by noting the changes at 5.3 MHz. The plus and minus signs following the change in SNR indicate whether the amplitude of the spatial frequency increased (+) or decreased (-) as a result of "camouflage."

Using the method presented herein, the interpretation to be applied to the numbers contained in Table 1 is as follows: In Case 2 (note Figure 4.b) where there is a contrast reduction due to a better match with the background, there is a 56-db improvement in camouflage (i.e., H-Factor) or a 36% improvement over Case 1 (i.e., 56 db/ 156 db).

In Case 3 (note Figure 4.c) where texture has been added to the background and where the corners together with parts of the front, back, and side edges of the tank have been disrupted with "camouflage foliage," there is a 68-db improvement in camouflage over Case 2 and a 114-db improvement over Case 1. These translate into improvements of 45% (i.e., 68 db/150 db) and 73% (i.e., 114 db/156 db), respectively.

Such types of measurements should be very significant to the tactical field commander and those interested in the "bottom line" for camouflage evaluation. Changes in the individual Fourier spatial frequency components can be expected to provide a great amount of insight for the camouflage specialist in understanding the effect of

Frequency	Case 1 (Fig. 4.a.) S/N Amplitude (db)	Case 2 (Fig. 4.b.) S/N Amplitude (db)	Case 2 Δ S/N H-Factor Case 1 vs Case 2	Case 3 (Fig. 4.c) S/N Amplitude	Case 3 Δ S/N H-Factor Case 3 vs Case 2	Case 3 Δ S/N H-Factor Case 3 vs Case 1
0.7	6	4	2-	0	4-	6-
(1.0)	(5)*	10	5+	14	4+	9+
1.2	10	8	2-	16	8+	6+
(1.4)	(0)*	(0)*	(0)*	8	8+	8+
1.6	10	16	6+	12	4-	2+
1.9	6	4	2-	0	4-	6-
(2.8)	(1)*	(1)*	(0)*	7	6+	6+
(3.6)	(2)*	7	5+	7	0	7+
3.8	13	14	1+	14	0	1+
4.1	8	2	6-	2	0	6-
(4.3)	(2)*	6	4+	6	0	4+
5.0	30	24	6-	20	4-	10-
(5.3)	(6)*	10	4+	16	6+	10+
5.5	29	23	6-	14	9-	15-
6.0	28	21	7-	10	11-	18-
	156 db	150 db	56 db (36%)		68 db (45%)	114 db (73%)

Table 1. Principal spatial frequency components, their amplitudes (S/N) in decibels, changes in amplitudes and overall camouflage evaluation, i.e., H-Factor, at bottom of Case 2 and Case 3 columns.

various camouflage measures. It is also by studying the structure and changes in structure of these same spatial frequencies that insights into feature extraction can be expected.

CONCLUSIONS: It is concluded that a valid theoretical basis and a valid method have been presented for the scientific and quantitative measurement of those camouflage measures which are designed to disrupt the shape of an object or reduce its contrast with its background. It is further concluded that DEFT technology makes the method adaptable for use in the tactical Army environment as well as the research laboratory. It is believed that this concept and method opens the door and is an initial step toward making camouflage a military science as well as a military art. As such, this effort is believed to be a significant advance toward fulfilling the words of Lord Kelvin, "When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind ...."

A word of caution is required. This concept, technique, and method requires understanding on the part of the user. It cannot be applied blindly, without training and experience in camouflage. It is actually a sophisticated tool, and like all tools, it requires understanding and judgment in its use. In the hands of the skilled camouflage specialist, it could lead to new insights into what produces "good" camouflage and perhaps a scientific basis for the design of new camouflage measures.

ACKNOWLEDGMENTS: For the potential military and scientific value this effort contains, the support of the Commander's ILIR program is acknowledged. Particular acknowledgment is made for the interest shown by COL. P.R. Hoge, Commander and Director, USAETL; COL. M.K. Kurtz (retired), former Commander and Director, USAETL; Mr. R.P. Macchia, Technical Director, USAETL; and Dr. A. Mancini, Director, Research Institute, USAETL.

Special acknowledgment is made to Dr. F.W. Rohde, Chief, Center for Theoretical and Applied Physical Sciences, Research Institute, USAETL, and Dr. E.A. Margerum, Mathmatician, Research Institute, USAETL, for many helpful technical discussions; and also Mr. D.L. Gee, Physicist, Camouflage Laboratory, MERADCOM for his interest and the use of scale models for the experimental investigations. In addition special acknowledgment is made to Messrs. A.H. Humphreys and J.H. Hopkins, both retired Chiefs, Camouflage Laboratory; Messrs. R.F. Carver (retired) and M.J. Damgaard (retired), R.E. Deacle (deceased) and G.H. Sigel (retired), former Section Chiefs, Camouflage Laboratory, for an awareness of the need for a scientific and quantitative measurement of camouflage and to all other associates whose discussions have enhanced the preparation of this paper.

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