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Fast determination of the element excitation of an active phased array antenna

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ABSTRACT (UNCLASSIFIED)

The far field radiation pattern of an active phased array antenna is determined by the excitation of its elements. The amplitude and phase of this excitation can be adjusted in an active phased array and have to be properly set in order to obtain a desired far field pattern.

This report describes a fast and easy method to determine this element excitation: the electric field in terms of amplitude and phase has to be measured in only one direction of interest of the far field of the antenna as a function of the element's amplitude and phase settings.

The method is called the "Element Excitation Method"(EEM).

Both theoretical and practical aspects can be found in this report. The method proved to be very useful in the alignment of the amplitude and phase settings of the elements of an active phased array at C-band.

rapport no : FEL-91-B038

titel : Een snelle bepaling van de excitatie van de elementen van een actieve phased array antenne

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instituut : Fysisch en Elektronisch Laboratorium TNO

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Onderzoek uitgevoerd o.l.v. : Ir. G.A. van der Spek

Onderzoek uitgevoerd door : Ir. J.G. van Hezewijk

SAMENVATTING (ONGERUBRICEERD)

Het verre veld stralingsdiagram van een actieve phased array antenne wordt bepaald door de excitatie van haar elementen. De amplitude en fase van deze excitatie kunnen veranderd worden in een actieve phased array en moeten goed zijn ingesteld om het gewenste antennepatroon te krijgen.

Dit rapport beschrijft een snelle en eenvoudige methode om deze elementenexcitatie te bepalen: de amplitude en fase van het elektrische verre veld moeten gemeten worden in slechts 1 richting in het verre veld van de antenne. De amplitude en fase-instellingen moeten hierbij gevarieerd worden.

Deze methode heet de 'elementen excitatie methode'.

Zowel de theorie als meetresultaten komen aan bod in dit rapport. De methode bleek zeer succesvol bij het kiezen van de optimale amplitude en fase-instellingen van de elementen van een actieve phased array antenne op C-band.

1 INTRODUCTION

The far field radiation pattern of a phased array antenna is determined by the excitation of its elements. The amplitude and phase of this excitation can be adjusted in an active phased array in order to obtain a desired far field pattern. If the amplitude and phase of the excitations are not properly set, an incorrect radiation pattern of the array may result. The alignment of the amplitude and phase settings of the antenna elements is therefore very important.
Recently, an active array antenna, called 'PHARS', has been developed at the TNO Physics and Electronics Laboratory in cooperation with the National Aerospace Laboratory NLR and the TUD (Technical University Delft). This antenna will be used in a Synthetic Aperture Radar (SAR) system. For a successful operation the radiation pattern of the antenna must switch between several beams. A procedure has been developed for the determination of the excitation of the elements of the array. These data can be used to find the optimum amplitude and phase settings for each scanning beam.
First, some theory about linear arrays is discussed and several definitions are given.
Second, the principles of the Element Excitation Method (EEM) are described.
The applications of the EEM are shortly mentioned. Measurement results of the excitation of the elements of the planar PHARS antenna are given in chapter 4. The excitation measurements are used to obtain radiation patterns in several scan directions and with sidelobes more than 12 dB below its peak maximum.
The EEM -method proved to be very successful.

2 THEORY

2.1 Linear array theory

We consider in this chapter only active linear phased arrays that consist of M equally spaced and identical receiving antenna elements as shown in Figure 1.
(The derivation of the EEM-method can be extended for planar arrays and transmitting arrays as well)

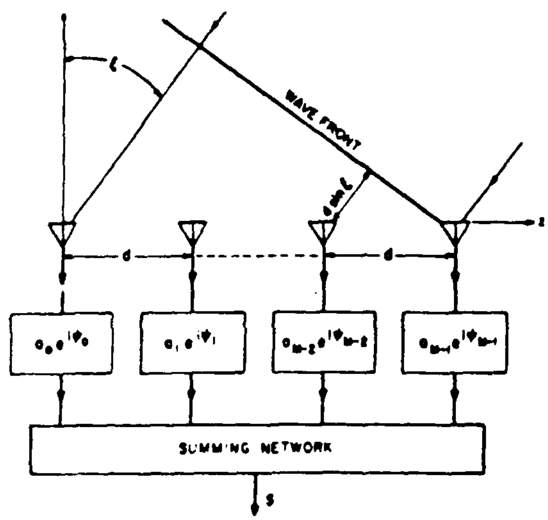


Fig. 1: Basic linear array configuration

Behind each antenna element a module is placed, that influences both the amplitude and the phase of the received signal. In practice, the amplitude and phase can often only be changed in discrete steps. The resulting received signal at the output of this array due to a plane wave arriving from the direction ξ is [1]:

$$S(\theta) = S_e(\xi) \sum_{m=0}^{M-1} a_m e^{j(\psi_m + m*2\cdot*d*\sin(\xi)/\lambda)} \qquad (1)$$

with $S_e(\xi)$ = 'element factor'
d = spacing between adjacent antenna elements
λ = wavelength
ξ = direction of arriving plane wave at array
$a_m e^{j\psi_m}$ = complex transfer function of module m

Let's confine our interest to signals arriving from the direction $\xi = 0°$. Eqn. (1) reduces to :

$$S(0) = S_e(0) \sum_{m=0}^{M-1} a_m e^{j\psi_m} \qquad (2)$$

2.2 Definition of element excitation

If the phase setting of only one module (i) is varied and the amplitude and phase settings of all the other elements are fixed, then the resulting signal will be:

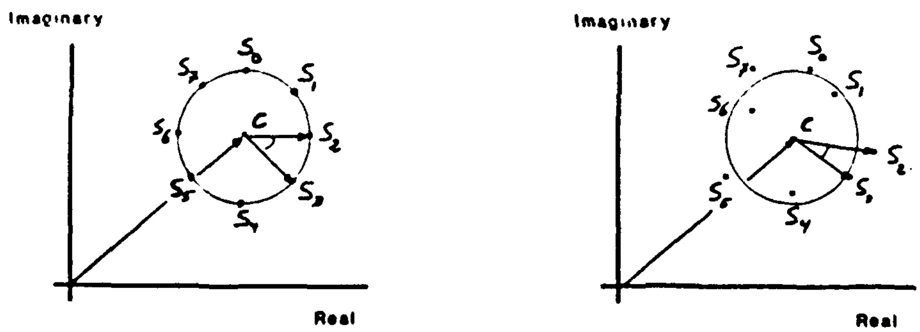
$$S(0) = S_e(0) \sum_{\substack{m=0 \\ m \neq i}}^{M-1} a_m e^{j\psi_m} + S_e(0)\, a_i e^{j\psi_i} \qquad (3)$$

The first term in the right hand part of eqn (3) is a constant contribution to S(0), while the contribution of the last term is dependent on the varying phase setting. The element excitation (EE) to be determined is denoted by the last term:

$$EE_i = S_e(0)\, a_i e^{j\psi_i} \qquad (4)$$

2.3 Examples of element excitations

An example of the received far field signal of a linear array, with the main beam pointed in the direction $\xi = 0°$, given by Eqn (3) is shown in Fig 2. The modules behind the antenna elements are equipped with 3 bit phase shifters for steering the beam. The expected phase step size is 45°.



(a) (b)

Fig. 2: Received signals and best fitting circle.

S_0,..,S_7 denote the measured complex signals for phase settings 0,..,7 of module i.

Figure 2a appears if mutual coupling can be ignored and the amplitude of the element under review is independent of the phase setting of the element. The measured signals are located on a circle. The element excitation is the vector between a measured signal S_i and the circle centre C.

Figure 2b is a more practical example. Due to a non-ideal phase shifter (the amplitude varies with the phase-state) the measured signals will not be exactly lying on a circle. A least square error algorithm [2, and appendix 1] can be used to calculate the 'best fitting circle' through the measurement points S_i. The element excitation is now approximated by the vector between the measured signal S_i and the calculated circle centre C.

To perform this calculation with a high accuracy, it is necessary that the contribution of the element under review (vector from circle centre C to point S_i) is relatively large compared to the constant contribution of the other elements (vector from origin of coordinate system to circle centre C). The contribution of the element under review will be negligible small compared to the contribution of the other elements, if an array with a few hundred or more elements is considered with most of the elements properly electrically aligned.

2.4 Element Excitation Method (EEM)

The element excitation method is described by the following procedure:

- Install the active phased array antenna in a far field antenna measurement system
- Put the antenna in the direction $\xi = 0°$
- The element excitation has to be determined for the array under operational conditions, i.e. with all active elements in operation. This is due to mutual coupling and temperature effects (high power amplifier usually produces a considerable amount of heat and can be temperature sensitive). They influence the excitation of an element.
- Measure the received signal of the array output in terms of amplitude and phase while varying the amplitude and phase settings of just one antenna element. Determine the element excitation of each setting with the 'best fitting circle'.
- Repeat the last step for each element.

As a result the excitations of the antenna elements as a function of their amplitude and phase setting are known.

In order to use the measured excitations for a desired antenna pattern, the theoretical excitations of the elements have to be known for each pattern. The practical excitations with the smallest deviation with the theoretical excitations is the 'optimum' setting (electrical alignment) and results in a radiation pattern most closely to the desired radiation pattern.

It is emphasized that each element excitation has to be determined only once during a simple antenna measurement for one beam direction. All desired radiation patterns can be obtained with these excitations.

It's actually not necessary to measure the electric far field of the antenna. The electric field in terms of amplitude and phase may be measured closer to the antenna. A compensation has then to be implemented for the phase and amplitude differences caused by the difference in path length between transmitting/receiving antenna and the elements under review.

3 APPLICATIONS OF ELEMENT EXCITATION METHOD

The two major applications of the EEM is the ability to detect errors in antenna elements and to align the antenna elements.

The element excitations are in general hampered by phase and amplitude errors introduced by defective elements, not perfect tracking of the modules, deviations in the feed network and the radiators itself.

Compensation of these errors is essential to obtain good radiation patterns.

Phase errors are mostly caused by deterministic differences in insertion phase between the elements. When all elements have zero phase setting of the phase shifter their insertion phases must be identical. Information on differences on insertion phase can be obtained from the measured element excitations for zero phase state of the phase shifters. Possible differences can be compensated by changing the settings of the phase shifters in the antenna elements. The degrees of phase error compensation depends on the phase resolution of the phase shifters and the accuracy of the differential phase shift. Amplitude errors can only be removed when the elements have the provision of variable gain control.

Further, the degradation of the phased array can be investigated by executing the EEM regularly.

4 EXPERIMENTS

4.1 Description of PHARS antenna

Measurements have been performed on the PHARS [3] antenna to investigate the practical value of this Element Excitation Method.

The 'PHARS' antenna has been developed at the TNO Physics and Electronics Laboratory in cooperation with the National Aerospace Laboratory NLR and the TUD(Technical University Delft). This antenna will be used in a Synthetic Aperture Radar (SAR) system.

The PHARS antenna is an active array with 8 clusters of 4 microstrip patches operating at C-band.

Figure 3 shows the front of the antenna with 32 microstrip patches.

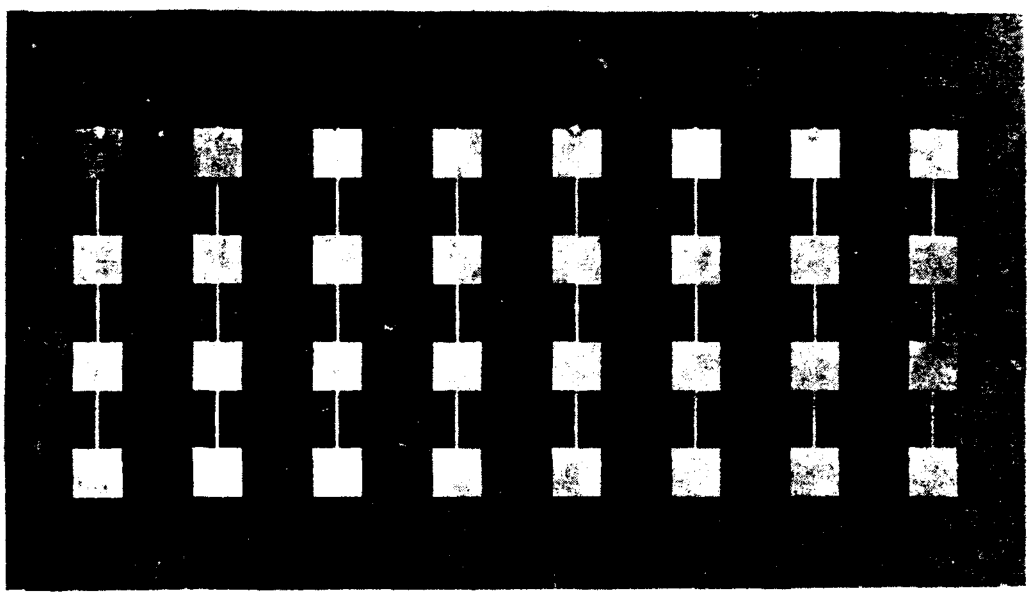


Fig. 3: Front of PHARS antenna.

Each cluster is connected to both a high power and a low noise amplifier for the transmitting and the receiving mode. Pulsed signals are transmitted with a pulse repetition frequency of 3500 Hz and a duty cycle of 5% at a carrier frequency of 5.3 GHz. The high power amplifier is a state of the art GaAs device with a 20 Watt output peak power.

Phase control for scanning the main beam is done with 4-bit phase shifters. (So 16 different phase-states are possible). The smallest phase step is nominal 22.5°. There is no amplitude control for the elements.

Reference [3] gives further details about this antenna.

4.2 Determined element excitation

The excitation of all the elements as a function of their phase-setting are determined.

Figure 4 shows a typical result of the excitation of one module (only the amplifier with switch) and of one element (module placed in antenna). The amplitude variation (only relative values) and the phase deviation from the nominal phase state as a function of the phase setting are depicted:

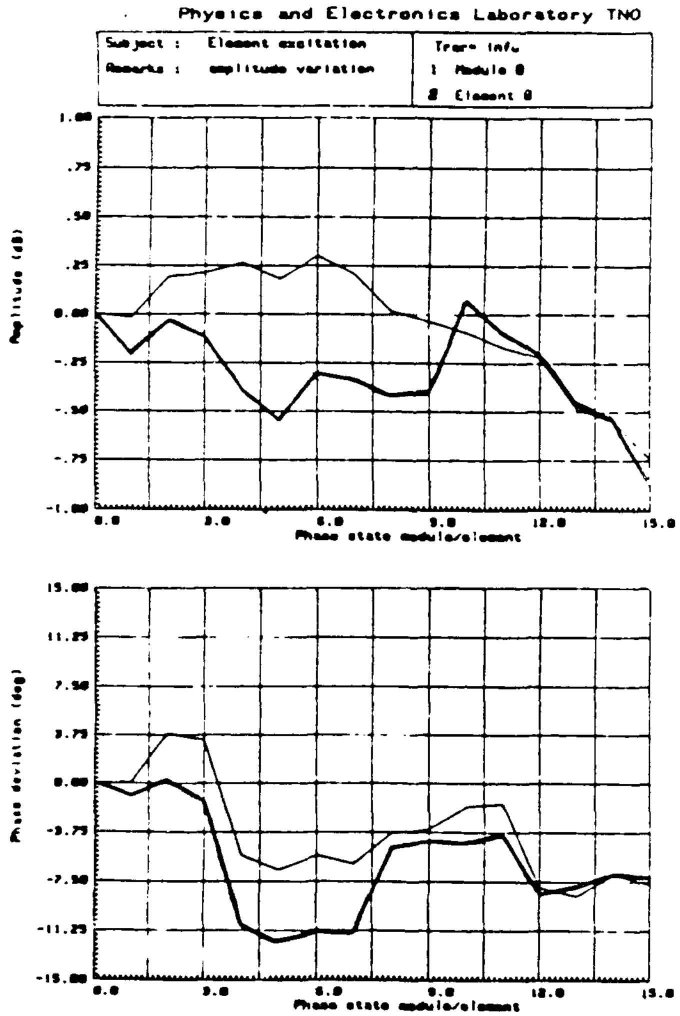


Fig. 4: Typical element excitation as a function of phase state:
a) amplitude variation (relative),
b) phase deviation from nominal phase state.

(The measured amplitude and phase of the element in phase state 0 is used as a reference for these plots)

Figure 4 shows clearly that the amplitude variation and the phase deviation varies with the phase setting of the module and element. There is not much difference between the behaviour of the phase-state of the module and of the element. The difference in behaviour of the amplitude variation is larger.

The measured amplitude variation of the element is ± .5 dB and the measured phase deviation is ± 6°.

The element excitations of all elements are slightly different.

4.3 Electrical alignment of elements

The measured element excitations are used to align the phase settings of the antenna elements for several scanning beams of the antenna with sidelobes more than 12 dB below the peak of the beam. The scanning-range is between θ_{scan}=-12° and θ_{scan}=+12°. In theory an array with a uniform amplitude excitation of the elements and a linear phase gradient dependent on the scan-angle θ_{scan} will have a radiation pattern that satisfies the criteria. The phase states of the elements were chosen such that the excitations agreed to the theoretical excitation. Figure 5 shows the radiation pattern of the antenna with the beam scanned in the θ=-10° direction.

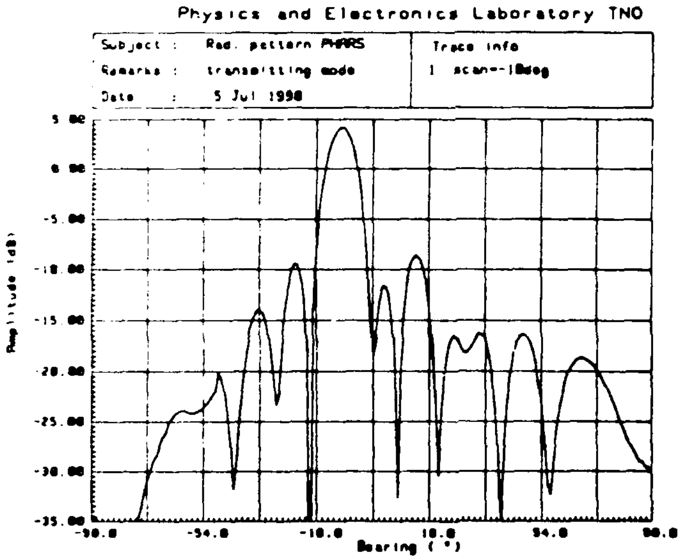


Fig. 5: Radiation pattern of the scanning PHARS antenna.

Figure 5 shows clearly that the desired radiation pattern is obtained. For other angles θ_{scan} similar results were obtained.

5 CONCLUSIONS

The Element Excitation Method (EEM) provides a simple and fast method to determine the excitation of antenna elements in an active phased array as a function of the amplitude and phase setting.

These element excitations can be used to align the amplitude and phase settings of the antenna elements of an active phased array for any desired radiation pattern.

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BEST FITTING CIRCLE PROCEDURE (Copied from [2])

A modified least square error criterion is

$$(1)\quad \sum_{i=1}^{N} \left[(x_i-A)^2 + (y_i-B)^2-R^2\right]^2 = \min$$

Where (x_i,y_i) represent the x-y coordinates of the i^{th} measured data point, N the number of data points, (A,B) the coordinates of the center, and R the radius of the circle. See Fig. 1.

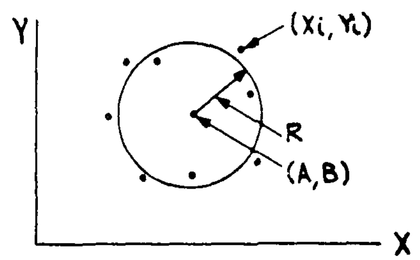

Figure 1.

Circle Fitting Procedure

Expanding (1)

$$(2)\quad f = \sum_{i=1}^{N} (x_i^2 - 2Ax_i + A^2 + y_i^2 - 2By_i + B^2 - R^2)^2 = \min$$

Now set the derivatives equal to zero

$$(3)\quad \frac{\partial f}{\partial A} = \frac{\partial f}{\partial B} = \frac{\partial f}{\partial R} = 0$$

And letting $\sum_{i=1}^{N} \triangleq \Sigma$

(4) $\frac{\partial f}{\partial R} = -4R\Sigma(x_i^2 - 2Ax_i + A^2 + y_i^2 - 2By_i + B^2 - R^2) = 0$

(5) $\frac{\partial f}{\partial A} = -4\Sigma(x_i^2 - 2Ax_i + A^2 + y_i^2 - 2By_i + B^2 - R^2)(x_i - A) = 0$

(6) $\frac{\partial f}{\partial B} = -4\Sigma(x_i^2 - 2Ax_i + A^2 + y_i^2 - 2By_i + B^2 - R^2)(y_i - B) = 0$

Note that (5) is of the form $\Sigma z_i x_i - \Sigma z_i A = 0$, where $z_i \triangleq (x_i^2 - 2Ax_i + A^2 + y_i^2 - 2By_i + B^2 - R^2)$. The sum $\Sigma z_i x_i \neq \Sigma z_i A$, therefore $\Sigma z_i x_i = 0$, and $\Sigma z_i A = 0$. So (4), (5) and (6) can be written

(7) $\Sigma z_i = 0$

(8) $\Sigma z_i x_i = 0$

(9) $\Sigma z_i y_i = 0$

Expanding gives

(10) $(2\Sigma x_i)A + (2\Sigma y_i)B + (N)C = \Sigma(x_i^2 + y_i^2)$

(11) $(2\Sigma x_i^2)A + (2\Sigma x_i y_i)B + (\Sigma x_i)C = \Sigma(x_i^3 + x_i y_i^2)$

(12) $(2\Sigma x_i y_i)A + (2\Sigma y_i^2)B + (\Sigma y_i)C = \Sigma(x_i^2 y_i + y_i^3)$

Where

(13) $C \triangleq (R^2 - A^2 - B^2)$

The above system of equations can be solved for A, B and C at this point, but to help in the computations let us shift the data to

(14) $x_i' = x_i - \frac{\Sigma x_i}{N}$

(15) $y_i' = y_i - \frac{\Sigma y_i}{N}$

Note that $\Sigma x_i' = \Sigma x_i - \Sigma \frac{\Sigma x_i}{N} = \Sigma x_i - N \frac{\Sigma x_i}{N} = 0$, and that $\Sigma y_i' = 0$ also applies. However $\Sigma(y_i')^2$, $\Sigma(x_i')^2$, $\Sigma x_i' y_i'$, etc $\neq 0$. With our new shifted data (10) through (12) can be written.

(16) $NC' = \Sigma[(x_i')^2 + (y_i')^2]$

(17) $[2\Sigma(x_i')^2]A' + [2\Sigma x_i' y_i']B' = \Sigma[(x_i')^3 + x_i'(y_i')^2]$

(18) $[2\Sigma x_i' y_i']A' + [2\Sigma(y_i')^2]B' = \Sigma[(x_i')^2 y_i + (y_i')^3]$

We can solve (17) and (18) for A' and B' then shift the answer to A and B by the following

(19) $$A = A' + \frac{\Sigma x_i}{N}$$

(20) $$B = B' + \frac{\Sigma y_i}{N}$$

From (16) we can solve for C' directly

(21) $C' = \frac{1}{N} \Sigma[(x_i')^2 + (y_i')^2]$

And C' also equals

(22) $C' = [R^2 - (A')^2 - (B')^2]$

Solving for R

(23) $$R = [C' + (A')^2 + (B')^2]^{1/2}$$

Solving (17) and (18) for A' and B'

(24) $$A' = \frac{\Sigma(y_i')^2 \Sigma[(x_i')^3 + x_i'(y_i')^2] - \Sigma x_i' y_i' \Sigma[(x_i')^2 y_i + (y_i')^3]}{2[\Sigma(x_i')^2 \Sigma(y_i')^2 - \Sigma x_i' y_i' \Sigma x_i' y_i']}$$

(25) $$B' = \frac{\Sigma(x_i')^2 \Sigma[(x_i')^2 y_i' + (y_i')^3] - \Sigma x_i' y_i' \Sigma[(x_i')^3 + x_i'(y_i')^2]}{2[\Sigma(x_i')^2 \Sigma(y_i')^2 - \Sigma x_i' y_i' \Sigma x_i' y_i']}$$

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FAST DETERMINATION OF THE ELEMENT EXCITATION OF AN ACTIVE PHASED ARRAY ANTENNA

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 POSITIONS)

THE FAR FIELD RADIATION PATTERN OF AN ACTIVE PHASED ARRAY ANTENNA IS DETERMINED BY THE EXCITATION OF ITS ELEMENTS. THE AMPLITUDE AND PHASE OF THIS EXCITATION CAN BE ADJUSTED IN AN ACTIVE PHASED ARRAY AND HAVE TO BE PROPERLY SET IN ORDER TO OBTAIN A DESIRED FAR FIELD PATTERN.
THIS REPORT DESCRIBES A FAST AND EASY METHOD TO DETERMINE THIS ELEMENT EXCITATION: THE ELECTRIC FIELD IN TERMS OF AMPLITUDE AND PHASE HAS TO BE MEASURED IN ONLY ONE DIRECTION OF INTEREST OF THE FAR FIELD OF THE ANTENNA AS A FUNCTION OF THE ELEMENT'S AMPLITUDE AND PHASE SETTINGS.
THE METHOD IS CALLED THE "ELEMENT EXCITATION METHOD"(EEM).
BOTH THEORETICAL AND PRACTICAL ASPECTS CAN BE FOUND IN THIS REPORT. THE METHOD PROVED TO BE VERY USEFUL IN THE ALIGNMENT OF THE AMPLITUDE AND PHASE SETTINGS OF THE ELEMENTS OF AN ACTIVE PHASED ARRAY AT C-BAND.

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ACTIVE ANTENNA	ALIGNMENT
ANTENNA ARRAYS	
PLANAR ANTENNA ARRAY	

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