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Radiation Power Pattern Distortion Analysis Using MATLAB for MST Radar System

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Abstract

Most often, in MST radar system, a few number of transmitters are non-operational due to various factors, making the liner sub-arrays corresponding to these transmitters in effective. This results in the thinning of the aperture and deviation of the excitation from the specified Taylor distribution. The array pattern will be distorted due to this deviation, when compared to the reference pattern. This chapter gives a complete analysis to quantify the distortion in the radiation pattern due to Aperture thinning. MATLAB was extensively used to analyze the results. The results of the radiation pattern in both principal planed and for different azimuth angles with and without thinning/tilt are presented. Radiation pattern is viewed in both polar and rectangular (2-D and 3-D) forms. Conclusions on the results obtained are presented.

Keywords: Array Factor, Distortion, Aperture thinning, MATLAB, Phased antenna, Polar Form, Rectangular form, Side Lobe Levels, Taylor distribution

1. Introduction

The ever-increasing demand for the software development of Aperture thinned Radiation Pattern has motivated to model the present work. The Indian MST radar is a phased antenna array, highly sensitive operating at 53 MHz with a peak power aperture product of 2.5×10^{10} W-m². One for each polarization, it consists of two collocated orthogonal sets of 1024 3-element Yagi-Uda antennas. They are arranged over an area of 130 m × 130 m in a 32 × 32 matrix (**Figure 1**). The complete array setup is illuminated using 32 distributed transmitters of varying power. In turn distributed transmitters each will feed a linear sub-array of 32 antennas with a 32 parallel runs of center-fed-series-feed structures [1].

Yagi-uda antenna is chosen for MST radar antenna array. Choice of an element for MST radar, advantages in favor Yagi element, requirements of side lobe level (SLL), antenna element design and modified Taylor distribution are explained [1–4]. Amplitude distribution, illumination efficiency and feeder efficiency are derived. Finally MST radar specifications are tabulated.

While planning for the antenna element designing, the sharing antenna elements architecture of fixed overlap sub array to avoid grating lobe in the antenna pattern technique is also considered [5].

An experiment made to generate low side lobe patterns optimizing ring radii and individual element excitations from concentric circular arrays [6] does not worked

Figure 1.
Geometry for MST radar system.

for MST radar array. The approach of array excitation weight vectors as imaginary number chromosomes are often used as a general tool for pattern synthesis of absolute arrays that uses decimal linear crossover [7]. WWII elevated the phased-array antennas and has become a perfect tool for RF systems [8]. Then the main focus on the G-band multifunction measuring instrument systems for the Land is developed [9]. A coupled structural-electromagnetic model of phased array antenna PAA is developed to explain the performances of antenna, and the result of random errors and mechanical distortion [10]. Random error is generated throughout the producing and assembly method, and mechanical distortion is caused by external masses like high thermal distinction, vibration and impact loads [11]. Arrays produce aperture errors [12] as their determination is sometimes neglected, being in several cases very troublesome, such errors area unit mutual effects between parts of AN array, scattering from and obstruction because of the feed of a parabolic reflector, and optical phenomenon at a lens antenna step etc. [13].

2. Geometry of MST radar

Indian MST Radar antenna array uses a two-dimensional filled antenna array for both transmission and reception. An inter-element spacing of 0.7λ (λ , being the radar wavelength) is used in both the principle directions, which allows a grating lobe free beam scanning up to an angle of about 24° from broadside direction [1].

2.1 Choice of the element

To obtain the gain of 36 dB as given in the MST radar specifications a filled aperture of roughly 21λ to 25λ is required. To fill this aperture the number of elements required are given as

$$N = \frac{\text{Total Aperture Area } A_p}{\text{Effective Area of Single Element } A_e} \quad (1)$$

Where $A_e = \lambda^2 G_e / 4\pi$.

S.No	Types of Elements	Effective Gain G_e	Effective Area A_e	No. of elements N	Approximate grid spacing
1	Isotropic	1	$\lambda^2 / 12$	63	0.29
2	Dipole	1.5	$\lambda^2 / 8$	42	.35
3	Dipole over ground Plane	3	$\lambda^2 / 4$	21	0.5
4	Yagi 3 element	5	$\lambda^2 / 2.5$	12	0.64
5	Yagi 4 element	8	$\lambda^2 / 1.5$	79	0.83

Table 1.
Different types of elements, and their number required to fill the aperture.

Table 1 gives the total number of elements required to fill up the aperture for different types of antenna elements. Comparative study of the various antennas as the potential elements in MST radar configuration was made the possibility of using following types. They are Crossed Dipole over a ground plane, Coaxial Collinear, Three –element Yagi, and Four-element Yagi.

Out of these elements, the crossed dipole over a ground plane has the gain of the order of 5 dB and hence total number of dipoles required to fill the same aperture is quite large compared to the Yagi types and would require a more complicated and expensive feed network. The Coaxial Collinear (*CoCo*) antenna, which again is another form of dipole over a ground plane, is apparently simple to fabricate. These can be directly constructed at the site using RG 8/U or equivalent RF cables, but maintenance and water proofing of such an array would be tough.

A *Yagi-Uda* array consists of many parallel dipoles with different lengths and spacing, out of which only one is actively fed and others are shorted at their feed points. Since only one of the dipoles is driven and all other elements are parasitic, the later functions respectively as a reflector or as a director. In general, the longest shorted element with length of the order of $\lambda/2$ is the reflector and the shorted element is the director. This can be viewed as the array of dipoles in which all but the driven elements (Exciters) are short-circuited. For three-element Yagi case Voltage is

$$V_m = \sum_{n=1}^3 I_n Z_{mn} \tag{2}$$

Where, I_n is the current on the n^{th} element
 m is the element number

Putting $V_1 = V_2 = 0$ and simultaneously solving these equations gives

$$\frac{I_1}{I_2} = \frac{Z_{13}Z_{32} - Z_{12}Z_{33}}{E} \tag{3}$$

$$\frac{I_3}{I_2} = \frac{Z_{13}Z_{12} - Z_{23}Z_{11}}{E} \tag{4}$$

Where, $E = Z_{11} Z_{33} - Z_{31} Z_{13}$.

Using these current rations, the input impedance, gain and radiation pattern can be calculated.

2.2 Antenna element design consideration

The single element gain and radiation pattern change considerably in the array environment. The physical area that each element couples limits the element gain in an infinite array [2, 3, 14] and is given by

$$g_r = (4\pi d_x d_y / \lambda^2) \cos\theta \tag{5}$$

for, $d_x = d_y = 0.7\lambda$

$$g_r = 4 \pi (0.49) = 6.157 = 7.89 \text{ dB} \tag{6}$$

A practical element with a gain higher than this value, would lead to overlap of effective areas, without any useful addition to the array gain. The three-element Yagi appears to be a practical choice as the element of the MST array. It has a higher front-to-back ratio, which is useful in minimizing the ground effects and it can be designed to have a gain between 6.5 dB to 8 dB.

Considering the isolated Yagi element gain as 7.2 dB, the total array gain at a taper frequency of 80% works out to be 36.3 dB. This would leave a margin of 0.3 dB towards gain loss due to amplitude and phase errors across the aperture, thus allowing us to realize a gain of 36 dB for the zenith beam. The diameter of the element was chosen to be 0.75 inch, which is a standard commercially available tube.

The following values were found to offer satisfactory performance

L1: Length of the reflector	=2.799 m.
L2: Length of the exciter	=2.677 m.
L3: Length of the director	=2.369 m.
D1: Distance between reflector and exciter	=1.245 m.
D2: Distance between director and exciter	=0.895 m.

The expected performance of three-element Yagi with the above parameters is tabulated below

Gain	7.236
Input Impedance	52.75 - j14.3
Front-to-back ratio	15 dB

2.3 Feeder network configuration

The feeder network of MST radar antenna array consists of two orthogonal sets; one for each polarization. The feeder network consists of thirty-two parallel runs of center-fed-series-feed (CFSF) structure. Thirty-two transmitters of varying power illuminate the array; each is feeding a linear sub-array of thirty-two antenna elements.

The feeder networks of all the sub-arrays are identical as far as the power distribution is concerned. The CFSF network, (shown in **Figure 2**) consisting of power divider at the center and a series of directional couplers on each side of it, connects the linear sub-array to the T/R switch, which delivers the transmitter output power to the array and the power received by the array to the corresponding low noise amplifier. Components of the feeder network are RG 1-5/8", RS 7/8" and air dielectric coaxial lines, Wilkinson type in-phase power divider, Distributed version of coupled line type directional couplers and Lumped version of hybrid type directional couplers [1].

Description of each of the above components is given below.

Figure 2.
 Center-fed-series-feed (CFSF) network.

2.4 Rigid cable

RG 1-5/8" cable is used to carry the output power of high power transmitters (70 kW – 120 kW range) to the CFSF network. RG 7/8" is used to carry the output power of low power transmitters (15 kW – 53 kW range) to the sub-array input. This cables use foam dielectric, which is having a velocity factor of 0.89 at 53 MHz, the operating frequency, these cables offer an attenuation of about 0.5 dB per 100 m.

2.5 Power divider/combiner

This device acts as a divider in the transmit mode and as a combiner in the receive mode. The circuit diagram of *Wilkinson type divider/combiner* is shown in **Figure 3**. All the three ports are terminated with characteristic impedance, Z_0 (50 Ω). Ports 2 and 3 are isolated. During the transmit mode the transmitter output power is fed to the port-1, which will be divided in phase equally between the output ports 2 and 3. In the receive mode the power received by the two halves of the linear sub-array will be delivered through series feed network to the ports 2 and 3 respectively which will be combined in phase at port-1.

The relationship between the voltages in the transmit mode at the output and input ports is given by

$$V_2 = V_3 = -j (V_1/V_2) \tag{7}$$

Figure 3.
 Wilkinson type divider/combiner.

The relationship between the voltages in the receive mode at the output and input ports is given by

$$V_1 = -j (V_2/V_3)/\sqrt{2} \quad (8)$$

Where, V_i is the voltage at the port-I. Since the two halves are symmetry $V_2 = V_3 = V$. Therefore.

$$V_1 = -j(\sqrt{2})V \quad (9)$$

2.6 Distributed versions of coupled line directional coupler (DC)

The coupled rod co-axial directional coupler is shown in **Figure 4**. In the **Figure 4**, section, 1–2 is the main line and 3–4 is the auxiliary line, which is coupled to the main line. As the electric current passes through Section 1–2 from port-1, it produces a magnetic field around it. This magnetic field couples with conductor 3–4 and induces current in it. Therefore, by varying the separation between the two conductors, we can control the coupling factor.

In the transmit mode port-1 is the input port to which the power will be fed. Port-2 is the direct output power and port-3 is the coupled port through which antenna will be energized. Port-4 is isolated with respect to port-1. The relationship between various voltages is given by

$$V_3 = k V_1 \quad V_2 = -j(\sqrt{(1 - K^2)}) \times V_1 \quad V_4 = 0 \times V_1 = 0 \quad (10)$$

Where V_i is the Voltage at port-i. This indicates that V_1 and V_3 are in phase and V_2 is lagging V_3 by 90° .

All the thirty-two antennas within a sub-array should get the excitation signals with same phase so as to produce a main beam in the broad side direction resulting in high gain. In order to achieve this, the lengths of the feeding cables (running from the coupled port to the antenna balun) are adjusted accordingly. This process is called *Phase equalization*.

In the receive mode the antenna delivers power to the coupled port (port-3) and port-2 will be fed by the power coming from the adjacent coupler. In this mode, as a consequence of the phase equalization, V_2 always leads V_3 by 90° . The relationship between the various voltages is given by

$$V_1 = (\sqrt{(1 - K^2)}) V_2 + k V_3 \quad (10a)$$

$$V_4 = (\sqrt{(1 - k^2)}) V_3 - k V_2 \quad (11)$$

Figure 4.
Coupled line directional coupler.

2.7 90° Hybrid coupler lumped version

This coupler comprises of four quarter-wave sections, two in series and two in shunt. Each quarter line is realized by equivalent π section of lumped elements (inductors and capacitors) [2, 3].

In this structure, diagonally opposite ports are coupled. Since the coupled signal travels a distance of two quarter-wavelengths, it will be out of phase with respect to the input port. Powers given at the port-1 will be distributed between the direct output port-2 and coupled port-3. Port-4 is isolated. The coupling factor is dependent on the normalized impedance of series and shunt arm quarter-wave line sections, Z_b and Z_a respectively. Coupling factor is given by.

$$k = -Z_b/Z_a \quad (12)$$

Condition for impedance matching is given by.

$$1/Z_b^2 - 1/Z_a^2 = 1 \quad (13)$$

2.8 Excitation coefficients in the transmit mode

The normalized amplitudes (C_n) for all antenna elements with respect to the first antenna from the divider is given by

$$C_n = V k_n \prod_{i=1}^{n-1} \sqrt{(1 - k_i^2)} \quad (14)$$

Where K_1 is the coupling factor of coupler 'I' from the center (divider).

2.9 Excitation coefficients in the receive mode

The normalized amplitudes (C_n) for all antenna elements with respect to the first antenna from the divider is given by

$$C_n = k_n \prod_{i=1}^{n-1} \sqrt{(1 - k_i^2)} \quad (15)$$

Where K_1 is the coupling factor of coupler 'I' from the center (divider).

2.10 Illumination efficiency

Since the weighing factors of the antenna elements are same for both transmit and receive modes, illumination efficiency will be same for both the modes. Illumination efficiency is defined as “the ratio of effective length of the sub-array to the physical length”, which can be expressed as

$$\eta_{\text{ill}} = \frac{1}{16C_1} \sum_{n=1}^{16} C_n \quad (16)$$

which is found to be 79%.

Feeder network consists of fifteen couplers on either side of the divider/combiner to feed 16 antennas on either side. The coupler rating in decibels and the

Coupler No. (N)	Coupler Rating In db	Coupling Factor Value(K _n)
1,2	10	0.316
3,4	9	0.355
5,6,7	8	0.398
8,9	7	0.448
10,11	6	0.501
12,13	5	0.562
14	4	0.631
15	3	0.709

Table 2.
The coupler ratings and their corresponding coupling factor.

Sub Array (N)	Coupling Coefficients(C _n)	Sub Array (N)	Coupling Coefficients (C _n)
1	1.0000	9	0.7699
2	0.9488	10	0.7697
3	1.0112	11	0.6610
4	0.9454	12	0.6467
5	0.9908	13	0.5349
6	0.9090	14	0.4968
7	0.8339	15	0.4330
8	0.8611	16	0.4330

Table 3.
The coupling coefficients of the coupler.

corresponding coupling factors of all the fifteen couplers are given in **Table 2**. The corresponding coupling coefficients (C_n) are given in **Table 3**.

2.11 Feeder network efficiency

Feeder network efficiency is defined as “the ratio of power delivered to the sub-array by the feeder network to the power output of the transmitter, feeding the sub array’. I the receive mode it is defined as “the ratio of the power delivered to LNA by the feeder network to the total power developed at the terminals of all thirty-two antenna elements during reception”. All feeder line components are assumed to the lossless in the computation of the feeder network efficiency. Normalized characteristic impedance of the system is assumed as unity in power calculations.

2.12 Transmit mode

When an input voltage of $\sqrt{2}$ volts is applied to the power divider, the voltage amplitude at the input of the first coupler will be one volt. The total power delivered to the sub-array is given by

$$P_{out} = 2 \sum_{i=1}^{16} A_n^2 \text{units} \tag{17}$$

Where A_n is the input voltage fed from the coupled ports of the directional couplers. Power input to the feeder network is,

$$P_T = \left(\sqrt{2\text{volts}}\right)^2 = 2\text{units}$$

Feeder efficiency η_{ft} is given by is found to be 100%

$$\eta_{ft} = \frac{P_{ant}}{P_r} \tag{18}$$

2.13 Receive mode

In the receive mode, all the antennas of the sub-array equal powers and deliver the same to the coupled ports of the feeder network. When an input voltage of 1 volt is applied to all the coupled ports, the input power to the feeder network is given by

$$P_{ant} = 32 \times (1)^2 = 32 \text{ watts.}$$

The output voltage of the combiner (which is fed to the LNA) is:

$$V_{out} = \left(\sqrt{2}\right) V_{0,1} \tag{19}$$

Where, $V_{0,1}$ is the output of the first coupler. The combiner output power is given by.

$$P_{out} = 2|V_{0,1}|^2 \tag{20}$$

Feeder network efficiency is given by

$$\eta_{fr} = \frac{P_{out}}{P_{tn}} \tag{21}$$

and found to be 92.8%. Note that the rest of the power will be dissipated in the isolated ports of the directional couplers.

In addition to this, there will be a combining loss (at IF level) of 0.6 dB, which is equivalent to an efficiency of 92.3%, and due to amplitude imbalance there will be some loss that should be accounted in the overall feeder line efficiency. Hence, the total feeder efficiency of the MST radar planar phased array is equal to 85.6%.The specifications of MST radar are listed here:

Type of the array	Phased antenna array
No of elements	1024
Grid	Square
Configuration	32 × 32 matrix
Inter-element spacing	0.7 wavelengths
Physical aperture	130 m × 130 m

Aperture distribution		Stepped modified Taylor across the principal planes
Effective aperture		100 m × 100 m
Peak power aperture product		2.5×10^{10} W-m ²
Gain		36 dB
Beam width		3° in the principal planes
Side lobe level		−20 dB
Beam steering		0 to 20° (in steps of 1°) from Zenith towards all directions
Feeder type		32 parallel runs of center-fed-Series-feed
Feeder efficiency (theoretical)	Transmit mode	100%
	Receive mode	92.8% in E-plane & 92.3% in H-plane
Feeder loss	Transmit mode	2.00 dB
	Receive mode	2.20 dB
Antenna element		Three-element Yagi-Uda
Frequency of operation		53 MHz
Wavelength		5.66 m
Length of the director		0.418 λ
Length of the exciter		0.471 λ
Length of the reflector		0.495 λ
Exciter-director spacing		0.158 λ
Exciter reflector spacing		0.219 λ
Radius of the element		0.00165 λ
Element pattern - Directive gain		7.8
Element pattern - Beam width (E-plane)		60°
Element pattern - Beam width (H-plane)		88°
Element pattern - Front-to-back ratio		14 dB

3. Aperture thinning of MST radar antenna Array

Most often, a few number of transmitters are non-operational due to various factors, making the linear sub-arrays corresponding to these transmitters ineffective. Even if the transmitters are operational, with in a sub-array, it is possible that some elements will not get the excitation signal due to weak connection or discontinuity problems in the feeder line. This results in the thinning of the aperture and the deviation of the excitation from the specified Taylor distribution. Due to this deviation, the array pattern will be distorted from the normal pattern. In this chapter, a detailed analysis is carried out to quantify the degradation in the radiation pattern due to aperture thinning. Phase-errors are assumed to the zero throughout.

3.1 Array pattern of 2 N MST radar

If the array aperture is in the x y-plane and sub-arrays are aligned parallel to y-axis with a spacing d_x , along the x-axis, array pattern can be expressed as

$$f(\theta, \phi) = \sum_{m=1}^{2N_x} \sum_{n=1}^{2N_y} I_{mn} e^{[-jk \sin \theta (md_x \cos \phi + nd_y \sin \theta)]} \quad (22)$$

Where d_x = sub-array spacing along the x-axis

d_y = element spacing within a sub-array (along the y-axis)

m = sub-array number along the x-axis

n = element number along the y-axis within a sub-array

θ = Field point angle from broadside

ϕ = Azimuth angle

I_{mn} = excitation current coefficient of n^{th} element in m^{th} row (sub-array)

$2N_x$ = number of sub-arrays in x-axis

$2N_y$ = Number of elements within a sub-array (along y-axis)

k = Phase constant (in free space)

For MST radar antenna array $dx = dy = d = 0.7\lambda$ and $2N_x = 2N_y = 2N = 32$. If each row has the same current distribution, even though the current levels are different in different rows, that is

$$\frac{I_{mn}}{I_{ml}} = \frac{I_{ln}}{I_{l1}} \quad (23)$$

Which is true for MST array case, and hence possible to separate the current distribution and the array factor can be expressed in the form

$$f(\theta, \phi) = f_x(\theta, \phi) f_y(\theta, \phi) \quad (24)$$

In which

$$f_x(\theta, \phi) = \sum_{m=1}^{2N} I_m e^{(-jmkd_x \sin \theta \cos \phi)} \quad (25)$$

$$f_y(\theta, \phi) = \sum_{n=1}^{2N} I_n e^{(jnk d_y \sin \theta \sin \phi)} \quad (26)$$

and

$$I_m = \frac{I_{m1}}{I_{11}} \quad (27)$$

$$I_n = \frac{I_{1n}}{I_{11}} \quad (28)$$

are the normalized current distributions in a row of elements parallel to x-axis and y-axis respectively. All the thirty-two elements are phase-equalized within a sub-array by adjusting the input feed cable lengths. Hence a linear sub-array, when excited alone, will produce a fan beam in the broadside direction. Beam tilting is done in E-plane (or $\phi = 0^\circ$ plane or xz-plane in this case) by providing progressive phase shift along the successive linear sub-arrays. The equations are executed in MATLAB to find the array patterns at different zenith angles.

If an array aperture is not fully excited, then it is said to be “Thinned”. When this thinning is applied for the MST radar array, which is a planar array with separable current distribution, the array pattern can be expressed as

$$f(\theta, \phi) = \sum_{m=1}^{2N} I_m e^{(-jmkd_x \sin \theta \cos \phi)} \sum_{n=1}^{2N} I_n e^{(jnk d_y \sin \theta \sin \phi)} \quad (29)$$

where I_m is proportional to the square root of output power of transmitters and f is proportional to the coupling coefficients of CFSF network. The array factors in both the principle planes, $\theta = 0^\circ$ (E-plane) and $\theta = 90^\circ$ (H-plane), respectively are

$$f_E(\theta) = f(\theta, 0) = \sum_{n=1}^{2N} I_n \sum_{m=1}^{2N} I_m e^{(-jmk_d x \sin \theta)} \quad (30)$$

$$f_H(\theta) = f(\theta, 90^\circ) = \sum_{m=1}^{2N} I_m \sum_{n=1}^{2N} I_n e^{(-jnk_d y \sin \theta)} \quad (31)$$

When some of the currents I_m are zero (which means the corresponding transmitters are off), it is clear that the shape of H-plane pattern, $f_H(\theta)$, will not be affected though its magnitude changes according to the first term in (31). However, the E-plane pattern, $f_E(\theta)$, will be distorted according to the second term of (30). So, when few transmitters are non-operational only the e-plane pattern will be distorted. To study the effect of aperture thinning on the radiation pattern, it is required to compute in MATLAB the array pattern by letting some of the I_m to zero, which is equivalent to putting the corresponding transmitters off.

4. Results and discussions

The antennas in the sub-arrays would not get excitation signal, if few transmitters are non-operational. Though they are physical present, electrically they are not effective. If an array aperture is not fully excited, then it is said to be 'thinned'. This results in the deviation of the excitation from the specified Taylor distribution. Due to this deviation, the array pattern will be distorted. To quantify the distortion in the radiation patterns in both E and H planes, the array pattern expressions are made to depend on the shape of the beam. Forcing some of the I_m to zero, which means these transmitters are non-operational, can effect array thinning. It is clear that the shape of H-plane pattern, $f_H(\theta)$, will not be affected, though its magnitude changes according to the first term in Eq. (31). However, the E-plane pattern, $f_E(\theta)$, will be distorted according to the second term of Eq. (30). Hence, we can conclude that only E-plane pattern will be distorted and needs to be examined in case few transmitters are non-operational. Programming in MATLAB helped a lot to examine these cases.

Array pattern is computed in the E-plane with different thinning configurations, that is by letting group of transmitters (or sub-arrays) ineffective. Radiation parameters are distorted for all the cases. The two important parameters that may affect the radar performance are gain and SLL. The variation of these two parameters with different array thinning configuration is tabulated in **Table 4**. Array pattern thinning obtained with and without tilting can be viewed from plot shown in the **Figures 5 and 6**.

Array pattern is computed for different azimuth angles using Eq. (30) by letting all transmitters (or sub-arrays) effective. The important parameters that may affect the radar performance are gain and SLL. The variation of the SLL parameter is tabulated in **Table 5**. Array pattern computed for different azimuth angles obtained without thinning and tilting can be viewed from **Figures 7–9**.

The antenna array 3-D array pattern obtained using MATLAB is shown in the **Figure 10**. Amplitude distribution is plotted using the Eq. (22). **Figure 11** shows a 3-D plot of antenna array when fully excited. Distortions of amplitude distribution due to array thinning are shown in **Figures 12 and 13**.

S.NO	Sub-arrays or TXs OFF	Loss in the gain (dB)	SLL (dB)
1	Nil	0.00	−19.9
2	3,4	0.40	−19.9
3	5,6	0.50	−22.0
4	3,4,5,6	1.00	−19.5
5	5,6,27,28	0.55	−17.5
6	1 to 8	2.00	−16.0
7	1 to 8 and 25 to 32	4.00	−13.5
8	9,10	0.50	−18.3
9	11,12	0.80	−17.7
10	13,14	0.80	−15.2
11	15,16	0.80	−14.2
12	13,14,15,16	1.90	−11.5
13	15,16,17,18,19	2.00	−09.0
14	9 to 6	3.30	−07.0
15	6,8,9,17,24,29,30,32	2.50	−14.5

Table 4.
 Variation of parameters with different array thinning configurations.

Figure 5.
 Array pattern for the two principal planes.

Polar plots plotted in MATLAB for both the principal planes are shown in the **Figures 14** and **15**. Radiation pattern for different azimuth angles obtained in MATLAB are shown in **Figures 16** and **17**.

4.1 MATLAB package

The entire software is developed using the MATLAB package. MATLAB was chosen for the numeric computation and visualization of the array pattern. Matalb

Figure 6.
Array pattern for a tilt of 10 degrees in E-plane.

S.No.	Azimuth angle ($\emptyset$)	SLL (dB)
1	0	-19.9
2	15	-21.5
3	30	-30.5
4	45	-39.5
5	60	-30.5
6	75	-21.5
7	90	-19.9

Table 5.
Variation of SLL standard configuration with different azimuth angles.

Figure 7.
H-plane pattern – without distortion and with a tilt of 10 deg.

is a helpful tool to develop portable and graphical user interface software. After entering into the package, the menu options as shown in **Figure 18** will be visible. The new file with the rated powers of the transmitters, and standard

Figure 8.
E plane pattern distortion due to array thinning transmitters off: 1 to 8 & 25-32 and tilt: 0 deg.

Figure 9.
E- plane pattern distortion due to array thinning transmitters off: 6, 8, 9, 17, 24, 29, 30 & 32 and tilt: 0 deg.

Figure 10.
3-D Array pattern.

Figure 11.
3-D power distribution for MST radar antenna array.

Figure 12.
3-D power distribution for MST radar antenna array transmitters off: 1-8, & 25-32.

Figure 13.
Transmitters off: 6, 8, 9, 17, 24, 29, 30 & 32.

Figure 14.
Radiation power pattern for both principal planes.

Figure 15.
Radiation power pattern for E-plane.

Figure 16.
Radiation power pattern for an azimuth angle of 15°.

parameters of the MST radar can be selected and will have. dat extension.
Figure 19 shows the window of the open file with open options such as m files, mat files etc.

Figure 17.
Radiation power pattern for an azimuth angle of 30°.

Figure 18.
Array factor distortion analysis menu options.

Figure 19.
Array factor distortion analysis file open selection option.

The display window will be of the format shown in **Figure 20**. The format of the display window is of 6 x 8 matrix. Press <O.K > button to clear the display. The sub menu allows the user to view as well as enter the values of your choice for both transmitters and parameters values, for the further processing. Format for entering the values in 6 x 8 matrix is shown in **Figure 21**. The accept button is pressed for processing the entered values.

The Config option allows the user with two sub menu options 1) Tx-power and 2) Parameters. The TX-Power option allows the user to change the transmitter power levels with the help of the slider as shown in **Figure 22**. The TX-Power have 4 sub menu options for each hut that is NH-1, NH-2, SH-1, and SH-2. The user can

Figure 20.
Transmitter power ON/OFF status.

Figure 21.
Format for entering transmitter power values.

Figure 22.
The transmitter power levels changes in north hut 1 (NH 1).

Figure 23.
Option to change the antenna array parameters.

change the parameters of the antenna array as shown in **Figure 23**, where the operational frequency in MHz, inter-element distance in wavelengths, number of rows and columns, tilt angle of the beam in degrees can be varied.

5. Conclusions

From the results obtained in MATLAB, it may be noticed that degradation in gain and SLL due to the absence of a few low power transmitters (**Table 4**)

(1–4 cases) is not significant. Surprisingly, SLL improves with some low power transmitters off (case-3), where the loss in directive gain is only marginal symmetrical thinning gives higher SLL than asymmetrical thinning (cases 4 & 5). If all low power transmitters are off (case-7), then the array is similar to standard radar array (almost uniform distribution) giving a SLL of -13.5 dB.

On the contrary, the absence of high power transmitters causes SLL to increase significantly. From cases 8–11 of the table, it is clear that absence of even two transmitters increases the SLL by 1.5–6 dB. It may be noted that SLL depends on the position of transmitters that are off. Absence of central sub-arrays results in higher SLL. Cases 12–14 demonstrates that absence of more than four power transmitters give unacceptable SLL (worse than Uniform distribution case). Finally, case 15 represents the real time status of the radar on a particular operational day, where eight transmitters were not functioning.

For different azimuth angles, Radiation power pattern of the MST radar antenna array is plotted. **Table 5** shows the radiation power pattern for different azimuth angles. and the variations of SLL for standard configuration of radar array, with different azimuth values. It is observed that the change in the SLL for different azimuth angles varies a lot compared to that of the SLL of the two principal planes. The main focus is on the analysis of distortion of array pattern due to thinning.

The following facts can be concluded from the pattern obtained using MATLAB:

- The first SLL rises by 0.4 dB.
- For a continuous distribution SLL taper off very fast. Far off, side lobe levels do not taper off fast.
- Around 45° the side lobe level rises roughly by 10 dB
- 3 dB beam width [15] found to be same.

The work presented in this report can further be extended to study in the following cases.

- Element pattern integrating with group pattern using MATLAB Antenna toolbox
- Mutual Coupling between antennas in the MST Radar antenna array using MATLAB Antenna toolbox

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