Optimization of Radial Line Slots Array Antenna Design for Satellite Communications

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Abstract—**This paper presents a numerical method of identifying the beam squinting optimal design parameters. It is aimed at eradicating the arbitrary method of selection of phi, (ϕ) thetaT(θ_T) and phiT(ϕ_T) which improves the overall production process. Arbitrary selection of design parameters for beam squinting method which has been identified to solve the inherent return loss problems associated with the linearly polarized radial line slots array (LP-RLSA) design is time wasting and slows satellite design and manufacturing process. Results from the numerical solutions are computed using CST microwave studio (CST 2010); an antenna design software. Simulation results were compared with those obtained from literatures and it showed excellent agreement)**

Keywords; Antenna; beam squinting; satellite missions; antenna gain;return loss

I. Introduction

Antennas are indispensable tool in space communications, it is the only means through which spacecraft communicates with the earth stations. There are different types of antennas; the choice depends on the type of applications to be deployed and to a large extent the distance of separation between the satellite in space and the earth station [1]. The parabolic reflector antenna has been widely used for satellite communications due to its high gain and efficiency. The RLSA antenna has recently been identified as a possible replacement because of the advantages it has over the parabolic reflector. It is compact, simple to design, has low loss, high efficiency and easy to install [2, 3]. So much study has been conducted on the design and optimization of the radial line slots array (RLSA) antenna with little or no attention given to the logical means to which optimal design parameters are chosen leaving designers to arbitrary selection of optimal design parameters which may retard satellite design process should poor parameters be chosen. Slots orientations for the beam squinting design on the radiating surface of RLSA antennas are manipulated using numerical method; it is defined by phi (ϕ) thetaT(θ_T)and phiT(ϕ_T) respectively. Computations using CST on very high speed computers take between (8-12) hours to complete. If arbitrary selection is made, and results to poor parameter selection, quality computation time would have been wasted. The numerical solution presented in this submission assists the RLSA antenna designer in identifying best design parameters that can lead to optimal antenna characteristics in terms of gain, return loss value and the overall antenna efficiency. Existing beam squinting equations [2], [4]are manipulated to form an objective function in terms of phi(ϕ) , thetaT(θ_T) and phiT(ϕ_T)for the numerical optimization using the concept of maxima and minima. MATLAB was used for the numerical computations of the optimal solutions.

Fig 1 (a) is geometry of the RLSA antenna showing the beam squinting parameters which defines the orientation of the slot on the radiating surface.

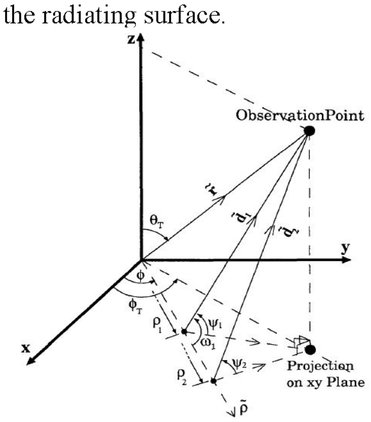

Figure 1. (a) Beam squinted geometry of RLSA [2]

ϕ : The current flow line. It is the angle between the direction of propagation and the position of slot on the radiating surface.

ϕ_T: The projection angle. It is the angle between the direction of propagation and the projection plane x, y.

θ_T : The squint angle; Slots orientation angle on the radiating surface.

Fig 1 (b) shows the geometry of the RLSA cavity waveguide as antenna feed and the copper radiating surface containing the slots arrangements.

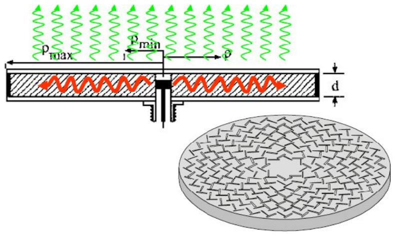

Figure 1: (b) Geometry of RLSA [5]

Good gain margin and high efficiency required for effective satellite communications will only be realized through adequate selection of these beam squinting design parameters. Since this is key; a logical mean of identifying them becomes necessary for a successful space mission where time and money is essential for the success. Design specifications for the Ku-band (11-14) GHz LP-RLSA Antenna are shown in TABLE 1.

TABLE 1: DESIGN CONSIDERATIONS

Parameter Specifications	**Symbols**	**Values**
Center frequency	f	12.5GHz
Cavity Wavelength	λ_g	15.72mm
Squint angles	θ_T	20Degrees
Slots length	l	$0.5\lambda_g$
Slots width	w	1mm
Antenna radius	r	300mm
Number of slots pair in First ring	n	16
Cavity thickness	d_1	6mm
Radiating element thickness	d	0.15mm
Cavity permittivity	ε_r	2.33
Cavity material	-	Polypropylene
Radiating element material and background	-	Copper

II. NUMERICAL SOLUTION FOR THE MANIPULATION OF RADIATING SLOT LENGTH AND THE AZIMUTHAL CELL SEPARATION

To realize a fair constant slots aperture illumination control over the radiating surface, the slot lengths is varied proportionally with respect to the radial length; and position of slots placed on the radiating surface as seen from the expression [1-5]:

$$L_{rad} = \left(5.8678 + 6.415\times10^{-3} * \rho\right) * \frac{12.5\times10^{9}}{f_o} \qquad (1)$$

Where ρ is the radius of the antenna, with f_o being the desired antenna frequency.

Similarly, maintaining constant slots surface density on the radiating surface of an RLSA antenna, the azimuthal slot separation S_ϕ is manipulated to maximize the value for a constant *K*. The constant *K* is used to determine the optimum relative radiated power density required for efficient antenna radiation characteristics. Hence, the product " $S_\rho * S_\phi$ " is minimized for a global best radiation characteristics. Since S_ρ is defined as:

$$s_\rho = \frac{\lambda_g}{1 - \sqrt{\varepsilon_r} * \sin\theta_T \cos(\phi - \phi_T)} \qquad (2)$$

$$s_\phi = \frac{2\pi\rho_{min}}{\psi} \qquad (3)$$

$$\sqrt{\varepsilon_r} = \sigma \qquad (4)$$

$$K = \frac{2\pi\lambda_g\rho_{min}}{\psi} \qquad (5)$$

$$s_\rho * s_\phi = \frac{1}{1 - \sigma * \sin\theta_T \cos(\phi - \phi_T)} \qquad (6)$$

Where

ψ is the number of slots in the innermost ring, (ρ_{min}) is minimum radius, ($\varepsilon_r = 2.33$) is the dielectric constant, and (λ_g) is the guide wavelength in *mm*

$$\left(s_\rho * s_\phi\right)_{min} = Min\frac{1}{1-\sigma*\sin\theta_T\cos(\phi-\phi_T)} \qquad (7)$$

Solving the objective function; a function of θ_T, ϕ_T, ϕ numerically with assumption that $\cos\theta_T \neq 0$ otherwise the solutions will run into series of recursive equations; thus defeating the aim of this study. A range of values for functions of the objective function within; $0 \le \phi \le 180$, $0 \le \theta_T \le 180$ and $0 \le \phi_T \le 180$ respectively is considered in this submission. Thus differentiating w.r.t θ_T, ϕ_T, ϕ ; gives:

$$\frac{\partial f}{\partial \theta_T} = \frac{+\sigma \cos \theta_T \cos(\phi - \phi_T)}{\left[1 - \sigma \sin \theta_T \cos(\phi - \phi_T)\right]^2} \tag{8}$$

$$\frac{\partial f}{\partial \phi} = \frac{-\sigma \sin \theta_T \sin(\phi - \phi_T)}{\left[1 - \sigma \sin \theta_T \cos(\phi - \phi_T)\right]^2} \tag{9}$$

$$\frac{\partial f}{\partial \phi_T} = \frac{\sigma \sin \theta_T \sin(\phi - \phi_T)}{\left[1 - \sigma \sin \theta_T \cos(\phi - \phi_T)\right]^2} \quad \ldots\ldots\ldots\ldots\ldots(10)$$

$$\theta_T = \tan^{-1}\left\{ \frac{1}{2}\left(\frac{\cos\phi \cos\phi_T + \sin\phi \sin\phi_T}{\sin\phi \cos\phi_T - \cos\phi \sin\phi_T} \right) \right\} \tag{11}$$

$$\cos \theta_T [\cos\phi \cos\phi_T + \sin\phi \sin\phi_T] = 0 \tag{12}$$

Assuming $\cos \theta_T \neq 0$ gives;

$$\cos\phi \cos\phi_T = -\sin\phi \sin\phi_T$$

$$\Rightarrow -\tan\phi \tan\phi_T = 1$$

$$\Rightarrow \tan\phi_T = \frac{-1}{\tan\phi} \Leftrightarrow \phi = \tan^{-1}\left\{ \frac{-1}{\tan\phi_T} \right\} \tag{13}$$

$$\Rightarrow \phi_T = \tan^{-1}\left\{ \frac{-1}{\tan\phi} \right\}$$

Equation (13) thus gives the required optimal solutions. Substituting eqn. (13) into eqn. (11) yields:

$$\theta_T^* = \tan^{-1}\left\{ \frac{1}{2}\left(\frac{\cos\phi \cos\left(\tan^{-1}\left\{\frac{-1}{\tan\phi}\right\}\right) + \sin\phi \sin\left(\tan^{-1}\left\{\frac{-1}{\tan\phi}\right\}\right)}{\sin\phi \cos\left(\tan^{-1}\left\{\frac{-1}{\tan\phi}\right\}\right) - \cos\phi \sin\left(\tan^{-1}\left\{\frac{-1}{\tan\phi}\right\}\right)} \right) \right\} \tag{14}$$

$$\phi_T^* = \tan^{-1}\left\{ \frac{-1}{\tan\phi^*} \right\} \tag{15}$$

$$\phi^* = \tan^{-1}\left\{ \frac{-1}{\tan\phi_T^*} \right\}$$

Equations (14) and (15) thus give; the optimal squint angle required for a best radiation characteristic.

Solving for the second derivatives of the respective differential equations (8), (9) and (10) gives;

$$\frac{\partial f}{\partial \theta_T} = \frac{+\sigma \cos \theta_T \cos(\phi - \phi_T)}{\left[1 - \sigma \sin \theta_T \cos(\phi - \phi_T)\right]^2} \tag{16}$$

$$\frac{\partial^2 f}{\partial \theta_T^2} = \frac{\begin{pmatrix} 2\sigma^2\cos^2(\phi-\phi_T)[\sin^2\theta_T\cos(\phi-\phi_T)+\cos^2\theta_T-\sigma\cos^2\theta_T\sin\theta_T\cos^2(\phi-\phi_T)]-\ldots\ldots \\ \sigma\sin\theta_T\cos(\phi-\phi_T)[1+\sigma^2\sin^2\theta_T\cos^2(\phi-\phi_T)] \end{pmatrix}}{\left[1-\sigma\sin\theta_T\cos(\phi-\phi_T)\right]^4}$$

$$\frac{\partial^2 f}{\partial \theta_T \partial \phi} == \frac{\left(\sigma\cos(\theta_T)\sin(\phi-\phi_T)[\sigma^2\sin^2\theta_T\cos^2(\phi-\phi_T)-1]\right)}{\left[1-\sigma\sin\theta_T\cos(\phi-\phi_T)\right]^4}$$

$$\frac{\partial^2 f}{\partial \theta_T \partial \phi_T} = \frac{\begin{pmatrix} \sigma\sin\theta_T\cos(\phi-\phi_T)[-2\sigma^2\sin^2\theta_T\sin^2(\phi-\phi_T)-\sigma^2\sin^2\theta_T\cos^2(\phi-\phi_T)+\ldots \\ 2\sigma\sin\theta_T\cos(\phi-\phi_T)-2\sin\theta_T-1] \end{pmatrix}}{\left[1-\sigma\sin\theta_T\cos(\phi-\phi_T)\right]^4}$$

$$\frac{\partial f}{\partial \phi} = \frac{-\sigma \sin \theta_T \sin(\phi - \phi_T)}{\left[1 - \sigma \sin \theta_T \cos(\phi - \phi_T)\right]^2} \tag{17}$$

$$\frac{\partial^2 f}{\partial \phi \partial \theta_T} = \frac{\begin{pmatrix} \sigma\cos(\phi-\phi_T)[2\sigma^2\cos^2\theta_T\cos(\phi-\phi_T)+2\sigma\sin^2\theta_T\cos(\phi-\phi_T)-\ldots. \\ 2\sigma^2\cos^2\theta_T\sin\theta_T\cos^2(\phi-\phi_T)-\sigma^2\sin^2\theta_T\sin\theta_T\cos^2(\phi-\phi_T)-\sin\theta_T] \end{pmatrix}}{\left[1-\sigma\sin\theta_T\cos(\phi-\phi_T)\right]^4}$$

$$\frac{\partial^2 f}{\partial \phi^2} = \frac{\begin{pmatrix} \sigma^2\sin^2\theta_T\sin^2(\phi-\phi_T)[1-2\sigma\sin\theta_T\cos(\phi-\phi_T)]+\sigma\sin\theta_T\cos(\phi-\phi_T)[2\sigma^2\sin\theta_T\cos(\phi-\phi_T)- \\ \sigma^2\sin^2\theta_T\cos^2(\phi-\phi_T)-1] \end{pmatrix}}{\left[1-\sigma\sin\theta_T\cos(\phi-\phi_T)\right]^4}$$

$$\frac{\partial^2 f}{\partial \phi \partial \phi_T} = \frac{\begin{pmatrix} \sigma^2\sin^2\theta_T\sin(\phi-\phi_T)\cos(\phi-\phi_T)[3\sigma\sin\theta_T\sin(\phi-\phi_T)-2\sigma]\ldots \\ -\sigma\sin\theta_T\cos(\phi-\phi_T)[2\sigma^2\sin\theta_T\sin(\phi-\phi_T)+1] \end{pmatrix}}{\left[1-\sigma\sin\theta_T\cos(\phi-\phi_T)\right]^4}$$

$$\frac{\partial f}{\partial \phi_T} = \frac{\sigma \sin \theta_T \sin(\phi - \phi_T)}{\left[1 - \sigma \sin \theta_T \cos(\phi - \phi_T)\right]^2} \tag{18}$$

$$\frac{\partial^2 f}{\partial \phi_T^2} = \frac{\begin{pmatrix} -\sigma\sin\theta_T\cos(\phi-\phi_T)[1+\sigma^2\sin^2\theta_T\cos^2(\phi-\phi_T)-2\sigma\sin\theta_T\cos(\phi-\phi_T)] \\ +2\sigma^2\sin^2\theta_T\cos^2(\phi-\phi_T)[1-\sigma\sin\theta_T\cos(\phi-\phi_T)] \end{pmatrix}}{\left[1-\sigma\sin\theta_T\cos(\phi-\phi_T)\right]^4}$$

$$\frac{\partial^2 f}{\partial \phi_T \partial \theta_T} = \frac{\left(\sigma\cos(\theta_T)\sin(\phi-\phi_T)[1-\sigma^2\sin\theta_T\cos^2(\phi-\phi_T)]\right)}{\left[1-\sigma\sin\theta_T\cos(\phi-\phi_T)\right]^4}$$

$$\frac{\partial^2 f}{\partial \phi_T \partial \phi} = \frac{\begin{pmatrix} \sigma\sin\theta_T\cos(\phi-\phi_T)[2\sigma\sin\theta_T+2\sigma\sin\theta_T\sin^2(\phi-\phi_T)+2\sigma\sin^2\theta_T\sin^2(\phi-\phi_T)\ldots. \\ -\sigma^2\sin^2\theta_T\cos^2(\phi-\phi_T)-1] \end{pmatrix}}{\left[1-\sigma\sin\theta_T\cos(\phi-\phi_T)\right]^4}$$

For confirmation, the determinant of the matrix equation formed for the respective partial differential solutions is solved. Thus;

$$\left|\begin{pmatrix} \frac{\partial^2 f}{\partial \theta_T^2} & \frac{\partial^2 f}{\partial \theta_T \partial \phi} & \frac{\partial^2 f}{\partial \theta_T \partial \phi_T} \\ \frac{\partial^2 f}{\partial \phi \partial \theta_T} & \frac{\partial^2 f}{\partial \phi^2} & \frac{\partial^2 f}{\partial \phi \partial \phi_T} \\ \frac{\partial^2 f}{\partial \phi_T \partial \theta_T} & \frac{\partial^2 f}{\partial \phi_T \partial \phi} & \frac{\partial^2 f}{\partial \phi_T^2} \end{pmatrix}\right| < 0 \tag{19}$$

Equation (19) implies that the solution is a maximum point since the value of the second derivative is less than zero.

$$\left|\begin{pmatrix} \frac{\partial^2 f}{\partial \theta_T^2} & \frac{\partial^2 f}{\partial \theta_T \partial \phi} & \frac{\partial^2 f}{\partial \theta_T \partial \phi_T} \\ \frac{\partial^2 f}{\partial \phi \partial \theta_T} & \frac{\partial^2 f}{\partial \phi^2} & \frac{\partial^2 f}{\partial \phi \partial \phi_T} \\ \frac{\partial^2 f}{\partial \phi_T \partial \theta_T} & \frac{\partial^2 f}{\partial \phi_T \partial \phi} & \frac{\partial^2 f}{\partial \phi_T^2} \end{pmatrix}\right| > 0 \tag{20}$$

The equation (20) implies that the solution is a minimum point since the value of the solution for its second derivative is greater than zero.

$$\left|\begin{pmatrix} \frac{\partial^2 f}{\partial \theta_T^2} & \frac{\partial^2 f}{\partial \theta_T \partial \phi} & \frac{\partial^2 f}{\partial \theta_T \partial \phi_T} \\ \frac{\partial^2 f}{\partial \phi \partial \theta_T} & \frac{\partial^2 f}{\partial \phi^2} & \frac{\partial^2 f}{\partial \phi \partial \phi_T} \\ \frac{\partial^2 f}{\partial \phi_T \partial \theta_T} & \frac{\partial^2 f}{\partial \phi_T \partial \phi} & \frac{\partial^2 f}{\partial \phi_T^2} \end{pmatrix}\right| = 0 \tag{21}$$

And equation (21) implies point of inflexion. Solutions of the determinants of the 3x3 matrix equations (19), (20) and (21) enables values of optimal solutions to be known as minimum, maximum or point of inflexions respectively. Thus assisting in identifying best antenna design parameters in terms of phi, thetaT and phiT respectively, as a result; computation time improved. Solving through the determinants of the matrix formed from the MATLAB computed results of the differentials of the objective function gives;

$$\begin{pmatrix} -16.8851 & -13.6853 & 21.5406 \\ 19.3282 & -21.3841 & -56.8298 \\ -2.0530 & -50.5399 & 19.75 \end{pmatrix} = 37268.035$$

This result indicates that; the global best solution is a minimum since the results of the determinant is a positive value from this condition:

$$\left|\begin{pmatrix} \frac{\partial^2 f}{\partial \theta_T^2} & \frac{\partial^2 f}{\partial \theta_T \partial \phi} & \frac{\partial^2 f}{\partial \theta_T \partial \phi_T} \\ \frac{\partial^2 f}{\partial \phi \partial \theta_T} & \frac{\partial^2 f}{\partial \phi^2} & \frac{\partial^2 f}{\partial \phi \partial \phi_T} \\ \frac{\partial^2 f}{\partial \phi_T \partial \theta_T} & \frac{\partial^2 f}{\partial \phi_T \partial \phi} & \frac{\partial^2 f}{\partial \phi_T^2} \end{pmatrix}\right| > 0$$

Which implies is a minimum point. It thus represents *K.* Some radiation characteristics computed by CST-2010 from optimal solutions of θ_T^* and ϕ obtained by the numerical computation of the objective function using MATLAB is shown in TABLE II.

TABLE II: RADIATION CHARACTERISTICS OF SOME SELECTED PARAMETERS OF THETAT (θ_T^*) AND PHI(ϕ)

Optimal Solution θ_T^* ***Deg***	ϕ ***Deg***	**Gain** ***(dB)***	**Total efficiency (%)**	S_{11} ***(dB)***
3	0.45560	27.26	53.60	<-20
20	0.45460	32.00	88.94	<-20
27	0.20630	19.80	89.84	<-20
42	-0.57220	23.30	93.85	<-25
45	0.46350	30.30	93.59	<-25
48	0.45750	28.20	93.88	<-25
133	0.46250	26.00	93.45	<-30
169	-0.07760	29.09	91.84	<-30

TABLE II confirms the claim by[6, 7],where it was reported that smaller squint angles shows deterioration of radiation performance as seen with the least squint angle 3 degree. MATLAB computations of the numerical solutions for optimal design parameters phi (ϕ) and thetaT(θ_T^*)is shown in Figure 2

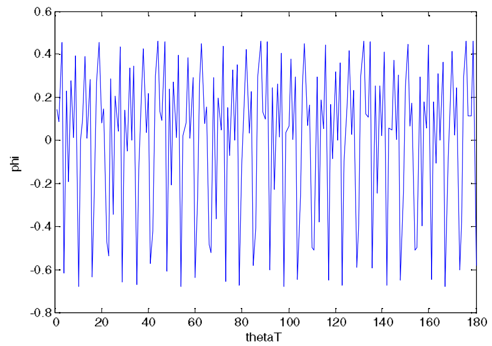

Figure 2: Graph of current flow line and optimal squint angles

III. RESULTS AND DISCUSSIONS

From Fig. 2 It is easy to notice that, the maximum positive values obtained from these computations are more likely to give best antenna performance in terms of return loss and directivity, it is also worth noting that the most minimum values indicates larger squint angles and are also more likely to give optimum return loss performance as well as good gain margin. Further solutions for the second derivatives confirm the solution as a minimum, maximum or a point of inflexion as the case might be. Return loss computations by CST microwave studio software are seen in figure 3.

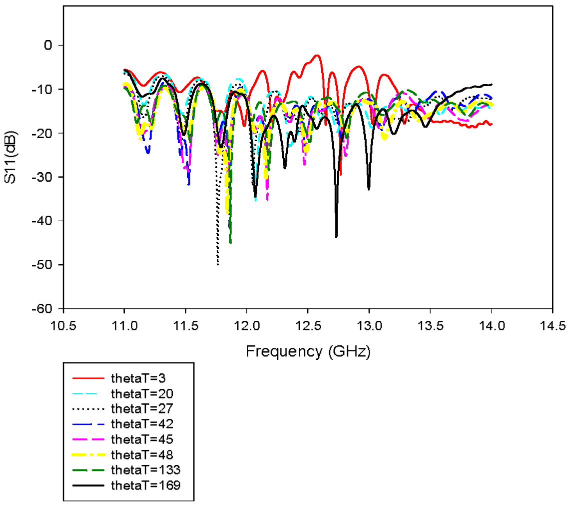

Figure 3: Return Loss graph for the numerical computation of optimal squint angle thetaT (θ_T^*) @ 12.5 *GHz*.

It can easily be seen from Fig. 3 that at center frequency of 12.5GHz which is the resonant frequency considered in this study, the optimal performance is obtained when thetaT=20, 45, 48, 169 and 133degs respectively with return loss values below -25dB. Best peak gain of 32dB was achieved at 20degree squint angle; this experienced a shift in center frequency to 12GHz with a return loss performance below -25dB. As a result, best performance is considered at 45deg squint angle since this conforms to the design frequency of 12.5GHz considered in this submission, this gives a gain value of 30.5dB. However it is worth noting that higher degrees squint angles gave incredible return loss performance across the entire frequency. This is in conformity with the solutions of the determinant for the second derivatives of the objective function matrix which indicates that the global best result (K) is a minimum point. Fig. 4 is the computed E plane radiation pattern for 20deg, 45deg, 169deg, 48deg and 03deg respectively.

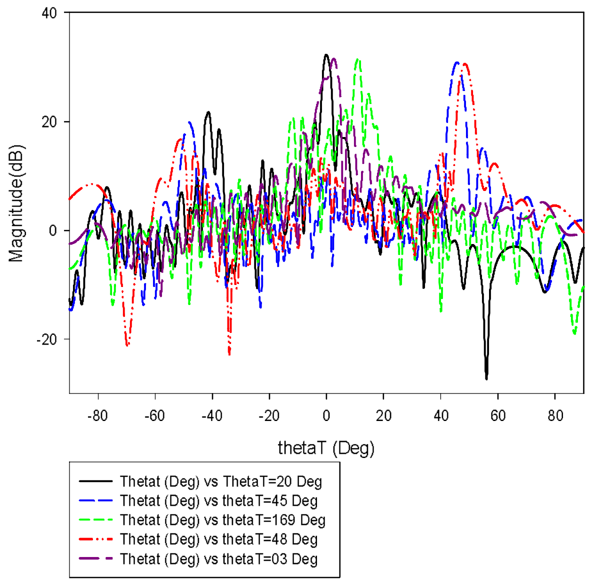

Figure 4: CST computed E-plane radiation patterns for 20*deg* beam-squint antenna.

Table III shows comparison between directivity, gain , return loss and efficiency of previous studies conducted on (20 and 15) degrees beam squinted RLSA antenna design at 12GHz, 17GHz and 12.5GHz respectively, with a dish diameter range between 277mm and 600mm as seen in [2] [6, 8-10] with this present studies.

TABLE III: COMPARISON OF SOME REFERENCED LP- RLSA RADIATION PERFORMANCE WITH THE SIMULATED RESULTS FROM PRESENT STUDY

References	2	6	8	10	Present study
Frequency *(GHz)*	12.50	17.00	12.00	12.00	12.50
Diameter *(mm)*	550.0	277.0	500.0	600.0	600.0
Beam squint Angle*(Deg)*	20.00	15.00	20.0	20.00	20.00
Directivity *(dBi)*	33.00	-	33.70	-	32.60
Gain *(dB)*	31.00	30.70	-	35.40	32.00
Efficiency (%)	57.00	50.00	67.00	65.00	88.94
Dielectric ε_r	2.230	2.200	-	1.440	2.330
Return loss *(dB)*	<-20	<-20	<-20	<-20	<-20
Radiating material	copper	copper	-	copper	copper

TABLE III shows published literatures on 20deg beam squinted linearly polarized radial line slot array antenna design and its agreement with the present study. This confirms the viability