

An Optimized Ku-Band Corrugated Feed Horn Antenna Design for a Cassegrain Reflector Using Multi-Objective Particle Swarm Optimization

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Abstract: - In this paper, a Ku-band corrugated feed horn antenna for a Cassegrain reflector is designed and optimized. The horn dimension parameters are optimized so that it has a radiation pattern with a specific beamwidth which would illuminate the sub-reflector of the Cassegrain antenna with the desired taper. It is also required that the horn must have low S_{11} parameter and low cross-polarization levels. Multi-objective particle swarm optimization is performed to optimize the horn dimensions to meet these requirements. The radiation characteristics of the optimized horn are analyzed using computer simulation. The far-field radiation pattern of the Cassegrain reflector for the optimized feed horn is also discussed and compared with the case of an un-optimized horn.

Key-Words: - Cassegrain reflector, Corrugated horn antenna, Multi Objective Particle Swarm Optimization.

1 Introduction

Horn antennas are widely used as feed antennas of reflectors or lenses [1], [2]. To be an efficient feed antenna, the horn antenna must have low S_{11} parameter, specific beamwidth, low levels of cross-polarization and low sidelobe levels [2], [3]. A corrugated horn antenna has all of these characteristics. This makes it a popular choice for a feed antenna.

A Cassegrain reflector is a dual reflector antenna system. Cassegrain antennas are used for satellite communication and deep space communication [3], [4]. In a Cassegrain reflector antenna, a feed antenna (usually a horn antenna) illuminates a hyperbolic sub-reflector. The sub-reflector in turn illuminates the main parabolic reflector which produces a pencil beam radiation pattern. The geometry of the Cassegrain reflector is shown in Fig. 1. For analysis, a typical set of dimension parameters for a Ku-Band (12-18 GHz) Cassegrain antenna is taken [5], [6].

The radiation pattern of the feed is called the primary pattern, whereas the radiation pattern of the composite Cassegrain antenna is called the secondary pattern [6]. The primary pattern depends on the materials, dimension parameters, geometry and type of the feed horn. The secondary pattern depends on the primary pattern. For satellite communication, it is necessary that the secondary pattern have a small beamwidth and sidelobe level. To achieve this, the primary pattern must provide

tapered illumination [5]. Tapered illumination implies that the electric field at the edge of the illuminated surface is less than the electric field at the center of the illuminated surface. The edge taper level is selected based on the secondary pattern requirements. Typical value of edge taper falls in the range of -10 dB to -14 dB [5]. To provide a certain edge taper in a Cassegrain reflector, the feed horn must have a specific beamwidth. From Fig. 1, it can be seen that the sub-reflector edge creates an angle of 11.89° at the aperture of the feed horn. So, if -12 dB edge taper is desired, the feed horn must have a -12 dB beamwidth of 11.89° .

Along with the desired beamwidth, a good feed horn must also have low values of S_{11} parameter [2], [4]. The reflection coefficient at the aperture of the horn antenna is denoted by S_{11} parameter. S_{11} parameter expressed in dB is known as return loss [7]. A low S_{11} parameter indicates a most of the microwave energy is directed outwards of the horn towards the sub-reflector and a small amount of energy is reflected back.

Another requirement of a good feed horn is to have low cross polarization level. In satellite communication, it is often required that the antenna be capable of handling two separate orthogonal polarizations and minimizing interference between them [3], [7]. This allows two communication channels to be created at the same frequency band. Cross-polarization level indicates how much the two

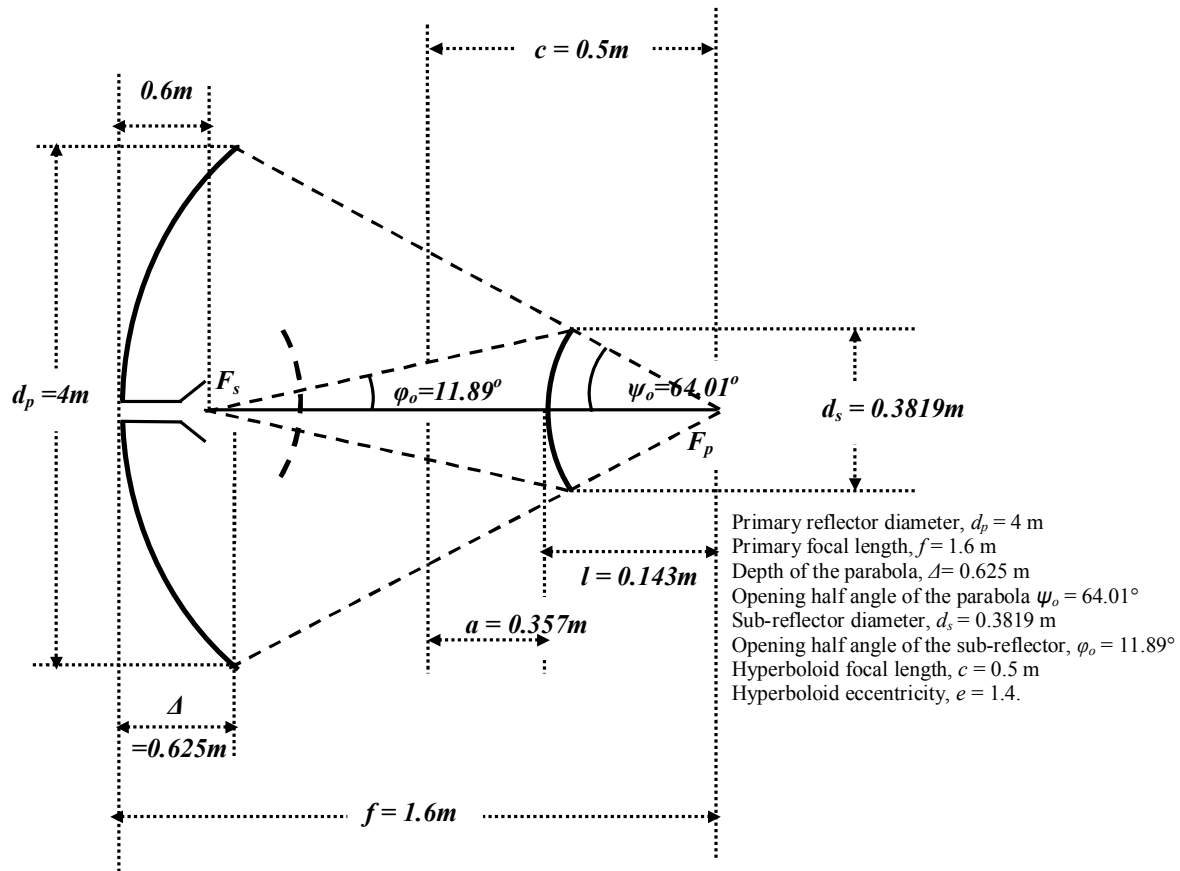


Fig. 1 Geometry of a Cassegrain reflector.

orthogonal polarizations interfere with each other. So, low level of cross-polarization is essential for a practical feed horn.

A corrugated horn antenna has all of the characteristics of a desired feed horn. But the dimensions of the corrugated horn must be selected such that the primary pattern beamwidth matches with the Cassegrain geometry requirements. Adjusting the dimensions of the horn for a specific beamwidth can change the cross-polarization levels, S_{11} parameter and other radiation characteristics of the horn. The relationship between the dimension parameters of the corrugated horn and its radiation characteristics is governed by complex mathematical equations. Therefore, the best set of horn dimensions for the design is not obvious and can not be determined analytically. In such cases, optimization algorithms can be used to find the desired dimension parameters.

Particle swarm optimization (PSO) is used here to optimize the horn dimensions. PSO is an evolutionary optimization algorithm based on the movement and intelligence of swarms [7]. The algorithm has found many applications in the field of electromagnetics [8]. The algorithm is fast and

easy to implement, which makes it an attractive tool for antenna designers. As the corrugated feed horn needs to satisfy multiple design criteria, a Multi-objective particle swarm optimization (MOPSO) algorithm is used here [9], [10].

Optimization algorithms have already been used to design corrugated horn with desired radiation characteristics [11], [12]. These works concentrated on the dimensions of the corrugations of the horn. The results of these works are corrugated horns with non-uniform corrugation with each corrugation having different width and depth. Some work has been done on profiled corrugated horns with uniform corrugations [13], [14]. These works meet all the design requirements. But the fabrication process becomes extremely difficult for profiled horns or horns with non-uniform corrugations. This makes such horns very expensive.

In this paper, the dimension parameters of a conical corrugated horn with uniform corrugations are optimized. Such horns are much easier and less costly to fabricate. In most practical cases, such horns can give satisfactory performance. To get the best performance, the horn length and aperture radius is selected properly by using PSO.

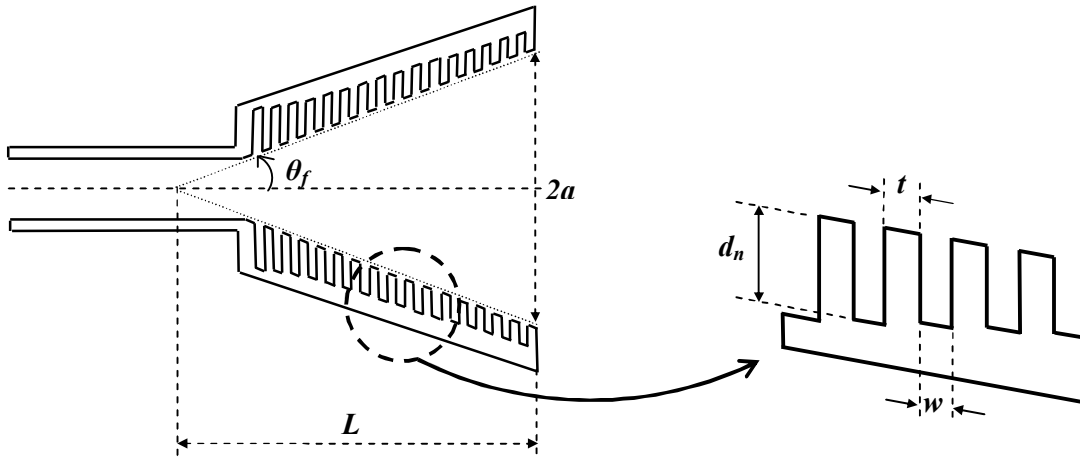


Fig. 2 Geometry of a conical corrugated horn antenna.

Optimizing a conical corrugated horn with uniform corrugations for the specific use as a feed of a Cassegrain reflector has not been covered thoroughly in literature. In this paper, an effective method for optimized feed design for a defined Cassegrain geometry is presented. The same method can be used for feed design of any single or dual reflector geometry.

2 Theory of Corrugated Horns

The geometry of a conical corrugated horn is shown in Fig. 2. The flare region of the horn contains the corrugated surface. A zoomed in view of the corrugated flare section is also shown in Fig. 2.

Here,

L = horn length,

a = horn aperture radius,

θ_f = semi-cone angle,

d_n = depth of the n th corrugation slot,

t = width of corrugation tooth, and,

w = width of corrugation slot.

The corrugation teeth width t is usually much smaller than corrugation slot width w . To reduce frequency sensitivity, t is chosen so that $t < 0.2w$ [3]. For uniform conical corrugated horns, t and w are constant for all corrugations. The corrugation slot depths d_n , vary from $\lambda/2$ at the start of the flare to $\lambda/4$ at the aperture [1]. Here, λ is the wavelength.

In a conical corrugated horn, a mixture of TE_{11} and TM_{11} mode propagates. This mode is called the hybrid HE_{11} mode. Under balanced hybrid condition for the dominant HE_{11} mode, and for $\theta_f < 35^\circ$, the

spherical electrical field components for the far-field region are approximately given by [3]:

$$E_\theta(r, \theta, \phi) = E_o ka \frac{e^{-jkr}}{r} F_\theta G_0(w) \cos \phi, \quad (1)$$

$$E_\phi(r, \theta, \phi) = -E_o ka \frac{e^{-jkr}}{r} F_\phi G_0(w) \sin \phi. \quad (2)$$

$G_0(w)$ is given by the integration:

$$G_0(w) = \frac{1}{a^2} \int_0^a J_0(p_{11} \rho'/a) J_0(w \rho') \times \exp(-jk \rho'^2/2L) \rho' d\rho'. \quad (3)$$

F_θ and F_ϕ are obliquity factors given by [3]:

$$F_\theta = \frac{1}{2} \left[1 + \frac{\beta}{k} \cos \theta + \Gamma \left(1 - \frac{\beta}{k} \cos \theta \right) \right], \quad (4)$$

$$F_\phi = \frac{1}{2} \left[\cos \theta + \frac{\beta}{k} + \Gamma \left(\cos \theta - \frac{\beta}{k} \right) \right]. \quad (5)$$

Here,

(r, θ, ϕ) = observation point spherical co-ordinates,

k = wave number = $2\pi/\lambda$,

E_o = amplitude of the dominant HE_{11} mode,

$w = k \sin \theta$ = angular co-ordinate,

Γ = reflection co-efficient at the horn aperture,

$J_m(\cdot)$ = Bessel function of the first kind & order m ,

$p_{11} = 1.841184 =$ first non-vanishing root of $J'_1(\cdot)$,
 $\rho' =$ variable of integration, and,
 $\beta =$ dominant HE₁₁ mode propagation constant,

$$= k \sqrt{1 - \left(\frac{2.4048}{ka}\right)^2} .$$

Using (1) and (2) along with (3), (4) and (5), the radiated electric field components of the corrugated horn at the far-field region can be determined. The co-polar and cross-polar components of the electric field can be calculated from Ludwig's third definition of co-polarization and cross-polarization [3], [15]:

$$\begin{bmatrix} E_{cp} \\ E_{xp} \end{bmatrix} = \begin{bmatrix} \cos(\phi - \phi_o) & -\sin(\phi - \phi_o) \\ -\sin(\phi - \phi_o) & -\cos(\phi - \phi_o) \end{bmatrix} \cdot \begin{bmatrix} E_\theta \\ E_\phi \end{bmatrix} . \quad (6)$$

Here,

- $E_{cp} =$ co-polar electric field component,
- $E_{xp} =$ cross-polar electric field component, and,
- $\phi_o =$ reference angle = 0°.

From the co-polar field component, the beamwidth at any given taper in any ϕ plane can be determined. Usually the beamwidth is determined at $\phi = 0^\circ$ or $\phi = 90^\circ$ plane. Maximum cross-polarization can be calculated from the cross-polar component. The value is usually determined at $\phi = 45^\circ$ plane [2], [4].

The reflection co-efficient can be calculated from the self-admittance y_{11} , which is given by [3]:

$$y_{11} = \frac{5.783}{(ka)^2} \frac{k}{\beta} \int_0^\infty \frac{w(2-w^2)}{\sqrt{1-w^2}} \times \frac{J_0^2(kaw)}{\{w^2 - (2.4048/ka)^2\}^2} dw . \quad (7)$$

The reflection co-efficient, which is the same as the S_{11} parameter, is given by [16]:

$$S_{11} = \Gamma = \frac{1 - y_{11}}{1 + y_{11}} . \quad (8)$$

Using the (1) to (8), all the required radiation characteristic of the conical corrugated horn can be calculated. Many of the integrations involved in the equations do not have any closed form expression. Numerical integration methods are used to

determine such integrals. As these equations are dependent on the dimension parameters a and L , selecting proper values of a and L can give the desired radiation characteristics.

3 Multi-objective PSO

In PSO, a population or swarm of particles is assigned random initial positions and initial velocities in an N dimensional solution space. The total number of particles is known as the population size. The position of each particle denotes a possible solution of the optimization problem. A fitness value is assigned to each particle by evaluating the fitness function at the position of the particle. The fitness function relates the algorithm to the physical problem [10]. The fitness value indicates how well the particle solves the optimization problems. The particles are moved through the solution space at each iterative step based on some deterministic and stochastic update rule [8]. As the particles move through the solution space, each particle knows its own best position (at which it achieved the best fitness value) that it has ever found. Each particle also knows the overall best position found by any particle of the swarm, known as global best. The motion of each particle is affected by its own personal best position and the global best position. In this way, at each iterative step, the particles move through the solution space until they converge to an optimum solution [8].

The position of a particle can be represented by N dimensional vector, $\mathbf{x} = (x_1, x_2, \dots, x_N)$. The velocities of the particle can be represented by a similar vector, $\mathbf{v} = (v_1, v_2, \dots, v_N)$. The position of the particle at $(t+1)^{th}$ iteration is calculated from the position at t^{th} iteration by using:

$$x_n(t+1) = x_n(t) + v_n(t), \quad n = 1, 2, \dots, N . \quad (9)$$

The velocities are modified as [10], [17]:

$$v_n(t+1) = wv_n(t) + c_1 r \{x_{pb,n} - x_n(t)\} + c_2 (1-r) \{x_{gb,n} - x_n(t)\} . \quad (10)$$

Here, x_n denotes the position of the particle at the n^{th} dimension and v_n denotes the velocity of the particle at the n^{th} dimension. The variable r is a random number between 0 and 1 taken from a uniform distribution and c_1 and c_2 are constants, both having the value 2 [8]. The variable w is known as inertial weight and it is linearly decreased from 0.9 to 0.4

over the iteration process. Global best and personal best is denoted by $x_{gb,n}$ and $x_{pb,n}$.

For the optimization of the corrugated horn, a two dimensional solution space is considered. The position of the particle is uniquely denoted by two co-ordinates. One dimension denotes the horn aperture radius a , and the other denotes the horn length L . The solution space is defined by limiting the values of a and L within a particular range. The value of a is limited from 2 cm to 16 cm and the value of L is limited from 10 cm to 25 cm. These ranges are selected from typical values of Ku-band corrugated horns [1], [4].

The objective of the optimization is select a and L so that the corrugated horn has -12 dB beamwidth of 11.89° and low S_{11} parameter. As conditions of low cross-polarization levels often coincide with conditions of low S_{11} parameter, it is assumed that optimizing for low S_{11} parameter will be sufficient to ensure low cross-polarization levels [3]. This assumption is verified after optimization. The fitness function must be defined so that it reflects these objectives.

To optimize the horn with two objectives, multi-objective PSO is required. In this paper, conventional weighted aggregation (CWA) method is used to perform multi-objective PSO [9], [10]. In CWA, a weighted combination of all objective functions is taken to form a single fitness function. In this case, the two objective functions are beamwidth, f_{BW} and S_{11} parameter value, f_{s11} . We define these two functions as:

$$f_{BW} = |BW - 11.89^\circ|, \tag{11}$$

$$f_{s11} = \frac{|S_{11,dB}|}{20} - 1.2. \tag{12}$$

Using CWA method, the overall fitness function is defined as:

$$f_{fitness} = 0.5f_{s11} - 0.5f_{BW}. \tag{13}$$

Here,
 $BW = -12$ dB beamwidth, and,
 $S_{11,dB} = S_{11}$ parameter in dB.

The beamwidth is calculated from co-polar electric field using (1) to (6) and the S_{11} parameter is calculated using (7) and (8). The constants used in (12) ensure that the objective functions have similar range of values. The values of the constants are selected based on expected values of the parameters

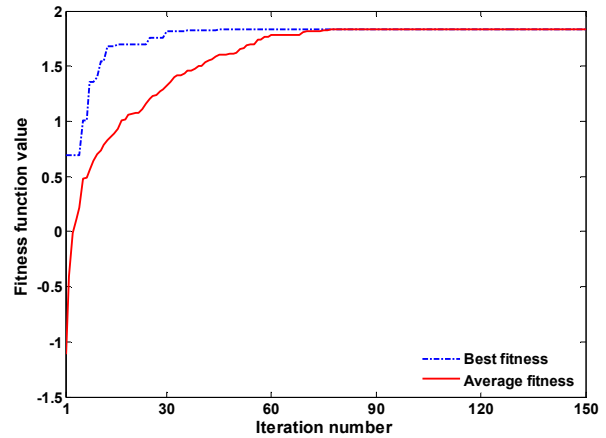


Fig. 3 Fitness function value vs. iterations curve.

and trail and error method. The weights in (13) are selected so that both objective functions are given equal priority. The positive/negative signs are selected such that maximizing overall fitness function gives the optimal results.

The corrugated horn is optimized for the center frequency of the Ku-band, which is 15 GHz. A standard population size of 20 particles is taken for simulation [10], [17]. As each iteration involves evaluating the fitness function 20 times (once for each particle), and multiple numerical integrations are required to compute the fitness function, extensive computation time is required to run the simulation. For this reason, maximum iteration number is limited to 150. It has been found that the optimization process converges within 150 iterations.

The results of the optimization process are shown in Fig. 3, Fig. 4 and Fig. 5. The variation of fitness function value with iterations is shown in Fig. 3. The average fitness value of the particles and the best fitness value of the swarm are shown on the same graph. It can be seen that the fitness values increase with iterations as the particles find better solutions and converge to optimum results. After approximately 100 iterations, both curves become flat, indicating that the optimization process is complete.

Fig. 4 and Fig. 5 show the solution values at each iterative step. The horn aperture radius and horn length vary from iteration to iteration, until an optimum set of values is reached. Fig. 4 show that after approximately 80 iterations, the horn aperture radius converges to a value of 0.0966 m. Similarly, Fig. 5 shows that, the horn length converges to a value of 0.4185 m. So, from the optimization process, the optimum aperture radius of the horn is found to be 9.66 cm and the horn length is found to

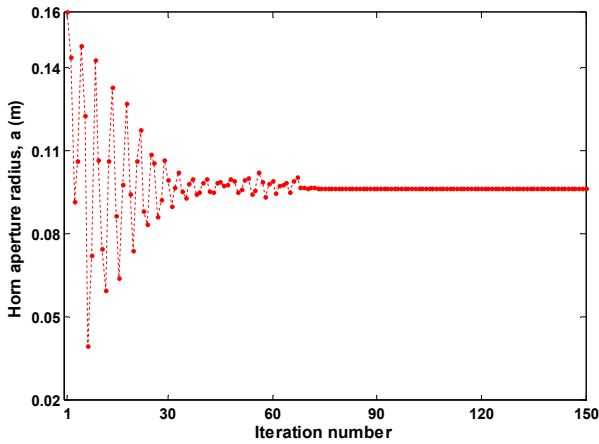


Fig. 4 Calculated horn aperture radius at each iterative step.

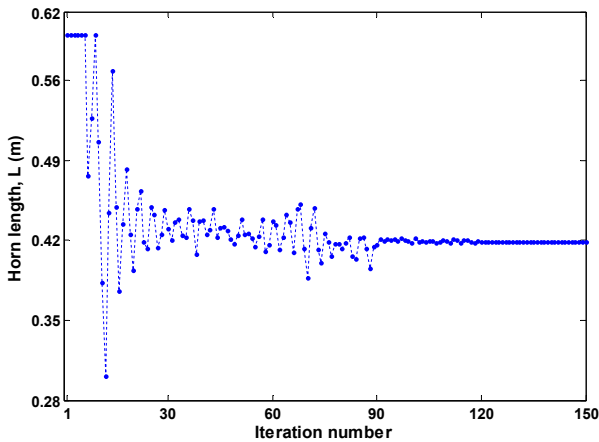


Fig. 5 Calculated horn length at each iterative step.

be 41.85 cm. For these dimension parameters, the S_{11} parameter is found to be -100.1 dB, and -12 dB beamwidth is found to be 12.0321° . The beamwidth is very close to the desired value. The S_{11} parameter is also acceptable.

4 Radiation characteristics of the optimized corrugated horn

From optimization, the optimum dimensions of the corrugated horn is found to be $a = 9.66$ cm and $L = 41.85$ cm. Using these dimension values, different radiation characteristics of the horn are analyzed to verify that the horn satisfies design requirements.

The electric field pattern of the optimized corrugated horn at $\varphi = 0^\circ$ plane for operating frequency of 15 GHz is shown in Fig. 6. It can be seen that the horn has a smooth main-lobe within the angle $\pm 11.89^\circ$, which will illuminate the sub-

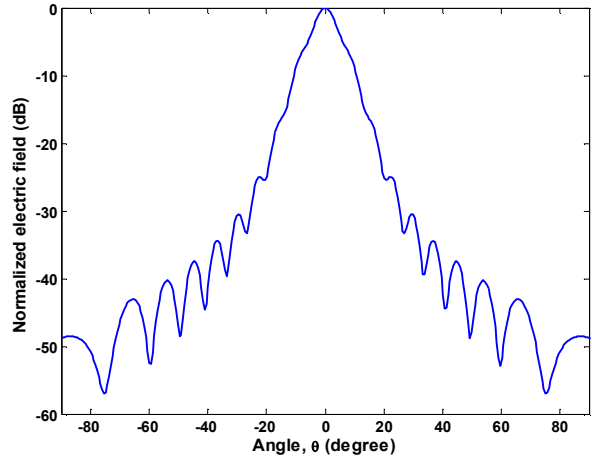


Fig. 6 Normalized electric field pattern of the optimized horn at $\varphi = 0^\circ$ plane ($f = 15$ GHz).

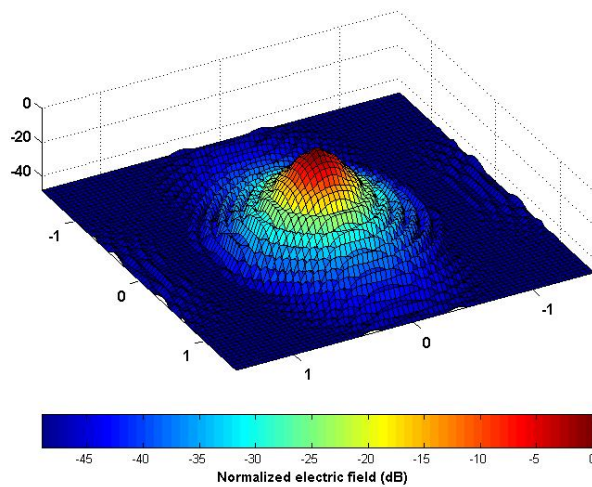


Fig. 7 Normalized three dimensional radiation pattern of the optimized horn ($f = 15$ GHz).

-reflector of the Cassegrain antenna. The sidelobes of the horn decrease rapidly which ensures a low spill-over loss [5], [6]. The electric field pattern is found to be almost exactly the same at $\varphi = 90^\circ$ plane. Almost identical patterns at both principle plane is a common characteristic of corrugated horns [3]. The three dimensional radiation pattern of the horn shown in Fig. 7, indicates that the horn pattern is almost symmetric in all planes.

The optimization process was done for an operating frequency of 15 GHz. But as the horn is designed for Ku-band, it must have satisfactory performance through out the entire Ku-band. For this reason, it is necessary to evaluate the radiation characteristics of the horn for the desired frequency

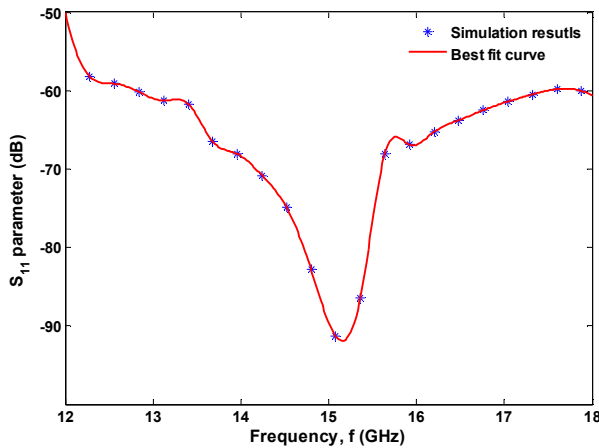


Fig. 8 S_{11} parameter vs. frequency curve of the optimized horn.

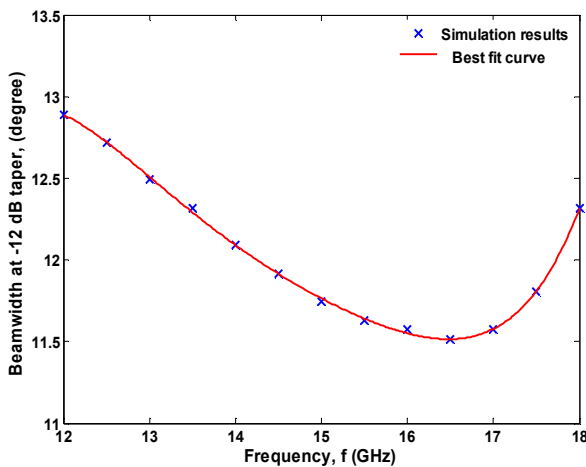


Fig. 9 Beamwidth vs. frequency curve of the optimized horn.

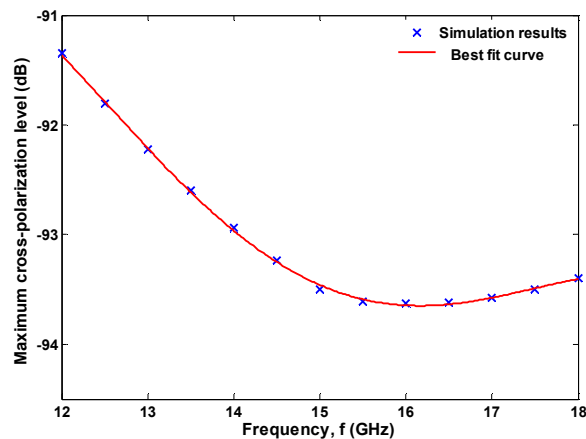


Fig. 10 Maximum cross-polarization level vs. frequency curve of the optimized horn.

range (12–18 GHz). For optimized horn, the S_{11} parameter, -12 dB beamwidth maximum cross-polarization level are calculated for frequencies 12 GHz to 18 GHz.

The S_{11} parameter vs. frequency curve of the optimized horn is shown in Fig. 8. The S_{11} parameter has minimum value at 15 GHz. This is expected as the horn was optimized for this frequency. It can be seen that S_{11} parameter is below -50 dB for the entire Ku-band. This value is acceptable for feed horns used in satellite communication [4].

Fig. 9 shows the beamwidth vs. frequency curve of the optimized horn. It can be seen that the -12 dB beamwidth varies from approximately 11.5° to 13° . As the desired beamwidth is 11.89° , the maximum deviation is only about 1.1° . So, it can be concluded that the horn will provide desired illumination for the entire frequency range.

The maximum cross-polarization level vs. frequency curve is shown in Fig. 10. Maximum cross polarization level is calculated at $\varphi = 45^\circ$ plane using (6). It can be seen that the maximum cross-polarization level is below -90 dB for the Ku-band frequencies. This value is extremely low, which is highly desired. The performance of the optimized horn is comparable with other corrugated horns with high aperture efficiency and low cross-polarization [18].

From analyzing radiation performance of the horn for the Ku-band frequencies, it is clear that the optimized corrugated horn antenna satisfies all the design requirements.

5 Radiation pattern of the Cassegrain reflector

As the radiation pattern of the feed horn (primary pattern) has been calculated, the radiation pattern of the Cassegrain reflector (secondary pattern) can easily be determined. Using aperture field integration, the normalized radiation pattern of the Cassegrain reflector is given by [19]:

$$f_N(\theta, \phi) = f_N(u) = \frac{6}{6 - g(2 + q)} \left[(1 - g)\Lambda_1(u) + (1 - \frac{q}{2})g\Lambda_2(u) + \frac{(q - 1)g}{3}\Lambda_3(u) \right] \quad (14)$$

Here,
 T = field taper at the edge of the sub-reflector,
 $g = 1 - T$,

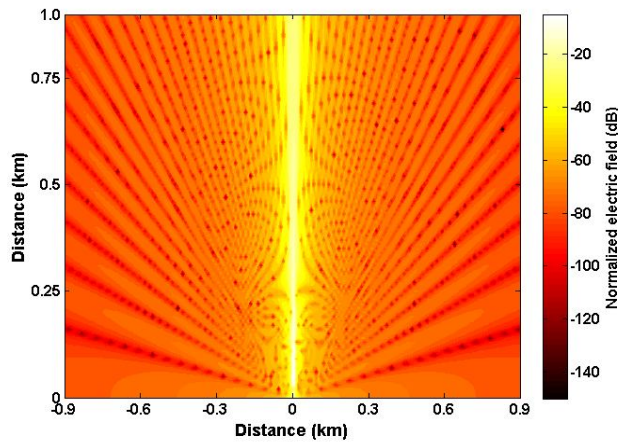


Fig. 11 Electric field around the Cassegrain reflector for uniform illumination.

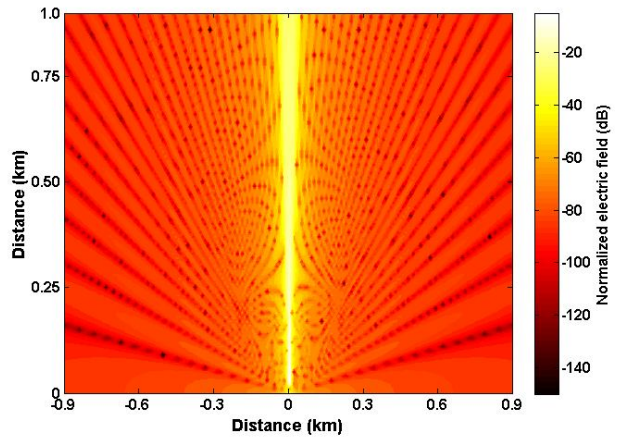


Fig. 12 Electric field around the Cassegrain reflector for optimized tapered illumination.

$$u = \frac{kd_p}{2} \sin \theta = \text{angular co-ordinate,}$$

d_p = diameter of the main reflector,
 q = feed horn characteristic parameter, and,
 $\Lambda_n(u)$ = lambda function of order n .

The lambda function is related to the Bessel function by:

$$\Lambda_n(u) = n! \frac{J_n(u)}{(u/2)^n} \quad (15)$$

The q parameter is related to the shape of the main-lobe of the feed horn. For a conical corrugated horn, a typical value of $q = 1.56$ is taken [19].

The edge taper, T , in (14) depends on the geometry of the Cassegrain reflector and the feed pattern. For analysis, the geometry shown in Fig. 1 is used. For a feed horn which is not optimized, the sub-reflector may have a uniform illumination. Uniform illumination implies $T = 1$ [5]. For the optimized corrugated horn feed, -12 dB edge taper ($T = 10^{-12/20} = 0.2512$) has been achieved, which is a desired edge taper. Using (14), the electric field around the Cassegrain reflector is calculated for uniform illumination and optimized illumination. However, (14) is independent of distance. To incorporate the effect of electric field weakening with distance, (14) is divided by the square of the distance between the observation point and the antenna. The results for uniform illumination are shown in Fig. 11. The Cassegrain reflector is positioned at (0, 0) point, which is at the centre of the horizontal axis. The Cassegrain reflector directs the radiation along the vertical axis. From Fig. 11, it

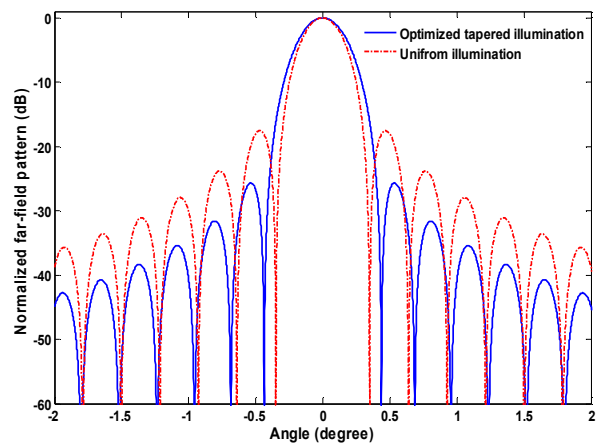


Fig. 13 Comparison of the radiation patterns of the Cassegrain reflector for uniform illumination and optimized tapered illumination.

can be seen that most of the radiated electric field is directed along the main-lobe. But the sidelobes are relatively strong, which is not desirable. The radiated power intensity changes gradually from main-lobe to the sidelobes. So, some power is wasted on undesired directions. Fig. 12 shows the electric field around the Cassegrain reflector when the optimized feed horn is used to provide the illumination. The antenna position, dimension scale and the color scale for Fig. 12 are same as that of Fig. 11. We can see from Fig. 12 that the electric value has high intensity along the main-lobe. But the electric field value falls very sharply along the sidelobes. This can be seen by the fact the Fig. 12 has much darker colored sidelobes (implying low values) compared to Fig. 11. So, much less power is wasted on undesired directions when optimized feed is used.

The radiation pattern of the Cassegrain reflector for uniform illumination and optimized illumination is shown in Fig. 13. It can be seen that, for optimized illumination, the main-lobe is slightly broader. But there is a noticeable difference in the sidelobe level. When the optimized feed horn is used, the sidelobe level is about 10 dB less than the case for uniform illumination. The significant decrease in sidelobe levels is very important for satellite communication. As each satellite in geostationary orbit is separated by a small angle, strong sidelobes from a ground station Cassegrain antenna may create unwanted interference for other nearby satellites [1], [3]. Also, high sidelobe level implies waste of radiated power in unwanted directions. So, it is necessary that most of the radiated power be limited to the narrow main-beam with minimum sidelobe levels. Fig. 11, Fig. 12 and Fig 13 verifies that when the optimized corrugated feed horn is used to illuminate the Cassegrain antenna, the sidelobe levels of the secondary pattern are much less compared to when an un-optimized feed horn is used.

6 Conclusion

The optimization of a conical corrugated horn with uniform corrugations is performed in this paper. The multiple optimization goals are set so that the horn can be used efficiently as a feed of a Cassegrain reflector. Using optimization is done using multi-objective PSO employing CWA method. From computer aided analysis of the radiation characteristics of the horn, it has been found that the horn meets the design requirements. Using radiation characteristics of the optimized feed horn, the radiation pattern of the Cassegrain reflector has been computed. From comparative analysis it has been found that, the optimized feed horn produces a more desirable secondary pattern with low sidelobe levels. The analysis method provide in this paper can be used to design optimized feed horns for any single or dual reflector geometry. As only the length and the aperture radius of the corrugated horn is taken as the optimizing parameters, the final optimized design gives a very practical antenna uniformly corrugated horn antenna which can be fabricated easily compared to non-uniformly corrugated horn. This makes the analysis provided here a suitable guideline for designing practical feed horns for reflector antennas.

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