Influences of Amplitude Tapering and Feed Blockage on the Radiation Characteristics of Ku-Band Parabolic Reflector Antennas

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***Abstract* —** In this work, the influences of amplitude tapering and feed aperture blocking in gain and first sidelobe level of Ku-band parabolic reflector antennas are investigated. Two different parabolic antenna configuration groups are proposed to determine each of these degradation factors. Designed parabolic reflectors are fed by pyramidal and conic horns to observe the blockage effect of feed type on Ku-band satellite reception applications. In the first examination to designate the influence of illumination loss due to amplitude tapering four parabolic reflectors are designed with 8 dB, 10 dB, 15 dB and 20 dB edge taper values on reflector apertures. Thereafter, thanks to the reflectors designed with the same edge taper value, but having different diameters, it became possible to observe, purely the influence of feed blockage on the radiation characteristics. Both theoretical and simulated patterns of reflector systems are presented.

***Index Terms* —** Amplitude tapering, conic horn, feed blockage, illumination loss, parabolic reflector antenna, pyramidal horn.

I. INTRODUCTION

Compared to other antenna configurations, parabolic reflector antennas are well-known for their capabilities to provide highly directive main beam and very low side lobe level (SLL) along with low fabrication costs [1-2]. During the past decade of space exploration, parabolic reflector antennas have been very popular with the increasing demand for high data-rate communications [3]. Increased data rates improve the communication channel signal-to-noise ratio. Obviously, enhancement in the antenna gain results with very high signal-to-noise ratio of the communication channel. Thus, various geometries of high gain reflector antennas have been investigated and developed for satellite applications.

Paraboidal reflectors illuminated by a feed antenna placed at their focus are widely used in many satellite applications [4-5]. However, single reflecting paraboidal surface limits the design flexibility [6]. An alternative design to improve the flexibility is employing an electrically large paraboloidal main reflector illuminated by a relatively smaller hyperboloidal subreflector [7-8]. In such a double reflector antenna system, locating the feed antenna near to main reflector enables to place necessary communications electronics equipment behind the main reflector. This minimizes antenna system dimensions and waveguide losses between the feed antenna and the amplifiers [9].

The main disadvantage of reflector antenna systems is the blockage losses caused by feed apertures. The feed blockage is an important issue concerning the antenna designers occurs when part of the reflected rays impinges upon the feed structure, depending on the feed physical dimensions [10-11].

In double reflector antenna systems, sub-reflector blockage which is characterized by the incidence of main reflector reflected rays upon the hyperboloidal sub-reflector also occurs besides the feed blockage. Although high gain and low SLL are crucial demands in satellite applications, these blockage mechanisms cause deleterious effects on gain and SLL of reflector systems [12-13]. Feed and subreflector blockage problems can be reduced by decreasing the sub-reflector radiation towards the feed and main-reflector radiation towards the subreflector. Axially displaced dual reflector antenna configurations are increasingly used with this aim. [14-16].

Illumination loss due to non-uniform amplitude distribution on the aperture plane of a reflector antenna is another considerable issue in reflector antenna system designs. Illumination loss also has deteriorating effects

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on single or double reflector antenna system radiations [17-18].

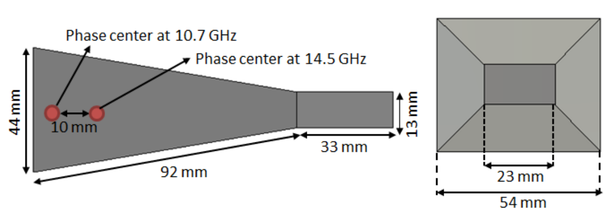
In this work, the influences of illumination loss and feed blockage on the radiation characteristics, namely gain and first SLL of single paraboloidal reflector antennas designed for Ku-band satellite applications are investigated [19]. As the first step to determine the illumination loss effects, designed parabolic reflector antennas are fed by pyramidal and conic horns operating at 10.7-14.5 GHz (Ku-band) frequency band. These parabolic reflectors having the same diameter are constituted considering 8 dB, 10 dB, 15 dB and 20 dB amplitude taper distribution on the reflector apertures. Gain and first SLL values regarding each design are analyzed and obtained first SLL values are compared with the theoretical results.

Then, in order to investigate feed blockage effects on the reflector radiation, similarly four different parabolic reflector antennas are designed. This time, these reflectors have different diameters but the same focal length to diameter ratio, *f/D* value. In these designs each reflector has the same edge taper value on their aperture planes. In this way, spillover losses which are associated with the power misses the reflector will be at the same level at each design. These latter designs enable to explore purely the feed blockage effects.

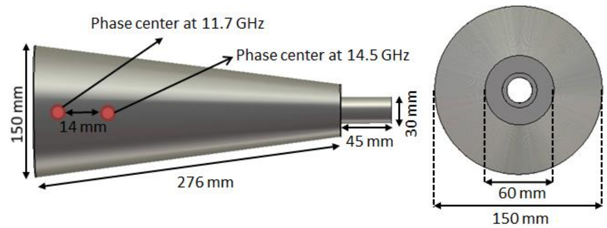
Designed parabolic reflectors fed by Ku-band pyramidal and conic horns are analyzed to observe the blockage effect of feed type on satellite reception applications. The simulations are performed by the Computer Simulation Technology (CST) software using the adaptive mesh refinement to obtain better accuracy with fewer unknowns [20].

II. PYRAMIDAL AND CONIC FEED HORN DESIGNS

Four different parabolic reflector antennas are designed for observing each of loss effects on the radiation. Since horn antennas are widely used in high-gain applications such as satellite communications, [21] constituted parabolic reflectors are fed by two different types of Ku-band horn antennas; a pyramidal horn and a conic horn to observe the blockage effect of feed type on satellite applications. Designed pyramidal and conic horns are shown in Fig. 1 with their physical dimensions.



(a) (b)



(c) (d)

Fig. 1. Feed horn antennas: (a) pyramidal horn side view, (b) pyramidal horn back view, (c) conic horn side view, and (d) conic horn back view.

In general, the phase center positions of wideband antennas move with the change of frequency. Nevertheless, this movement is considerably low in horn antennas [22]. This characteristic enables horn antennas suitable for wideband satellite applications. Indeed, in the whole operating band, the phase centers of both designed feeds exhibit almost a stable behavior as signed in Fig. 1. The phase center locations given in Fig. 1 are determined from radiation pattern simulation results of feed horns considering where the phases of feed antenna beams are nearly constant within the related beam-width. Good matching is achieved at Ku-band with both designed feed horns as given in Fig. 2. It can be seen in Fig. 2 that S_{11} variations of feeds are almost lower than -15 dB in both receive (10.7–12.7 GHz) and transmit (12.7–14.5 GHz) satellite communication bands.

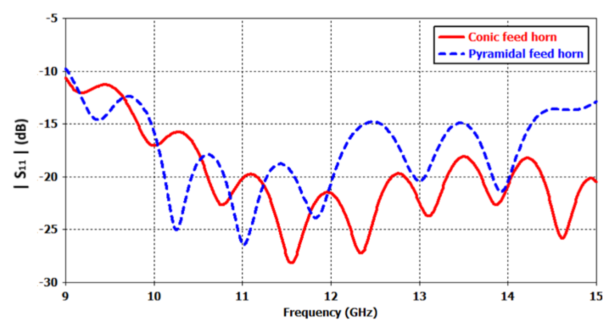
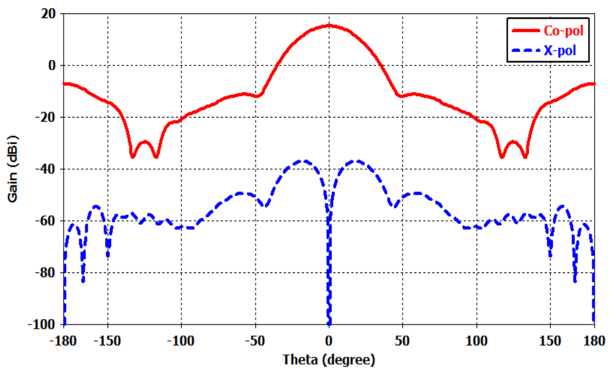
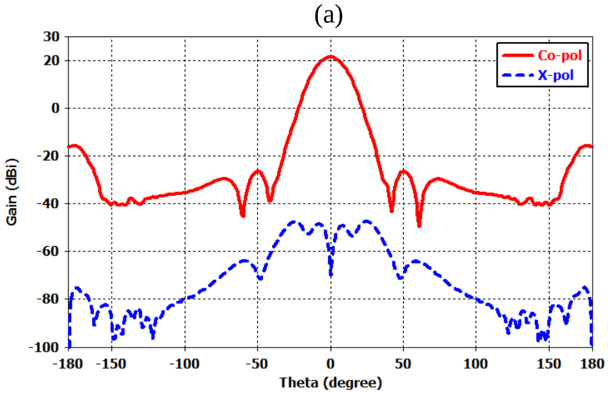


Fig. 2. Reflection coefficient variation of the feed horns with frequency. S_{11} variation of the feed is almost lower than -15 dB in the Ku-band.

Figure 3 exhibits the Co-pol and cross-pol gain patterns of feed horns at 11.7 GHz. Cross-pol isolation of both feed antennas are higher than 50 dB at 11.7 GHz receiving frequency. Due to the almost symmetrical gain patterns in elevation and azimuth planes, only elevation patterns are exhibited. More than 20 dBi gain is obtained by the conic feed horn at 11.7 GHz where the gain of pyramidal horn is 15.2 dBi at the same frequency. The gain of conic horn is higher than pyramidal horn since electrical length of conic feed is higher than the pyramidal feed as given in Fig. 1.



(a)



(b)

Fig. 3. Co-pol and X-pol gain patterns of feed antennas at 11.7 GHz: (a) pyramidal horn and (b) conic horn.

III. EFFECTS OF AMPLITUDE TAPERING

In this section, the influence of amplitude tapering on gain and first SLL of a parabolic reflector antenna is studied. Kirchoff's scalar formulation is used to obtain the influence of amplitude tapering theoretically on the aperture plane. Then, four parabolic reflector antennas designed considering 8 dB, 10 dB, 15 dB and 20 dB edge taper values on the reflector aperture are fed by Ku-band pyramidal and conic horns. The effective aperture of designed conic feed horn is larger than the pyramidal horn. Thus, the blockage effects of feed type on satellite reception applications are analyzed.

A. Theoretical analysis of amplitude tapering effects

For aperture antennas the source of radiation is the electric-field distribution across the aperture. The electric field of the energy over the reflector aperture is called the electric-field aperture distribution, $E_a(\rho,\phi)$. In Fig. 4, it can be described in terms of an imaginary aperture representing the electric field distribution across a plane in front of the reflector. On the aperture plane, the amplitude of electric field only depends on the distance from the reflector aperture center. Thus, electric-field aperture distribution can be described as $E_a(\rho)$.

Kirchoff's scalar formulation can be used for evaluating the electromagnetic radiation by the aperture plane for large aperture antennas; namely the reflector aperture should be at least several wavelengths along both its principle planes [22].

The aperture plane in Figure 4 is illuminated by the electric field distribution of $E_a(\rho)$. Q is defined as the observation point on the observation plane. Considering the Kirchhoff's scalar diffraction theory, the phasor of radiated electric field from the reflector aperture can be given as:

$$\tilde{E}(r,\theta,\phi) = \frac{j}{\lambda}\left(\frac{e^{-jkr}}{r}\right)\tilde{h}(\theta,\phi)\,, \tag{1}$$

where

$$\tilde{h}(\theta,\phi) = \iint_S \tilde{E}_a(\rho,\phi)\times e^{jk\rho\sin\theta\cos(\phi-\phi')}ds\,. \tag{2}$$

When the differencial surface area of the aperture is defined as $ds = \rho d\rho d\phi'$ in cylindrical coordinate system. The form factor $\tilde{h}(\theta,\phi)$ of $\tilde{E}(r,\theta,\phi)$ can be defined as follows:

$$\tilde{h}(\theta,\phi) = \int_0^{\rho} E_a(\rho)\times\rho\left[\int_0^{2\pi} e^{jk\rho\sin\theta\cos(\phi-\phi')}d\phi'\right]d\rho\,. \tag{3}$$

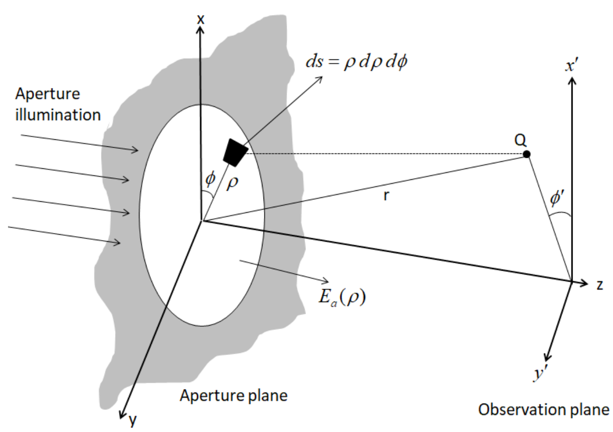


Fig. 4. Radiation by the aperture of a parabolic reflector antenna. Note that standard variables refer to the aperture plane and primed ones denote the observation plane.

The power density of the radiated wave is defined as $S(r,\theta,\phi) = \left|\tilde{h}(\theta,\phi)\right|^2 / 2\eta_0\lambda^2r^2$. Thus, the radiation pattern of a reflector antenna can be obtained using the square of form factor's amplitude given in (3).

In this work since the diameter of designed parabolic reflector is 45 λ at 11.7 GHz frequency, the following amplitude tapering function for the electric field distribution on the aperture plane is used:

$$E_a(\rho) = \cos^n\left(\frac{\pi \times 10^{-2}}{\lambda} \times \rho\right). \quad (4)$$

Here, n determines the amplitude tapering distribution type on the reflector aperture. The value $n=1$ gives an edge taper of 10 dB and $n = 0.8, 1.5$ and 2 corresponds to 8 dB, 15 dB and 20 dB edge taper values, respectively. When $n=1$, for $\rho = 0$ the electric field strength reaches its maximum value of 0 dB and this value decreases to -10 dB for $\rho = 45\lambda$.

The normalized radiation patterns obtained theoretically using Kirchhoff's scalar formulation in the elevation plane are exhibited in Fig. 5. It should be noted that feed blockage effect is not considered in the radiation patterns. It can be seen in Fig. 5 that the highest first SLL is experienced for the 8 dB edge taper illumination and this value decreases with the increase in the edge taper distributions. Eventually, the first SLL is -31.5 dB for 8 dB edge taper and decreases to -40.6 dB for 20 dB edge taper values on the aperture plane. Thus, the greater amplitude taper on the surface of a parabolic reflector produces lower first side lobes than a more uniform amplitude distribution and consequently reducing the edge taper increases the first SLL. Moreover, it is clear from Fig. 5 that increment in the edge taper results with the 3-dB beamwidth enlargement. Thus, it can be concluded that when the edge taper increases on the reflector aperture the gain of the reflector system decreases.

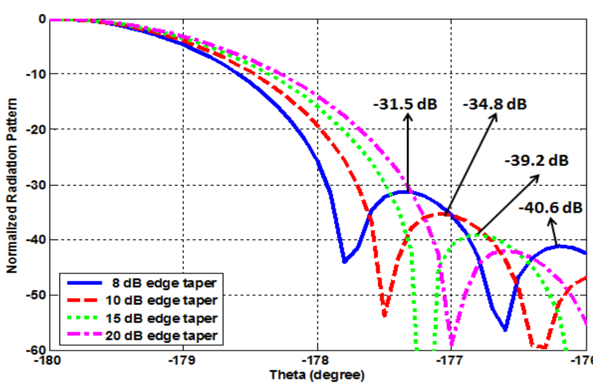


Fig. 5. Evaluated first SLL values as the function of feed tapers using Kirchhoff's scalar formulation.

B. Amplitude tapering effects of feed horn types

This sub-section explains the effects of illumination loss on the radiation characteristics of a parabolic reflector antenna when it is fed by different types of horn antennas. Four different parabolic reflectors fed by pyramidal and conic horns are designed with this aim. All designs have the same diameter since the gain of a reflector system is directly proportional with its collecting effective area. The phase center location of the feed horns at 11.7 GHz frequency are coincided with the reflector focus.

The reflectors illuminated by pyramidal feed considering -8 dB, -10 dB, -15 dB and -20 dB amplitude taper distributions on the reflector apertures results with 1.13, 1.04, 0.87 and 0.74, *f/D* values, respectively. Designed parabolic reflector antennas fed by the pyramidal horn are exhibited in Fig. 6. These values are evaluated regarding the half-subtended angle of the reflector, ψ_0 which is related with *f/D* by:

$$\psi_0 = 2\tan^{-1}\frac{1}{4f/D}. \quad (5)$$

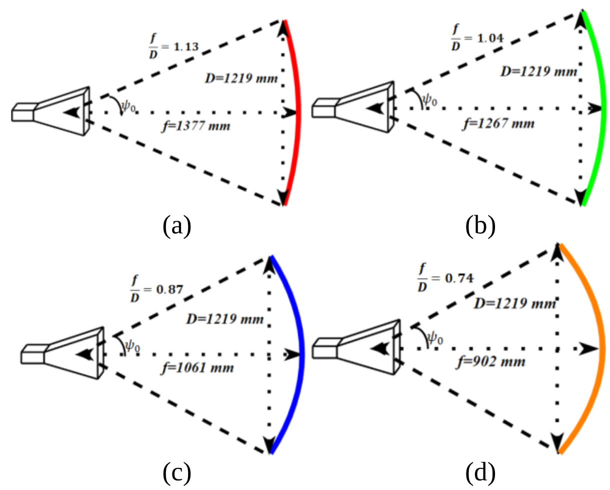


Fig. 6. Pyramidal horn fed parabolic reflector antennas designed with edge taper values of: (a) 8 dB, (b) 10 dB, (c) 15 dB, and (d) 20 dB.

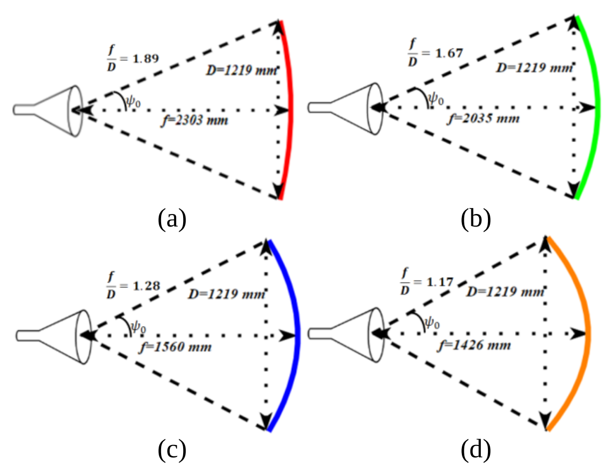
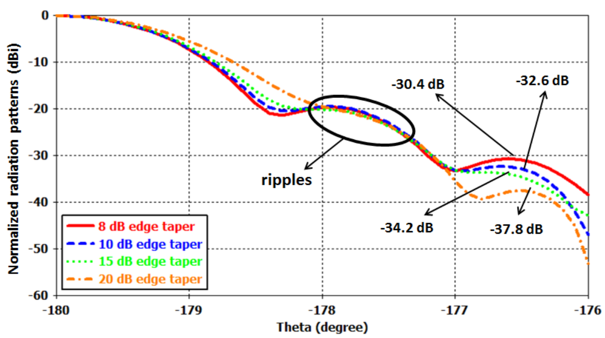


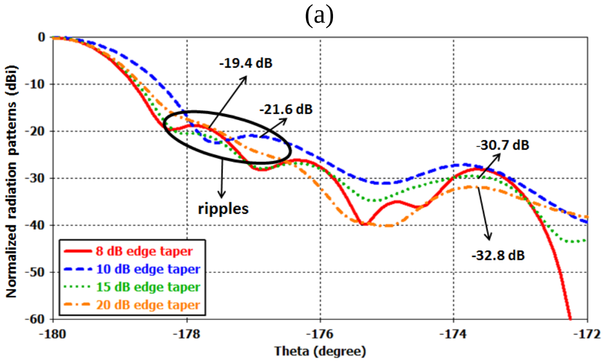
Fig. 7. Conic horn fed parabolic reflector antennas designed with taper values of: (a) 8 dB, (b) 10 dB, (c) 15 dB, and (d) 20 dB.

Four more parabolic reflectors having the same diameter value with the reflectors given in Fig. 6 are designed. Designed parabolic reflectors are fed by the conic horn to observe the blockage effect of feed type on Ku-band satellite reception applications. *f/D* values of 1.89, 1.67, 1.28 and 1.17 are evaluated considering -8 dB, -10 dB, -15 dB and -20 dB amplitude taper distributions on the reflector apertures, respectively. The parabolic reflector antennas fed by conic horn are highlighted in Fig. 7.

The first SLLs of simulated radiation patterns in the elevation plane regarding to pyramidal and conic horn fed reflector antenna systems are highlighted in Fig. 8 (a) and (b).



(a)



(b)

Fig. 8. The first SLLs as the function of feed tapers for: (a) pyramidal feed horn and (b) conic feed horn.

It can be seen in Fig. 8 (a) that the highest first SLL is experienced for the 8 dB edge taper illumination of reflector aperture when it is fed by the pyramidal horn. The first SLL is decreasing with the increase in the edge taper distribution. Eventually, the first SLL is -30.4 dB for 8 dB edge taper and decreases to -37.8 dB for 20 dB edge taper distribution. Thus, the greater amplitude taper on the surface of a parabolic reflector produces lower first side lobes than a more uniform amplitude distribution and consequently reducing the edge taper increases the first SLL.

When these first SLLs are compared with the theoretical results, it can be said that first SLLs are slightly increased due to the pyramidal feed aperture blocking.

The first SLLs obtained when the reflector antennas are fed by conic horns are given in Fig. 8 (b). Quite higher first SLLs are occurred compared with the levels obtained by pyramidal horn fed reflector antenna.

It is clear from Fig. 8 (a) that small ripples are appeared in the radiation patterns due to the pyramidal feed aperture blocking. Nevertheless, these ripples are small to be considered as SLLs. As it can be seen in Fig. 8 (b), the ripples at the same theta direction are deeper when the blockage is occurred by the conic feed horn. It can be seen in Fig. 1 that the blocking aperture of conic horn is approximately 9 times larger than the pyramidal horn blocking aperture. Thus, the deeper ripples in Fig. 8 (b) can be explained with the higher blockage of radiation by the conic feed horn.

The influence of illumination loss on gain of pyramidal and conic horn fed designed reflector antennas are summarized in Table 1. While the gain is 41.2 dBi for 8 dB edge taper of pyramidal horn fed reflector antennas, it reduces to 38.1 dBi for 20 dB edge taper on the reflector surface. Similar comments can also be made for conic horn fed reflector designs. The highest gain is achieved with the 8 dB edge taper on the reflector surface and this value decreases to 40.25 dBi with the influence of illumination losses. Thus, it can be said from Table 1 that an increase in edge taper results with the decrease in gain. These gain values obtained by the simulation results are compatible with the theoretically obtained normalized radiation patterns given in Fig. 5 where the edge taper results with the 3 dB beam-with enlargement.

Table 1: Gain variations with the edge taper of pyramidal and conic horn fed reflector antennas

Gain (dBi)	**8 dB Edge Taper**	**10 dB Edge Taper**	**15 dB Edge Taper**	**20 dB Edge Taper**
Pyramidal horn	41.2	40.15	39.4	38.1
Conic horn	41.9	41.65	41.2	40.25

Considering the results presented in Fig. 5, Fig. 8 and Table 1, it can be said that increase of edge taper results with a decrease in the first SLL and in gain. Finally, it can be concluded that the decrease in gain and the increase in the first side-lobe level in a parabolic reflector antenna are highly dependent on the nature of the aperture-distribution function.

IV. EFFECTS OF FEED BLOCKAGE

In this section to dissipate the illumination loss effects on the radiation and so that to specify purely the influence of feed blockage, four different parabolic antennas having the same edge taper value of 20 dB are designed. These reflector configurations are fed by the pyramidal and conic horns as given in Fig. 9. All parabolic reflector antennas given in Fig. 9 (a) have the *f/D* value of 0.74 and edge taper value of 20 dB on their aperture. Similarly, conic horn fed reflector antennas given in Fig. 9 (b) are also designed considering 1.17 *f/D* value results width 20 dB edge taper on the reflector aperture. Pyramidal horn feed will cast a rectangular and conic horn will cast a circular shadow on the parabolic reflectors as given in Figs. 9 (c) and (d), respectively. The focal length and diameter values of each reflector antenna given in Fig. 9 are summarized in Table 2.

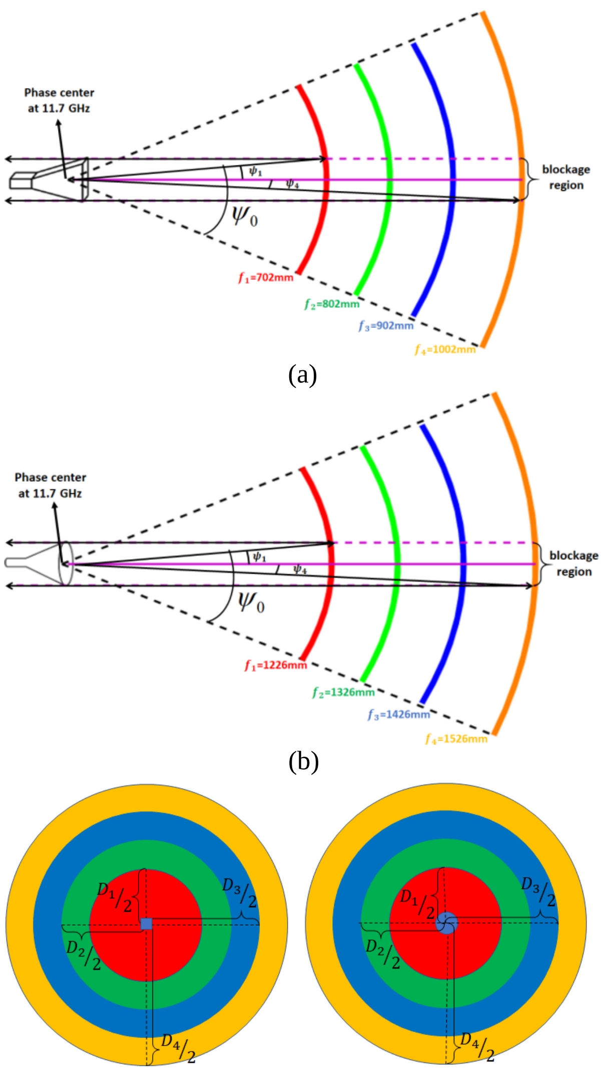


Fig. 9. Parabolic reflector antennas designed with 20 dB edge taper value fed by: (a) pyramidal horn side view, (b) conic horn side view, (c) pyramidal horn back view, and (d) conic horn back view.

Table 2: Focal length and diameter values of the reflector antenna designs given in Fig. 9

Feed Antenna	f_1, D_1	f_2, D_2	f_3, D_3	f_4, D_4
Pyramidal Horn	702, 948	802, 1083	902, 1219	1002, 1354
Conic Horn	1226, 1047	1326, 1113	1426, 1219	1526, 1304

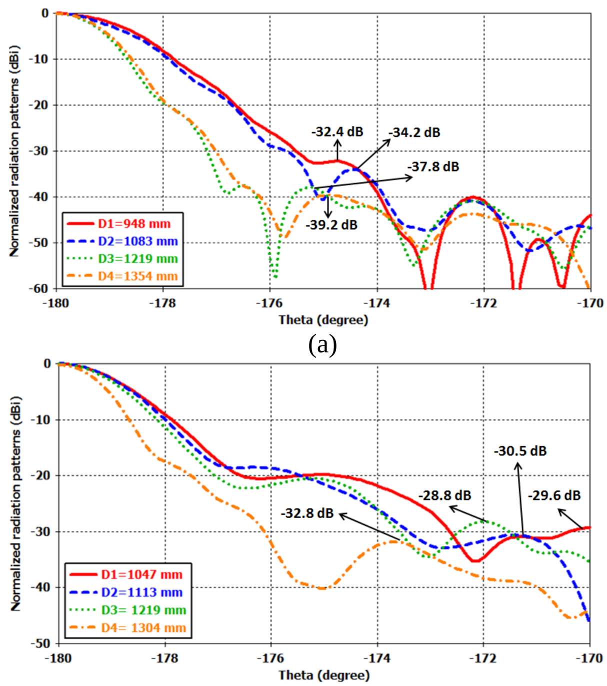
In reflector applications phase error, illumination, spillover and feed blockage losses have deteriorating effects on the antenna radiation characteristics. Since the feed blockage effects are investigated at 11.7 GHz frequency throughout this work, the phase error loss that occurs due to the phase center displacement will not exist. Thanks to the reflector configurations designed with the same edge taper thus with the same *f/D* value as given in Fig. 9, the illumination loss will be at the same level in each reflector configuration. The spillover losses concerning each configuration will also be same since the half-subtended angles, ψ_0 of pyramidal and conic horns are equal for each parabolic reflector groups as given in Figs. 9 (a) and (b).

The first side lobe levels of radiation patterns regarding to the designed reflector configurations are highlighted in Figs. 10 (a) and (b). As explained in Section III, the first SLL of a reflector antenna is strictly related with the edge taper values on the reflector aperture. Thus, as expected first SLLs given in Figs. 10 (a) and (b) have very close values to each other since the edge tapers equal to 20 dB in all reflector apertures. The first SLLs obtained when the reflectors are fed by conic horns given in Fig. 10 (b) are slightly higher. This can be explained with the larger feed blockage aperture of conic feed horn as mentioned in Section III.

In case, the reflector antennas having different diameters are fed by the pyramid horn given in Fig. 9 (a), 35.4 dBi gain is obtained by the smallest reflector (D_1=948 mm). This value increases with the enlargement of the reflector effective areas. The gain values of reflector antennas occur as 36.3 dBi, 38.1 dBi and 38.9 dBi for the reflectors with the diameters of D_2=1083 mm, D_3=1219 mm and D_4=1354 mm, respectively.

Similar comments can be made for the gain values of reflectors fed by conic horn as given in Fig. 9 (b). The lowest gain value of 36.6 dBi is obtained by the smallest reflector antenna (D_1=1047 mm) and this value increases with the enlargement of reflector effective areas to 37.9 dBi for D_2=1113 mm, to 40.25 dBi for D_3=1219 mm and finally to 42.1 dBi for the largest reflector antenna, D_4=1304 mm.

The increment of the gain with the enlargement of the reflector surfaces can be explained with the blockage amount of the reflected energy by the feed horns. In Fig. 9 (a), it is shown that the pyramidal horn aperture blocks some of the reflected energy from the reflector antennas. The radiation of pyramidal horn with the subtended angle of $\psi_1 = 2^\circ$ is blocked by the smallest reflector and this angle decrease to $\psi_4 = 1.3^\circ$ for the largest reflector. It is clear from Fig. 9 (a) that the enlargement of the reflector surfaces results with smaller ψ angles consequently, decrease in the blocked energy amount of the feed horn.



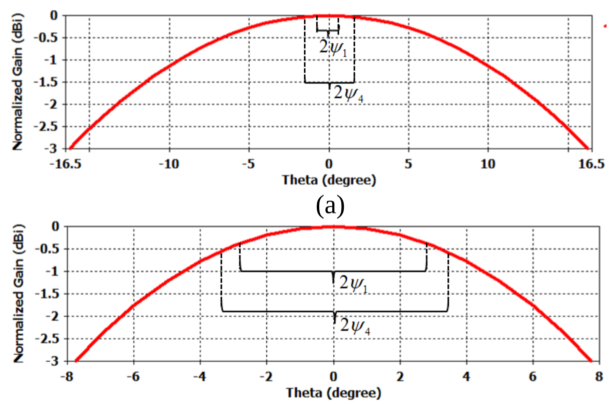
(b)

Fig. 10. The first SLL values of various size parabolic reflector antennas fed by: (a) pyramidal horn and (b) conic horn.

When the reflector antennas fed by conic horns given in Fig. 9 (b) are investigated, it can be said that the blocked amount of reflected energy will decrease again with the enlargement of reflector surfaces. Here, ψ_1 value of the blocked energy of the feed horn is 3.5° degree for the smallest reflector and it decreases to $\psi_4 = 2.8^\circ$ for the largest one.

The normalized gain pattern of pyramidal feed horn is given in Fig. 11 (a) to emphasize the 3-dB beam-width of the feed and blocked reflected radiation amount. Similarly, Fig. 11 (b) shows the normalized gain pattern of the conic horn for the 3 dB beam-width and the blocked energy amounts by the feed aperture. According to Fig. 11 (a) the aperture of the pyramidal horn blocks approximately 0.15 dB beam-with of its radiation for the largest reflector surface and this value decreases to 0.1 dB beam-with of its radiation for the smallest reflector antenna. When Fig. 11 (b) is investigated it can be said that due to the larger aperture of conic horn feed, the blocked energy will be higher in these reflector designs. Approximately, 0.4 dB beam-with of conic horn's radiation is blocked with the smallest reflector illumination. This value decreases to 0.6 dB beam-with for the largest reflector illumination.

The higher blockage amount of radiation by the conic feed horn aperture as given in Fig. 11 explains the higher decreases in the gain values of conic horn fed reflector antennas.



(b)

Fig. 11. Normalized gain patterns given within 3-dB beam-widths of the radiation of: (a) pyramidal horn and (b) conic horn. The blocked energy amounts are also marked in the gain patterns.

Thus, it can be concluded that the degradation effects due to the feed blockage on the antenna gain dramatically decrease with the enlargement of the feed antenna aperture.

V. CONCLUSION

High gain and low SLL are crucial demands to provide high signal to noise ratio for satellite applications. The amplitude tapering and feed blockage are considered to have deteriorating effects on reflector antenna radiation patterns. We introduced influences of amplitude taper and feed blockage on the radiation characteristics of Ku-band parabolic reflector antennas by presenting theoretical and simulation results regarding to gain and first SLL.

The role of edge taper in parabolic antennas is studied utilizing four reflectors having the same diameter value, however different edge tapers on their aperture. Designed parabolic reflectors are fed by pyramidal and conic horns to observe the blockage effect of feed type on Ku-band satellite reception applications. It can be concluded that the increase in the first side-lobe level in a parabolic reflector antenna are highly dependent on the nature of the aperture-distribution function. In fact, the first SLL also increases with a larger aperture blocking.

In order to detect purely the role of feed blockage on the gain similarly, four reflectors are designed. These designed reflectors have the same half subtended angle are fed by pyramidal and conic horns. It is proved that the degradation effects due to the feed blockage on the antenna gain dramatically decrease with the enlargement of the feed antenna aperture.

As a result, to avoid the degradation effects of feed blockage and obtaining higher gain and lower first SLL, greater uniformity of radiation field distribution should be maintained. This can be achieved utilizing electrically larger reflector antennas. However, enlarging the reflector surface results with increase in waveguide losses between the feed antenna and the amplifiers. Designing a planar feed antenna will allow to minimize feed blockage effects but this time, the phase center movement of a planar high gain feed antenna will lead to high level of phase error losses.

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