Performance Analysis of a Patch Antenna Array Feed For A Satellite C-Band Dish Antenna

Ibigbami Nelson O. and Adediran Y. A

***Abstract--* This paper proposes a patch antenna array as an alternative feed for dish antennas on board satellites to solve the weight problem constituted by conventional feed horns. An 8x1 linear, C-Band, circular patch antenna array configuration with a broadside radiation pattern is designed as feed for a dish antenna with F/D ratio of 0.36 corresponding to aperture illumination of 140^0. The result of analysis and simulations of the model using MATLAB and PCAAD5.0 software suggest that the patch antenna array feed radiation performance is very competitive when compared to that achieved with conventional feeds for dish antennas of the same *F/D* ratio.**

***Index Terms*— array configuration; aperture illumination; signal excitation amplitudes; illumination taper; feed pattern**

I. INTRODUCTION

Wireless communications is a field of prominent economical and technological interest is that of, especially satellite-based. Weight and dimensions must be as low as possible on the satellite where mass and size limitations are extremely strict. The antenna subsystems on majority of satellites, when fully deployed, utilize parabolic reflectors for their earthward beams. Over the past decades, the conventional feed for parabolic reflector antennas on-board satellites has been the horn, since it provides the required directivity. One of the goals of the satellite antenna designer is to minimize the weight as much as possible without sacrificing the overall performance of the antenna.

The problem here is the weight of these horns which tend to be bulky. Weight is a strong factor that affects cost of design and the overall cost of the launch campaign. High weight also increases the failure tendency in space missions. Some of the principal advantages of patch antennas are light weight and low volume [1]. Patch antennas have therefore been used successfully in satellite communications. The small size of patch antennas limits control of the pattern and one must use arrays of patches since the desire is to control its pattern [2]. In this paper a patch antenna array is modeled to operate in the C-band.

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Analysis and simulations of a patch antenna array feed for a C-band dish are then carried out using the model developed. Attempt is then made to tailor the patch antenna array feed in order to provide radiation characteristics similar to those of conventional feed horns.

The results obtained are presented succinctly. The inferences from the results are also presented.

II. DESIGN OF THE PATCH ANTENNA ARRAY

A. *The single patch antenna array element*

The first step in the design of a patch antenna array is to specify the dimensions of a single patch antenna. The patch antenna can be of any shape. The aim is to choose a simple geometry for the patch antenna. This is to simplify the analysis and performance prediction. So here, the circular patch antenna is chosen as the array element. Its characteristic parameters are the radius *a*, and thickness *h* as shown in figure1.

The most popular models for the analysis of patch antennas are the transmission line model, the cavity model, and the full wave model [3]. The transmission line model is the simplest of all and it gives good physical insight but it is less accurate. The cavity model is more accurate and gives good physical insight though complex in nature. The full wave models are extremely accurate and versatile but are far more complex in nature. In this work, the cavity model is applied to analyze the circular patch antenna array element.

There are three essential parameters required for the design of a circular Patch Antenna. These are: frequency of operation (*f*), Dielectric constant of the substrate (ε_r), and Height of dielectric substrate (*h*):

Frequency of operation, f

The resonant frequency of the antenna must be selected appropriately. The antenna is to be used for satellite communications in the C-Band frequency range, which is 4-8 GHz. Therefore a resonant frequency of 6.0 GHz is selected for the purpose of this work.

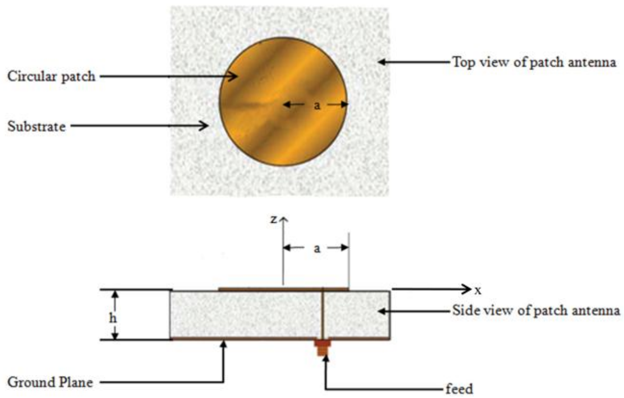

Fig.1. The single circular patch antenna element, a = 0.88 cm

Dielectric constant of the substrate $\mathcal{E}_r$

For the patch antenna to be part of a satellite payload, it is essential that the antenna is not bulky. This is the primary consideration in the choice of the substrate. The substrate selected for this antenna is made of RT/Duroid 5870 from Rogers Corporation. This material has a relative permittivity of 2.33. It also has heritage in the space industry.

Height of dielectric substrate, h

To minimize losses and maximize the radiation efficiency of a patch antenna, the thickness of substrate must satisfy the relation [4].

$$\frac{h}{\lambda} \leq \frac{0.3}{2\pi\sqrt{\varepsilon_r}} \quad (1)$$

Substituting values for λ and $\mathcal{E}_r$ in (1) gives

$$h \leq \frac{0.3\times5}{2\pi\sqrt{2.33}} \quad (2)$$

That is, $h \leq 1.6\ mm$

Thus the height h of the dielectric substrate is selected as 1.6 mm for this design purpose.

Hence, the essential parameters for the design are:
Frequency of operation, f = 6.0 GHz
Dielectric constant of the substrate, ε_r = 2.33
Height of dielectric substrate, h = 1.6 mm

The physical radius a, of the circular patch antenna is given by the expression [3]

$$a = \frac{F'}{\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{\frac{1}{2}}} \quad (3)$$

where $$F' = \frac{8.791\times10^9}{f\sqrt{\varepsilon_r}} \quad (4)$$

a and h are in centimeters
Substituting values for the parameters gives

$$F' = \frac{8.791\times10^9}{6\times10^9\sqrt{2.33}} = 0.9599 \quad (5)$$

Therefore, the physical radius is

$$a = \frac{0.9599}{\left\{1+\frac{2\times0.16}{\pi\times2.33\times0.9599}\left[\ln\left(\frac{\pi\times0.9599}{2\times0.16}\right)+1.7726\right]\right\}^{\frac{1}{2}}} \quad (6)$$

$$= 0.8825$$

Thus, the estimated physical radius of the single circular patch antenna element $a \cong 0.88$ cm

B. The Dish Antenna

The antenna selection for the purpose of this work is based on the *F/D* ratio. Most commercial microwave antennas use *F/D* ratio of 0.25 to 0.38, with 0.32 to 0.36 the most common [5]. Thus an *F/D* ratio of 0.36 is selected.

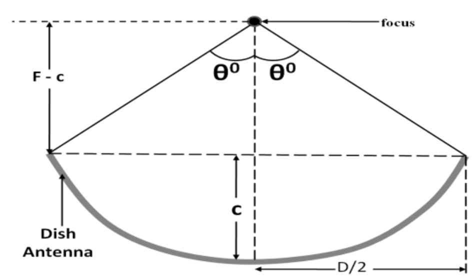

Fig. 2. Basic dish antenna geometry

From basic dish antenna geometry (figure 2), the focal distance F is related to the diameter D of the dish by [6],

$$F = \frac{D^2}{16\times c} \quad (7)$$

where c is the depth of the parabola at its center. Also we observe that 2θ is the total angle subtended by the dish at its focus. This represents the dish aperture illumination. From the geometry,

$$\tan\theta = \left[\frac{\left(\frac{D}{2}\right)}{F-c}\right] \quad (8)$$

Substituting the values and expanding (8), gives

$$Aperture\ Illumination = 2\tan^{-1}\left[\frac{8\left(\frac{F}{D}\right)}{16\left(\frac{F}{D}\right)^2-1}\right] \quad (9)$$

Therefore, it can be deduced that the aperture illumination of any dish is only determined by its F/D ratio and the relationship is given in equation (9). Therefore, substituting the values,

$$\text{Aperture Illumination} = 2\tan^{-1}\left[\frac{8\times0.36}{16\times(0.36)^2-1}\right] \cong 140^0 \qquad (10)$$

This means that the selected F/D ratio of 0.36 corresponds to an aperture illumination of 140^0.

III. THE PATCH ANTENNA ARRAY FEED DESIGN

For a dish antenna, feed selection should be done in such a manner that the feed achieves a compromise of illumination loss and spillover loss which yields maximum performance. The traditional rule of the thumb for this compromise is that the best efficiency occurs when the illumination energy is 10 dB down at the edge of the dish [7]. In order to replace conventional feeds by a patch antenna array, it is important that the array provides similar radiation pattern to the conventional feeds (i.e. up to -10 dB beamwidth).

As discussed earlier, the aim is to maintain a simple geometry and configuration for the patch antenna array. Thus an 8x1 linear array configuration (fig. 3) with a broadside radiation pattern is selected.

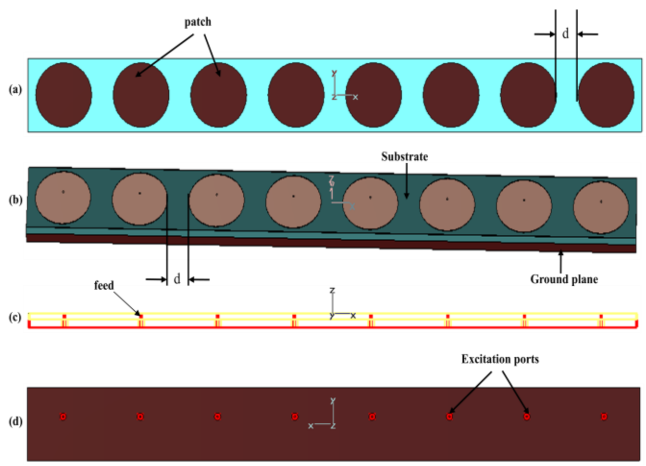

Fig. 3. The 8x1 patch antenna array feed for 6 GHz (a)Top view, (b) Perspective view, (c) Wireframe view, (d) Bottom view

A. *Assumptions for the patch antenna array design*

The following are the assumptions made for the purpose of this design:

1. The array configuration is perfectly linear
2. The inter-element distance for the patch antenna array elements is equal.
3. The array elements have uniform signal excitation amplitude.
4. The array elements have uniform phase.
5. All the elements in the array have identical patterns.
6. The array configuration is symmetric about the mid-point.

The design approach is to eliminate illumination loss and maximize the gain. The first step in this approach is to calculate the uniform array inter-element distance that will give us a beamwidth between the first nulls (FNBW) of 140^0 with uniform normalized array element excitation amplitude.

B. *Modeling the inter-element distance*

The beamwidth between the first nulls (FNBW) is selected to minimize illumination loss. Beamwidth for uniform amplitude broadside arrays can be calculated by the following relation [3].

$$\Theta_n = 2\left[\frac{\pi}{2} - \cos^{-1}\left(\frac{\lambda}{Nd}\right)\right] \qquad (11)$$

where Θ_n is the first null beamwidth, λ is the wavelength, N is the number of array elements and d is the uniform inter-element distance in cm. Leaning on the earlier indicated assumption of a symmetry about the mid-point for the broadside configuration, it can be deduced that;

$$\cos\left[\frac{\pi}{2} - \frac{\Theta_n}{2}\right] = \cos\left[\cos^{-1}\left(\frac{\lambda}{Nd}\right)\right] \qquad (12)$$

From trigonometric relations, this becomes

$$\sin\frac{\Theta_n}{2} = \frac{\lambda}{Nd} \qquad (13)$$

Therefore, inter-element distance d is given by

$$d = \frac{\lambda}{N\sin\left(\frac{\Theta_n}{2}\right)} \qquad (14)$$

For the C-band patch antenna array, the resonant frequency of 6 GHz corresponds to a wavelength λ given by

$$\lambda = \frac{v}{f} \qquad (15)$$

Here, $v = 3\text{x}10^8$ m/s (speed of electromagnetic radiation). Thus, substituting values, the wavelength is computed as

$$\lambda = \frac{3\times10^8}{6\times10^9} = 0.05\text{ m} = 5\text{ .0 cm} \qquad (16)$$

Substituting values gives the inter-element distance as

$$d = \frac{5.0}{8\sin\left(\frac{140^0}{2}\right)} \cong 0.67\ cm \qquad (17)$$

Therefore, the patch antenna array inter-element distance is 0.67 cm = 0.133λ. The radiation pattern for this configuration is depicted in fig. 4.

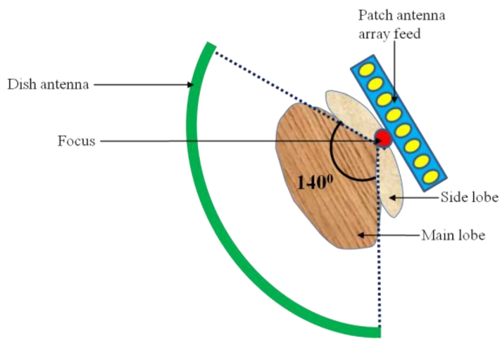

Fig. 4. Aperture Illumination = First Null Beam Width (FNBW) = 140⁰

IV. ANALYSIS OF THE DESIGN

A. *Simulation*

The beamwidth between the first nulls (FNBW) for patch antenna array feed was varied while keeping the normalized signal excitation amplitudes and phases of the array elements uniform and constant. This is achieved by varying the inter-element distance. Conventional feeds have a wide main lobe that maximizes the illumination efficiency. The best efficiency occurs when the illumination energy is about 10 dB down at the edge of the dish [7].

The array designs resulting from this approach are simulated and their performances analyzed. To accomplish this objective, the software utilized was Personal Computer Aided Antenna Design (PCAAD 5.0). This software, based on the method of moments (MOM) is used to simulate the array feed and analyze the RF characteristics. PCAAD 5.0 is a specialized tool for fast and accurate three-dimensional electromagnetic simulations of high frequency problems

Further simulations were carried out on inter-element distances, d = 0. 5cm and d = 1.35 cm (corresponding to inter-element distance, $d > \lambda/4$) to find out the effect on the radiation pattern presented by the 8x1 patch antenna array feed for the C-Band dish. The simulated far-field radiation pattern plots are shown in the figures 5-8.

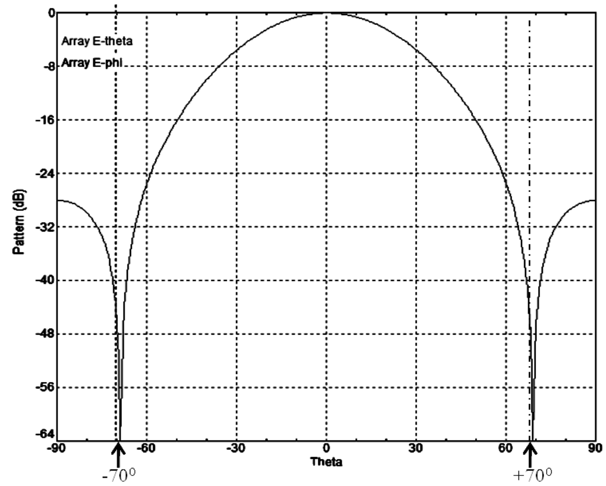

Fig. 5. Rectangular planar radiation pattern plot for 8X1 patch antenna array feed, d = 0.67cm (using PCAAD 5.0)

From the radiation pattern plots in figures, we obtain a 3 dB beamwidth of 44.2^0

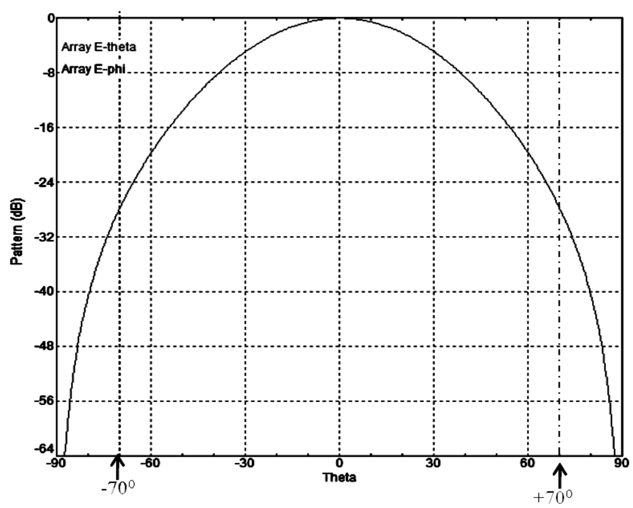

Fig. 6. Rectangular planar radiation pattern plot for 8X1 patch antenna array feed, d = 0.625cm (using PCAAD 5.0)

From the radiation pattern plots, it is observed that the feed pattern radiated over the effective aperture of the dish is continuous with an illumination taper of 27.8 dB. The 3 dB beamwidth has widened to 46.87^0 implying that more energy is concentrated on the effective aperture of the dish. The illumination taper for this continuous pattern is not so efficient when compared with the 10 dB required [7].

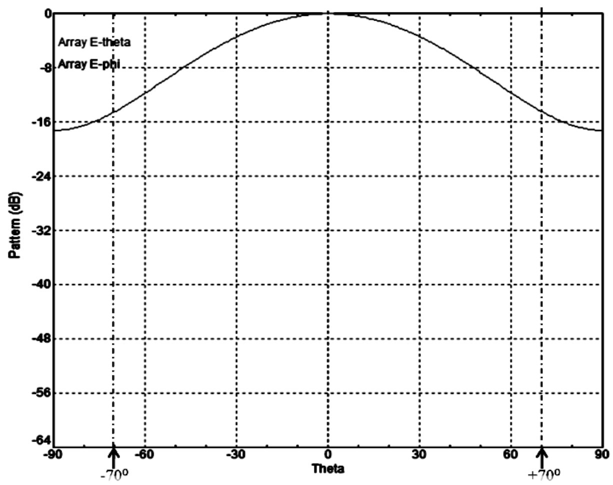

Fig. 7. Rectangular planar radiation pattern plot for 8X1 patch antenna array feed, d = 0. 5cm (using PCAAD 5.0)

From the radiation pattern plots for the 8x1 patch antenna array feed for inter-element distance, d = 0. 5cm shown above, it is observed that the feed pattern radiated over the effective aperture of the dish is continuous with an improved illumination taper of 14.5dB. The 3 dB beamwidth widened to 56.06^0 implying that even more energy is concentrated on the dish effective aperture. The illumination taper is comparable to the 10dB required [7].

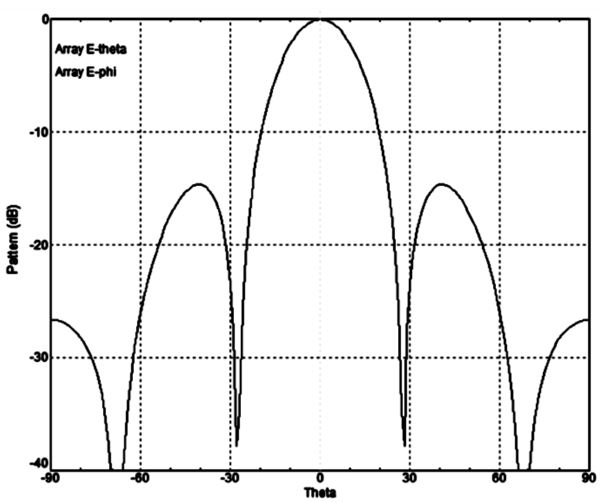

Fig. 8. Rectangular planar radiation pattern plot for 8X1 patch antenna array feed, d = 1.35cm (using PCAAD 5.0)

The simulated radiation pattern plots for the patch antenna array feed for inter-element distance, d = 1.35cm is presented in figure 8. For this configuration, where the inter-element distance is greater than one quarter wavelength, it is observed that the feed pattern radiated over the aperture of the dish includes four nulls at -30^0 $+30^0$,-70^0 and $+70^0$ accompanied with substantial side lobes. The presence of the nulls and sidelobes has a tendency of reducing the overall aperture efficiency of the dish for this configuration.

B. Efficiency Computation

A linear array of 8 patch antennas was considered, in which the antennas were assumed uncoupled (coupling causes variation in the element impedance, reflection coefficients, and overall antenna pattern in a finite element array), symmetrically situated, conjugated symmetrically excited around the center, and equally spaced. The array factor (AF) for normalized, linear, uniformly spaced, non-uniform amplitude, broadside 8-element arrays is given by [3].

$$\mathrm{AF} = \sum_{\mathrm{n}=1}^{4} a_n \cos\left[\frac{(2\mathrm{n}-1)}{2}\psi\right] \tag{18}$$

Where, $\psi = kd\,cos\,\theta + \beta$

a_n= amplitude excitation of the *n*th element.

β = progressive phase shift between individual elements.

$k = 2\pi/\lambda$ is the wave number.

d = inter-element spacing

θ = angle between the axis of the array (*z*-axis) and the radial vector from the origin to the observation point.

The illumination efficiency of the C-Band 8X1 patch antenna array feed for each inter-element distance is calculated by integrating the feed pattern radiated over the area of the reflector and dividing it by the total integrated feed pattern [7]. This is done in this case by integrating the radiation pattern over the effective aperture of the dish antenna (20^0 to 160^0) and dividing it by the total integrated pattern (0^0 to 360^0) with the assumption of uniform array element excitation amplitude and phase. Also, all other efficiency components due to radiation, polarization, blocking, focus and surface error [8] are not considered.

This modifies (18) to become;

$$\mathrm{AF}(\theta) = \sum_{\mathrm{n}=1}^{4} a_n \cos\left[\frac{(2\mathrm{n}-1)}{2} kd\cos\theta\right] \tag{19}$$

Thus,

$$Eficiency = \frac{\int_{20^0}^{160^0} |AF| d\theta}{\int_{0^0}^{360^0} |AF| d\theta} \tag{20}$$

This analysis was carried out using MATLAB with a uniform radiated power of 0 dB on each array element of the 8X1 patch antenna array feed. The progressive phase shift, β between individual elements was also taken to be 0. The result of this analysis is presented in Figures 9 and 10.

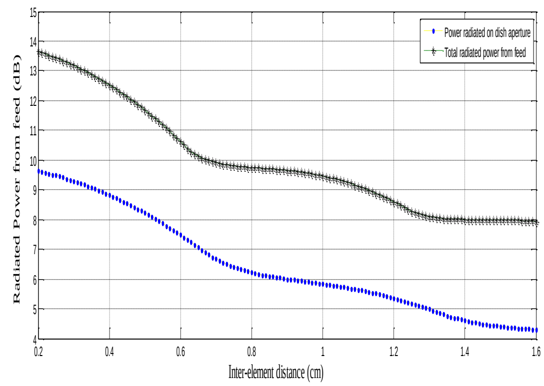

Fig. 9. Inter-element distance vs Radiated Power for the C-Band patch antenna array feed

From figure 9, it is observed that for the patch antenna array feed, the total radiated power decreases with increasing uniform inter-element distances for a uniform array element amplitude excitation. Similarly, the total radiation over the effective aperture of the dish antenna decreases with increasing inter-element spacing for this configuration. This means that ideally, the elements should be kept closer to achieve a higher gain from the feed.

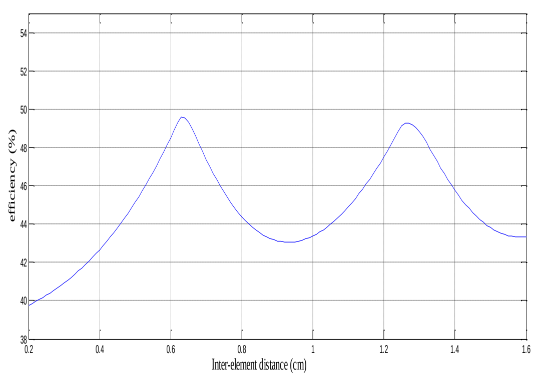

Fig. 10. Inter-element distance vs illumination Efficiency for the C-Band patch antenna array feed

From the figure above, the aperture efficiency of the patch antenna array feed was also observed to decrease progressively as the inter-element distance is moved away (either positively or negatively) from 0.63cm which is about λ/8.

V. CONCLUSION AND RECOMMENDATIONS

A. Conclusion

Designs of the 8X1 patch antenna array feed for C-Band dish (F/D=0.36) have been considered. The designs were simulated and the results of the simulations were analyzed. From the graphs and simulations, it can be inferred that the ideal inter-element spacing for the 8X1 patch antenna array feed for C-Band dish (*F/D*=0.36) is about 0.63cm (≈*λ/8*) in order to achieve good aperture efficiency and gain for the feed. At this spacing, the simulated efficiency while keeping all the other efficiency components constant is about 49.6%. This is very competitive when compared to that achieved with conventional feeds for the same *F/D* ratio of 0.36 which is between 50-75% [7]. Also at this spacing, the total weight of the feed is 91.3g and total array length is approximately 18.5cm which satisfies the condition of reduced weight and dimensions required for on-board satellite applications where mass and size limitations are extremely strict.

B. Recommendations

The patch antenna array feed is recommended for C-Band and higher band dishes on board a satellite mainly because of its compactness and light weight. Future works should focus more on aperture illumination, patch antenna element configuration, array configuration and so on for improvement on the efficiency. The effect of varying the aperture illumination (*F/D* ratio) for the dish antenna on the performance of the feed with respect to gain and efficiency should be investigated for this configuration. This will help in determining the most suitable *F/D* ratio. Other patch antenna array element configurations such as square, triangular, elliptical, circular ring, and so on should be investigated to determine how the element configuration affects the aperture efficiency of the selected dish aperture illumination.

Other patch antenna array feed configurations (e.g planar and cylindrical) should be investigated including configurations with non-uniform inter-element distances, phases and amplitude excitations. This will enable the determination of the effect of the different configurations on the total radiated power from the feed, gain, beamwidth and the aperture efficiency. The effect of the number of array elements on the performance should also be analyzed. All these will serve as a tool for antenna designers.

VI. ACKNOWLEDGEMENT

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