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A Review on Multi-Geometrical Antenna Reflector

Mohamad Faiz Mohamed Omar[1,2], **Asrulnizam Abd Manaf**[2], **Mohd Fadzil Ain**[3*] and **Sharul Kamal Abdul Rahim**[1*]

[1]Wireless Communication Centre (WCC), Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310, UTM Skudai, Johor, Malaysia.
[2]Collaborative Microelectronic Design Excellence Center (CEDEC), Sains@USM, Persiaran Bukit Jambul, 11900, Bayan Lepas, Pulau Pinang, Malaysia.
[3]School of Electrical and Electronic Engineering, Universiti Sains Malaysia, 14300, Nibong Tebal, Pulau Pinang, Malaysia.

*Corresponding authors: eemfadzil@usm.my, sharulkamal@utm.my

Abstract: Parabolic antennas are among the most important devices for long-distance communications because of their significant advantages in terms of directivity, gain, and power handling capabilities. Hat feeds are frequently used as feeders for parabolic antennas because they exhibit low levels of cross-polarisation, low sidelobes, and low reflection coefficients. However, hat feeds possess a limited impedance bandwidth (IBW) range of just 30% and are not suitable for use in wideband applications. More work is being done with the objective of increasing the hat feed's bandwidth capacity. The fundamental structure of a hat feed comprises a hat sub-reflector, circular waveguide, and dielectric material to provide structural support. The hat feeder had a bandwidth capacity of 10% at first. Later, the Chinese hat feed was introduced and used, resulting in a notable enhancement of the bandwidth, with an increase of 18%. The hat feed's geometric structure is redesigned with the help of a generic algorithm optimisation to further enhance the bandwidth, resulting in a 33% improvement.

Keywords: Coaxial feed, hat feeder, parabolic antennas, pyramidal horn antenna, planar antennas

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1. INTRODUCTION

Heinrich Hertz was the first to discover the reflector antenna, following his discovery of electromagnetic (EM) wave transmission in the late 19th century. Geometrical configurations vary in shape, including plane, corner, and curved reflectors [1, 2]. The paraboloid is the most often favoured form because it can produce a high degree of gain with a narrow beam, sometimes known as a pencil beam.
Besides, its radiation pattern is characterised by having a low cross-polarisation with suppressed side lobes. It is extensively employed in point-to-point communication, wireless backhaul, long-distance wireless surveillance, and radio links for remote control [3, 4].

In the context of broadcasting, the compact and cost-effective parabolic antenna is particularly necessary for large-scale data transmission at a high-efficiency level. There are several variations of parabolic antennas, each equipped with a different feeder. Hat feed is one of them. In Malaysia, hat-fed parabolic antennas are widely used, particularly by Telekom Malaysia Berhad, simply known as “TM”. At present, TM uses a couple of parabolic antennas that work within certain frequency ranges. The first antenna operates within the frequency range of 12.75 GHz to 13.25 GHz (Ku band), the second antenna operates within the frequency range of 14.4 GHz to 15.35 GHz (Ku band), and the third antenna operates within the frequency range of 17.7 GHz to 19.7 GHz (both Ku and K bands). This type of feeder is best known for its advantageous features, such as low cross-polarisation, excellent illumination efficiency, and low side lobe level [5, 6].

In 1984, a study on the hat antenna design started with the development of the primary feeder by Per-Simon Kildals. This feeder, known as the "dipole-disk feed with ring," was meant to serve as the reflector [7]. The study on characterising feeds to enhance the aperture efficiency of the reflector was subsequently extended until the introduction of the hat antenna, a novel parabolic antenna equipped with a hat feed. Theoretical analysis of the line feed radiation from the Arecibo radio telescope formed the basis for the development of the hat antenna.

The first developed antenna was deployed in an armed forces radio communication system. Theoretically, the presence of a corrugated "hat" might potentially improve the efficiency of radiation [8]. Unfortunately, the hat antenna's initial design was incapable of serving any application due to its severely restricted bandwidth. However, after years of intensive study, the hat antenna with a favourable radiation pattern, as well as low levels of cross-polarisation and return loss was developed by focusing on the modifications of the shape geometry. Ongoing research is now being actively conducted to improve the hat feed antenna's bandwidth. So far, the hat feed antenna's bandwidth is limited to a maximum of 33%, which is insufficient for the transmission of large volumes of data.

A number of studies are now being conducted with the objective of improving the hat feed’s bandwidth. The fundamental configuration of a hat feed comprises a circular waveguide, a hat sub-reflector, and a dielectric material housed inside the hat to provide structural support. The early prototype design of the hat feed had a bandwidth of 10% when it was first completed [9]. Later, the Chinese hat feed was found, resulting in an enhancement of the bandwidth to 18% [10]. In the early 21st century, the hat feed's bandwidth was enhanced by almost 30% by optimising its structure using a genetic algorithm [11]. Wei et al. [12] introduced a novel hat feed without the use of dielectric material, which led to a bandwidth expansion of up to 26%. From 1986 to 2015, researchers from all over the world continued to work to boost the capacity and performance of the hat feed antenna. However, the improvement achieved during this period was limited, with a maximum increase in bandwidth of up to 33%. The most recent study on hat feed antennas was done in 2016. It operates within two frequency bands (Ka-band and V band), with impedance bandwidth (IBW) of 10% and 6.7%, respectively [13].

2. GAIN AND EFFICIENCY

Antenna gain, in essence, refers to the measure of the difference between the power received by an isotropic antenna compared to the amount of power that the antenna under test (AUT) received. The parabolic antenna gain can be determined by working with Equation (1) [14, 15].

$$G = 10\log_{10}\frac{4\pi A}{\lambda^2}e_A = 10\log_{10}\frac{\pi^2 d^2}{\lambda^2}e_A \tag{1}$$

where:

- e_A is the antenna's effective aperture.
- A is the size of the antenna aperture area.
- d is the parabolic reflector's diameter.
- λ is the electromagnetic wave's wavelength.

The e_A is being considered to alleviate many factors that might diminish the overall performance of the parabolic antenna, resulting in a decrease in its maximum gain. The primary variables that decrease the effective aperture (e_A) in parabolic antennas are [16, 17]:

- The illumination loss.
- The reflector spillover loss.
- The error of focal point.
- The beam blockage by the feeder.
- The beam blockage by the supporting structures.
- The curvature of the parabolic surface with flaws.
- The loss from the feedline mismatch.

A transmit antenna's angular beamwidth is measured based on its half-power beamwidth (HPBW), where the angle θ value between two points on the antenna's radiation pattern is defined at which the power drops by half from its highest value. Equation (2) can be used to determine the value of θ [14, 15].

$$\theta = \frac{70\lambda}{d} \tag{2}$$

where d is the antenna reflector's diameter. Equation (3) illustrates the relationship that exists between the gain and beam width [14, 15].

$$G = 10\log_{10}\left(\frac{70\pi}{\theta}\right)e_A \tag{3}$$

3. PARABOLIC ANTENNA

A unit of parabolic reflector is shaped like a paraboloid geometry. The parabolic reflector serves as a reflecting surface, allowing waves to be reflected by the surface while maintaining their phase connection. The antenna's feeder receives electrical power from an RF cable at the transmitter side, which is then transformed into electromagnetic waves. Upon reaching the surface of the reflector dish, the EM waves are deflected and turned into a parallel beam, before being transmitted into the air. The receiving antenna reflects the electromagnetic waves that come in off the dish and redirects them onto the antenna's feeder. The feeder then transforms the received waves into electrical power, which is transmitted to the receiver via a transmission line [14, 15].

As illustrated in Figure 1, the sum of X1 + X2 is equivalent to Y1 + Y2, preserving the system's phase integrity. At the focal point, the incoming EM waves are added, while the outgoing EM waves are redirected in a parallel direction away from the reflector dish [18, 19].

A low-gain feeder, such as a half-wave dipole, is often integrated with the parabolic antenna to achieve optimal performance. Most of the time, the feeder is installed at the centre of the reflector, which is its focal point. The focal point is the specific location where all the reflected waves converge and become concentrated. The focal length of the parabolic antenna, which is specifically defined as the distance between the focus point and the centre of the reflector, can be calculated based on Equation (4) [14, 15].

$$f = \frac{D^2}{16d} \tag{4}$$

where f is the reflector's focal length, D is the diameter of the reflector in metres, and d is the depth of the reflector dish in metres. The D and d of the reflector are measured because the actual size varied from reflector to reflector due to tolerance, even reflector is a standard manufactured unit. Based on Equation (5), a large f/D will increase the reaction of the reflector on the feed, which causes an impedance mismatch. Hence, the value of the f/D ratio should be controlled within the range of 0.2 to 0.5 for a single reflector antenna [20]. The f/D ratio for the parabolic antenna can be calculated using Equation (5) [14, 15].

$$\frac{f}{D} = \frac{\text{focal length (m)}}{\text{diameter of reflector (m)}} \tag{5}$$

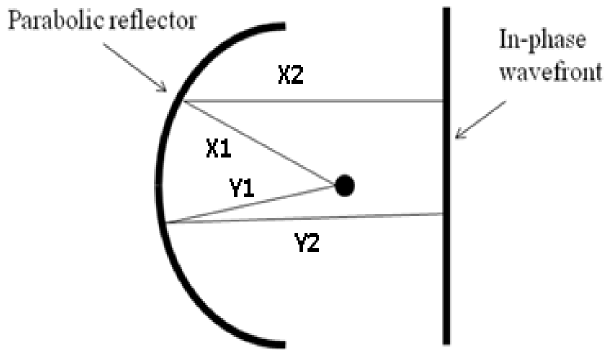


Figure 1. A paraboloid shape of the reflector allows for the coherent combination of wavefronts, preventing them from being out of phase

Multiple options of feed systems for parabolic reflectors are available for choosing. Each individual has unique features that may be used in many applications [18, 19].

i. Front feed – When it comes to feeding a parabolic antenna, this is the most typical method. In this setup, the feeder is placed right at the centre, exactly at the focal point in front of the reflector (see Figure 2). The aperture efficiency can only be as high as 60% due to the support and feeder structures restricting the signal beam.

ii. Offset axis feed – The antenna's feeder is placed at the periphery of the reflector (off the dish axis), as the reflector dish itself is a non-symmetrical segment of a paraboloid (Figure 3). This feed arrangement allows the beam to pass through without any obstruction.

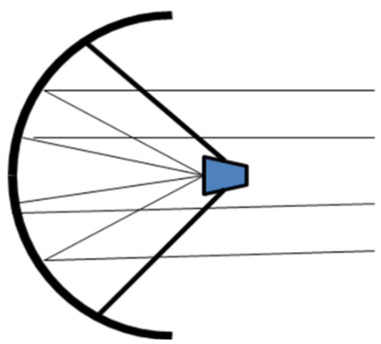


Figure 2. Front or axial feed

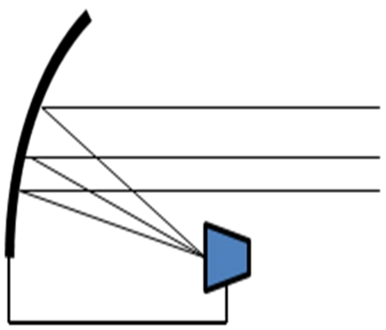


Figure 3. Offset axis feed

iii. Cassegrain feed – The antenna's feeder is mounted either on or behind the reflector. The signal waves propagate in a forward direction and are then reflected by a convex hyperboloidal secondary reflector at the focal point (Figure 4). The radio waves from the secondary reflector are subsequently reflected onto the dish plate forming the outgoing beam. This feed configuration has an aperture efficiency that is somewhere between 65% and 70%.

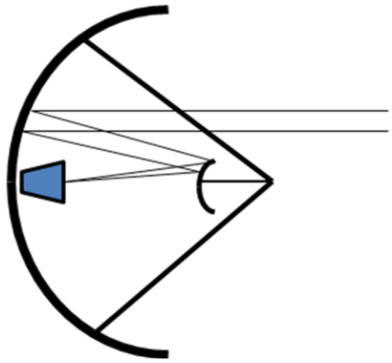


Figure 4. Cassegrain feed

iv. Gregorian feed – The design of the structure is relatively similar to that of the Cassegrain, except for the fact that the additional second reflector's geometry is concave. Practically, the Gregorian feed has an aperture efficiency that is more than 70% (Figure 5).

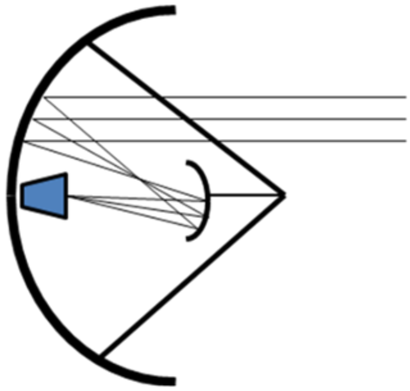


Figure 5. Gregorian feed

4. PYRAMIDAL HORN ANTENNA

One of the feeds for the parabolic antenna is the pyramidal horn antenna. It can be fed by a coaxial feed or other exciters, such as rectangular or circular waveguides [21-23]. However, the bandwidth of these exciters is limited. Over the years, multiple concepts have been put forward for a transition from coaxial to waveguide probes, but almost all of them have bandwidths of < 35% [24]. Multiple studies were conducted on the use of printed circuit designs as the exciters for pyramidal horn antennas, including microstrip probes, dipole, and patch antennas [25, 26]. However, the highest achievable bandwidth was roughly 30%.

As reported by [27], a stacked patch antenna effectively excites a horn antenna, leading to a 30% bandwidth coverage at a centre frequency of 94 GHz. A coplanar waveguide (CPW) fed stacked patch antenna with a pyramidal horn is illustrated in Figure 6.

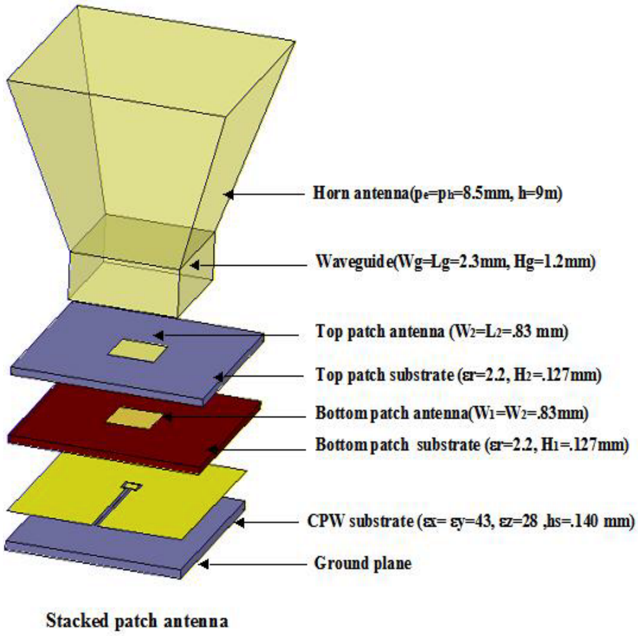
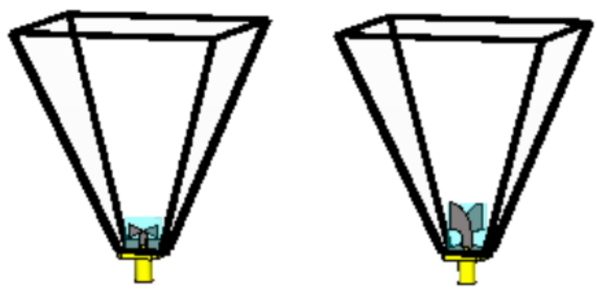


Figure 6. The configuration of a pyramidal horn antenna with layered patches [27]

An alternative excitation technique is described by [27], involving a direct placement of the planar antenna at the base of the pyramidal horn, as seen in Figure 7. When mounted inside the horn, both the Vivaldi slot and bow-tie dipole antennas show a wide bandwidth of more than 18 GHz.



(a) (b)

Figure 7. A pyramidal-shaped horn antenna internally excited by planar antennas: (a) Bow-tie dipole; (b) Vivaldi [27]

In 2006, [28] introduced a novel integrated arrangement of a pyramidal-shaped horn antenna that is excited by a square-shaped microstrip patch antenna, mounted right inside the horn. In addition to having a maximum gain of 11 dBi, this configuration also earned a bandwidth of >100 MHz that is centred at 3.3 GHz. The prototype of the proposed pyramidal horn antenna design is shown in Figure 8, wherein the horn antenna is incorporated with a suspended square-shaped patch antenna.

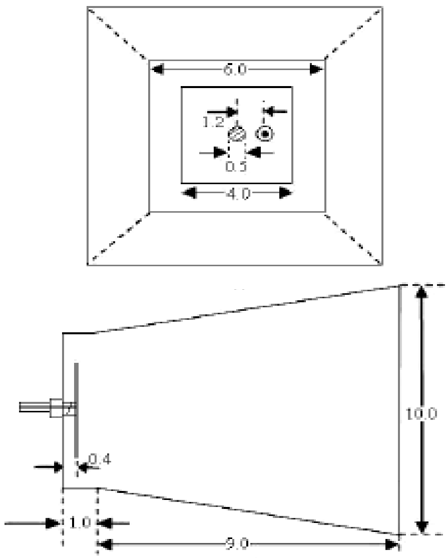


Figure 8. The structure of a pyramidal horn antenna incorporated with a suspended square-shaped patch antenna [28]

Later in 2011, a study published by [27] reported a novel technique to excite a dual-polarised pyramidal horn antenna using a microstrip patch. The antenna may reach a maximum gain of 12 dBi, with a bandwidth exceeding 4%. Figure 9 illustrates the setup of a dual-polarised antenna, where a microstrip patch is mounted at the base of a pyramidal horn antenna.

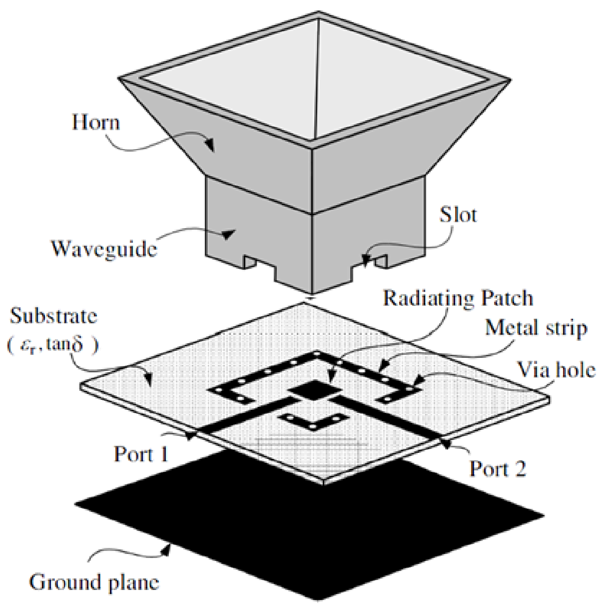


Figure 9. The structure of the pyramidal horn held up by a patch antenna [27]

5. HAT FEEDER

A hat feeder is another kind of conventional feeder used for the parabolic antenna. The first attempt was made in the mid-19th century by Cutler [30], who introduced the idea of a reflector employing a self-supported waveguide feed as a means to avoid blockage caused by struts. Later, in the year 1997, [31] introduced a novel self-supported feed known as the "hat feed". This feed consists of a "hat" element that looks like a corrugated brim surface supported by a dielectric joint (the "head") mounted at the end of a waveguide (the "neck"), as seen in Figure 10.

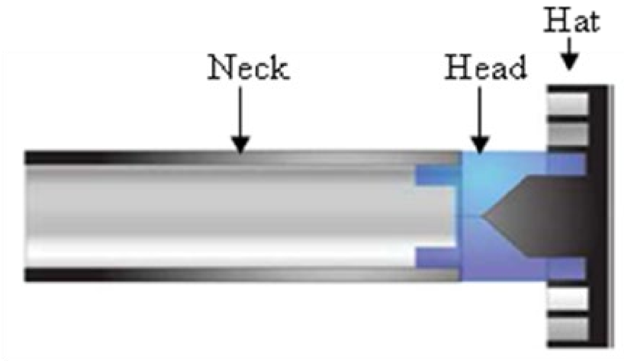
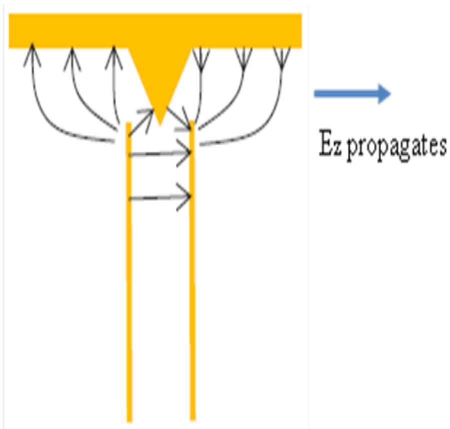


Figure 10. The configuration of hat feed with dielectric support (head), waveguide (neck), as well as corrugated brim (hat) [9]

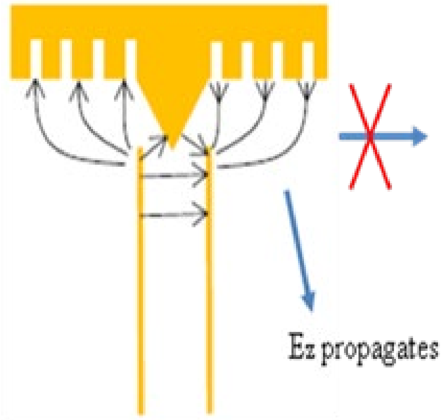
Hat feed offers low cross-polarisation and good side-lobe suppression, making it an ideal option for use as a parabolic antenna feeder [29]. Figure 11 depicts the two-dimensional structure of the hat feeder, which includes both the corrugated and non-corrugated versions.

As seen in Figure 11(a), the z-component of the electric field propagates tangentially over the surface of the hat when a smooth, non-corrugated metal surface is employed for the hat. This will lead to a strong field illumination on the periphery of the reflector and the growth of the far-out sidelobes' level.

However, the bandwidth of the hat feed is somewhat limited. Works to improve the bandwidth capacity of the hat feed have been ongoing since 1986 and continue to this day [7]. Table 1 provides a summary of some studies aimed at improving the bandwidth of the hat feed.



(a)



(b)

Figure 11. The working mechanism of two different hat feeders (a) non-corrugated surface on hat, (b) corrugated on hat [29]

Table 1. A brief summary of hat feed measurements with improved impedance bandwidth.

References	Bandwidth (%)	Frequency range (GHz)
[31]	10	26 - 31
[32]	18	26 -33
[10]	33	6.58 - 10
[12]	26	9 - 14
[33]	26	9 - 14
[9]	29.7	10.75-14.5
[13]	10 and 6.7	38- 42 and 58- 62
[34]	4.8 and 3.3	20.2- 21.2 and 30- 31

5. CONCLUSION

The parabolic antenna illustrates that the bandwidth of the antenna is dependent upon its feeding structure. There are several types of feeders for the parabolic antenna such as hat feeder (waveguide type) and horn antenna. The hat feeder is preferred due to its appealing qualities, which include minimal cross-polarisation and great side-lobe suppression, making it ideal for use as a feeder for a parabolic antenna. However, it operates within a limited bandwidth. Even now, researchers are still working on how to make the hat feed antenna's bandwidth better. However, at this point, the bandwidth has only been increased to 33%, which is insufficient to carry larger amounts of data.

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