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Self-Supporting Circularly Polarized Backfire Helix Feed Antenna with Reflector and Director for Deep Dish Reflector Antennas in the L-Band

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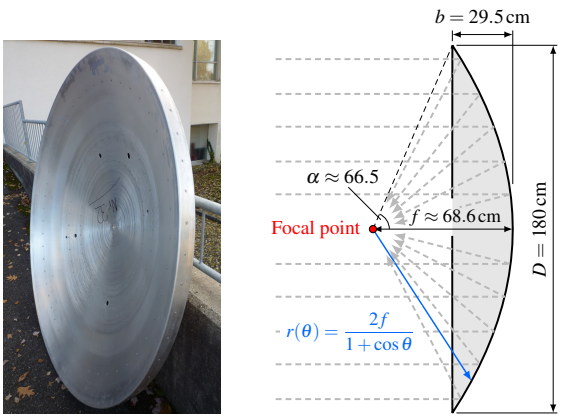
Abstract

Backfire helix antennas are particularly interesting candidates for use as feeds of reflector antennas due to their natural circular polarization, lightweight construction, and minimal blockage. An additional reflector element can provide further degrees of freedom to optimize the illumination efficiency, reduce the backlobe and increase cross-polarization isolation. The result is an efficient, lightweight and versatile feed antenna, particularly well-suited for deep dish reflector antenna applications in the L-band.

1 Introduction & Overview

Reflector antennas have come a long way, since Heinrich Hertz basically invented them, back in 1888 [1]. Even though a large variety of reflector antennas exists, nowadays, standard feed solutions can be applied in many cases. However, most of the common feed antenna types cannot be easily applied at low frequencies and for deep dish reflectors, such as the one in Fig. 1. The general methodology for choosing suitable feed antennas is reviewed in Sec. 2. Following that, in Sec. 3, backfire helix antennas are introduced as particularly well-suited candidates for this and similar cases. The addition of a reflector behind the helix leads to a Yagi-like configuration, with enhanced forward-to-backward ratio and further degrees of freedom for optimizing the reflector illumination. Finally, Sec. 4 briefly addresses the realized prototypes, before concluding remarks.



(a) (b)

Figure 1. The studied deep dish reflector.

2 Illumination of Deep Dish Reflectors

This project began with the parabolic dish shown in Fig. 1(a), gifted to the HSR by a friendly amateur radio operator. The aim was to use it for amateur radio satellite communications, high-performance GPS/GNSS signal reference, earth-moon-earth (EME) experiments as well as for other research and educational purposes.

2.1 Properties of Deep Dish Reflectors

All parabolic reflectors have the same parabolic curvature. They are merely different regions of the parabola, which extends all the way to infinity. Depending on the choice of the region, asymmetric or symmetric dish reflectors can be obtained, where the latter can be either shallow or deep.

As illustrated in Fig. 1(b), this parabolic reflector has a diameter of $D \approx 1.8\,\mathrm{m}$ and a depth of $b \approx 29.5\,\mathrm{cm}$. From these parameters, the focal ratio f/D can be calculated via [2]

$$f/D = \frac{D}{16b} \approx 0.38. \tag{1}$$

According to varying definitions, a parabolic reflector with a focal ratio f/D of less than 0.33 to 0.4 can be classified as "deep dish". In general, deep dish reflectors are better able to isolate surrounding noise, but are more difficult to illuminate. All reflectors with the same f/D essentially lead to the same requirements on the shape of the feed antenna pattern; the polarization can be application-dependent, but usually circular polarization is required.

2.2 Gain Estimation & Requirements

The maximum achievable gain using this dish reflector can be estimated from the dish area, A_{dish}, (assuming uniform illumination) as follows:

$$G_{\max} \approx \frac{A_{\mathrm{dish}}}{\frac{\lambda^2}{4\pi}} = \left(\frac{\pi D}{\lambda}\right)^2 = \begin{cases} 27.5\,\mathrm{dBi} & @\,1.27\,\mathrm{GHz} \\ 29.4\,\mathrm{dBi} & @\,1.575\,\mathrm{GHz} \end{cases} \tag{2}$$

The actual gain is lower: $G = \eta G_{\max} \leq G_{\max}$. The overall efficiency η may be reduced by multiple factors:

$$\eta = \eta_{\mathrm{ill}}\,\eta_{\mathrm{spill}}\,\eta_{\mathrm{phase}}\,\eta_{\mathrm{XP}}\,\eta_{\mathrm{block}} \cdot \eta_{\mathrm{mis}}\,\eta_{\mathrm{pos}}\,\eta_{\mathrm{rad}}\,\eta_{\mathrm{geom}}\,\eta_{\mathrm{surf}}\,\eta_{\mathrm{others}} \tag{3}$$

- η_{ill}, η_{spill}: Illumination error & spillover, see Sec. 2.3.
- η_{phase}, η_{XP}: Phase error & cross-polarization (XP), minimized by pattern symmetry and XP isolation.
- η_{mis}: Impedance mismatch, minimized by adequate impedance matching over the required bandwidth.
- η_{block}: Blockage, particularly important to avoid for deep dish reflectors, since they have small areas.
- η_{rad}: Radiation efficiency, maximized via sufficiently thick, good conductors, to minimize dissipation loss.
- η_{pos}: Feed position errors, minimized by accurate and robust positioning. Withstanding wind and weather is mandatory. However, for ease of interchangeability, avoiding extra arms or guy-wires is highly desirable.
- η_{geom}, η_{surf}: Geometry errors & surface roughness of the reflector, independent of the feed antenna.

2.3 Optimum Feed Gain for Deep Dishes

Focusing on the first two efficiency terms in (3), the achievable gain in the main beam direction can be factorized into $G(\alpha) = G_{\max} \cdot g(\alpha)$, where $g(\alpha) = \eta_{\text{ill}}\eta_{\text{spill}}$ is the α-dependent illumination factor. Restricting to rotationally symmetric feed gain patterns $G_{\text{feed}}(\theta)$, it can be given as [2]

$$g(\alpha) = \left| \cot\left(\frac{\alpha}{2}\right) \cdot \int_0^{\alpha} \sqrt{G_{\text{feed}}(\theta)} \tan\left(\frac{\theta}{2}\right) d\theta \right|^2 . \quad (4)$$

Thus, the illumination factor depends on the feed gain pattern $G_{\text{feed}}(\theta)$ and the reflector opening angle α. However, it remains the same for all reflectors with the same focal ratio f/D, as mentioned in Sec. 2.1.

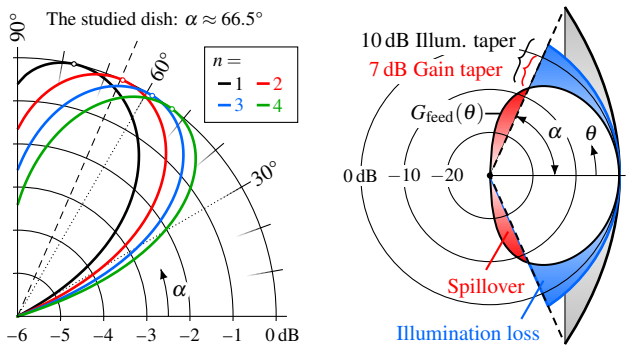
For the simplest cases, the feed pattern $G_{\text{feed}}(\theta)$ can be approximated by powers of the cosine:

$$G_{\text{feed}}(\theta) \approx \begin{cases} G_n \cos^n \theta & 0 \le |\theta| \le \pi/2 \\ 0 & \text{otherwise} \end{cases} , \quad (5)$$

where the gain factors $G_n = 2(n+1)$ ensure the condition $\int_0^{4\pi} G_{\text{feed}}(\theta)\, d\Omega = 4\pi$ be satisfied. The first few powers $n = 1$ to 4 lead to the following feed gains: $G_1 \approx 6.0\,\text{dBi}$, $G_2 \approx 7.8\,\text{dBi}$, $G_3 \approx 9\,\text{dBi}$, and $G_4 = 10\,\text{dBi}$.

By inserting (5) into (4), the illumination factors $g_n(\alpha)$ for each cosine power n can be obtained. In Fig. 2(a), they are plotted against α for $n = 1$ to 4. As can be seen, the simple squared-cosine ($n = 2$) feed gain model is nearly optimal in this case. Therefore, a medium-gain (around 7 dBi) feed antenna has to be designed to illuminate the reflector in Fig. 1.

Similar points can be made using the well-established optimal 10-dB illumination taper [2] (more precisely 10.8 dB) towards the dish edge, as shown in Fig. 2(b). The curvature adds about $40 \log_{10} \sec|\alpha/2| \approx 3.2\,\text{dB}$ path loss at the edges, compared to the center of the reflector. Thus, an additional feed gain taper of about 7 to 7.5 dB is required to obtain the near-optimal trade-off between spillover and illumination loss. As illustrated, this is again closely realized by a squared-cosine feed pattern with around 7 to 8 dBi.



(a) Aperture efficiencies $g_n(\alpha)$ (b) Illumination loss vs. spillover

Figure 2. Illustrations of (maximum) aperture efficiencies, illumination taper und spillover for the deep dish.

2.4 Feed Antenna Types for Deep Dishes

Many feed antenna types are used for parabolic dish applications, each providing its own advantages and disadvantages. However, depending on the focal ratio of the parabolic dish, the operating frequency band, and other requirements, only few feed types are actually applicable.

In general, the majority of reflector feed antennas are waveguide based. However, below a few GHz, waveguide-based feed antennas become prohibitively large and heavy. Moreover, particularly for such a small reflector, the size of the waveguide and horn flaring would lead to considerable blockage. Waveguide-based feeds are more suitable for higher frequencies and larger reflectors and/or focal ratios.

Dipole-based feed antennas provide many degrees of freedom, can be optimized efficiently [3] and generally lead to minimal weight. Blockage is reduced, unless large ground planes are used. Most importantly, however, dipole-based feeds usually exhibit unsymmetrical radiation patterns and are suboptimal candidates for circular polarization.

Patch or spiral antenna feed designs are uncommon, but not unheard of. Blockage by the ground plane is an issue, especially at low frequencies. Dielectrics could be used to reduce the antenna and ground plane size. However, for reflectors antennas, the use of dielectrics is rather uncommon, as they are either expensive or lead to reduced efficiency and/or power handling capability, and always add weight.

Helical antennas are particularly well-suited for use as feed antennas. They are naturally circularly polarized, provide pattern symmetry and lead to lightweight and simple solutions. Their main drawback is, once again, blockage due to their ground planes. Backfire helices resolve this issue: by reducing the ground-plane size, the radiation becomes aimed backwards, towards the ground plane, rather than away from it [4–6]. Recently, the enhancement by additional ground planes, acting as Yagi-like directors, has been considered [7]. Here, the addition of a similarly Yagi-like reflector is proposed, instead. Both follow in principle the original ideas of backfire feed antennas [8–10].

3 Backfire Helix with Yagi-Like Reflector

3.1 From Endfire to Backfire and "Beyond"

Fig. 3 illustrates the progression from a regular endfire (axial-mode) to a backfire helical antenna, as the ground-plane (director) size is decreased while the helix size remains the same. The rather large remaining co-polarized backlobe observed in Fig. 3(c), would impair the overall cross-polarization isolation of the entire reflector antenna. However, the addition of a reflector plane behind the helix resolves this issue, as shown in Fig. 3(d): the backlobe is almost completely gone, without any further optimization.

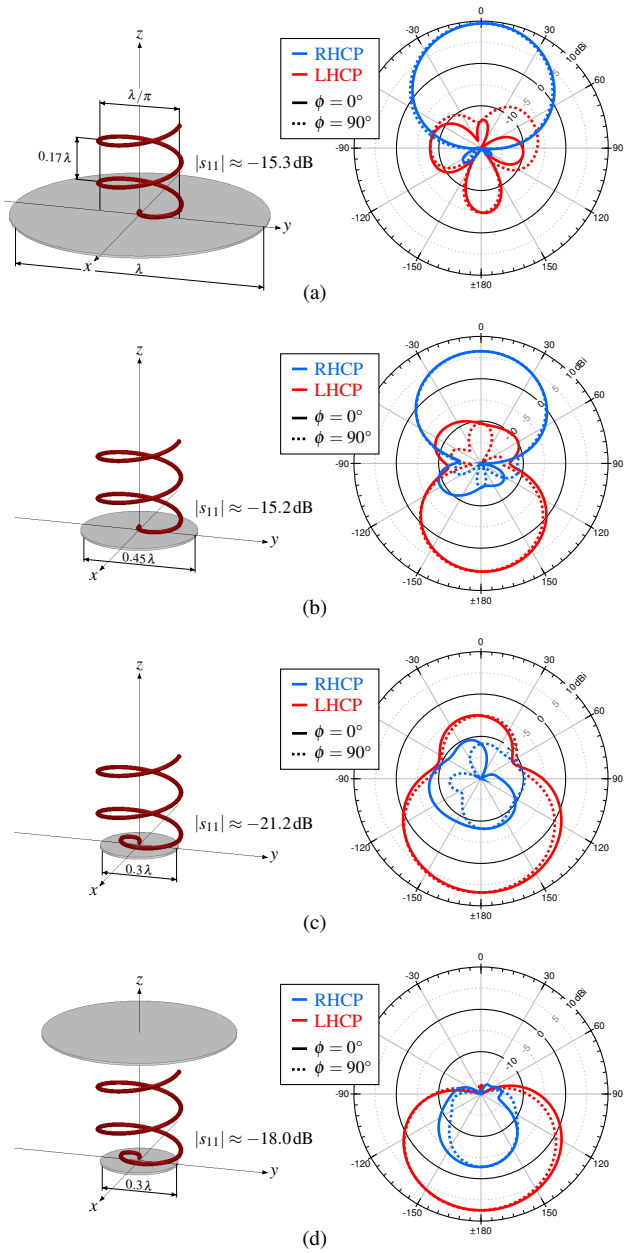


Figure 3. Evolution of the backfire helix antenna with director and reflector: (a) to (c) endfire to backfire radiation as a function of the ground-plane size and (d) with reflector. All simulations have been carried out using ANSYS HFSS.

In essence, this feed antenna resembles a Yagi-like three-element antenna array, consisting of an active element (helix), a director (ground plane) and a reflector. As such, it provides various degrees of freedom for further optimizing the radiation pattern, impedance matching and bandwidth according to application specific requirements.

3.2 Feed Reflector vs. Blockage

One of the arguments that lead to the selection of the backfire helix as feed antenna has been its reduced blockage, compared to regular helical, patch, and other antennas. With the addition of the large reflector disk behind the helix, this argument now seems voided. However, the reflector size can be minimized with techniques similar to patch antenna minimization, as shown in Fig. 4.

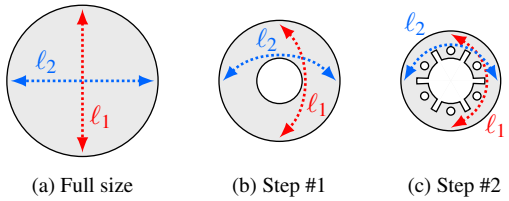


Figure 4. Step-wise size reduction of the reflector disk, similar to patch antenna minimization.

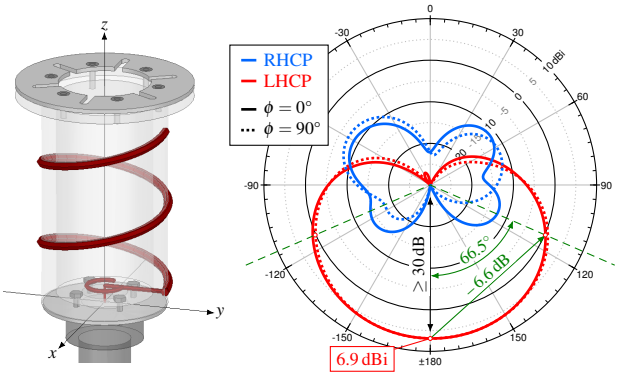
The current has to flow around the cut-out area in the middle of the disk, as illustrated by the dotted arrows. Thus, the physical size of the disk can be decreased, while the electrical lengths of the current paths ℓ_1 and ℓ_2 remain the same. With additional cuts, the effect can be made even stronger, while having negligible impact on the overall performance.

3.3 Self-Supporting Design Aspects

Supporting structures, such as guy-wires and additional arms, can have substantial influence on the overall performance of a reflector antenna, e.g., by causing phase errors and increasing blockage. However, the low weight of this antenna (ca. 250 g) enables possibilities of designing a self-supporting feed structure, similar to some waveguide feeds. As it turns out, a conductor rod in the direction of the main beam (away from the small ground plane) has a minimal effect on the overall performance; it merely slightly increases the optimal director disk size. With a light-weight metal pipe (25 mm diameter, 2 mm thick), it is possible to easily mount and interchange the antennas, while also maintaining a precise focal position and withstanding wind and snow.

4 Feeds for GPS L1 & L2C Measurements

For GPS L1 and L2C measurement applications, two similar and easily interchangeable feed antennas were designed: one centered at 1.27 GHz (L2C) and one at 1.575 GHz (L1), each with at least 5% bandwidth. Since the polarization for all applications is RHCP, the feeds have to be LHCP. The final model for the 1.27 GHz-version is shown in Fig. 5.



(a) 3D model (b) Feed antenna gain, θ-cuts

Figure 5. The optimized 1.27 GHz backfire helix model with minimized reflector and internal matching network and its simulated feed patterns in ANSYS HFSS.

The director and reflector disks as well as the mounting rod are made of aluminum. The helix is wound from 4 mm-thick, gold-plated copper wire and the holding structure is manufactured from plastic (POM). A tuning stub, bent around the antenna axis, helps achieve the desired bandwidths (exceeding 10%) with minimal effect on pattern symmetry. The vertical-profiled metallic plate [11] typically used as matching device for helical antennas becomes less effective for backfire designs.

Preliminary measurements confirm that the gains promised in (2) can be met to about 1 dB, corresponding to 80% aperture efficiency. Moreover, the achieved cross-polarization isolation is sufficient for the desired applications.

5 Summary & Conclusion

Backfire helix antennas have been revisited as a suitable choice for feeding dish reflectors, particularly at frequencies in the L-band. They naturally provide key ingredients, such as circular polarization, pattern symmetry, and low weight, as well as several useful degrees of freedom for optimization. The addition of a Yagi-like reflector further increases the versatility of this feed antenna. Blockage can be minimized by adopting well-known and easy to implement patch antenna miniaturization techniques. Lastly, this feed antenna can be mounted onto a metal pipe connect to the director disk, which can then be used to accurately hold the entire feed antenna in place at the focal point of the reflector and withstand wind and weather, without the need of additional guy-wires.

Acknowledgment

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Figure 6. The Yagi-like backfire helix-fed dish reflector antenna (1.27 GHz feed mounted), installed on the roof of one of the buildings at the HSR, Rapperswil, Switzerland.

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