E.T.S. de Ingeniería Industrial,
Informática y de Telecomunicación

# Simulation, analysis and optimization of innovative high-efficiency multiple-beam spline-profiled antenna structures

Grado en Ingeniería
en Tecnologías de Telecomunicación

## Trabajo Fin de Grado

Daniel Valcázar Berdofe

Jorge Teniente Vallinas

Pamplona, 25 de Junio de 2015

upna
Universidad
Pública de Navarra
Nafarroako
Unibertsitate Publikoa

## Acknowledgments

This work would have been unrealizable without both the resources put at my disposal and the warm welcoming conveyed to me by every single person involved with the Anteral team, and for that they sincerely have my gratitude. The experience of the last months is one that I will not soon forget.

Over the course of these four years of personal and intellectual growth I've been fortunate enough to forge new relationships, some of which I hope will last for years to come. To all these friends, past and present and in various locations around the globe, thank you for being there.

However unimportant it may seem to some, it is clear to me that as human beings we are but a product of our own environment, and bearing that in mind I owe an unpayable debt to my always supportive family, my forever attentive parents in particular. From the bottom of my heart, I love you both very much. Mom, thanks. Papá, gracias.

"*It's not that I'm so smart, it's just that I stay with problems longer.*"

-Albert Einstein

## Abstract

The following work deals with the design and optimization of five high-efficiency spline-profiled feedhorn antennas to be used aboard a future communications satellite as part of a multibeam reflector system. Design requirements are discussed, and the final profile and projected frequency performance for every antenna is provided along with insight into the process that led to each particular design. A background of the theory behind spline-walled horns, multiband and multibeam systems is also studied, as to provide a sufficient framework to understand the key concepts discussed in the main body of work. As a conclusion, important observations about the work are analyzed and possible lines of future investigation are explored.

## Index Terms

Spline, Feedhorn, Multiple-beam, Multiple-band, High-efficiency

# Table of Contents

# Chapter 1

## Introduction

In recent years there has been an increasing need for an alternative to the well-established corrugated horn to use in certain communication applications. For instances where weight is a critical factor to take into account, it was becoming more and more apparent that using corrugated antennas was not a viable option [1]. Additionally, the manufacture of corrugated horns for high-frequency systems, especially those operating above Q band (50 GHz) was proving incrementally difficult due to the inverse proportionality of components' sizes and their operating frequencies (the higher the frequency, the smaller the component size).

A possible solution to these problems was discovered circa 2003, when Christopher Granet and his team came up with a way to design a smooth-walled feedhorn that offered a comparable performance to that of a corrugated antenna [2]: the spline-profiled feed. This design's cross-polar response was improved upon by Lingzhen Zeng's 2009 design [3], and continues to be researched as a cutting edge substitute to more traditional approaches.

Although they take slightly more time to design than corrugated horns (due to the increased number of discrete points necessary to define the profile), spline feedhorns are proving to be advantageous [1] in situations where, as previously stated, weight and/or production costs are limiting aspects. Additionally, smooth-walled spline feedhorns are fit for use in arrays where, because of the limited space available, aperture diameters need to be as small as possible (and corrugated horns' diameters are often not small enough).

This is the case with modern spaceborne communication satellites; the main body of this work deals with the design and optimization of five different feedhorns, which are part of a Multiple-beam antenna (MBA) system for one such satellite. The designs had to meet a set of size, frequency, temperature, return loss and cross-polarization requirements (among others) in order to function optimally while onboard the spacecraft.

It is worth noting that these requirements were particularly rigid and pushed the employed optimization methods to the near-limits of their computing power. A detailed study of each design is provided, including various graphs and antenna profiles to illustrate precisely how the requirements are being met.

It is also worth mentioning that initially, the designs discussed were going to be the finalized models. However, as time went on it started to become evident that they weren't going to be finished by this project's due date, and thusly the most recent (but not final) versions are presented here.

The structuring of the remaining chapters is as follows:

- Chapter 2 deals with multibeam and multiband antennas, their uses and the basic theory behind them.
- Chapter 3 deals with spline-profiled feedhorn antennas, their origin and their advantageous features.
- Chapter 4 is a summary of the design and optimization process of each of the five contracted feedhorn models.
- Chapter 5 presents a conclusion of the obtained results, as well as an overview of possible advances to be made in the future.

## References

[1] T. S. Bird and C. Granet, “Chapter 5. Profiled Horns and Feeds,” in *Handbook of Reflector Antennas and Feed Systems. Volume II. Feed Systems*, 1st ed., S. Rao, S. K. Sharma, and L. Shafai, Eds. Artech House, 2013.

[2] C. Granet, R. Bolton, and G. Moorey, “A smooth-walled spline-profile horn as an alternative to the corrugated horn for wide band millimeter-wave applications,” *IEEE Trans. Antennas Propag.*, vol. 52, no. 3, pp. 848–854, 2004.

[3] L. Zeng, C. L. Bennett, D. T. Chuss, and E. J. Wollack, “A low cross-polarization smooth-walled horn with improved bandwidth,” *IEEE Trans. Antennas Propag.*, vol. 58, no. 4, pp. 1383–1387, 2010.

# Chapter 2

## Multiple-Beam Antennas

### Advantages and Frequency Reuse Plan

In recent times there has been a spike in the use (and therefore demand) of multiple-beam antennas (MBAs) for a variety of spacecraft-based telecom infrastructures, including military and personal communication satellites, mobile satellites and direct broadcast satellites. The concept behind MBAs is a relatively simple one: on the satellite, several feedhorns are placed opposite one or more reflectors (which are usually offset parabolic reflectors), with the trajectory that each feedhorns' beam takes once it bounces off its reflector determining what area said beam will cover when it reaches Earth's surface (as is illustrated in Figure 2.1).

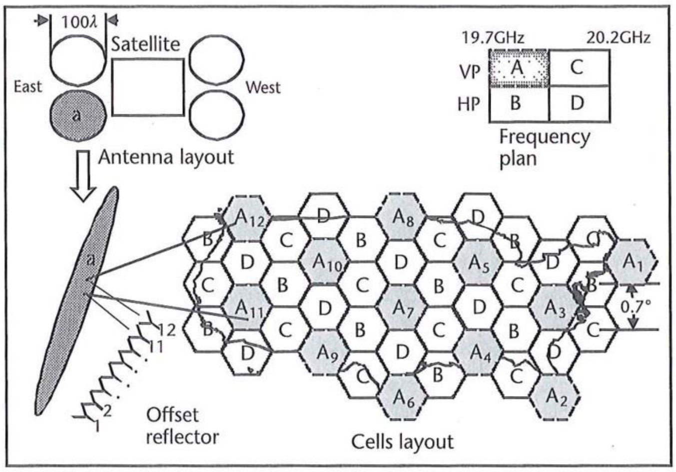


**Fig. 2.1** *Hexagonal beam layout for a four-cell FRS on a four-reflector multibeam antenna system* [3]

The importance of MBA-based systems lies within a concept known as *frequency reuse* [1]. Employing a different frequency for every spot beam would be impossible given that the amount of available bandwidth for any application is finite. Therefore, in some cases the only way to effectively increase said bandwidth is to split it up into sub-bands and use these smaller frequency sets to service multiple spot beams, which are geographically separated in order to avoid interferences. The amount of "gain" in the number of effective frequency channels (frequency reuse factor, or FRF) is essentially the relationship between the number of spot beams and the number of frequency sub-bands/channels (proportionate to each sub-band's bandwidth). Additionally, each frequency can be used in conjunction with one of two non-overlapping polarization modes (usually right-hand and left-hand circular polarizations) to double the effective available spectrum, although this implies making cross-polarization ("leakage" from one polarization into the other) a primary concern.

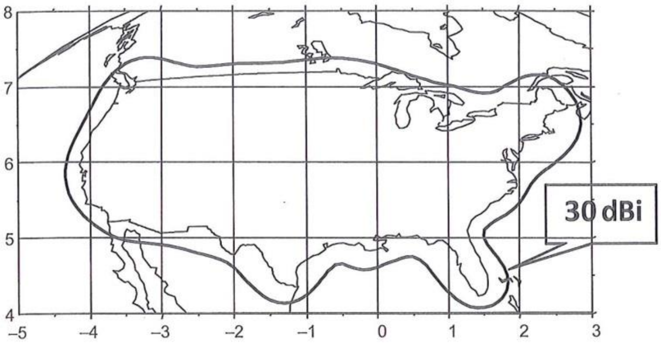


**Fig. 2.2** *CONUS coverage with a contour beam antenna design* [1]

This multi-spot strategy contrasts greatly with the more established contoured-beam coverage approach. Said approach involves employing an offset-reflector antenna whose reflective surface is shaped in a way that makes the single generated spot beam's contour fit an established on-the-ground coverage pattern, as is seen in Figure 2. When comparing both systems there are several evident advantages of using a multi-beam coverage over a contoured-beam one (aside from the aforementioned effective spectral bandwidth improvement), including [1]:

- An increase in typical minimum coverage area directivity (gain before antenna losses); the smaller the spot size (and the larger the number of spots), the higher the directivity (but the more complex the system becomes). More directivity on the satellite's end means less ground antenna gain is needed, and therefore smaller-sized ground terminals can be deployed.
- Additionally, this leads to increased equivalent isotropic radiated power (EIRP) on the satellite-ground link and increased antenna gain-to-noise temperature (G/T) on the ground-satellite link.
- Increased flexibility for the satellite's operators, who can offer more secure links between users (as the spots guarantee that only the spots intervening in a particular communication receive the transmitted information) as well as the possibility of offering increased capacity/speeds to the satellite operator's users, or to be able to give service to a higher number of users with a similar per-user capacity.

As for the frequency reuse scheme of an MBA, or how "often" a frequency channel is spatially repeated, it is dependent on the application at hand as well as on the user density in the covered region [1]. The most optimal uniform solution to have non-interrupted coverage is to employ a "beehive" hexagonal grid system, not unlike the one employed in GSM architectures, where the circular coverage spots are approximated with hexagons to ensure both minimum overlap and the absence of coverage "dead-zones".

This layout can be achieved in a number of different fashions, with the most common number of cells in an N-cell reuse scheme (different frequency channels) being three, four and seven. Given that for certain applications which require larger capacities this may not be enough, spectral reuse can be mixed with employing various feedhorn sets and apertures [1] to increase the number of generated beams. An example of this is illustrated in Figure 3, where a seven-cell reuse scheme (frequency cells are denoted with Arabic numbers) is used in combination with four apertures (each one represented by a Roman numeral). Usually these apertures are implemented as reflectors, with the number of reflectors aboard a spacecraft being heavily reliant on the maximum weight of said satellite, the amount of available stowage space, etc.

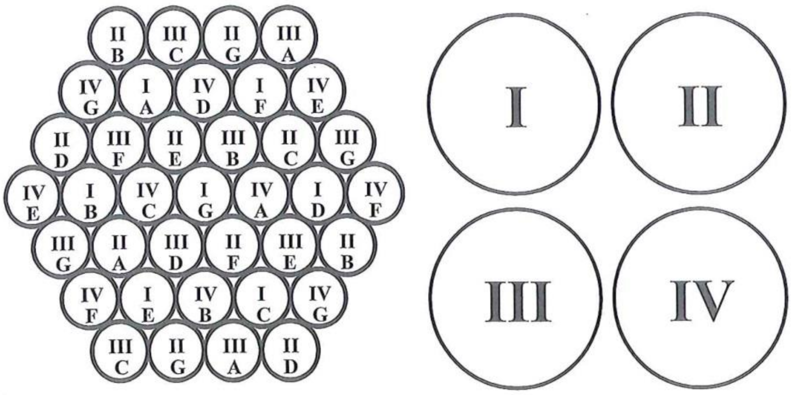


**Fig. 2.3** *7-cell FRS using four apertures* [1]

As widespread as uniform cell reuse is, some applications require non-uniform or hybrid uniform/non-uniform cell reuse schemes. Direct broadcast satellite (DBS) systems are an example of the former; they provide downlink beams for local television station broadcast, where each designated market area (DMA) has a different extension and size. This means that smaller, higher gain beams are typically used over more densely populated areas and wider, lower gain beams are used to service more scarcely inhabited regions [1]. To be able to attain the desired coverage beam shapes and sizes, it is necessary to use various reflectors, each one fed by multiple feedhorns of different size and with different spacing.

An example of a hybrid system would be that of a personal communication satellite (PCS) service, in which a uniform hexagonal-grid beam layout is employed to cover the target region but each beam employs a varying number of frequency channels within it depending on the required capacity: more tight-packed (three or four) cell reuse for more densely populated areas, and higher (seven or more) cell reuse for less populated areas [1]. This type of system is advantageous because, being designed based on population compactness, it doesn’t “waste” bandwidth in areas that have little-to-no user base.

## Multibeam and Multiband Antennas

Aside from being able to support multiple beams, systems aboard satellites employed for bi-directional communication (like the one studied in Chapter 4 of this work), that is, for both Rx (uplink) and Tx (downlink) links, need to be able to function at two or more separate frequency bands: they need to be multiband as well as multibeam.

Traditionally, several conventional reflector antenna designs have been used to support dual-band transmission with a single reflector [2]. Two of these designs are shown in Figure 4. The first one uses a frequency selective surface (FSS) as a subreflector to separate both frequency bands: the high band is sent from a feed at the base of the reflector, bounces off the subreflector and again off of the main reflector, while the low band is sent from a feed opposite the main reflector, passes through the FSS and bounces off the main reflector. A long coaxial line is needed to transport the low band signal from the rear of the main reflector to its appropriate feedhorn, as to be able to minimize the losses produced by the FSS, both bands need to be sufficiently separated spectrally. Both these factors prove to be huge disadvantages when used for space applications.

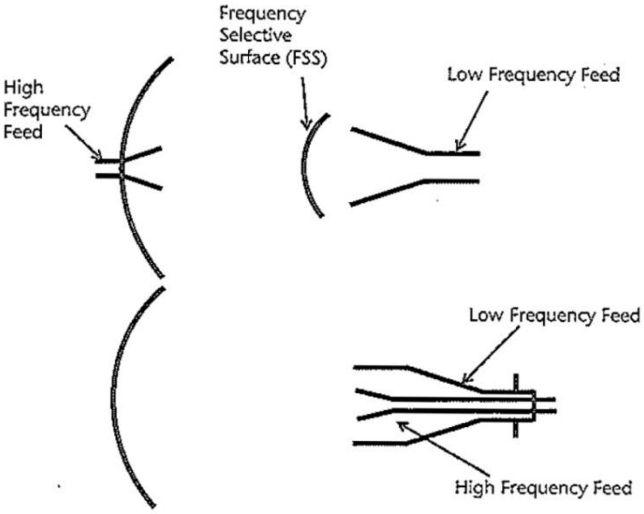


**Fig. 2.4** *Conventional methods of generating dual-frequency bands using a common reflector antenna* [2]

The other method, better than the previous one, employs only one reflective surface with a dual-band feed placed at the opposite side; the high band employs a central waveguide, but the low band uses a coaxial structure. This last structure is extremely sensitive to leakage from the high band's signals, which if not properly isolated (I.E., using absorbent materials) can penetrate the outer coaxial structure and cause coaxial mode propagation [2]. For this method to work properly, it is necessary for both bands to be sufficiently separated along the frequency spectrum; in the case of the feedhorns studied in Chapter 4 (which operate at K/Ka band), the spacing between the Tx and Rx bands is not enough to be able to use such a system.

In recent times however, a series of advances regarding multiple-band reflector antenna design have been made leading to several different types of antennas, including stepped-reflector antennas, multiband antennas supporting several frequency bands, dual-band antennas with single feeds and dual-band antennas with multiple feeds. What follows is a more detailed description of this last variety.

### Dual-Band Reflector Antenna with Multiple Feeds

These types of systems have been primarily employed on satellites servicing personal communication networks, that is, providing telecom links between users located in a certain area by utilizing multiple overlapping beams [2]. This is achieved via a two-way link system that utilizes both the spaceborne satellite and on-the-ground transmission stations, or ground hubs, to form forward and return links. The former provide the connection from a gateway to a terminal, while the latter are used for the opposite connection. Each spot beam is generated by a single feedhorn, and directed towards the Earth's surface using a four-reflector configuration.

Said configuration is the evolution of an eight-reflector arrangement, in which four reflectors are used for downlink and another four for uplink. Obviously, this implies a significant increase in the space needed to house these reflectors on a spacecraft and limits their maximum size due to weight restrictions. However, when compared to a single-reflector scheme, the four-reflector design allows incrementing the feed aperture size by a factor of two, greatly improving the antenna's spillover efficiency [3].

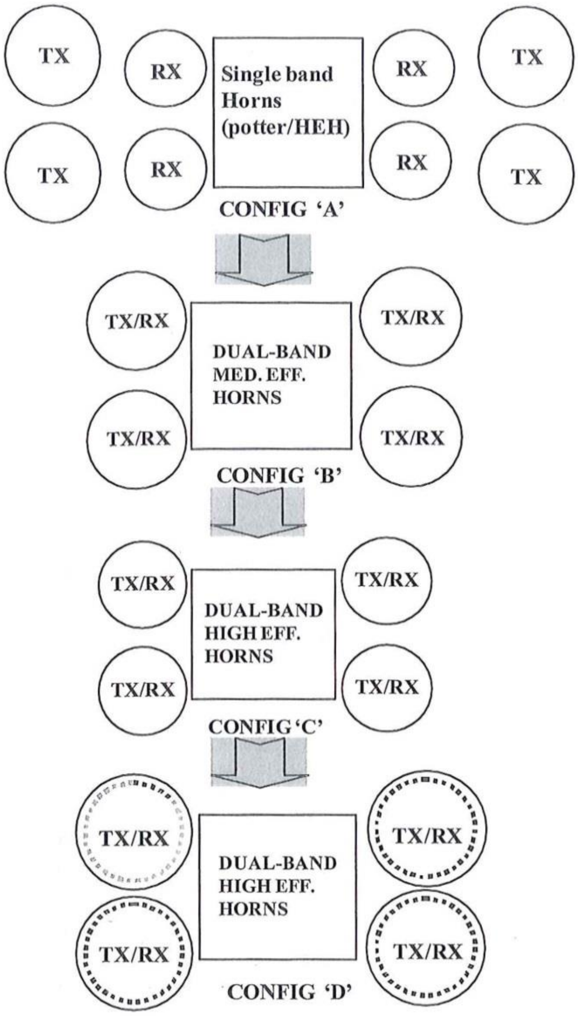


**Fig. 2.5** *Evolution of reflector MBA technology* [1]

The multiband four-reflector layout (with each reflector being able to serve both Tx and Rx links) solved this issue, but came at the cost of having to employ heavy, low-efficiency corrugated horns to feed the reflectors. In time this was solved by employing more modern smooth-walled high-efficiency horns (like the ones discussed in the following chapters), which weigh considerably less [1]. The evolution of these different models can be seen in Figure 2.5.

## References

[1] S. Rao and C. B. Ravipati, “Chapter 2. Reflector Antennas for Space Communications,” in *Handbook of Reflector Antennas and Feed Systems. Volume III.Applications of Reflectors*, 1st ed., S. Rao, S. K. Sharma, and L. Shafai, Eds. Artech House, 2013.

[2] S. Rao, “Chapter 5. Multiband Reflector Antennas,” in *Handbook of Reflector Antennas and Feed Systems. Volume III.Applications of Reflectors*, S. Rao, S. K. Sharma, and L. Shafai, Eds. Artech House, 2013.

[3] A. K. Bhattacharyya and G. Goyette, “Chapter 4. Smooth Wall Multimode Horns for High Aperture Efficiency. Theory, Design and Applications,” in *Handbook of Reflector Antennas and Feed Systems. Volume II. Feed Systems*, 1st ed., S. Rao, S. K. Sharma, and L. Shafai, Eds. Artech House, 2013.

# Chapter 3

## Spline-Profiled Horn Antennas

## Original Design and Initial Manufacturing Trials

Spline-profile feedhorns are becoming increasingly crucial in a wide variety of applications. Although their design is more time-consuming than that of the now-standard corrugated-profile horn, they are proving to be advantageous in conditions where weight and/or production costs are critical [1], like space satellites or systems that operate at high frequencies (which require smaller, harder to manufacture horns) respectively. Additionally, smooth-walled spline feedhorns are fit for use in arrays where, because of the limited space available, aperture diameters need to be as small as possible while offering as high an aperture efficiency as possible (and, for the same directivity radiation pattern, corrugated horns' diameters are often not small enough when compared to those of their smooth-walled equivalents).

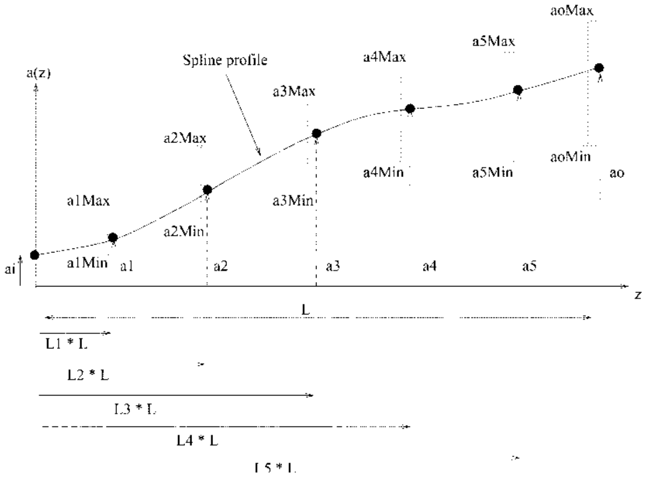


**Fig. 3.1** *Spline-profile horn geometry* [2]

The first venture into engineering a spline horn occurred when trying to create a corrugated antenna to operate across the 80 – 116 GHz frequency band [2]: the wavelengths associated to these frequencies are increasingly smaller, as would be the size of the corresponding corrugated horn that functions in that range. This undoubtedly implied a significant increase in the complexity of manufacturing such an antenna, and because of this, the possibility of using an alternative smooth-walled profile was considered, and eventually employed.

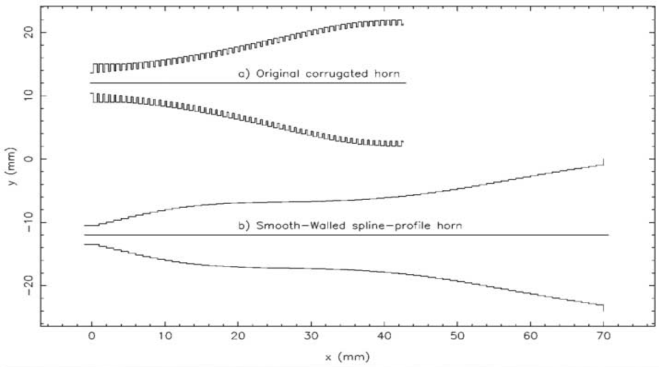


**Fig. 3.2** *Geometry of the original corrugated horn and the spline-profiled alternative* [2]

Several corrugated antennas were successfully produced via a method known as electroforming, which is very costly due in part to the small size of the corrugations and the effort it takes to make them sufficiently rigid [2]. Thusly, a new approach was envisioned: fitting a continuous spline curve onto seven points (one point at each end and five along the antenna) that delimit six separate sections (as seen in Figure 3.1). The length and radius of these sections is adjusted employing a program that computes the far-field radiation patterns of the antenna using the mode-matching technique. This procedure equates each section of the horn to a scatter matrix, and then cascades them all to yield accurate numerical results (as long as enough waveguide EM-modes are taken into consideration).

These results are then compared to the desired radiation patterns, which are specified as a series of weighted limits for both the co-polarized and cross-polarized components of each frequency. The difference between these results yields a certain amount of error, being the program's job to adjust each radius within a user-defined margin until said error is reduced as much as it can be [2]. These margins are set in place so that the result of the optimization is one that can be incorporated into the system at hand and is physically possible to assemble.

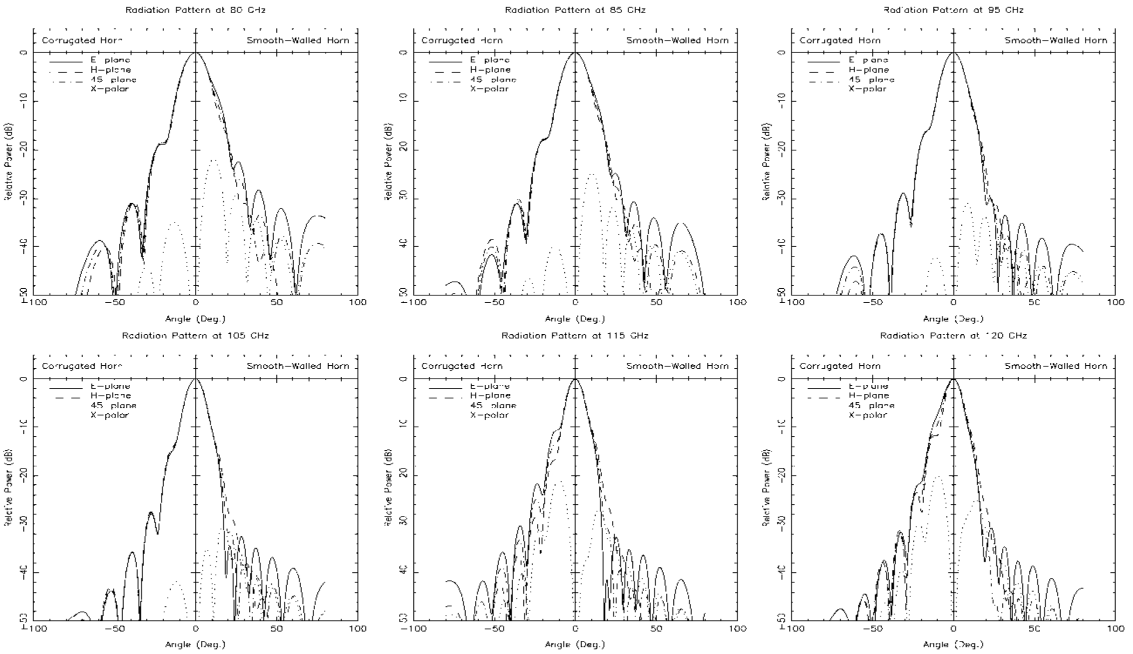


**Fig. 3.3** *Corrugated/Spline radiation pattern comparison* [2]

When comparing the theoretical outcomes of both the corrugated horn and its spline counterpart (profiles in Figure 3.2, graphs in Figure 3.3), it was verified that the new smooth-walled model offered results that were comparable to, but not better than, those of the corrugated design [2]. The most significant difference between the two designs is the fact that the spline horn has noticeably higher levels of cross-polarization (noticeable in Figure 3.3); whether or not this poses a real problem is dependent on the system for which the horns are being used. Feedhorns employed for multiple-beam antennas require low crosspolar levels, but not as low as those designed for contoured-beam antennas, since the latter use a shaped reflector that significantly increases the crosspolar level.

## Updated Model with Improved Cross-Polarization Response

A more recent foray into the design of spline horns [3] set out to improve on the original design, seeking to obtain a smooth-walled horn with better cross-polarization and bandwidth values (comparable to those of conventional corrugated feedhorns). As with the previous design, the antenna was modeled using a profile made up of discrete waveguide sections, each one with a constant radius. It was determined empirically that a section length of one twentieth the size of the cutoff wavelength of the input guide or lesser was a sufficiently adequate finite approximation of the continuous profile (which has an infinite number of sections).

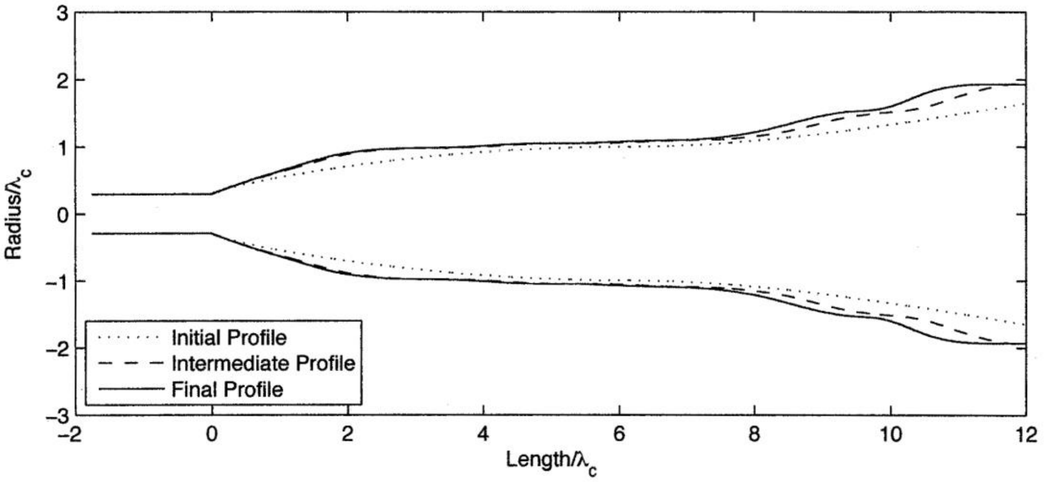


**Fig. 3.4** *Initial, intermediate and final profiles* [3]

The angular response at the aperture of the spline antenna was calculated by matching the border conditions of each successive section, starting at the throat of the horn (fed with a circular waveguide $TE_{11}$ mode) and moving forward. Because the feedhorn is cylindrically symmetrical, it is only possible for modes with the same azimuthal structure as the fundamental mode $TE_{11}$ ($TE_{1n}$, $TM_{1n}$) to be active, therefore the full beam patterns can be obtained by adding the effect of these modes to the basic patterns of the *E* and *H* planes [3].

As for the optimization of the antenna itself, it was done employing a modification of Powell's method, taking the necessary precautions to avoid potential corrugation-like spline curves by ensuring that the radius of each section was never smaller than that of the previous one. Said optimization was carried out in two separate phases: an initial phase, using a 20-point approximation and setting the cross-polarization and return loss thresholds to be better than 30 dB, and a second phase, employing 560 points and thresholds of 34 dB or better. It was found that the first approach never reached the optimal solution, settling instead on a less exact profile. However, it did serve as a good starting point on which to begin executing the second approach, significantly reducing the computation time and resource consumption that running the 560-point optimization from the start would have implied [3]. The different profiles can be seen in Figure 3.4.

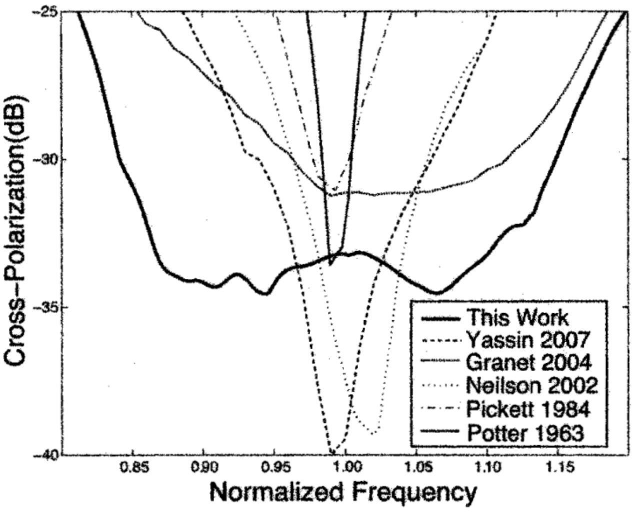


**Fig. 3.5** *Maximum cross-polar response of the prototype feedhorn compared to other implementations of smooth-walled horns* [3]

Given that the final profile was reproduced with a virtually insignificant amount of error, it was surmised that it would be possible to obtain a more efficient solution using less than 20 points along the horn if the length of each section was independently variable. At any rate, aside from having a lower cross-polarization response (at least 30 dB below maximum gain across the 33-45 GHz frequency band) the resulting spline horns presented an operating bandwidth of 30%, as opposed to the 15-20% bandwidths obtained with the original design [3]. A graph comparing this design to several others can be seen in Figure 3.5.

## References

[1] T. S. Bird and C. Granet, “Chapter 5. Profiled Horns and Feeds,” in *Handbook of Reflector Antennas and Feed Systems. Volume II. Feed Systems*, 1st ed., S. Rao, S. K. Sharma, and L. Shafai, Eds. Artech House, 2013.

[2] C. Granet, R. Bolton, and G. Moorey, “A smooth-walled spline-profile horn as an alternative to the corrugated horn for wide band millimeter-wave applications,” *IEEE Trans. Antennas Propag.*, vol. 52, no. 3, pp. 848–854, 2004.

[3] L. Zeng, C. L. Bennett, D. T. Chuss, and E. J. Wollack, “A low cross-polarization smooth-walled horn with improved bandwidth,” *IEEE Trans. Antennas Propag.*, vol. 58, no. 4, pp. 1383–1387, 2010.

# Chapter 4

## Optimization of High Efficiency Spline Antennas for Use as Multibeam Feedhorns

## Initial Design Requirements and Considerations

A project was contracted with the end goal of designing the profiles for five separate spline-curve based multiband antenna horns, which were to be used as feeds in a multibeam reflector system onboard a communications satellite.

At the start of said project, several global prerequisites were given for the feedhorns' performances:

- **Return Loss** of 30 dB or better.
- **Cross-Polarization** levels at least 26 dB below maximum gain.
- **Maximum Antenna Length** of 200 mm.

As was mentioned in the previous chapter, smooth-walled spline antennas intrinsically have comparatively "bad" cross-polar response levels (especially when paired up against corrugated horns [1]), and with such a relatively short antenna length it is even harder for this already tough requirement to be met.

Because each antenna was meant for a different use and operated over a different set of frequency bands, every design had its own particular requirements, the most important of which are detailed in the following table:

| Antenna | Diameter (mm) | Tx Bands (GHz) | Rx Bands (GHz) | Units |
|---|---|---|---|---|
| **TUB-1** | 70 | 19.70 – 20.20 | 29.50 – 30.00 | 8 |
| **TUB-2** | 53 | 18.25 – 18.525 | 28.30 – 28.50<br>29.25 – 29.50 | 2 |
| **TUB-3** | 90 | 19.70 – 20.20 | 29.50 – 30.00 | 14 |
| **TGW-1** | 70 | 17.70 – 20.20 | 27.40 – 30.00 | 7 |
| **TGW-2** | 58 | 17.70 – 20.20 | 27.40 – 30.00 | 3 |

As can be surmised from this table, there are two distinct types of feedhorns. The first three ("user beam" types) could be considered narrowband and are meant to service what are known as user spots, that is, connections with individual users present in the coverage area, usually established using standard terminal equipment for every user [2]. The last two horn designs (“gateway” types) present wider band usage and are employed for both user spots and gateway connections, the latter of which are utilized to link terrestrial gateway stations with their associated user terminals. Gateway stations are the bridge between these terminals and the Internet, and are placed at fixed locations which have been selected to minimize weather impact and overall cost [2]. They are also equipped with parabolic antennas and other equipment which is “customized” to fit the particular conditions of each gateway.

For the user beam antennas, the goal was set to achieve the best spillover efficiency at a 13º taper across the desired frequencies, while for the gateway horns a “sub-band prioritization” was established on the downlink (Tx) side. This was done in order to make sure that the frequency sub-bands intended for user spots were designed with the maximum possible spillover efficiency, specifically from 19.70 to 20.20 GHz for both gateway horns and 18.10 to 18.90 GHz for TGW-1.

Spillover efficiency refers to the relationship between the amount of power radiated by a feedhorn and how much of that power is reflected by its reflector: the higher this ratio is, the more efficient the reflection is, however a ratio of one (no radiation loss) is not possible because reflectors are not infinite in size. For a certain antenna, spillover efficiency can be increased by either augmenting the size of the reflector or by placing it closer to the horn (and therefore incrementing the angle seen from the horn’s point of view).

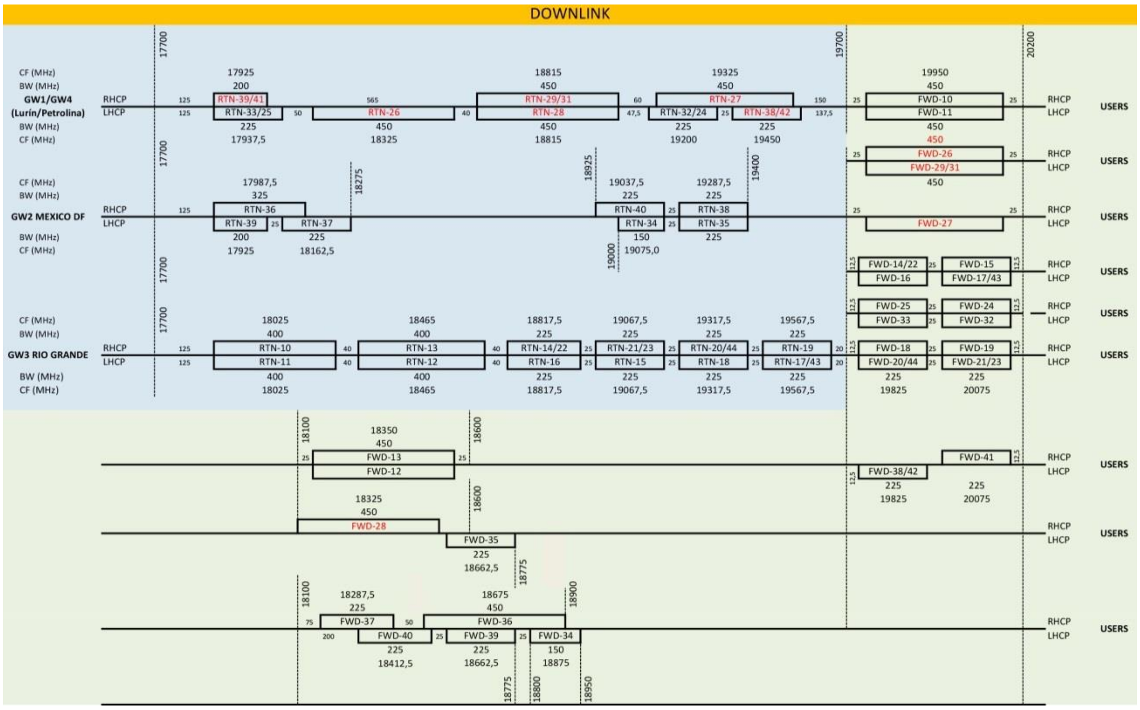


**Fig. 4.1** *Satellite system Downlink frequency allocation plan*

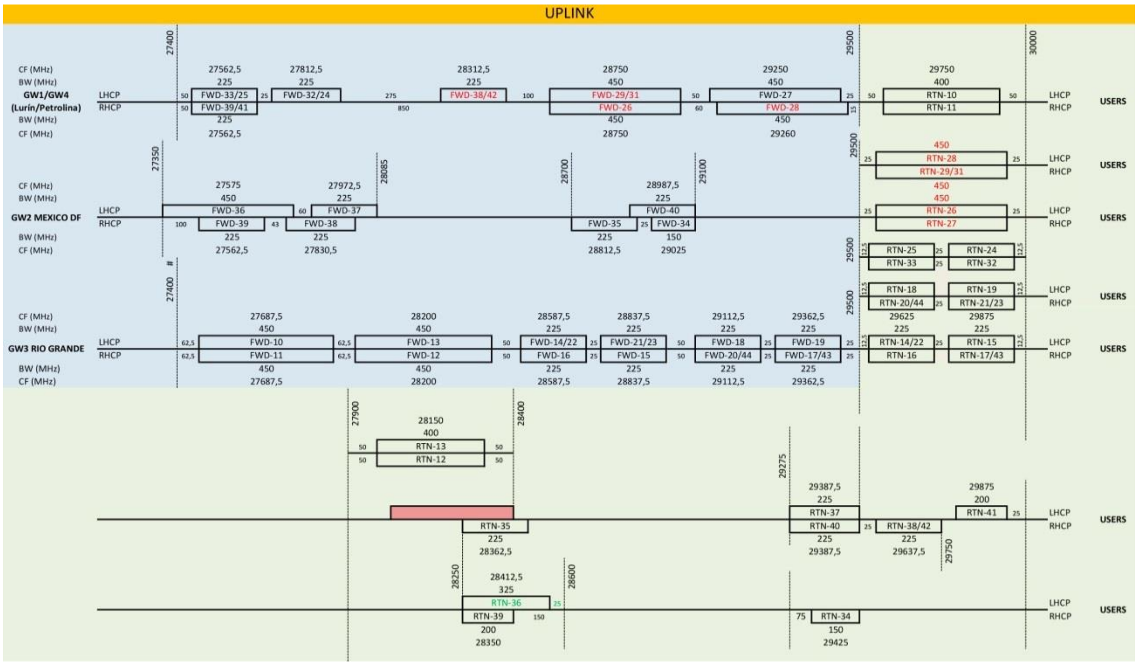


**Fig. 4.2** *Satellite system Uplink frequency allocation plan*

Figures 4.1 and 4.2 (showing the detailed frequency channel allocation plan for user beams as well as for gateway spots) clearly differentiate forward channels (gateway uplink and user downlink) from return channels (user uplink and gateway downlink) [2]. This can be seen in Figure 4.3, with the solid arrows representing the forward link and the dotted arrows portraying the return link. Note that two different polarizations are employed (Right and Left Hand Circular) along with a hexagonal spatial-reuse scheme for user spots (as is explained in Chapter 2 of this paper), multiplying the number of effective channels over a limited set of frequency bands.

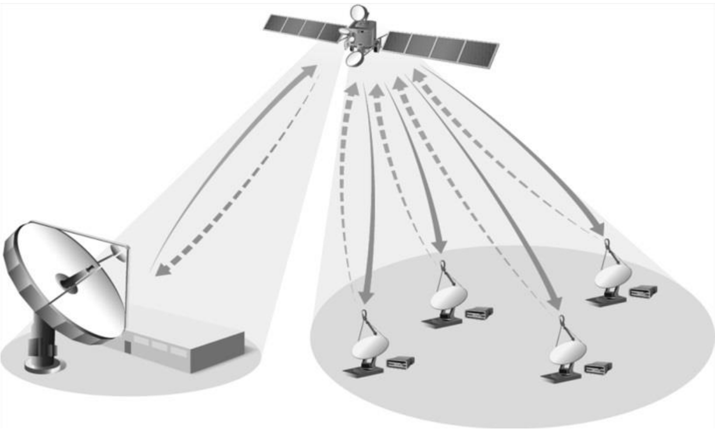


**Fig. 4.3** *Forward and return links in a PCS system* [2]

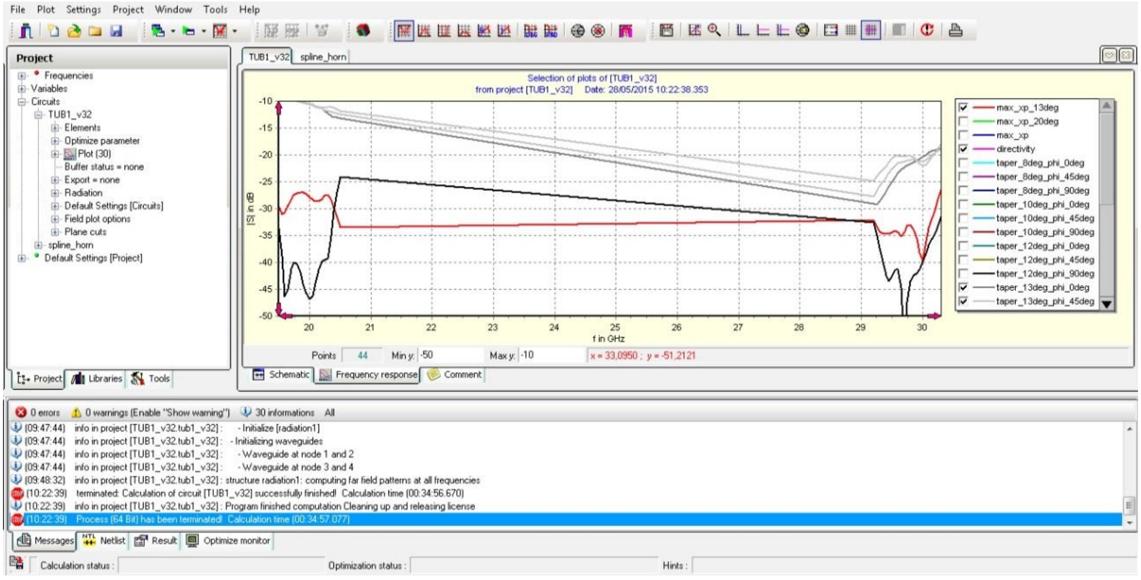
It is worth noting that these frequency requirements did not take temperature excursion into account; because of the high temperature contrast that a spaceborne satellite experiences, important differences can be observed in the antennas' frequency performance [3]. To counteract this effect, 500 MHz bands were "added" at both the start and end of each band, complicating the optimization but at the same time ensuring optimal operation under extreme conditions.

Early endeavors at designing the feedhorns were fairly successful, however when any alteration was made to the optimization (like modifying the number of radiuses along the length of the horn, for example) a new “version” of the antenna was created in order to keep track of the changes that were beneficial to the reduction of the error function, as well as to have a record of modifications or approaches that didn’t work well. Obtaining feedback about each of these successive versions was crucial because, as it turned out, meeting these requirements at the pertinent frequency bands alone wasn’t enough for some of the antenna designs.

The larger the number of incrementally improved versions that were sent for testing with the satellite’s reflectors (whose design was purposefully left undisclosed), the more it was evident that spillover efficiency was extremely important to the antennas’ operation in combination with the reflectors. Once this was learnt, the adjustments made to the antennas during the optimization process were able to be much more precise.

## Optimization Process and Finalized Designs

After several months of optimizing the different antenna profiles, including the process of requesting, obtaining and applying feedback, designs for all five of the requested feedhorns were more or less finalized, with results comparable to the values requested. Figure 4.4 shows a screenshot of the program employed for optimization and simulation.



```
0 errors   0 warnings (Enable "Show warning")   30 informations   All
(09:47:44)  info in project [TUB1_v32.tub1_v32] :     - Initialize [radiation1]
(09:47:44)  info in project [TUB1_v32.tub1_v32] :   - Initializing waveguides
(09:47:44)  info in project [TUB1_v32.tub1_v32] :     - Waveguide at node 1 and 2
(09:47:44)  info in project [TUB1_v32.tub1_v32] :     - Waveguide at node 3 and 4
(09:48:32)  info in project [TUB1_v32.tub1_v32] : structure radiation1: computing far field patterns at all frequencies
(10:22:39)  terminated: Calculation of circuit [TUB1_v32] successfully finished!  Calculation time (00:34:56.670)
(10:22:39)  info in project [TUB1_v32.tub1_v32] : Program finished computation Cleaning up and releasing license
(10:22:39)  Process (64 Bit) has been terminated!  Calculation time (00:34:57.077)
```

**Fig. 4.4** *MICIAN* Microwave Wizard *main screen*

As has been stated before, these five designs are not the final ones. This is due to the fact that after most of the designs were approaching completion, the contracting company discovered that they needed to change the requirements for the designs: lower Return Loss levels across both bands (40 dB instead of the initial 30 dB) as well as lower crosspolar levels on the Rx side (around -35 dB as opposed to -26 dB). Because of this change, the project was behind schedule and thusly was not at the expected stage at the date of this work’s completion.

What follows is a list of each of the different antennas, including information detailing the process behind their design. Specifically, the antenna profile and six radiation patterns (at first, middle and last frequencies for both the Tx and the Rx bands) are shown for every feedhorn.

## TUB-1

### Final Design Profile and Measurements

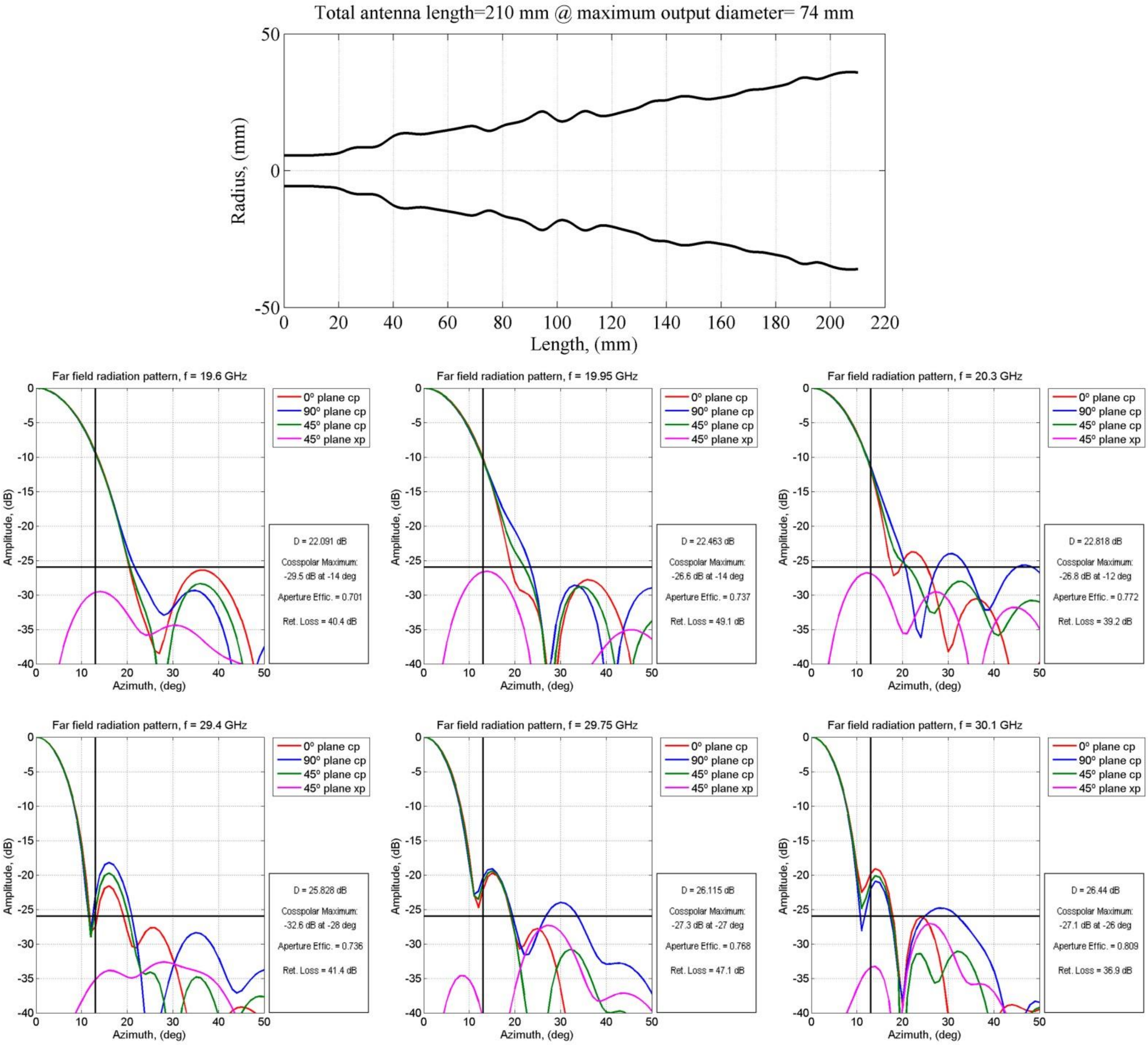


**Fig. 4.5** *TUB-1 feedhorn v34 results*

## Optimization Process

The horn that was first optimized was based on a preliminary model that had been generated during a study to determine if the projected demands were feasible ones or not. The optimization started out employing a uniform 20-point distribution along the length of the antenna horn (one point every 10mm), with a 0.25mm discrete step length. After a few different versions were obtained, the internal diameter was incremented from 70 to 72mm in order to allow for greater directivity (and reduced spillover loss).

To be able to be more precise, at one point the number of spline sections was doubled to 40, which yielded one problem: while the frequency results were better, the obtained profiles were either very difficult or impossible to machine [3]. This issue was solved when a new way to employ a larger number of sections was discovered within the optimization program, allowing for smoother transitions that eliminated the machining issue.

Once this problem was dealt with, several more different versions were sent for testing, with the objective of trying to maintain crosspolar and return loss levels below the established thresholds while maximizing both spillover and aperture efficiencies.

### TUB-2

Final Design Profile and Measurements

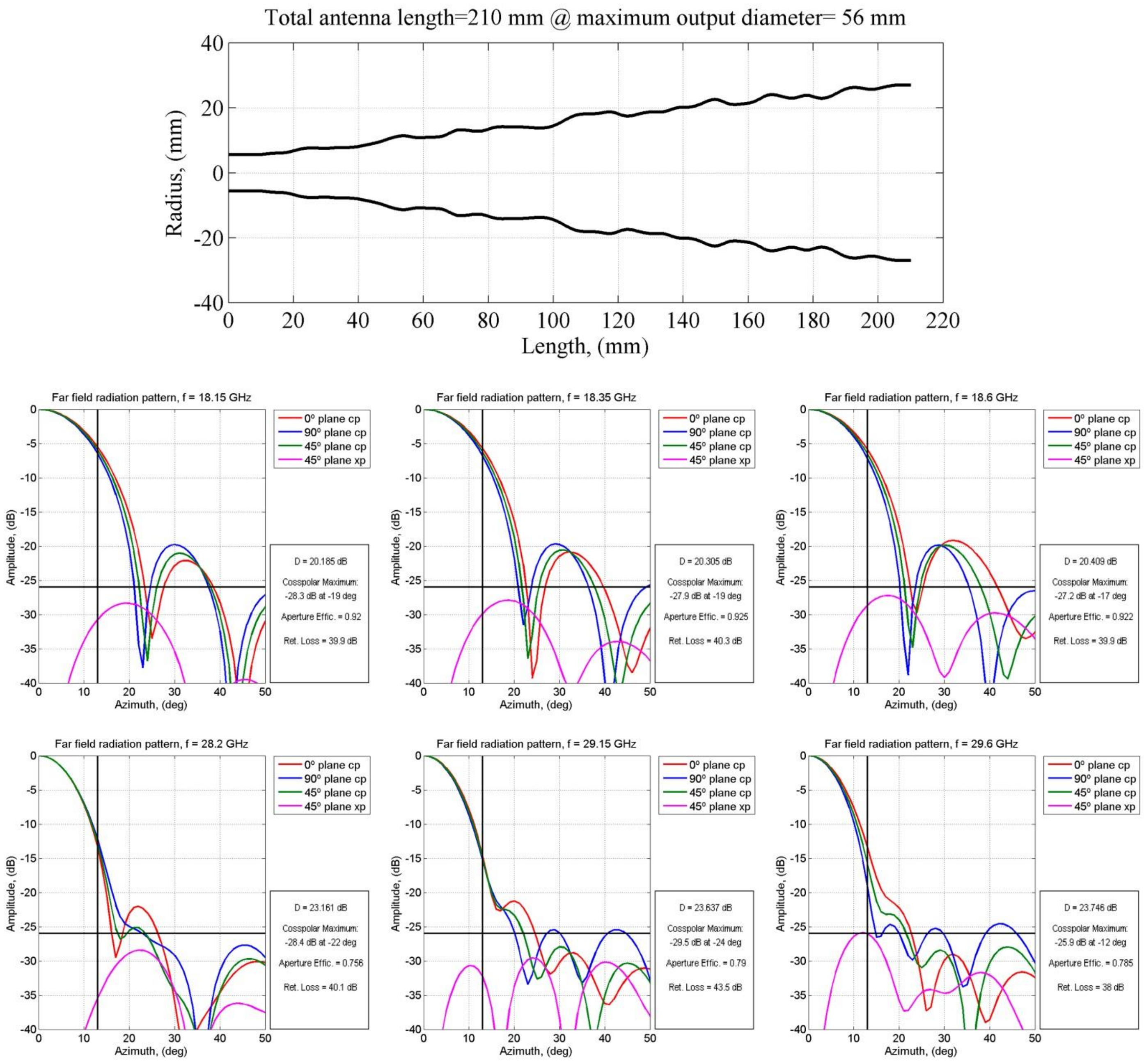


**Fig. 4.6** *TUB-2 feedhorn v17 results*

### Optimization Process

Unlike the first antenna, the process was started employing a “flat” conic horn with a 0.2 mm step length and a 50 mm internal output diameter, as well as 20 uniformly distributed points to form the optimized spine curve.

Due to the results of the first few versions being sub-par and knowing that they were unlikely to improve without significant changes, a brand new conic horn was created, with 3 mm more internal output diameter and double the spline points (40). Not long after, a third conic horn was generated to be optimized, this time with the same specifications as the second one but utilizing 60 points, to be able to compare them and see if the difference the additional 20 points made was worth the extra computing time.

Eventually the internal output diameter was allowed to increase to 54 mm and the discrete steps were lengthened by 0.05 mm in order to speed up optimization.

## TUB-3

### Final Design Profile and Measurements

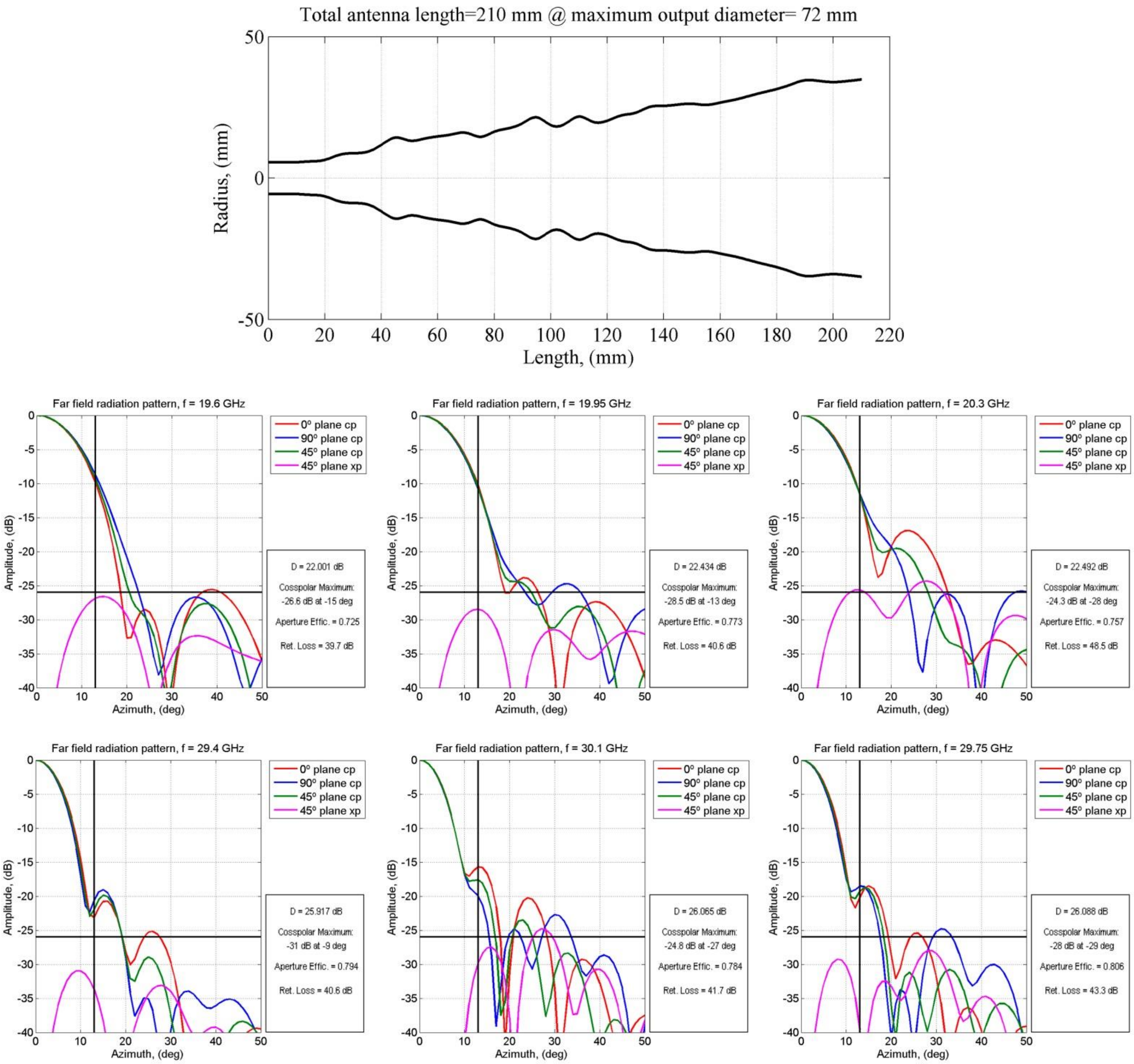


**Fig. 4.7** *TUB-3 feedhorn v12 results*

### Optimization Process

Similarly to the previous antenna, this feedhorn was initialized using a conic profile with a 90 mm interior output diameter, 20 spline points and 0.25 mm step size. After changing the number of radiuses to 40 and the step size to 0.2 mm and continuing the optimization process, it was discovered that some sections close to the antenna's output were exceeding the maximum output radius by a substantial margin, and thus to be able to manufacture [3] had to be manually limited before letting the optimizer resume its course.

The issue with this particular feedhorn was that, despite having to be an "improved" version of the TUB-1 antenna (because they shared the same initial requirements with the exception of the aperture radius/diameter), it performed less efficiently than said antenna with regards to spillover efficiency. To remedy this issue, a new version of the TUB-3 horn was created based on a previous TUB-1 design, leaving its output radius (initially 72 mm) free to change along with the optimization (that is, making it smaller than the initially required 90 mm). The spillover results yielded by this approach were notably superior, and for several more versions the optimization parameters were modified to steer the process towards achieving greater directivity, especially in the Rx (higher) band.

## TGW-1

### Final Design Profile and Measurements

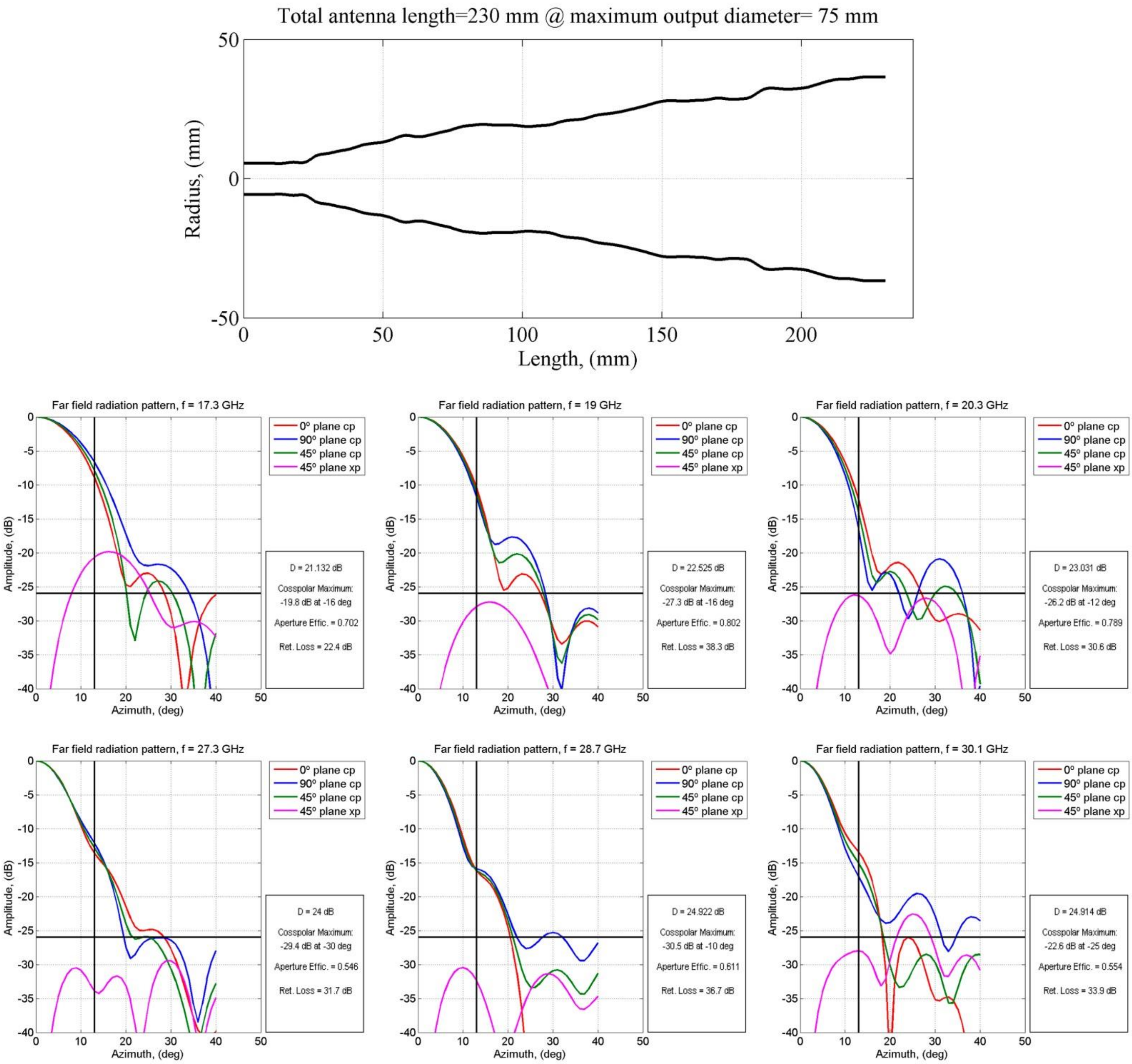


**Fig. 4.8** *TGW-1 feedhorn v23 results*

### Optimization Process

The design of both gateway horns (this one and the following one) was started later than that of the user beam horns, and therefore required fewer trials due to having already established the most important optimization criteria and therefore only needing comparatively minor adjustments. The optimization was initialized using a 40-point profile with 0.5 mm steps, with the main objective after several version trials and their respective feedback fixed as maximizing the spillover efficiency along the “priority” Tx sub-band (18.1 – 18.6 GHz).

## TGW-2

### Final Design Profile and Measurements

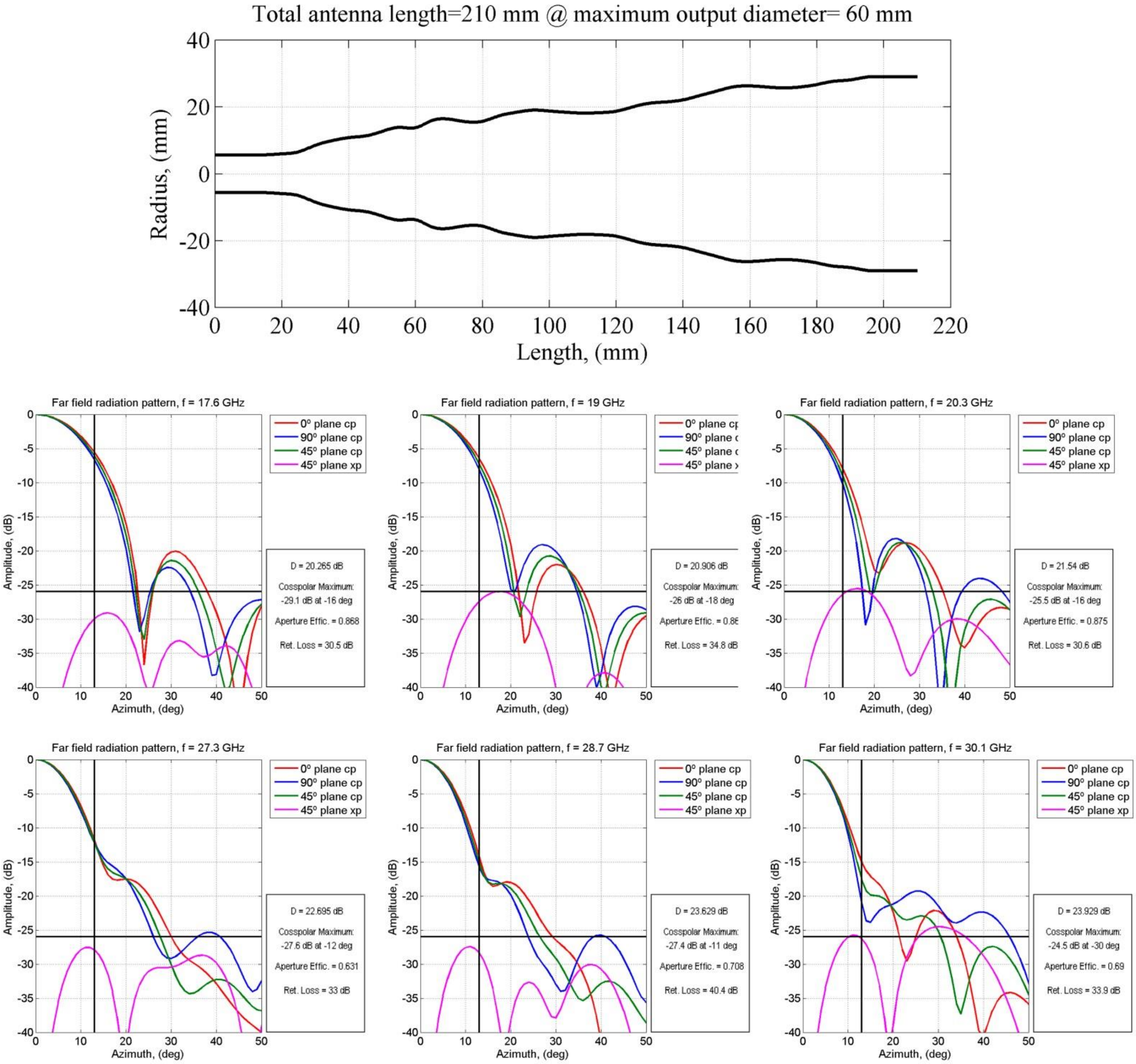


**Fig. 4.9** *TGW-2 feedhorn v11 results*

### Optimization Process

This antenna was probably the most problematic out of all five designs. During the optimization (started with a 40-point spline and 0.25 mm steps), it was observed that unusual peaks were appearing at certain frequencies and that they were caused by internal resonances. Occurrences like this one can be avoided by augmenting the number of frequencies that the optimizing software takes into account, to try and flatten the resonant peak that otherwise might remain “hidden” because it lies between two frequency points and isn’t being considered by the software. After this was done, several more versions were more successfully sent for testing.

## References

[1] C. Granet, R. Bolton, and G. Moorey, “A smooth-walled spline-profile horn as an alternative to the corrugated horn for wide band millimeter-wave applications,” *IEEE Trans. Antennas Propag.*, vol. 52, no. 3, pp. 848–854, 2004.

[2] J. Petranovich, “Mitigating the Effect of Weather on Ka-band High-Capacity Satellites,” pp. 1–15, 2012.

[3] C. Granet, G. L. James, and a R. Forsyth, “Chapter 3. Aperture Antennas : Waveguides and Horns,” in *Modern Antenna Handbook*, 1st ed., C. A. Balanis, Ed. Wiley, 2008, pp. 142–144.

# Chapter 5

## Conclusions and Future Developments

## Conslusions

Over the course of the last four months, the focus of this final degree report has been to work on the optimization of five feedhorn antenna models whose finalized versions will be operating as part of the communication system of telecom satellite *Amazonas 5*. It is safe to say that the project's requisites were met and in some cases exceeded.

Although the results presented in Chapter 4 are not final, they are very much representative of what can be achieved; the main difference between these results and the final ones will lie within minor adjustments made to the spillover efficiency.

## Future Developments

As was mentioned in Chapter 3, one approach that hasn't been employed in this work, and which could indeed yield improved results, would be to optimize a spline feedhorn using points whose location is not fixed along the length of the horn. It has been said [1] that having these locations be optimizable variables could provide significantly different results, possibly even reducing computing time. This line of investigation is one worth exploring, given that if combined with the use of upwards of forty spline points it could represent the next "leap" in horn antenna design.

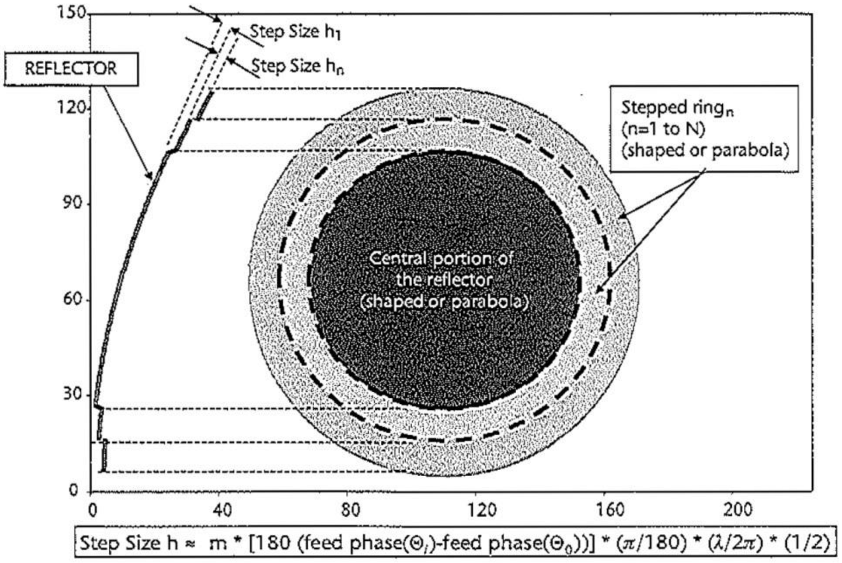


**Fig. 5.1** *Stepped-reflector antenna concept for multiple bands* [3]

As for future developments in the field of multiband antenna (MBA) apertures, it seems like they will be headed in the direction of employing stepped-reflectors (a typical stepped-reflector is shown in Figure 5.1) in conjunction with high-efficiency smooth-walled feedhorns. The next "evolutionary step" in reflector technology (Configuration D in Figure 2.5), stepped-reflectors combined with advances in spline-profiled horns will bring about significant performance increases for future MBAs employed in PCSs (personal communication satellites) [2].

Typically, one such multiband stepped-reflector antenna (SRA) presents markedly different beamwidths at each frequency band. This presents a problem, given that in a dual-band setup both bands need to cover the same area on the ground, and thusly need beamwidths that are as similar to each other as possible [3]. By employing a step of height *h* near the outer edge of the reflector, a 180º phase reversal between both resulting regions can be obtained, which makes for a broadened “flat top” type beam at the higher-frequency band. In order for this not to affect the lower band, several measures are to be taken. First, an optimal size of *h* with regard to both the high and low bands must be employed, usually a quarter wavelength at the high band. Since this implies a smaller fraction of a wavelength at the lower band, the system’s feedhorn must be designed with a nonuniform phase distribution. Such a model provides a reduction of satellite pointing errors, as well as an additional dB of edge of coverage gain and a 3 dB improvement in copolar isolation.

These hopeful prospects, along with the ever-increasing speed and power of computer processors, are sure to bring about important improvements to the design, optimization and manufacture of multiple-beam antenna systems in the not-too-distant future. Although it isn’t likely that spline-profiled smooth-walled feedhorns will ever replace their corrugated counterparts, it is safe to say that, despite being far more complex, spline horns will one day be as important and widespread as corrugated horns are nowadays, if not moreso.

## References

[1] L. Zeng, C. L. Bennett, D. T. Chuss, and E. J. Wollack, “A low cross-polarization smooth-walled horn with improved bandwidth,” *IEEE Trans. Antennas Propag.*, vol. 58, no. 4, pp. 1383–1387, 2010.

[2] S. Rao and C. B. Ravipati, “Chapter 2. Reflector Antennas for Space Communications,” in *Handbook of Reflector Antennas and Feed Systems. Volume III.Applications of Reflectors*, 1st ed., S. Rao, S. K. Sharma, and L. Shafai, Eds. Artech House, 2013.

[3] S. Rao, “Chapter 5. Multiband Reflector Antennas,” in *Handbook of Reflector Antennas and Feed Systems. Volume III.Applications of Reflectors*, S. Rao, S. K. Sharma, and L. Shafai, Eds. Artech House, 2013.