Optimizing Feed Horn Antenna Design using Particle Swarm Optimization

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In an effort to exceed the performance of the W2IMU horn – a standard in feed horn design – I conducted an optimization study using computer simulation. By employing the Particle Swarm Optimization (PSO) algorithm, I have identified designs that demonstrate the potential to surpass the performance of the conventional W2IMU horn.

Introduction

For prime-focus parabolic antennas with an F/D ratio of 0.5 or higher, the W2IMU horn is widely used as the feed antenna. Its popularity stems from several key advantages **[1]** :

- High illumination efficiency of the parabolic reflector.
- Low sidelobe levels.
- Established simple design methodologies with high reproducibility.
- Relative ease of fabrication.

The high illumination efficiency and low sidelobe characteristics are achieved by utilizing the TE_{11} and TM_{11} modes; antennas based on this design are known as dual-mode horns. However, the W2IMU horn's superiority is relative to simple horns, and there remains room for improvement.

One method for improvement is the use of higher-order modes beyond TE_{11} and TM_{11}, resulting in what is known as a multi-mode horn **[2]**. Design methodologies are generally categorized into two types: analytical derivation of multi-mode excitation **[3][4]**, and the use of optimal solution search algorithms **[5]**. This paper adopts the latter, attempting the optimized design of a multi-mode horn via a search algorithm.

Is it the "JA6XKQ Horn" ?

The results of the optimization trials are shown in **Figure-1** through **Figure-3**. **Figure-4** through **Figure-6** illustrate the characteristics of the W2IMU horn for comparison.

Comparing the radiation patterns in **Figure-2** and **Figure-6** reveals that the sidelobes of the "JA6XKQ Horn" (tentative name) are well suppressed. A further characteristic of the JA6XKQ Horn is the symmetry of the H/V polarization in the main lobe. This is the result of a search for an optimal solution focused on "main lobe H/V symmetry" and "pseudo-G/T characteristics" (**Figure-3** and **Figure-6**). Note that the G/T values shown in **Figure-3** and **Figure-6** are pseudo-values without units (dB/K); higher values indicate relatively superior G/T performance.

The external dimensions (normalized by wavelength) shown in **Figure-1** are as follows. Dimensions are defined per **Figure-7**.

R0 = 0.466	
R1 = 0.688	L1 = 0.680
R2 = 1.013	L2 = 0.235
R3 = 0.616	L3 = 0.603
R4 = 0.663	L4 = 0.231
R5 = 0.986	L5 = 0.503
R6 = 0.777	L6 = 0.196

Horn Geometry

Figure-1 and **Figure-4** show the external views rendered by Xnecview **[6]**. Excluding the coax-to-waveguide transition at the base, the JA6XKQ horn consists of 6 conical sections, whereas the W2IMU horn consists of 2 sections.

Looking at **Figure-1**, one might ask, "Is this actually feasible to fabricate?" At present, this work remains within the realm of computer simulation; fabrication and empirical performance verification have not yet been performed. This paper serves as a report on numerical experiments of multi-section multi-mode horns.

To understand the concept, consider the W2IMU horn (**Figure-4**). The transition at the base generates the TE_{11} mode. The subsequent tapered section (1st section) generates higher-order modes. The following cylindrical section (2nd section) adjusts the phase relationship between the TE_{11} and TM_{11} modes so that they are phased correctly at the aperture to cancel out sidelobes.

Since the taper generates more than just the TM_{11} mode (though excitation levels can be adjusted via the flare angle), a two-section design lacks sufficient degrees of freedom (design parameters). The 2-section W2IMU horn can be understood as the minimum necessary optimal shape to utilize dual-mode – the simplest form of multi-mode – operation. Expanding this logic, one naturally arrives at a multi-section design to control characteristics using multiple modes.

Optimization Methodology

While increasing design parameters provides more freedom, the challenge lies in determining the dimensions.

I was not previously familiar with simulations based on Modal Analysis **[3] [4]**. My primary tool is NEC2++, which allows for the analysis of nearly any antenna geometry. While NEC2++ cannot directly derive dimensions from desired characteristics, it can calculate characteristics for given dimensions. Therefore, the approach taken was an iterative process: provide dimensions to NEC2++, evaluate the results, determine a direction for improvement, and repeat until an optimal solution is reached.

Scientific methods for performing such searches include the Nelder-Mead Downhill Simplex Method, Genetic Algorithms (GA), and Particle Swarm Optimization (PSO) **[7]**. The Simplex method searches for local optima, while GA and PSO search for global optima.

My optimization journey progressed from Simplex to GA, and finally to PSO. The Simplex method's reliance on initial values felt like a contradiction for this project's goals. While GA seemed promising, its "mutations" - essentially random stabs in the dark – frequently led to invalid dimensions that broke the NEC2++ solver.

Beyond these technical hurdles, I found the GA's fundamental mechanism unappealing for this specific application. The process of cutting and splicing "genes" to create "offspring" felt too crude; the resulting horn shapes often appeared electromagnetically "clumsy" or "unsightly." This lack of functional beauty and engineering grace ultimately drove me to abandon GA in favor of the more fluid and coherent optimization offered by PSO.

Ultimately, I used PSO to find a global optimum and then used that result as the initial value for a Simplex search to fine-tune the local optimum.

The GA and PSO algorithms were implemented by porting the MATLAB code exemplified in Ref. **[7]** to GNU Octave. Similarly, the Simplex method was implemented by porting the PASCAL code shown in Ref. **[8]** to GNU Octave.

In implementing PSO, the algorithm parameters required fine-tuning to ensure fast and reliable convergence. Following the methodology in Ref. **[9]**, the parameters were set as follows:

- Cognitive factor: c1 = 2.0
- Social factor : c2 = 2.0
- Inertia factor : w = 1.0 to 0.0 (inversely proportional to the number of iterations)

PSO is an algorithm inspired by the collective behavior of swarms of birds or fish when foraging for food or escaping predators. The cognitive factor represents the weight assigned to the search toward an individual's own best position, while the social factor represents the weight toward the global best position of the entire swarm. The inertia factor can be interpreted as a weighting to prevent the particles from overshooting the target (the optimal position); for instance, when approaching food, they initially fly or swim with high momentum but must gradually decelerate as they get closer.

The PSO was executed with a population size of 80 particles and a maximum of 120 iterations.

NEC2++ Improvements

I modified NEC2++ to fix bugs related to surface patches, removed the upper limit on meshing segment counts, and integrated Intel MKL for BLAS/LAPACK support to enable high-speed simulation of large-scale models **[10]**. This allows a single simulation of a W2IMU-sized horn to complete in approximately 0.5 seconds

The Cost Function

In an automobile analogy, PSO and NEC2++ can be compared to the engine, suspension, and steering. However, to reach a destination by car, you also need a navigator and a driver. Where is the destination? In which direction is it? Are we getting closer or farther away? In optimization, the cost function serves as both the navigator and the driver.

The "destination" (objectives) for a feed antenna is to achieve:

1. High illumination efficiency for the parabolic reflector.
2. Symmetry in the H/V polarization characteristics of the main lobe.

3 Low side-lobe levels.
4 Low pickup of ground thermal noise from the reflector edges.

These multiple objectives must be satisfied simultaneously. In optimization, a metric called "cost" indicates how far we are from these objectives. The lower the cost, the closer we are to the goal.

While the third and fourth points are causally related, we evaluated "low side-lobe levels" during the cost function study to simplify the calculations.

To evaluate both the first point (high illumination efficiency) and the fourth point (low ground noise pickup), there is an index called "edge taper." This indicates how much the radiation pattern of the main lobe is reduced at the reflector edge. Generally, an edge taper of -12 dB is considered appropriate for balancing these two factors. Therefore, we set our objective for the radiation characteristic to be -12 dB at the angle where the feed horn subtends the reflector edge (hereafter referred to as the "taper angle"), defining the cost as the deviation from this target.

The definitions of "main lobe" and "side lobe" used above were based on the taper angle:

- Main lobe: Up to twice the taper angle.
- Side lobe: Greater than twice the taper angle.

The cost function was evaluated as the sum of the following three types of costs:

- Average value of the H/V polarization difference in the main lobe.
- Average value of the side-lobe levels.
- The deviation from -12 dB at the taper angle.

The results of the optimization using this cost function are shown in **Figure-8** through **Figure-10**. (Note: The results shown in **Figure-1** through **Figure-3** are from an improved cost function based on these findings.)

The external dimensions (normalized by wavelength) shown in **Figure-8** are as follows:

R0 = 0.466	
R1 = 0.636	L1 = 0.285
R2 = 0.696	L2 = 0.298
R3 = 0.873	L3 = 0.379
R4 = 0.969	L4 = 0.444
R5 = 0.472	L5 = 0.320
R6 = 0.963	L6 = 0.446

The performance was evaluated by summing the following three types of costs as the cost function:

- The average difference between H/V polarization in the main lobe.
- The average sidelobe level.
- The deviation from –12 dB at the taper angle.

Figure-8 through **Figure-10** show the results of the optimization attempted with this cost function. (Note: Figures 1 through 3 show the improved results after refining the cost function based on these initial findings.) An examination of the radiation pattern in Figure 9 reveals that the optimization was indeed performed according to the cost function, as evidenced by the following:

- The H/V polarization symmetry of the main lobe remains favorable up to the taper angle (49° at $F=0.55$).
- However, the symmetry becomes distorted between the taper angle and twice that angle.
- Sidelobes (backlobes) are suppressed to a low level.
- The –12 dB reduction at the taper angle is satisfactory.
- Although not explicitly included in the cost function, the main lobe roll-off is gradual, avoiding the steep drop-off characteristic of multi-mode operation.

In the above analysis, the second and fifth points are areas where multi-mode behavior is involved. However, the cost function does not directly evaluate the involvement of multi-mode components, and an optimization approach based on trial and error rather than analytical methods cannot be expected to yield improvements.

Consequently, the advantages of increasing the structural complexity to six sections and expanding the number of dimensional parameters do not appear to have been fully utilized.

Refining the Cost Function

While a cost function that directly evaluates the multimode interaction would be ideal, a quantitative metric for this remains elusive. Although the calculation results from NEC2++ include the current distribution on surface patches – which could theoretically be used to determine the excitation status of higher-order modes – I have yet to successfully integrate this into a cost function, either qualitatively or quantitatively.

Returning to the fundamental objectives of a feed antenna, the requirements are:

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- High illumination efficiency for the parabolic reflector.
- Symmetry in H/V polarization characteristics of the main lobe.
- Low side-lobe levels.
- Minimal pickup of ground thermal noise from the reflector edges.

Reflecting on previous attempts, it is clear that the cost functions used did not adequately evaluate these factors. To achieve "high illumination efficiency," the efficiency should be calculated directly. Similarly, to "lower side-lobes and minimize ground noise pickup," the antenna equivalent noise temperature should be calculated directly. In essence, these two points converge on the optimization of G/T (Gain-to-Noise Temperature ratio). Although I initially sought simpler cost functions, the problem ultimately returned to G/T, the standard evaluation method for antenna systems. Optimizing for G/T should inherently lead to the appropriate excitation of multiple modes. The "12 dB taper at the edge" is merely a heuristic for G/T optimization, not necessarily the ultimate goal; the optimal result might be -11 dB or -13 dB.

Implementing "Pseudo G/T": Based on this reflection, I have refined the cost function. Ideally, this would be the total G/T of the combined feed and parabolic reflector system. however, calculating the full radiation pattern for the entire parabolic antenna structure is computationally prohibitive. Therefore, I have developed a cost function that evaluates a "Pseudo G/T" using only the characteristics of the standalone feed antenna.

Gain (G): Since gain is proportional to illumination efficiency, I calculate the feed antenna's illumination efficiency directly.

Noise Temperature (T): When the parabolic antenna is directed toward the zenith, the antenna noise temperature is substituted by integrating the feed antenna's radiation pattern over the equivalent noise temperature of the reflector (i.e., the sky noise temperature) and the ground noise temperature seen beyond the reflector edges.

While this "Pseudo G/T" does not allow for an absolute comparison of feed antenna characteristics, it is effective for comparing relative performance during optimization.

Calculation Methodology: To calculate illumination efficiency, I ported the BASIC code from Reference **[11]** to GNU Octave. For the pseudo noise temperature, I assumed a sky temperature (T_{sky}) of 30 K and a ground temperature (T_{gnd}) of 300 K. The calculation involves integrating the radiation pattern multiplied by: T_{sky} for the angles subtended by the parabolic reflector. T_{gnd} for the region from the reflector edge to the horizon. T_{sky} for the region from the horizon back to the zenith.

The "Pseudo G/T" is derived from these G and T values. Since the optimization algorithm seeks to minimize a value, the cost is defined as T/G. Reference **[12]** provides further details on G/T evaluation and calculation methods.

Final Cost Function Definition: The improved cost function to be minimized is the sum of the following two metrics:

- The average difference between H-plane and V-plane polarization in the main lobe.
- The Pseudo T/G ratio.

Figure-1 through **Figure-3** (shown previously) illustrate the results of the optimization using this refined cost function. The resulting geometry – characterized by a negative flare angle in the tapered section (narrowing rather than widening) - clearly indicates the successful excitation and adjustment of multimode performance.

Conclusion

Using open-source simulation tools and PSO, I attempted the optimized design of a feed antenna. The result is a unique geometry that suggests complex multi-mode excitation, achieving both excellent H/V symmetry and a superior G/T profile.

Future challenges include physical fabrication, empirical measurement to verify simulation accuracy, and resolving the manufacturing difficulties posed by the unique multi-section shape.

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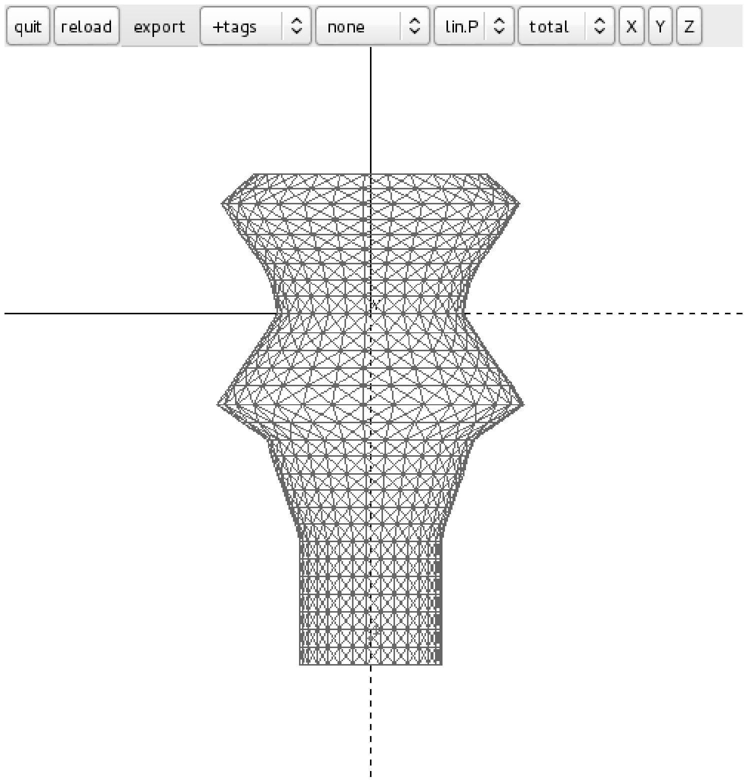

Figure-1 : Simulation model – Pseudo G/T optimized horn antenna (F = 0.55)

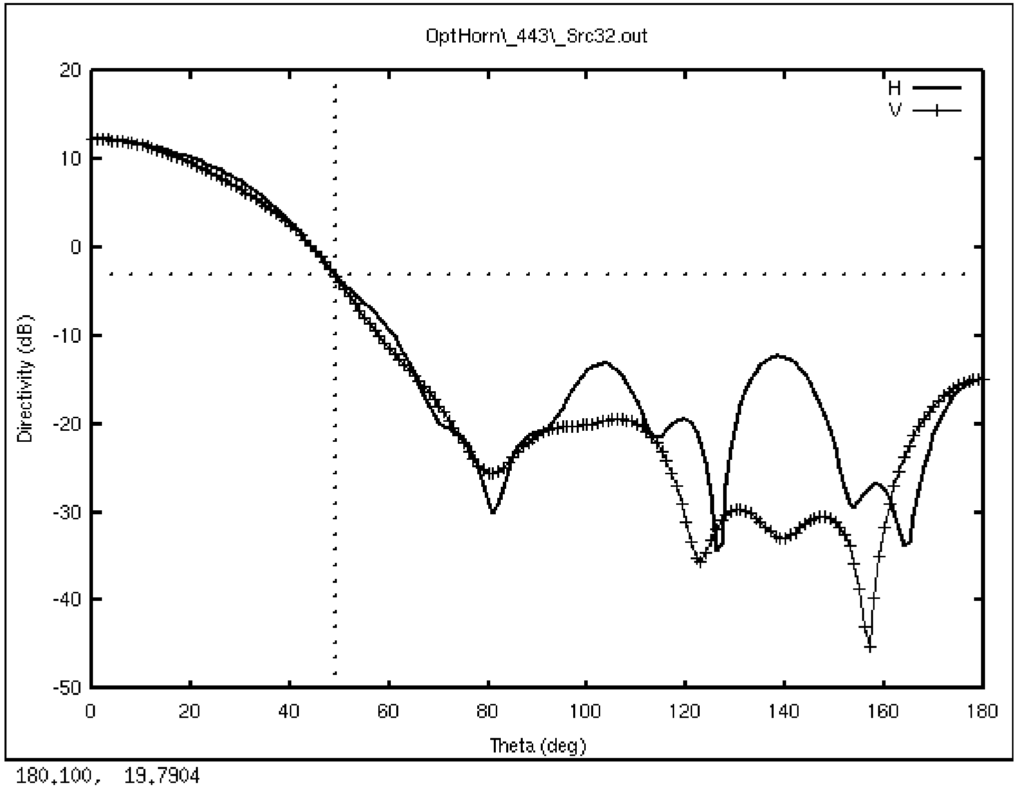

Figure-2 : Radiation pattern – Pseudo G/T optimized horn antenna (F = 0.55)

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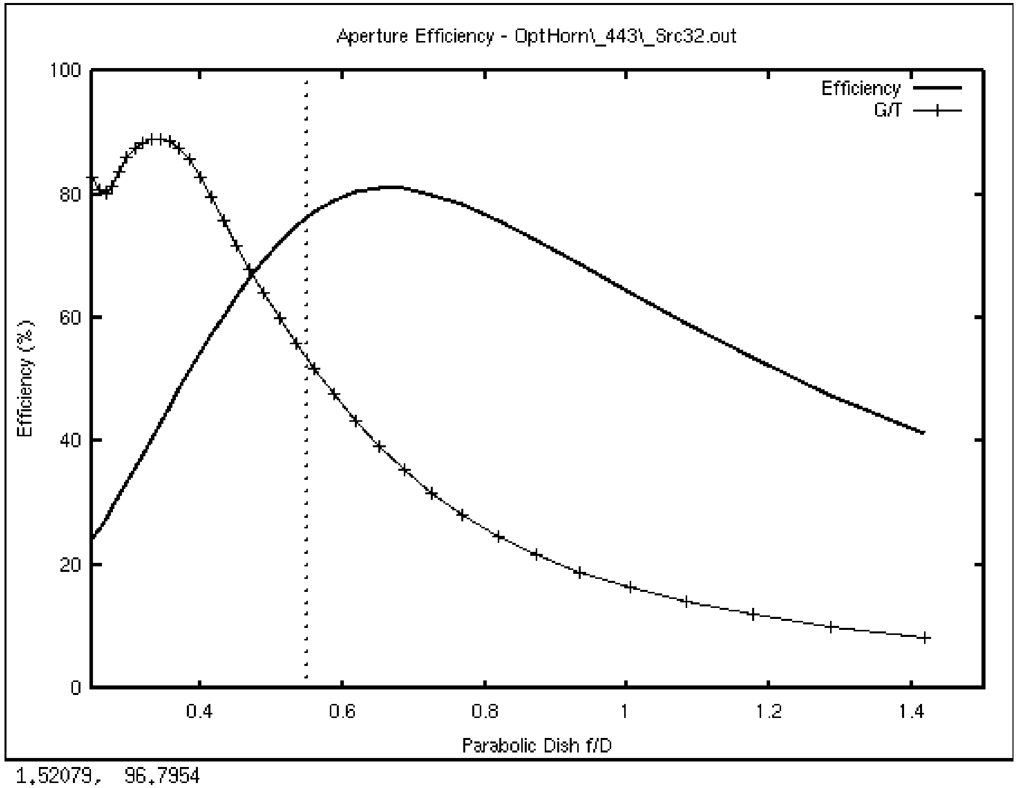

Figure-3 : Illumination efficiency / Pseudo G/T – Pseudo G/T optimized horn antenna (F = 0.55)

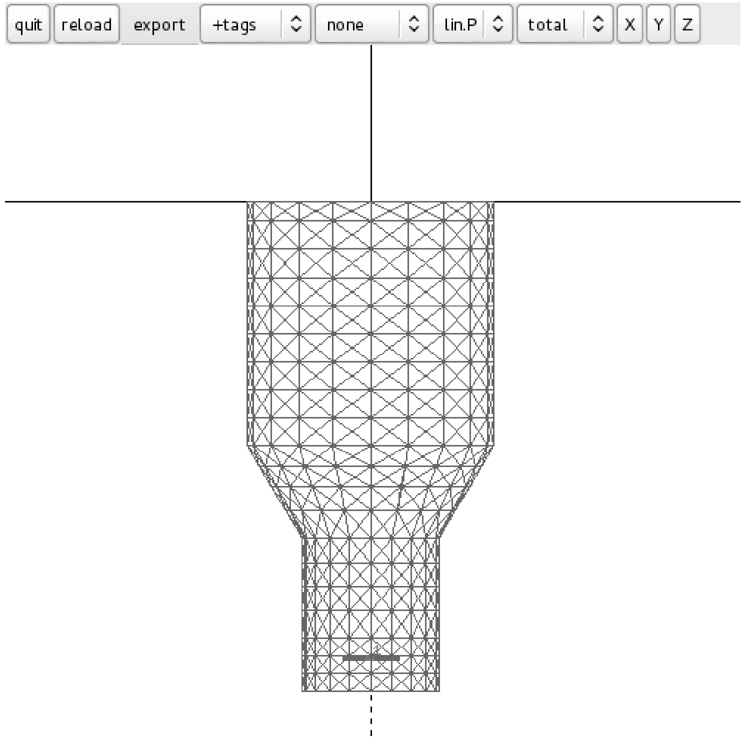

Figure-4 : Simulation model – W2IMU horn antenna (F = 0.55)

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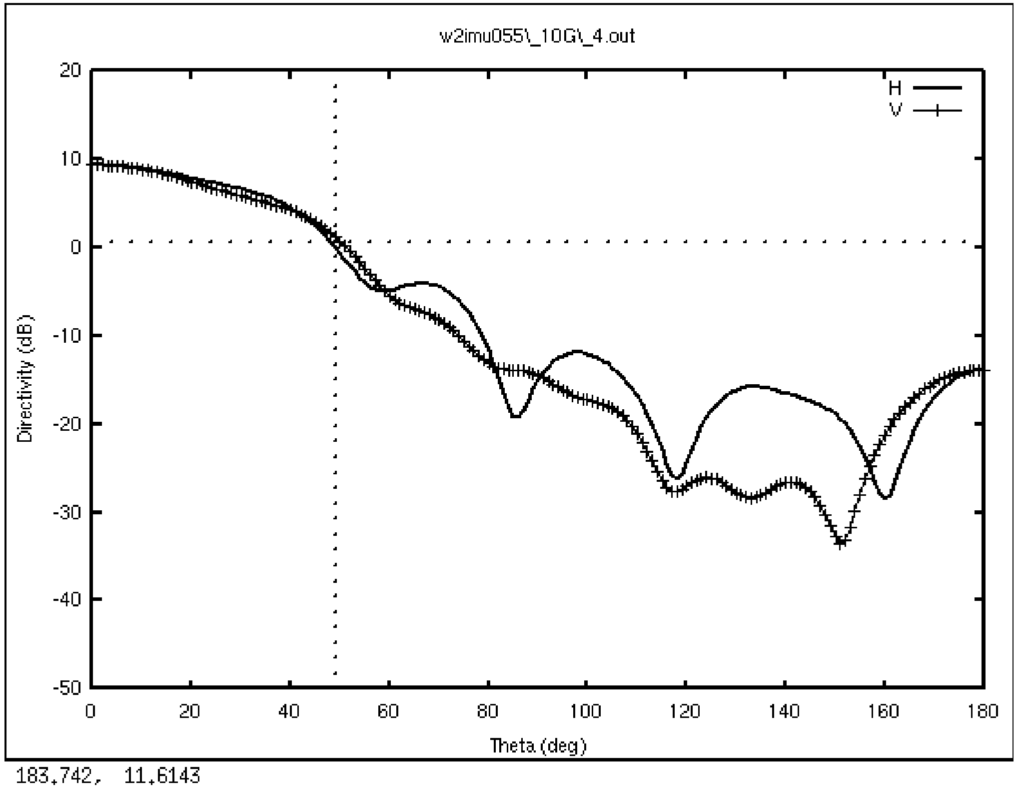

Figure-5 : Radiation pattern – W2IMU horn antenna (F = 0.55)

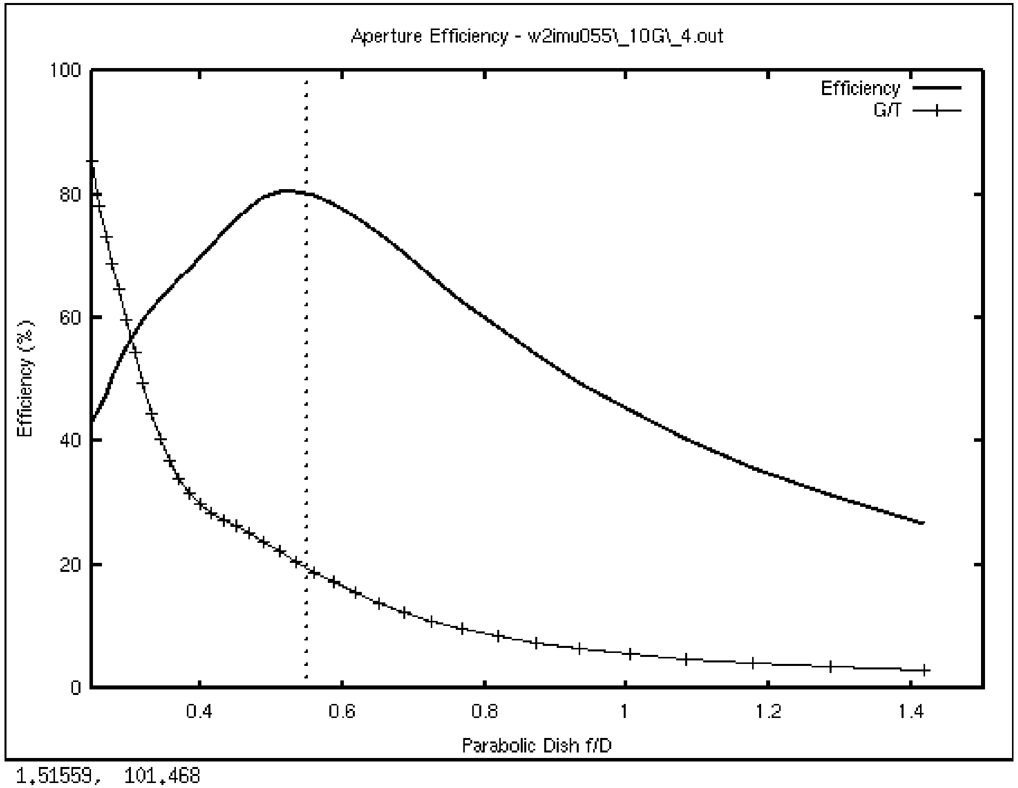

Figure-6 : Illumination efficiency / Pseudo G/T
– W2IMU horn antenna (F = 0.55)

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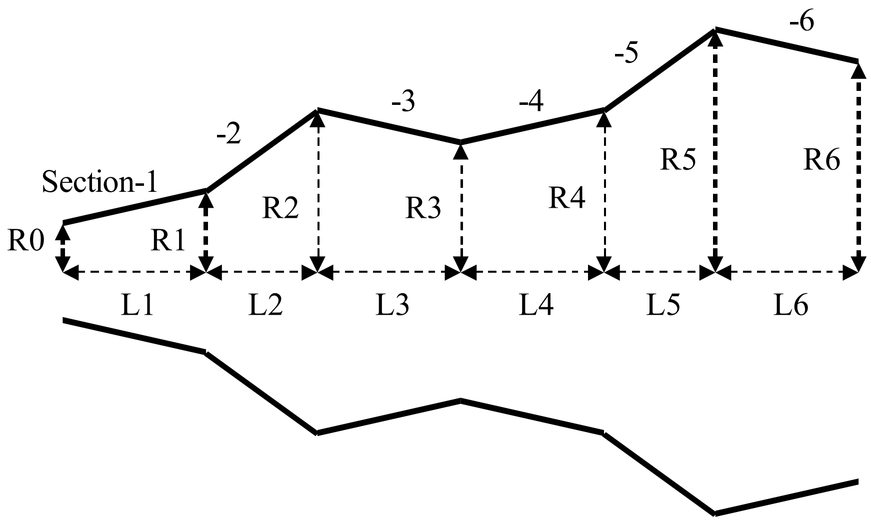

Figure-7 : Dimensional definition of six-section horn antenna

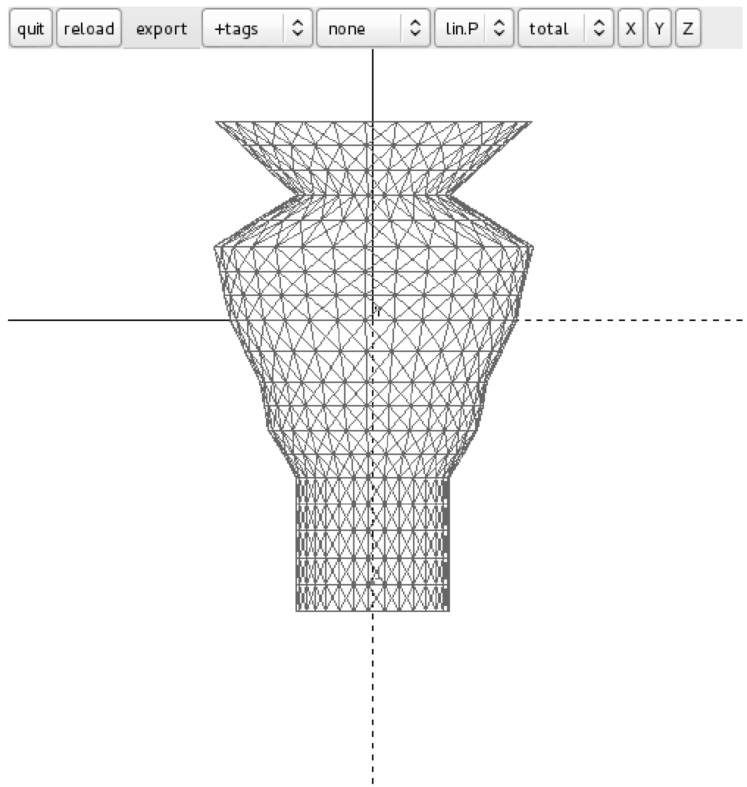

Figure-8 : Simulation model
– Illumination taper optimized horn antenna (F = 0.55)

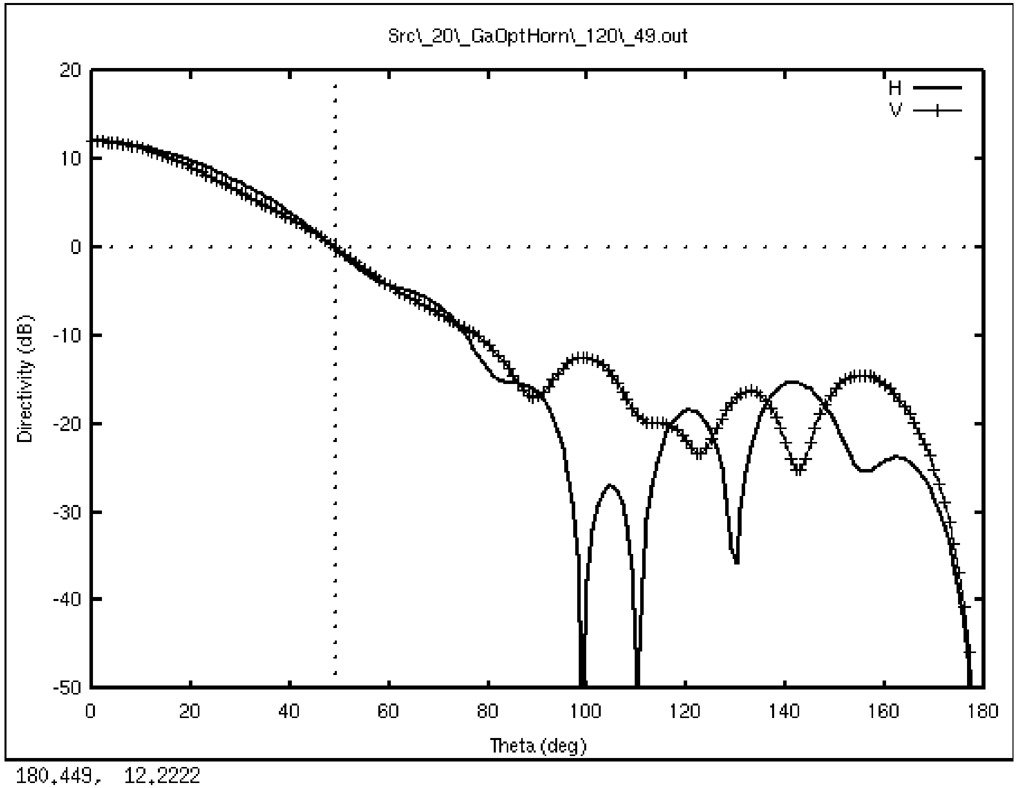

Figure-9 : Radiation pattern
- Illumination taper optimized horn antenna

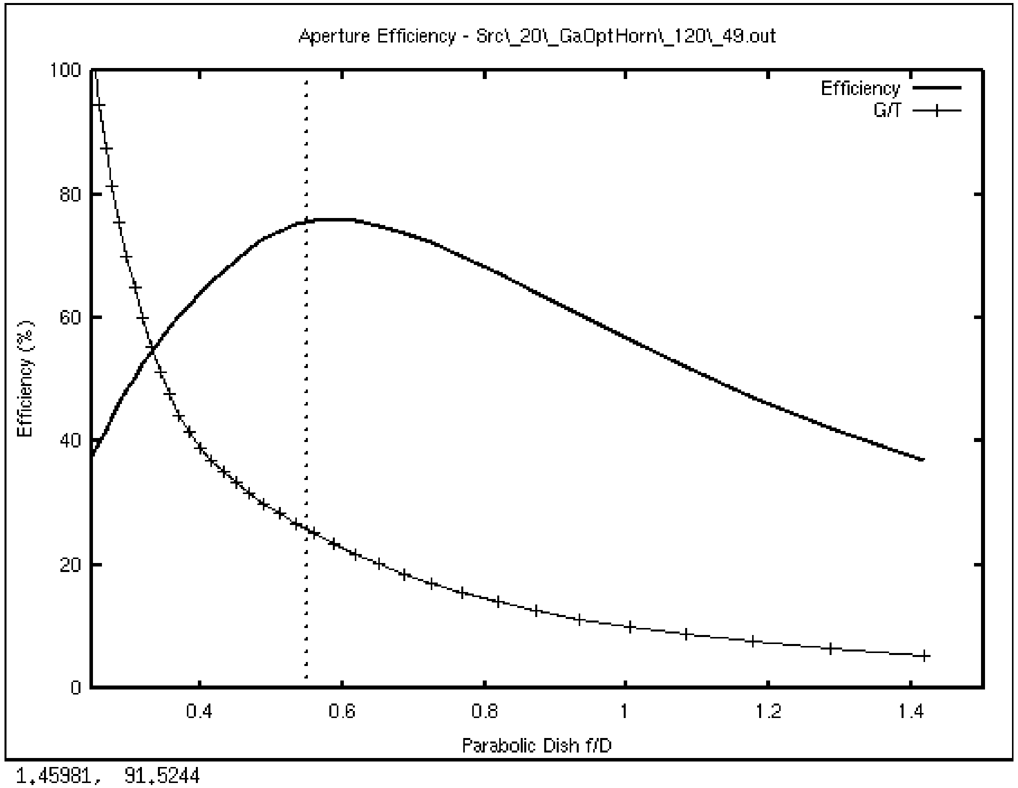

Figure-10 : Illumination efficiency / Pseudo G/T
- Illumination taper optimized horn antenna